GJO–2001–297–TAR
MAC–GWSHP1.9

Final Ground Water Compliance Action Plan for Remediation at the Shiprock, New Mexico, UMTRA Site

July 2002

Work Performed Under DOE Contract No. DE–AC13–96GJ87335 for the U.S. Department of Energy

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Prepared by
U.S. Department of Energy
Grand Junction Office
Grand Junction, Colorado

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Acronyms and Abbreviations

ACL	alternate concentration limit
cfs	cubic feet per second
COC	contaminants of concern
DOE	U.S. Department of Energy
EA	Environmental Assessment
EPA	U.S. Environmental Protection Agency
ft	feet
ft^3	cubic feet
GCAP	Ground Water Compliance Action Plan
gpm	gallons per minute
HELP	Hydrologic Evaluation of Landfill Performance
LTSM	Long-Term Surveillance and Maintenance
MCL	maximum concentration limit
mg/L	milligrams per liter
mi	mile
mi^2	square mile
NECA	Navajo Engineering and Construction Authority
PEIS	Programmatic Environmental Impact Statement
RAP	Remedial Action Plan
SDWA	Safe Drinking Water Act
SOWP	Site Observational Work Plan
T&E	threatened and endangered
UMTRA	Uranium Mill Tailings Remedial Action

1.0 Introduction

This Final Ground Water Compliance Action Plan (GCAP) for the Shiprock, New Mexico, Uranium Mill Tailings Remedial Action (UMTRA) Project site describes the scope of ground water remediation activities, which are planned to be conducted in two phases. The first phase of site remediation consists of extraction of ground water from the terrace east area of the site, extraction of ground water from the contaminant plume on the floodplain area as an aid to the natural flushing process, monitoring of the contamination levels in the floodplain, and monitoring of water levels and contamination levels in the terrace area. Conceptually the second phase of remediation consists of the installation of a flow barrier and interceptor drain in the floodplain at the base of the escarpment. The purpose of the barrier is to stop contaminated terrace ground water from entering the floodplain should any still exist in the terrace east area after remedial action. This will allow natural flushing on the floodplain to proceed.

Remediation of surface contamination was achieved by the U.S. Department of Energy (DOE) when the disposal cell at the Shiprock site was completed in 1986. The Remedial Action Plan (RAP) (DOE 1985) documents the design and compliance aspects of the disposal cell. A summary of the site history and extent of ground water contamination are provided in this GCAP as background information. Detailed information about the site and nature and extent of contamination is in the Final Site Observational Work Plan (SOWP), Revision 2, for the UMTRA Project Site at Shiprock, New Mexico (DOE 2000).

The GCAP provides a brief background of the site and describes the compliance strategy, the selected remediation method, and components of the remediation. Section 2.0, “Site Information,” summarizes contamination in the ground water, describes the terrace and floodplain ground water systems and their interaction with surface water in the area, and discusses the extent of contamination of the terrace and floodplain systems. Section 3.0, “Ground Water Compliance Strategy,” discusses the regulatory drivers and documents how the compliance strategy selection process defined in the Programmatic Environmental Impact Statement (PEIS) (DOE 1996) was used to select the compliance strategies at the Shiprock site. Section 4.0, “Selected Remedial Action,” describes the remediation method that will be used to comply with the standards in 40 CFR 192, discusses the implementation plan for the remediation, and discusses limitations of the remediation method. Included as appendices are the monitoring plan for ground and surface water in the terrace and floodplain areas, and the design drawings and construction specifications for the remediation system constructed as Phase I on the terrace and floodplain and the Phase II construction of the flow barrier and interceptor drain on the floodplain.

End of current text

2.0 Site Information

2.1 Site Location and Information

The Shiprock UMTRA site is in the Navajo Nation in San Juan County in the northwest corner of New Mexico, approximately 28 miles (mi) west of Farmington (Figure 2–1). 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 is on the NECA facility. The UMTRA disposal cell, which covers 76 acres, is immediately east of the NECA facility. From the center of the town of Shiprock (junction of U.S. Highways 64 and 666), the disposal cell on the site is about 1 mi to the south, on an elevated, gravel and cobble-covered terrace overlooking the northwest-flowing San Juan River and its floodplain. The site area is south of the San Juan River and extends from the disposal cell about 1 mi to the southeast and 1.5 mi to the northwest.

The UMTRA site lies at an elevation of approximately 5,000 feet (ft). The desert climate has an average annual precipitation of about 7 inches. Almost half of this precipitation falls in the form of brief, intense downpours during the Southwest monsoonal storms that occur during months of July through October. Average snowfall is less than 10 inches per year. The arid climate and relatively thin air result in diurnal temperature variations of about 35 °F. Summer maximum and minimum Fahrenheit temperatures average in the 90's and 50's, respectively, while winter maximum and minimum Fahrenheit temperatures average in the 40's and the teens. The all-time record high is 109 °F, and the record minimum is –26 °F.

The disposal cell and adjacent former millsite area sit on an elevated terrace overlooking the floodplain of the San Juan River. The terrace is trisected by two minor north-northeast drainages, Bob Lee Wash and Many Devils Wash. At the northeast edge of the terrace, an escarpment 50 to 60 ft high forms the boundary between the San Juan River floodplain and the terrace area to the south. The crescent-shaped floodplain area immediately north of the disposal cell extends southeast upstream from the U.S. Highway 666 bridge to a point about 1,500 ft downstream from Many Devils Wash confluence. The horizontal distance from the disposal cell to the San Juan River is about 600 ft. The site and vicinity are shown in Figure 2–2.

A layer of gray Mancos Shale of Cretaceous age forms the bedrock underlying the entire site. Ground water in the floodplain is hydrologically connected to the San Juan River and receives inflow from an artificial ground water system in the terrace. In the northwest part of the site west of U.S. Highway 666, a distributary channel (former river channel) of the San Juan River is adjacent to the escarpment. The south edge of the site area is marked by the appearance of weathered Mancos Shale that forms a subtle upland area. In the subsurface, this boundary is abrupt in the form of a buried bedrock escarpment that marks the south edge of terrace alluvial material deposited by the ancestral San Juan River.

In this high desert environment, vegetation is sparse in the nonirrigated areas of the terrace and in the upland, and sparse to thick in the riparian environment in the San Juan River floodplain. Some agriculture occurs on the terrace in the northwest part of the site where irrigation is supplied by the Helium Lateral Canal system.

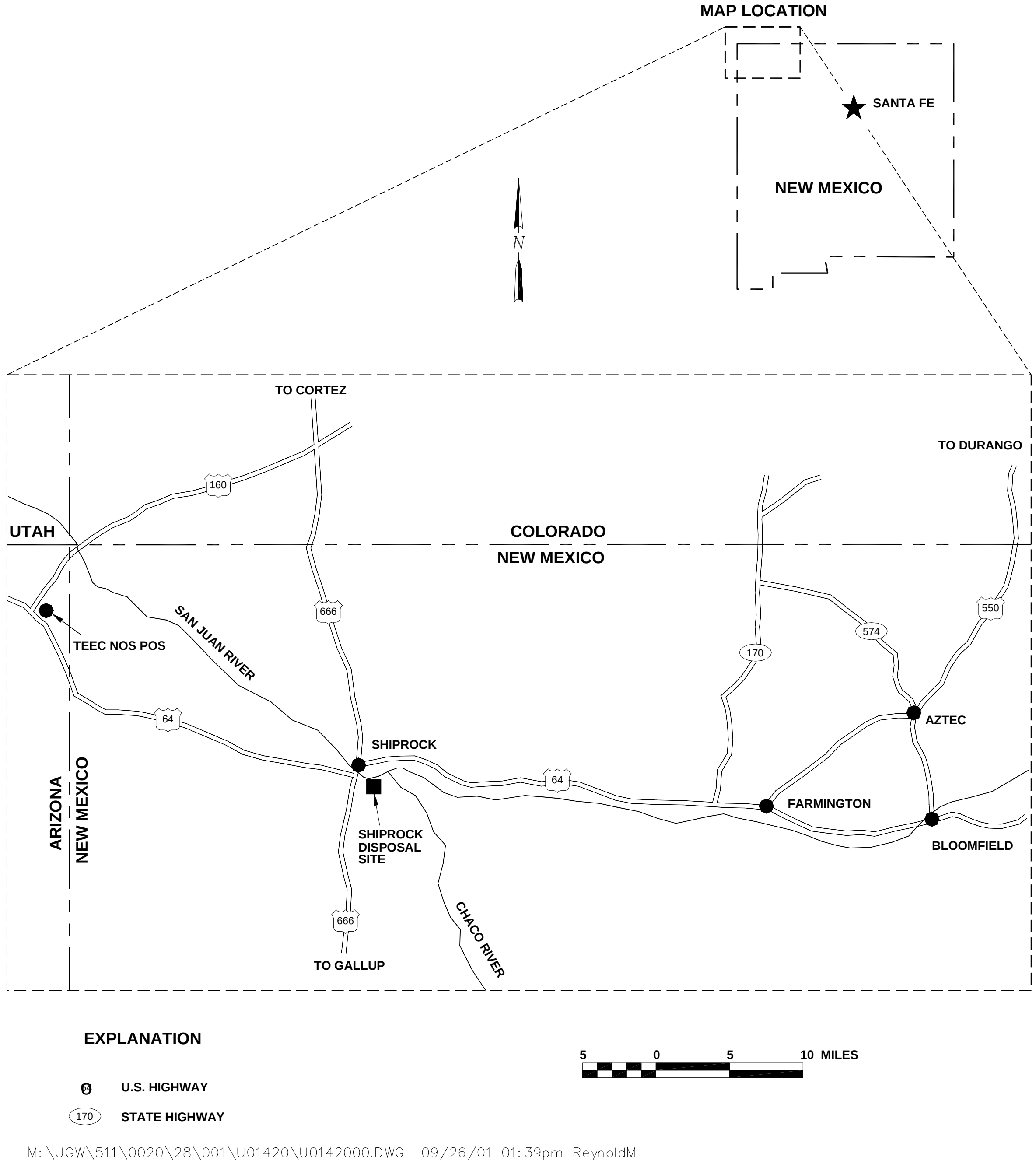

Figure 2–1. Site Location Map

Several thousand people live in the site area south of the San Juan River in the south part of the sprawling unincorporated community of Shiprock. Land use is varied across the site area. Grazing of a few sheep, goats, and cows occurs in the open lands southeast of the NECA gravel pit and in the upland area south of the disposal cell. The only perennial source of surface water available for these animals is the San Juan River. Grazing of some cows and horses also occurs in the fields irrigated by water from the Helium Lateral Canal in the northwest part of the site. No grazing is allowed in the floodplain area immediately north of the disposal cell.

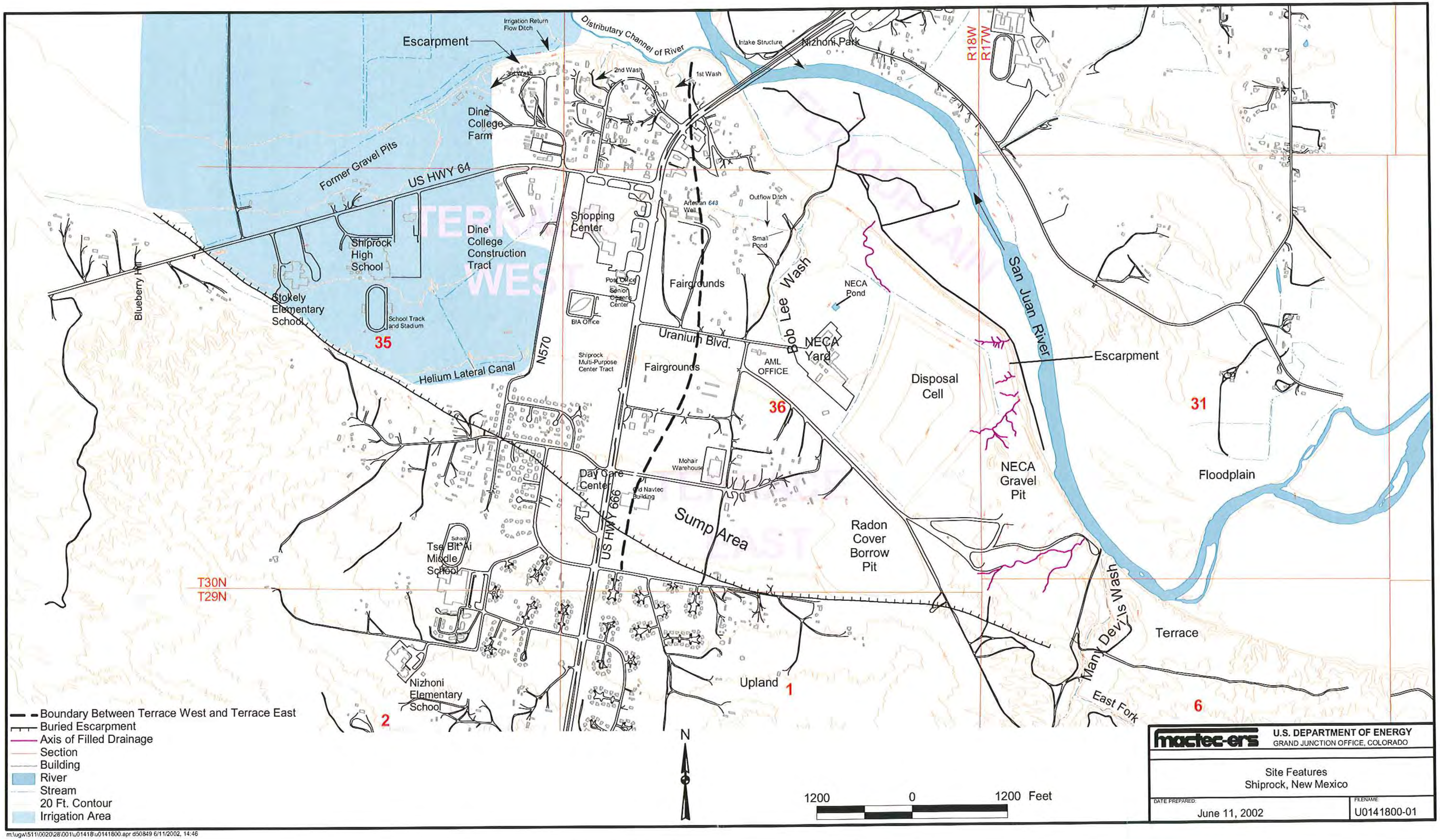

Figure 2–2. Shiprock Site and Surrounding Area

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Commercial and administrative developments and various housing areas are about 0.5 to 1 mi west of the disposal cell. An elementary school, a high school, and a new site for Diné College (under construction) are just more than 1 mi to the west. No ground water from the floodplain is being used in the site area. The only known ground water use from the terrace area is at the high school property where a well is used for irrigating the school grounds, and about 0.5 mi northwest of the disposal cell where water from a deep artesian well is infrequently used for livestock watering.

The terrace is further divided into terrace west and terrace east areas for compliance strategy purposes, reflecting different amounts of contamination and a different balance of ground water recharge. The boundary between the two areas of the terrace is shown in Figure 2–2.

2.2 History

The uranium-vanadium mill, known as the Navajo Mill, operated from 1954 to 1968. The site had been leased from the Navajo Nation, and control reverted to the Navajo Nation when the leases expired in 1973. During its operating lifetime, the mill processed about 1.5 million tons of ore, producing about 7.9 million pounds of U_3O_8 and 35.4 million pounds of V_2O_5. The mill was initially designed for an acid cure process, in which ore was allowed to “cure” by soaking in a sulfuric acid solution for 12 hours or longer. The acid cure process is designed primarily to recover vanadium. A decrease in the vanadium market about 1 year after the plant opened led to its conversion to an agitation leach process, with recovery of uranium only. Shortly thereafter, a solvent extraction process was added to supplement, and eventually to replace, the original fixed-bed ion exchange process. By 1957, the solvent extraction process had been modified into a two-stage process that included vanadium recovery with a strong acid solution. The two solvent extraction processes used di(2-ethylhexl) phosphoric acid (EHPA) and tributyl phosphate (TBP) in a base of high flash-point kerosene. Alcohol was probably added as a modifying agent, nitrate and ammonium complexes were added as ion exchange strippers to concentrate uranium, and ammonia was used for pH adjustment of the slurry (Merritt 1971).

Tailings from the washing circuit were pumped to ponds on two tailings piles just to the east. Raffinate from the solvent extraction operation was allowed to evaporate in up to ten unlined raffinate ponds that covered approximately 20 acres just south and southwest of the tailings piles. Water for the milling process was pumped from the San Juan River at an intake about 0.6 mi east-southeast of the mill.

The Shiprock mill was shut down in 1968. Between 1968 and 1973, when the lease on the millsite reverted to the Navajo Nation, some of the mill buildings and most of the equipment were dismantled and placed in the west tailings pile. Shortly after the Navajo Nation assumed control of the site in 1973, the Navajo Tribal Chairman asked officials from the U.S. Environmental Protection Agency (EPA) and other federal agencies for assistance in stabilizing the tailings piles. EPA subsequently surveyed the site and recommended decontaminating the site and stabilizing the tailings. Decontamination work under EPA guidance began in January 1975 and continued until 1980.

Uranium Mill Tailings Radiation Control Act legislation in 1978 specified significant changes to remedial action criteria for former uranium millsites compared with the decommissioning work that had already taken place at the Shiprock site. A series of surface and ground water characterization studies were performed in the early 1980s for preparation of the RAP in 1985. The DOE conducted surface remedial actions in late 1985 and 1986 consisting of removing windblown and water-transported contaminated soils from the area surrounding the millsite and tailings piles and placing this material in an engineered disposal cell on site. The two tailings piles were consolidated and encapsulated to form the disposal cell.

A long-term surveillance plan was prepared for the disposal site in 1994. After this plan was approved, the U.S. Nuclear Regulatory Commission issued a license in September 1996 to the DOE–Grand Junction Office for the long-term care of the site; the license also deferred site ground water cleanup to the UMTRA Ground Water Project.

2.3 Ground and Surface Water Characteristics

This section summarizes hydrologic characteristics of surface and ground water at the Shiprock site, along with a description of the water quality of the San Juan River. A more complete and detailed description of site hydrology is presented in the SOWP.

2.3.1 Hydrology

The hydrology of the Shiprock site consists of a number of surface water systems: San Juan River; flowing artesian well 648; numerous seeps, springs, and washes; irrigation return flow; wetlands on the floodplain at the mouth of Bob Lee Wash; and the ground water systems, both natural and artificial, on the floodplain, the terrace, and the bedrock flow system. These systems were discussed in detail in the SOWP. The following sections summarize key information about the site.

2.3.1.1 Surface Water

The San Juan River drains an area of approximately 12,900 square miles (mi^2) upstream from the town of Shiprock. The average historic flow in the San Juan River at Shiprock is 2,175 cubic feet per second (cfs). The construction in 1963 of Navajo Dam, 78 mi upstream of Shiprock, moderated the former extreme variability in flow rates; maximum and minimum flow rates since 1963 have been 15,000 and 80 cfs, respectively. Since 1963, Navajo Dam has also reduced the average flow rate in the San Juan River to an estimated 1,000 cfs.

The San Juan River is classified as a domestic water supply for primary and secondary human contact and for other purposes. The town of Shiprock and the city of Farmington draw most of their water supplies not from the San Juan River, but from Farmington Lake, which is fed by the Animas River. However, the town of Shiprock has a secondary water intake, used in an emergency water-supply situation, that draws from the north bank of the San Juan River, just across the river from the floodplain part of the Shiprock UMTRA site. Consequently, stringent water quality standards are applied to the San Juan River that directly impact the remediation of the Shiprock site.

The Chaco River, which drains more than 4,000 mi^2, joins the San Juan River about 2 mi upstream of the Shiprock site. The Chaco River drains many areas in the San Juan Basin that contain coal and uranium. Flow in the Chaco River ranges from 10 to 30 cfs during non-storm periods, though much of the flow is reported to be effluent from the Four Corners Power Plant about 12 mi southeast of the Shiprock site.

Bob Lee Wash is just northwest of the UMTRA site. Discharge from flowing artesian well 648 drains eastward in a ditch to Bob Lee Wash. The well discharge of approximately 64 gallons per minute (gpm) accounts for essentially all of the surface water in Bob Lee Wash. A wetland of about 5 acres is on the floodplain near the mouth of Bob Lee Wash. Discharge from the wetland flows slowly northwestward along a drainage (abandoned distributary) channel on the floodplain and enters the San Juan River just upstream from the U.S. Highway 666 bridge.

Many Devils Wash is southeast of the UMTRA site. Surface water in Many Devils Wash is confined largely to the northernmost, or lower, 1,800 ft of the wash bottom. The source of water in the wash is likely from the west, derived from the artificially saturated terrace alluvium and underlying weathered Mancos Shale. Discharge at the mouth of Many Devils Wash has been measured at 0.3 gpm, which flows into the San Juan River.

Three additional washes drain the terrace area west of the U.S. Highway 666 bridge. These washes, which have no formal name, are designated 1st, 2nd, and 3rd Washes, east to west, respectively. Estimates of the rate of discharge in winter 1999 were 1.5 gpm in 1st Wash and about 0.2 gpm in 2nd Wash. No flow has been seen in 3rd Wash. These washes discharge to the distributary channel of the San Juan River west of the U.S. Highway 666 bridge.

The escarpment along the San Juan River west of the mouth of Many Devils Wash contains numerous active seeps and springs that issue from the Mancos Shale cliffs. The seepage flow is very low, normally visible as damp zones along the cliff face. White efflorescent crust at other locations along the cliffs suggests that seepage has been more common in the past than it is today. Spring-fed flow has been measured at 1 gpm at seeps 425 and 426; spring flow at location 935 has been estimated at 1.5 gpm near the mouth of 1st Wash, and the spring at location 786 under the U.S. Highway 666 bridge has a comparable flow. Numerous springs and ponds are north of Shiprock High School. Surface flows from these locations enter the irrigation return flow ditch and ultimately discharge northward to the San Juan River via the distributary channel.

2.3.1.2 Ground Water

The floodplain alluvial aquifer is north of the disposal cell in the millsite floodplain area between the San Juan River and the base of the escarpment. It consists of unconsolidated medium- to coarse-grained sand, gravel, and cobbles that are in direct hydrologic communication with the San Juan River. The SOWP presented hydrographs showing that the aquifer responds to fluctuations in San Juan River levels. The other boundary of the floodplain system is at the contact with the base of the escarpment, where the flux is dependent on the head. A portion of the surface water from Bob Lee Wash (discharged from well 648) is being channeled from the outflow ditch into a small pond, which leaks considerably and discharges onto the floodplain just west of the mouth of Bob Lee Wash. Also, some flow from well 648 continues in the outflow ditch eastward from the small pond and into Bob Lee Wash.

The contribution from Bob Lee Wash is the major source of water to the floodplain and dominates the hydrodynamics of the floodplain. Table 4–5 in the SOWP presented the water balance on the floodplain, showing that the discharge from Bob Lee Wash constituted about 56 percent of the total inflow for the floodplain alluvial aquifer. The other sources of inflow to the floodplain were the San Juan River and the terrace via the Mancos Shale, which each contributed 16 percent of the total inflow, and recharge of precipitation and runoff, which contributed 12 percent of the total. (The total inflow shown in Table 4–5 in the SOWP is incorrect. The actual total inflow is 22,120 cubic feet [ft^3] per day.) The total volume of water in the floodplain alluvial aquifer is estimated at 20.1 million ft^3 or 150 million gallons.

The terrace ground water system occupies the alluvial material deposited over the Mancos Shale by the ancestral San Juan River. Along the south part of the terrace system, the ancestral river channel eroded a swale in the underlying Mancos Shale bedrock. A buried escarpment (similar to the present escarpment north of the disposal cell) at the south edge of the swale marks the south boundary of the terrace system. Water flow in the terrace system moves to the northwest, as shown in the piezometric surface map of the site in Figure 2–3, along the axis of the channel toward the area irrigated by the Helium Lateral Canal.

Aerial photographs of the future millsite area taken in 1935 show no surface water or surface-water-dependent vegetation in the terrace, and no evidence of seepage along the escarpment. No ground water has been found in any of the test wells 1 to 2 mi east-southeast of the disposal cell in a similar terrace area that receives no recharge from irrigation. Therefore, all of the ground water in the terrace system is assumed to be anthropogenic.

In the SOWP, the terrace water balance estimated that the total infiltration into the terrace system from milling activities was about 308 million gallons. The present volume of water in the terrace east system was estimated as 38 million gallons. It is likely that infiltration of water during the period of milling operations was sufficient to create the terrace east ground water system, but that natural recharge is insufficient to create a natural aquifer. Ground water modeling performed subsequent to the final SOWP indicates that the net recharge of the terrace east ground water system is significantly lower than the estimates in the SOWP. The total annual inflow and outflow on terrace east is presently estimated at about 2.2 million gallons. This would be insufficient to create a natural aquifer. However, a net infiltration of 80 to 85 million gallons into the terrace east system during the years of milling would have been more than enough to have created the 38-million-gallon terrace east system.

Initial numerical modeling of contaminant concentrations presented in the SOWP suggested that drainage from the disposal cell was about 4.2 million gallons per year (or approximately 8 gpm). More recent modeling by Knight Piesold and Company (2002) using the Hydrologic Evaluation of Landfill Performance (HELP) model to simulate infiltration of precipitation through the disposal cell resulted in values of flow from the disposal cell ranging from 2.5 to 4.8 gpm.

However, the seepage flux emanating from the disposal cell is uncertain and could be much less than the seepage range predicted in recent modeling. The DOE has elected, with the support of the Navajo Nation, to implement Phase I remedial action and use the observational approach to determine seepage flux effects on the performance of the remedial action.

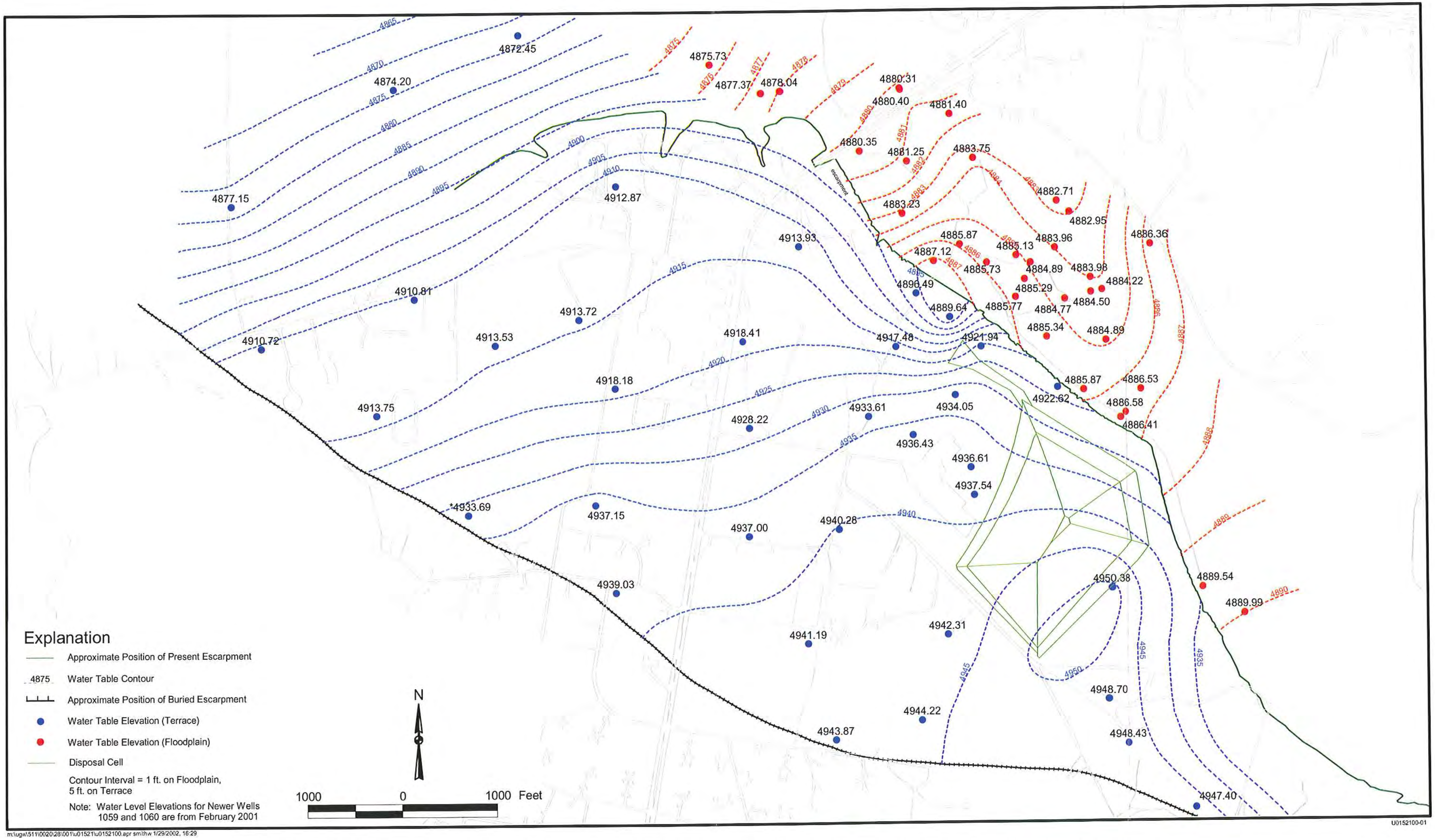

Figure 2–3. Approximate March 1999 Contours of Piezometric Surface for Both Floodplain Alluvial Aquifer and the Terrace Ground Water System

2.3.2 Water Quality of the San Juan River

Table 2–1 presents results of water quality monitoring performed by DOE at sample locations 940, at the edge of the floodplain along the south bank of the San Juan River, and 956, on the north bank of the river in the vicinity of the emergency intake for the water supply of the town of Shiprock. This table also shows the flow rate of water in the river on the day that sample was taken. The river flow rates were measured at the U.S. Geological Survey gauge 09368000 at the emergency intake structure. With only one exception, the concentrations of the selected analytes are below the standards for domestic and primary human-contact designated uses in the surface water quality standards of the Navajo Nation (Table 2–2). The exception is the uranium concentration from water sampled at location 940 in February 2000; this concentration exceeded both the Navajo Nation surface water quality standard and the EPA ground water maximum concentration limit (MCL) of 0.044 milligrams per liter (mg/L). In general, the results indicate that millsite-related contaminants do not pose a threat to the quality of the water in the San Juan River. However, the fact that one analysis has indicated a potential threat under certain conditions shows that continued monitoring will be required.

Table 2–1. Surface Water Quality in San Juan River

South Bank of San Juan River (Location 940)							
Date	**Flow, cfs**	**Arsenic (mg/L)**	**Nitrate (mg/L)**	**Selenium (mg/L)**	**Sulfate (mg/L)**	**TDS (mg/L)**	**Uranium (mg/L)**
06/06/1999	7,030	<0.001	0.513	<0.001	41	158	0.00032
02/03/2000	835	<0.0004	22.5	<0.001	504	1020	0.0469
06/20/2000	674	0.00045	0.781	0.0006	138	362	0.0035
07/14/2000	295	0.00094	0.102	0.00047	142	400	0.0021
11/16/2000	526	0.00032	1.42	0.0007	169	435	0.0021
02/08/2001	524	NA	3.18	0.00055	211	497	0.0055
North Bank of San Juan River (Location 956)							
Date	**Flow, cfs**	**Arsenic (mg/L)**	**Nitrate (mg/L)**	**Selenium (mg/L)**	**Sulfate (mg/L)**	**TDS (mg/L)**	**Uranium (mg/L)**
06/16/2000	938	0.0004	0.394	0.00041	102	297	0.0015
07/12/2000	427	0.00045	0.109	0.00052	139	378	0.002
11/17/2000	942	0.00036	1.53	0.00078	160	408	0.002
02/13/2001	801	NA	1.73	0.00074	176	430	0.0019

NA = Not analyzed

Table 2–2. Navajo Nation Surface Water Quality Standards for Domestic Purposes for Selected Constituents

Constituent	Surface Water Quality Standards, in mg/L
Arsenic	0.05
Total Nitrogen	10
Selenium	0.05
Sulfate	NS
TDS	NS
Uranium	0.035

NS = No standard exists

2.4 Ground Water Contamination

The contaminants of concern (COCs) that have been identified for the Shiprock site are ammonium, manganese, nitrate, selenium, strontium, sulfate, and uranium.

During active uranium and vanadium milling, 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 the winter months, raffinate was also disposed of by evaporation in separate holding ponds. The milling operations, as noted above, used large amounts of sulfuric acid and ammonia, as well as smaller amounts of organic solvents, which were transported to the tailings and raffinate ponds (Merritt 1971). Ground water contamination at the site is believed to have resulted from infiltration of the milling fluids, and leaching of ore and uranium mill tailings constituents by mill water and rainwater. Using data from Merritt (1971) for the average flow to the tailings ponds, site evaporation rates calculated from pan evaporation data to estimate losses from the ponds to evaporation, and an estimate of total runoff to the floodplain alluvium from a U.S. Department of Health, Education, and Welfare (1962) study, the SOWP estimated that the cumulative volume of water infiltrated into the terrace alluvium during the 14 years of milling operations was approximately 308 million gallons.

Water has been added to the terrace area of the site from sources other than the Navajo Mill. From 1944 through the 1950s, water was used in a helium-processing plant built by the U.S. Bureau of Mines at the present site of the Shiprock Shopping Center (Figure 2–2). Starting in the late 1950s, irrigation water was brought to the terrace west area by a siphon from the Hogback Canal, which diverts water from the San Juan River; this siphoned water was distributed into the Helium Lateral Canal system for agricultural use. In 1961 a test hole was drilled on the terrace about 0.5 mi northwest of the disposal cell area. This hole, drilled to a depth of 1,850 ft into the Morrison Formation, was not capped. Artesian flow from this hole, now known as site well 648, has continued since 1961 and is currently flowing at a rate of about 64 gpm across the terrace into Bob Lee Wash, which drains to the floodplain and eventually to the San Juan River. This flow has been beneficial in flushing milling-related contamination from the northwest part of the floodplain.

2.4.1 Terrace

The boundary between terrace west and terrace east areas is just east of and roughly parallels U.S. Highway 666 as it passes through the town of Shiprock south of the San Juan River (Figure 2–2). The disposal cell and former millsite are in the terrace east system. Saturated thicknesses of the alluvial material in the terrace east system north of the sump area, shown in Figure 2–4, are thin to nonexistent; whereas, saturated thicknesses in the terrace west system increase from essentially zero at the boundary between the two areas to more than 16 ft in the area near the escarpment to the west of 1st Wash. A hydrologic connection between terrace east and terrace west ground water is shown in Figure 2–4 by the saturated alluvial material thickness of at least 4 ft extending northwest from the sump area to the area of borehole 834 in terrace west. This connection follows the ancestral river channel along the south edge of the terrace system.

Section 4.4.2.2 of the SOWP describes the terrace contamination in detail. Table 2–3 lists the concentrations of COCs in the terrace ground water system. No background concentrations are listed because no water has been detected at any of the wells that have been drilled in terrace

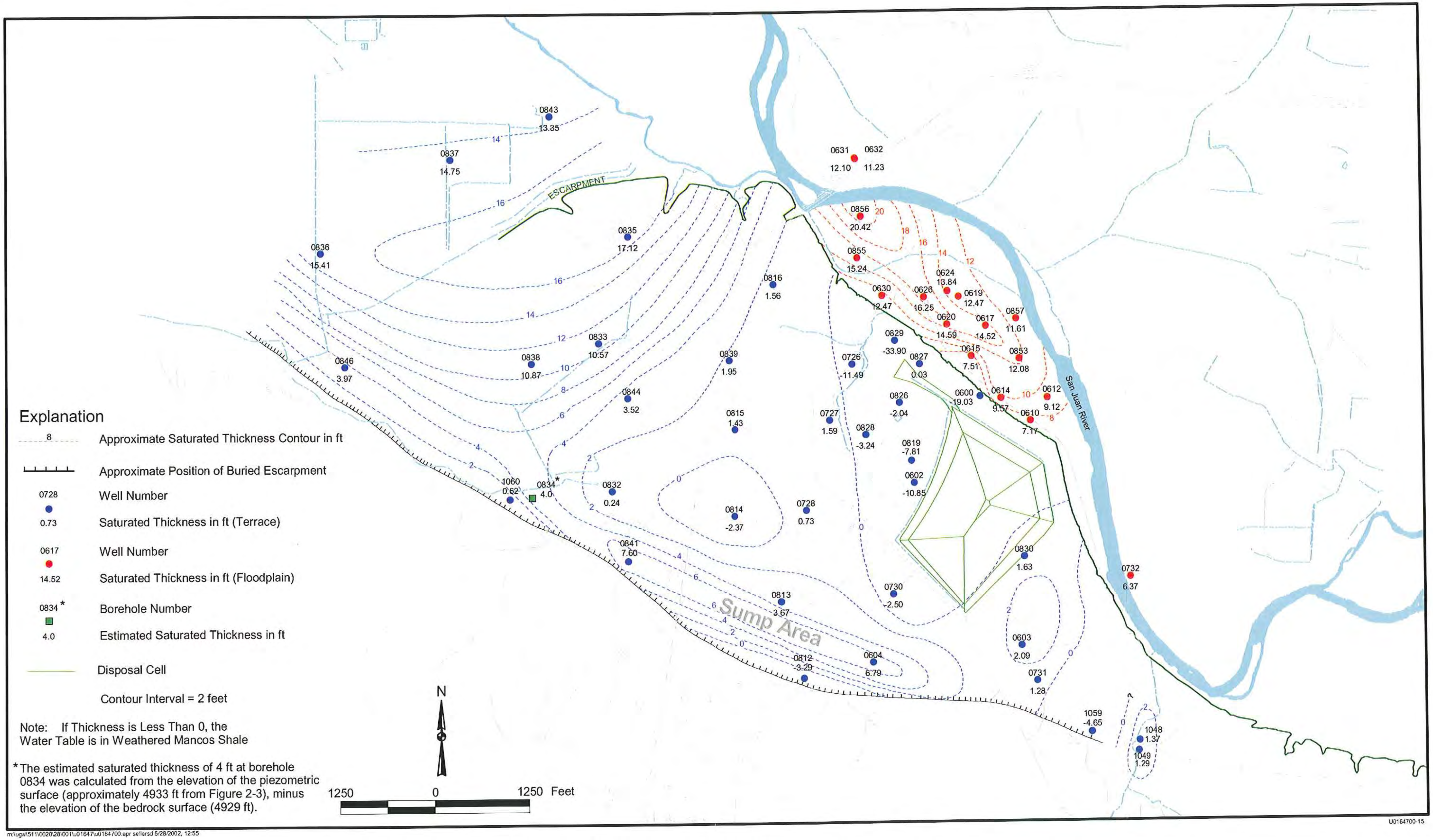

Figure 2–4. Saturated Thickness in Alluvial Material for Floodplain Alluvial Aquifer and Terrace Ground Water System

locations upgradient from the site. Therefore, no background concentrations have been identified for the terrace ground water system.

Table 2–3. Terrace Ground Water Data Summary

Terrace Contaminant	Frequency of Detection	Range mg/L	Mean mg/L
Ammonium	33/43	<0.0047 – 2,280	150
Manganese	40/43	<0.0001 – 22.6	1.93
Nitrate	43/43	0.315 – 10,300	1,588
Selenium	41/42	<0.0001 – 7.02	0.6645
Strontium	42/42	0.28 – 19.5	8.72
Sulfate	43/43	1,190 – 17,500	7,565
Uranium	43/43	0.0017 – 3.26	0.2963

The distribution of contaminants on the terrace is shown in the plume maps, Figure 2–5 through Figure 2–11. Several patterns of contamination are shown by the various contaminant plume maps. Ammonium concentrations (Figure 2–5) are highest mainly in areas of the former raffinate ponds and former millsite. Manganese concentrations (Figure 2–6) are highest in and near the former raffinate ponds area. High concentrations of the relatively mobile constituents nitrate (Figure 2–7) and sulfate (Figure 2–10) occur in much of the same areas and reflect movement from the raffinate pond area toward the sump area and Many Devils Wash; in addition, sulfate concentrations are also high in the former millsite area. High concentrations of selenium (Figure 2–8) and strontium (Figure 2–9) occur mainly in the sump area and may reflect migration from the raffinate ponds area or may reflect high natural concentrations of these elements in Mancos Shale, or a combination of both. Highest concentrations of uranium (Figure 2–11) are in the former millsite/ore storage area and a filled drainage east of the disposal cell; some migration of uranium has occurred to the west and southwest (sump area) from the millsite/ore storage area.

2.4.2 Floodplain

Section 4.4.2.1 of the SOWP describes the floodplain contamination in detail. Table 2–4 compares concentrations of the COCs, using sampling data from March 1999 through September 2001, to background levels, including the concentration ranges, frequency of detection, and means. The background concentrations are based on sampling data from June 1999 and February 2000 from three monitor wells (850, 851, and 852) in the San Juan River floodplain about 1 mi upstream from the millsite floodplain.

Table 2–4. Floodplain Alluvial Ground Water Data Summary

Floodplain Contaminant	Frequency of Detection	Background mg/L	Range mg/L	Mean mg/L
Ammonium	57/58	0.045	<0.0047 – 651.0	70.72
Manganese	35/35	1.24	0.0404 – 12.3	3.34
Nitrate	23/25	0.12	<0.0314 – 4,000	846
Selenium	32/35	<0.001	<0.0001 – 1.81	0.1865
Strontium	35/35	2.26	0.8450 – 20.1	9.28
Sulfate	74/74	1,432	423 – 31,500	9,679
Uranium	74/74	0.007	0.0297 – 4.4400	1.3979

The distribution of COCs on the floodplain is shown in the plume maps (Figure 2–12 through Figure 2–19). Contaminant concentrations are generally low in the northwest part of the floodplain as a result of the flushing effect of water from Bob Lee Wash (contributed by water from flowing artesian well 648) entering the floodplain. Low concentrations similarly occur in the east and southeast part of the floodplain adjacent to the San Juan River, which has recharged the aquifer and diluted the contaminants. The contaminant plume extending along the base of the escarpment from east of the disposal cell to north of the disposal cell and then in an arc northward across the floodplain to the San Juan River is well shown by the sulfate (Figure 2–18) and uranium (Figure 2–19) concentrations. Ammonium concentrations are highest along the base of the escarpment east of the disposal cell. Highest concentrations of manganese (Figure 2–13) and selenium (Figure 2–16) are in the arc-shaped plume across the floodplain north of the disposal cell. Strontium (Figure 2–17) concentration differences are subtle and are highest at the mouth of Bob Lee Wash and near the San Juan River at the north end of the arc-shaped plume.

Nitrate concentrations have been found to vary with depth of sampling in the floodplain ground water. Shallow samples constitute those collected from test pits and well points that were installed using a backhoe (less than 10 ft deep). Deeper samples were collected from borehole wells that are screened mainly in the lower part of the alluvial aquifer (mainly greater than 10 ft deep). Nitrate concentrations in shallow samples (Figure 2–14) are highest in the northern part of the arc-shaped floodplain plume, near the San Juan River. Nitrate concentrations from wells (Figure 2–15) show that the contaminant plume at deeper levels is mainly close to the escarpment. Ammonium oxidizes to nitrate, and this process is shown from the presence of high ammonium concentrations at shallow depths (Figure 2–12) and the high nitrate concentrations that develop (from oxidation) at deeper levels both east of the disposal cell and downgradient northward along the base of the escarpment.

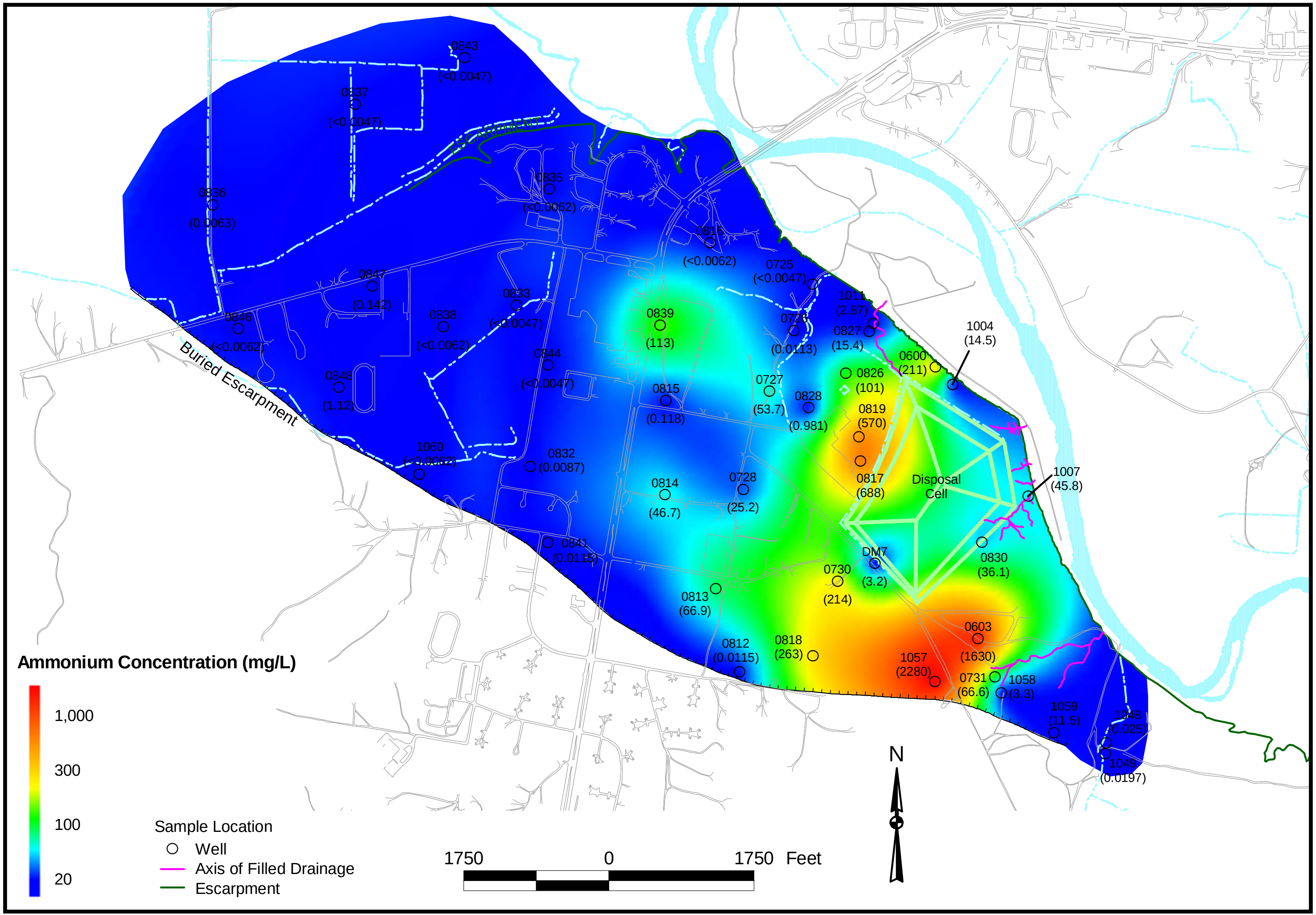

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Figure 2–5. Ammonium Concentrations in Terrace Ground Water (December 1998 through September 2001 data)

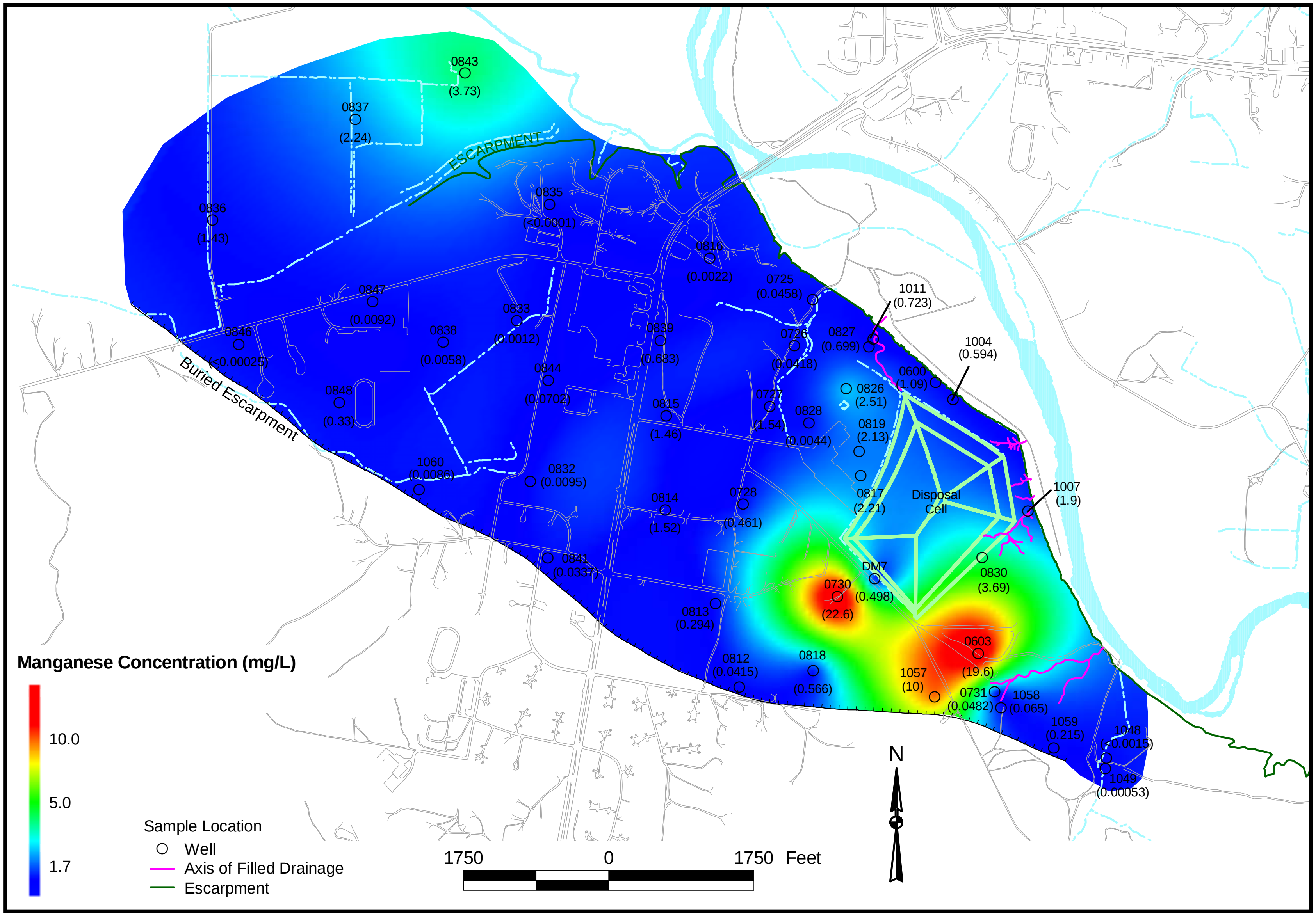

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Figure 2–6. Manganese Concentration in Terrace Ground Water (December 1998 through September 2001 data)

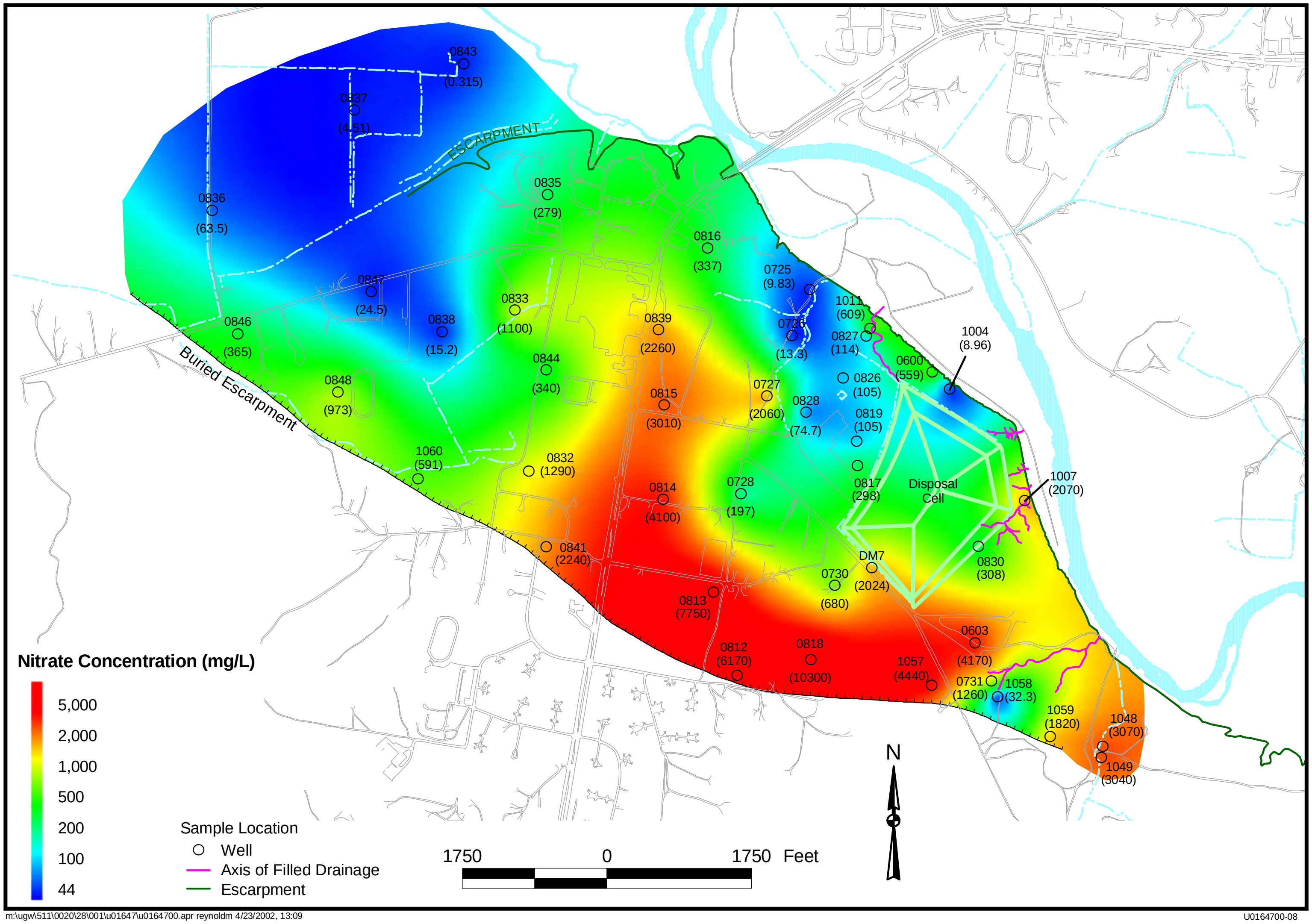

Figure 2–7. Nitrate Concentrations in Terrace Ground Water (December 1998 through September 2001 data)

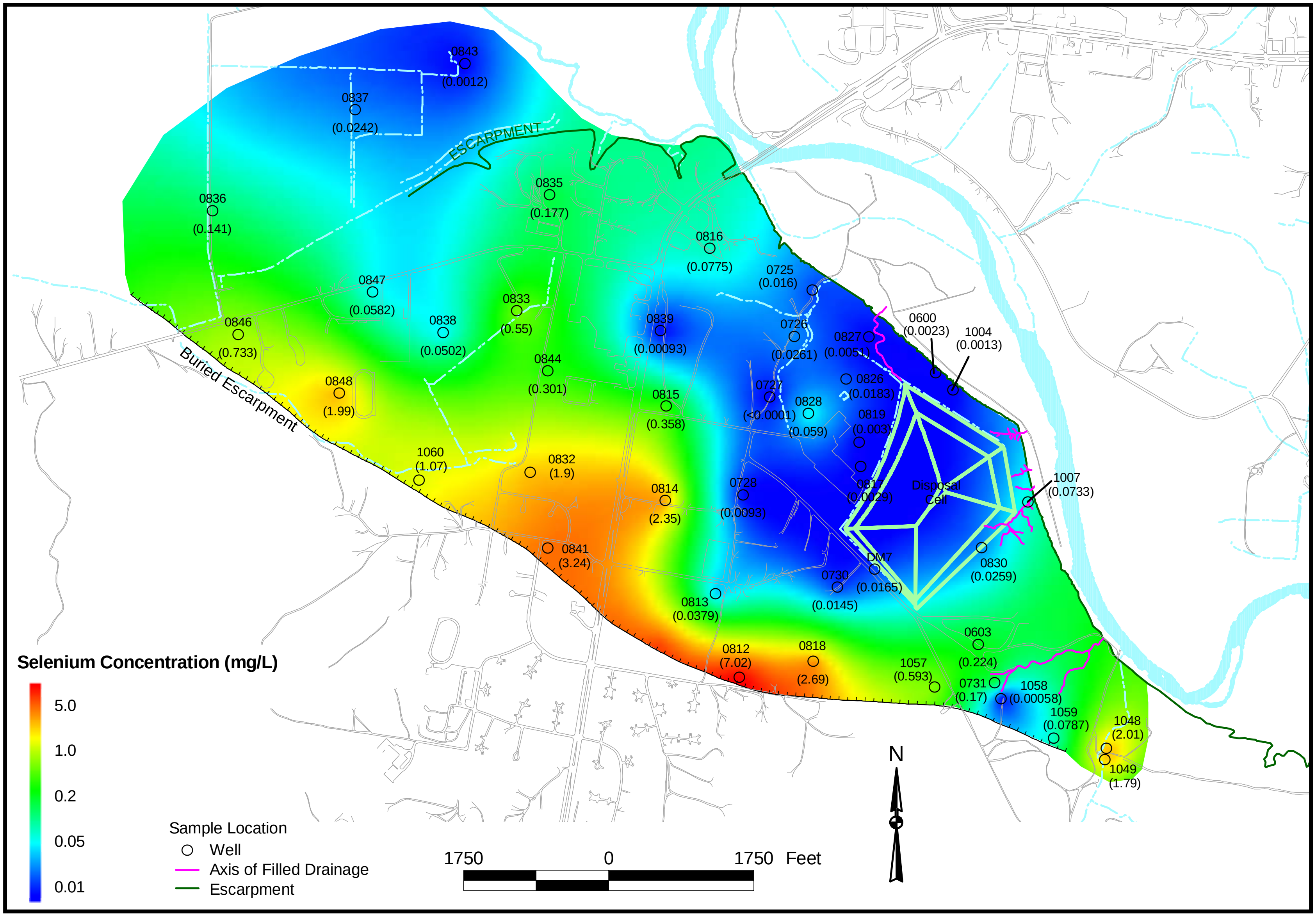

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Figure 2–8. Selenium Concentrations in Terrace Ground Water (December 1998 through September 2001 data)

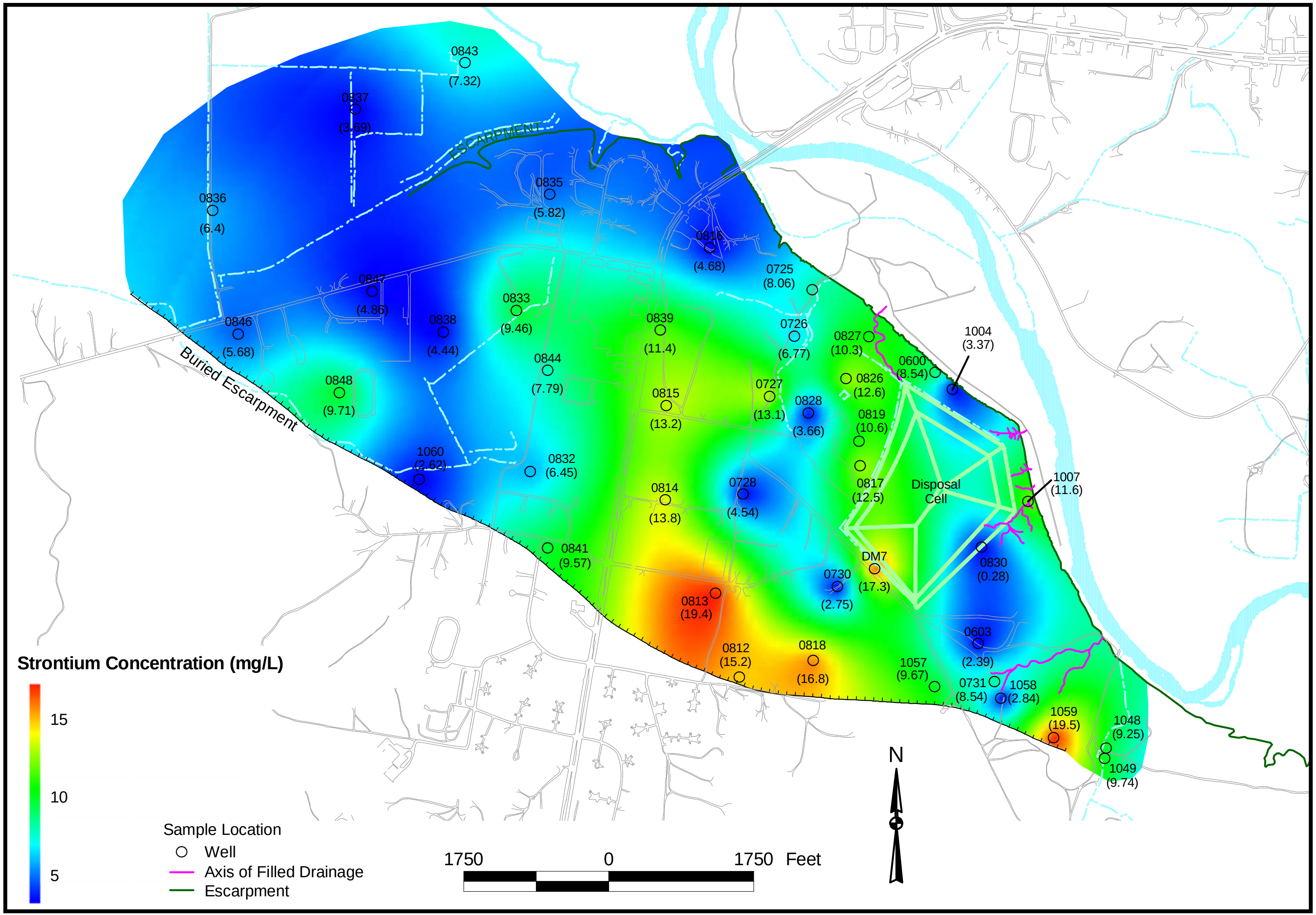

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Figure 2–9. Strontium Concentrations in Terrace Ground Water (December 1998 through September 2001 data)

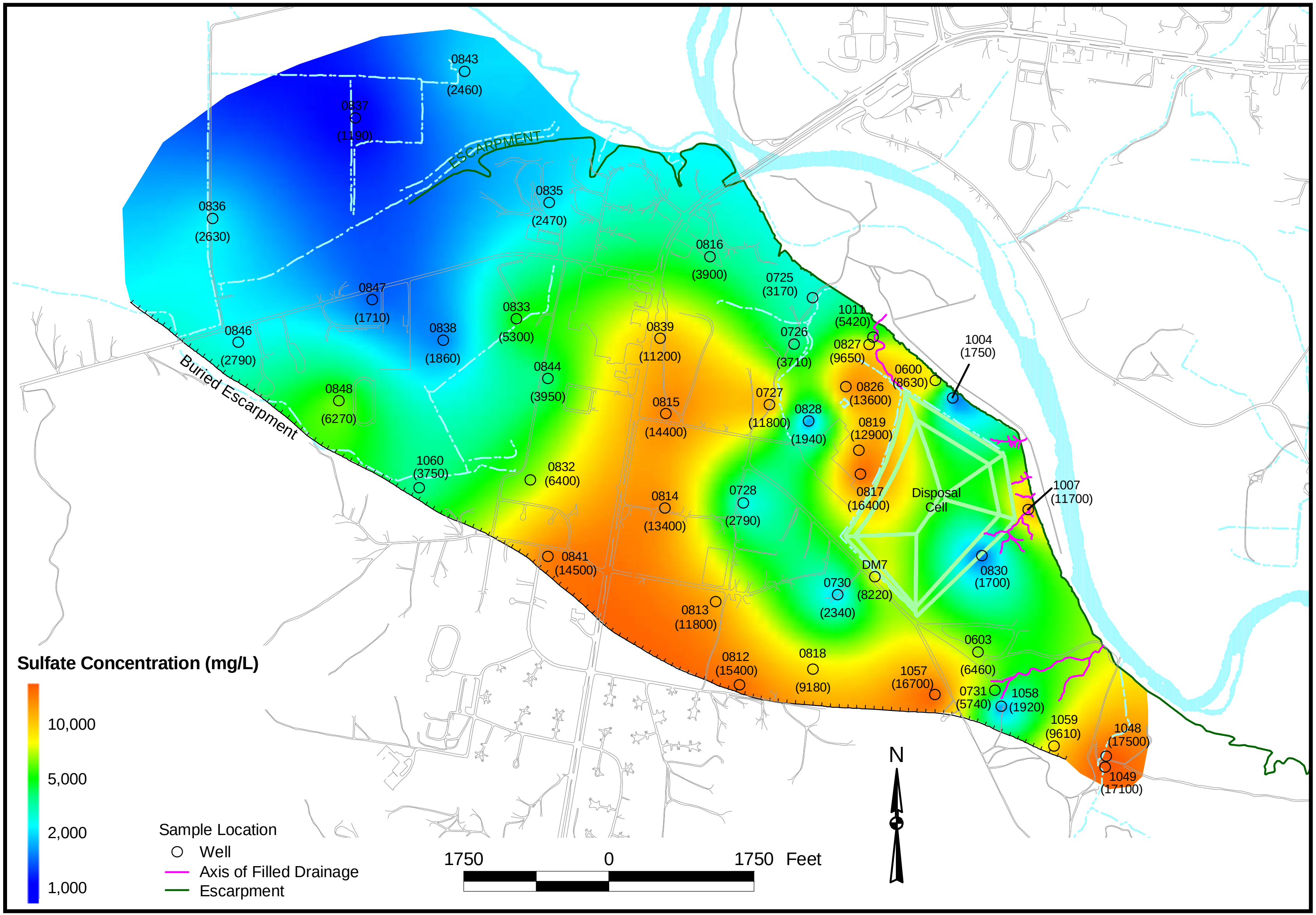

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Figure 2–10. Sulfate Concentrations in Terrace Ground Water (December 1998 through September 2001 data)

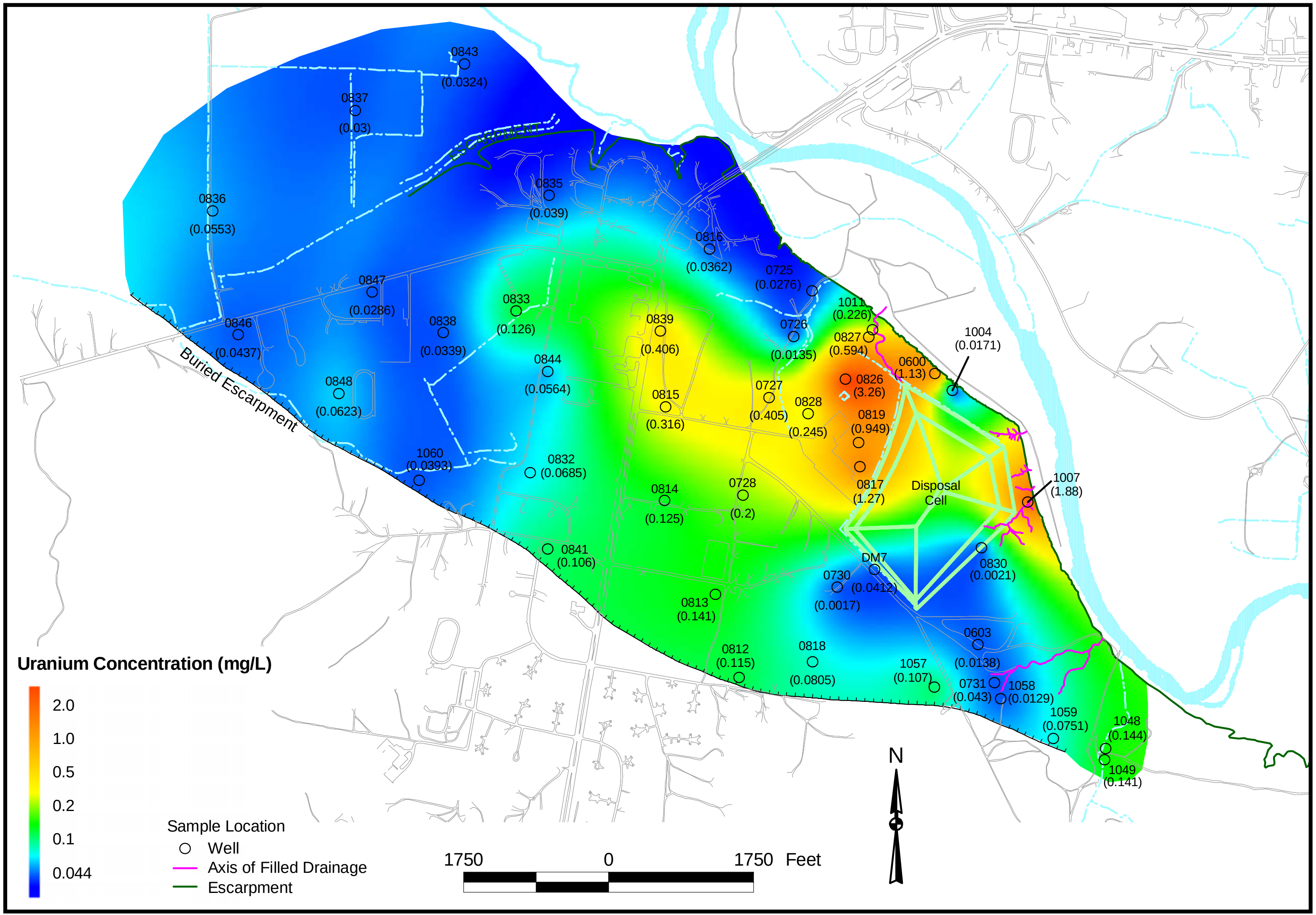

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Figure 2–11. Uranium Concentrations in Terrace Ground Water (December 1998 through September 2001 data)

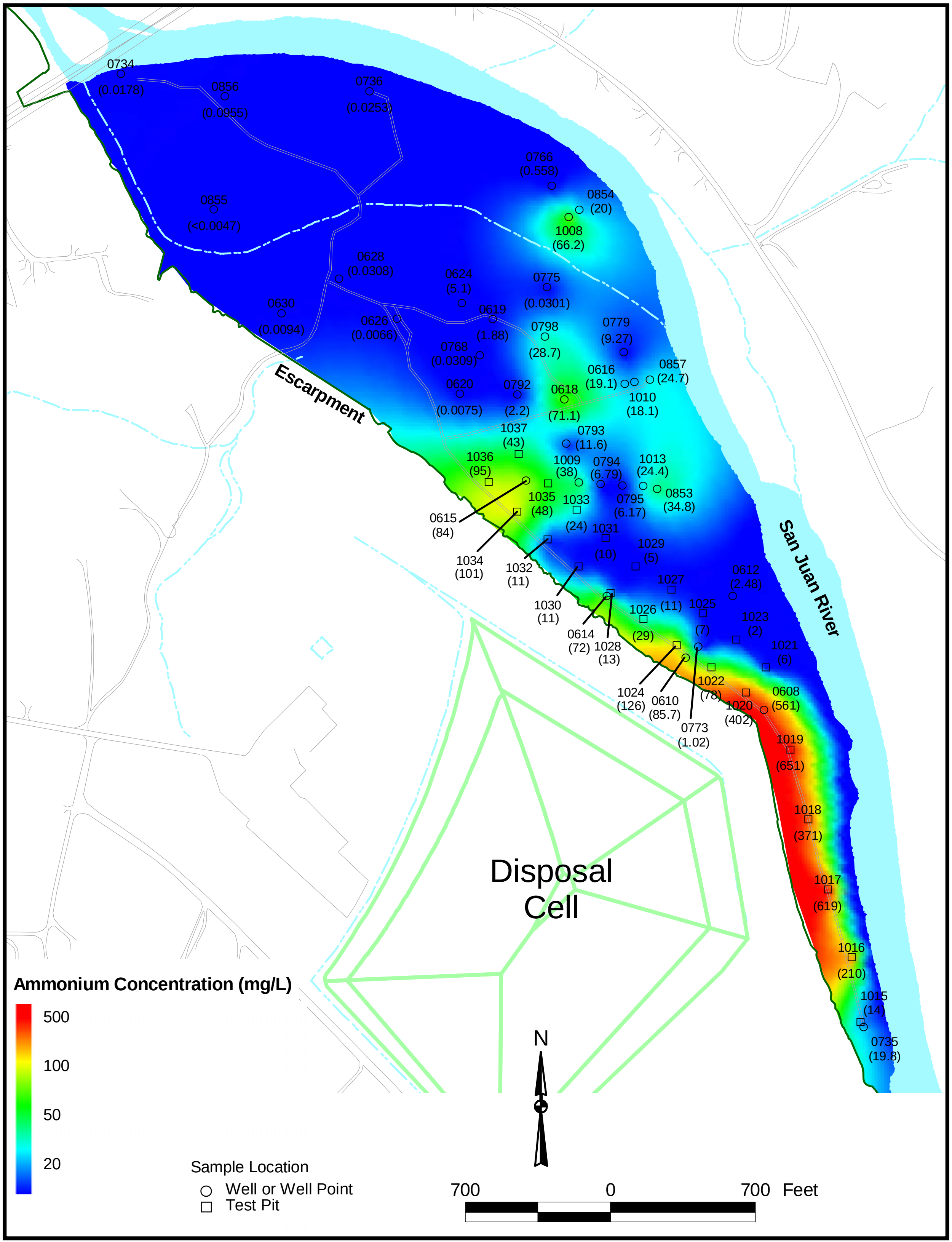

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Figure 2–12. Ammonium Concentration in Floodplain Ground Water (March 1999 through September 2001 data)

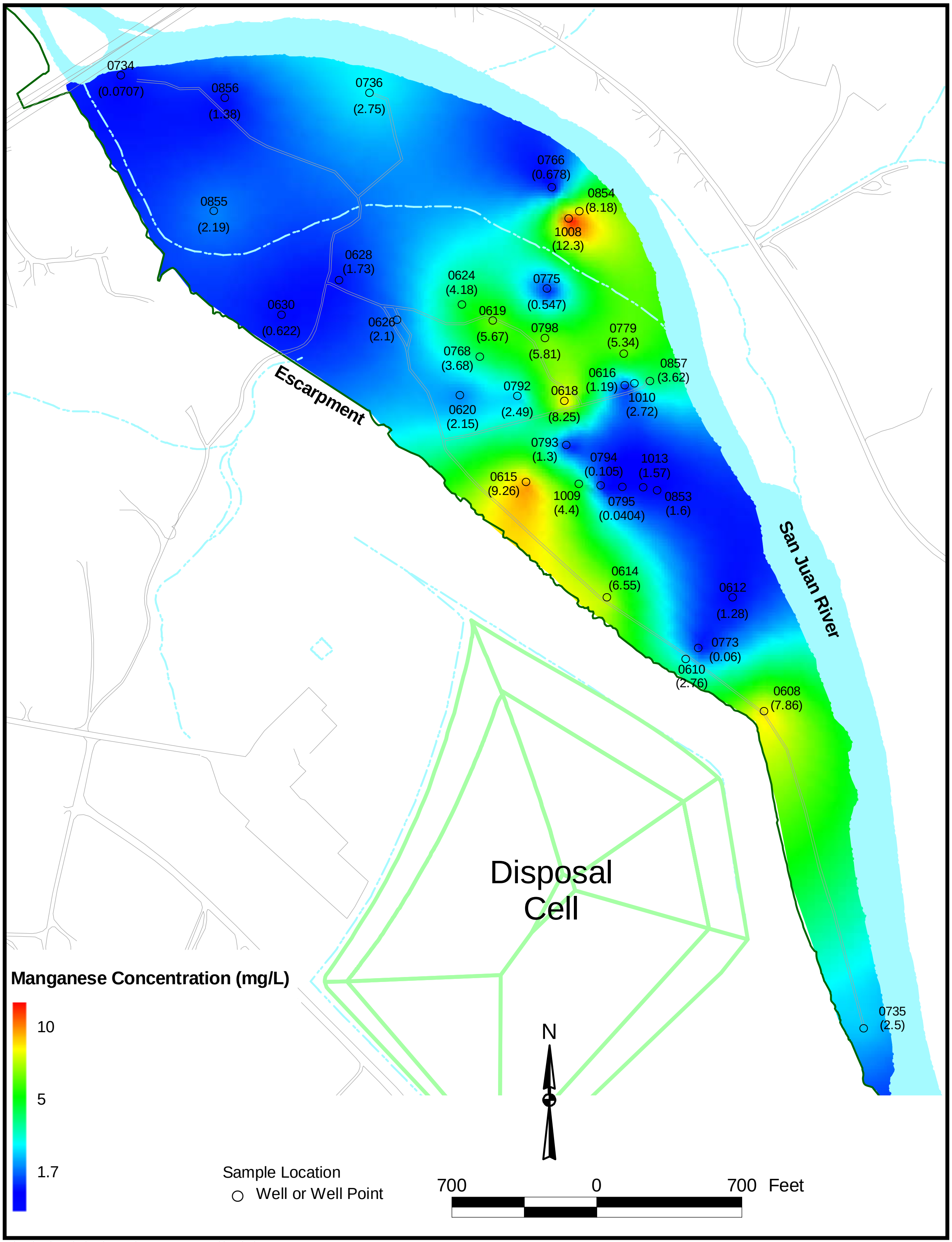

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Figure 2–13. Manganese Concentrations in Floodplain Ground Water (March 1999 through September 2001 data)

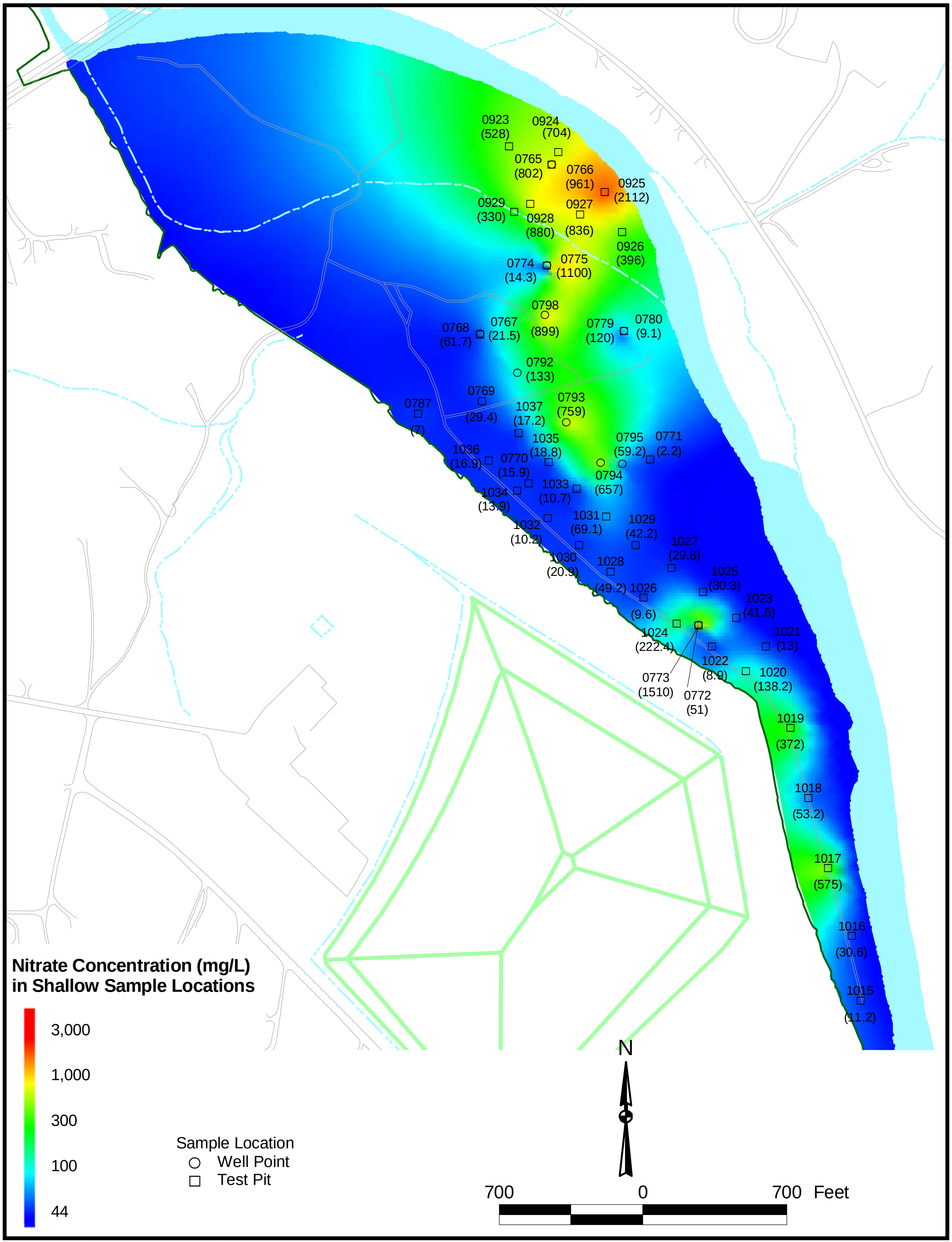

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Figure 2–14. Nitrate Concentrations in Shallow Depths in Floodplain Ground Water (March 1999 through September 2001 data)

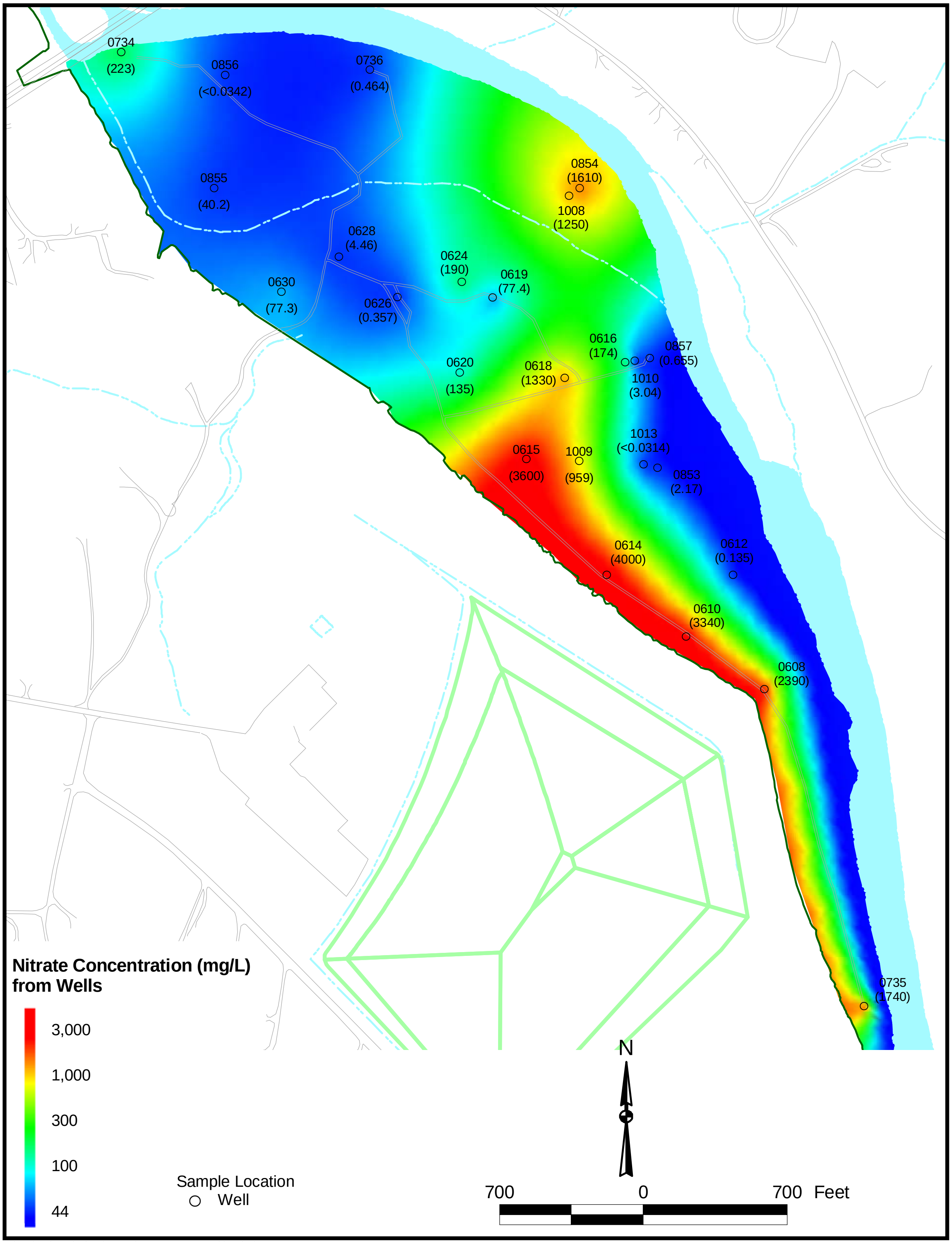

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Figure 2–15. Nitrate Concentrations in Wells in Floodplain Ground Water (March 1999 through September 2001 data)

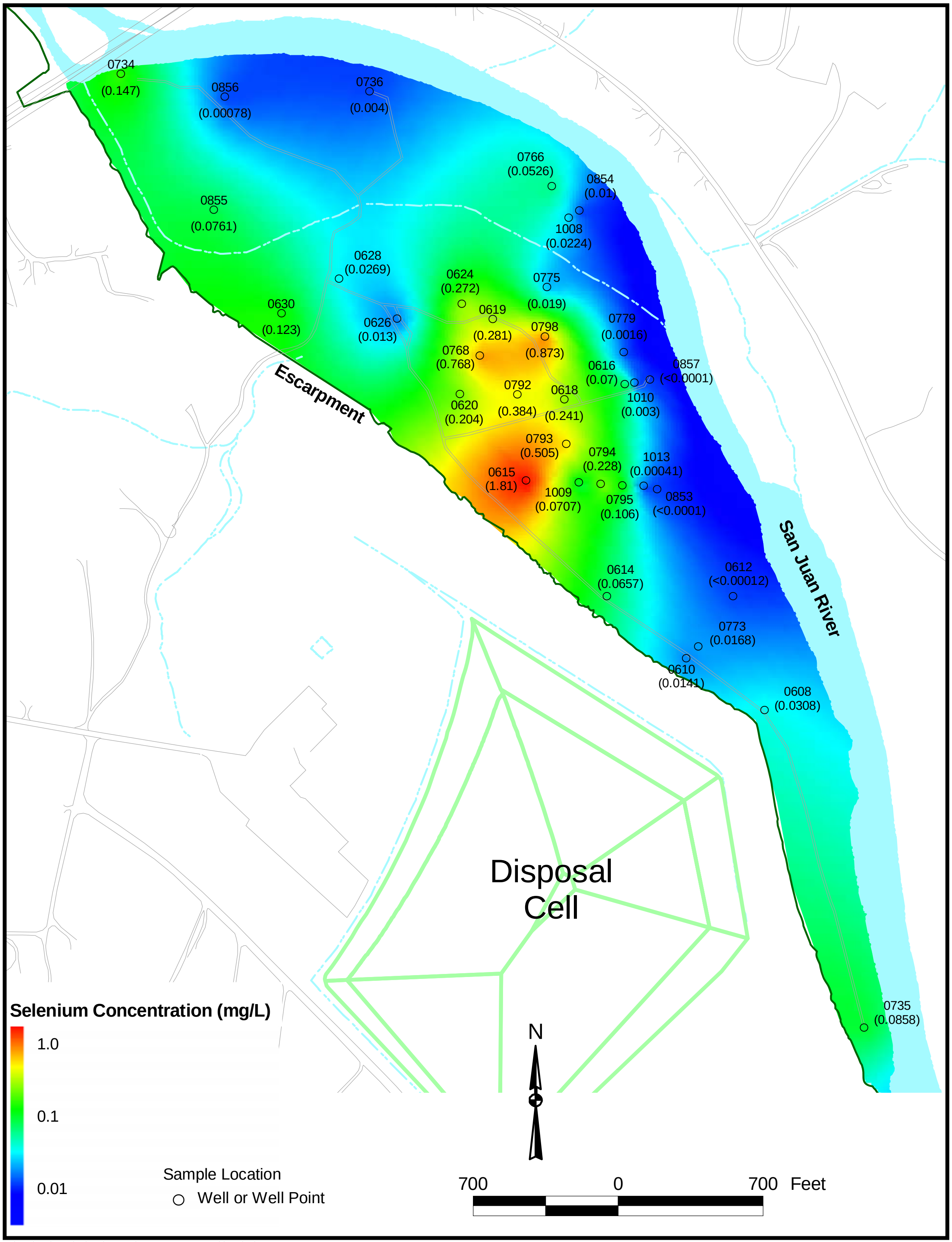

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Figure 2–16. Selenium Concentrations in Floodplain Ground Water (March 1999 through September 2001 data)

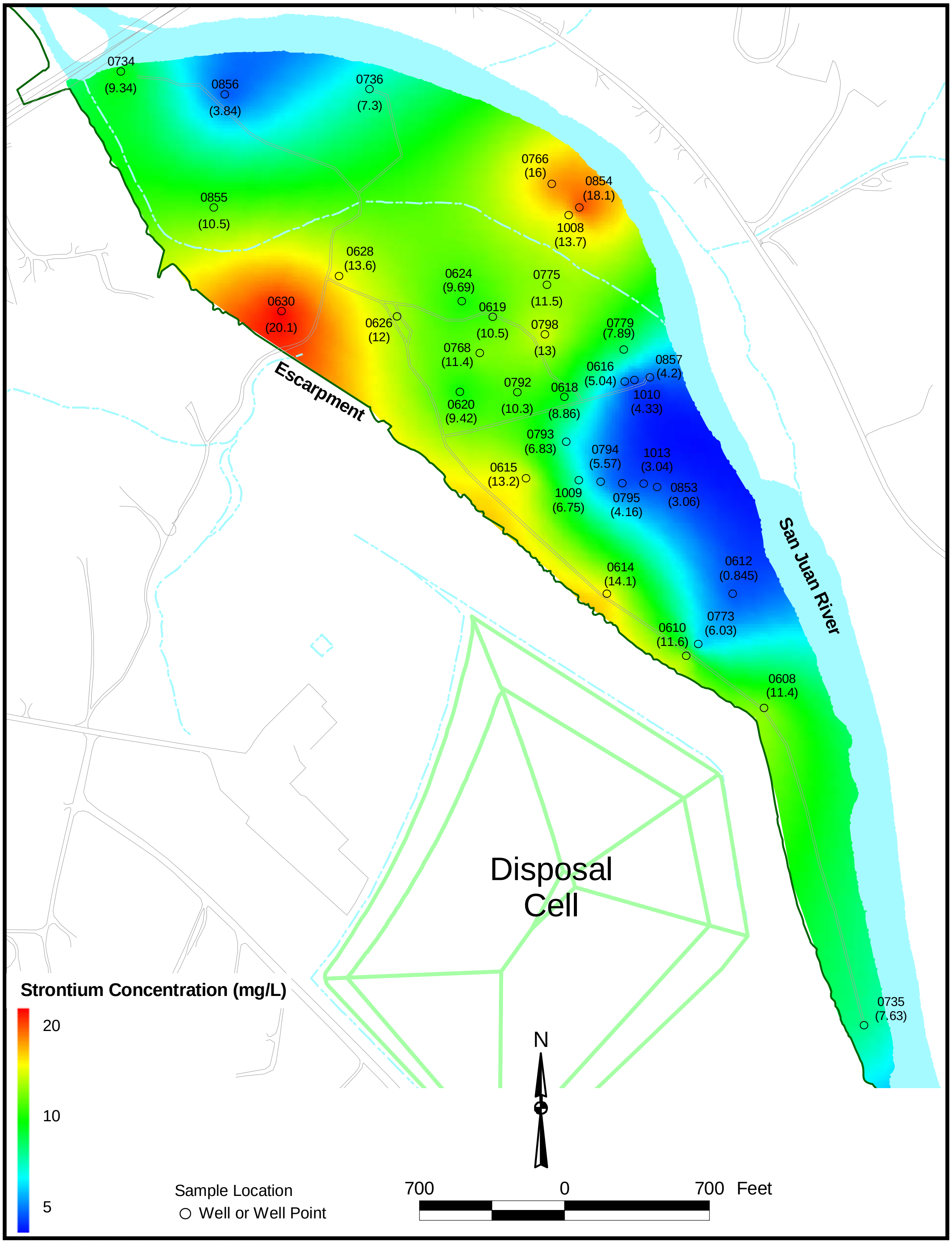

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Figure 2–17. Strontium Concentrations in Floodplain Ground Water (March 1999 through September 2001 data)

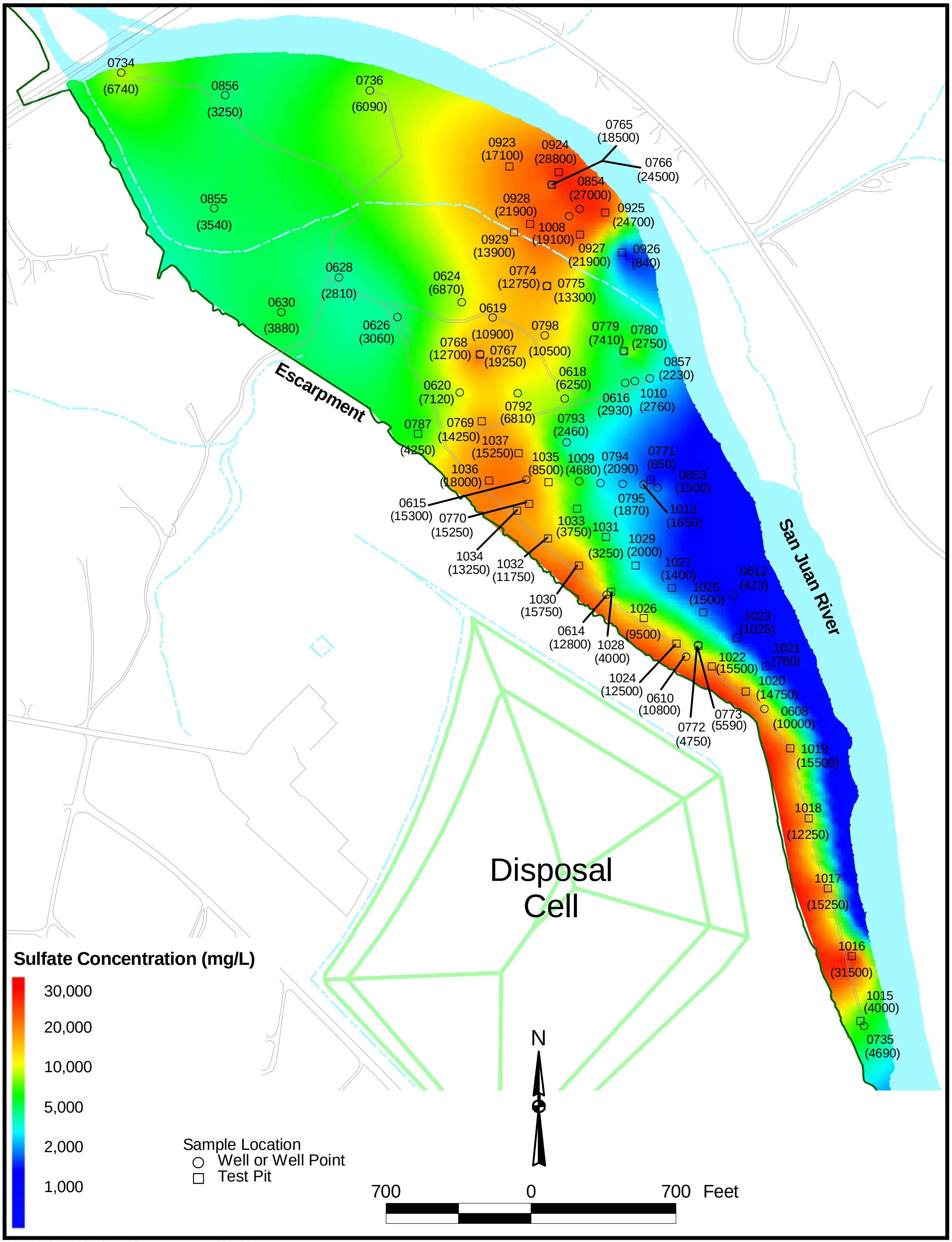

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Figure 2–18. Sulfate Concentrations in Floodplain Ground Water (March 1999 through September 2001 data)

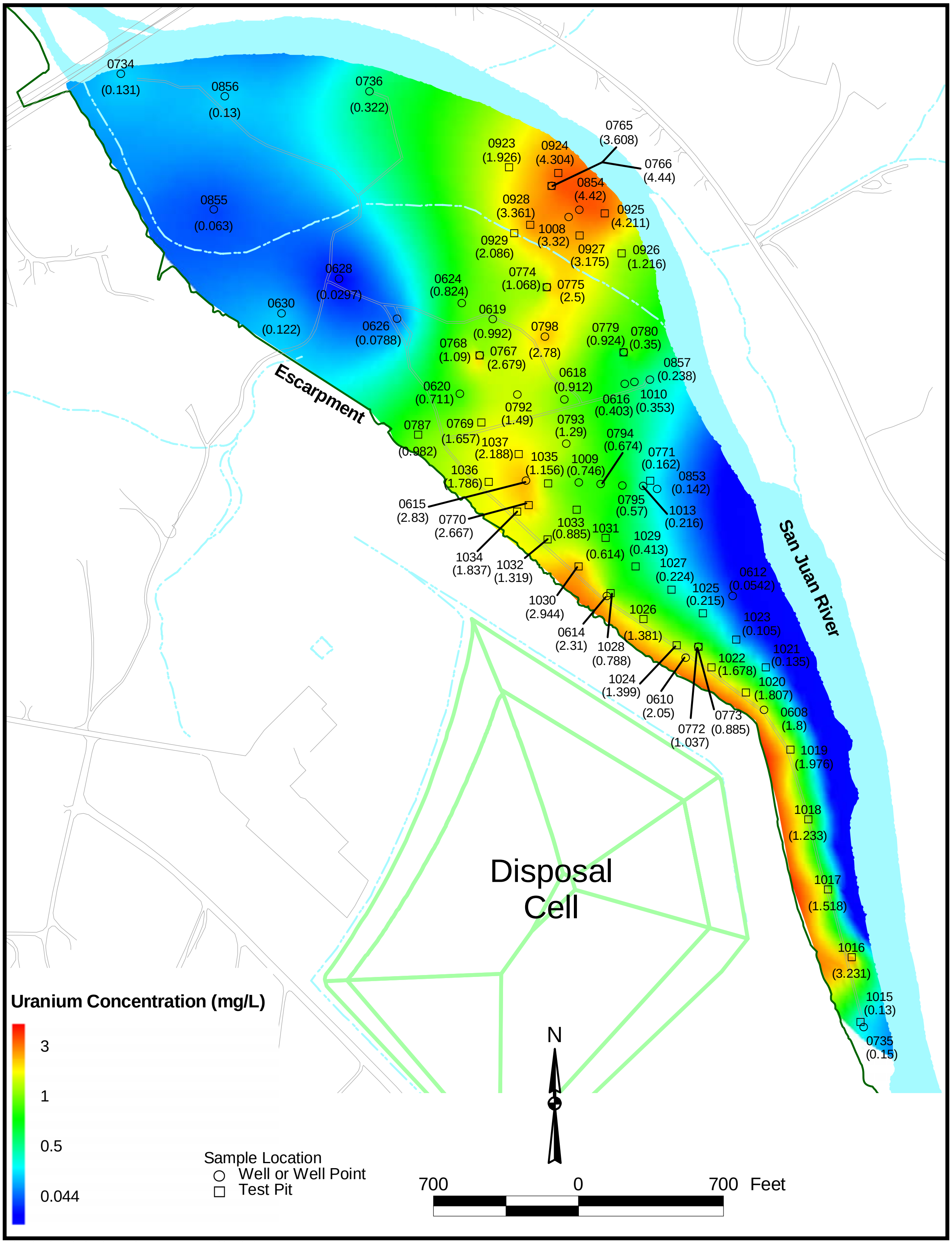

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Figure 2–19. Uranium Concentrations in Floodplain Ground Water (March 1999 through September 2001 data)

3.0 Ground Water Compliance Strategy

This section describes the proposed ground water compliance strategy at the Shiprock UMTRA site for remediation of contaminants that are attributable to milling activities. Ground water compliance decisions at the Shiprock site were made by using the compliance selection framework described in Section 3.1 and shown in Figure 3–1. This compliance selection framework is documented in Section 2.0 of the PEIS (DOE 1996) and is supported by the PEIS Record of Decision (62 FR 81). The *Environmental Assessment of Ground Water Compliance at the Shiprock Uranium Mill Tailings Site* (EA) (DOE 2001a) contains details of the selected compliance strategy and environmental impacts. Appendix A lists those aspects of the compliance and remediation strategy for which commitments to various agencies and stakeholders were listed in the EA.

3.1 UMTRA Ground Water Compliance Selection Process

The framework defined in the PEIS governs selection of the strategy to achieve compliance with EPA ground water standards, which are listed in Table 3–1 for the COCs at the Shiprock site. The framework takes into consideration human health and environmental risk, stakeholder input, and cost. The PEIS outlines a step-by-step approach that results in the selection of one of the three general compliance strategies listed below.

Table 3–1. Ground Water COCs for the Shiprock Site and EPA MCLs

Contaminant	MCL (40 CFR 192)
Ammonium	NA
Manganese	NA
Nitrate (as N)	10 mg/L (equivalent to 44 mg/L as NO_3)
Selenium	0.01 mg/L
Strontium	NA
Sulfate	NA
Uranium (234 + 238)	30 pCi/L (equivalent to 0.044 mg/L assuming secular equilibrium)

Notes: NA means that the contaminant does not have a MCL in 40 CFR 192.
pCi/L – picocuries per liter

- ***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 alternate concentration limits (ACLs), as defined on page 2–2 of the PEIS in a description of ground water compliance strategies. Supplemental standards are supplemental to background levels, MCLs, or ACLs. An ACL is a numerical concentration for a contaminant that is higher than the MCL or background, but for which it can be shown that human health and the environment would not be adversely affected.

- ***Natural flushing*—**This strategy allows 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.

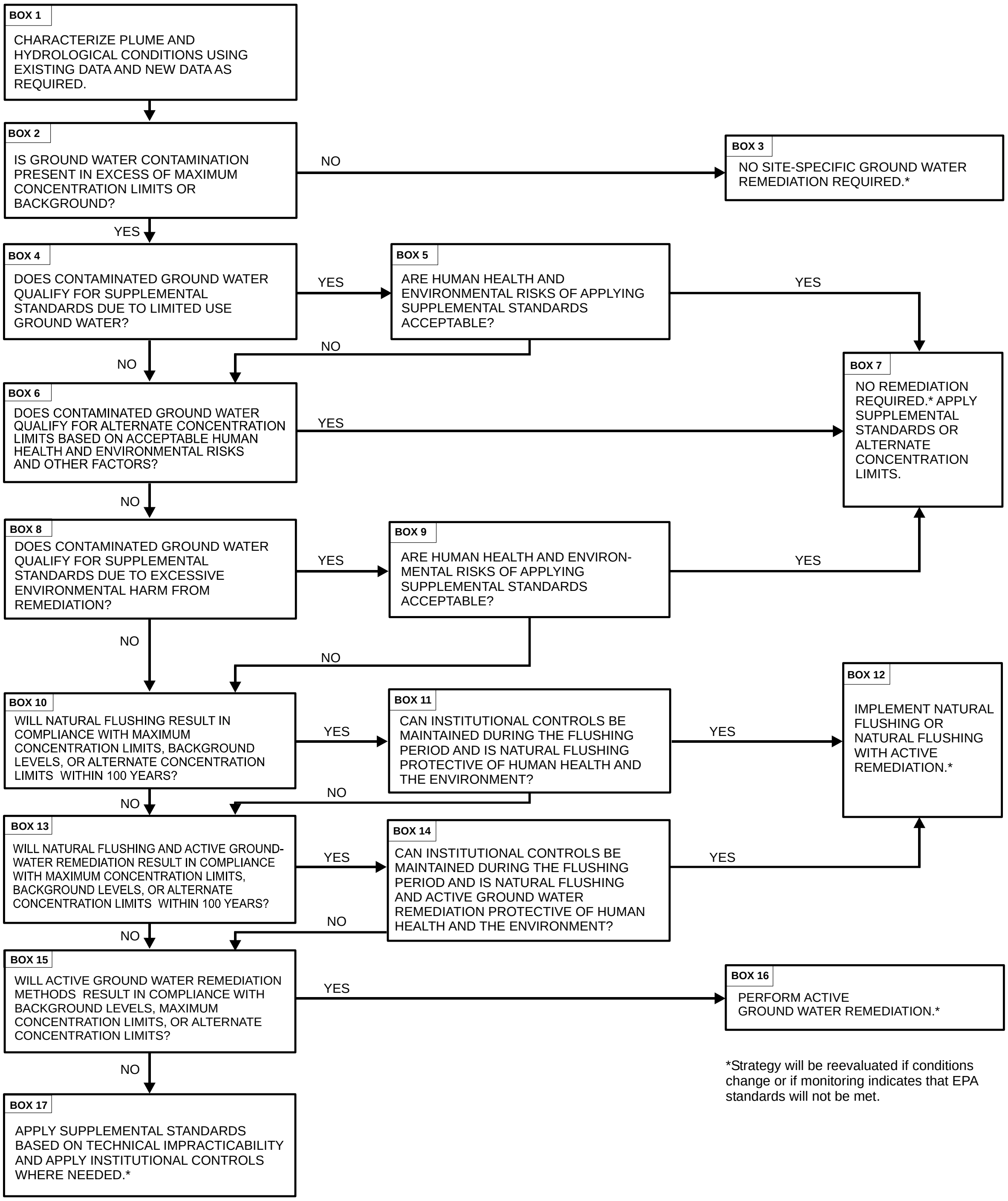

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Figure 3–1. Compliance Selection Framework

- ***Active ground water remediation***—This strategy requires 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.

The general compliance strategy for Shiprock incorporates each of these strategies in the various areas of the site. The process of developing the compliance strategy for Shiprock was described in the SOWP. This discussion will cover the results of the evaluation process described in the SOWP, including the revisions that have been made to the compliance strategy since the SOWP was issued in fall 2000.

3.2 Shiprock Ground Water Compliance Strategies

Because the Shiprock site is divided physiographically and hydrologically into two regions, the terrace and floodplain, the compliance strategies for ground water in each region, the terrace ground water system and the floodplain aquifer, are considered separately. In addition, the terrace system is subdivided into two areas, terrace east and terrace west. Interim actions, described in Section 3.3, necessary to protect humans and ecological receptors from contaminated terrace ground water that surfaces at several seeps and washes, were completed in 2000. The compliance strategies proposed for the two areas in the terrace are described in Section 3.4, and the compliance strategy for the floodplain is described in Section 3.5.

3.3 Interim Actions

Contaminated ground water from the terrace system discharges to the surface mainly in upper Bob Lee Wash, lower Many Devils Wash, and at seeps 425 and 426. To minimize potential risks to human health and ecological receptors from these exposure pathways, DOE completed several interim actions in summer 2000. The interim actions consisted of covering pools of water in the washes with geotextile and large rock, fencing around the washes to prevent livestock access, and fencing and netting around the seeps to prevent bird access. Repairs and modifications will be made as necessary to these interim actions as determined by inspections conducted at least annually.

Extensive repairs have already been required to fix damage caused by a flood in July 2001. The heavy rainfall amount causing the flood was estimated to be a 20 to 25 year occurrence. Repairs, mostly in the form of covering exposed pools of contaminated water, were made in May 2002 where the worst damage occurred in lower Many Devils Wash.

3.4 Terrace Compliance Strategies

3.4.1 Terrace East Compliance Strategy

The proposed compliance strategy for terrace east is active remediation until potential risks to humans and the environment have been eliminated. Specifically, milling-related water from the anthropogenic ground water system will be pumped from extraction wells and collected in interceptor drains along Many Devils and Bob Lee Washes. Collectively, the removal of water by the wells and interceptor drains will dry the seeps and curtail surface expression of ground water in Many Devils and Bob Lee Washes. The extracted water will be piped to an evaporation pond on the terrace. The objective of this action is to eliminate the current exposure pathways at the washes and seeps. It will also reduce the flow of ground water from the terrace to the floodplain. As noted in Section 7.2.2.1 of the SOWP, cleanup standards such as MCLs are irrelevant to a remediation strategy that adopts this objective. The terrace east ground water is not an aquifer and represents relict water emplaced by milling and other anthropogenic processes. Modeling indicates that extracting water for approximately 7 years will be required to reduce ground water levels sufficiently to hydrologically isolate contaminated ground water from seeps in the washes and to create a separation between the terrace east and terrace west ground water systems. A performance assessment of the ground water extraction in terrace east will be conducted, as described in the monitoring plan (Appendix B). Water levels in wells in and adjacent to the sump area and in a well in the filled drainage east of the disposal cell will be measured semiannually. Time plots of these water levels will be compared to modeled decline rates, and results will be reported annually.

3.4.2 Terrace West Compliance Strategy

After extracting ground water in the sump area in the terrace east system for a period of approximately 7 years, the terrace east system will be cut off from the terrace west system. As determined by modeling, the approximate boundary between the two systems after this period is shown in Figure 2–2.

The proposed compliance strategy for the terrace west ground water system is application of supplemental standards with monitoring. Supplemental standards is justified because the terrace west system qualifies as limited use ground water (that is not a current or potential source of drinking water), based on the existence of widespread ambient contamination not related to milling activities that cannot be cleaned up using treatment methods normally used in public water systems.

Contamination in the ground water west of U.S. Highway 666 (which roughly parallels the nearby boundary of terrace west and terrace east) results partly from millsite processing activities and partly from leaching of uranium, sulfate, and selenium from underlying Mancos Shale bedrock by irrigation water. Nitrate and ammonium, other COCs that occur west of U.S. Highway 666, may also be derived from sources other than milling activities, such as fertilizers and septic systems. These conclusions have been verified by uranium isotope analysis, which established that the terrace west part of the ground water system is influenced by Mancos Shale. The uranium isotopic ratios from ground water west of U.S. Highway 666 and other geochemical studies of ground water associated with Mancos Shale support the hypothesis that this marine shale of Late Cretaceous age is being leached and that COCs in this region may never be reduced to MCL levels. This further supports the application of supplemental standards.

Irrigation water will continue to provide a source of ground water recharge to the terrace west system after it is separated from the terrace east system after approximately 7 years of active remediation, which will lower the ground water surface. After this time, some flushing of contaminants from the terrace west system may occur. However, as discussed in Section 4.4.8 of the SOWP, it is highly probable that some constituents in the system—notably uranium, selenium, and sulfate—are derived from leaching of Mancos Shale, and standards may never be achieved for this region. A cost analysis study for ground water in the Grand Junction, Colorado, area showed that treatment of that water, which is in a similar geological and geographical setting, is economically infeasible compared with the use of alternative water sources

(DOE 1999). Because other drinking water sources are readily available in the Shiprock area, it is unlikely that treatment of terrace west water for drinking water purposes would be economical. However, in areas of terrace west where water yield is sufficient, water quality is suitable for agriculture and livestock watering. Therefore, the application of supplemental standards to terrace west ground water is protective of human health and the environment.

DOE plans for monitoring (Appendix B) this area during Phase I remediation activities include sampling ground water to determine if concentrations of COCs are increasing and measuring water levels to determine if recharge is decreasing. This use of the observational approach will indicate the effectiveness of remediation and, if necessary, the need for interim actions or expanded remediation scope. The hydrologic connection between terrace east and terrace west should be reflected early in Phase I remediation during extraction of ground water from wells in the sump area east of U.S. Highway 666. For a 2-year period after extraction from the wells to the east of the highway begins, monitoring data (water levels and contaminant concentrations) from wells west of the highway will be analyzed. A drop in water levels and contaminant concentrations west of the highway is expected, but if that does not occur, a decision will be made on whether to install additional extraction wells in the terrace west area just west of the sump area. Also evaluated in the decision to install additional wells will be the migration of contaminants and the amount of contaminant mass removed.

Surface water in 1st and 2nd Washes and in the adjacent San Juan River distributary channel contains millsite-related contamination at levels slightly above UMTRA ground water standards. This exposed water may pose a risk to threatened and endangered (T&E) species such as the Southwestern willow flycatcher, which has potential habitat in this area. The U.S. Fish and Wildlife Service has plans to conduct a T&E survey in the distributary channel area to determine the presence of the flycatcher. As ground water extraction is conducted in terrace east, the seeps in 1st and 2nd Washes related to this ground water are expected to diminish in flow. Planned sampling and monitoring of this surface water should document the declining flows and contaminant concentrations; if this does not occur, then interim actions will be considered.

3.5 Floodplain Compliance Strategy

The compliance strategy for the floodplain surficial aquifer proposed in Section 7.2.1 of the SOWP was active remediation in combination with natural flushing. This strategy was to be implemented by a combination of extraction wells located in the most contaminated part of the plume, and monitoring of the floodplain and terrace to determine the extent and nature of drainage from the disposal cell.

Subsequent to the publication of the SOWP, additional data from field investigations and modeling suggested that, although the compliance strategy was sound, the plan proposed in the SOWP was overly aggressive. A piezocone investigation conducted in fall 2001 on the disposal cell indicated that the tailings are partially saturated and that scattered saturated lenses of sand-slime material occur throughout the tailings (DOE 2002). The moisture present in these tailings will continue to drain from the disposal cell in an unsaturated condition for a long period of time into the underlying terrace alluvium and weathered Mancos Shale. Earlier monitoring data in 2000 from neutron hydroprobes installed in the disposal cell cover indicated that the radon barrier (silt cover material) was essentially saturated (DOE 2001b). From the piezocone results and the data on saturated conditions in the cover material, modeling was conducted jointly by MACTEC–ERS and Knight Piesold and Company using the HELP model to determine the infiltration rate of moisture passing through the cover and recharging the tailings. Modeling results indicated that 4.8 gpm would leak out of the bottom of the disposal cell. Adjusting the modeling to use conductivity values taken from aquifer and packer testing yielded a lower leakage value of approximately 2.5 gpm. The modeling considered the 4.8 gpm as a high-flow case and the 2.5 gpm as a low-flow case. To prevent the disposal cell leakage from entering the floodplain, the modeling proposed that a flow barrier be keyed into unweathered Mancos Shale along the base of the escarpment. An interceptor drain located just upgradient of the barrier was modeled to collect the disposal cell water, which would be piped to the evaporation pond. With the flow barrier in place and disposal cell flows to the interceptor drain from 3 to 5 gpm, the modeling shows that the floodplain will flush clean (to less than the UMTRA ground water standard for uranium of 0.044 mg/L) in approximately 60 years. At this time, the interceptor drain could be decommissioned by breaching it on its northern end and allowing drainage water to flow into the floodplain and mix with flows from Bob Lee Wash. Modeling indicates that uranium mass loading from the drainage water should be less than approximately 3.0 milligrams/minute before the drain is decommissioned. Nitrate is also forecasted by modeling to flush on the floodplain to below the UMTRA ground water standard of 44 mg/L in approximately 40 years.

The proposed compliance strategy for the floodplain aquifer, as supported by recent field investigations and modeling discussed above, is natural flushing supplemented by extraction of ground water from the contaminant plume where it is close to the San Juan River as a best management practice. In addition, ground water that infiltrates down to the floodplain from the terrace system will be collected in an interceptor drain upgradient of a flow barrier along the base of the escarpment. The extracted water from the contaminant plume near the river and the interceptor drain will be piped to the evaporation pond on the terrace. This floodplain remediation infrastructure is planned for construction in two phases.

Phase I construction will consist of the installation of two extraction wells in the most highly contaminated area of the floodplain adjacent to the San Juan River. A sample of San Juan River water collected in February 2000 that contained a high concentration of uranium (Table 2–1) indicated that the ground water contaminant plume in the adjacent floodplain could pose a potential risk to aquatic life. Hydrologic modeling has indicated that this risk can be alleviated by placement of a single extraction well in the floodplain at the point of convergence of the contaminant flow lines. Pumping from this well will serve two purposes—(1) to alleviate exposure risk to aquatic life along the nearby San Juan River, and (2) to supply makeup water that will be piped to the evaporation pond for its initial filling. The initial extraction rate for this well will be at least 7 gpm until the evaporation pond is adequately filled. Installation of a second well, only about 150 ft away from the first well, is planned to ensure that the evaporation pond fills quickly at the beginning of remediation. During the initial remediation period when the pond is filling, the extraction rate for each well will average from 7 to 10 gpm. After the pond is sufficiently filled, a combined extraction rate of 7 to 10 gpm is planned for these wells for the duration of the initial period of remediation, currently estimated to be 7 years. At the end of this period, remediation progress will be reviewed to determine if additional actions are necessary to reach compliance standards and cleanup goals in the floodplain. If additional extraction wells are required, their installation and cleanup goals would be included in a later part of Phase II construction.

Pumping from these extraction wells may continue for as much as 20 years in response to supplying adequate water for the evaporation pond and to removing ground water contaminants.

When pumping ends, natural flushing will continue to remove remaining contamination. During and following the operation of these extraction wells, DOE will monitor water levels and ground water chemistry in nearby floodplain wells to follow plume movement according to the monitoring plan in Appendix B.

Phase II construction is conceptual at this time and DOE will use the observational approach to determine the actual need, time frame, and appropriate design for the elements of Phase II. In a few years after Phase I, Phase II plans consist of building a flow barrier and interceptor drain along the base of the escarpment. The objective of the barrier is to completely cut off the contribution of ground water from the terrace system to the floodplain aquifer. To block all flow, the barrier would be constructed to a depth reaching the unweathered Mancos Shale, estimated at about 30 ft. The interceptor drain would be constructed parallel to and just upgradient (closer to the escarpment) of the flow barrier. Intercepted water in the drain would be collected in sumps and pumped through piping to the evaporation pond. Flows into the interceptor drain predicted by modeling are 3 to 5 gpm. After a period of up to approximately 60 years, the floodplain ground water will have flushed to below the UMTRA standard for uranium and the interceptor drain could be decommissioned. Modeling indicates that at the time of decommissioning, the mass loading of uranium from the drain water should be less than 3.0 milligrams/minute. If this mass loading rate is achieved, then the interceptor drain could then be breached at its northern end allowing the drainage water to drain into the floodplain and mix with flows from Bob Lee Wash. Monitoring of concentrations of COCs in the floodplain ground water according to the monitoring plan in Appendix B will track the progress of floodplain flushing. The flow in the interceptor drains will be measured periodically and the drain water will be sampled and analyzed for concentration of COCs to track progress of anticipated decreases in flow and COC concentrations. Location and frequencies for these measurements and sampling will be in a revision to the monitoring plan.

The COCs for human health on the millsite floodplain are manganese, nitrate, selenium, sulfate, and uranium. Plume maps for these contaminants are in Section 2.0. Compliance standards and cleanup goals for the human health COCs are in Table 3–2. For uranium and nitrate, compliance standards are their respective UMTRA standards of 0.044 and 44 mg/L. For manganese, the cleanup objective is the maximum background concentration, which is currently 2.74 mg/L. This value may change if higher background concentrations are found in future sampling.

Table 3–2. Compliance Standards and Cleanup Goals for Floodplain Human Health COCs

Contaminant	Compliance Standard or Cleanup Goal
Uranium	0.044 mg/L (UMTRA standard)
Nitrate	44 mg/L (UMTRA standard)
Manganese	2.74 mg/L (maximum background concentration)
Sulfate	Proposed – approximately 2,000 mg/L (maximum background concentration or concentration in ground water from flowing artesian well 648)
Selenium	0.05 mg/L (proposed ACL using Safe Drinking Water Act primary standard)

No EPA MCL exists for sulfate; however, a secondary (unenforceable) standard of 250 mg/L exists under the Safe Drinking Water Act (SDWA). Because of high background concentrations of sulfate, which range up to 1,920 mg/L, and the sulfate concentration of water from artesian well 648 that ranges up to 2,340 mg/L, the low concentration of 250 mg/L under the SDWA is not attainable at the Shiprock site. The artesian well 648 water provides most of the flow in Bob Lee Wash, which enters the floodplain aquifer. As long as the artesian well is flowing (a requirement for the proposed remediation), concentrations of sulfate in the floodplain near the mouth of Bob Lee Wash are not expected to decrease below about 2,000 mg/L. The cleanup goal for sulfate is, therefore, proposed at approximately 2,000 mg/L.

The relatively high concentrations of selenium in the millsite floodplain aquifer make it unlikely that the UMTRA standard of 0.01 mg/L can be met within the statutory limit of 100 years. Therefore, as noted in the SOWP, DOE proposes that an ACL value of 0.05 mg/L from the SDWA primary standard be adopted as the cleanup standard.

3.5.1 Institutional Controls

Institutional controls on the floodplain to minimize the potential for risk to human health and the environment include:

1. Grazing restrictions for a 7-year period during the initial remediation in which affected grazing allottees will be compensated.

2. DOE and Navajo Nation control of access to the floodplain area.

3. A DOE-Navajo Nation agreement to prohibit drilling of new wells or other use of ground water in the floodplain until remediation is completed.

4. Assurance from the Navajo Nation Water Code Administration that flowing artesian well 648 will be allowed to continue flowing into Bob Lee Wash and onto the floodplain. Flow from the well for the past 40 years has flushed contaminants from much of the floodplain and the success of the proposed remediation depends on its continued flow.

A water use permit may be required for the ground water extracted from the floodplain wells because this water is hydrologically connected to the nearby San Juan River. The Navajo Nation Water Code Administration is in the process of determining the need for a permit.

4.0 Selected Remedial Action

This section describes the remediation components, treatment technologies, and implementation plan that will be used to meet the compliance strategies for the Shiprock site.

4.1 Overview

The remediation method for the terrace east area at the Shiprock site is containment of risk by diversion of contaminated water away from the existing seeps into a interceptor drain collection system, thereby eliminating the risk associated with exposure to, or ingestion of, the contaminated water. An outfall drainage channel diversion will be constructed to facilitate drainage of surface water from the disposal cell into lower Bob Lee Wash. This will reduce recharge from the terrace to the escarpment seeps just to the north. Remediation of the terrace east also will include extraction of water from wells in the sump area southwest of the disposal cell to further reduce ground water flowing toward the washes and seeps and toward terrace west. The extracted ground water from the terrace will be treated in a solar evaporation pond in the south part of the former radon cover borrow pit.

The remediation method for the floodplain will be natural flushing supplemented by extraction of ground water from wells in the contaminant plume where it is close to the San Juan River as a best management practice to reduce risk. The floodplain wells may extract water for up to 20 years to ensure that adequate water is supplied to the evaporation pond and to remove plume contaminants. A second construction phase on the floodplain will build a flow barrier and interceptor drain along the base of the escarpment to intercept and cut off the flow of ground water from the terrace system to the floodplain aquifer. Water from the drain, to operate for up to 60 years, will be piped to the evaporation pond. After approximately 60 years when the floodplain contaminants have flushed to below the UMTRA standards for uranium and nitrate, the drain will be decommissioned and further drainage water will mix on the floodplain with outflows from Bob Lee Wash.

4.2 Development of Remediation Approach

The Shiprock SOWP documented the evaluation process that was used to develop remediation and treatment alternatives for the Shiprock site. The alternatives evaluation involved a qualitative review of all available treatment technologies to determine those that would be suitable for the site. This alternatives evaluation was used as a basis for discussions between DOE and the stakeholders. As a result of these discussions, a remediation and treatment system was developed that included the following components, shown in Figure 4–1:

- Interceptor drains in Bob Lee and Many Devils Washes
- Outfall drainage channel diversion from the disposal cell to Bob Lee Wash
- Six extraction wells in the terrace east area
- Two extraction wells in the floodplain
- A flow barrier and interceptor drain in the floodplain along the base of the escarpment
- An 11-acre solar evaporation pond to consume the water collected by the interceptor drains and the extraction wells

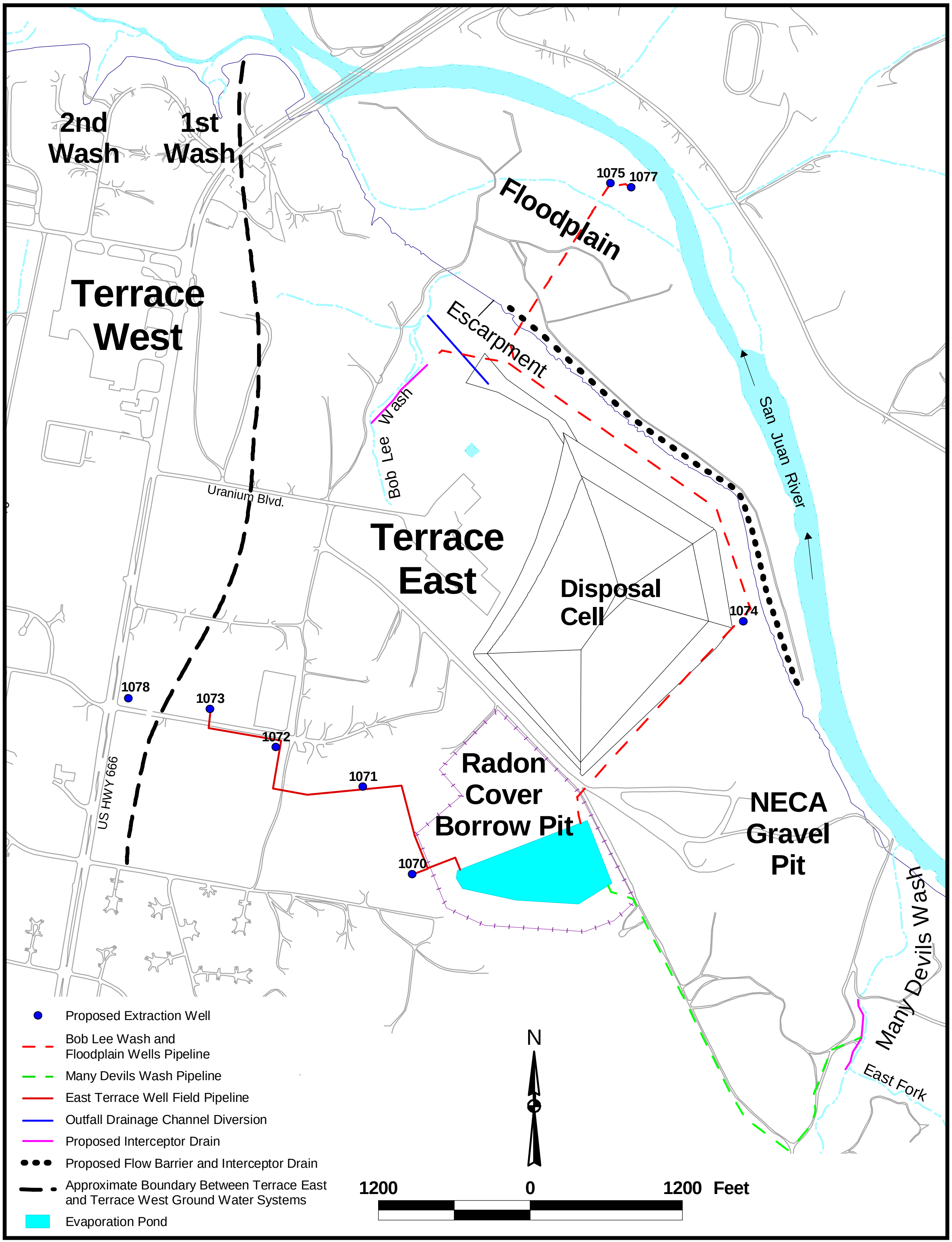

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Figure 4–1. Remediation System Components at the Shiprock Site

Monitoring of the performance of the remediation components will consist of measurements and sampling of ground and surface waters in the terrace and floodplain areas.

4.3 Remediation System Components

Design drawings and specifications for the remediation components to be built during Phase I construction are in Appendix C. A general description of these components is in the following subsections. The flow barrier and interceptor drain proposed for Phase II construction in the floodplain is briefly described in subsection 4.4.3, and the design drawings and specifications for this remediation component will be prepared in 2003 and will constitute Appendix D at that time.

4.3.1 Drain System—Terrace East

Seepage along Bob Lee and Many Devils Washes will be collected in subsurface interceptor drains. The drains will be offset from the centerline of each wash to minimize infiltration of surface water. These drains consist of a perforated pipe surrounded by drain rock and are lined with impermeable geomembrane and geotextile filter fabric. Drain locations are shown in Figure 4–1, and Figure 4–2 shows a cross section of the drain construction.

The single drain in Bob Lee Wash will discharge to a pipeline in which water will flow northward along the wash to a collection sump. Water from this collection sump will be pumped northward across a short section of terrace to intersect the pipeline carrying water from the floodplain wells. This combined water will then be piped southeastward on the terrace along the north and east sides of the disposal cell to intersect the short pipeline carrying water from the extraction well (1074) in the filled drainage. All this collected water will then be routed by pipeline to the southwest to the evaporation pond. The drain in Many Devils Wash will be discharged to a sump, and this water will be pumped through a pipeline northwest to the evaporation pond.

4.3.2 Outfall Drainage Channel Diversion—Terrace East

Surface water shed from the disposal cell during infrequent high-intensity rainfall events presently drains from the cell northwest to a rock-lined dissipation area and then spills into upper Bob Lee Wash. At times, water has become ponded in the rock-lined dissipation area where it infiltrates the terrace alluvial material and weathered Mancos Shale, eventually recharging the escarpment seeps. High flows not contained in the dissipation area have caused erosion along the drainage course west to the upper part of Bob Lee Wash, where an interceptor drain will be constructed.

The outfall drainage channel diversion, shown in Figure 4–1, will redirect surface water from the dissipation area northwest to the lower part of Bob Lee Wash. The new channel will be graded to prevent water from ponding in the dissipation area, and the new channel will not interfere with the interceptor drain in upper Bob Lee Wash.

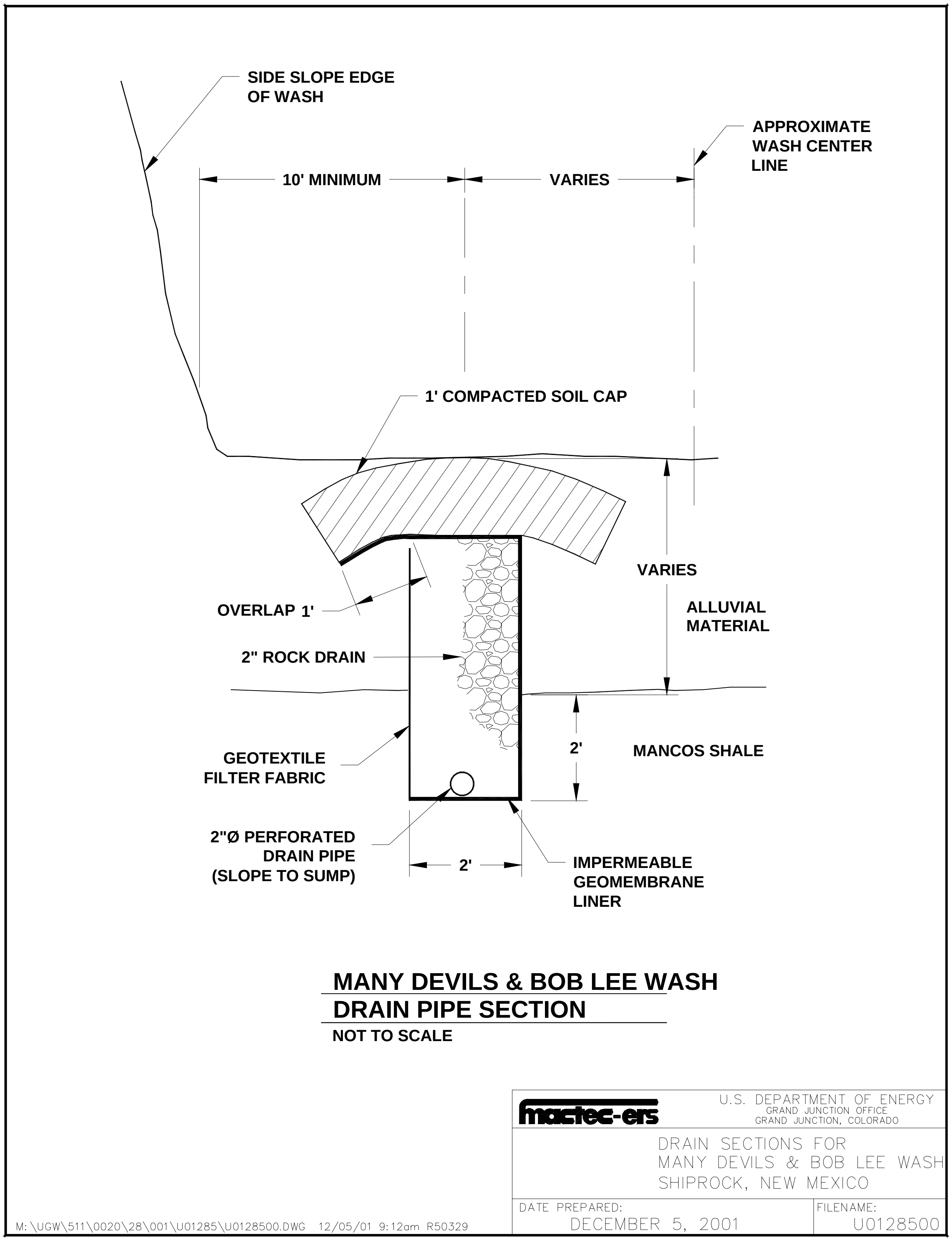

Figure 4–2. Cross Section of the Interceptor Drain Construction in Bob Lee and Many Devils Washes

4.3.3 Extraction System—Terrace East

The extraction system for the terrace east area consists of six vertical extraction wells, which are shown in Figure 4–1. Five of the wells (1070 through 1073 and 1078) are in the sump area west and northwest of the radon cover borrow pit, and the sixth well (1074) is just east of the disposal cell in a drainage course (that was later filled in) from the terrace to the floodplain.

The design of these wells will be similar to that of terrace well 818, which was used for pumping tests. The design of well 818 is shown in Appendix A of the SOWP. Well 818 was drilled by the casing advance method using an air rotary hammer, and the terrace east extraction wells will be drilled using an equivalent method. The depth of the terrace wells in the sump area will be approximately 40 to 60 ft from ground surface. The saturated thickness in the area of these wells is approximately 10 ft. The depth of the extraction well in the filled drainage will be between 40 and 50 ft; saturated thickness in the area of that well is less than 5 ft. The six extraction wells are expected to have a combined flow capacity of 10 to 12 gpm. The water from the five extraction wells in the sump area will be collected in a pipeline and sent eastward to the evaporation pond. The design for piping for extraction well 1078 just east of U.S. Highway 666 will be included as a revision to Appendix C. This well, which is actually just inside the terrace west area shown in Figure 4–1, is considered as part of the terrace east remediation because it will extract ground water from the same sump area as wells 1070 through 1073. Well 1078 was recently added to the terrace east well field to help intercept ground water flows to the terrace west area. The water from the extraction well just east of the disposal cell will join the pipeline that collects water extracted from the drain system in Bob Lee Wash and from the floodplain wells.

4.3.4 Extraction System—Floodplain

The extraction system for the floodplain initially consists of two vertical closely-spaced extraction wells shown in Figurer 4–1. The design of these wells will be similar to that of floodplain well 858. The design of well 858 is shown in Appendix A of the SOWP. Well 858 was drilled by the casing advance method using an air rotary hammer, and drilling of the floodplain wells will utilize the same method. The depth of the wells will be approximately 20 ft. The saturated thickness on the floodplain is approximately 13 to 15 ft.

Ground water pumped from the extraction wells will be piped to the evaporation pond. The floodplain extraction wells will operate at the rate required to maintain a minimum liquid level in the evaporation pond. This combined extraction rate after initial pond filling is expected to be from 7 to 10 gpm for the first 7 years of remediation. This extraction rate may increase during later remediation to compensate for less ground water being present on the terrace.

A flow barrier and interceptor drain will be built as Phase II of remedial construction. They will be close to the base of the escarpment and may be up to 4,000 ft long, as shown in Figure 4–1. The interceptor drain will be parallel to and just upgradient (closer to the escarpment) of the flow barrier. Water intercepted in the drain will be collected in sumps and piped up to the evaporation pond.

4.3.5 Evaporation Pond

The selected method for treating the extracted ground water from the interceptor drains and extraction wells is solar evaporation. The contaminated water will be pumped to a single-lined evaporation pond that will be constructed in the south part of the radon cover borrow pit area. The pond will be lined with a scrim-reinforced polypropylene geosynthetic underlain by a compacted soil base. In-situ soils are fine-grained loess that will be conditioned to provide a practically impermeable sub-base, eliminating the need for a second liner layer. Stringent quality control/quality assurance testing of the liner will be conducted during and after installation to ensure no leaks are present before the pond is filled. A leak detection system is not included in the pond design.

The amount of water that can be evaporated in the pond was calculated by determining the annual evaporation rate at the site, and modifying this value by introduction of correction factors that adjust laboratory measurements based on real-world considerations. Annual evaporation rates are usually reported as *pan evaporation*, collected by allowing water to evaporate from a shallow pan over an extended period of time. Because the pan allows heat conduction along the sides and the bottom, pan evaporation rates overstate actual evaporation that can be achieved in a lake or pond in which the sides and base do not conduct heat. Also, pan evaporation studies use water of negligible salinity. The presence of dissolved salts significantly inhibits the evaporation rate. Reported pan evaporation rates must be corrected for pan effects, salinity, and natural precipitation.

Annual pan evaporation at the Shiprock site is approximately 65 inches per year, and the pan evaporation factor, which corrects pan evaporation rates to pond and shallow lake evaporation is 0.72 (NOAA 1982). Thus, the corrected annual evaporation at the Shiprock site is 46.8 inches. The annual precipitation in Shiprock is approximately 7 inches.

Evaporation rates are adjusted for the inhibiting effect of salinity using a correction factor called the *activity*. Pure water has an activity of 1.00, and activity decreases as salinity increases. An independent consultant working on the Tuba City, Arizona, UMTRA ground water remediation project determined that the activity of the brine in the evaporation pond at the site will vary from a maximum of 1.00 during periods of low evaporation, when the pond contents are being diluted by inflow, to a minimum of about 0.63 during periods of high evaporation when the dissolved salts content is highest. The formulas to calculate brine activity from salt content that were derived for the Tuba City site were also applied to Shiprock, which has a similar ground water contaminant profile.

The surface area of the pond will be approximately 11 acres, measured at the top. Assuming an average reliability of 95 percent for the extraction system, a pond with an area of 11 acres and a depth of approximately 10 ft can treat a total influent rate of up to 25 gpm for up to 7 years, or up to 20 gpm for 40 years. The design depth of 10 ft will provide a freeboard of 2 ft and a final solids depth of 2 ft. The extraction wells on the floodplain can be operated at a variable rate sufficient to maintain a minimum liquid depth of at least 6 inches to prevent wind transport of precipitated material.

4.3.6 Monitoring

The monitoring plan presented in Appendix B contains specifications for measurements and sampling of ground and surface waters in the terrace and floodplain areas. The plan applies to remediation infrastructure constructed during Phase I, and the specifications also apply to the floodplain area after Phase II construction of the flow barrier and interceptor drain. Additional flow measurements and water sampling will be required for water in the interceptor drain to evaluate its performance. The location and frequencies for these additional measurements and sampling will be in a revised monitoring plan.

4.4 Implementation Plan

DOE’s main criterion in implementing the Shiprock remediation is to achieve the remediation goals for each area of the site. The implementation will use the observational approach, employing capture-zone analysis, optimization modeling studies, and monitoring, to track the progress of the remediation and make adjustments to the placement and number of extraction wells and interceptor drains as needed.

Detailed design of components of Phase I construction has been completed. Construction is scheduled for completion by December 1, 2002, at which time the system will begin operation (filling of evaporation pond begins). For the remainder of fiscal year 2003, remedial systems from Phase I construction will operate and their performance will be evaluated. Design of Phase II construction of the flow barrier and interceptor drain is planned for the first half of fiscal year 2004. Construction of these Phase II elements is planned for the second half of fiscal year 2004 and fiscal year 2005.

Extraction in the terrace east area is expected to continue for 7 years. During this time, the condition of the terrace will be continuously re-evaluated to determine if the goals of the extraction—drying the seeps and curtailing surface expression of the ground water at washes—have been achieved. After 2 years of extraction in terrace east, an evaluation will be made to assess the reduction in ground water levels in terrace west wells and to determine the need for additional extraction wells in terrace west (in the area west of U.S. Highway 666 northwest of the sump area). Operation of any particular extraction well may be discontinued at any time if it is determined that continued extraction of contaminated water in its vicinity is no longer practical. However, the extraction will not be terminated at any location as long as sources of exposure remain in that area. Thus, extraction from a particular well may be terminated earlier than 7 years, or it may continue after that period if it is necessary. At the conclusion of extraction on the terrace, a confirmation report will be produced to demonstrate that the remediation of the terrace has alleviated the threats to human and animal health posed by leakage of millsite-related contaminants from seeps and washes.

Monitoring of contaminant concentrations on the floodplain will continue, in accordance with the plan presented in Appendix B, for the 7-year duration of pumping on the terrace. During this time, contaminant concentrations will be compared with the predictions of the hydrologic modeling. At the end of the 7-year terrace ground water extraction period, the progress of remediation on the floodplain will be reviewed. Adjustments to the rate of pumping from the two wells on the floodplain, possibly including the installation of additional extraction wells, will be made at that time if the results of the monitoring and modeling effort indicate that such adjustments are required. Monitoring will continue to evaluate the effectiveness of plume mass removal by the extraction wells and natural flushing after installation of the flow barrier.

When extraction from wells on the floodplain and terrace east has been terminated, responsibility for monitoring concentrations and water levels, to confirm that terrace seeps and ground water surface expressions remain curtailed, and that the progress of the natural flushing process is satisfactory, would be transferred to DOE's Long-Term Surveillance and Maintenance (LTSM) Program. The LTSM Program will be responsible for producing the final confirmation report for the floodplain. The final confirmation report for the floodplain will not be issued until the final compliance standards and cleanup goals have been met by natural flushing.

4.5 Uncertainties and Contingencies

The chief uncertainties in the Shiprock remediation are whether the planned terrace east extraction will decrease the amount of ground water flowing to terrace west and diminish flows from the seeps and washes in both terrace east and terrace west; and what is the volume of water continuing to infiltrate from the terrace onto the floodplain and how long will it continue. The monitoring plan is designed to evaluate the first uncertainty; the second uncertainty will be evaluated by measures included in a revised monitoring plan to be prepared before Phase II construction of the flow barrier/interceptor drain.

Several contingency measures can be used if ground water levels and seep flows do not decrease, or concentrations of COCs do not decrease to achieve compliance with standards or cleanup goals, as predicted during remediation. These measures include:

- Increasing the flow of contaminated ground water from the terrace east area by installing additional extraction wells
- Increasing the flow of contaminated ground water from the floodplain by installing additional extraction wells or operating the existing wells at higher rates
- Installing extraction wells in terrace west if, after 2 years of extraction from terrace east, ground water levels do not show a lowering trend
- Constructing one or more interceptor drains in lower Many Devils Wash to collect water from seeps in the lower part of the wash (below the knickpoint) that are not dried up by the water collected in the interceptor drain in the upper part of Many Devils Wash. The drain in lower Many Devils Wash may be placed on the east side of the wash. Also, if flows to Many Devils Wash do not decline, installation of an extraction well upgradient to the west may be necessary.
- Instituting interim actions in the area of 1st and 2nd Washes in terrace west if seeps and flows in the area do not decrease after extraction of ground water in terrace east, and it is determined from surveys that the threatened and endangered Southwest willow flycatcher is present in the distributary channel area constituting an ecological risk.

As documented in the SOWP, initial hydrologic modeling suggested that effective remediation of the Shiprock site could require a combined extraction rate, from the terrace and floodplain systems, of 100 gpm or higher. The remediation plan described in this GCAP uses a much lower extraction rate. The observational approach will be used to determine whether the current planned extraction rates are adequate to remediate the site ground water. Should it become apparent that higher rates are required, extraction flow rates could be increased in existing wells or additional extraction wells could be installed, or both. Large increases in extraction rates in either ground water system would require increasing the site evaporation capability. This could be done by enhanced evaporation methods or by constructing additional solar evaporation ponds. On the other hand, if less water is required to be extracted, fewer wells would be necessary and pumping might be staged at various locations.

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Appendix A

Comprehensive List of EA Commitments

Commitment	Primary Agency(ies)
Institutional Controls	Navajo UMTRA
Range Management – Grazing Permits	Shiprock Chapter
Well Permits	Navajo Water Code
Right-Of-Way Application	Bureau of Indian Affairs
Mesa Verde Cactus Mitigation	Navajo Fish and Wildlife Service
Ground Water and Surface Water Monitoring	Navajo UMTRA/Navajo EPA
Cultural Resources Mitigation	Navajo Natural Heritage Program
Endangered Species Consultation	U.S. Fish and Wildlife Service
Secure Water Rights	New Mexico State Engineer's Office/Navajo Water Management Branch
Wildlife Management Plan/Biological Assessment	U.S. Fish and Wildlife Service/Navajo Fish and Wildlife Service
404 Permits	U.S. Corps of Engineers
Air Monitoring	Navajo EPA
Waste Management	Navajo EPA
ACLs	Navajo UMTRA/EPA/NRC

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Appendix B

Ground and Surface Water Monitoring Plan
Shiprock, New Mexico, Site

Contents

Figure

Tables

Attachment

1.0 Introduction

Topographic and hydrologic features divide the Shiprock, New Mexico, Uranium Mill Tailings Remedial Action (UMTRA) ground water site into two regions known as the floodplain and the terrace. Contaminated surface water, an expression of ground water contamination, occurs at scattered locations around the site in both the floodplain and terrace regions. Because of different degrees of contamination and different sources of ground water recharge, the terrace is further divided into terrace east and terrace west. Active remediation using interceptor drains and extraction wells to collect contaminated water was selected as the compliance strategy for the terrace east area. The compliance strategy selected for the terrace west area was supplemental standards with monitoring, based on limited use ground water and widespread ambient contamination derived from Mancos Shale not related to milling activities. Ground water modeling has predicted that after about 7 years of active remediation in the terrace east system, recharge from terrace east to terrace west should be hydraulically cut off, and the source of milling-related contamination will no longer affect the terrace west area. Contaminants of concern (COCs) in terrace ground and surface water are ammonium, manganese, nitrate, selenium, sulfate, uranium, and strontium. Monitoring of the terrace east ground and surface waters is necessary to evaluate the progress of the active remediation and the extent and nature of any continuing source from the disposal cell. Monitoring of the terrace west ground and surface waters would be conducted to ensure that milling-related constituents do not affect water quality and to confirm that elevated concentrations of certain constituents continue to be present as a result of leaching from Mancos Shale.

The compliance strategy for the floodplain is natural flushing with monitoring supplemented as a best management practice by some active remediation from two wells, which would extract ground water from the most contaminated part of the floodplain plume for at least 20 years. The floodplain ground and surface water COCs are the same as for the terrace. Compliance standards and cleanup goals for human health COCs in the floodplain are listed in Table B–1. Monitoring of ground and surface water is necessary for the first 7 years to evaluate the success of contaminant removal from the two floodplain wells and active remediation on terrace east. Success would be seen in decreasing concentrations of milling-related constituents resulting from mass removal from the plume and from reduction in the amount of water in the terrace east system (less water available to migrate down to the floodplain system). Monitoring on the floodplain after 7 years would evaluate the success of contaminant removal from the two extraction wells and the efficiency of natural flushing over the rest of the floodplain. This plan describes the monitoring and sampling approach for the terrace and floodplain.

Table B–1. Compliance Standards and Cleanup Goals for Floodplain Human Health Contaminants of Concern

Contaminant	Compliance Standard or Cleanup Goal
Uranium	0.044 mg/L (UMTRA standard)
Nitrate	44 mg/L (UMTRA standard)
Manganese	2.74 mg/L (maximum background concentration)
Sulfate	Approximately 2,000 mg/L (maximum background concentration or concentration in ground water from flowing artesian well 648)
Selenium	0.05 mg/L (Proposed ACL using Safe Drinking Water Act standard)

2.0 Purpose and Scope

A brief site background is provided first in this plan. More detailed descriptions of the site are in the *Final Site Observational Work Plan for the Shiprock, New Mexico, UMTRA Project Site* (DOE 2000a). The monitoring plan is then described and includes a discussion of the monitoring network, analytes, sampling methods and procedures, and quality assurance/quality control (QA/QC) measures. Data evaluation and an evaluation of the progress of natural flushing are also discussed. Lastly, environmental compliance issues are addressed.

3.0 Site Background

The Shiprock site lies south of the San Juan River and is centered around the disposal cell, which is about 1 mile (mi) south of the junction of U.S. Highways 64 and 666 (center of town of Shiprock). The disposal cell contains the uranium-mill tailings that were stabilized in place from two former tailings piles and raffinate ponds associated with the former millsite buildings immediately adjacent to the west. This disposal cell and millsite are on a broad terrace about 50 to 60 feet (ft) above the San Juan River floodplain. An escarpment separates the terrace from the floodplain below.

Ground water is present at depths of about 5 ft in alluvium constituting the floodplain aquifer along the San Juan River. Ground water below the terrace surface, however, is artificial and anthropogenic. Historical photographs from the 1930s show that the terrace and the washes cutting through it were dry. Starting in the 1940s with the construction of the helium processing plant and continuing in the 1950s with the construction of the Navajo (uranium and vanadium) Mill and Helium Lateral Canal providing irrigation, the terrace ground water system was created. After milling and helium processing ended, irrigation continued, disposal cell construction occurred, and a large residential population occupied the terrace area, continuing to add water to the terrace system. No ground water has been found in a geologically similar terrace area unaffected by human developments that is 1 to 2 mi east of the Shiprock site. Therefore, a comparison of Shiprock terrace system ground water to background conditions is not possible.

Contaminants associated with milling were slurried into nearby tailings piles and raffinate ponds situated on a high area of the Mancos Shale bedrock, which is below the thin ancestral San Juan River alluvium covering the terrace surface. Over the 14 years of milling and subsequent site remediation and disposal cell construction, these milling contaminants have migrated radially across the terrace along pathways through the porous terrace alluvium and underlying weathered and fractured Mancos Shale. Contaminated ground water has traveled southeast where it emerges as seeps in Many Devils Wash, northwest where seeps occur in Bob Lee Wash and 1st and 2nd Washes, and north where seeps along the escarpment drain into the floodplain. Ecological risk concerns are present where this contaminated ground water reaches the surface as seeps and contributes to surface flows. Ground water also traveled southwest where it resides in alluvium on a shallow bedrock swale (or sump area) formed by the ancestral San Juan River channel. The bedrock swale is abruptly bounded to the south by a buried bedrock (Mancos Shale) escarpment that forms the boundary of the terrace system. The terrace and floodplain features of the site are shown in Figure B–1. Although water supplied by milling and reclamation activities is no longer being added to the terrace system, some saturated slimes are still present in the unlined disposal cell and water from precipitation on the cell may be contributing to continued movement of contaminants across the terrace and down to the floodplain.

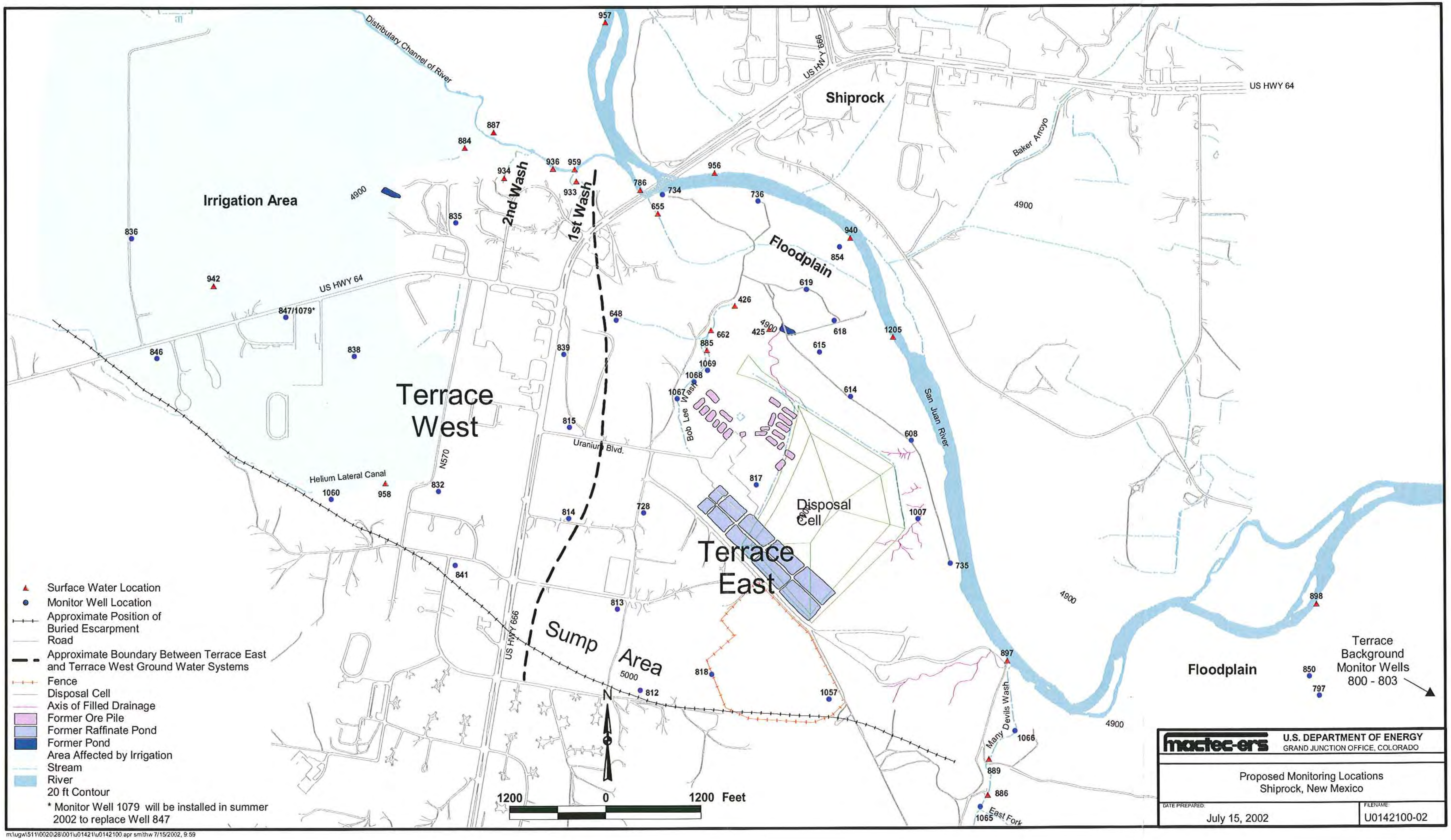

Figure B–1. Proposed Monitoring Locations for the Shiprock Site

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Milling contaminants are present in the floodplain north of the disposal cell in an arcuate plume that extends northward to the San Juan River. Floodplain contamination formerly was more extensive and covered the western part of the floodplain, but this area has been flushed by relatively clean ground water produced since the early 1960s by the flowing artesian well on the terrace whose flow has been routed to Bob Lee Wash and onto the floodplain. Flushing of milling contaminants has also occurred in the part of the terrace west area where San Juan River water in the Helium Lateral Canal system has been used for irrigation since the late 1950s.

4.0 Ground and Surface Water Sampling and Analysis

4.1 Terrace Monitoring Strategy

The monitoring strategies for the two areas on the terrace, terrace east and terrace west, are as follows:

1. Terrace east—Determine the effectiveness of active remediation (extraction wells and interceptor drains) in cutting off recharge to terrace west and in drying up the seeps on the escarpment and in the washes.

2. Terrace west—Determine that recharge from terrace east is being cut off, resulting in drying up of seeps in washes, and that milling-related constituents do not affect the current beneficial, limited use of the ground water.

Location numbers of ground water (from wells) and surface water sampling and measurements, along with monitoring purpose, analyses/measurements to be performed, and monitoring frequency are shown for terrace east and west in Table B–2. These monitoring locations are shown on the site map in Figure B–1. Sampling and measurements are scheduled to begin in September 2002 and repeat in March 2003 for a fall-spring semiannual frequency. Terrace west ground and surface water samples and terrace east surface water samples will be analyzed for the seven COCs, including strontium for ecological risk concerns. These samples will also be analyzed for major-ion chemistry and field parameters (alkalinity, conductivity, oxidation-reduction potential, and pH).

One well in terrace east and nine wells in terrace west have been selected for semiannual water sampling for the first 7 years during active remediation. The sole well in terrace east (817) was selected because of the anomalously high uranium concentration (approximately 9.5 mg/L) found in the March 2002 sampling. After the first 7 years, sampling would occur annually for the next 5 years, and once every 5 years thereafter. Water levels will also be measured in these wells at the time of sampling. In addition, water level measurements only will be made at the same frequency in eleven additional terrace east wells and in two additional terrace west wells. Plots of water level measurements from these numerous wells should be adequate to determine if the ground water levels are decreasing, indicating the success of ground water extraction by the six wells and by the two interceptor drains in the terrace east area. Analyses for COCs and other chemical characteristics should allow tracking of plumes of contaminated water and the effectiveness of ground water flushing by irrigation in part of the terrace west area. Ground water from well 847 on the Shiprock High School property in terrace west has been used for irrigation of the school grounds. Because of the uncertain continued use of this well and its unknown installation/well construction details, a replacement well to be used for monitoring/sampling purposes will be drilled and installed in summer 2002. Annual water level measurements will be made for the next 5 years at four terrace background wells (800 through 803) about 1 to 2 mi east of the site. If water levels rise in these wells, which has not be detected in the past 3 years, then the presence of ground water would be indicated in this terrace area unaffected by the anthropogenic water sources.

Table B–2. Summary of Monitoring Requirements for Terrace East and Terrace West Areas

Location	Purpose	Analyses/Measurement	Frequency
Flowing artesian well 648	Cleanup standards for floodplain	COCs: Ammonium, manganese, nitrate, selenium, sulfate, uranium; strontium for ecological risk concerns Water chemistry: calcium, chloride, magnesium, potassium, sodium On-site field analyses: alkalinity, conductivity, oxidation-reduction potential, pH, water level	Semiannual flow measurements; sample for chemical analyses every 2 years (last sampled in February 2001)
Terrace east well: 817 Terrace west wells: 832, 835, 836, 838, 839, 841, 846, 847/1079, 1060	Water level and ground water chemistry		Semiannually through the 7 year extraction period, then annually through year 12, and every 5 years thereafter Sample 958 for chemical analysis once every 2 years (last sampled in February 2001)
Terrace east wells: 728, 812, 813, 818, 1007, 1057, 1065, 1066, 1067, 1068, 1069 Terrace west wells: 814, 815	Monitor lowering of water levels	Water level	
Terrace east surface water: 425, 426, 662, 786, 885, 886, 889 Terrace west surface water: 884, 933, 934, 936, 942, 958	Monitor for ecological risks and lowering of water levels	COCs: Ammonium, manganese, nitrate, selenium, sulfate, uranium; strontium for ecological risk concerns Water chemistry: calcium, chloride, magnesium, potassium, sodium On-site field analyses: alkalinity, conductivity, oxidation-reduction potential, and pH Water level for 885, 886, and 889 Flow rate for 425, 426, and 786	
Terrace background wells: 800, 801, 802, 803	Presence of ground water in terrace background	Water level	Annually for the first 5 years

A performance assessment of ground water extraction in terrace east will be conducted as a best management practice by measuring the water level in nine wells. Eight of the wells 728, 812, 813, 814, 815, 818, 841, and 1057) are in and adjacent to the sump area, and one well (1007) is in a filled drainage east of the disposal cell. At these wells, baseline water levels will be measured in September 2002 followed by semiannual water level measurements. Plots of decline in water levels over time at the wells will be compared to the modeled decline rate. It is expected that within 7 years, water levels in wells near the boundary of terrace east and terrace west (wells 814, 815, and 728) will decline to dryness. A letter report of the results of terrace east remediation, with the water levels compared to the model, will be prepared annually.

Seven surface water sample locations in terrace east and six surface locations in terrace west have been selected for sampling for the same frequency as stated above for the terrace wells. The only exception is water from location 958, which is from the siphon outlet of San Juan River water that flows into the Helium Lateral Canal system. Sampling and analysis of this water will occur once every 2 years, starting in either March or September 2003 (depending on availability of water in the system). Analysis of this water will provide characteristics of the irrigation water applied to part of the terrace west area that has been beneficial in flushing milling-related contaminants.

Three of the surface water sample locations (425, 426, and 786) in terrace east are seeps along the escarpment where flow rates will be measured. A decrease in flow rate (and the drying up) of these seeps will provide a measure of the efficiency of active remediation in terrace east. Measurements of water levels at three surface locations (885 in Bob Lee Wash and 886 and 889 in Many Devils Wash) in terrace east will be made from PVC casings installed in the wash bottoms. These water level measurements will provide evidence for effectiveness of terrace east remediation and decreasing of the amount of ground water appearing in the washes. Sampling of the seeps in the terrace east area will provide chemical data to evaluate ecological risk present in the nearby floodplain toward which the seeps drain. Sampling of surface water at location 662 in lower Bob Lee Wash will provide chemical data on the mix of water from flowing artesian well 648 and water containing milling-related contaminants from upper Bob Lee Wash.

Sampling of the seeps in the terrace west area from 1st Wash, 2nd Wash, and an escarpment area between the washes (locations 933, 934, and 936, respectively) will provide evidence for the effectiveness of terrace east remediation in reducing the level of contamination in the seeps. Also, chemical data from sampling of these seeps will be used to evaluate ecological risk in the nearby San Juan River distributary channel toward which the seeps drain. Sampling of surface water at locations 942 and 884 (a spring flowing from terrace gravel deposits and water in the irrigation return flow ditch, respectively) will provide chemical data to assess the effectiveness of flushing in the area affected by irrigation from the Helium Lateral Canal (942) and to evaluate ecological risk in the nearby distributary channel toward which the irrigation return flow ditch (884) drains.

During the initial 7-year extraction period of semiannual sampling, results will be shared with stakeholders and regulators. These results will be reviewed after 7 years and trends will be analyzed to determine if less frequent sampling is justified.

The continued flow of relatively clean water from flowing artesian well 648 is important to ensure the continued flushing of the northwest part of the floodplain. Flow from the well was measured at approximately 64 gallons per minute in 1999; however, the wellhead has a valve and the flow rate has been variable in the past. The flow rate will be measured semiannually to ensure that flow restrictions do not occur. The chemistry of the large volume of water from well 648 also affects the floodplain ground water and its cleanup standards. Sulfate concentration of well 648 water is elevated at approximately 2,000 milligrams per liter (mg/L). Because of this influx of well water, the floodplain ground water where influenced by the well cannot be flushed or cleaned up for sulfate to less than 2,000 mg/L. The chemistry of well 648 water will be analyzed, similar to other terrace wells, from sampling every 2 years. The next sampling of well 648 will be in March 2003.

4.2 Floodplain Monitoring Strategy

The monitoring strategy for the floodplain is designed to determine the progress of the natural flushing process in meeting compliance standards for site COCs and to determine the effectiveness of ground water removal from two extraction wells in removing contaminants from the most contaminated part of the plume to prevent them from reaching the San Juan River.

Location numbers of ground water (from wells) and surface water sampling, along with monitoring purpose, analyses/measurements to be performed, and monitoring frequency are shown for the floodplain in Table B–3. These monitoring locations are shown on the site map in Figure B–1. Sampling and measurements are scheduled to begin in March 2002 and repeat in September 2002 for a spring-fall semiannual frequency. Floodplain ground and surface water samples will be analyzed for the seven COCs, including ammonium and strontium for ecological risk concerns. These samples will also be analyzed for major-ion chemistry and field parameters (alkalinity, conductivity, oxidation-reduction potential, and pH).

Table B–3. Summary of Monitoring Requirements for the Floodplain

Location	Purpose	Analyses/Measurement	Frequency
Wells 608, 614, 615, 618, 619, 734, 735, 736, 854	Compliance action levels (40 CFR 192)	COCs: Manganese, nitrate, selenium, sulfate, uranium (and ammonium and strontium based on ecological concerns) Water chemistry: calcium, chloride, magnesium, potassium, sodium On-site field analyses: alkalinity, conductivity, oxidation-reduction potential, pH, water level (in wells)	Semiannually through the first 7 year period, then annually through year 12, and every 5 years thereafter
Wells 797,850	Floodplain, background		
Surface 898	San Juan River, background		
Surface 897, 940, 1205	San Juan River on site, risk		
Surface 956	Intake on north side of San Juan River, risk		
Surface 957	San Juan River, downgradient, risk		
Surface 655	Floodplain drainage channel, risk		
Surface 887	Distributary channel, risk		
Surface 959	Distributary channel, risk		

Eleven wells in the floodplain have been selected for semiannual water sampling for an initial 7-year period. After the first 7 years, sampling would occur annually for the next 5 years, and once every 5 years thereafter. Water levels will also be measured in these wells at the time of sampling.

Seven of the wells are in the contaminant plume in the floodplain just north and east of the disposal cell. Well 854, situated between the two extraction wells in a highly contaminated part of the plume, is designated a point of compliance well. Analyses of samples from this well will track the progress of reducing the mass of the contaminant plume by the extraction wells. After the first 7-year period, less frequent sampling and analysis of ground water from the seven wells will show the progress of natural flushing.

Wells 734 and 736 are in the floodplain west of the main contaminant plume. Well 734 is in the northwest corner of the floodplain and has had the highest contaminant concentrations in that part of the floodplain. Well 736 is near the west edge of the main contaminant plume and has had high contaminant concentrations earlier when the plume was farther to the west. Monitoring of these wells will track the progress of flushing in the floodplain and detect any lateral movement of the plume.

Ground water compliance standards and cleanup goals for human health COCs (manganese, nitrate, selenium, sulfate, and uranium) on the floodplain, listed in Table B–1, are as follows:

- For uranium and nitrate, the UMTRA standards of 0.044 and 44 mg/L, respectively.
- For manganese, the cleanup goal is the maximum background concentration (currently 2.74 mg/L) from ground water sample analyses of the floodplain background wells 797 and 850.
- For sulfate, which is uncertain and under review by the U.S. Environmental Protection Agency, the value will likely be 2,000 mg/L or higher because of contribution from flowing artesian well 648.
- For selenium, a proposed alternate concentration limit using the value of 0.05 mg/L from the Safe Drinking Water Act.

Two remaining wells (797 and 850) are in the floodplain background area, approximately 1 mi upstream (east) of the disposal cell. Sampling and analyses of ground water from these wells will provide background concentrations of COCs, particularly for those contaminants such as manganese, which do not have UMTRA Project compliance standards. The cleanup goal for manganese will be the maximum concentration found in the background samples.

Nine surface water sample locations have been selected for sampling for the same frequency as stated above for the floodplain wells. Six locations are on the San Juan River, two are on the distributary channel, which receives drainage from terrace west, and one is on a drainage channel in the northwest end of the floodplain.

San Juan River sample locations upgradient (background) and downgradient are 898 and 957, respectively. River locations onsite include 897, 1205, and 940. Location 940, the site of a sample collected in February 1999 that contained uranium slightly exceeding the UMTRA ground water standard and exceeding the Navajo Nation surface water standard, is designated as a point of exposure and is where the floodplain contamination plume reaches or comes close to the river. Sample location 956 is along the north side of the river at the site of the intake for an emergency water supply for the town of Shiprock.

Analyses of samples from locations 887 and 959 in the distributary channel should provide evidence for the success of remediation in the terrace east system, which would dry up the seeps in 1st and 2nd Washes that drain into the distributary channel area. Analyses of samples from location 655 in the floodplain drainage channel will track the progress of natural flushing in the northwest part of the floodplain.

4.3 Ground and Surface Water Sampling

Ground and surface water sampling will be conducted in accordance with the *Sampling and Analysis Plan for the UMTRA Ground Water Project* (DOE 2001a) and the *Environmental Procedures Catalog* (Manual 6) (DOE continually updated). Ground water samples will be collected from each of the wells and the surface water locations specified in Tables B–2 and B–3 and submitted to the Grand Junction Office (GJO) Analytical Laboratory for analysis. Sampling frequencies and analyses for fiscal year 2002 for the Shiprock site are listed in the *FY 2002 Sampling Frequencies and Analysis* (DOE 2001b); some changes to these frequencies and analyses for the site are in this monitoring plan.

The ground water sample protocol will be based on classification of each well according to their hydraulic properties, as shown in the Sampling and Analysis Plan (DOE 2001a). Category I wells produce a minimum of 100 milliliters per minute (mL/min); most of the floodplain wells will be in this category and will be sampled using a low-flow purging method. Category II and III wells produce less than 100 mL/min and have initial water levels above and within the screened interval, respectively; most of the terrace wells will be in these categories and will be sampled using low volume purge techniques or with a bailer.

A list of specific procedures used for this sampling is found in Table 1–1 of the Sampling and Analysis Plan (DOE 2001a). These procedures are also in the *Environmental Procedures Catalog* (DOE continually updated).

4.4 GJO Laboratory Analysis

Ground water and surface water samples will be submitted to the GJO Analytical Laboratory. All procedures will be checked for accuracy through internal laboratory QC checks (e.g., analysis of blind duplicates, splits, and known standards). Sample preservation will consist of storing the samples in an ice chest with Blue Ice (or equivalent) to cool samples during field sampling, packaging, and shipping. Ground and surface water samples will be analyzed for five major ions—calcium, chloride, magnesium, potassium, and sodium; samples will also be analyzed for the seven COCs—ammonium, manganese, nitrate, selenium, strontium, sulfate, and uranium. Analytical methods to be used are detailed in *Analytical Chemistry Laboratory Handbook of Analytical and Sample Preparation Procedures* (DOE 2001c).

4.5 Quality Assurance and Quality Control

The objective of QA and QC measures is to provide systematic control of all tasks so as to maximize accuracy, precision, comparability, and completeness. Basic sampling procedures are presented in the Sampling and Analysis Plan (DOE 2001a) and *Environmental Procedures Catalog* (DOE continually updated). Deviations from these procedures will be noted in a Field Variance Log with an explanation and a description of its possible effect on data quality.

4.5.1 Sample Control

To maintain evidence of authenticity, the samples collected must be properly identified and easily distinguished from other samples. Samples collected at the Shiprock site will be identified by a label attached to the sample container specifying the sample identification number, location, date collected, time collected, and the sampler’s name or initials.

Ground water and surface water samples for laboratory analysis will be kept under custody from the time of collection to the time of analysis. Chain-of-custody forms will be used to list all sample transfers to show that the sample was in constant custody between collection and analysis.

While the samples are in shipment to the GJO Analytical Laboratory, custody seals will be placed over the cooler opening to ensure that the integrity of the samples has not been compromised. The receiving laboratory must examine the seals on arrival and document that the seals are intact. Upon opening the container, the receiving laboratory will note the condition of the sample containers (e.g., broken or leaking bottles).

4.5.2 Laboratory Quality Control

Laboratory QC will be performed in accordance with the *Analytical Chemistry Laboratory Administrative Plan and Quality Control Procedures* (DOE 2001d). Quality control will include analysis of blanks, duplicates, spikes, and check samples.

5.0 Data Evaluation and Interpretation

Analyses from seven rounds of sampling (December 1998 through September 2001) are available for most of the wells. The wells in the 600 and 700 series are older and have more than seven sampling rounds, and the 1000 series of wells are newer and have only about three sampling rounds. No contaminant concentration trends have been noticed in the floodplain or terrace well sampling data. Fewer sampling rounds (than for wells) are available for surface water samples, and no concentration trends have been noted from these data.

After the initial 7-year period of remediation on the terrace and the floodplain, the progress of natural flushing will be monitored and analyzed from the sampling results. The progress of natural flushing during successive periods on the terrace and floodplain will also be evaluated. One method that could be used to determine the effectiveness of flushing by identifying trends is the nonparametric Mann-Kendall test. A description of this test methodology is in Attachment B–1. The following discussion of the test is from the *Ground Water Compliance Action Plan for the Old Rifle, Colorado, UMTRA Project Site* (DOE 2001e). The test does not require any particular data distribution and will accommodate missing values and data reported as less than the detection limit. Essentially it analyzes a series of data by subtracting the values of earlier collected data from later collected data. The number of resulting positive values are summed and resulting negative values are summed. The difference of these sums is determined by subtracting the number of negative values from the number of positive values. The result is the S statistic. This is compared to a probability table to determine the probability that the series of values does not represent an increasing or decreasing trend. Therefore, the smaller the probability, the greater the confidence that a real trend exists.

Use of the Mann-Kendall statistic does not assist in comparing predicted versus observed contaminant concentrations, but it does give a measure of how much significance should be attached to otherwise qualitative conclusions. If wells in critical locations at the site (e.g., plume centers) began to exhibit data that showed no clear trends, and if concentrations at those wells were unacceptably high, this could be an indication that natural flushing is not working and that the compliance strategy should be reassessed. If, on the other hand, data from critical wells continued to display decreasing trends, it could mean that natural flushing should continue to operate. Although it may not provide a clear answer, results from the Mann-Kendall test may help in the decision-making process. As each round of sampling data becomes available, the statistical calculations should be updated and results reported.

6.0 Environmental Compliance and Waste Management

6.1 Compliance Requirements

National Environmental Policy Act (NEPA): The entire area has had surveys and investigations completed. No additional cultural resources or threatened and endangered surveys are required. DOE has categorically excluded the activities in this monitoring plan from further NEPA review.

Transportation Requirements: Transportation of hazardous materials and regulated waste will be performed in compliance with the regulatory requirements of the U.S. Department of Transportation at 49 CFR Parts 106-180 and applicable local and state transportation requirements.

6.2 Waste Management

Investigation Derived Waste (IDW): Although few regulatory requirements exist that are directly applicable to field-generated IDW management, DOE remains committed to managing IDW in a manner that is protective of human health and the environment through the use of best management practices.

All *liquid IDW,* consisting of well purge water, will be dispersed on the ground at the well from which the water was extracted. This is according to the *Management Plan for Field-Generated Investigation Derived Waste* (DOE 2000b).

Solid IDW includes disposable sampling equipment, personal protective equipment, used field test kits, and trash. All solid IDW must be containerized in plastic bags and managed as solid waste at a permitted, licensed, or registered solid or industrial waste disposal or treatment facility. A radiological field evaluation is not required because the sampling is not being conducted in a supplemental standards area and because solid IDW that has come in incidental contact with contaminated ground water is not considered residual radioactive material.

7.0 References

U.S. Department of Energy, 2000a. *Final Site Observational Work Plan for the Shiprock, New Mexico, UMTRA Project Site*, Rev. 2, GJO–2000–169–TAR, MAC–GWSHP 1.1, U.S. Department of Energy, Grand Junction Office, Grand Junction, Colorado, November.

———, 2000b. *Management Plan for Field-Generated Investigation Derived Waste,* MAC–GWADM 21.1–1, Rev. 1, U.S. Department of Energy, Grand Junction Office, Grand Junction, Colorado, July.

———, 2001a. *Sampling and Analysis Plan for the UMTRA Ground Water Project,* P–GJPO–2353, Rev. 5, prepared for the U.S. Department of Energy, Grand Junction Office, Grand Junction, Colorado, October.

U.S. Department of Energy, 2001b. *FY 2002 Sampling Frequencies and Analyses*, GJO–2001–267–TAR, Rev. 7, prepared for the U.S. Department of Energy, Grand Junction Office, Grand Junction, Colorado, October.

———, 2001c. *Analytical Chemistry Laboratory Handbook of Analytical and Sample Preparation Procedures*, U.S. Department of Energy, Grand Junction Office, Grand Junction, Colorado.

———, 2001d. *Analytical Chemistry Laboratory Administrative Plan and Quality Control Procedures*, U.S. Department of Energy, Grand Junction Office, Grand Junction, Colorado.

———, 2001e. *Ground Water Compliance Action Plan for the Old Rifle, Colorado, UMTRA Project Site*, GJO–2000–177–TAR, prepared by U.S. Department of Energy, Grand Junction Office, Grand Junction, Colorado, June.

———, (continually updated). *Environmental Procedures Catalog* (Manual 6), U.S. Department of Energy, Grand Junction Office, Grand Junction, Colorado.

End of current text

Attachment B–1

Description of Mann-Kendall Test

16.3.3 Intervention Analysis and Box-Jenkins Models

If a long time sequence of equally spaced data is available, intervention analysis may be used to detect changes in average level resulting from a natural or man-induced intervention in the process. This approach, developed by Box and Tiao (1975), is a generalization of the autoregressive integrated moving-average (ARIMA) time series models described by Box and Jenkins (1976). Lettenmaier and Murray (1977) and Lettenmaier (1978) study the power of the method to detect trends. They emphasize the design of sampling plans to detect impacts from polluting facilities. Examples of its use are in Hipel et al. (1975) and Roy and Pellerin (1982).

Box-Jenkins modeling techniques are powerful tools for the analysis of time series data. McMichael and Hunter (1972) give a good introduction to Box-Jenkins modeling of environmental data, using both deterministic and stochastic components to forecast temperature flow in the Ohio River. Fuller and Tsokos (1971) develop models to forecast dissolved oxygen in a stream. Carlson, MacCormick, and Watts (1970) and McKerchar and Delleur (1974) fit Box-Jenkins models to monthly river flows. Hsu and Hunter (1976) analyze annual series of air pollution SO_2 concentrations. McCollister and Wilson (1975) forecast daily maximum and hourly average total oxidant and carbon monoxide concentrations in the Los Angeles Basin. Hipel, McLeod, and Lennox (1977*a*, 1977*b*) illustrate improved Box-Jenkins techniques to simplify model construction. Reinsel et al. (1981*a*, 1981*b*) use Box-Jenkins models to detect trends in stratospheric ozone data. Two introductory textbooks are McCleary and Hay (1980) and Chatfield (1984). Box and Jenkins (1976) is recommended reading for all users of the method.

Disadvantages of Box-Jenkins methods are discussed by Montgomery and Johnson (1976). At least 50 and preferably 100 or more data collected at equal (or approximately equal) time intervals are needed. When the purpose is forecasting, we must assume the developed model applies to the future. Missing data or data reported as trace or less-than values can prevent the use of Box-Jenkins methods. Finally, the modeling process is often nontrivial, with a considerable investment in time and resources required to build a satisfactory model. Fortunately, there are several packages of statistical programs that contain codes for developing time series models, including Minitab (Ryan, Joiner, and Ryan 1982), SPSS (1985), BMDP (1983), and SAS (1985). Codes for personal computers are also becoming available.

16.4 MANN-KENDALL TEST

In this section we discuss the nonparametric Mann-Kendall test for trend (Mann, 1945; Kendall, 1975). This procedure is particularly useful since missing values are allowed and the data need not conform to any particular distribution. Also, data reported as trace or less than the detection limit can be used (if it is acceptable in the context of the population being sampled) by assigning them a common value that is smaller than the smallest measured value in the data set. This approach can be used because the Mann-Kendall test (and the seasonal Kendall test in Chapter 17) use only the relative magnitudes of the data rather

From Gilbert, Richard O., 1987. Statistical Methods for Environmental Pollution Monitoring, Van Nostrand Reinhold, NY 320p.

than their measured values. We note that the Mann-Kendall test can be viewed as a nonparametric test for zero slope of the linear regression of time-ordered data versus time, as illustrated by Hollander and Wolfe (1973, p. 201).

16.4.1 Number of Data 40 or Less

If n is 40 or less, the procedure in this section may be used. When n exceeds 40, use the normal approximation test in Section 16.4.2. We begin by considering the case where only one datum per time period is taken, where a time period may be a day, week, month, and so on. The case of multiple data values per time period is discussed in Section 16.4.3.

The first step is to list the data in the order in which they were collected over time: $x_1, x_2, \ldots, x_n$, where x_i is the datum at time i. Then determine the sign of all $n(n - 1)/2$ possible differences $x_j - x_k$, where $j > k$. These differences are $x_2 - x_1, x_3 - x_1, \ldots, x_n - x_1, x_3 - x_2, x_4 - x_2, \ldots, x_n - x_{n-2}, x_n - x_{n-1}$. A convenient way of arranging the calculations is shown in Table 16.1.

Let $\operatorname{sgn}(x_j - x_k)$ be an indicator function that takes on the values 1, 0, or -1 according to the sign of $x_j - x_k$:

$$\begin{aligned} \operatorname{sgn}(x_j - x_k) &= 1 \quad \text{if } x_j - x_k > 0 \\ &= 0 \quad \text{if } x_j - x_k = 0 \\ &= -1 \quad \text{if } x_j - x_k < 0 \end{aligned} \tag{16.1}$$

Then compute the Mann-Kendall statistic

$$S = \sum_{k=1}^{n-1} \sum_{j=k+1}^{n} \operatorname{sgn}(x_j - x_k) \tag{16.2}$$

which is the number of positive differences minus the number of negative differences. These differences are easily obtained from the last two columns of Table 16.1. If S is a large positive number, measurements taken later in time tend to be larger than those taken earlier. Similarly, if S is a large negative number, measurements taken later in time tend to be smaller. If n is large, the computer code in Appendix B may be used to compute S. This code also computes the tests for trend discussed in Chapter 17.

Suppose we want to test the null hypothesis, H_0, of no trend against the alternative hypothesis, H_A, of an upward trend. Then H_0 is rejected in favor of H_A if S is positive and if the probability value in Table A18 corresponding to the computed S is less than the a priori specified α significance level of the test. Similarly, to test H_0 against the alternative hypothesis H_A of a downward trend, reject H_0 and accept H_A if S is negative and if the probability value in the table corresponding to the absolute value of S is less than the a priori specified α value. If a two-tailed test is desired, that is, if we want to detect either an upward or downward trend, the tabled probability level corresponding to the absolute value of S is doubled and H_0 is rejected if that doubled value is less than the a priori α level.

EXAMPLE 16.1

We wish to test the null hypothesis H_0, of no trend versus the alternative hypothesis, H_A, of an upward trend at the $\alpha = 0.10$

Table 16.1 Differences in Data Values Needed for Computing the Mann-Kendall Statistic S to Test for Trend

Data Values Listed in the Order Collected Over Time							*No. of + Signs*	*No. of − Signs*
x_1	x_2	x_3	x_4	$\cdots$	x_{n-1}	x_n		
	$x_2 - x_1$	$x_3 - x_1$	$x_4 - x_1$	$\cdots$	$x_{n-1} - x_1$	$x_n - x_1$		
		$x_3 - x_2$	$x_4 - x_2$	$\cdots$	$x_{n-1} - x_2$	$x_n - x_2$		
			$x_4 - x_3$	$\cdots$	$x_{n-1} - x_3$	$x_n - x_3$		
				$\ddots$	$\vdots$	$\vdots$		
					$x_{n-1} - x_{n-2}$	$x_n - x_{n-2}$		
						$x_n - x_{n-1}$		
						$S =$	$\overline{\begin{pmatrix}\text{sum of}\\ \text{+ signs}\end{pmatrix}}$ +	$\overline{\begin{pmatrix}\text{sum of}\\ \text{− signs}\end{pmatrix}}$

Table 16.2 Computation of the Mann-Kendall Trend Statistic S for the Time Ordered Data Sequence 10, 15, 14, 20

Time	*1*	*2*	*3*	*4*	*No. of + Signs*	*No. of − Signs*
Data	*10*	*15*	*14*	*20*		
		15 − 10	14 − 10	20 − 10	3	0
			14 − 15	20 − 15	1	1
				20 − 14	1	0
				S =	5 −	1 = 4

significance level. For ease of illustration suppose only 4 measurements are collected in the following order over time or along a line in space: 10, 15, 14, and 20. There are 6 differences to consider: 15 − 10, 14 − 10, 20 − 10, 14 − 15, 20 − 15, and 20 − 14. Using Eqs. 16.1 and 16.2, we obtain $S = +1 + 1 + 1 - 1 + 1 + 1 = +4$, as illustrated in Table 16.2. (Note that the sign, not the magnitude of the difference is used.) From Table A18 we find for $n = 4$ that the tabled probability for $S = +4$ is 0.167. This number is the probability of obtaining a value of S equal to +4 or larger when $n = 4$ and when no upward trend is present. Since this value is greater than 0.10, we cannot reject H_0.

If the data sequence had been 18, 20, 23, 35, then $S = +6$, and the tabled probability is 0.042. Since this value is less than 0.10, we reject H_0 and accept the alternative hypothesis of an upward trend.

Table A18 gives probability values only for $n \leq 10$. An extension of this table up to $n = 40$ is given in Table A.21 in Hollander and Wolfe (1973).

16.4.2 Number of Data Greater Than 40

When n is greater than 40, the normal approximation test described in this section is used. Actually, Kendall (1975, p. 55) indicates that this method may be used for n as small as 10 unless there are many tied data values. The test procedure is to first compute S using Eq. 16.2 as described before. Then compute the variance of S by the following equation, which takes into account that ties may be present:

$$\mathrm{VAR}(S) = \frac{1}{18}\left[n(n-1)(2n+5) - \sum_{p=1}^{g} t_p(t_p - 1)(2t_p + 5)\right] \qquad 16.3$$

where g is the number of tied groups and t_p is the number of data in the pth group. For example, in the sequence {23, 24, trace, 6, trace, 24, 24, trace, 23} we have $g = 3$, $t_1 = 2$ for the tied value 23, $t_2 = 3$ for the tied value 24, and $t_3 = 3$ for the three trace values (considered to be of equal but unknown value less than 6).

Then S and VAR(S) are used to compute the test statistic Z as follows:

$$\begin{aligned} Z &= \frac{S-1}{[\mathrm{VAR}(S)]^{1/2}} && \text{if } S > 0 \\ &= 0 && \text{if } S = 0 \\ &= \frac{S+1}{[\mathrm{VAR}(S)]^{1/2}} && \text{if } S < 0 \end{aligned} \qquad 16.4$$

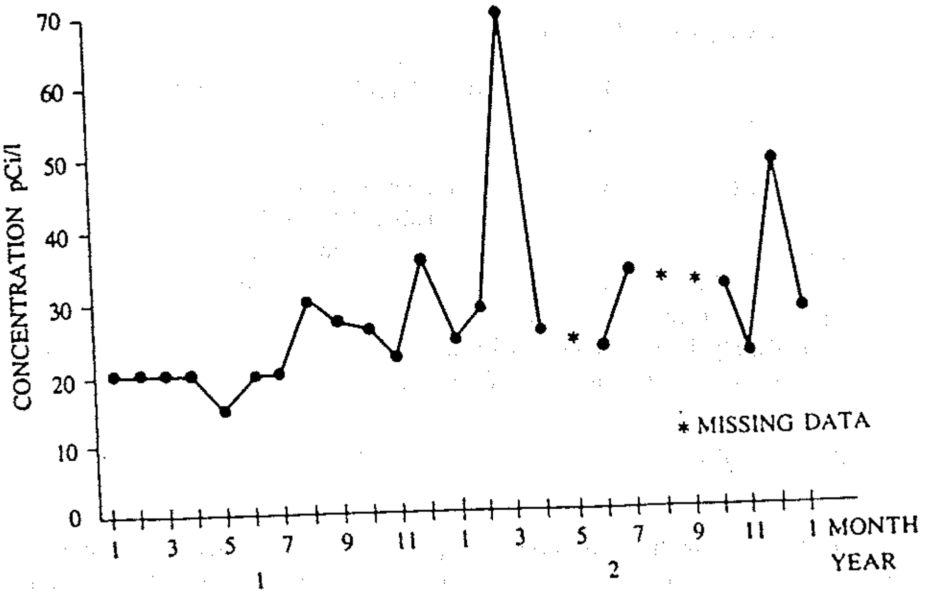

Figure 16.2 Concentrations of ^{238}U in ground water in well E at the former St. Louis Airport storage site for January 1981 through January 1983 (after Clark and Berven, 1984).

A positive (negative) value of Z indicates an upward (downward) trend. If the null hypothesis, H_0, of no trend is true, the statistic Z has a standard normal distribution, and hence we use Table A1 to decide whether to reject H_0. To test for either upward or downward trend (a two-tailed test) at the α level of significance, H_0 is rejected if the absolute value of Z is greater than $Z_{1-\alpha/2}$, where $Z_{1-\alpha/2}$ is obtained from Table A1. If the alternative hypothesis is for an upward trend (a one-tailed test), H_0 is rejected if Z (Eq. 16.4) is greater than $Z_{1-\alpha}$. We reject H_0 in favor of the alternative hypothesis of a downward trend if Z is negative and the absolute value of Z is greater than $Z_{1-\alpha/2}$. Kendall (1975) indicates that using the standard normal tables (Table A1) to judge the statistical significance of the Z test will probably introduce little error as long as $n \geq 10$ unless there are many groups of ties and many ties within groups.

EXAMPLE 16.2

Figure 16.2 is a plot of $n = 22$ monthly ^{238}U concentrations x_1, x_2, x_3, . . . , x_{22} obtained from a groundwater monitoring well from January 1981 through January 1983 (reported in Clark and Berven, 1984). We use the Mann-Kendall procedure to test the null hypothesis at the $\alpha = 0.05$ level that there is no trend in ^{238}U groundwater concentrations at this well over this 2-year period. The alternative hypothesis is that an upward trend is present.

There are $n(n-1)/2 = 22(21)/2 = 231$ differences to examine for their sign. The computer code in Appendix B was used to obtain S and Z (Eqs. 16.2 and 16.4). We find that $S = +108$. Since there are 6 occurrences of the value 20 and 2 occurrences of both 23 and 30, we have $g = 3$, $t_1 = 6$, and $t_2 = t_3 = 2$. Hence, Eq. 16.3 gives

$$\begin{aligned}\mathrm{VAR}(S) &= \tfrac{1}{18}\,[22(21)(44 + 5)\\ &\quad - 6(5)(12 + 5) - 2(1)(4 + 5) - 2(1)(4 + 5)]\\ &= 1227.33\end{aligned}$$

or $[\mathrm{VAR}(S)]^{1/2} = 35.0$. Therefore, since $S > 0$, Eq. 16.4 gives $Z = (108 - 1)/35.0 = 3.1$. From Table A1 we find $Z_{0.95} = 1.645$. Since Z exceeds 1.645, we reject H_0 and accept the alternative hypothesis of an upward trend. We note that the three missing values in Figure 16.2 do not enter into the calculations in any way. They are simply ignored and constitute a regrettable loss of information for evaluating the presence of trend.

16.4.3 Multiple Observations per Time Period

When there are multiple observations per time period, there are two ways to proceed. First, we could compute a summary statistic, such as the median, for each time period and apply the Mann-Kendall test to the medians. An alternative approach is to consider the $n_i \geq 1$ multiple observations at time i (or time period i) as ties in the time index. For this latter case the statistic S is still computed by Eq. 16.2, where n is now the sum of the n_i, that is, the total number of observations rather than the number of time periods. The differences between data obtained at the same time are given the score 0 no matter what the data values may be, since they are tied in the time index.

When there are multiple observations per time period, the variance of S is computed by the following equation, which accounts for ties in the time index:

$$\begin{aligned}\mathrm{VAR}(S) = \frac{1}{18}\Bigg[&n(n-1)(2n+5) - \sum_{p=1}^{g} t_p(t_p-1)(2t_p+5)\\ &- \sum_{q=1}^{h} u_q(u_q-1)(2u_q+5)\Bigg]\\ &+ \frac{\sum_{p=1}^{g} t_p(t_p-1)(t_p-2)\sum_{q=1}^{h} u_q(u_q-1)(u_q-2)}{9n(n-1)(n-2)}\\ &+ \frac{\sum_{p=1}^{g} t_p(t_p-1)\sum_{q=1}^{h} u_q(u_q-1)}{2n(n-1)}\end{aligned} \tag{16.5}$$

where g and t_p are as defined following Eq. 16.3, h is the number of time periods that contain multiple data, and u_q is the number of multiple data in the qth time period. Equation 16.5 reduces to Eq. 16.3 when there is one observation per time period.

Equations 16.3 and 16.5 assume all data are independent and, hence, uncorrelated. If observations taken during the same time period are highly correlated, it may be preferable to apply the Mann-Kendall test to the medians of the data in each time period rather than use Eq. 16.5 in Eq. 16.4.

Table A18 Probabilities for the Mann-Kendall Nonparametric Test for Trend

	Values of n					Values of n		
S	4	5	8	9	S	6	7	10
0	0.625	0.592	0.548	0.540	1	0.500	0.500	0.500
2	0.375	0.408	0.452	0.460	3	0.360	0.386	0.431
4	0.167	0.242	0.360	0.381	5	0.235	0.281	0.364
6	0.042	0.117	0.274	0.306	7	0.136	0.191	0.300
8		0.042	0.199	0.238	9	0.068	0.119	0.242
10		$0.0^{2}83$	0.138	0.179	11	0.028	0.068	0.190
12			0.089	0.130	13	$0.0^{2}83$	0.035	0.146
14			0.054	0.090	15	$0.0^{2}14$	0.015	0.108
16			0.031	0.060	17		$0.0^{2}54$	0.078
18			0.016	0.038	19		$0.0^{2}14$	0.054
20			$0.0^{2}71$	0.022	21		$0.0^{3}20$	0.036
22			$0.0^{2}28$	0.012	23			0.023
24			$0.0^{3}87$	$0.0^{2}63$	25			0.014
26			$0.0^{3}19$	$0.0^{2}29$	27			$0.0^{2}83$
28			$0.0^{4}25$	$0.0^{2}12$	29			$0.0^{2}46$
30				$0.0^{3}43$	31			$0.0^{2}23$
32				$0.0^{3}12$	33			$0.0^{2}11$
34				$0.0^{4}25$	35			$0.0^{3}47$
36				$0.0^{5}28$	37			$0.0^{3}18$
					39			$0.0^{4}58$
					41			$0.0^{4}15$
					43			$0.0^{5}28$
					45			$0.0^{6}28$

Source: From Kendall, 1975. Used by permission.

Repeated zeros are indicated by powers; for example, $0.0^{3}47$ stands for 0.00047.

Each table entry is the probability that the Mann-Kendall statistic S equals or exceeds the specified value of S when no trend is present.

This table is used in Section 16.4.1.