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Refinement of Conceptual Model and Recommendations for Improving Remediation Efficiency at the Shiprock, New Mexico, Site

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The plate is not available in electronic format.
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Executive Summary

A uranium-vanadium ore processing mill operated near Shiprock, New Mexico, from 1954 to 1968. By September 1986, all tailings and associated materials at the former millsite were encapsulated in a disposal cell built on top of the two existing tailings piles on the site. The cell occupies approximately 77 acres and contains 2,520,000 wet tons (approximately 1.9 million cubic yards) of contaminated materials, including contaminated materials from off-site vicinity properties. Ground water in the area of the millsite was contaminated by uranium, nitrate, sulfate, and associated constituents as a result of the milling operations. The Uranium Mill Tailings Remedial Action (UMTRA) Ground Water Project was responsible for characterizing and remediating ground water at the Shiprock site (DOE 1996). In October 2003, the UMTRA Ground Water Project sites, including Shiprock, were transferred to the DOE Office of Legacy Management (LM). LM now has responsibility for operating the remediation system at Shiprock and must comply with applicable regulations.

In March 2003, the UMTRA Ground Water Project initiated pump-and-treat remediation of ground water at the Shiprock site as prescribed in the Final Ground Water Compliance Action Plan (GCAP) (DOE 2002). The Shiprock site is divided physiographically and hydrologically into two regions, terrace and floodplain, that are separated by an escarpment. Ground water is currently removed from the subsurface through 10 extraction wells and 2 interceptor drains. The rate of ground water extraction during the first 10 months (March through December 2003) of operation was less than the design rate. The extraction wells and interceptor drains were expected to produce about 20 gallons per minute (gal/min) but are currently producing only about 13 gal/min.

The purpose of this report is to assess the remediation design of the ground water treatment system based on a reevaluation of the site conceptual model and to provide recommendations for improvement of the system. Many of the recommendations are based on the observational approach that formed the technical approach used by the UMTRA Ground Water Project for ground water remediation. A seven-member multidisciplinary team was formed to assess the remediation design.

Prior Conceptual Model

Terrace ground water is not an aquifer and consists of relict water emplaced by uranium-vanadium milling and other anthropogenic processes. Water in the system is held in alluvial sand and gravel and in the underlying weathered Mancos Shale bedrock. Some ground water is also likely present in fractures deeper in competent Mancos Shale. The terrace ground water system receives no natural recharge from the Mancos Shale, but it does receive some ground water from areal recharge (precipitation), infiltration of water at the Navajo Engineering Construction Authority gravel pit located south of the disposal cell, and sporadic irrigation that are all insufficient to sustain a water table. Approximately 88 million gal of ground water are present in the alluvium on the east portion of the terrace.

Terrace ground water is contaminated with high concentrations of nitrate, sulfate, and uranium. Contaminated ground water discharges to the floodplain along the escarpment and in Bob Lee and Many Devils Washes. South of the disposal cell, the terrace ground water system is contaminated mainly by high concentrations of nitrate, selenium, and sulfate. Ground water in

the eastern end of a bedrock swale south of the disposal cell discharges to Many Devils Wash through fractured and weathered shale of the Mancos Shale. Ground water in the western end of the swale flows west to northwest toward U.S. Highway 491; farther to the northwest, contaminant concentrations decline where ground water in the eastern portion of the terrace mixes with recharge from irrigation water in the western portion. Irrigation water leaches selenium, sulfate, and uranium from the underlying Mancos Shale in the western portion of the terrace.

Drainage of residual moisture (transient drainage) from the disposal cell transports contamination to the terrace and, thence, to the floodplain. Transport modeling suggests that the floodplain alluvial aquifer would naturally flush if the flux of contamination from the terrace was small. Estimates of contaminant flux from the disposal cell range from insignificant to as much as 8 gal/min. This seepage is a potential cause of ground water degradation in the floodplain alluvial aquifer. Concentrations of contaminants of concern (COCs) immediately below the escarpment have not changed significantly over time.

Floodplain alluvial ground water is held in alluvial sand and gravel of the present San Juan River floodplain and in the underlying weathered Mancos Shale. Approximately 150 million gal of ground water is present in the floodplain alluvium. The floodplain contaminant plume extends along the base of the escarpment northward across the floodplain. The ground water contains high concentrations of nitrate, sulfate, and uranium. In the northwest part of the floodplain, ground water contaminant concentrations are low as a result of the flushing effect of surface water recharge from Bob Lee Wash.

Refinements to Conceptual Model

Data collected since the installation of the remediation system resulted in some modification to the previous understanding of the ground water system.

Reevaluation of the bedrock topography on the terrace, based on new drilling data, resulted in a more accurate position of the buried escarpment that forms the boundary of the terrace ground water system, shifting it slightly southward. In addition, a minor bedrock ridge was identified just north of and parallel to the swale axis. Thick saturation in the alluvial material in the swale promotes ground water movement mostly northwestward along the swale axis rather than north through the less permeable weathered Mancos Shale. Partly because of these newly identified features, the compliance strategy for the floodplain, which includes minimizing contributions of contaminated ground water to the floodplain from the terrace, may be less effective than previously thought.

Evidence from recent investigations suggests that the alluvium is less continuous than previously thought. Operation of the terrace extraction well system indicates that pumping rates are significantly lower than would be expected in wells tapping a continuous sand and gravel aquifer. Drawdown data from a pump test indicate the presence of a barrier boundary and further suggest limited aquifer continuity. Limited connectivity will decrease the effect that pumping in the swale will have on escarpment seeps.

Previous modeling investigations attempted to account for transport of contaminated ground water through the Mancos Shale using limited information about the nature of ground water in

this formation. Such limited information is unfortunate because the Mancos Shale may significantly influence the ultimate fate of terrace ground water contaminants. The saturated thickness of alluvium within the terrace is small compared to the saturated thickness in the underlying Mancos Shale. Several lines of evidence suggest that ground water movement in the Mancos Shale occurs within preferential paths rather than uniformly throughout the shale.

Most alluvial ground water elevations on the terrace appear to have decreased during the past several years. Decreases in alluvial ground water levels in the terrace may be due to drainage of contaminated ground water to deeper portions of the ground water system; however, the temporal effect of the current drought may also affect water levels. Water levels in wells drilled in the Mancos Shale have also decreased over time. In some terrace wells, ground water elevations increased during and shortly after major rain events. An 8-foot (ft) increase in ground water elevation observed in well 0730 is the result of infiltration of ponded water in the adjacent radon-cover borrow pit. This source of recharge has been ignored in previous remediation planning and may extend the length of time required for ground water extraction. Transpiration flux from an existing sparse tamarisk stand in the radon-cover borrow pit is estimated at 0.5 gal/min. With additional plantings, transpiration flux could perhaps be increased to about 29 gal/min.

New data resulted in few changes to the conceptual model for the floodplain system. The ground water extraction rates are considerably lower than expected because of, at least in part, poor well efficiency. Contaminant concentrations have remained relatively constant near the escarpment, implying that natural flushing of the floodplain is not being achieved at present.

Efficiency of Extraction System

A ground water extraction system has operated since March 2003. Ground water is treated by evaporation in an 11-acre pond south of the disposal cell in terrace east. Experience gained while operating the remediation system suggests that drilling methods and well construction methods are partially responsible for poor well production. Only 2 of 16 wells are able to sustain a pumping rate greater that 1 gal/min, and the maximum sustainable rate is only 1.9 gal/min.

Wells drilled using the cable tool method are extremely low producers (0.01 to 0.25 gal/min); but well construction, location, and local hydraulic conductivity may affect production. Most wells installed using the rotasonic drilling technique are poor producers (most produce 0.1 to 0.7 gal/min). Wells installed using the casing-advance drilling method commonly produce more water; one well on the floodplain drilled with this method produces 60 gal/min. Wells installed with mud rotary are typically moderate producers, and one well installed in a trackhoe-dug trench produces about five times that of a nearby well. We concluded that wells installed using casing advance and trackhoe methods will likely be the best producers. This conclusion is consistent with wells installed at other LM sites in similar cobble-dominated alluvial aquifers.

Layers of mineral precipitation and biofilms were observed on some downhole tools, in some distribution pipes, and in the Bob Lee Wash interceptor drain. These mineral and biofilm deposits diminish well production over time. Some improved production was observed after treating the Bob Lee Wash interceptor drain with chlorine. A systematic effort to remove these deposits and a preventive maintenance program are needed to improve well efficiency.

Subsurface interceptor drains designed to collect ground water seepage were installed in Bob Lee and Many Devils Washes as part of the terrace remediation system. The drain at Bob Lee Wash is above the contact with the Mancos Shale and may allow some underflow. The Bob Lee Wash drain is 600 ft long and produces about 5.8 gal/min and the Many Devils Wash drain is 470 ft long and produces about 0.5 gal/min.

Summary of Prior Compliance Strategy

Active remediation, the compliance strategy for terrace east ground water, involves extracting ground water from wells in the south part of the system. After pumping for approximately 7.5 years, exposure pathways at escarpment seeps and at Bob Lee and Many Devils Washes will be eliminated. Active remediation will continue until potential risks to human health and the environment have been eliminated. Ground water is also collected in interceptor drains along Many Devils and Bob Lee Washes. Water from the extraction wells and water collected in a sump at each interceptor drain is piped to an 11-acre pond east of the extraction wells where it is evaporated. Time plots of the water levels and flow rates will be compared to modeled decline rates, and the results will be reported annually (in the performance monitoring report) during the 7.5-year extraction period. Monitoring results will be reviewed with the stakeholders and regulators after 7.5 years to determine if less frequent sampling is justified and if extraction can be discontinued.

Application of supplemental standards with monitoring is the compliance strategy for terrace west ground water. The ground water qualifies as limited-use (not a current or potential source of drinking water) ground water based on the existence of widespread ambient contamination, particularly from Mancos Shale underlying the west half of terrace west. Concentrations of COCs in ground water samples and ground water elevations are monitored. If water levels in the terrace west wells do not decrease after 2 years, installation of extraction wells in the terrace west area will be considered. As ground water extraction continues in terrace east, the flows in seeps in 1st and 2nd Washes west of U.S. Highway 491 are expected to diminish and contaminant concentrations are expected to decrease. If the seep flows do not diminish and the contaminant concentrations do not decrease, interim actions will be considered to protect threatened and endangered species in the distributary channel area.

Although the remediation system was implemented primarily according to the GCAP, some modifications were necessary. At the start of terrace east remediation in March 2003, ground water was extracted from only four wells and two interceptor drains. Total production from the wells in the south part of terrace east was only about 3 gal/min, which was less than expected. To increase the extraction rate in the south part of terrace east, four additional extraction wells were installed in July 2003. Total production from these new wells has been less than 1 gal/min, also less than expected.

Drawdown in selected terrace monitor wells is used as a metric to gauge performance of the remediation system. Predicted drawdowns are relatively small and match actual drawdowns within limits of modeling uncertainty and data accuracy. Therefore, the terrace remediation system will require monitoring for a longer time period (probably at least 5 to 7 years from initiation of remediation) to evaluate its performance accurately.

The ground water compliance strategy for the floodplain is natural flushing and is to be accomplished in two phases. Extraction of ground water from the contaminant plume on the floodplain close to the San Juan River is used as a best management practice. Phase I includes two extraction wells, a production rate from each well at 7 to 10 gal/min until the evaporation pond fills, then a combined extraction rate of 7 to 10 gal/min for an initial 7.5-year period. The compliance strategy for the floodplain is tied to compliance actions on the terrace. Extraction of ground water from the terrace system is expected to stop contaminated seepage from the terrace to the floodplain. After that time, the only source of contamination to the floodplain will be from transient water seeping from the tailings in the disposal cell. Because the terrace is expected to dewater in about 7.5 years, remediation progress will be reviewed at that time to determine if additional actions are necessary to reach compliance standards and cleanup goals. Pumping from the extraction wells may continue for as long as 20 years. During and following operation of the extraction wells, water levels and water chemistry will be monitored at nine observation wells to follow plume movements on the floodplain.

Phase II of floodplain remediation consists of construction of a flow barrier and an interceptor drain along the base of the escarpment to cut off potential contribution of ground water from the terrace system to the floodplain aquifer. The observational approach will be used to determine the actual need, time frame, and appropriate design for the elements of Phase II. Intercepted water in the drain, predicted by modeling as 3 to 5 gal/min, would be collected in sumps and piped to the evaporation pond. After approximately 60 years as predicted by modeling, floodplain ground water will have flushed to below the UMTRA standard for uranium (about 0.044 mg/L) and the interceptor drain could be breached at its north end if the mass loading of the uranium concentrations in the drain water is less than 3 milligrams per minute.

Production of ground water from the two floodplain extraction wells was much less than expected. In June 2003, one of the original wells was replaced by a new well installed in a trackhoe-dug trench. Total production from the initial well and the new well has increased to nearly 7 gal/min, but still less than expected. Because extraction of ground water from the terrace has been less than expected, significant lowering of the ground water level on the terrace is likely to require a longer time period unless actions are taken to increase extraction rates. Contaminant concentrations on the floodplain are not expected to decrease until significant ground water is removed from the terrace.

Recommended Refinements to Compliance Strategy for Terrace

- Install three new 6-inch diameter extraction wells using a casing-advance drilling method.
- Install two new wells immediately upgradient of the Bob Lee Wash interceptor drain using a trackhoe to key the wells into the Mancos Shale.
- Develop and plumb seeps 425 and 426 to the evaporation pond.
- Improve efficiency of extraction wells using modern well-restoration methods.
- Use deep-rooted plants to enhance evapotranspiration in the radon-cover borrow pit.

Recommended Refinements to Compliance Strategy for Floodplain

- Install a second trackhoe-dug extraction well near the San Juan River in the highest concentration portion of the contaminant plume.

- Install a trackhoe-dug extraction well near monitor well 0615 in the heart of the contaminant plume.
- Construct two ground water collection (interceptor) drains along the base of the escarpment. Each drain will be approximately 200 ft long and 25 ft deep.

Monitoring of Remediation System

Monitoring of ground water levels in alluvial wells on the terrace should continue. Special attention should be given to the area where water levels are increasing. In addition, water levels should be monitored in 11 terrace wells screened in the Mancos Shale, 3 sets of nested Mancos wells on the terrace, and 2 sets of nested wells on the floodplain. Water levels should be measured semiannually during the initial 7.5 years of pumping and more often following heavy rainfall events. A water-level datalogger should be installed in well 0730 to monitor ground water elevations in an area that has had large increases associated with rainfall events. A second water-level datalogger should be installed in monitor well 1069 to assess water level changes near the interceptor drain in Bob Lee Wash.

Contaminant concentrations in ground water samples from monitor wells in terrace west and in terrace east well 0817 should continue to be measured because this well has the highest concentration of uranium (10 mg/L) at the site. In addition, the chemistry of ground water at well 0730 should be measured to evaluate the potential for surface water recharge in the area of the radon-cover borrow pit and to help establish the feasibility of growing deep-rooted plants. Ground water chemistry should continue to be monitored in wells on the floodplain.

No changes to the surface water monitoring program are recommended for the terrace, although observation of seeps in Many Devils Wash is suggested. Two additional surface sample locations along the San Juan River, which were established for the last sampling round, should continue to be monitored.

Flow meters should be installed on the three discharge pipes entering the evaporation pond to corroborate flow data from individual extraction wells and drain sumps, and to identify leaks in the distribution system. In addition, sampling of all extraction wells is recommended to estimate the mass of COC removal.

Contingencies

After 5 to 7 years of remediation, the overall performance of the remediation system should be reviewed. At this time, estimates of cleanup time will be improved. In addition to the possibility of adding extraction and treatment capacities, other contingency measures should be considered if the system is not predicted to clean up within a reasonable time period. Possible contingencies include

- Remediation of ground water contaminants using chemical reactants
- Installation of an interceptor drain and a permeable reactive barrier at the base of the escarpment
- Installation of a flow barrier and interceptor drain at the base of the escarpment
- Extraction of contaminated water from beneath the disposal cell

1.0 Introduction

A uranium-vanadium ore processing mill operated near Shiprock, New Mexico, from 1954 to 1968. Radiologic contaminants on the surface of the site were remediated by the UMTRA Surface Project from 1985 to 1986 by placing tailings and mill-related wastes in an engineered on-site repository. Ground water in the area of the millsite was contaminated by uranium, nitrate, sulfate, and associated constituents as a result of the milling operations. The UMTRA Ground Water Project was responsible for characterizing and remediating ground water at the Shiprock site (DOE 1996). UMTRA Ground Water Project efforts to characterize the ground water system included the installation of more than 180 monitor wells and analysis of more than 1,800 ground water samples. From 2000 through 2002, interim remedial actions were conducted to minimize surface discharge of contaminated water to washes and seeps. In October 2003, the UMTRA Ground Water Project sites, including Shiprock, were transferred to DOE's new Office of Legacy Management (LM). LM now has responsibility for operating the remediation system at Shiprock and must comply with applicable regulations.

In March 2003, the UMTRA Ground Water Project initiated pump-and-treat remediation of ground water at the Shiprock site as prescribed in the Final Ground Water Compliance Action Plan (GCAP) (DOE 2002). The Shiprock site is divided physiographically and hydrologically into two regions, terrace and floodplain, that are separated by an escarpment; site physical features and remediation components described in this report are shown on Plate 1.

Contaminated ground water is currently removed from the subsurface through 10 extraction wells and 2 interceptor drains. The rate of ground water extraction during the first 10 months (March through December 2003) of operation was less than the design rate. The extraction wells and interceptor drains were expected to produce about 20 gallons per minute (gal/min) but are currently producing only about 13 gal/min. Approximately half of the production is from two wells on the floodplain, one of which produces nearly 6 gal/min. On the terrace, the remainder of the production is from two interceptor drains (4 gal/min) and eight extraction wells (3 gal/min). By the end of 2003, approximately 5 million gallons (gal) of ground water had been extracted by the system: 3 million gal from the terrace and 2 million gal from the floodplain.

The purpose of this report is to assess the remediation design of the ground water treatment system based on a reevaluation of the site conceptual model and to provide recommendations for improvement of the system. A seven-member multidisciplinary team was formed to conduct this work. The team has many years of combined experience in hydrology, geochemistry, geology, compliance, engineering, and ground water issues at the Shiprock site. To ensure a wide range of expertise was applied to this activity, other personnel that possess special expertise or historical knowledge were consulted on specific issues.

This report presents discussions of the conceptual model described in the Final Site Observational Work Plan, Rev. 2, (SOWP, Rev. 2) (DOE 2000) and modifications to the conceptual model based on recent data and observations made during operation of the remediation system for 10 months. An evaluation of the efficiency of the extraction portion of the remediation system is also presented. A summary of the compliance strategy described in the GCAP is presented, and a revised compliance strategy is proposed. Performance monitoring requirements are evaluated and recommendations are made for contingency measures.

The recommendation, performance monitoring, and contingency sections provide information that is fundamental to the observational approach that forms the technical approach used by the UMTRA Ground Water Project for ground water remediation (DOE 1993). Subsurface investigations inherently have a high degree of uncertainty associated with them. Elimination of uncertainty would require collection of data at such a high density that is impractical. Areas of major uncertainty at the Shiprock site include:

- flow velocity (magnitude and direction) on the terrace, particularly through the fractured Mancos Shale
- influx of river water to ground water on the floodplain
- pathway and flux of contamination from the terrace to the floodplain
- flux of precipitation through the disposal cell cover
- contributions of disposal cell runoff and storm-related precipitation to the terrace ground water system
- biogeochemistry of the nitrogen cycle
- nature of localized sources of contamination resulting from the highly varied milling processes
- effects of biochemical sorption on ground water contamination (e.g. is there a large inventory of sorbed contaminant that is released during high water?)

Using the observational approach, a conceptual understanding of the subsurface is rendered using a reasonable amount of characterization data. A remediation strategy, based on the conceptual model, is developed. The system is monitored during remediation and changes are made, if needed.

2.0 Summary of Prior Conceptual Model

The Shiprock site is divided into two distinct areas, the floodplain and the terrace (Plate 1). An escarpment forms the boundary between the two areas. The floodplain ground water occurs in unconsolidated medium- to coarse-grain sand, gravel, and cobbles underlain by Mancos Shale. This aquifer is hydraulically connected to the San Juan River.

The terrace is divided into terrace west and terrace east. The terrace alluvial ground water system extends southwestward from the escarpment for about 1 mile, where it is abruptly bounded by a buried escarpment. The terrace alluvium mainly consists of unconsolidated alluvium in the form of medium- to coarse-grain sand, gravel, and cobbles deposits covered by silt and underlain by the Mancos Shale.

The site conceptual model summarized in this section is presented in more detail in the Final SOWP, Rev. 2, and is shown on Figure 5−2 in that document. Modeling for the Final SOWP, Rev. 2, consisted of a four-layer model that evaluated the interactions between the terrace and floodplain. The distinction (boundary) between terrace east and terrace west was established based on model simulations of ground water flow paths in the four-layer model. After approximately 7.5 years of ground water extraction at 8 gal/min from the terrace east alluvium, the model predicts a boundary just east of U.S. Highway 491 that prevents ground water flow from terrace east to terrace west.

2.1 Terrace

2.1.1 Sources of Ground Water

Terrace ground water is not an aquifer and consists of relict water emplaced by uranium-vanadium milling and other anthropogenic processes. Water in the system is held in alluvial sand and gravel and in the underlying weathered Mancos Shale bedrock. Some water is likely present in fractures deeper in competent Mancos Shale. Many sources of water have contributed to the formation of the terrace ground water system during the past 60 years. The terrace ground water system receives no natural recharge from the Mancos Shale. However, it does receive water from areal recharge (precipitation), the Navajo Engineering and Construction Authority (NECA) gravel pit, the disposal cell, and sporadic irrigation that are all insufficient to sustain a water table.

2.1.2 Flow of Ground Water and Contaminant Concentrations

Residual radioactive material (RRM) partly contaminates the terrace ground water with nitrate, sulfate, and uranium (Figure 2–1 through Figure 2–3, respectively). Much of the RRM-contaminated ground water discharges along the escarpment from 3rd Wash eastward and in Bob Lee and Many Devils Washes. Ground water from various other sources of recharge (e.g., Helium Lateral Canal) returns to the San Juan River and its distributary channel through the gap formed between 3rd Wash and the western edge of the terrace system where the escarpment is not present. In some wells in the area affected by irrigation from the Helium Lateral Canal, ground water contains concentrations of uranium and selenium that slightly exceed maximum contaminant levels (MCLs). These concentrations are believed to be not related to RRM but result from chemical dissolution in the Mancos Shale.

High concentrations of sulfate and uranium (Figure 2–2 and Figure 2–3) occur in terrace ground water near the former ore storage area and processing site. This ground water flows west toward Bob Lee Wash and is exposed in seeps and springs in the upper part of the wash. Some ground water also flows northward and is exposed in Mancos Shale along the lower part of the escarpment at seeps 425 and 426. This ground water has lower concentrations of nitrate, sulfate, and uranium than the exposed ground water in Bob Lee Wash. Disposal cell runoff collected in the rock-lined dissipation area and water from the NECA pond and equipment washing areas are believed to be the recharge sources feeding the seeps.

South of the disposal cell, nitrate, selenium, and sulfate are the primary contaminants in the terrace ground water system. Ground water in the eastern end of a bedrock swale (Figure 2–4) flows east and southeast toward Many Devils Wash along the top of a thin, east-dipping (about 1 degree or less), resistant, calcareous siltstone bed in the Mancos Shale and in the fractured and weathered shale of the Mancos Shale immediately below. This water discharges into Many Devils Wash, mainly from the confluence of the East Fork downstream to about 150 yards below the knickpoint (Plate 1).

Ground water in the west part of the swale flows west to northwest toward U.S. Highway 491. The GCAP indicates a hydrological connection between the terrace east swale and terrace west along an ancestral river channel where alluvial saturated thicknesses exceed 4 ft. Farther to the northwest beyond the highway, contaminant concentrations decline where ground water originating from terrace east mixes with ground water recharge from irrigation water that is sporadically supplied by the Helium Lateral Canal. Ground water in this zone of mixing discharges to the San Juan River either through the irrigation return flow ditch or through ground water discharge directly to the river. Selenium, sulfate, and uranium are probably leached from the underlying Mancos Shale by irrigation water in terrace west. Contaminant concentrations exceed MCLs in ground water west of U.S. Highway 491, and this ground water appears to discharge north to the distributary channel along the escarpment west to approximately 3rd Wash (Plate 1).

2.1.3 Volume of Ground Water

The volume of contaminated ground water has implications for cleanup efforts. Bedrock contour and water table data were used to estimate the volume of ground water in the saturated alluvium, but these data are insufficient to provide a meaningful evaluation of the volume of contaminated ground water in the Mancos Shale.

Data presented in the GCAP on the saturated thickness of alluvial material in the terrace indicated an area referred to as a sump (referred to as a swale in this report) where saturated thicknesses exceeded 6 ft in the south end of terrace east. Contaminated ground water in this buried ancestral San Juan River channel (the swale) was estimated at 38 million gal (SOWP Table 4−6). This volume, based on a porosity of 30 percent, represents only a portion of the terrace east area.

An estimated volume of ground water for the entire terrace east area is included as Appendix A. Using an average saturated thickness of alluvium (1.7 ft) from monitor wells in the terrace east area, extending from the terrace east/terrace west boundary east to Many Devils Wash (approximately 23.1 million square feet), and an alluvium porosity of 30 percent, the volume of ground water for the terrace east area is 88 million gal.

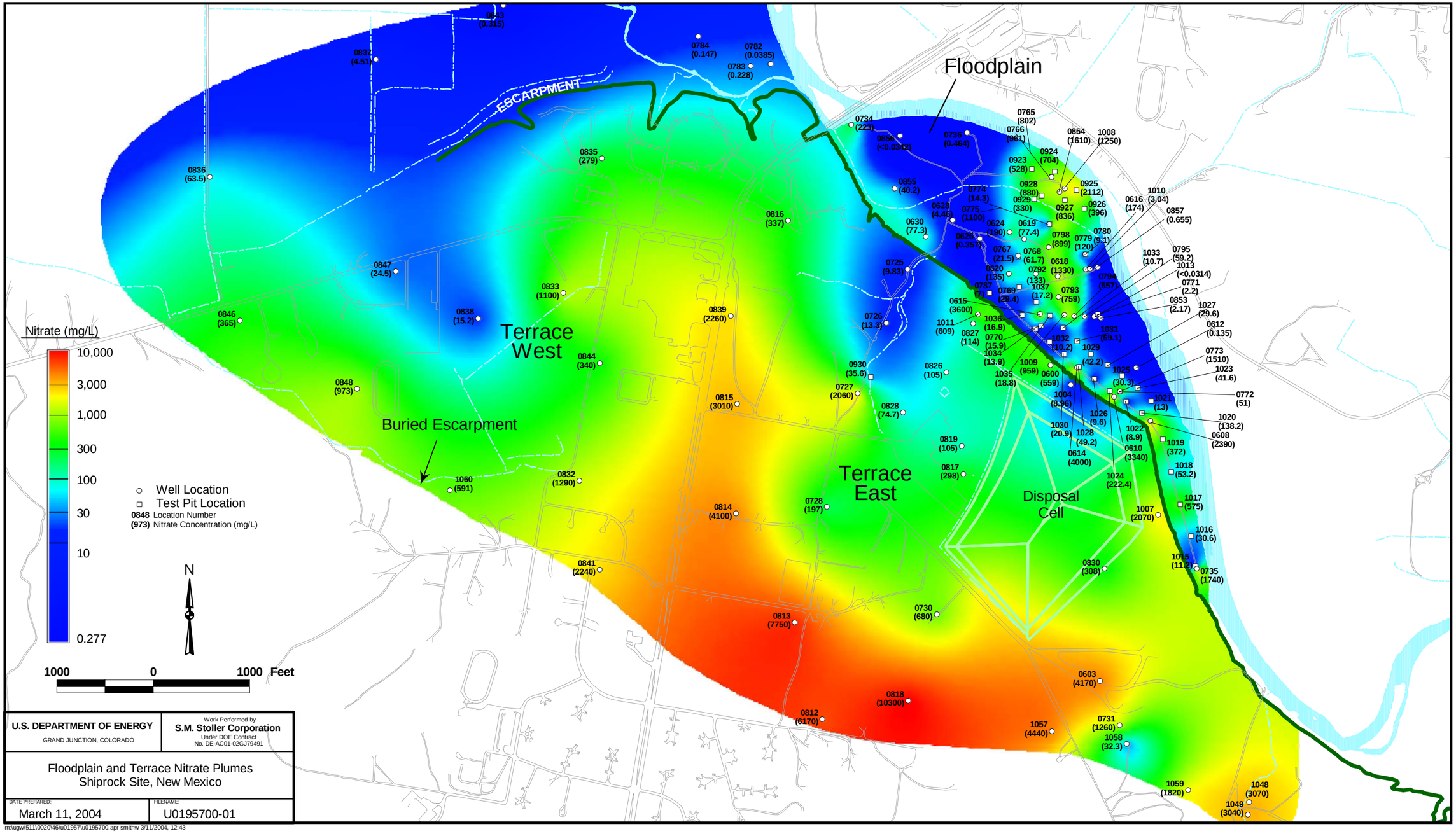

Figure 2–1. Nitrate Concentrations in Terrace and Floodplain Ground Water

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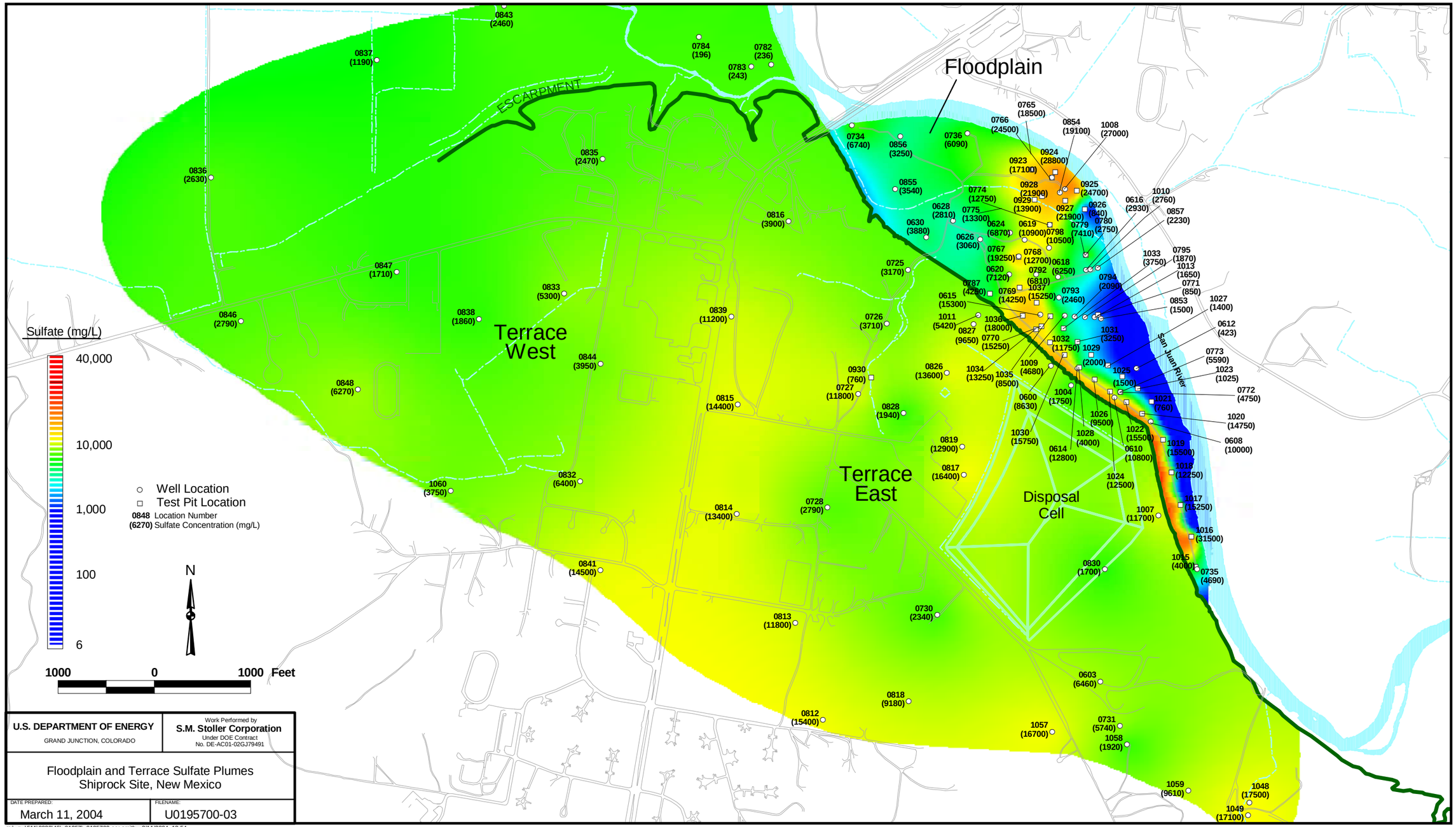

Figure 2–2. Sulfate Concentrations in Terrace and Floodplain Ground Water

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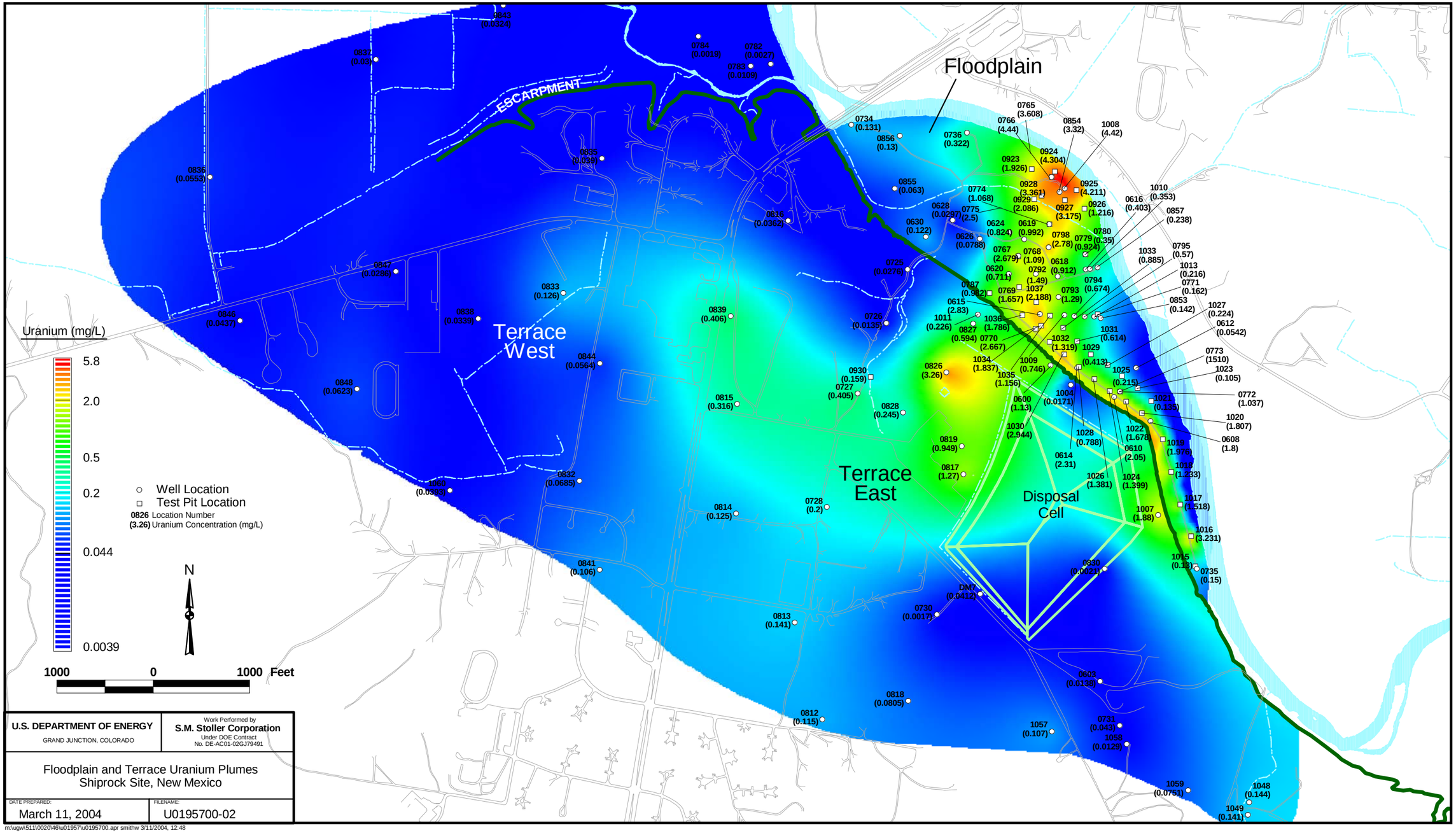

Figure 2–3. Uranium Concentrations in Terrace and Floodplain Ground Water

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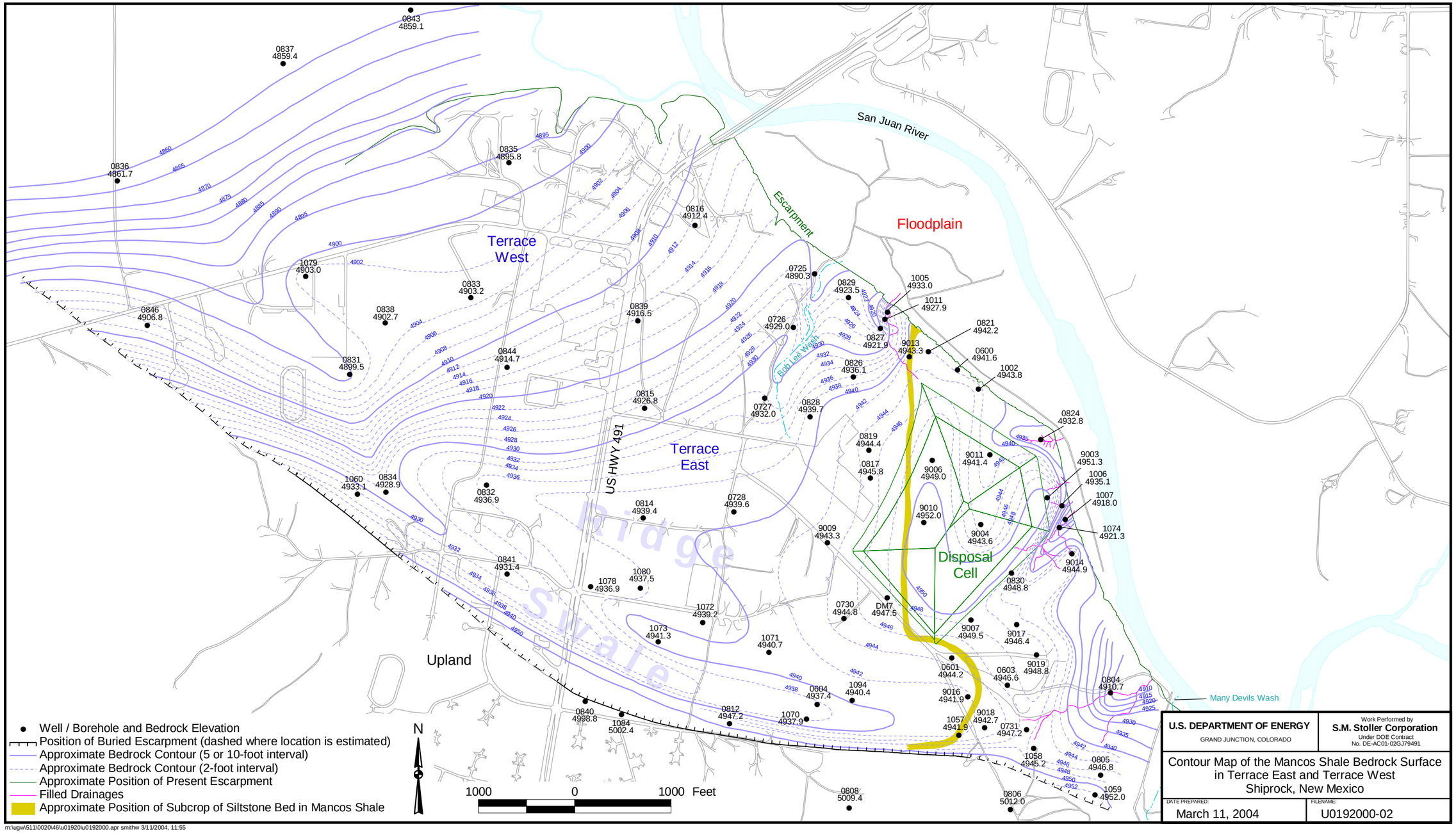

Figure 2–4. Contour Map of the Mancos Shale Bedrock Surface Elevation in Terrace East and Terrace West

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2.2 Floodplain

Floodplain alluvial ground water is held in alluvial sand and gravel of the present San Juan River floodplain and in the underlying weathered Mancos Shale. The volume of ground water in the alluvial material of the floodplain aquifer was estimated as 150 million gal (Section 4.3.2.1 SOWP, Rev. 2).

2.2.1 Contaminant Flux From Terrace to Floodplain

Drainage of residual moisture (transient drainage) from the disposal cell is speculated to transport contamination to the terrace and alluvial flow systems. Ground water contained in the swale should decrease in volume with pumping of terrace east extraction wells. In the SOWP, Rev. 2, recharge to the floodplain alluvial aquifer was estimated at 9.8 million gallons per year (18.7 gal/min) from ground water discharge off the terrace. This seepage is a potential source of degradation of the water quality of the floodplain alluvial aquifer. Concentrations of contaminants of concern (COCs) immediately below the escarpment have not changed significantly over time, suggesting that RRM-laden fluids continue to flow to the floodplain aquifer or that this ground water is nearly stagnant.

To refine estimates of cell leakage and to evaluate optimal methods for remediation of ground water at the site, modeling was conducted by Knight Piesold and Company (2002) using the Hydrologic Evaluation of Landfill Performance (HELP) model to simulate infiltration of precipitation through the disposal cell. Results of this modeling, some of which were used in preparation of the GCAP, yielded somewhat lower values of flux from the disposal cell ranging from 2.5 to 4.8 gal/min. As stated in the GCAP, the seepage flux draining from the disposal cell still remains uncertain.

2.2.2 Distribution of Contaminants

The floodplain contaminant plume extends along the base of the escarpment from the narrow part of the floodplain east of the disposal cell northward to directly north of the disposal cell. The plume then extends north across the floodplain and bends toward the north-northeast in an arc that reaches the San Juan River. The maps of nitrate, sulfate, and uranium concentrations (Figure 2–1 through Figure 2–3, respectively) show this floodplain plume configuration.

In the northwest part of the floodplain, ground water contaminant concentrations are generally low as a result of the flushing effect of surface water from Bob Lee Wash (contributed mainly by water from flowing artesian well 0648) entering the floodplain. Low ground water contaminant concentrations similarly occur in an area of the floodplain northeast of the disposal cell that is adjacent to the San Juan River in an area up to 500 ft wide, where the river has recharged the aquifer and diluted the contaminants. In addition to nitrate, sulfate, and uranium, high concentrations of ammonium in floodplain ground water have persisted along the base of the escarpment northeast and north of the disposal cell.

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3.0 Refinements to Conceptual Model

3.1 Terrace

Additional data collected or reevaluated subsequent to the preparation of the SOWPs and the GCAP contributed to changes to the conceptual model for the terrace system. The most relevant of these refinements are described in this section.

3.1.1 Bedrock Swale and Ridge in South Part of Terrace East

A buried Mancos Shale bedrock escarpment approximately 50 ft high abruptly forms the south boundary of terrace east. North of this escarpment, the Mancos Shale bedrock was covered first by coarse alluvial deposits of the ancestral San Juan River channels and later by a wedge of windblown silt (loess) deposits that thin northward. The loess deposits have formed a gently north-sloping surface that has covered (buried) all traces of the escarpment. The estimated position of the buried escarpment has been inferred from drilling data for several boreholes and monitor wells that contact bedrock. Figure 2–4 shows the approximate position of the buried escarpment, the contour elevations of the bedrock surface north of the buried escarpment, and the elevations of bedrock identified in boreholes and wells.

The prior compliance strategy (GCAP) is based on an assumption that during pumping in the swale, ground water will flow through terrace alluvium from the escarpment to the swale. If all flow is through alluvium, then the elevation of the top of the bedrock will affect flow paths.

3.1.1.1 Refinements to Bedrock Surface

The bedrock surface in terrace east presented on Figure 4−7 of the SOWP, Rev. 2, has been modified, based on information derived from additional boreholes and wells drilled to bedrock in 2002 and 2003. As identified in SOWP, Rev. 2, a shallow, linear bedrock low, referred to as a sump that slopes gently to the west and northwest, occurs north of the buried escarpment; bordering the sump to the north was a low bedrock ridge extending westward that was defined by bedrock identified in boreholes for wells 0728, 0814, and 0832. Data from additional boreholes and wells have improved the understanding of the bedrock surface (Figure 2–4); however, borehole and well spacing is still sparse and the existence of the shallow valley or swale and the low ridge are known in only a general sense. Bedrock elevation data for only one well (1094) of the four new closely spaced extraction wells (1091 through 1094) were included on Figure 2–4. Bedrock elevation data from several of the old wells installed by Jacobs Engineering Corporation in the early 1980s were not included on Figure 2–4 because the bedrock lithologic interpretations or survey elevation, or both, were suspect or the bedrock elevations exceeded the contours that are based on post-1990 well elevation data.

Characteristics of the bedrock swale and ridge from the recent bedrock elevation data, as shown on Figure 2–4, are

- The elevation difference between the bottom of the swale and the subtle ridge to the north is approximately 6 ft, as shown by bedrock elevations for wells 0832, 0841, 1070, and 0730. This elevation difference changed slightly from the elevation presented in the SOWP, Rev. 2.

- The bottom of the swale is approximately along the trend (from east to west) of wells 1057, 1070, and 0841 and borehole 834. This swale axis roughly parallels the nearby buried escarpment and shows that the ancestral river channel dropped 2 ft vertically in a distance of 1,000 to 1,500 ft, which is similar to the gradient of the San Juan River in its present channel. The position of the swale has shifted slightly south from the location given in SOWP, Rev. 2.

- The position of the buried escarpment was shifted slightly south from the escarpment position in the SOWP, Rev. 2, based on 2002 geoprobe borehole bedrock data.

- The position of the subtle ridge is little changed from the ridge position given in the SOWP, Rev. 2. A minor bedrock ridge may be present just north of and parallel to the swale axis, as shown by the bedrock elevations for boreholes 1071, 1072, and 1073. The existence of several more of these minor ridges in the area of the swale is likely; however, additional bedrock elevation data would be necessary for their verification.

3.1.1.2 Refinements to Saturated Thicknesses

Saturated thicknesses as much as 7 ft thick occur in the alluvial material overlying the bedrock in the swale. Along the subtle ridge at wells 0728, 0814, and 0832, saturated thicknesses in alluvial material are less than 1 ft, or the water level is 2 ft down into the weathered Mancos Shale as in well 0814. Thicker saturation in the alluvial material in the swale would promote ground water movement mostly northwest along the swale axis rather than north through the less permeable weathered Mancos Shale.

3.1.1.3 Implications

The existence of a subtle bedrock ridge to the north of the swale may limit migration of ground water from the alluvial material in the swale to the seeps (e.g., locations 425 and 426) in the Mancos Shale north of the disposal cell. Thus, the compliance strategy for the floodplain, which includes minimizing contaminated ground water contributions from the terrace by extraction of ground water from terrace east wells, may be less effective than previously thought.

3.1.2 Connectivity in the Terrace Alluvium

During previous investigations and as described in the previous section, a bedrock swale was identified in the southern portion of terrace east in which saturated alluvium is thicker than elsewhere. Alluvium in this area was previously thought to be continuous and quite extensive and to contain a significant quantity of water that migrated west of U.S. Highway 491. Lithologic logs of wells drilled into the local alluvium and limited aquifer test data were used to project that pumping rates from the alluvium would be 2 to 5 gal/min per well. Evidence from subsequent investigations suggests that the alluvium is less continuous than previously thought.

3.1.2.1 Evidence From Ground Water Extraction Rates

Review of operation data for the terrace extraction well system indicates that pumping rates are lower than projected. Although low production rates are partly attributable to well-efficiency problems (Section 4.1.1), data collected from terrace wells in alluvium also suggest that the low production rates are due to limited connectivity between isolated pockets of alluvium.

Sustainable pumping rates in terrace east extraction wells have ranged from about 0.01 to 1.5 gal/min. These rates are significantly lower than would be expected in wells tapping a continuous sand-and-gravel aquifer with an average saturated thickness greater than 5 ft.

3.1.2.2 Evidence From Aquifer Test

Relatively low extraction rates do not by themselves prove that the lateral extent of the aquifer is limited; however, hydraulic data from an aquifer test conducted at terrace east extraction well 0818 provide evidence that the alluvium, at least at this locale, is laterally discontinuous. Specifically, drawdown data obtained during the test indicated the presence of a barrier boundary about 20 ft from the pumping well. The barrier boundary caused the rate of change in drawdown in the pumping well to vary greatly from the rate that would be expected in an aquifer with no barriers (Figure 3–1). Without additional investigation, the cause of this boundary effect is difficult to determine. Possibly, elevated areas of Mancos Shale bedrock surface or other less permeable materials are acting as impediments to local ground water flow in terrace alluvium near well 0818.

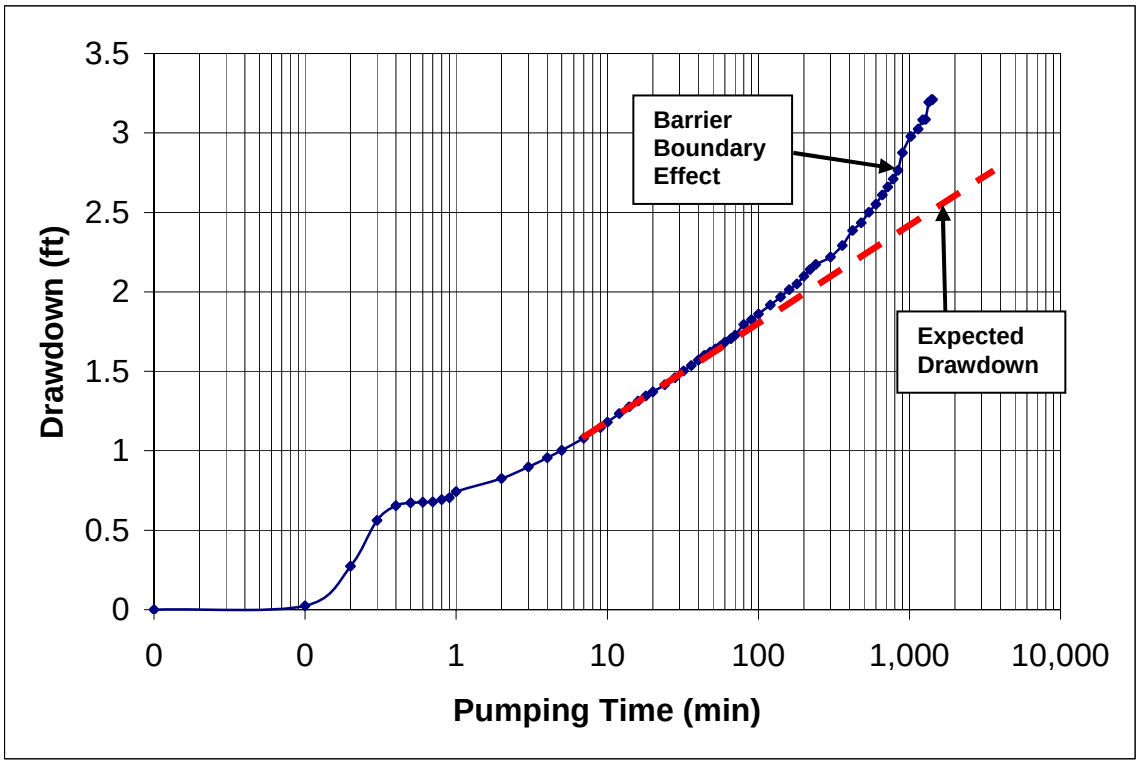

Figure 3–1. Semilogarithmic Plot of Drawdown in Relation to Time at Terrace East Extraction Well 0818

3.1.2.3 Implications

Lack of connectivity in the terrace alluvium has implications for the compliance strategy. Limited connectivity would decrease the effect that pumping in the swale would have on escarpment seeps. At a minimum, lower than expected pumping rates from terrace alluvium wells suggest that ground water processes in terrace alluvium are not well understood, although the lower than expected pumping rates could also be related to well installation techniques.

Uncertainty regarding flow in this ground water system is exacerbated by the limited number of wells that have been drilled into and screened in the alluvial sediments.

3.1.3 Storage and Transport in the Mancos Shale

Previous investigations did not recognize significant transport of contaminated ground water by the Mancos Shale. Even if terrace alluvial wells produced substantially more ground water, large quantities of ground water might continue to move to the floodplain from the terrace through the Mancos Shale. It is possible that the Mancos Shale exerts more influence on the ultimate fate of terrace ground water contaminants than the alluvium does. Because the screened intervals of some of the terrace extraction wells extend a short distance into Mancos Shale, a small amount of the ground water is also pumped from the shale.

3.1.3.1 Saturated Thicknesses and Storage Capacity

The likelihood that Mancos Shale ultimately controls contaminant transport to the floodplain appears even greater when the thicknesses of contaminated alluvium and contaminated shale beneath the terrace are compared. The saturated thicknesses of alluvium within the terrace east and terrace west areas tend to be small, with values ranging from 0 to 7 ft being common. In contrast, the saturated thickness of the underlying Mancos Shale ranges from 0 to 50 ft. The greater saturated thickness does not necessarily mean that more contaminated water is stored in the shale than in the alluvium. If ground water in the shale occurs predominantly in fractures, the effective void space in the shale is probably less than the pore space available in the alluvium. Nonetheless, the Mancos Shale could significantly contribute to the storage capacity of contaminated ground water.

3.1.3.2 Evidence for Fracture Flow and Transport in Shale

Several lines of evidence suggest that water movement in the Mancos Shale tends to occur within preferential paths (e.g., Charbeneau and Daniel 1993) rather than uniformly throughout the shale. Many such zones appear to occur along bedding planes, such as at the top of thin bentonite beds and the top of the prominent calcareous siltstone bed (Figure 2–4), whereas others are probably associated with fractures that cut across bedding planes. The potential for preferential flow to dominate ground water flow and, therefore, contaminant transport in fractured portions of the Mancos Shale makes the prediction of contaminant fate and the effects of ground water extraction on site remediation more problematic than would be the case if ground water moved solely through alluvial sediments.

Evidence for fracture flow in the Mancos Shale is in three well clusters (0820 through 0822, 0823 through 0825, and 1002 through 1004) installed between the disposal cell and the escarpment separating the terrace from the floodplain (Plate 1). Water level measurements in the three wells that are screened in Mancos Shale at each cluster show a large moisture variation in the shale, with some wells containing water and others completely dry. Moreover, there is no apparent correlation of moisture with depth. The tendency to encounter both completely dry and saturated conditions in wells close to each other is also observed in wells in Mancos Shale just west of Many Devils Wash. For example, monitor well 0805 at the south end of the NECA gravel pit is dry at its total depth of 51 ft (elevation approximately 4,900 ft), whereas monitor well 1059 about 200 ft to the south was drilled to a depth of 50 ft (elevation approximately

4,918 ft) and encountered ground water about 6 ft below the base of alluvium at an elevation of 4,947 ft.

Additional evidence of preferential flow is the occurrence of seeps within distinct beds in the Mancos Shale on the east bank of Many Devils Wash but not on the west side, suggesting that ground water moves southeastward under confined flow conditions below the wash and subsequently moves upward on the east side of the wash. Fractures likely provide the flow routes associated with such migration.

Further evidence of preferential contaminant flow paths is documented by the large variation in uranium concentrations in ground water samples, such as contaminant concentrations in samples from a pair of Mancos Shale wells (about 0.7 and 10.0 mg/L in wells 0602 and 0817, respectively) within 20 ft of each other and screened over similar vertical intervals. One explanation for the large concentration difference is that the higher concentrations occur within a preferential migration path (e.g., fractures) and the lower concentration is associated with contaminants migrating outward to less permeable portions of the shale.

3.1.3.3 Flow Paths in Many Devils Wash

In October 2003, ground water levels rose in the vicinity of Many Devils Wash and in some areas contaminated ground water seeped from the bank a few feet above the wash bed. In addition to the moist banks, several puddles of water were observed in the wash bed. Several weeks later, soil moisture in the area had partly returned to low levels more typical in the wash. The temporary rise in water levels appeared to be associated with a local rainfall event that occurred a few days earlier and probably contributed water to the local ground water system. Recharge to localized parts of the shale apparently caused a wave of ground water to flow through fractured parts of the formation. The high ground water levels took several days to attenuate. The large water-level increases were probably associated with recharge to limited areas of the shale near fractures; the porosities typically associated with fractured shale are much lower than those in alluvial sediments.

3.1.3.4 Implications

The potential for preferential flow and transport in the Mancos Shale to dominate contaminant migration from the terrace to the floodplain has several implications for cleanup of the Shiprock site. For one, the associated tendency of ground water flow to occur primarily in isolated zones, such as fractures across bedding planes in some areas and not in others, suggests that it will be difficult to locate such zones through well drilling. Similarly, it is difficult to identify specific locales where downward-migrating ground water is moving along the top of less permeable thin bentonite beds.

Fracture-dominated flow also affects the rate that contaminants dissolved in Mancos Shale ground water will be transported to the floodplain. Potential exists for contaminants to diffuse away from fractures into matrix portions of the shale where the tendency of some contaminants to sorb to shale materials increases. Both sorption processes and the tendency for contaminants to migrate into less permeable parts of the shale affect contaminant transport by retarding the rate at which contaminants migrate from shale to the floodplain.

During episodic rain fall events, ground water recharge in isolated locations can cause large, abrupt changes in ground water levels, which can radically alter ground water flow directions (e.g., Moline et al. 1998). Potential exists for ground water levels in the shale to rise occasionally by 5 to 10 ft or more in response to episodic heavy rainfall on the site. During the surge in piezometric levels, some of the contamination in both aqueous and solid (sorbed) phases and residing in what are normally unsaturated portions of the shale can be entrained in the rising ground water. Thus, contaminant flushing from the Shiprock site may not occur at a steady rate but could instead fluctuate with rain events.

3.1.4 Changes in Terrace Ground Water Levels

Linear regression analyses were made of plots of ground water elevations in relation to time for 43 terrace wells to evaluate changes in ground water levels (Appendix B). Thirty-two of the wells are screened solely in the alluvium or across the alluvium−Mancos Shale contact. The remaining 11 wells are screened in Mancos Shale. Most of the water-level measurements are from 1999 to November 2003; however, some well data span only the last 3 years.

3.1.4.1 Alluvium

Most alluvium (includes wells screened across the alluvium−Mancos shale contact) water levels have decreased over time, with a maximum decrease of 8.2 ft in well 0830 (Figure 3–2). Decreases in ground water levels in the terrace may be due to the slow drainage of anthropogenic water stored in the terrace alluvium during milling operations; however, the temporal effect of the current drought may also affect water levels. In contrast, ground water elevations increased in wells 0846 and 1060 in terrace west. Levels also increased in an area southwest of the disposal cell with a maximum increase of 4.4 ft observed in well 0730. Alluvium ground water levels also increased slightly just east of Many Devils Wash.

In some terrace wells, increases in ground water elevations correlate to major rain events. Rapid increases in ground water elevations occurred in well 0830 during major rain events, followed by more gradual decreases in water levels and a net decrease in the water level from 1999 to 2003 (Figure 3–3). The low uranium concentration in ground water samples from well 0830 suggest that ground water recharge is not from the nearby disposal cell.

The large increases in ground water levels observed in well 0730 (Figure 3–3) are the result of infiltration of ponded water in the adjacent radon-cover borrow pit. The radon-cover borrow pit is a closed basin that collects rainwater runoff from an area about twice the size of the basin. Local ponding has been observed immediately after several heavy rainfall events in the lowest part of the radon-cover borrow pit just east of well 0730. Tamarisks are growing at scattered locations in the lowest part of the radon-cover borrow pit, indicating the presence of a shallow ground water table. Ground water levels in well 0731 reflect major rain events similar to those in well 0730. The response in well 0731 is attributed to infiltration from ponded water in local surficial depressions in the adjacent NECA gravel pit area. For additional discussion, see Appendix B of this report.

Ground water extraction by plants has not been considered in terrace remediation designs. In the radon-cover borrow pit area (where silt was removed and used as a radon barrier in disposal cell construction), ground water extraction by plant uptake is occurring and could perhaps be enhanced to improve remediation efficiency. Passive phytoremediation (use of plants to help

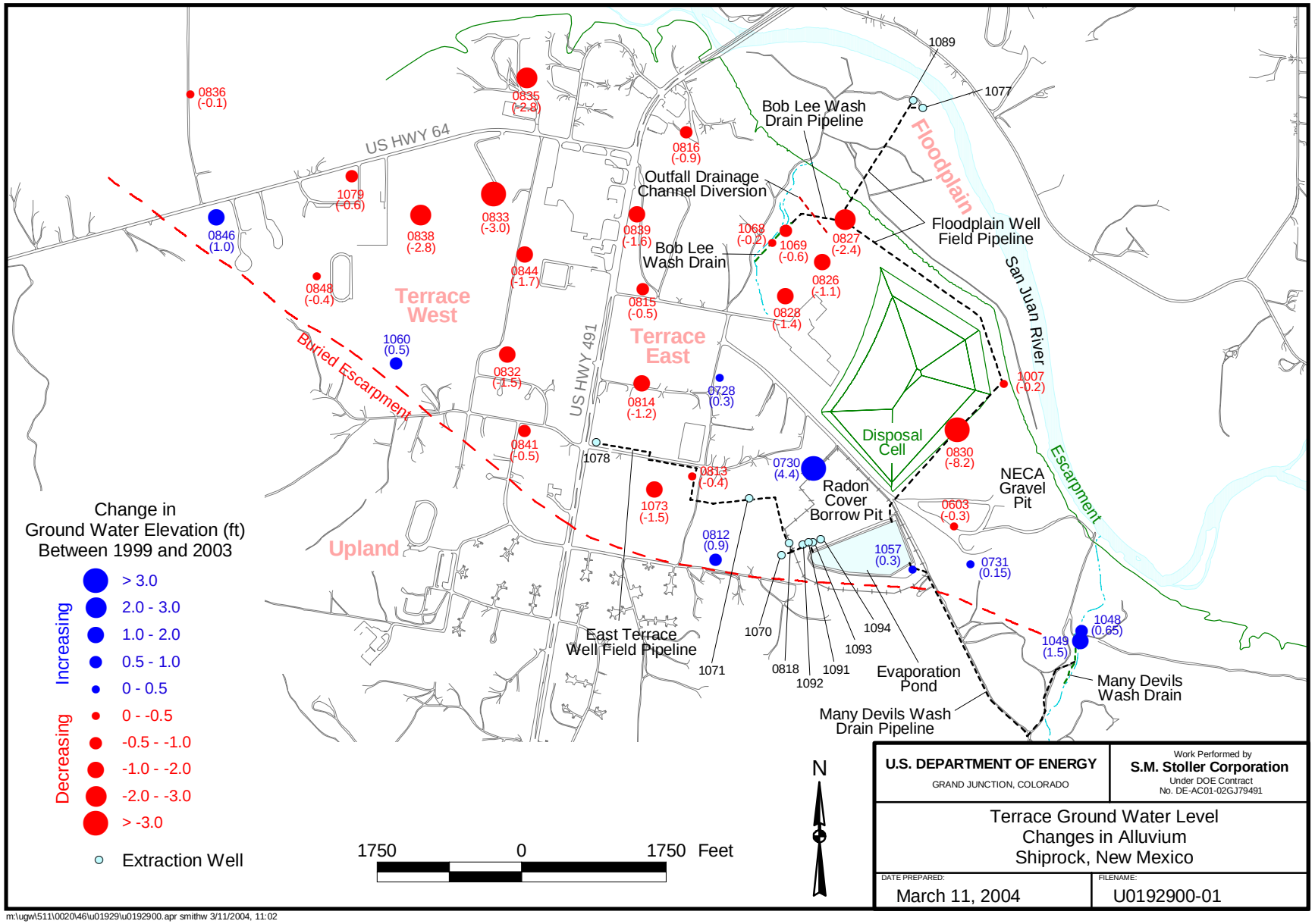

Figure 3–2. Ground Water Level Changes in Alluvium and Alluvium/Mancos Shale on the Terrace

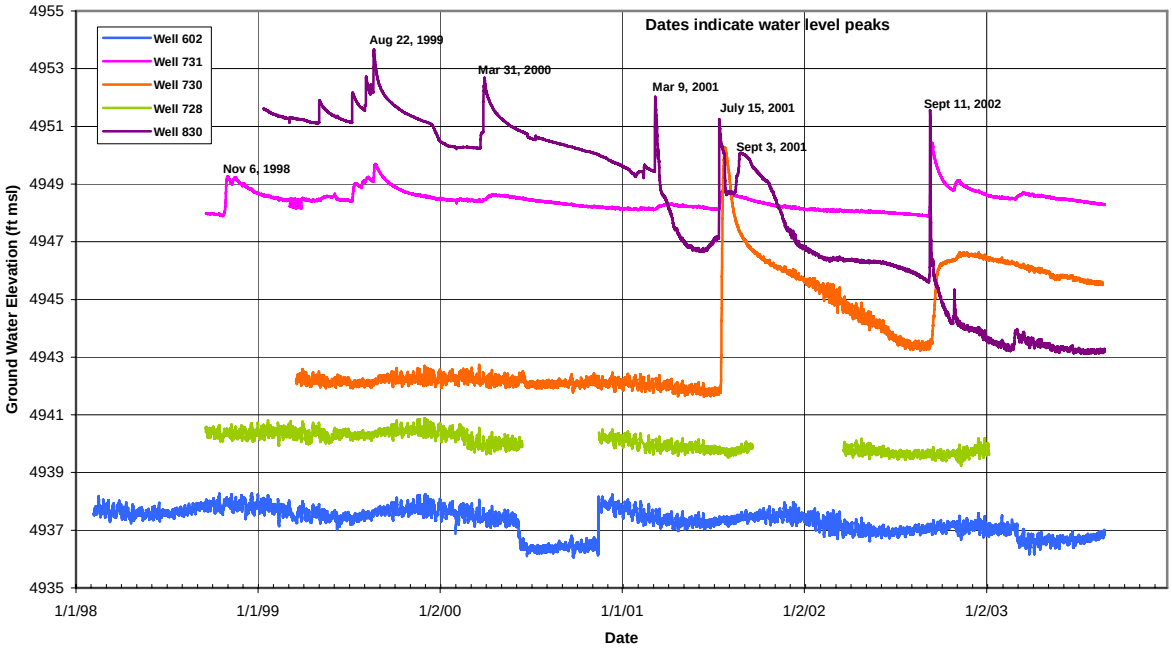

Figure 3–3. Datalogger Information for Specific Terrace Wells

remediate a contaminated site) is ongoing in the radon-cover borrow pit area. The tamarisk stand at the low (north) end of the borrow pit area is currently extracting water, nitrate, ammonia, and possibly other ground water constituents. An estimate of the maximum transpiration rate for tamarisk stands growing under climatic conditions similar to Shiprock is 78 inches per year (Glenn and Nagler 2003; King and Bawazir 2003; Waugh and Van Reyper 2003). Transpiration from the existing sparse tamarisk stand, which covers roughly 0.5 acre, is likely no more than 20 inches per year. If these values are used, an initial approximation of the existing plant water extraction rate is about 0.5 gal/min.

3.1.4.2 Mancos Shale

Water level changes from linear regression analyses for 11 wells are shown on Figure 3–4. Many of the wells completed in Mancos Shale show a decrease in water levels similar to the alluvial wells. An exception is just west of Bob Lee Wash at well 0726, which shows an increase of 14 ft. The results suggest that water levels are naturally declining in the Mancos Shale, possibly because of the gradual drainage of mill-related ground water.

3.1.4.3 Implications

The large increases in water table elevation at well 0730 following large rainfall events suggest that a significant amount of recharge occurs when water ponds in the radon-cover borrow pit. This source of recharge has been ignored in previous remediation planning. If not curtailed, this recharge may extend the length of time required for active ground water remediation. Vegetation in the radon-cover borrow pit may be capable of extracting a substantial amount of ground water that could offset the amount added by infiltration.

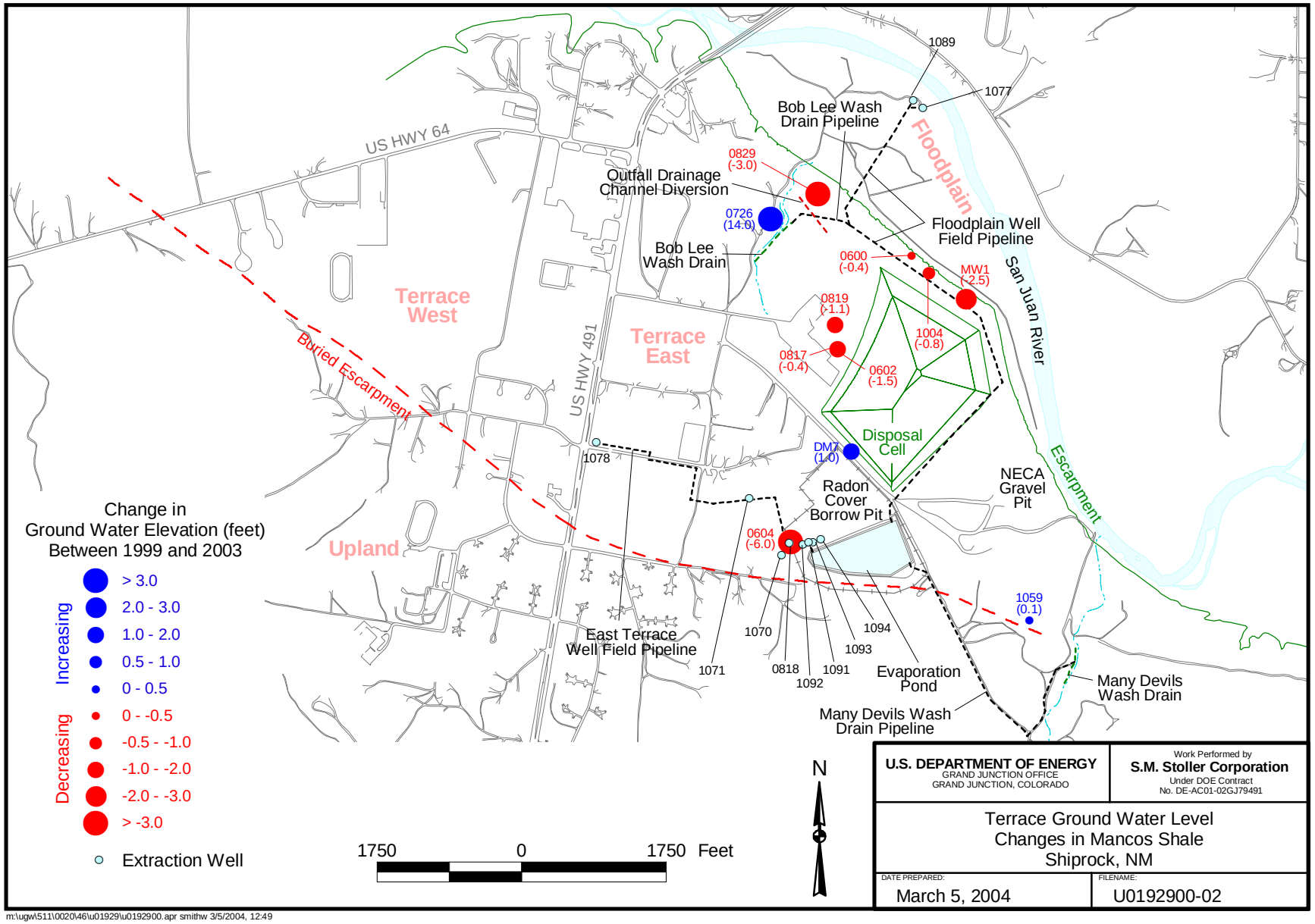

Figure 3–4. Ground Water Level Changes in Mancos Shale on the Terrace

3.2 Floodplain

Additional data collected or reevaluated subsequent to the SOWP Rev. 2 and the GCAP have resulted in few changes to the conceptual model for the floodplain system. Ground water extraction rates are less than expected, and contaminant concentrations near the escarpment have changed little.

3.2.1 Ground Water Extraction Rates

Well performance issues associated with the two floodplain extraction wells have limited the volume of ground water removed from the floodplain alluvium. Since the installation of well 1089 in July 2003 to replace well 1075, the average flow rate for the floodplain component of the extraction system has been approximately 5.5 gal/min; well 1089 has contributed approximately 5.0 gal/min of this total flow rate.

This extraction rate is considerably lower than the expected rate, as suggested from earlier pump tests using floodplain wells. No additional modeling was completed, but at the current flow rate the cone of depression produced by the floodplain extraction wells is expected to be limited. As a result, the current pumping rate is not expected to significantly affect the ground water contaminant concentration in the floodplain.

3.2.2 Changes in Contaminant Concentrations

The prior conceptual model suggests that concentrations of contaminants in floodplain ground water should decrease over time if the contaminant flux from the terrace is minimal. A metric, based on mean uranium concentrations in samples from selected monitor wells in the floodplain contaminant plume, is used to evaluate concentration time trends (Figure 3–5). Wells were selected for the metric based on (1) locations in the plume, (2) monitor history of at least 4 years, and (3) monitoring will continue. Monitor well 0854 was used instead of 1008, 1077, or 1089 because it has a longer time trend and is in the same area as these wells. Not all monitor wells were sampled during all sampling events; if a well was not sampled, an average concentration was used for the metric.

The metric uranium concentration has not changed substantially over time (Figure 3–5). The mean uranium concentration in the plume is about 2.3 mg/L. Concentration trends for sulfate and nitrate are similar to uranium. Time trends of uranium concentrations in samples from individual wells vary with some trending up and some down. Operation of the remediation system, including the escarpment collection drains as recommended in Section 6.2, should consider the spatial distribution concentration trends.

Reasons for the continued high concentrations of contaminants in ground water in the floodplain are uncertain. The remediation system has been operational for such a short period of time that trends cannot yet be determined. Also, the effect of pumping on the concentrations of contaminants in terrace east ground water is likely to be less than predicted. Alternatively, the flux of contaminated seepage from the terrace is higher than previously thought. However, this explanation is inconsistent with the observation that the highest uranium concentrations are near the river rather than near the escarpment (Figure 2–3). Possibly, the flow rate of floodplain ground water is slower than previously estimated or there are stagnant zones that are not being affected by natural flushing. Also, aquifer sediments and Mancos Shale fractures may contain high concentrations of contaminants that continue to bleed into the ground water.

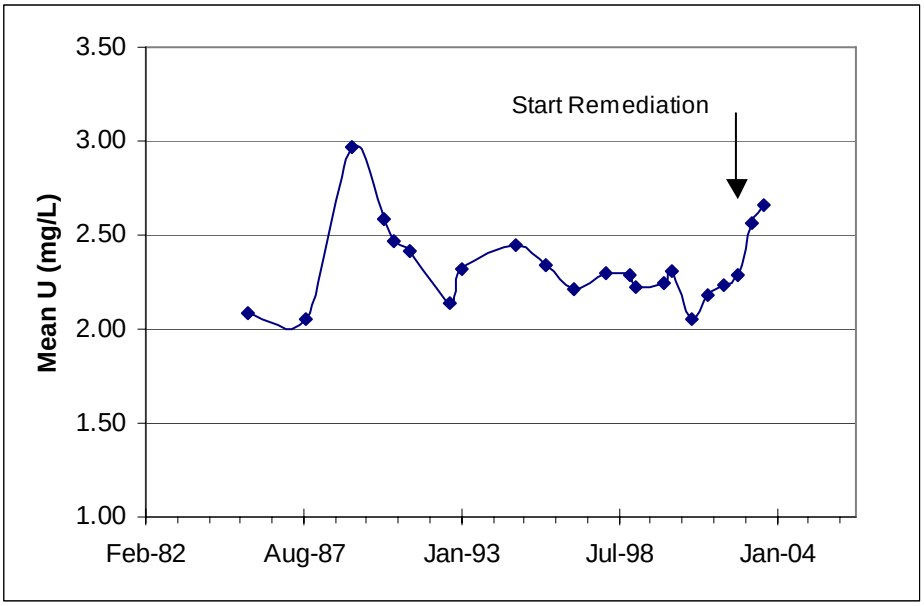

Figure 3–5. Uranium Concentration Metric (mean concentration of samples from wells 0608,0614, 0615, 0618, 0619, and 0854 in the floodplain).

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4.0 Efficiency of Extraction System

A ground water extraction system has been in operation at the Shiprock site since March 2003. Ground water is treated by evaporation in an 11-acre pond south of the disposal cell on terrace east. Experience gained while operating the remediation system suggests that drilling methods and well construction methods are responsible, at least in part, for poor well production. This section evaluates as-built construction of the wells, efficiency of the extraction wells (Section 4.1), and effectiveness of the interceptor drains (Section 4.2). Lessons learned about correlation of drilling methods with well efficiency at other LM sites is also discussed.

4.1 Extraction Wells: Construction and Efficiency

4.1.1 Shiprock Site

A variety of drilling methods have been used for extraction well installation at the Shiprock site. Since the startup of the treatment system in March 2003, a number of questions have been raised regarding the lack of production by some of the wells and the roles well drilling methods and well construction techniques may have on well efficiency. At Shiprock, the large cobbles in the floodplain and terrace alluvium created difficult drilling conditions for the hollow-stem auger and direct rotary methods. Larger drill rigs using the casing-advance or rotasonic methods were used for their ability to drill through the cobble-dominated alluvium. The following section describes the effects of different methods of installation and construction on the performance of the wells at the Shiprock site and provides a summary of the fieldwork completed in December 2003 that was designed to address some of these issues.

Terrace Extraction Wells Eight extraction wells are removing ground water from the terrace alluvium. The average pumping rate of the wells ranges from 0.01 (well 1094) to 1.5 gal/min (well 0818). Well 0818 was installed as a monitor well in October 1998, but was converted to an extraction well after the treatment system was installed because of its sustainable pumping rate and location (adjacent to the pipeline). Well 0818, drilled with the casing-advance method, is the only terrace extraction well that produces more than 1 gal/min.

Pertinent construction information and performance data for the terrace and floodplain extraction wells are presented in Table 4–1. Also listed are eight monitor wells that were tested for their favorability as extraction wells. A variety of drilling techniques and well construction designs have been utilized for the terrace wells, but removing ground water from the terrace alluvial system has been difficult regardless of the drilling method used. Only 2 of the 16 wells included in Table 4–1 were able to sustain pumping rates greater that 1 gal/min, and the maximum sustainable rate is only 1.9 gal/min.

Table 4–1. Well Completion, Construction, and Performance Summary for Terrace and Floodplain Wells

Terrace Well Completion/Construction Information											Well Performance Information		
Well	**Location**	**Date Installed**	**Drilling Method**	**Dia (in.)**	**Slot Size (in)**	**Sand Pack**	**Total Depth (ft bgs)**	**Screen Interval (ft bgs)**	**Static WL (ft bgs)**	**Screen Formation/ Lithology**	**Test Date**	**Pumping Period (hr)**	**Sustainable Q (gal/min)/ Yield (ft)**
0818[a]	SW of cell	Oct-98	casing advance	5	0.01 (vee-wire)	20/40	62	52 to 61.5	~55	alluv (SP)	Mar-03	Na	1.5 gal/min
1070[a]	SW of cell	Sep-02	rotasonic	6	0.04 (vee-wire)	8/12	65	52.5 to 62	~55	alluv (GW)/Mancos (minor)	Mar-03	Na	0.5 gal/min
1071[a]	SW of cell	Sep-02	rotasonic	6	0.04 (vee-wire)	8/12	49	36.5 to 46	~43	alluv (GW)/Mancos (minor)	Mar-03	Na	0.1 gal/min
1078[a]	SW of cell	Aug-02	rotasonic	6	0.04 (vee-wire)	8/12	48	35.5 to 45	~43	alluv (GP, SP)/Mancos	Mar-03	Na	0.7 gal/min
1091[a]	NW of pond	Jul-03	cable tool	4[b]	0.01 (mach slot)	native	43	~25 to 35	~30	alluv (GW)/Mancos (minor)	Mar-03	Na	0.2 gal/min
1092[a]	NW of pond	Jul-03	cable tool	4[b]	0.01 (mach slot)	native	43	~25 to 35	~30	alluv (GW)/Mancos (minor)	Mar-03	Na	0.15 gal/min
1093[a]	NW of pond	Jul-03	cable tool	4[b]	0.01 (mach slot)	native	43	~25 to 35	~30	alluv (GW)/Mancos (minor)	Mar-03	Na	0.25 gal/min
1094[a]	NW of pond	Jul-03	cable tool	4[b]	0.01 (mach slot)	native	43	~25 to 35	~30	alluv (GW)/Mancos (minor)	Mar-03	Na	0.01 gal/min
0603	east of pond	Jun-83	mud rotary	2	0.01 (mach slot)	8/12	40.9	25.9 to 35.9	~30	alluv (GP)/Mancos	May-03	0.25	less than 0.5 gal/min/5 ft
0604	south of pond	May-83	mud rotary	2	0.01 (mach slot)	8/12	77.7	62.7 to 72.7	~52	Mancos	May-03	0.1	less than 0.5 gal/min/11 ft
0730	north of pond	Mar-93	ODEX[d]	2	0.05 (mach slot)	8/12	39	27 to 37	~35	alluv (GM)/Mancos	May-03	0.1	less than 0.5 gal/min/11 ft
0813	SW of cell	Oct-98	casing advance	2	0.01 (mach slot)	20/40	51	40.8 to 50.8	~43	alluv (GW)/Mancos	May-03	0.5	less than 1 gal/min/4 ft
0817	NECA yd	Oct-98	casing advance	5	0.01 (vee-wire)	20/40	32	21.6 to 31.6	~19	Mancos	Mar-99	24	0.25 gal/min/11 ft
1007	east of cell	Apr-00	rotasonic	2	0.01 (mach slot)	20/40	46.6	36.8 to 46.3	~45	alluv (GM)/Mancos	Nov-03	0.5	less than 0.5 gal/min
1057	SE of pond	Mar-00	rotasonic	2	0.01 (mach slot)	20/40	36.5	31.2 to 36.2	~36	alluv (GW)	May-03	0.75	1.9 gal/min/1.5 ft
1059	near MDW	Apr-00	rotasonic	2	0.01 (mach slot)	20/40	49.3	39.5 to 49	~23	Mancos	May-03	0.5	less than 0.5 gal/min/25 ft
Floodplain Well Completion/Construction Information											**Well Performance Information**		
1077[a]	~290 ft from river	Aug-02	rotasonic	6	0.01 (vee-wire)	8/12	17.5	5 to 14.5	~7	alluv (GW)	Mar-03	na	0.5 gal/min
1089[a]	~290 ft from river	Jun-03	backhoe/culvert	4[c]	0.04 (vee-wire)	native	15.2	~5 to 15	~7	alluv (GW)	Jun-03	na	~5 gal/min
1075[b]	~290 ft from river	Aug-02	rotasonic	6	0.01 (vee-wire)	8/12	18.5	6 to 15.5	~7	alluv (GW)	Mar-03	na	1.5 gal/min
0618	~580 ft from river	Sep-85	mud rotary	4	0.05 (mach slot)	8/12	18	11 to 16	~7	alluv (GP)	May-03	0.5	~11 gal/min/6 ft
0619	~820 ft from river	Sep-85	mud rotary	4	0.05 (mach slot)	8/12	15	8 to 13	~7	alluv (SP)	May-03	0.25	less than 3 gal/min/7 ft
0858	~230 ft from river	Sep-98	casing advance	5	0.01 (vee-wire)	native	20.6	10.2 to 20.2	~7	alluv (GW)	Mar-99	18	~60 gal/min/10 ft
1008	~290 ft from river	Apr-00	rotasonic	4	0.01 (mach slot)	20/40	17.2	6.9 to 16.9	~7	alluv (GW)	Apr-03	3	~2.5 gal/min/7 ft

Footnotes:
[a]extraction well.
[b]Polyvinyl chloride casing set inside perforated steel casing.
[c]screen diameter inside the 24-in. culvert.
[d]casing-advance drilling method.

Abbreviations:

bgs	below ground surface
GP	sandy gravel
SP	sand, sandy gravel
GW	sandy gravel
GM	silty sand and gravel
MDW	Many Devils Wash
WL	water level

The four extraction wells drilled near the evaporation pond (wells 1091 through 1094) using the cable tool method are extremely low producers (0.01 to 0.25 gal/min). However, a number of factors other than drilling technique may contribute to this low production. For example, the construction of these wells may limit production, or the local hydraulic conductivity of the alluvium may be less than other areas of the site (these four wells are within 300 ft of each other).

Extraction wells 1070, 1071, and 1078 were installed using the rotasonic drilling technique and produce 0.1 to 0.7 gal/min. The relatively low production of these wells may result from the rotasonic drilling technique, as illustrated by comparing production of well 1070 (rotasonic) with well 0818 (casing advance). The distance between 1070 and 818 is only 150 ft, and both wells have similar diameters and screen intervals. Well 0818 produces three times as much ground water as well 1070. However, the drilling method may not be the sole limiting factor for extraction rate. Well 1057, near the southeast corner of the evaporation pond, that was also installed using the rotasonic method was able to sustain 1.9 gal/min for 45 minutes.

Floodplain Extraction Wells Information in Table 4–1 suggests (compare sustainable rates in wells 1075 and 1077 with those of well 1089) that low production from floodplain wells is associated with the rotasonic drilling method. All three wells are in the same area of the floodplain (within 200 ft of each other); wells 1075 and 1077 were installed using the rotasonic method, and well 1089 was installed into a trackhoe-dug trench inside a section of slotted galvanized steel culvert. Well 1089 produces approximately 5 gal/min, whereas wells 1075 and 1077 sustain rates of only 1.5 and 0.5 gal/min, respectively, raising the question if poor well efficiency is associated with the rotasonic drilling method. Reasons that the rotasonic method adversely affects the ability of the well to transmit ground water include (1) agitation and vibration during drilling compacts the alluvial material adjacent to the well bore and reduces its porosity and permeability and (2) smearing and caking of finer grain material (silt and clay) on the borehole wall, possibly caused or enhanced by heating during drilling.

A variety of drilling techniques have been used to install other floodplain wells. Well 0858, which has the ability to sustain up to 60 gal/min for 18 hours, was installed using the casing-advance method, although this well is also the closest well to the San Juan River. Two other floodplain wells (well 0618 and 0619) were installed using the mud rotary method. These wells sustain approximately 3 (well 0619) to 11 gal/min (well 0618). The production rate for floodplain wells installed using techniques other than rotasonic vary with location.

Though aquifer heterogeneity and drilling techniques might play key roles in affecting floodplain well production, a detailed aquifer test conducted at one of the floodplain wells suggests that well-efficiency problems will be significant regardless of where a well is located on the floodplain or the method used to install it. During a step-drawdown test conducted at well 0858, pumping rates to 60 gal/min were achieved. However, analysis of the data from this test indicated that the two-thirds of the drawdown occurring in this well could be attributed to head losses across the well screen, (i.e., the well was only 33 percent efficient). The conclusion drawn from this test is that the floodplain aquifer in some locations can be quite prolific, but it is difficult to design and construct efficient wells in the sands and gravels that tend to dominate floodplain aquifer sediments.

December 2003 Field Investigation A field investigation conducted in December 2003 addressed two important issues regarding well production: (1) the low production of wells drilled with cable tools (wells 1091 through 1094) on the terrace and (2) the well efficiency associated with the floodplain culvert well (well 1089).

The pump removed from well 1094 was covered with a thin layer of gypsum. A downhole camera showed the presence of precipitate inside the polyvinyl chloride (PVC) screen in well 1094. The inside of the screen was cleaned and the pump was re-installed. No precipitate was observed downhole or on the pump from well 1093, which is within 100 ft of well 1094. The PVC casing was removed from well 1093, and a small-scale step drawdown test (3-hour pumping period) was performed; the well sustained an extraction rate of 0.5 gal/min. The pump was reinstalled within the steel casing to determine if pumping for an extended period would increase the flow rate. Prior to removal of the PVC casing, the average production rate from this well was 0.25 gal/min. After about 2 months, no significant change in production rates have been reported for wells 1093 and 1094 and, therefore, the PVC screen does not appear to limit production.

At floodplain well 1089, water levels were measured both inside and outside the PVC casing while the pump was operating. Measured drawdowns indicate that the two sets of water levels had less than 0.03 ft of difference at any given time, which indicates that the PVC casing and screen in well 1089 do not cause efficiency problems. The downhole camera detected biofouling on the outside of the PVC slots, but the slot openings were clear of any obstructions.

4.1.2 Extraction/Monitor Well Efficiency at Other Uranium Mill Tailings Sites That Have Cobble-Dominated Alluvium

Experience with drilling methods and well efficiency gained at other sites was reviewed for application to Shiprock. Other uranium mill tailings sites with cobble-dominated terrace or floodplain alluvium include Rifle, Grand Junction, and Slick Rock, Colorado, and Moab, Utah. For each of these sites, the following summaries provide drilling methods used for extraction or monitor wells and their efficiencies:

- At Rifle, monitor wells installed in the late 1990s were drilled using the air-hammer casing advance method, and pumping rates during well development have been satisfactory.
- At Grand Junction, numerous monitor wells were installed in 1997 using the hollow-stem auger drilling method. Some of these wells had poor production during development. Two additional wells were installed in 1998 using the casing-advance (ODEX) drilling method. These two wells had significantly improved well efficiencies and higher hydraulic conductivity values during well development. Use of the casing-advance drilling method resulted in less disturbance to the adjacent alluvial materials.
- At Slick Rock, monitor wells were installed in 2000 using the rotasonic drilling method. Pump tests on these wells yielded noticeably lower sustainable pumping rates compared to previously installed adjacent wells that were drilled using the air rotary method.
- At Moab, extraction wells were installed in 2003 using the dual-wall, air-percussion hammer (air-hammer, casing-advance) drilling method. Pumping rates during well development and extraction rates have been satisfactory.

In summary, well efficiency information for wells at Shiprock and other sites where wells are installed in cobble-dominated alluvial material indicate that the air-hammer, casing-advance drilling method creates wells that have higher extraction rates than those installed by other drilling methods.

4.2 Interceptor Drains: Construction and Efficiency

Two subsurface interceptor drains designed to collect contaminated ground water were installed in Bob Lee and Many Devils Washes (in December 2002 and November 2002, respectively) as part of the terrace remediation system (Plate 1). These drains, which were offset from the wash centerline to minimize surface water infiltration, consist of a perforated pipe surrounded by drain rock and impermeable geomembrane and geotextile fabric liners. Figure 4–1 provides a schematic cross section of the interceptor drain construction.

This section includes discussions regarding the installation, performance, and system modifications that may increase flow into the drains.

4.2.1 Bob Lee Wash

As Figure 4–1 shows, the design specified that the base of the drainpipe was to be keyed into the Mancos Shale bedrock, which was expected to be approximately 4 ft below ground surface. However, ground water entered at such a rate during trench excavation that (1) reaching bedrock proved to be difficult because of caving and (2) the volume of ground water entering the trench was thought to be sufficient to meet the designed volume requirements. As a result, the majority of this drain was set above the Mancos Shale contact. Figure 4–2 presents the as-built plan and profile for this drain.

A pump was installed inside the drain sump during the first week of January 2003. Initially the ground water flow rate into the sump from the drain was 14.9 gal/min. After 1 week the rate decreased to approximately 9 gal/min, and steadily decreased to approximately 7 gal/min by mid-February 2003.

When the system began operation in mid-March 2003, the discharge rate from the sump was just below 7 gal/min. During the early stages of operation, ponded water was visible on the surface near the sump, suggesting ground water was bypassing the drain because the pump could not accommodate the volume of ground water entering the drain. By early May 2003, the ponded water was no longer present, suggesting that the pump discharge rate was keeping up with the inflow rate (the pumping rate at this time was approximately 5.5 gal/min). As of January 2004. the drain was removing 5.8 gal/min of contaminated ground water.

During the summer months, some bacterial growth was observed clogging the filter. Chemical treatment appeared to remedy this problem, although a number of treatments were necessary to control this growth. Once the daily temperature cooled down in fall 2003, the bacterial growth decreased.

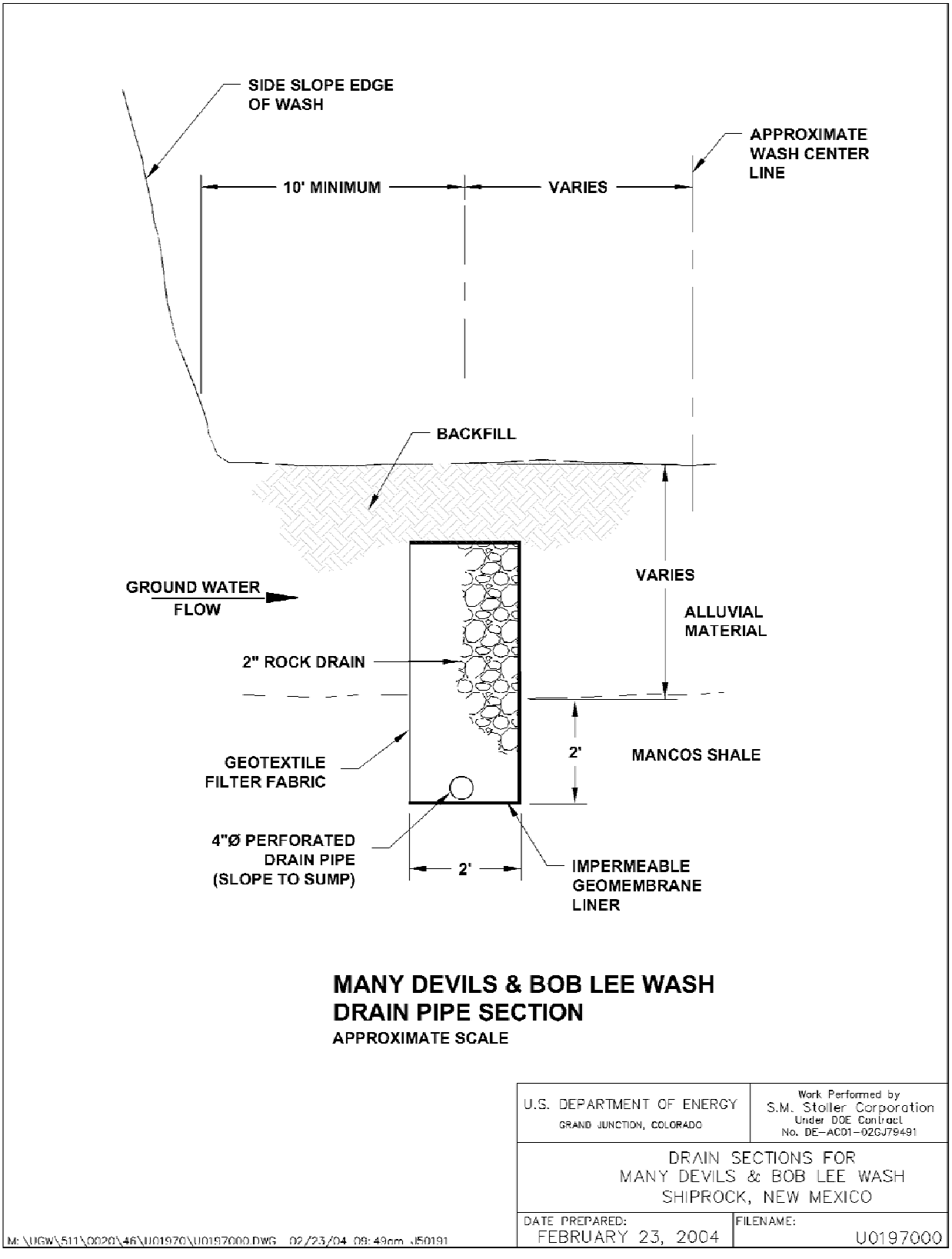

Figure 4–1. Schematic Cross Section of the Interceptor Drain Pipe Construction in Bob Lee and Many Devils Washes

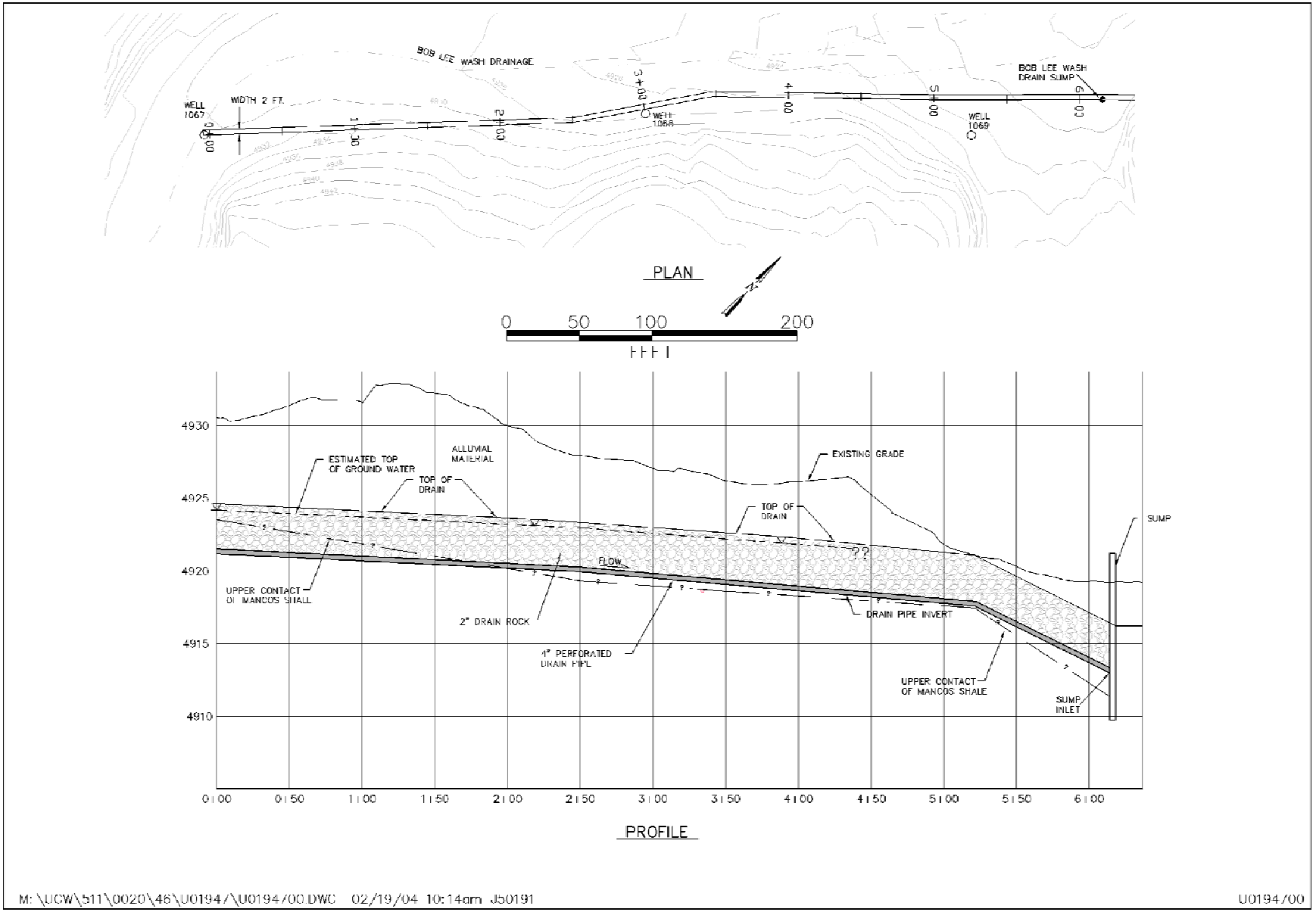

Figure 4–2. As-Built Plan and Profile of the Interceptor Drain in Bob Lee Wash

Deeper installation of the drain so that its entire length would be in the bedrock would possibly increase access to a larger volume of available ground water for removal. A larger volume of ground water in conjunction with a higher capacity pump would increase the volume of contaminated ground water removed from this area of the site.

4.2.2 Many Devils Wash

The initial design of the Many Devils Wash drain specified that the drain would extend north as far as the knickpoint in the wash. However, the drain line was extended only to its present location (approximately 150 ft north of the sump), which is approximately halfway between the sump and the knickpoint. Figure 4–3 presents the as-built plan and profile for this drain. The drain was not constructed north to the knickpoint because of conditions identified during trench excavation. As trench excavation advanced north from the sump, the alluvial material and shale bedrock became less saturated. Also, trench excavation became more difficult in the resistant calcareous siltstone bed in the Mancos Shale and in the underlying unweathered shale as the trench progressed northward. Trench excavation ended at a point where the subsurface was nearly dry.

A pump was installed in the sump, and a ground water recharge rate into the drain of 0.5 gal/min was measured in mid-February 2003. When the remediation system began operation in mid-March, ground water was being removed from the sump at a pumping rate of 0.25 gal/min. The rate during the first 3 months of system operation gradually decreased to 0.1 gal/min.

During spring 2003, water began ponding on the surface of the wash from the sump south to the confluence of the East Fork (Plate 1). By June 2003, the water had not been removed by the drain and had not evaporated. The source of this water was believed to be seeps fed by ground water upgradient from the south end of the drain. In an effort to capture this water, a french drain was added in late 2003 to the main drain at its south end near the East Fork confluence. In response to the modification to the drain, the pumping rate doubled (from approximately 0.1 to 0.2 gal/min) and the ponded water dried up for several months. During a site visit in December 2003, ponded water was again observed in the main channel, apparently originating from seeps west of the main drain south of the sump. Also, from October 2003 to early January 2004, the pumping rate increased to approximately 0.4 gal/min. This higher pumping rate could be because of less evaporation during fall and winter, resulting in more available ground water, or could be because additional ground water was reaching the Many Devils Wash area from the west, or a combination of both. The pumping rate increased again in early January 2004 to nearly 0.8 gal/min, which was maintained to early February. This abrupt increase in pumping may be caused in part by a large rain and snowfall event in early January.

An accumulation of silt and mud in the rock covering the french drain may restrict flow of surface water and ground water into the drain at the south end of the interceptor drain. Silt was deposited on top of the rock during several rainfall events that created flows down the wash. Periodic removal of the built-up accumulation of silt would increase the flow to the french drain. In addition, the use of a netting material (as opposed to the geotextile filter fabric) and extending the drain farther south may also increase flow into the drain.

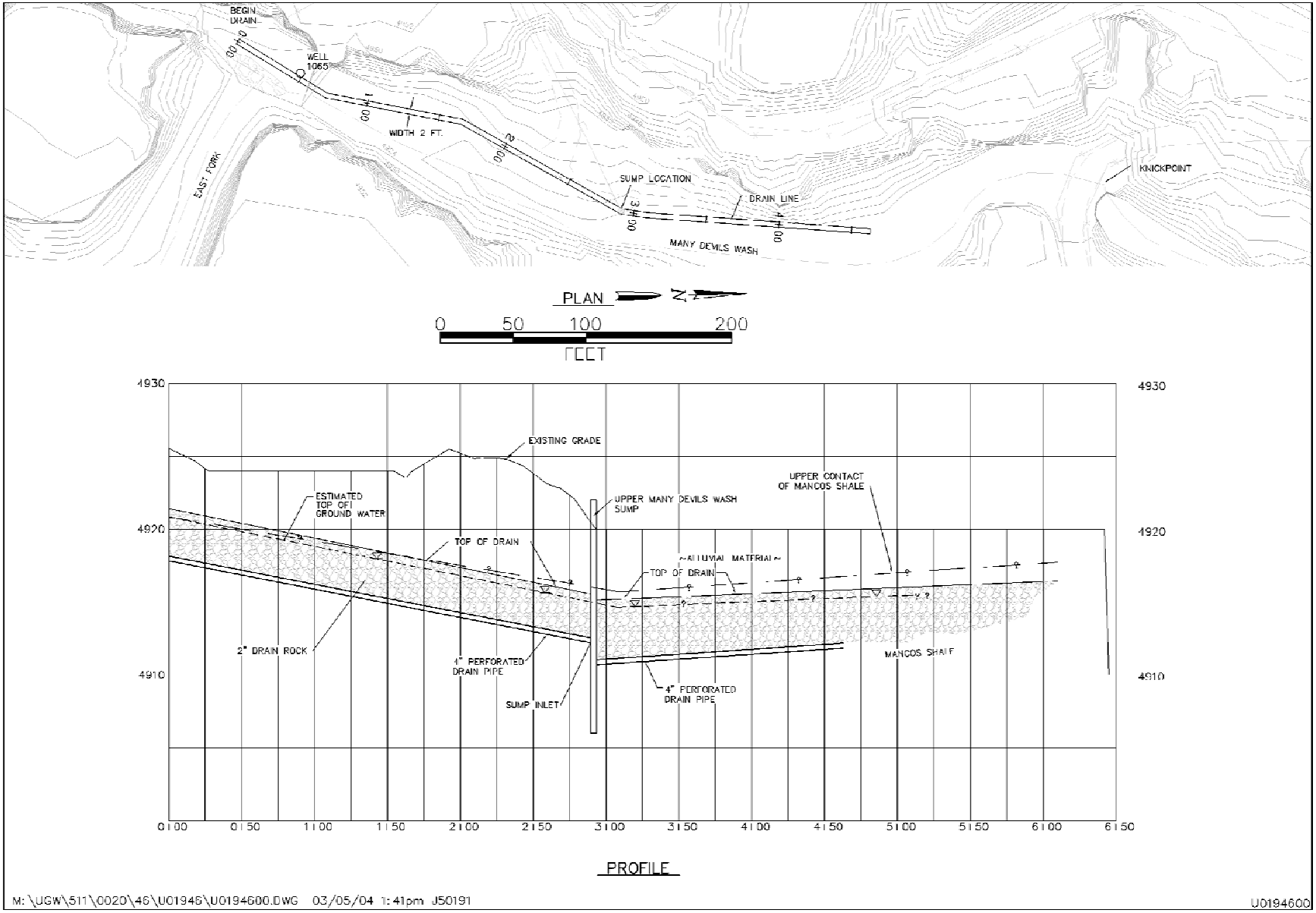

Figure 4–3. As-Built Plan and Profile of the Interceptor Drain in Many Devils Wash

End of current text

5.0 Summary of Prior Compliance Strategy

Compliance strategies for the terrace and floodplain are summarized from the GCAP. A remediation system, based on ground water extraction and evaporation, was constructed and began operation in March 2003 to implement these strategies. Recommended modifications to the compliance strategy based on the findings of this current assessment are presented in Section 6.0.

5.1 Terrace

5.1.1 Terrace East

Active remediation is the compliance strategy for terrace east with ground water being extracted from wells in the south part of the system. After pumping for approximately 7.5 years, contaminated ground water from the terrace east would be hydrologically isolated from the escarpment seeps and Bob Lee and Many Devils Washes. Ground water will also be collected in interceptor drains along Bob Lee and Many Devils Washes. Water from the extraction wells and water collected in a sump at each interceptor drain will be piped to an 11-acre pond east of the extraction wells where it will be evaporated. Water-level measurements in wells and flow rates from seeps will provide data for evaluating the remediation performance. Baseline measurements made just before the start of remediation will be followed by semiannual measurements. Time plots of the water levels and flow rates will be compared to modeled decline rates, and the results will be reported annually for the first 7.5-year extraction period. Monitoring results will be reviewed with the stakeholders and regulators after 7.5 years to determine if less frequent sampling is justified and if extraction can be discontinued.

5.1.2 Terrace West

Terrace west ground water represents the distal part of contaminated ground water in terrace east. Application of supplemental standards with monitoring is the compliance strategy for terrace west. The system qualifies as limited use (not a current or potential source of drinking water) ground water based on the existence of widespread ambient contamination, particularly from Mancos Shale underlying the west half of terrace west. Monitoring will consist of sampling ground water to determine if concentrations of COC are increasing and measuring water levels in wells to determine if recharge from terrace east is decreasing. To evaluate the hydrologic connection between terrace east and terrace west, ground water levels in wells west of U.S. Highway 491 will be recorded for the initial 2-year period of extraction from terrace east wells. Trends in water levels in these wells will be evaluated during the 2-year period in the semiannual performance reports. If water levels in the terrace west wells do not decrease after the 2-year period, then a decision will be made on whether to install extraction wells in the terrace west area. As ground water extraction occurs in terrace east, seeps in 1st and 2nd Washes west of U.S. Highway 491 (Plate 1) are expected to diminish in flow and contaminant concentrations are expected to decrease. If seep flows do not diminish and contaminant concentrations do not decrease interim actions will be considered to protect threatened and endangered species in the distributary channel area.

5.1.3 Duration of Terrace Ground Water Remediation

The initial time estimate of 7.5 years to reach remediation goals associated with the terrace ground water system is based on ground water modeling results presented in the SOWP, Section 4.5.5 (DOE 2000). This modeling effort was designed to evaluate the time required for Many Devils Wash and Bob Lee Wash to become hydraulically isolated from the buried channel south of the disposal cell and the ground water that originates as drainage from the disposal cell.

The model included an extraction system for the terrace consisting of a combination of two extraction wells and two interceptor trenches. The extraction rates of the two terrace wells were set at 1 and 3 gal/min. The extraction rates of the two interceptor trenches that were assumed to be keyed into the weathered Mancos Shale bedrock were expected to stabilize to 1 and 3 gal/min as well. As a result, the total ground water extraction rate for the terrace system was expected to stabilize at 8 gal/min.

At this extraction rate, water levels were predicted to decline to the point that the trenches would no longer intercept ground water, the simulated water levels were predicted to decline near the disposal cell, and the terrace gravel was predicted to dry out 5.1 to 7.5 years after startup of the system, which is the minimum time required for the compliance strategy to be achieved.

Whereas the expected flow rates are close to actual flow rates measured since system startup in March 2003 (through December 2003 the average pumping rate of the terrace extraction system has been approximately 7.5 gal/min), other aspects of the model are based on assumptions that have become suspect. The two modeling assumptions that have the most significant effects on the estimated cleanup time of the terrace are the configuration of the bedrock surface and the assumed ground water flow paths.

Limited data regarding the depth to the bedrock surface on the terrace results in a number of possible interpretations of the bedrock surface configuration (less than four data points were available to contour a critical area within the terrace east of a 5.6-million-square-foot area). The interpretation of the data presented in the SOWP used for the model shows a bedrock low along the south edge of terrace east (SOWP Figure 4−7). Subsequent depth-to-bedrock data (obtained from drilling the extraction wells) have improved the understanding of the bedrock low (Figure 2–4) and show that ground water in the swale area likely discharges to the northwest.

This alternative to the bedrock configuration not only affects the estimated saturated thickness in the terrace (which in turn affects the simulated water levels and the time to draw down the water surface in the terrace alluvium) but also alters the ground water flow paths within the terrace. Initially it was thought that the seeps discharging onto the floodplain were recharged by ground water contained within the sump area. Upon further review, the ground water flow path direction is more complex. The biggest unknown factor is the apparent role of the underlying Mancos Shale on ground water migration from the terrace to the floodplain.

5.1.4 Implemented Deviations From GCAP

Although the remediation system was implemented for the most part according to the GCAP, some modifications were necessary. At the start of terrace east remediation in March 2003, ground water was extracted from only four wells and two interceptor drains. Production from the wells in the south part of terrace east was only about 3 gal/min, which is less than expected. Six extraction wells had been planned in the GCAP. To increase the extraction rate in the south part of terrace east, four additional extraction wells were installed in July 2003. Total production from these new wells has been less than 1 gal/min, also less than expected. Poor extraction rates are attributed to problems with aquifer continuity (Section 3.1.2) and with well efficiency (Section 4.1).

Drawdown in selected terrace monitor wells is used as a metric to gauge performance of the remediation system. Actual drawdowns are compared to a model simulation that has been updated using measured pumping rates from September 2003 for all the extraction wells.

Whereas the extraction system was updated for the model predictions, the bedrock surface used in the model has the configuration that was estimated for the SOWP and does not represent the latest interpretation as presented on Figure 2–4. Because of the uncertainties in bedrock configuration and in modeling, the predicted drawdowns are not expected to match the drawdowns measured at the site after 1 year of pumping.

Thirteen monitor wells were added to the model to provide comparisons to measured drawdowns from the start of pumping and extending to 7.5 years. The monitor wells are screened in the alluvium or across the alluvium−Mancos Shale contact. To bracket the range of modeled drawdowns, the model was run three times using different initial head files. Each file produced approximately the same results and similar model calibrations. Table 5–1 presents the range of modeled drawdowns at each monitor location after 1 and 7.5 years of pumping from the terrace and the drawdown measured in the field after about 6 months of pumping in August 2003.

Predicted drawdowns are relatively small and match actual drawdowns within limits of modeling uncertainty and data accuracy. Therefore, we conclude that the remediation system requires monitoring for a longer period, probably at least 5 years, before its performance can be accurately determined.

Table 5–1. Predicted Terrace Drawdowns After 1 and 7.5 Years of Pumping.

Monitor Well Number	Expected Drawdown Range (ft) After 1 yr	Measured Drawdown (ft) August 2003[a]	Expected Drawdown Range (ft) After 7.5 yr	Comments
0727	0 to 0.1	0.29	0.3 to 1.7	One of the three model simulations shows the cell dries out after 7 yr of pumping
0728	0.1 to 0.2	0.26	1.5 to 1.7	
0730	0.3 to 0.5	0.66	na	Model cell dries out after 4 yr of pumping
0812	0.3 to 0.4	0.03	2.0 to 2.3	One of the three model simulations shows the cell dries out after 4 yr of pumping
0813	0 to 0.2	0.04	1.3 to 2.0	
0826	na	-0.21	na	Model cell dries out after pumping starts
0827	na	-0.09	na	Model cell dries out after pumping starts
0828	na	0.24	na	Model cell dries out after pumping starts
1057	na	-0.03	na	Model cell dries out after pumping starts
1067	0	na (well dry)	1.8	Two models show the cell dries out after pumping starts
1068	na	0.22	na	Model cell dries after pumping starts
1073	0 to 0.1	0.47	1.3 to 1.9	

Note: na = not applicable
[a]Drawdown measured after 6 months of pumping; negative values represent an increase in the ground water elevation. Data from DOE (2003).

5.2 Floodplain

The ground water compliance strategy for the floodplain is natural flushing. Extraction of ground water on the floodplain from the contaminant plume that is close to the San Juan River is used as a best management practice. Floodplain remediation is planned in two phases; the second phase is conceptual at this time (DOE 2002).

5.2.1 Phase I Remediation

As stated in the GCAP, Phase I includes installation of two extraction wells, a production rate of 7 to 10 gal/min from each well until the evaporation pond fills, and then a combined extraction rate of 7 to 10 gal/min for an initial 7.5-year period. The compliance strategy for the floodplain is tied to compliance actions on the terrace. It is assumed that terrace dewatering will cause contaminated seepage from the terrace to the floodplain to cease. After that time, the only source of contamination to the floodplain would be from transient water seeping from the tailings in the disposal cell. Because the levels of the terrace ground water system are expected to be lowered to a level is that ground water no longer feeds the terrace seeps after about 7.5 years, remediation progress will be reviewed at that time to determine if additional actions are necessary to reach compliance standards and cleanup goals. Pumping from the extraction wells may continue for as long as 20 years. During and following operation of the extraction wells, water levels and water chemistry will be monitored in samples from nine observation wells to follow plume movements on the floodplain.

5.2.2 Phase II Remediation

Phase II consists of construction of a flow barrier and interceptor drain along the base of the escarpment to cut off potential contribution of ground water from the terrace system to the floodplain aquifer (DOE 2002). The observational approach will be used to determine the actual need, time frame, and appropriate design for the elements of Phase II. Intercepted water in the drain, predicted in the GCAP by modeling as 3 to 5 gal/min, would be collected in sumps and piped to the evaporation pond. After approximately 60 years, as predicted by modeling, floodplain ground water will have flushed to below the UMTRA Ground Water Project standard for uranium (about 0.44 mg/L) and the drain could be breached at its north end, providing that the mass loading of uranium in the drain water is less than 3 milligrams per minute (Knight Piesold and Company 2002). Monitoring of concentrations of contaminants in the floodplain ground water will be used to track the progress of flushing. The flow in the interceptor drain will be measured and samples of the drain water will be analyzed for contaminants to track the progress of anticipated decreases in flow and contaminant concentrations.

5.2.3 Implemented Deviations From GCAP

Production of ground water from the two initial extraction wells in spring 2003 was less than 3 gal/min, which is much less than expected. In June 2003, one of the original wells was replaced by a new well installed in a trackhoe-dug trench. Production from the initial well (well 1077) and the new well (well 1089) has increased to nearly 7 gal/min, which is still less than expected. Because extraction of ground water from the terrace has been less than expected, significant lowering of the water surface is likely to require a longer time period unless actions are taken to increase extraction rates. Contaminant concentrations on the floodplain are not expected to decrease until a significant volume of ground water is removed from the terrace

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6.0 Recommended Refinements to Compliance Strategy

The following philosophy was used in recommending modifications and additional costs for continued ground water remediation. In general, much of the site has been highly characterized during the past 20 years, particularly near the disposal cell, former milling area, and floodplain. Outlying parts of terrace east and terrace west were characterized only during the past 5 years and are less well known. Although there are still many uncertainties about the transport of contamination in the subsurface system, the cost-to-benefit ratio of additional characterization has increased to a relatively high level. The team believes that more benefit will be derived by stressing the system through continued remediation than from additional characterization efforts. This approach for Shiprock is the observational approach used by DOE and forms the basis of the technical approach to ground water restoration for the UMTRA Ground Water Project (DOE 1993). Additional understanding of the subsurface can be derived by using the observational approach to evaluate responses to remediation and thereby minimize characterization costs.

The team believes that the effectiveness of the remediation system cannot yet be determined because it has operated for only a limited time and extraction rates have been less than predicted. All the recommendations involve additions or refinements of the existing remediation system with a goal of increasing the extraction rate of contaminated ground water. Recommended refinements to the remediation system are shown on Figure 6–1. The team's recommendations are presented in Sections 6.1 (Terrace) and 6.2 (Floodplain); modifications requiring more details (enhanced phytoremediation and operation of collection drains) are covered in subsections.

6.1 Terrace

- Install three new 6-inch diameter extraction wells using a casing-advance drilling method. One well will offset extraction well 1070 that is a poor producer. The purpose of offsetting is that the new well can be used as an observation well while well 1070 is operating; such a pump test can be used to determine if well efficiency is a major cause of difficulty in extracting ground water from the terrace. Another well will be placed as an offset to monitor well 1057; initial flow tests on well 1057 indicate it would be a good producer, but its diameter is only 2 inches. The small diameter prevents its use as an extraction well. A third well will be placed on the axis of the bedrock swale where saturated thickness is greatest. *Purpose*: The purpose of all three wells is to increase ground water extraction from the swale area of terrace east.
- Install two new wells immediately upgradient (east) of the Bob Lee Wash interceptor drain using a trackhoe to key the wells into the Mancos Shale. *Purpose*: The purpose of these wells is to increase collection of highly contaminated ground water. Most of the ground water currently being extracted from the terrace is from the drain at Bob Lee Wash, but the drain does not intercept all the ground water available in the lowermost part of the alluvium (Figure 4–2). Installation of the wells by trackhoe is an inexpensive and proven means to increase production by ensuring that the new wells are set in the lower part of the alluvium and weathered Mancos Shale.
- Develop and plumb seeps 425 and 426 to the well field pipeline in the floodplain that delivers ground water to the evaporation pond. *Purpose*: The purpose of plumbing the seeps is to increase ground water extraction from the terrace and to decrease the exposure of contaminated ground water to the environment.

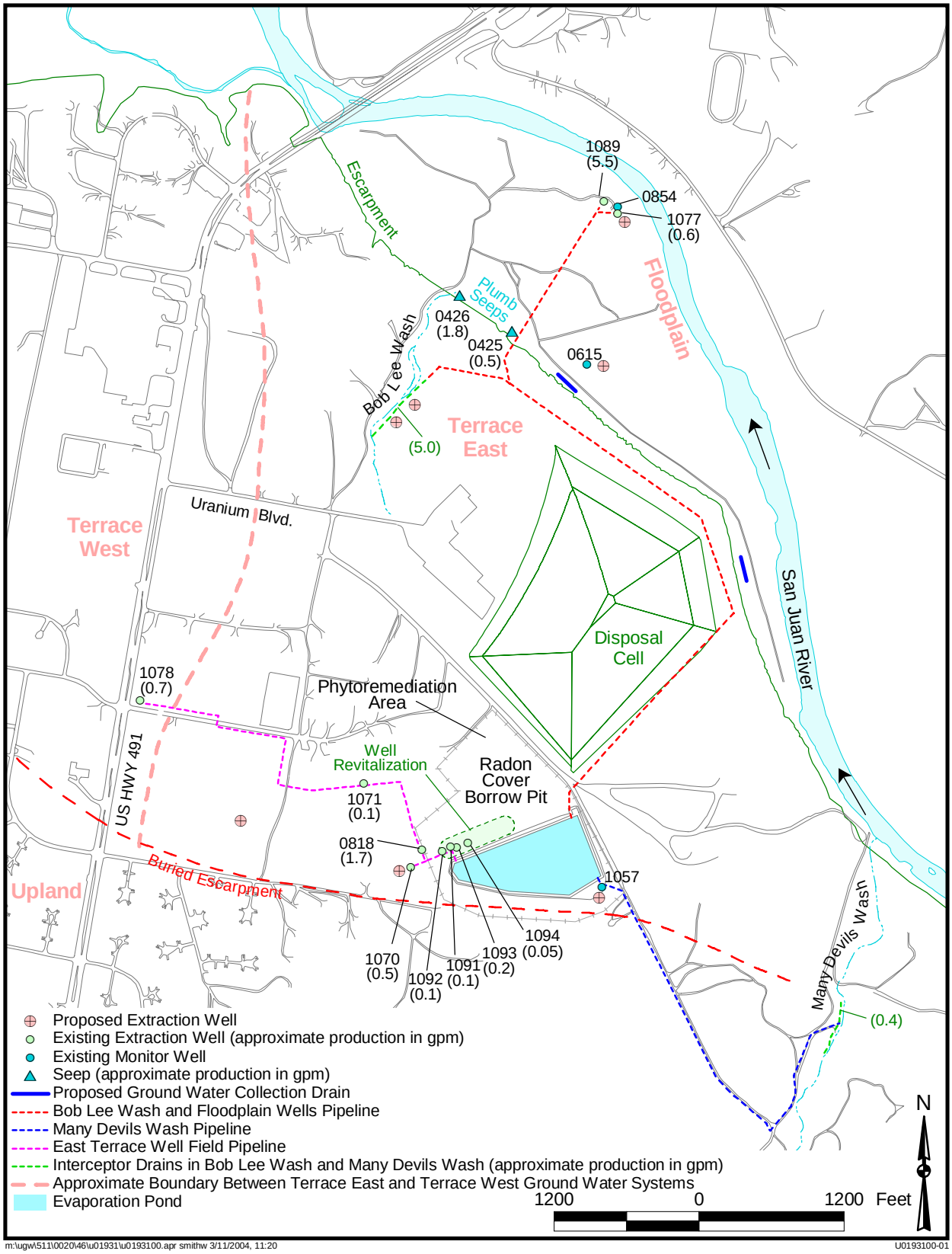

Figure 6–1. Existing Remediation System and Proposed Enhancements

- Improve the efficiency of extraction wells 1091 through 1094 (drilled by the cable tool method). Currently the combined production of these four wells is only about 0.6 gal/min. Mineral deposits have been noted recently on piping and downhole equipment in these wells. The inside PVC well casing and screen will be pulled from each borehole and the screen will be cleaned. *Purpose*: The purpose of well restoration activities is to increase ground water extraction rates from terrace east.
- Improve efficiency of extraction wells that were installed using the rotasonic drilling method by using jetting and air-lifting development techniques, followed by treatment with clay dispersants. Establish a well maintenance schedule to control mineral deposit accumulation and bacterial growth inside the wells. *Purpose*: The purpose of these well restoration activities is to increase ground water extraction rates from the terrace from existing wells.
- Design and conduct a pilot-scale investigation using deep-rooted plants to enhance evapotranspiration in the radon-cover borrow pit. *Purpose:* The purpose of the pilot test is to increase extraction rate of contaminated ground water from terrace east.

6.1.1 Enhanced Phytoremediation

Higher rates of water extraction by plants would improve hydraulic control in the radon-cover borrow pit. Hydraulic control, in the context of phytoremediation, can be defined as the use of plants to remove ground water through uptake and consumption to contain or control the migration of contaminants (EPA 2000). An increase in water extraction rates may occur naturally as the existing tamarisk stand matures. However, if feasible, manipulation of the plant ecology to accelerate water extraction by plants—enhanced phytoremediation—may be an economical addition to the current remedy. One scenario would involve expanding the existing tamarisk stand or replacing tamarisks with native cottonwoods in a 5-acre area of the radon-cover borrow pit where depth to ground water is relatively shallow and planting black greasewood or fourwing saltbush in the surrounding 15 acres where depth to ground water is greater. Assuming transpiration rates of 78 inches per year for tamarisk and cottonwood (Glenn and Nagler 2003; King and Bawazir 2003; Waugh and Van Reyper 2003), and 12 inches per year for greasewood and fourwing saltbush (McKeon et al. in press), an initial approximation of enhanced water extraction for the 20-acre area is about 29 gal/min. Estimates of the nitrate extraction rate for this enhanced phytoremediation scenario, based on the results of McKeon et al. (in press) for fourwing saltbush and black greasewood, range from 1,300 to 2,600 pounds per year. Actual water extraction rates could be more or less than this scenario.

The success of enhanced phytoremediation in the radon cover borrow pit area would depend on several factors: depth to ground water, phytotoxicity of ground water constituents, site preparation methods, plant species selection, planting methods, soil amendments, and natural disturbances. Some of the needed information, such as depth to ground water and phytotoxicity of ground water constituents, can be acquired from well data and published literature. A pilot study or demonstration is recommended to acquire other needed information, such as the most appropriate site preparation methods, plant species, planting methods, and soil amendments and to acquire more reliable estimates of plant water-extraction rates.

6.2 Floodplain

- Install an extraction well using a trackhoe near extraction well 1077. This well will replace well 1077, which is a poor producer. A trackhoe-installed well (well 1089) previously placed in this area increased production by about 5.5 gal/min (about half the current production from extraction wells on the entire site). *Purpose*: The purpose of this well is to increase ground water extraction in the highly contaminated portion of the plume near the San Juan River. Ground water extraction in this area is needed to decrease flux to the river.
- Install an extraction well using a trackhoe near monitor well 0615 in the heart of the contamination plume. *Purpose*: The purpose of this well is to increase extraction of highly contaminated ground water in the floodplain and prevent it from flowing north to the river.
- Construct two ground water collection drains along the base of the escarpment. Each drain will be approximately 200 ft long and 25 ft deep. One drain would be placed near monitor well 0615 to capture ground water from a portion of the plume that has the highest uranium concentrations. The other drain would be in the southeast portion of the floodplain where high concentrations of ammonium are present along the base of the escarpment and may extend a short distance east to the river. *Purpose*: The purpose of the collection drains is, primarily, to capture highly contaminated ground water from the escarpment area to prevent it from migrating to the floodplain and, secondarily, to investigate the feasibility and the cost of constructing the drain described conceptually for Phase II in the GCAP. Details about the operation of the collection drains is provided in the next section.

6.2.1 Operation of Collection Drains

The proposed collection drains in the floodplain alluvium will be sited and operated to maximize the accumulation of contaminant mass for delivery to the evaporation pond. The drains will be installed at the base of the escarpment, where most of the contamination enters the floodplain as ground water discharge from Mancos Shale beneath the terrace. Each drain will passively capture contamination flowing directly into it from the terrace and when actually pumped, will also draw in contaminated ground water lying adjacent to it. Much of the water drawn in will come from either end of the drains in highly contaminated areas at the base of the escarpment. To avoid overextraction of less contaminated water occurring closer to the San Juan River, pumping will be cycled between drains. This will allow one drain to accumulate natural inflow of the most contaminated ground water while pumping occurs in the other drain.

If installed and operated optimally, the drains will achieve substantial contaminant mass removal while preventing most, if not all, of the discharge of contaminated water to the San Juan River. Accomplishing the latter of these objectives will eventually lead to natural flushing of much of the floodplain aquifer because the source of most of the ground water flowing through the floodplain aquifer in the vicinity of the drains is from upstream river losses. Preliminary cross-sectional model simulations of the floodplain ground water system indicate that cyclic pumping of a drain will prevent contaminants that have bypassed it during nonpumping periods from migrating beyond the capture zone of the drain. This hydraulic means of controlling contaminant migration and mixing may avoid the use of more expensive remedial actions involving construction of a slurry wall.

7.0 Monitoring of Remediation System

Monitoring is a fundamental component of the observational approach (DOE 1993). Monitoring, as described in the GCAP (DOE 2002), should continue and minor changes are recommended. Recommendations and rationales for terrace and floodplain monitoring are discussed in Sections 7.1 and 7.2, respectively. The summaries of monitoring requirements for terrace east and terrace west in Table 7–1 and for the floodplain in Table 7–2 are modified from Tables B−2 and B−3, respectively, in the GCAP. Recommended changes that are approved by DOE will be included in the revision of the GCAP (in progress).

7.1 Terrace

7.1.1 Terrace Water Levels

Monitoring of changes in ground water levels for the terrace should continue to help determine whether the current drought is causing the general decreases in ground water levels across the terrace or whether the terrace is losing its anthropogenic water. Changes in ground water levels will also show the effect that remedial action is having on the terrace ground water system. Special attention should be given to the area showing increasing water levels southwest of the disposal cell to determine if the rising ground water level is caused by sporadic heavy rainfall events or by a long-term condition. Thirty-three wells, screened in the alluvium or across the alluvium−Mancos Shale contact, are recommended for water-level sampling (Table 7–1).

To determine changes in the ground water of the Mancos Shale and the effectiveness of remediation on the terrace, 11 terrace wells screened in the Mancos Shale should be monitored (Table 7–1). Water levels should also be measured in three sets of nested wells in the Mancos Shale near the escarpment. Water levels should be measured semiannually during the initial 7.5 years of pumping or more frequently following heavy rainfalls.

A datalogger should be placed in well 0730 to track the effects of rainfall events on ground water levels in wells near the radon-cover borrow pit. A datalogger should also be used in monitor well 1069 near the interceptor drain in Bob Lee Wash.

To verify flows from the extraction wells and interceptor drains into the evaporation pond, flow meters should be installed on the three discharge pipes and monitored. Flow meter data can be used to corroborate flow data currently being collected at individual extraction wells and sumps and to identify leaks in the distribution system.

No changes to the surface water monitoring program are recommended, although continued observation of the locations and fluxes from seeps in Many Devils Wash is suggested. Correlation of seepage flux with major rainfall events should be monitored.

Table 7–1. Summary of Monitoring Requirements for Terrace East and Terrace West Areas
{items in braces are changes from the GCAP}

Location	Purpose	Analyses/Measurement	Frequency
Flowing artesian well 0648	Cleanup standards for floodplain	COCs: Ammonium, manganese, nitrate, selenium, sulfate, and uranium; strontium for ecological risk concerns Water chemistry: calcium, chloride, magnesium, potassium, and sodium On-site field analyses: alkalinity, conductivity, oxidation-reduction potential, pH, and water level	Semiannual flow measurements; sample for chemical analyses every 2 years (last sampled in March 2003)
Terrace east wells: {0730}, 0817 Terrace west wells: 0832, 0835, 0836, 0838, 0839, 0841, 0846, 1060, 1079, {omit 0847} {Extraction wells and sumps: 0818, 1070, 1071, 1078, Bob Lee Wash sump (1087), Many Devils Wash sump (1088), 1091, 1092, 1093, 1094}	Ground water chemistry in terrace west; evaluation of mass removed by remediation		Semiannually through the 7 year extraction period, then annually through year 12, and every 5 years thereafter
Alluvial terrace east wells: {0603}, 0728, {0730, 0731}, 0812, 0813, {0816, 0826, 0827, 0828, 0830}, 1007, {1048, 1049}, 1057, 1067, 1068, 1069, {1073; omit 0818, 1065, 1066} {Mancos Shale terrace east wells: 0600, 0602, 0604, 0726, 0817, 0819, 0829, 1004, 1059, MW1, DM7} Alluvial terrace west wells: 0814, 0815, 0832, {0833}, 0835, 0836, 0838, 0839, 0841, {0844}, 0846, {0848}, 1060, 1079	Monitor decreases or increases in water levels	Water level	
{Nested well sets: (0820, 0821, 0822), (0823, 0824, 0825), (1002, 1003)}	Monitor water level changes deep in the Mancos Shale		
{Three discharge pipes into evaporation pond}	Verification of extraction rates from wells and interceptor drains	Flow rate	
Terrace east surface water: 0425, 0426, 0662, 0786, 0885, 0889, {omit 0886} Terrace west surface water: 0884, 0933, 0934, 0936, 0942, 0958	Monitor for ecological risks and lowering of water levels	COCs: Ammonium, manganese, nitrate, selenium, sulfate, and uranium; strontium for ecological risk concerns Water chemistry: calcium, chloride, magnesium, potassium, and sodium On-site field analyses: alkalinity, conductivity, oxidation-reduction potential, and pH Water level at 885 Flow rates for 425, 426, and 786	Sample 958 for chemical analysis once every 2 years (last sampled in August 2003)
Terrace background wells: 0800, 0801, 0802, 0803	Presence of ground water in terrace background	Water level	Annually for the first 5 years

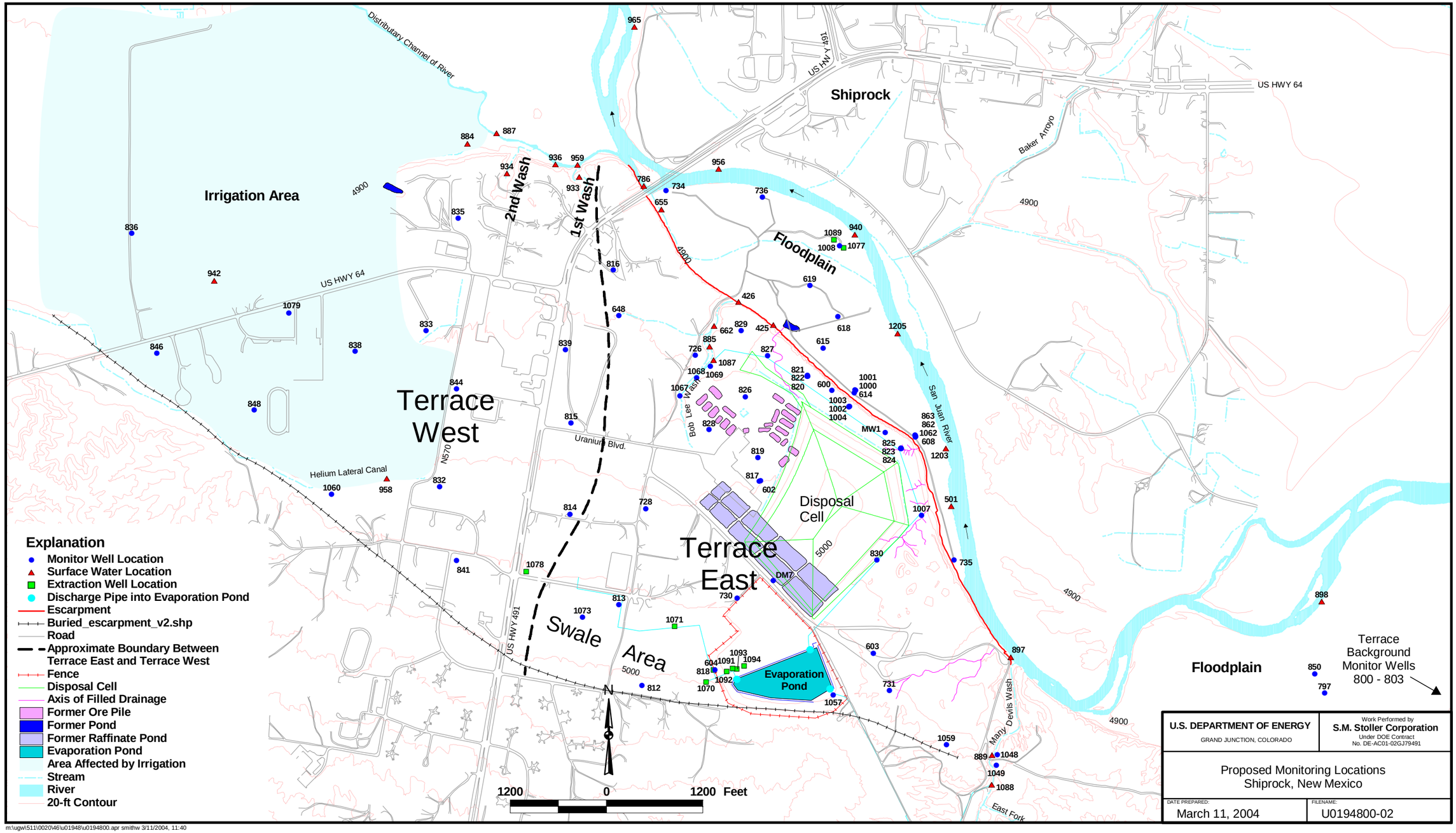

Figure 7–1. Proposed Monitoring Locations for the Shiprock Site

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Table 7–2. Summary of Monitoring Requirements for the Floodplain
{items in braces are changes from the GCAP}

Location	Purpose	Analyses/Measurement	Frequency
Wells 0608, 0614, 0615, 0618, 0619, 0734, 0735, 0736, {1008, and extraction wells 1077 and 1089, omit 0854}	Compliance action levels (40 CFR 192)	COCs: Manganese, nitrate, selenium, sulfate, and uranium (and ammonium and strontium based on ecological concerns) Water chemistry: calcium, chloride, magnesium, potassium, and sodium On-site field analyses: alkalinity, conductivity, oxidation-reduction potential, pH, and water level (in wells)	Semiannually through the first 7.5-year period, then annually through year 12, and every 5 years thereafter
Wells 0797 and 0850	Floodplain, background		
Surface 0898	San Juan River, background		
Surface {0501}, 0897, 0940, {1203}, 1205	San Juan River on site, risk		
Surface 0956	Intake on north side of San Juan River, risk		
Surface {0965}	San Juan River, downgradient, risk		
Surface 0655	Floodplain drainage channel, risk		
Surface 0887 and 0959	Distributary channel, risk		
{Nested well sets: (0614, 1000, 1001), (0608, 0862, 0863, 1062)}	Monitor water level changes in Mancos Shale	Water level	Semiannually through the first 7.5-year period, annually through year 12, and every 5 years thereafter

7.1.2 Terrace Ground Water Chemistry

The chemistry of ground water samples from monitor wells in terrace west should be determined to evaluate the effects of ground water extraction. Chemistry of the extracted ground water should be monitored to estimate the mass of contaminant removed by the remedial action. The chemistry of ground water at well 0817 shall continue to be measured because this well has the highest concentration of uranium (10 mg/L) at the site. The chemistry of ground water at well 0730 should be measured to determine if the area receives recharge from meteoric water.

7.2 Floodplain

Monitoring of COCs in samples from extraction wells and a number of monitor wells is recommended (Table 7–2). For the extraction wells, chemical analyses and the measured volumes of water pumped to the evaporation pond will allow computation of the mass of contaminant removal from floodplain ground water. Monitoring of other wells in the contaminant plume will provide an evaluation of the success of the remedial action. Inspections should be performed along the escarpment to determine the occurrence of seeps. Two additional surface sample locations (501 and 1203) along the San Juan River were established for the last sample round (Figure 7–1). These locations should continue to be sampled to determine if COCs are entering the river. Water levels should be monitored in the two sets of nested wells near the escarpment to complement the water-level measurements in nested wells on the terrace.

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8.0 Contingencies

After 5 to 7 years of remediation (2008 to 2010), the overall performance of the remediation system should be reviewed. In addition to the possibility of adding extraction and treatment capacities, other contingency measures will be considered if the system is not meeting expectations. This section conceptually presents other remediation actions that may be considered to meet regulatory standards.

8.1 Remediation of Ground Water Contaminants Using Chemical Reactants

During the last decade, chemical reactants were developed that can be injected into the subsurface and that have the capability to immobilize or degrade contamination. Numerous reactants have been bench-scale tested and several have been demonstrated effective at a field scale. It may be practical to use chemical reactants to remediate contaminants in the subsurface at the Shiprock site. In particular, injection of reactants into the floodplain aquifer near the escarpment could help prevent this concentrated zone of contamination from spreading. The choice of reactants and the means of application would be decided after conducting pilot tests of candidate reactants and careful consideration of the chemical and microbial environment in the targeted aquifer. Several reactants are candidates for injection into floodplain aquifer.

Ferric oxyhydroxide is noted for its ability to adsorb trace metals and uranium from ground water and is often thought to be the naturally occurring substance most responsible for enhancing natural attenuation. The natural inventory of ferric oxyhydroxide in an aquifer can be increased by the injection of dissolved ferric chloride solution (Morrison et al. 1996). Dissolved ferric chloride solution reacts with aquifer minerals (carbonates and silicates) to precipitate ferric oxyhydroxide. As ferric oxyhydroxide ages, adsorbed contaminants become less susceptible to desorption, and eventually the adsorption becomes irreversible.

Many metals and uranium become immobile under chemically reducing conditions. Injections of sodium dithionite have been used to produce chemically reducing conditions. Dithionite reduces solid-phase ferric iron to ferrous iron; subsequently, ferrous iron fixes ground water contamination. Dithionite injections have successfully immobilized chromium in ground water at DOE's Hanford site (Vermeul et al. 2002) and at a U.S. Coast Guard site in North Carolina (Paul et al. 2002). Dithionite has also been used for the in situ reductive degradation of chlorinated solvents at Ft. Lewis, Washington (Jon Fruchter, personal communication).

Liquid phosphate is another potential candidate for uranium immobilization. Abundant bench-scale data indicate that uranium forms insoluble phosphate compounds. Dissolved phosphate can be injected into the subsurface where it is sorbed by mineral grains. The uranium concentration in the ground water then combines with the phosphate to form insoluble phases.

Another means to immobilize uranium and other metals is to stimulate microbial growth by injecting electron donors. Acetate, lactate, and molasses have been effective in promoting reducing conditions through the stimulation of microbial growth. These organic materials can be injected in liquid form. The reducing conditions and microbial interactions immobilize uranium and metals. The microbes can also cause denitrification of nitrate and reduction of sulfate concentration in ground water. Work funded by the UMTRA Project demonstrated that uranium concentrations could be reduced by the application of acetate (Abdelouas et al. 1999).

Subsequent work by DOE's Natural and Accelerated Bioremediation Research (NABIR) program confirmed uranium reduction by acetate at the LM Rifle site.

8.2 Interceptor Drain and Permeable Reactive Barrier

Discussions presented in this report indicate that there is considerable uncertainty in estimates of the flux of contaminated seepage from the terrace to the floodplain. If a significant flux of contamination persists for long time periods, remediation of the floodplain by natural flushing may be impractical. Significant fluxes will only occur if the disposal cell cover were to leak in excess of the design rate. A possible remedy for higher than expected seepage of contamination to the floodplain is to implement an interceptor drain to collect the seepage as suggested by personnel at University of New Mexico (UNM) (Thomson et al. 1996; Thomson 1995). The UNM studies indicated that contaminated seepage collected by the interceptor drain could be treated in a permeable reactive barrier (PRB) (Figure 8–1). The PRB would contain a mixture of cellulosic materials (e.g., sawdust, peat, hay, or wheatstraw) to promote nitrate- and sulfate-reducing conditions capable of fixing uranium.

8.3 Flow Barrier and Interceptor Drain

Personnel with the Knight Piesold and Company (2002) expanded the interceptor drain concept to include a flow barrier constructed of low permeability bentonite slurry to further prevent contaminated seepage from reaching the floodplain. Seepage could be pumped to the evaporation pond in lieu of using a PRB. The Knight Piesold design includes an interceptor drain approximately 4,000 ft long that extends from the ground surface down about halfway to the top of Mancos Shale (Figure 8–1). The flow barrier is also 4,000 ft in length and is placed just downgradient of the interceptor drain. The flow barrier penetrates the alluvium and is keyed into the underlying Mancos Shale. This design assumes that insignificant flux enters the floodplain through Mancos strata deeper than the slurry wall.

Modeling presented by Knight Piesold and Company (2002) suggests that, with a flow barrier and interceptor drain, uranium concentrations on the floodplain could flush to less than the regulated concentration of 44 micrograms per liter in 60 years. These simulations assume a perpetual flux of contaminated seepage to the floodplain, as suggested by preliminary simulations of disposal cell cover leakage using the HELP modeling code. As long as the flow barrier and interceptor drain remain active, uranium concentrations on the floodplain would remain less than regulatory levels. However, if active remediation were discontinued, modeling results suggest that the floodplain would again become contaminated. Unless actual seepage flux is less than predicted by the HELP model, the flow barrier and interceptor drain would need to remain active in perpetuity.

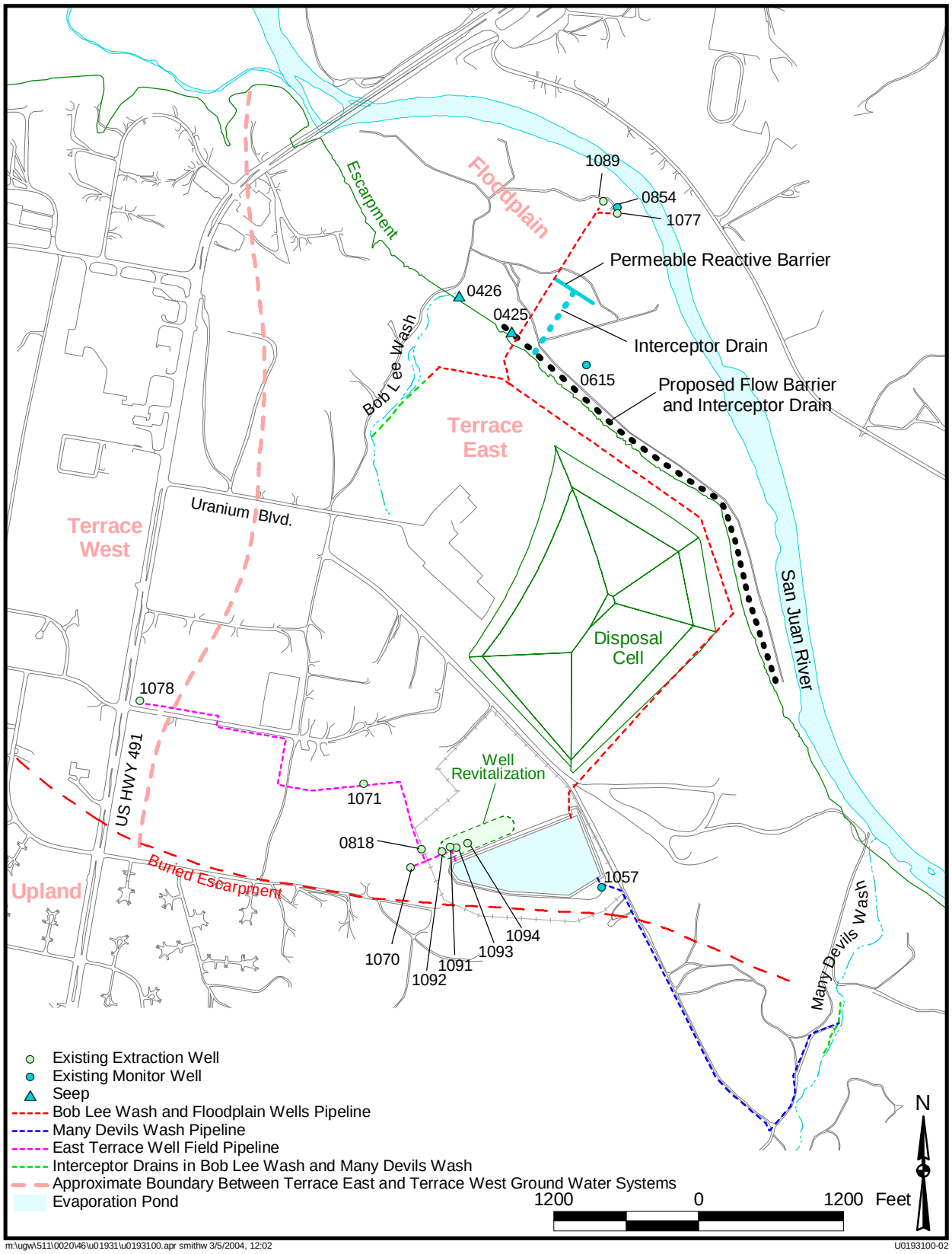

Figure 8–1. Location of Possible Contingency Remediation Measures for Floodplain

8.4 Extraction From Beneath the Disposal Cell

Another means of minimizing contaminant flux to the floodplain is to actively extract seepage water from directly beneath the disposal cell. Extraction would be accomplished by using vertical wells drilled through the tailings and pumping extracted water to the evaporation pond. This approach would intercept tailings seepage at the first possible point of access. Multiple penetrations of the disposal cell would be required for this approach to be effective. An extraction system of this nature would be difficult to implement. Drilling equipment would need to be mobilized on top of the rock cover on the disposal cell, and radioactive controls would be required. An alternative is to use horizontal extraction wells. Because no wells have been completed on the disposal cell, it is currently unknown if ground water is present beneath the cell.

8.5 Evapotranspiration Cover

Cleanup of the floodplain may be prolonged if the disposal cell is a continuing source of contaminated water. A relatively inexpensive conversion of the existing rock cover into an evapotranspiration (ET) cover may reduce the likelihood of seepage from disposal cell, reduce recharge of runoff at the edge of the disposal cell, and eliminate the need for regular weed control with herbicides.

The cover for the Shiprock disposal cell, constructed in 1986, consists of three layers from bottom to top: a 7-foot thick compacted soil layer (CSL) to limit radon releases and water percolation, a 6-inch thick coarse sand layer to drain precipitation laterally, and 12-inch thick layer of durable rock to armor the surface. Designers believed the CSL, consisting of a highly compacted silt loam soil, would have a saturated hydraulic conductivity of 1×10^{-7}cm/s or less, and thereby provide a long-term barrier to percolation of rainwater (DOE 1989; Caldwell 1992).

Monitoring activities since construction have produced the following information about the performance of the cover:

- The saturated hydraulic conductivity of the CSL is highly variable and significantly greater than the design target of 1×10^{-7} cm/s (DOE, 2001).
- The CSL and upper tailings layer remain saturated or nearly so year around (DOE, 2001); therefore, rainwater percolating through the cover and tailings may be a continuing source of contaminated seepage from the disposal cell.
- Voids in the rock layer have half filled with windblown silt and fine sand since construction, creating favorable habitat for the growth of deep-rooted plants (DOE, 2001).
- The abundance of plants on the cover increases yearly and the composition is shifting from shallower-rooted annual weeds to deeper-rooted woody shrubs.

Evapotranspiration (ET) cover designs rely on a thick soil *sponge* to store rainfall and plants to dry the soil during the growing season as the means for preventing saturation and deep percolation (EPA, 2003). The existing Shiprock cover may be well suited for conversion to an ET cover without the need for expensive earth-moving operations. The existing loam CSL has a high water storage capacity and is a good soil for establishment of sustainable native vegetation with relatively high transpiration rates. Conversion may result in a sustainable, low-maintenance cover providing long-term containment of the source.

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