DOE–LM/GJ1212–2006

Annual Performance Report April 2005 Through March 2006 for the Shiprock, New Mexico, Site

July 2006

U.S. Department of Energy

Office of Legacy Management

Work Performed Under DOE Contract No. DE–AC01–02GJ79491
for the U.S. Department of Energy Office of Legacy Management.

DOE−LM/GJ1212-2006

Annual Performance Report April 2005 Through March 2006 for the Shiprock, New Mexico, Site

July 2006

Work Performed by S.M. Stoller Corporation under DOE Contract No. DE–AC01–02GJ79491
for the U.S. Department of Energy Office of Legacy Management, Grand Junction, Colorado

This page intentionally left blank

Contents

1.0 Introduction....1–1
1.1 Remediation System Performance Standards....1–1
1.2 Contaminants of Concern and Remediation Goals....1–3
1.3 Hydrogeological Setting....1–3
1.3.1 Floodplain Alluvial Aquifer....1–4
1.3.2 Terrace Ground Water System....1–4
2.0 Subsurface Conditions....2–1
2.1 Floodplain Subsurface Conditions....2–1
2.1.1 Ground Water Level Trends and Flow Directions....2–1
2.1.2 Contaminant Distributions....2–5
2.2 Terrace System Subsurface Conditions....2–18
2.2.1 Ground Water Level Trends and Flow Directions....2–18
2.2.2 Seep Flow Rates....2–19
2.2.3 Drain Flow Rates....2–22
3.0 Remediation System Performance....3–1
3.1 Floodplain Remediation System....3–1
3.1.1 Extraction Well Performance....3–1
3.1.2 Floodplain Drain System Performance....3–3
3.2 Terrace Remediation System....3–3
3.2.1 Extraction Well Performance....3–3
3.2.2 Terrace Drain System Performance....3–4
3.2.3 Evaporation Pond....3–9
3.2.4 Terrace Drainage Channel Diversion....3–11
4.0 Performance Summary....4–1
5.0 Recommendations....5–1
6.0 References....6–1

Figures

Figure 1–1. Location Map.... 1–2
Figure 2–1. Locations of Wells Discussed in This Report.... 2–2
Figure 2–2. Floodplain Ground Water Elevations from Manual Measurements.... 2–3
Figure 2–3. Floodplain Ground Water Elevations from Datalogger Measurements.... 2–4
Figure 2–4. Precipitation and San Juan River Flow.... 2–4
Figure 2–5. Floodplain Ammonia (total as N) Ground Water Concentrations.... 2–6
Figure 2–6. Floodplain Manganese Ground Water Concentrations.... 2–7
Figure 2–7. Floodplain Nitrate Ground Water Concentrations.... 2–8
Figure 2–8. Floodplain Selenium Ground Water Concentrations.... 2–9
Figure 2–9. Floodplain Strontium Ground Water Concentrations.... 2–10
Figure 2–10. Floodplain Sulfate Ground Water Concentrations.... 2–11
Figure 2–11. Floodplain Uranium Ground Water Concentrations.... 2–12
Figure 2–12. Floodplain Ammonia (total as N) Ground Water Concentrations Versus Time. 2–13
Figure 2–13. Floodplain Manganese Ground Water Concentrations Versus Time.... 2–13
Figure 2–14. Floodplain Nitrate Ground Water Concentrations Versus Time.... 2–14
Figure 2–15. Floodplain Selenium Ground Water Concentrations Versus Time.... 2–14

Figure 2–16. Floodplain Strontium Ground Water Concentrations Versus Time 2–15
Figure 2–17. Floodplain Sulfate Ground Water Concentrations Versus Time......................... 2–15
Figure 2–18. Floodplain Uranium Ground Water Concentrations Versus Time...................... 2–16
Figure 2–19. Nitrate Concentration in the San Juan River 2–17
Figure 2–20. Uranium Concentration in the San Juan River 2–17
Figure 2–21. Terrace Ground Water Elevation Changes from Baseline to Current Conditions 2–20
Figure 2–22. Terrace East Datalogger Ground Water Elevations 2–21
Figure 2–23. Terrace West Datalogger Ground Water Elevations 2–21
Figure 3–1. Well 1089 Pumping Rate and Cumulative Ground Water Volume Extracted........ 3–2
Figure 3–2. Well 1077 Pumping Rate and Cumulative Ground Water Volume Extracted........ 3–2
Figure 3–3. Well 1104 Pumping Rate and Cumulative Ground Water Volume Extracted........ 3–3
Figure 3–4. Well 0818 Pumping Rate and Cumulative Ground Water Volume Extracted........ 3–5
Figure 3–5. Well 1070 Pumping Rate and Cumulative Ground Water Volume Extracted........ 3–5
Figure 3–6. Well 1071 Pumping Rate and Cumulative Ground Water Volume Extracted........ 3–6
Figure 3–7. Well 1078 Pumping Rate and Cumulative Ground Water Volume Extracted........ 3–6
Figure 3–8. Well 1091 Pumping Rate and Cumulative Ground Water Volume Extracted........ 3–7
Figure 3–9. Well 1092 Pumping Rate and Cumulative Ground Water Volume Extracted........ 3–7
Figure 3–10. Well 1093 Pumping Rate and Cumulative Ground Water Volume Extracted...... 3–8
Figure 3–11. Well 1095 Pumping Rate and Cumulative Ground Water Volume Extracted...... 3–8
Figure 3–12. Well 1096 Pumping Rate and Cumulative Ground Water Volume Extracted...... 3–9
Figure 3–13. Bob Lee Wash Pumping Rate and Cumulative Ground Water Volume Extracted 3–10
Figure 3–14. Many Devils Wash Pumping Rate and Cumulative Ground Water Volume Extracted 3–10
Figure 3–15. Total Ground Water Volume Transported to the Evaporation Pond.................. 3–11

Tables

Table 3–1. Terrace Extraction Well Average Pumping Rate and Total Ground Water Volume Removed 3–4
Table 3–2. Estimated Total Mass of Selected Constituents Pumped from Terrace and Floodplain 3–12

1.0 Introduction

This report evaluates the performance of the ground water remediation system at the disposal and processing site in Shiprock, New Mexico, for the period of April 2005 through March 2006. The Shiprock site, a former uranium mill tailings facility under the Uranium Mill Tailings Remedial Action (UMTRA) Project, is currently managed by the U.S. Department of Energy (DOE) Office of Legacy Management (DOE−LM). This evaluation is based upon comparison of the site conditions in March 2006 to the baseline site conditions presented in the Baseline Performance Report (DOE 2003). The baseline conditions were established using data collected primarily from March 2003. A detailed description of the site conditions is presented in the Site Observational Work Plan (SOWP) (DOE 2000), and the compliance strategy is presented in the Ground Water Compliance Action Plan (GCAP) (DOE 2002).

The Shiprock site is divided into two distinct areas, the floodplain and the terrace. An escarpment forms the boundary between the two areas. The terrace is further divided into terrace west and terrace east. Initially, the remediation system (Figure 1–1) consisted of two floodplain ground water extraction wells, four terrace east ground water extraction wells, two interceptor drains (one installed in Bob Lee Wash and the other installed in Many Devils Wash), a lined evaporation pond, and a terrace drainage channel diversion structure. The terrace ground water extraction wells and interceptor drains became operational in late February 2003, and the floodplain extraction wells became operational in March 2003. Four additional extraction wells were installed on the terrace east portion of the site in July 2003; they were piped into the remediation system in early August 2003 in an attempt to increase the volume of ground water removed from the terrace. The site conceptual model was refined in 2004 to determine the feasibility of extracting more ground water from the terrace alluvial flow system; this resulted in the recommendation to install three new extraction wells in the terrace east area DOE (2004). Two of these wells were installed in March 2005; the third could not be emplaced because of failure to obtain access right-of-way. In addition, the site conceptual model update recommended installing subsurface collection trenches at the base of the escarpment on the floodplain. Construction of the trenches was in progress at the close of this reporting period in March 2006.

1.1 Remediation System Performance Standards

This performance assessment is based on the analysis of ground water quality and ground water level data obtained from site monitor wells in addition to ground water flow rates associated with the drains and seeps.

Specific performance standards as established for the Shiprock floodplain ground water remediation system in the Baseline Performance Report (DOE 2003) are summarized as follows:

- Ground water flow directions in the vicinity of the extraction wells should be toward the extraction wells.
- Pumping on the floodplain should intercept contaminants of concern (COCs) that would otherwise discharge to the San Juan River.

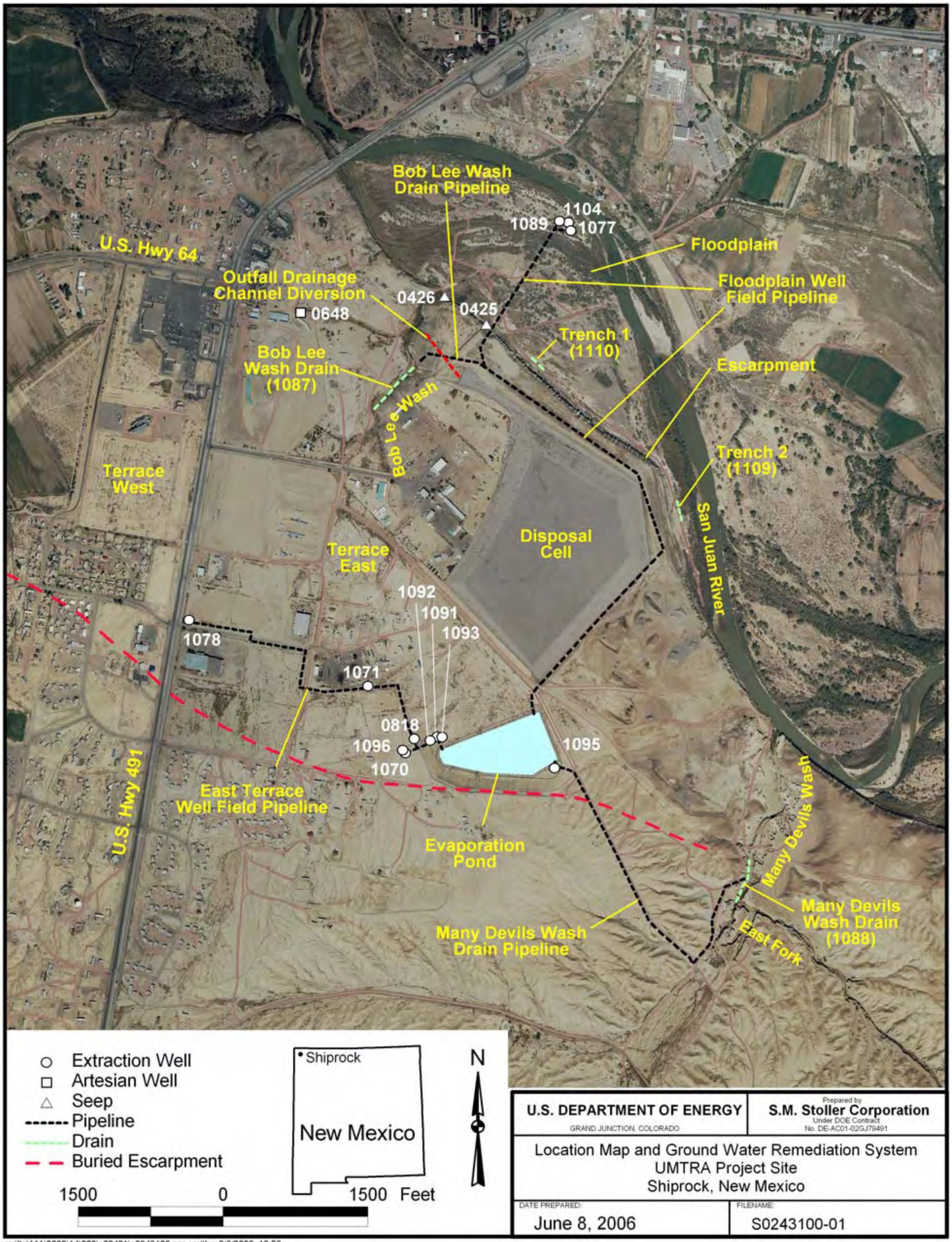


Figure 1–1. Location Map

Specific performance standards as established for the Shiprock terrace ground water remediation system in the Baseline Performance Report (DOE 2003) are summarized as follows:

- Terrace ground water surface elevations should decrease as water is removed from the terrace system.
- Ground water flow directions in the vicinity of the extraction wells should be toward the extraction wells.
- The volume of water discharging to the interceptor drains located in Bob Lee and Many Devils Washes should decrease over time as ground water levels on the terrace decline.
- The flow rates of seeps located at the escarpment face (locations 0425 and 0426) should decrease over time as ground water levels on the terrace decline.

1.2 Contaminants of Concern and Remediation Goals

Ground water at the site is contaminated as a result of uranium milling activities between 1954 and 1968. The COCs for both the floodplain and terrace are ammonia (total as NH_4), manganese, nitrate (nitrate+nitrite as N), selenium, strontium, sulfate, and uranium.

Floodplain compliance standards for uranium and nitrate are their respective UMTRA Project standards of 0.044 and 44 milligrams per liter (mg/L). A secondary standard of 250 mg/L for sulfate exists under the Safe Drinking Water Act. However, studies conducted by the Centers for Disease Control in conjunction with the U.S. Environmental Protection Agency (EPA) have shown that no adverse effects from sulfate ingestion occur at concentrations of up to 1,200 mg/L (EPA 1999). The report notes that other studies have shown that concentrations of sulfate exceeding 2,000 mg/L may have little to no adverse effect on humans and animals. Because of high background sulfate concentrations at the site in floodplain ground water (up to 1,920 mg/L) and the high sulfate concentration of water entering the floodplain from flowing artesian well 0648 (up to 2,340 mg/L), the proposed cleanup goal for floodplain sulfate is 2,000 mg/L. Relatively high selenium concentrations in the floodplain make it unlikely that the UMTRA Project standard of 0.01 mg/L for this constituent can be met while contaminated terrace water is still providing a source. DOE proposed an alternate concentration limit for selenium of 0.05 mg/L (DOE 2003), which is the EPA maximum contaminant level for drinking water. The cleanup objective for manganese is the maximum background concentration for the floodplain, which is currently 2.74 mg/L. There are no cleanup standards or background concentrations established for ammonia (total as NH_4) and strontium.

Ground water compliance for the terrace is based on hydrologic control, and concentration standards do not apply.

1.3 Hydrogeological Setting

A summary of the floodplain and terrace ground water systems is provided below. A more detailed description is available in the SOWP (DOE 2000).

1.3.1 Floodplain Alluvial Aquifer

The thick Mancos Shale of Cretaceous age forms the bedrock underlying the entire site. A floodplain alluvial aquifer occurs in unconsolidated medium- to coarse-grained sand, gravel, and cobbles that were deposited in former channels of the San Juan River above the Mancos Shale. The floodplain aquifer is hydraulically connected to the San Juan River; the river is a source of ground water recharge to the floodplain aquifer in some areas and receives ground water discharge in others. In addition, the floodplain aquifer almost certainly receives some inflow from a ground water system in the terrace area. The floodplain alluvium is up to 20 feet (ft) thick and overlies Mancos Shale, which is typically soft and weathered for the first several feet below the alluvium.

Most ground water contamination in the floodplain lies close to the escarpment east and north of the disposal cell. A plume extends northward from this contaminated area in an arc-shape as it crosses the floodplain and reaches the San Juan River near the floodplain extraction wells (Figure 1–1). This plume configuration is best characterized by elevated concentrations of sulfate and uranium. Contamination does not occur along the escarpment base in the northwest part of the floodplain because relatively uncontaminated surface water from Bob Lee Wash discharges into the floodplain, recharging local ground water and then flowing to the north and west. Surface water in Bob Lee Wash originates primarily as deep ground water from the Morrison Formation that flows to the land surface via artesian well 0648. Well 0648 flows at approximately 65 gallons per minute (gpm) and drains eastward into lower Bob Lee Wash. Background ground water quality in the floodplain aquifer has been defined by monitor wells installed in the floodplain approximately 1 mile upriver from the site.

1.3.2 Terrace Ground Water System

The terrace ground water system occurs partly in unconsolidated alluvium in the form of medium- to coarse-grained sand, gravel, and cobbles deposited in the floodplain of the ancestral San Juan River. Terrace alluvial material is Quaternary in age; it varies from 0 to 20 ft thick, and caps the Mancos Shale. Though less well mapped, some terrace ground water also occurs in weathered Mancos Shale underlying the alluvium. The Mancos Shale is exposed in the escarpment overlooking the present floodplain.

The terrace ground water system extends southwestward from the escarpment separating the terrace from the floodplain for up to 1 mile, where it is abruptly bounded by a buried escarpment. Terrace alluvial material is exposed at the terrace/floodplain escarpment, but southwestward from there it is covered by an increasing thickness of eolian silt, or loess. At the southwest edge of the terrace aquifer, along the base of the buried escarpment, up to 40 ft of loess overlies the alluvium. The alluvium in this latter area consists of coarse, ancestral San Juan River deposits.

Mancos Shale in the terrace area is weathered (fractured and soft) several feet below its contact with the alluvium. Ground water is known to occur in the weathered shale and may flow through deeper portions of the shale that might be fractured and along bedding surfaces.

2.0 Subsurface Conditions

This section summarizes hydraulic and water quality characteristics of the floodplain and terrace ground water systems in March 2006, approximately 3 years after startup of the treatment system. Figure 2–1 shows the locations of all wells that are discussed in this report.

2.1 Floodplain Subsurface Conditions

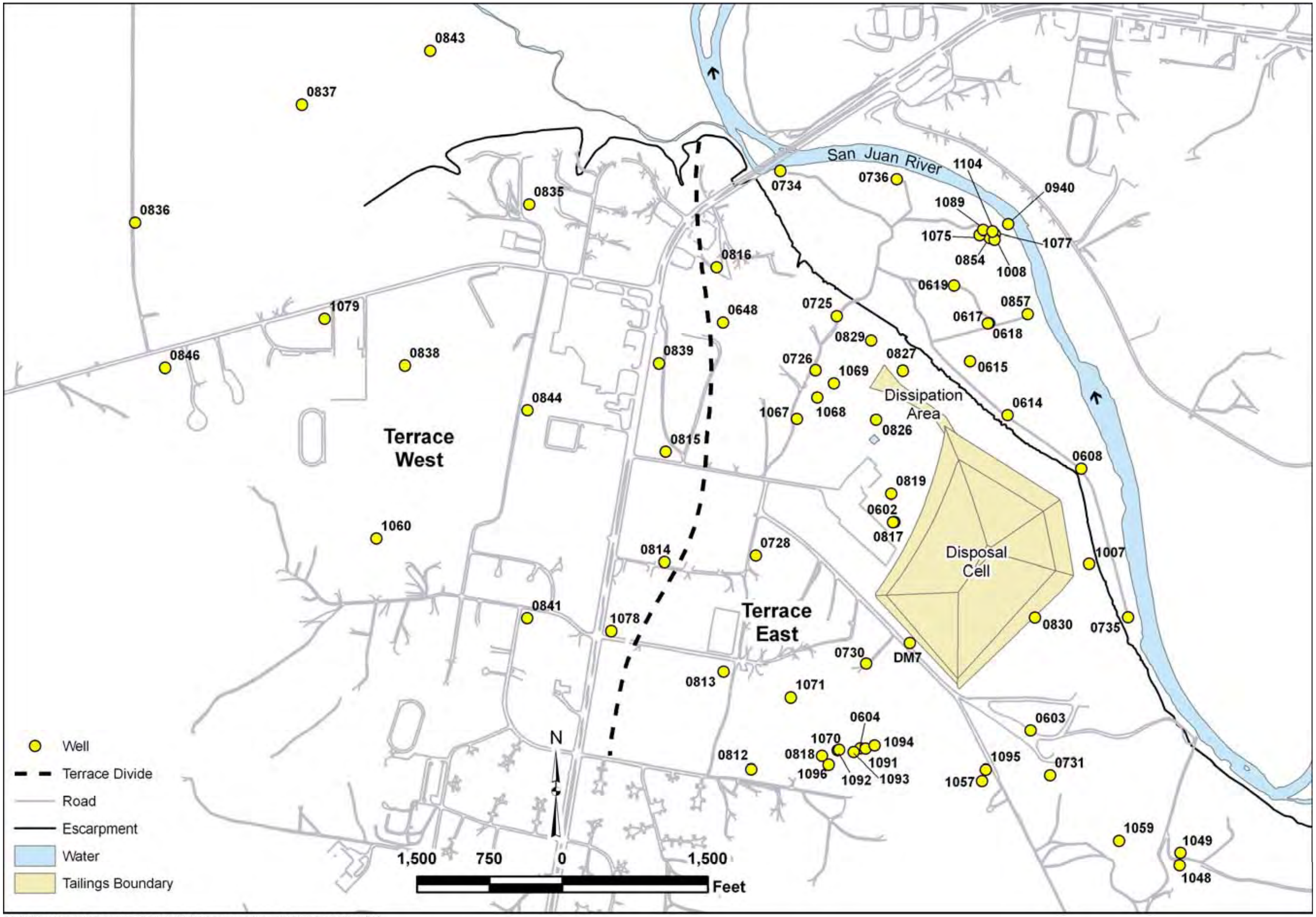
The discussion of current subsurface conditions of the floodplain is based on collection and analysis of ground water samples and ground water level data through March 2006. Analyses of ground water level trends and flow directions, and contaminant distributions in the floodplain are discussed below. Results are compared to baseline conditions established in March 2003 in the Baseline
Performance Report (DOE 2003) to evaluate the effectiveness of the floodplain treatment system.

2.1.1 Ground Water Level Trends and Flow Directions

Horizontal hydraulic gradients and flow directions in the floodplain were initially determined from three-point analysis of ground water level data. Measurements were initiated using March 2003 ground water level data, which were subsequently compared to March 2004 and March 2005 data. The objective of these analyses was to determine horizontal gradients and flow directions across the floodplain system and to demonstrate that the flow of ground water was predominantly toward the extraction wells. Analysis of ground water level and flow data was also important to observe recharge and discharge effects of the floodplain aquifer caused by interaction with flow dynamics of the San Juan River and seasonal variability of river flow and precipitation. There was also an effect on the alluvial system because of ground water discharging to the surface from artesian well 0648 and then flowing across the floodplain into the river.

Results of the three-point analyses over a 3-year period showed very little change in ground water flow directions and demonstrated that the flow system in the floodplain was operating as expected, taking into account the variabilities mentioned above. There was also adequate indication that flow was toward the extraction wells to the extent anticipated with the relatively low flow rates. Therefore, these measurements have been discontinued, as they do not represent any additional value to interpretation and assessment of the performance standards for remediation at the Shiprock site.

Ground water levels in the floodplain aquifer are manually recorded every 6 months during routine ground water sampling events (Figure 2–2). Ground water level fluctuations in the floodplain wells over the past 3-year period have been on the order of 2 ft. Higher ground water levels appear to have coincided with elevated flows in the San Juan River during the March sampling event. Ground water levels declined throughout the remainder of the growing season, lower ground water levels occur in conjunction with minimum flows in the San Juan River. Ground water levels recovered throughout the balance of the dormant season. Over the 3-year period, ground water elevations have risen slightly in the floodplain, which is likely related to regional phenomena.



M:\LTS\111\0020\14\002\S02433\S0243300.mxd smithw 6/8/2006 11:15:00 AM

Figure 2–1. Locations of Wells Discussed in This Report

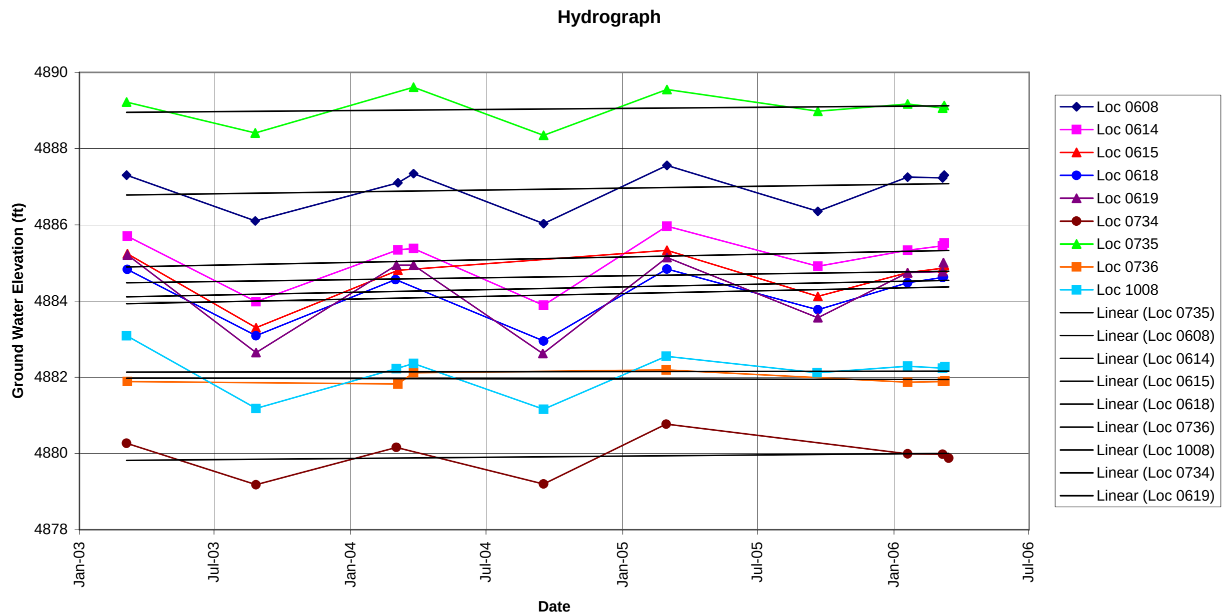


Figure 2–2. Floodplain Ground Water Elevations from Manual Measurements

Ground water elevations in the floodplain aquifer are also measured every 4 hours by pressure transducers installed in five monitor wells (0617, 0736, 0854, 0857, and 1008) and connected to dataloggers (Figure 2–3). Datalogger information is available starting in early January 2004 and beyond. Manual ground water level measurements recorded during routine ground water quality sampling events every 6 months for monitor well 1008 are shown for comparison with datalogger information (Figure 2–3).

Flow data from the U.S. Geological Survey Gaging Station 09368000 in the San Juan River at Shiprock, NM, are plotted on Figure 2–3. The river flow on the day the March 2003 water level data were measured was 649 cubic feet per second (cfs), while the flow on the day the March 2006 data were measured was 551 cfs. In terms of stage, or water surface elevation, the San Juan River flows measured in 2006 and the 2003 flows are approximately the same.

Precipitation data showing the influence of rainfall in the area are also available from the site and region. During this performance period, the ground water recovery was aided by a 13,200-cfs spike in the flow of the San Juan River, which occurred on May 25, 2005 (Figure 2–4). This flow spike in the San Juan River probably occurred in response to above average precipitation measured at Farmington, New Mexico, and at Durango, Colorado, during April and May 2005. (http://www.wunderground.com/history/airport/KFMN/2004/9/19/DailyHistory.html; http://www.wunderground.com/history/airport/KDRO/2004/9/19/DailyHistory.html). Precipitation data from the meteorological station at the Shiprock site are shown along with flow data from the San Juan River (Figure 2–4).

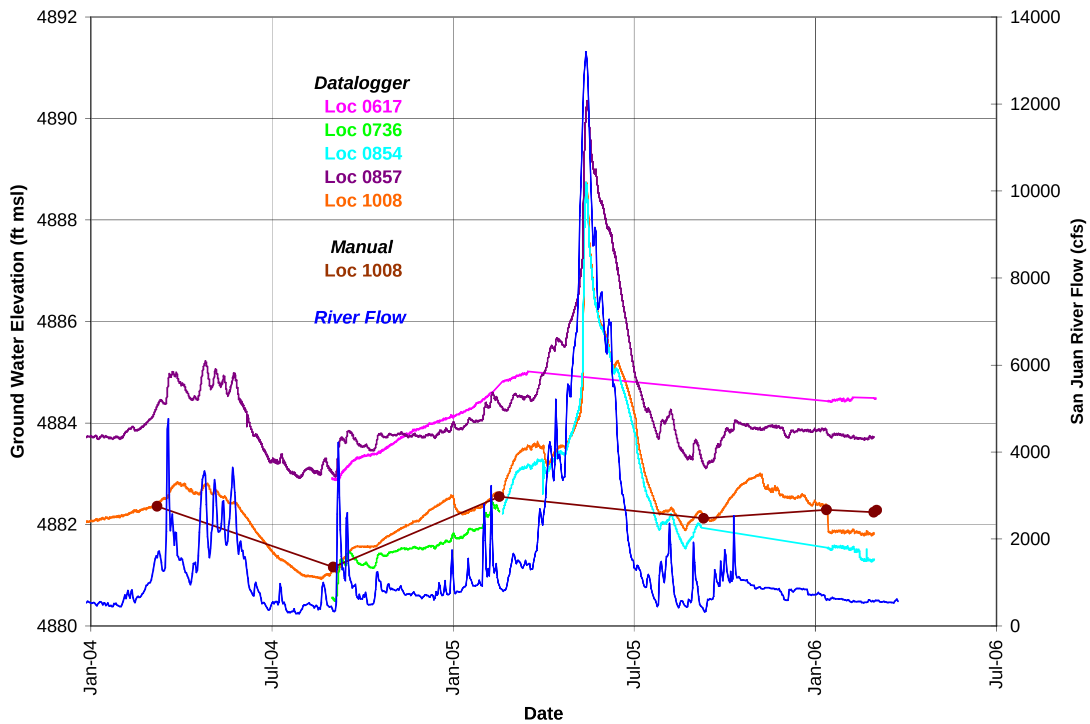


Figure 2–3. Floodplain Ground Water Elevations from Datalogger Measurements

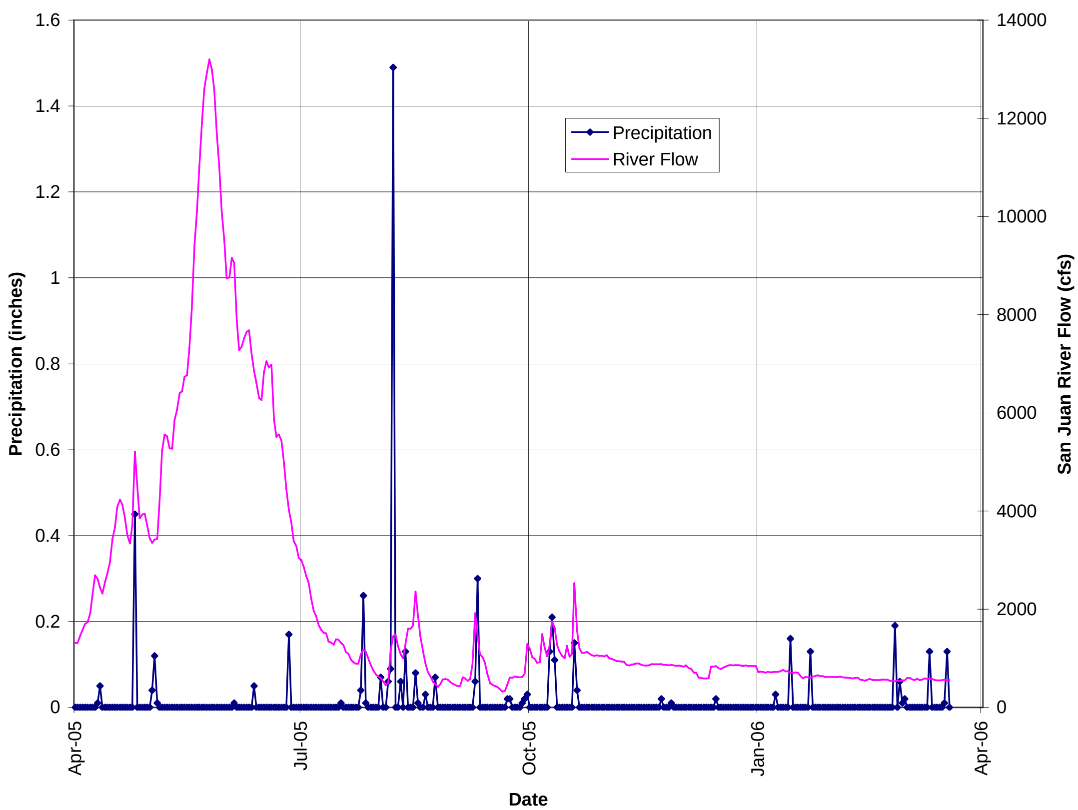


Figure 2–4. Precipitation and San Juan River Flow

The datalogger plots show very close correlation between ground water levels with the flow patterns of the San Juan River, indicating relatively rapid recharge and discharge of the aquifer related to change in river flow and surface water levels (Figure 2–3). It is known that most of the water entering the floodplain aquifer does so via San Juan River losses along the southernmost tip of the aquifer. Thus, it is logical to assume that inflow from the river increases during high runoff, and that this produces flow directions east of the disposal cell that are in a more northward to northwestward direction than normal. The potential for greater mixing of relatively clean water from the river with contaminated ground water emanating from the Mancos Shale would likely increase under such circumstances, which possibly leads to greater dilution of ground water contaminants in the aquifer and enhances natural flushing of contaminants from the floodplain aquifer.

2.1.2 Contaminant Distributions

Ground water samples were collected from selected floodplain monitor wells in September 2005 and March 2006. Locations of the wells sampled are shown in Figure 2–5 through Figure 2–11, which illustrate the spatial distribution of concentrations measured in March 2006 for ammonia (total as N), manganese, nitrate (nitrate + nitrite as N), selenium, strontium, sulfate, and uranium, respectively. To compare the data sets, it was necessary to convert the concentrations for ammonia and nitrate listed in the Baseline Performance Report (DOE 2003). Ammonia concentrations were converted from “ammonia total as NH_4” to “ammonia total as N.” The baseline nitrate concentrations were converted from “nitrate as NO_3” to “nitrate + nitrite as N.” These conversions were made in response to different analyses being requested with a change in laboratories.

Variations in concentration versus time of these constituents from March 2003 (baseline) through March 2006 are shown in Figure 2–12 through Figure 2–18. Linear trendlines are shown on the graphs to indicate changes in concentrations over the past 3 years. There is a certain amount of periodic variation in concentrations of constituents that is not necessarily indicative of the overall longer-term trend. Concentrations of constituents in ground water in the floodplain alluvium are affected by seasonal changes in climate, river stage influence, discharge of ground water from the artesian well that flows into Bob Lee Wash and then onto the floodplain, and pumping rates of the extraction wells.

Ammonium concentrations in ground water have generally decreased over the past 3 years (Figure 2–5). The maximum concentration in monitor well 0608 adjacent to the disposal cell has gone from 420 mg/L to 240 mg/L over the past year; this compares with 303 mg/L in March 2003 (Figure 2–12). Concentrations in all other wells are less than 50 mg/L and generally stable.

Concentrations of manganese have been variable over the past 3 years, ranging from 0.83 mg/L to 8.80 mg/L during the March 2006 sampling event (Figure 2–6). There is noticeable but inconsistent variation on a seasonal basis in some of the wells. Over the past 3 years there has been a downward trend in manganese concentrations in ground water in four of the nine wells (Figure 2–13).

Nitrate concentrations in ground water ranged from less than 1 mg/L to 870 mg/L and have increased in four of the nine monitor wells over the past 3 years (Figure 2–7). Again, there has been seasonal variation in some of the wells contrary to the longer-term trends (Figure 2–14).

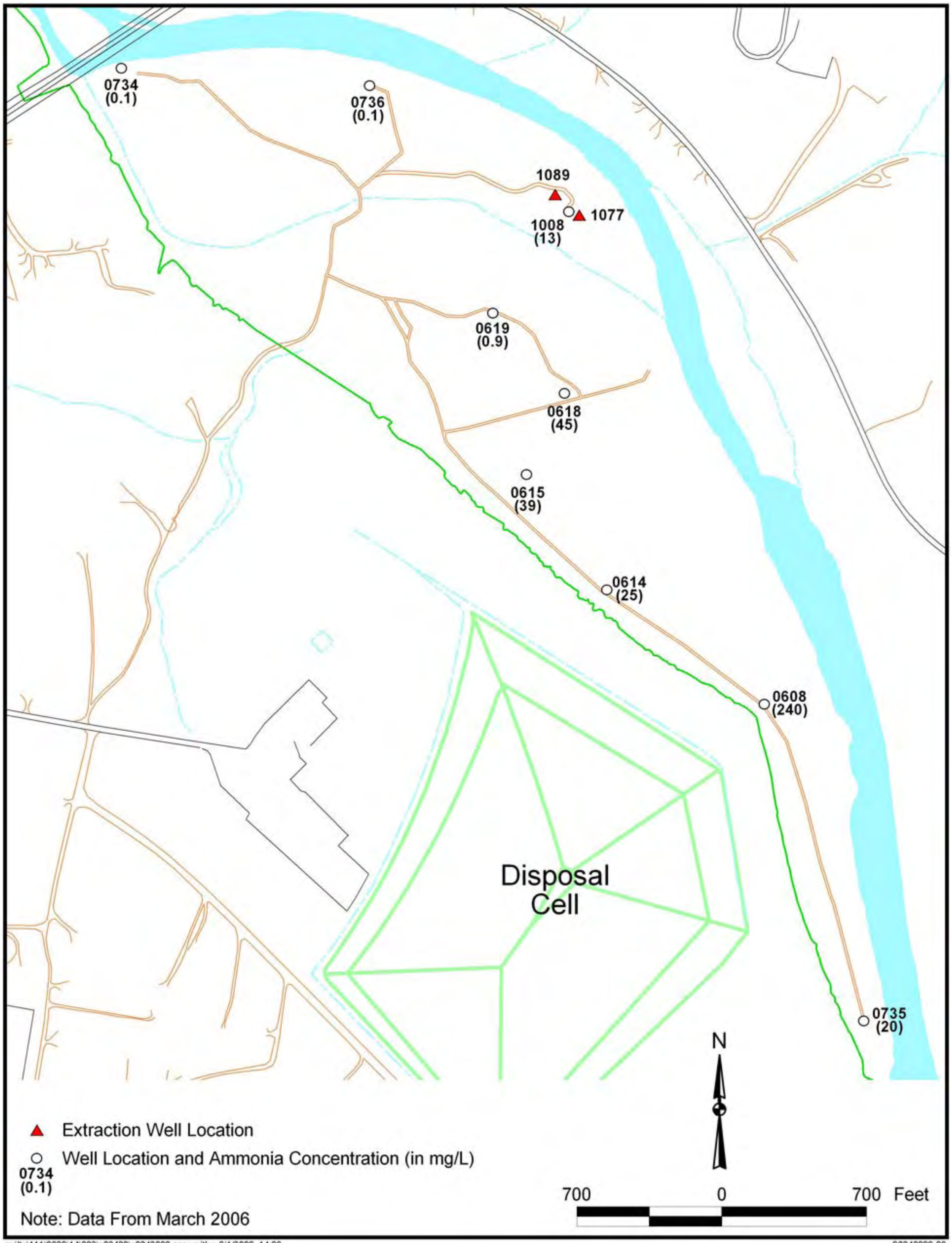


Figure 2–5. Floodplain Ammonia (total as N) Ground Water Concentrations

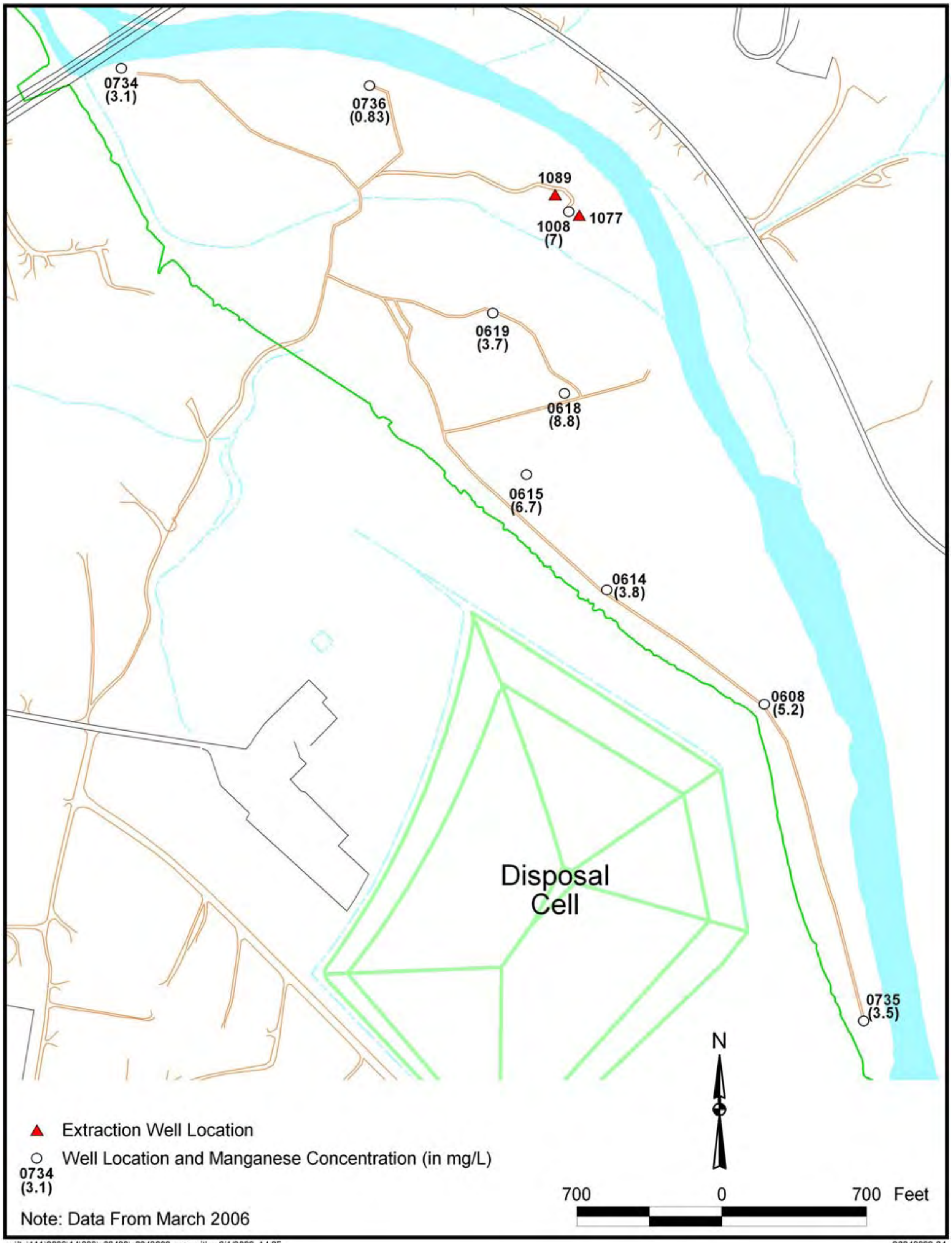


Figure 2–6. Floodplain Manganese Ground Water Concentrations

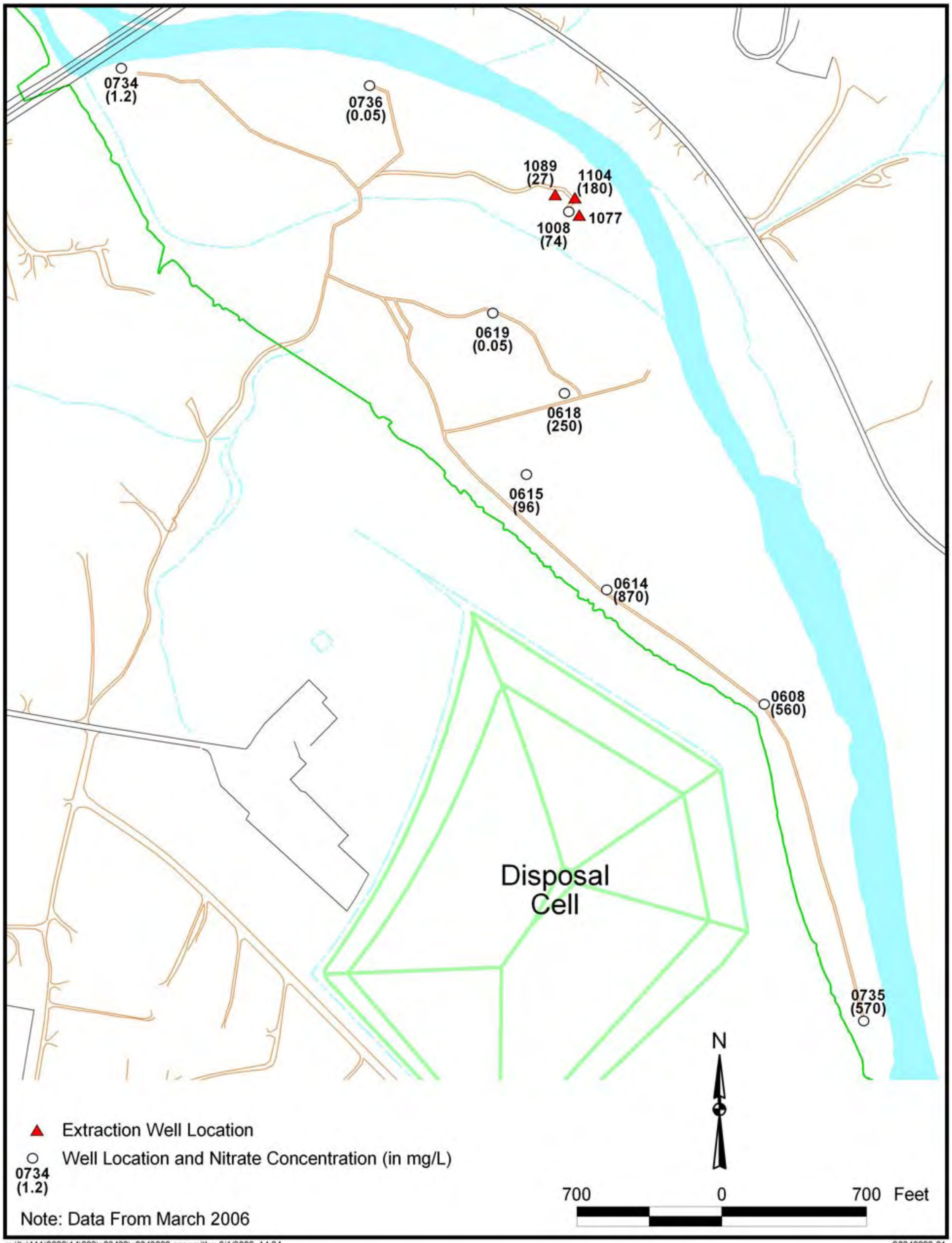


Figure 2–7. Floodplain Nitrate Ground Water Concentrations

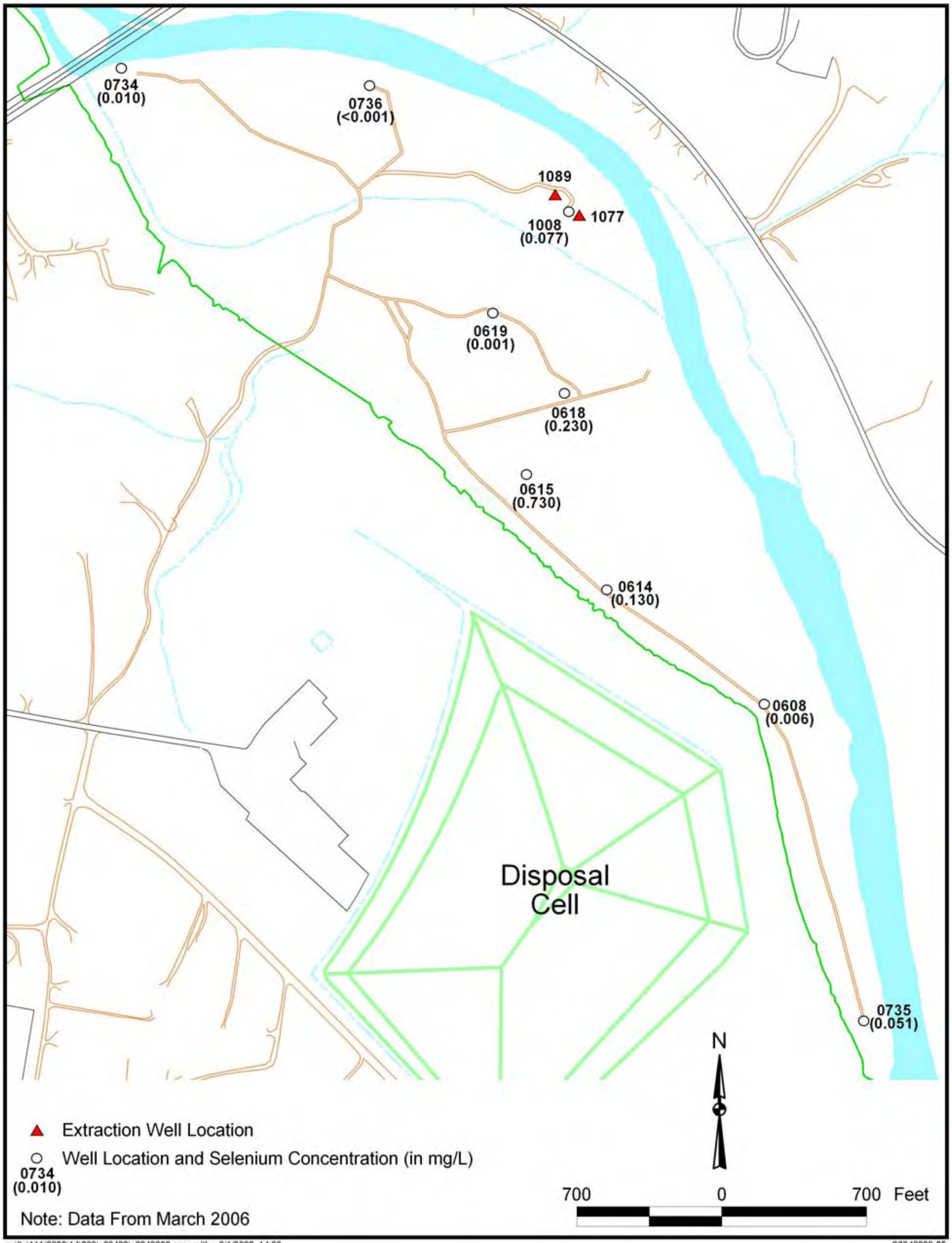


Figure 2–8. Floodplain Selenium Ground Water Concentrations

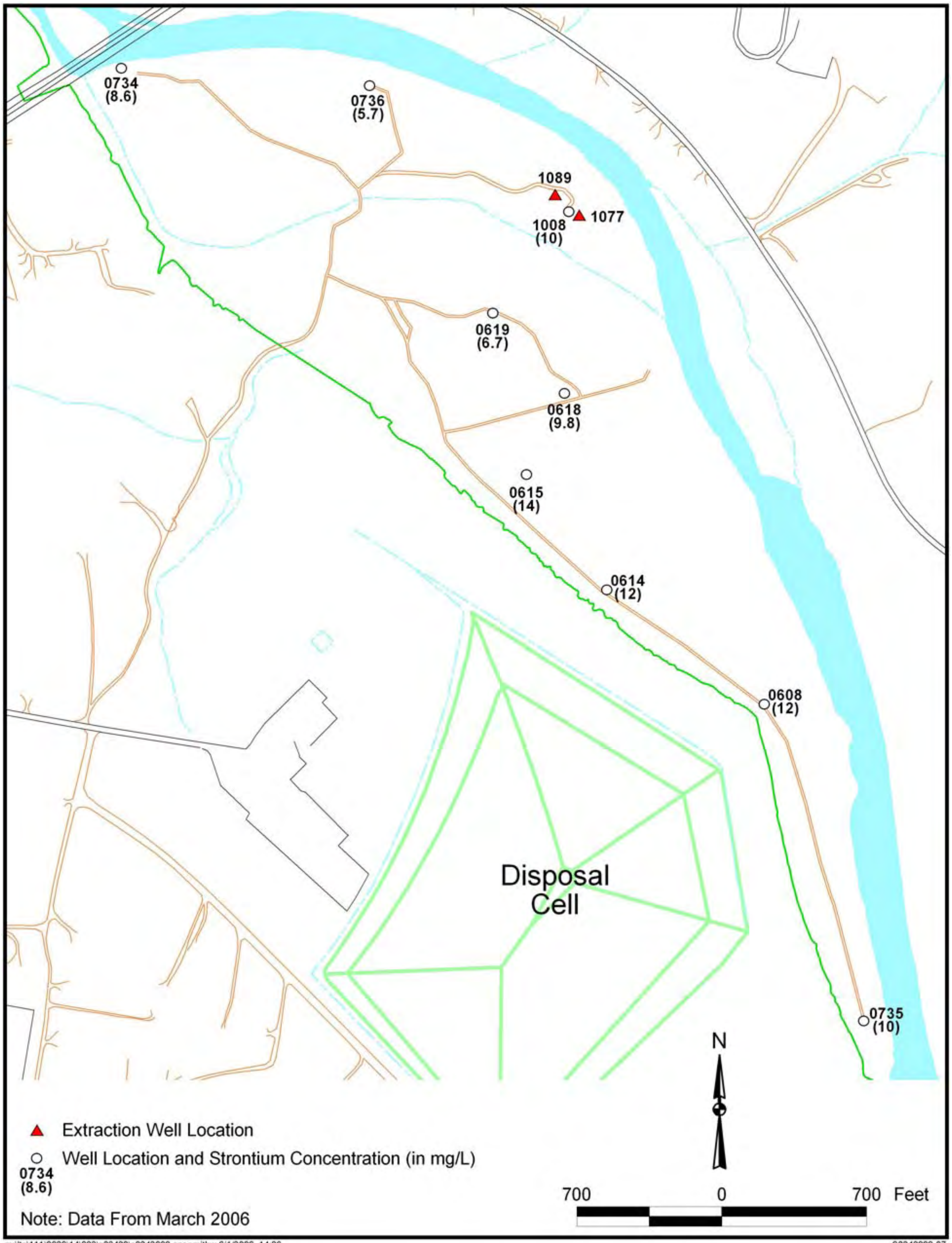


Figure 2–9. Floodplain Strontium Ground Water Concentrations

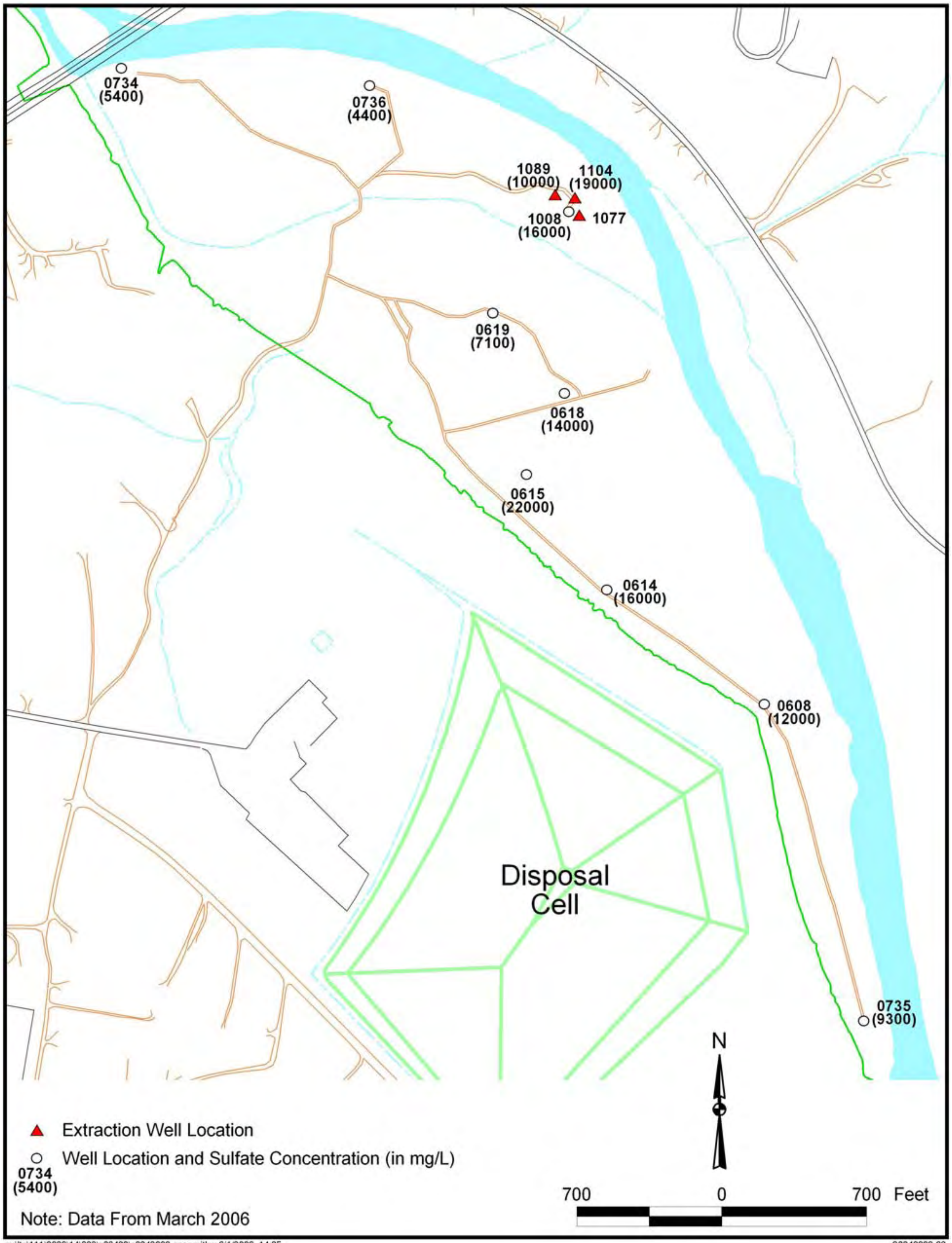


Figure 2–10. Floodplain Sulfate Ground Water Concentrations

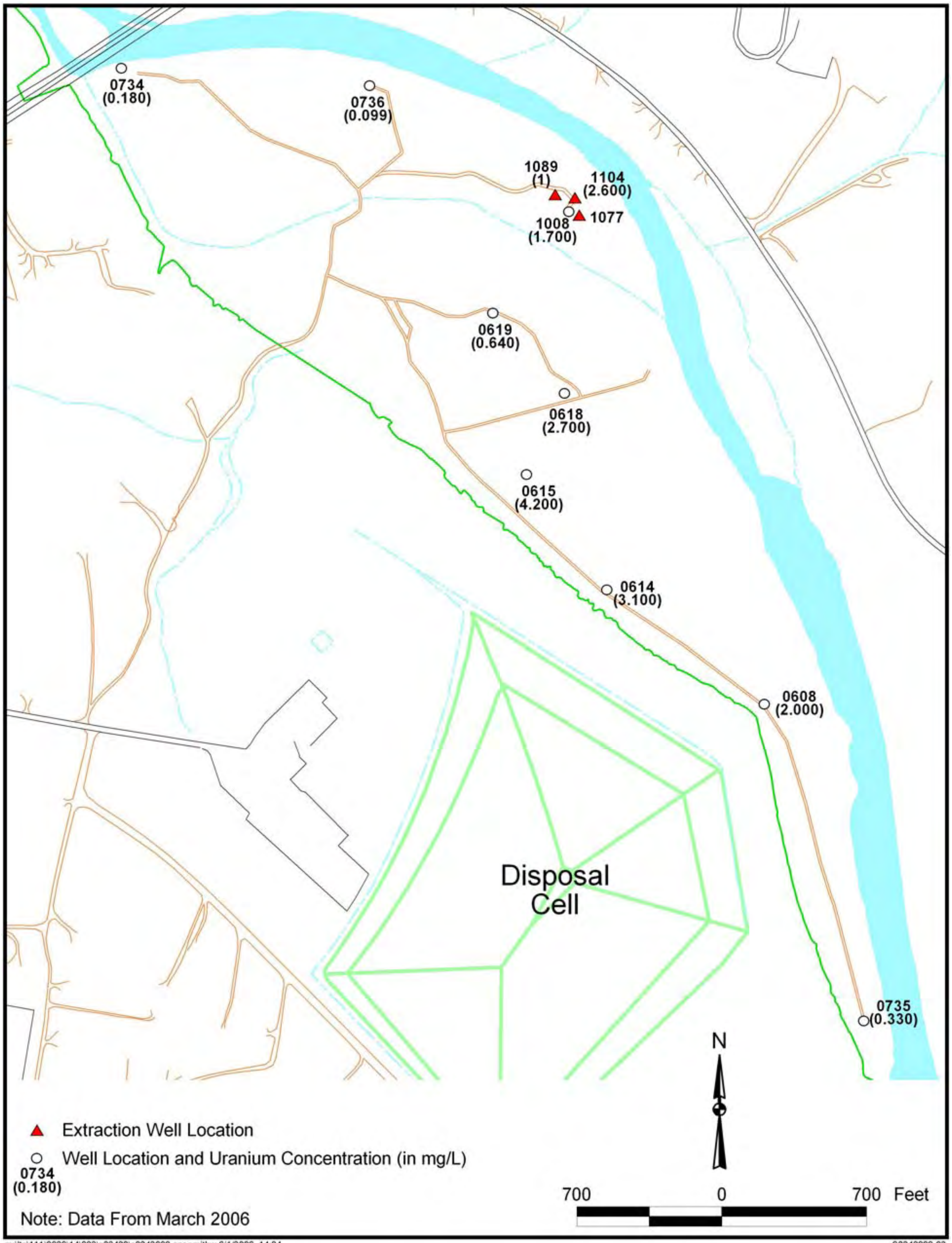


Figure 2–11. Floodplain Uranium Ground Water Concentrations

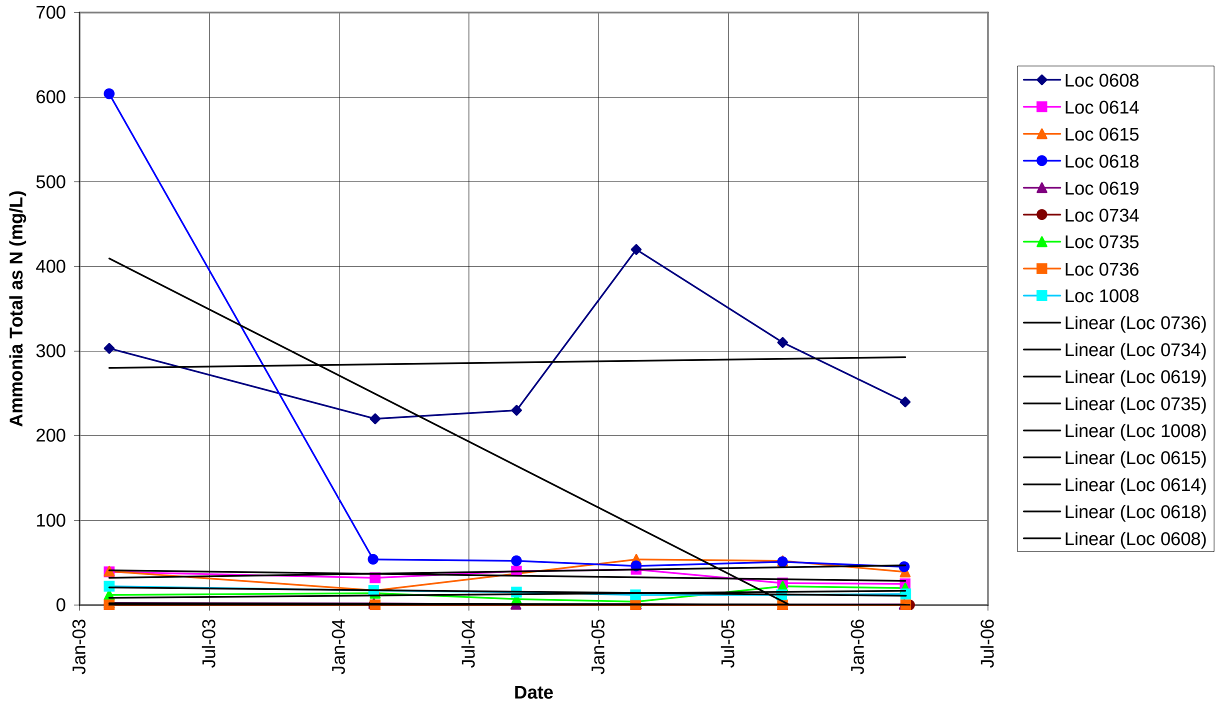


Figure 2–12. Floodplain Ammonia (total as N) Ground Water Concentrations Versus Time

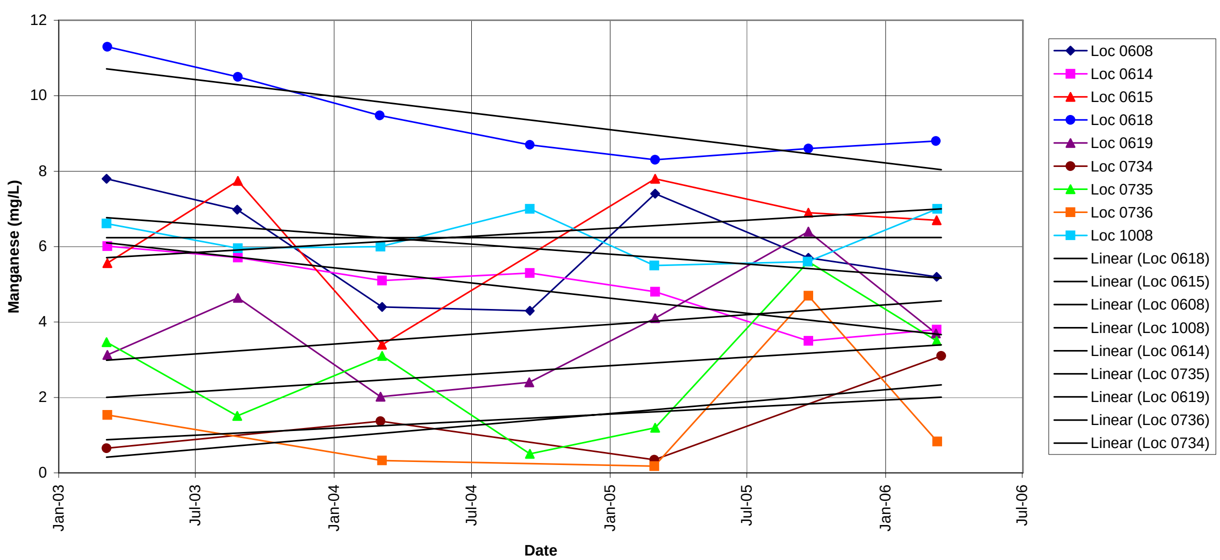


Figure 2–13. Floodplain Manganese Ground Water Concentrations Versus Time

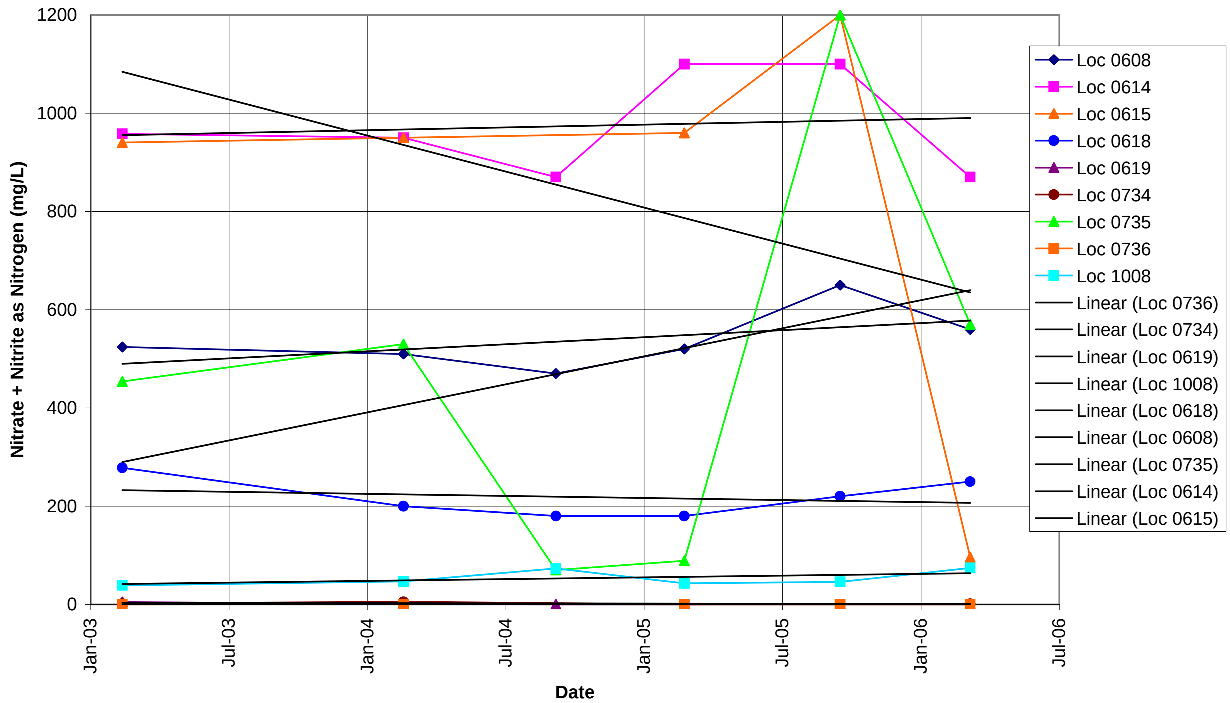


Figure 2–14. Floodplain Nitrate Ground Water Concentrations Versus Time

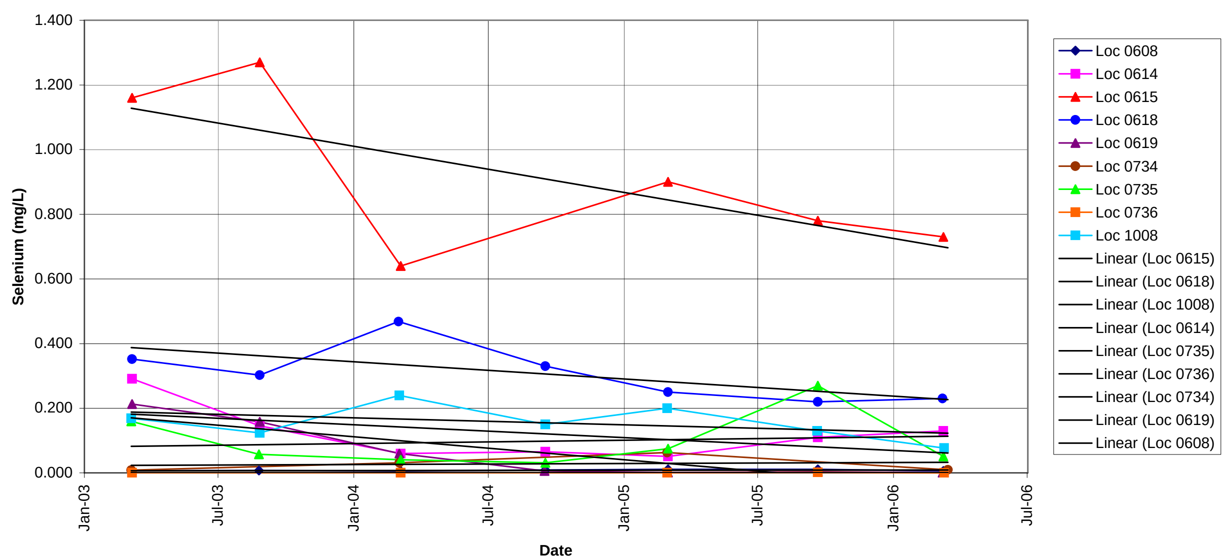


Figure 2–15. Floodplain Selenium Ground Water Concentrations Versus Time

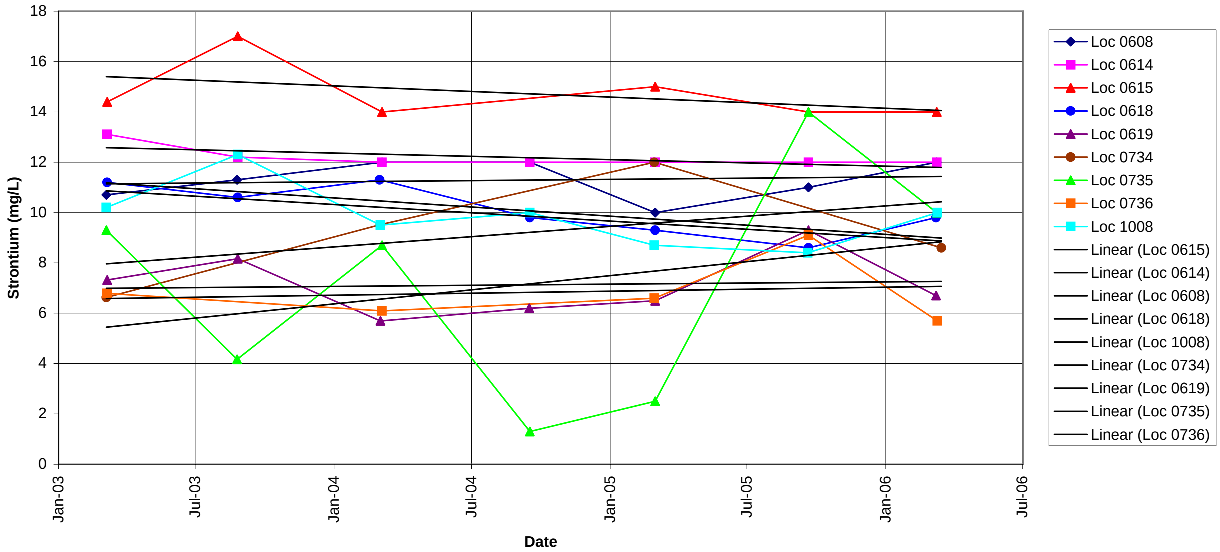


Figure 2–16. Floodplain Strontium Ground Water Concentrations Versus Time

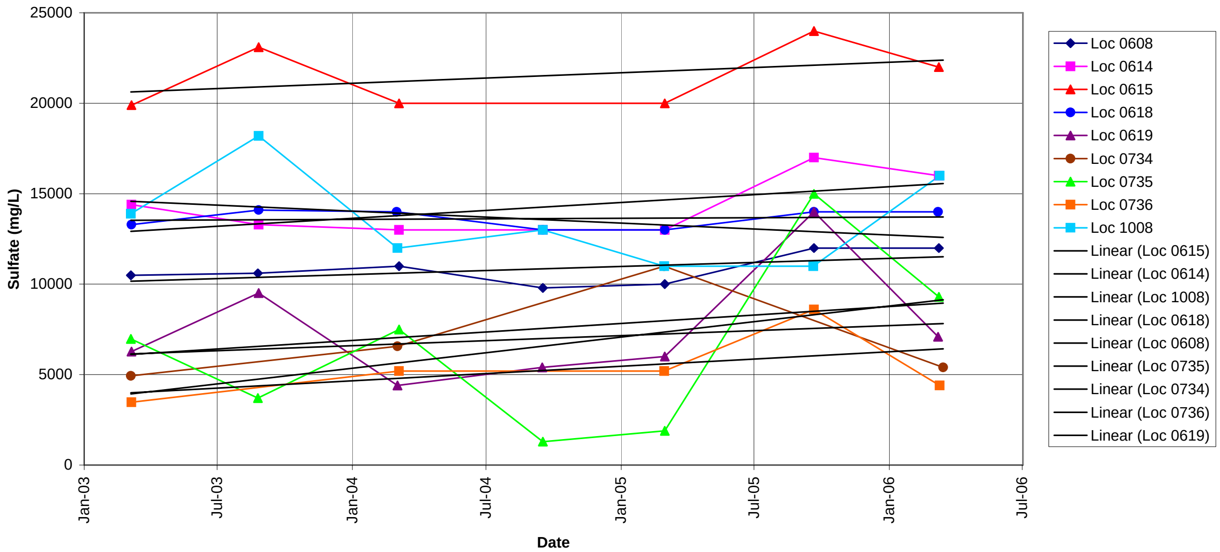


Figure 2–17. Floodplain Sulfate Ground Water Concentrations Versus Time

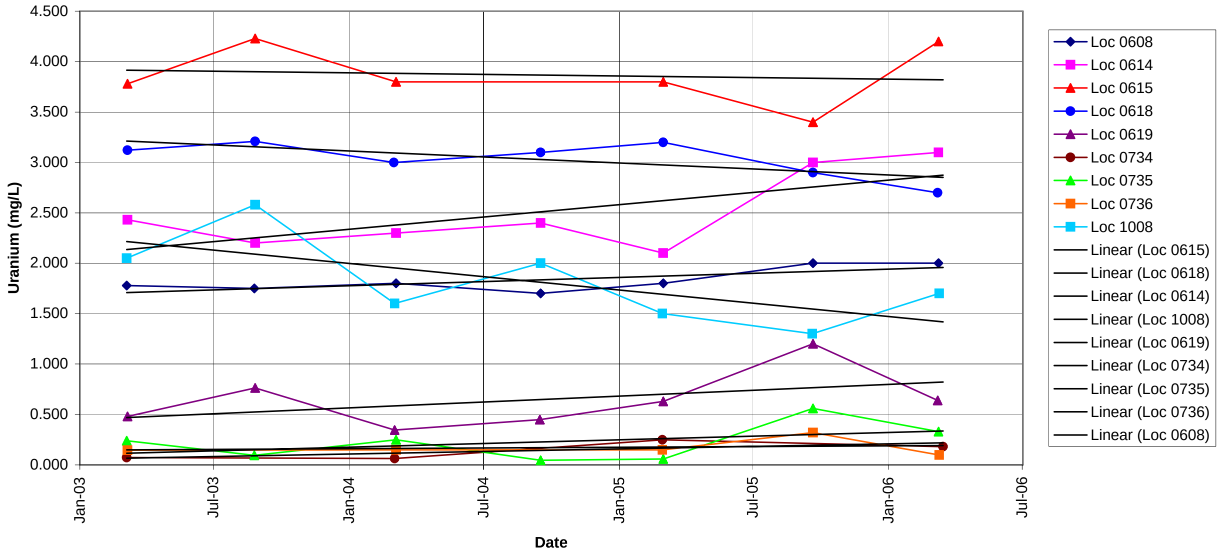


Figure 2–18. Floodplain Uranium Ground Water Concentrations Versus Time

Concentrations of selenium in ground water have generally been decreasing over the past 3 years (Figure 2–8). The maximum concentration during the March 2006 sampling event was 0.73 mg/L; levels were greater than 0.05 mg/L in five of the nine monitor wells (Figure 2–15).

Concentrations of strontium have generally decreased over the past 3 years (Figure 2–9). Concentrations decreased or were stable in seven of the nine monitor wells and ranged from 5.7 mg/L to 14 mg/L during the March 2006 sampling event (Figure 2–16).

Sulfate concentrations in ground water have generally increased over the past 3 years (Figure 2–10). Again, variability is noted in some wells with recent decreases but overall upward trends, which may be the effect of seasonal variation and interaction with surface water from the San Juan River (Figure 2–17).

Uranium concentrations in ground water ranged from 0.099 mg/L to 4.200 mg/L during the March 2006 sampling event (Figure 2–11). Trends over the past 3 years have been variable; concentrations increased in some wells and decreased in others. Again, seasonal variations may be contrary to longer-term trends (Figure 2–18).

During the first 3 years of operation of the remediation system at the Shiprock site a significant mass of contaminants has been removed from the alluvial ground water system by the extraction wells and trenches (see Section 3.2.3). Also, natural flushing is having an effect, as the floodplain system is dynamic with the interaction of recharge and discharge of surface water from the San Juan River, precipitation, and the influx of ground water from the artesian well discharging into Bob Lee Wash. The addition of two trenches at the base of the escarpment (Figure 1–1) will enhance the amount of ground water and mass of constituents removed from the alluvial system.

Another indication that pumping of ground water from the floodplain system is having an apparent effect is the fact that concentrations of nitrate (as NO_3) and uranium in surface water in the San Juan River (location 0940) have remained below the upgradient background benchmark values (statistically derived), even during low flow periods, since 2004 (Figure 2–19 and Figure 2–20).

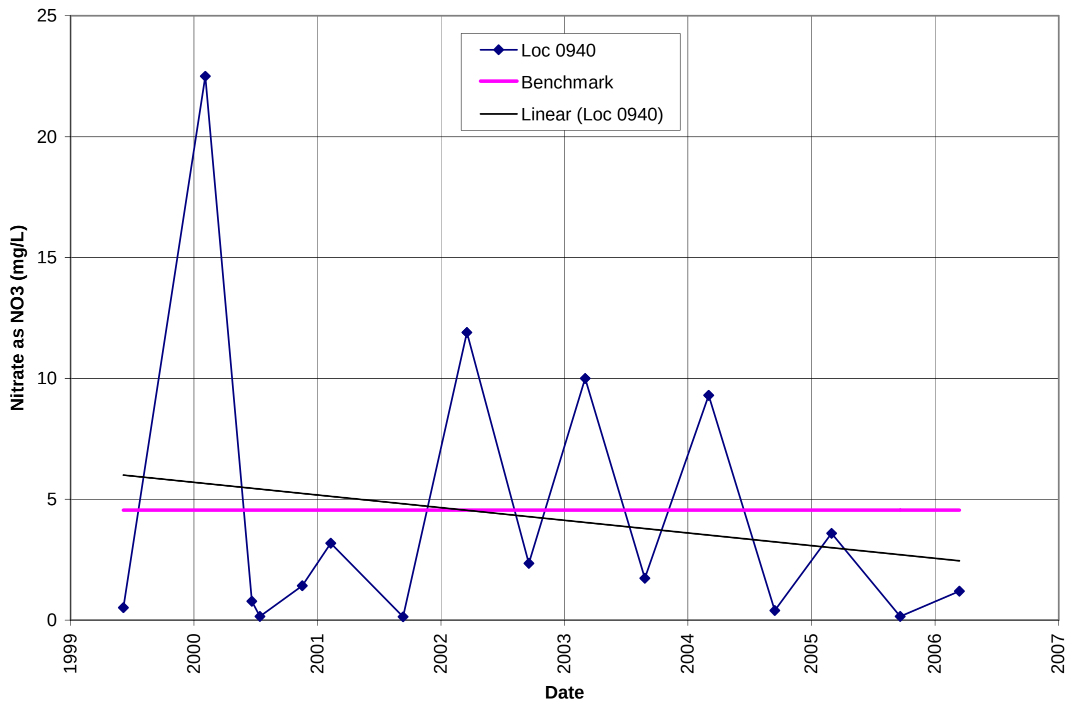


Figure 2–19. Nitrate Concentration in the San Juan River

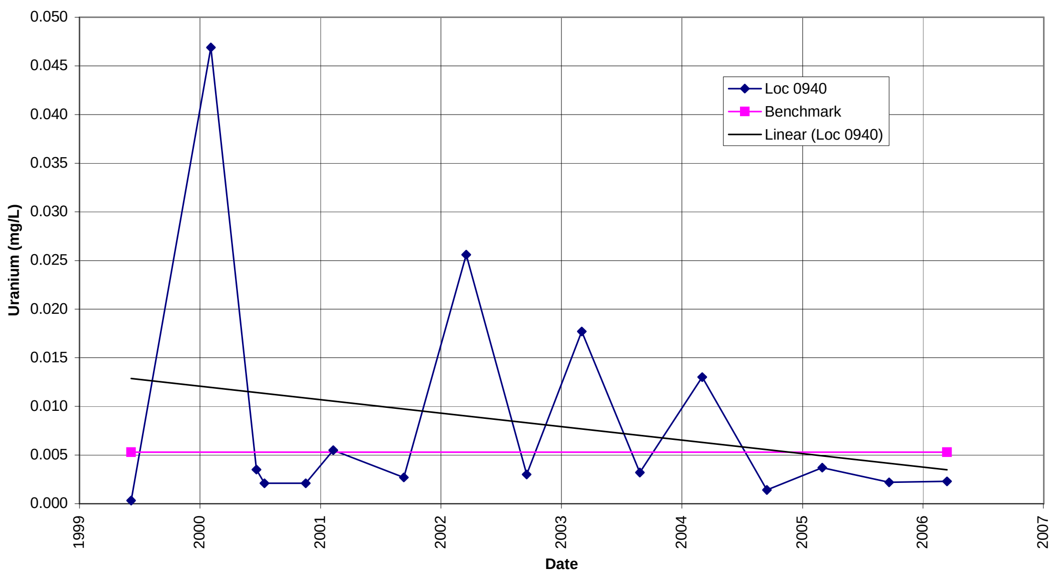


Figure 2–20. Uranium Concentration in the San Juan River

2.2 Terrace System Subsurface Conditions

The discussion of current subsurface conditions of the terrace is based on collection and analysis of ground water level data through March 2006. Analyses of ground water level trends and flow directions, drain flow rates, and seep flow rates associated with the terrace are discussed below. Results are compared to baseline conditions established in March 2003 in the Baseline Performance Report (DOE 2003) to evaluate the effectiveness of the terrace treatment system.

There are no concentration-driven performance standards for the terrace system because compliance is based on hydrologic control. However, as a best management practice, selected contaminant concentrations are measured at each extraction well, drain, and seep. Estimates of mass removal from the terrace system, compiled during this performance period, are presented in Section 3.2.3 of this report.

2.2.1 Ground Water Level Trends and Flow Directions

Horizontal hydraulic gradients and flow directions beneath the terrace were initially determined from three-point analysis of ground water level data. Measurements were initiated using March 2003 ground water level data, which were subsequently compared to March 2004 and March 2005 data. The objective of these analyses was to determine horizontal gradients and flow directions across the terrace system and to demonstrate that flow of ground water was predominantly toward the extraction wells.

Results of these three-point analyses over a 3-year period showed very little change in ground water flow directions and demonstrated that the flow system beneath the terrace was operating as expected. At the scale of the three-point vector plots, the pumping rates on the terrace over the period of observation had a negligible impact on ground water flow directions near the extraction wells. Therefore these measurements have been discontinued, as they do not represent any additional value to interpretation and assessment of the performance standards for remediation at the Shiprock site.

Ground water level data from the terrace collected during the March 2006 sampling event were compared to baseline ground water elevations presented in the Baseline Performance Report (DOE 2003). Figure 2–21 presents a qualitative map view of some of the ground water elevation increases and decreases. Ground water elevations appear to be declining slightly across the entire terrace ground water system. Of the 23 measurements of ground water levels taken in March 2006, 18 results showed declines relative to the baseline period of March 2003, and only one well showed a very minimal increase. The greatest ground water level decrease was 4.09 ft at well 0730. This well is just southeast of the evaporation pond. The maximum increase in water level elevation (0.12 ft) occurred in well 0827, which is just west of the disposal cell.

Although ground water elevations have generally declined in the terrace east ground water system since remediation began, the decline due to pumping is difficult to isolate, partly because it is likely masked by the above-normal precipitation and, presumably, ground water recharge. As of March 2006, the cumulative volume of water removed from the terrace extraction system since pumping began was approximately 11,000,000 gallons (33.8 acre-ft), and pumping records showed that approximately 3,600,000 gallons (11.0 acre-ft) were removed during the period April 2005 through March 2006. The observation wells nearest the extraction well field are 0812 and 1057. The water levels in each of these wells in 2006 had declined both relative to baseline conditions and relative to water level measurements made in 2005. In consideration of the additional precipitation that was potentially available as recharge to the terrace ground water system, especially during the winter and early spring of this reporting period, it can be tentatively concluded that the extraction well field is beginning to have the desired effect on ground water levels in terrace east.

Water levels have also been monitored using pressure transducers that were installed in selected wells on the terrace prior to treatment system startup. Plots of ground water elevation data collected from pressure transducers connected to dataloggers in terrace east wells 0602, 0604, 0731, 0813, 0819, 0826, 0827, and 0830 are shown on Figure 2–22. With the exception of wells 0813 and 0819, water level changes in these wells are not presented on Figure 2–21; consequently, the plots provide additional means to evaluate trends in the terrace east ground water flow system. The datalogger in well 0604 indicates how the pumping at well 0818 apparently affected neighboring ground water elevations during 2005 and 2006. The average pumping rate for this well for the period was 0.69 gpm, with a notable increase during the last 3 months. Also, initiation of pumping of extraction wells 1095 and 1096 in January 2006, with an average pumping rate of approximately 1.36 gpm, is noted by the decrease in water level measured in well 0604 by approximately 2.5 ft. The decline in water levels at the remaining terrace east locations has been less impressive, perhaps as a consequence of higher-than-normal precipitation during this performance period. Continuous water level monitoring records for terrace east wells 0731, 0813, and 0826 show that water levels in these wells remained about the same as those published in the previous performance report (DOE 2005). It is possible that the overall extraction volume from terrace east needs to increase before the effects of pumping become discernible at the remaining wells.

Plots of ground water elevation data collected by dataloggers in terrace west wells 0837, 0841, 0843, 0846, and 1060 are shown on Figure 2–23. The graphs of wells 0837, 0843, 0846, and 1060 indicate that ground water elevations are influenced by irrigation practices in the terrace west area. Evidence of irrigation is absent in well 0841 because it is approximately 1,200 ft upgradient of the Helium Lateral Canal (Figure 2–1). Therefore, information from these dataloggers does not appear to be relevant to assessing performance of the remediation system at the Shiprock site.

2.2.2 Seep Flow Rates

Rates of ground water discharge at seeps 0425 and 0426 were measured in September 2005 and March 2006. The flow rate at seep 0425 in September 2005 was 0.5 gpm, which is the same as in March 2003. The flow rate at seep 0426 in September 2005 was 1.3 gpm, which is lower than the measured rate of 1.8 gpm in March 2003. The flow rate at seep 0425 in March 2006 was 0.08 gpm, which is significantly lower than the rate measured in March 2003 (0.5 gpm). Seep 0426 was not flowing in March 2006, which compares with a measured rate of 1.8 gpm in March 2003. The seep was not dry, but the level was so low that it was not flowing out of the pipe, which is the usual measuring point. It has been previously noted that flow measurements at the seeps are subject to considerable temporal variability. Therefore, measurements will continue as scheduled.

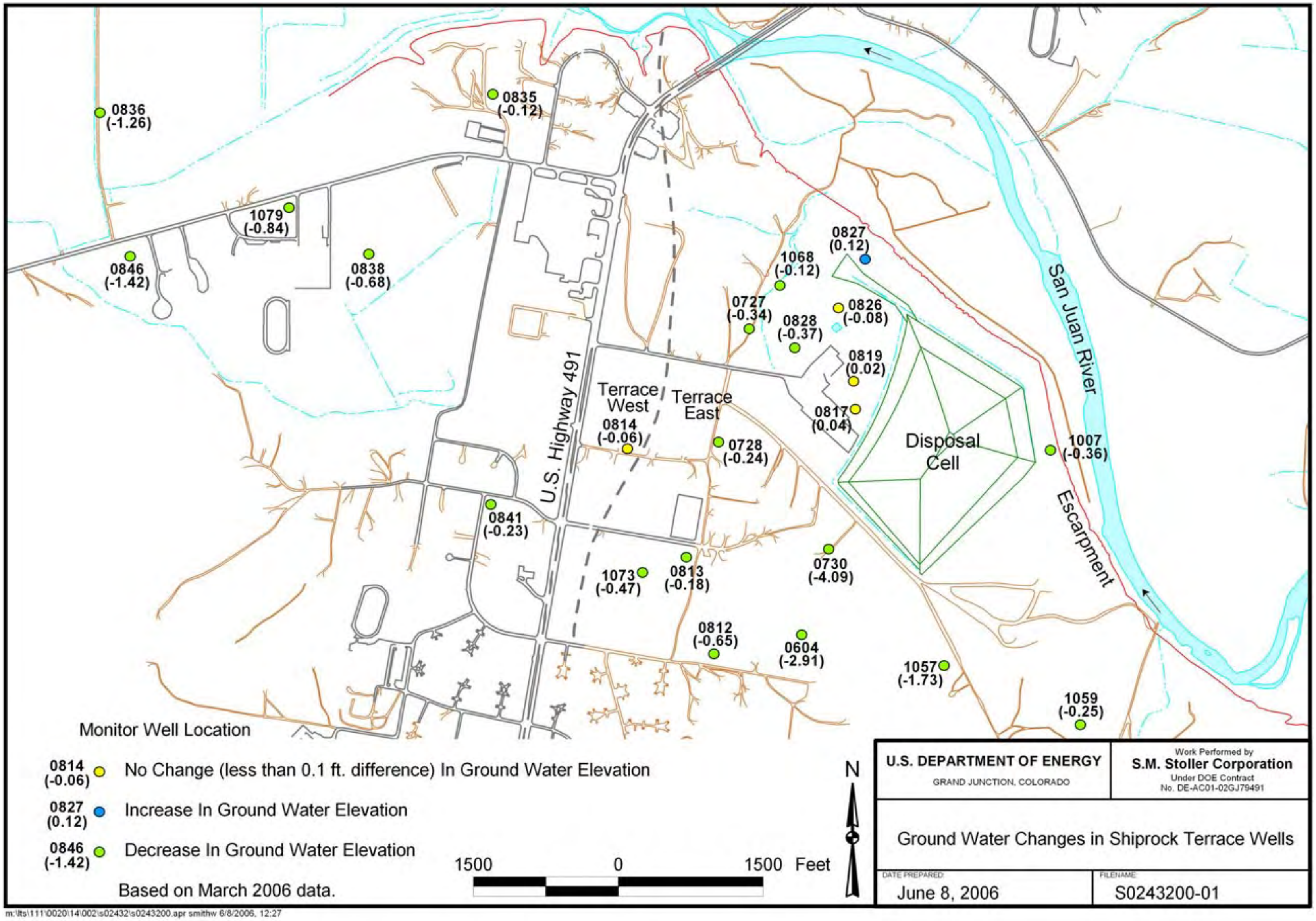


Figure 2–21. Terrace Ground Water Elevation Changes from Baseline to Current Conditions

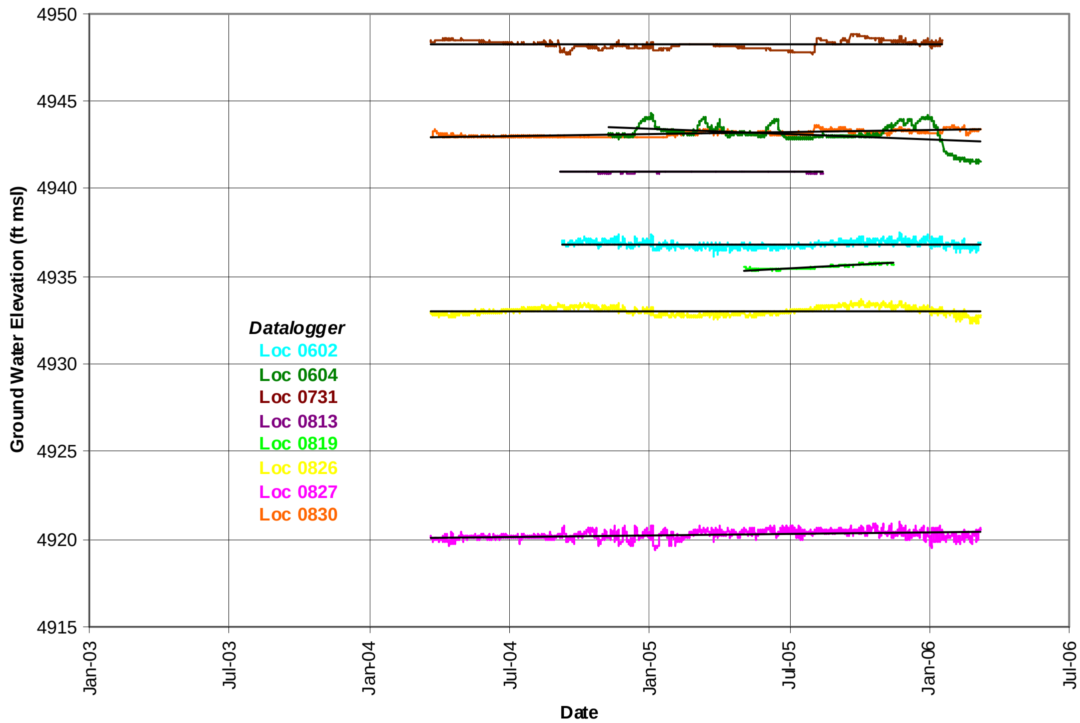


Figure 2–22. Terrace East Datalogger Ground Water Elevations

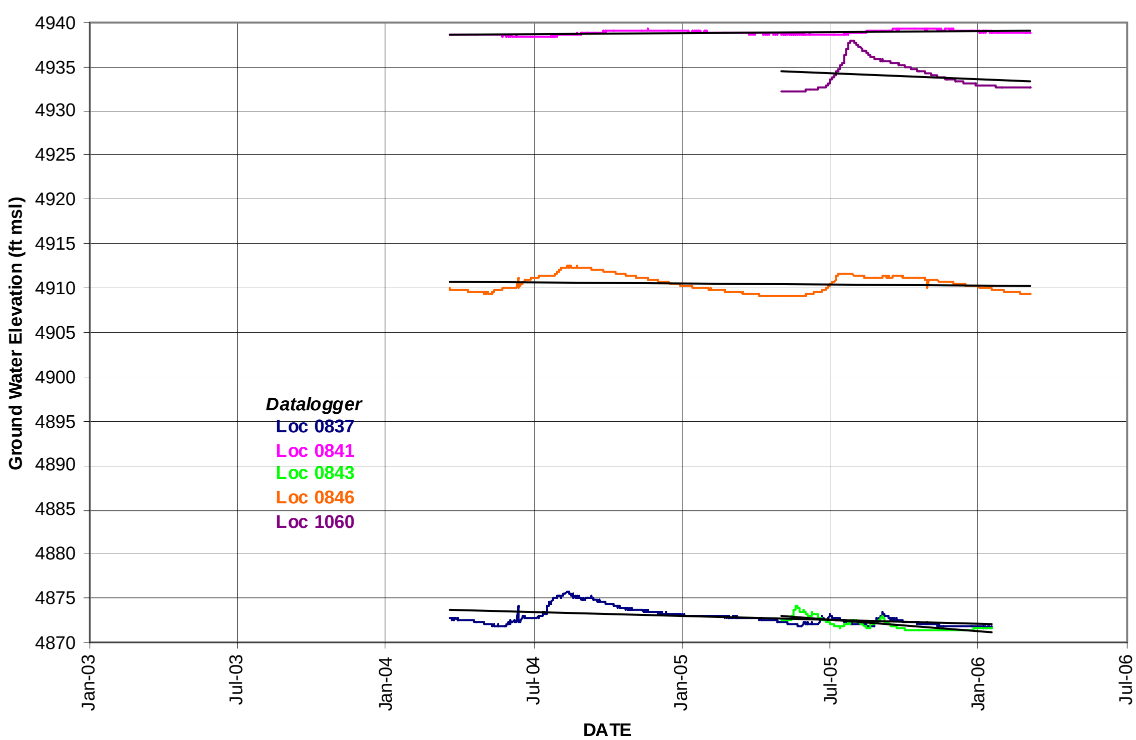


Figure 2–23. Terrace West Datalogger Ground Water Elevations

2.2.3 Drain Flow Rates

As discussed in the Baseline Performance Report (DOE 2003), the flow rates of the pumps removing water from the drains installed in Bob Lee and Many Devils Washes were expected to decrease as ground water levels in the terrace declined. The average pumping rate from Bob Lee Wash during the performance period was 3.34 gpm, fluctuating from 5.10 gpm in April 2005 to 2.20 gpm in March 2006. The average pumping rate from Many Devils Wash during the performance period was 1.21 gpm, fluctuating from 0.39 gpm in August 2005 to 1.60 gpm in May 2005 and March 2006.

The pumping rates at both washes do not support the expectation that discharges to the drains are decreasing in response to decreasing terrace ground water levels. It is too early in the performance evaluation process to understand why a decreasing trend in pumping rates has not occurred.

3.0 Remediation System Performance

The following sections provide a brief description of the components of the floodplain and terrace ground water remediation systems and summarize their performance during the current reporting period.

3.1 Floodplain Remediation System

The objective of the floodplain ground water extraction system is to reduce the mass of COCs in alluvial ground water near the San Juan River. Pumping is focused at this location to lessen exposure risk to aquatic life. All ground water collected from the floodplain extraction wells is piped south to the terrace where it feeds into the evaporation pond. A more complete description of the floodplain extraction system is presented in the Baseline Performance Report (DOE 2003).

3.1.1 Extraction Well Performance

The floodplain remediation system initially consisted of wells 1075 and 1077. These wells were drilled to approximately 20 ft below ground surface and had saturated alluvial thicknesses of 8 to 10 ft. After nearly 4 months of pumping, neither well was producing more than 3 gpm, far below the goal of 10 to 20 gpm per well. Both wells were re-developed a number of times in an attempt to increase the extraction rates. Ultimately, well 1075 was replaced with well 1089, which was installed just north of 1075 using alternative methods. Specifically, well 1089 was constructed using a slotted culvert placed in a trench excavated to bedrock. After installation of the culvert, the pump was removed from well 1075 and placed inside the new well. During the current period, well 1077 was also replaced with a culvert-type well (1104), which started operation in December 2005.

Figure 3–1 presents measured pumping rates and the cumulative volume of extracted ground water at well 1089 from April 2005 to March 2006. Elevated pumping rates during early spring 2005 are attributed to the higher river stage of the San Juan River at that time. The higher river stage during the spring produces an increased saturated thickness and, consequently, more available drawdown in the pumping well. By the end of March 2006, well 1089 had removed just over 8,000,000 gallons of water from the floodplain ground water system since the start of operations in March 2003. Approximately 2,600,000 gallons of water were removed during this performance period at an average pumping rate of 4.68 gpm.

During the period from April 2005 through December 2005, well 1077 produced approximately 240,000 gallons of water at an average pumping rate of 0.91 gpm. This brings the total volume of extracted ground water from this well to approximately 820,000 gallons (Figure 3–2). Well 1104 started pumping ground water in December 2005 and has currently produced approximately 180,000 gallons of water at an average pumping rate of 1.19 gpm (Figure 3–3).

During the 3-year period since the start of the remediation system, just over 3,000,000 gallons of ground water have been extracted from the alluvial aquifer, at an average pumping rate of 2.26 gpm.

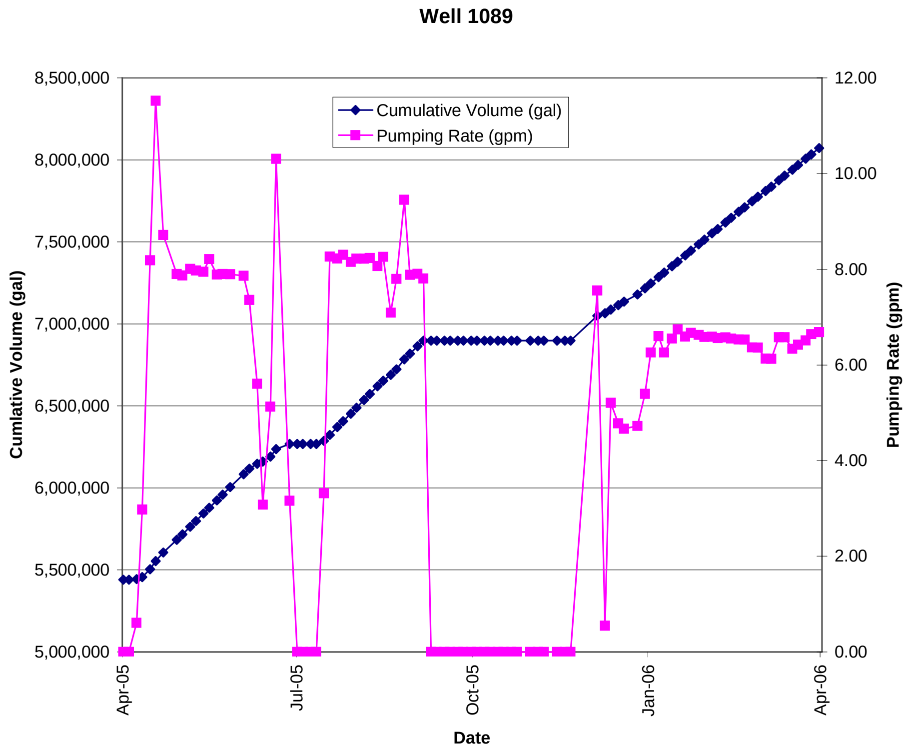


Figure 3–1. Well 1089 Pumping Rate and Cumulative Ground Water Volume Extracted

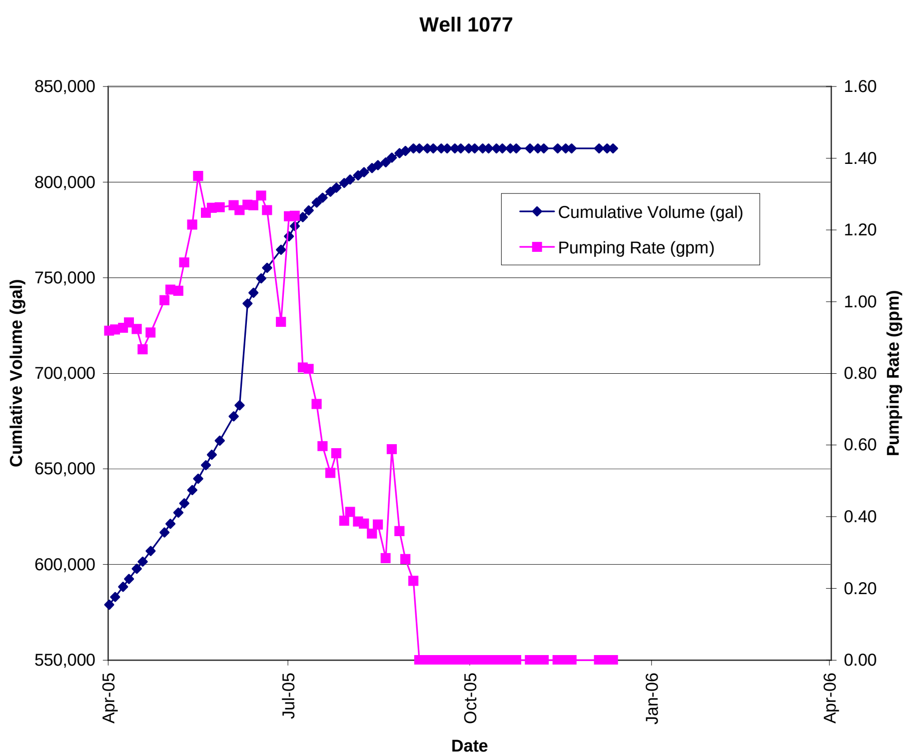


Figure 3–2. Well 1077 Pumping Rate and Cumulative Ground Water Volume Extracted

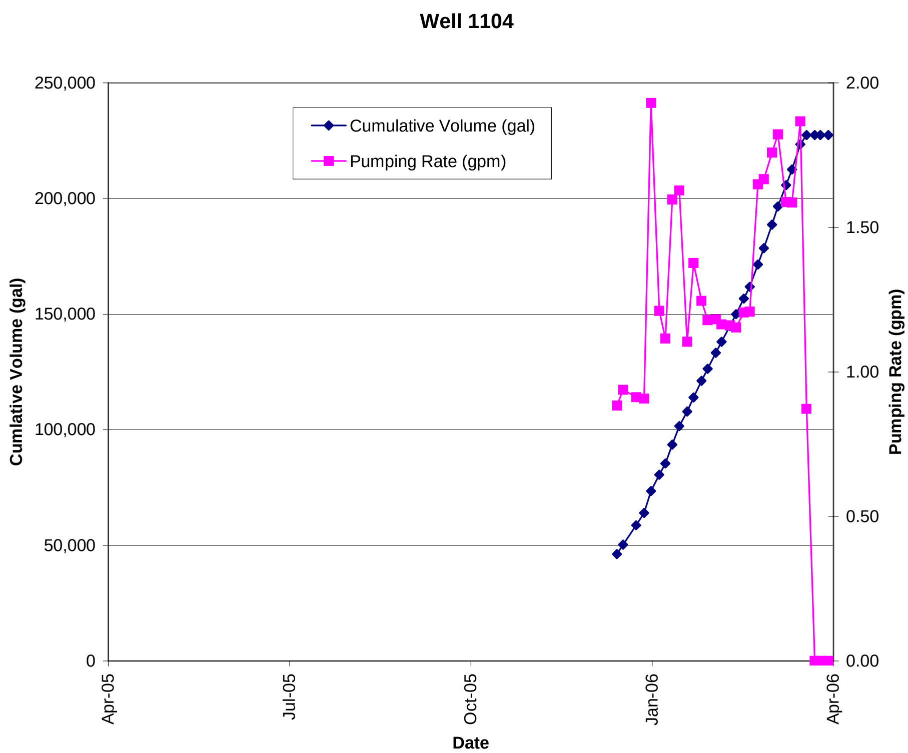


Figure 3–3. Well 1104 Pumping Rate and Cumulative Ground Water Volume Extracted

3.1.2 Floodplain Drain System Performance

Two drainage trenches were recently installed in the floodplain just below the escarpment (Figure 1–1). Data are not available for pumping rates and cumulative volume extracted from the trenches at this point. These data will be included in the next annual report.

3.2 Terrace Remediation System

The objective of the terrace remediation system is to remove ground water from the south part of the area so that current exposure pathways at seeps and at Bob Lee and Many Devil Washes are eventually eliminated and flow of ground water from the terrace to the floodplain is reduced. Since ground water compliance for the terrace is based on hydrologic control, concentration standards for COCs do not apply. The terrace remediation system consists of four components: the extraction wells, the terrace drains (Bob Lee and Many Devils Washes), the evaporation pond, and the terrace outfall drainage channel diversion (Figure 1–1). A more complete description of the terrace extraction system is presented in the Baseline Performance Report (DOE 2003).

3.2.1 Extraction Well Performance

During the current period, the terrace remediation well field consisted of wells 0818, 1070, 1071, 1078, 1091, 1092, 1093, and 1094. Because of low yields in the current well field, two additional extraction wells (1095 and 1096) were drilled in the terrace east system during March 2005

(Figure 2–1). During three-day pumping tests, wells 1095 and 1096 produced 2.8 gpm and 1.3 gpm, respectively. Both of these wells were brought on line during December 2005, at which time pumping from well 1094 was discontinued because of the low extraction rate from this well.

The pumping rates and corresponding ground water volumes removed from wells 0818, 1070, 1071, 1078, 1091, 1092, 1093, 1094, 1095, and 1096 from April 2005 through March 2006 are presented in Figure 3–4 through Figure 3–12, respectively. Measured pumping rates and corresponding volumes of ground water removed from the terrace ground water extraction wells during the recent performance period are available in the database at the DOE Office in Grand Junction, Colorado. Table 3–1 compares each well's current-period and previous-period average pumping rate and total ground water volume removed. The current-period average pumping rates ranged from 0.02 (well 1071) to 1.37 gpm (well 1095), and the total ground water volume removed from each well during this period ranged from 12,411 (well 1071) to 348,931 gallons (well 0818). The cumulative total volume removed during the current period was approximately 15 percent more than during the previous reporting period. This increase is mainly attributed to the addition of 2 new extraction wells (1095 and 1096) during the period.

Table 3–1. Terrace Extraction Well Average Pumping Rate and Total Ground Water Volume Removed

Well	Previous Period (April 1, 2004, through March 31, 2005)		Current Period (April 1, 2005, through March 31, 2006)	
	Average Pumping Rate (gpm)	Total Ground Water Volume Removed (gallons)	Average Pumping Rate (gpm)	Total Ground Water Volume Removed (gallons)
0818	1.05	527,905	0.69	348,931
1070	0.19	98,885	0.12	60,868
1071	0.02	11,274	0.02	12,411
1078	0.38	183,144	0.45	241,098
1091	0.08	38,024	0.06	30,381
1092	0.13	65,129	0.11	58,285
1093	0.18	91,432	0.09	49,141
1094	0.01	4,818	0	0
1095			1.37	193,204
1096			1.35	182,918
Total	**2.04**	**1,020,611**	**4.26**	**1,177,237**

3.2.2 Terrace Drain System Performance

The terrace extraction system collects seepage from Bob Lee and Many Devils Washes using subsurface interceptor drains. These drains, which consist of perforated pipe surrounded by drain rock and are lined with impermeable geomembrane and geotextile filter fabric, are offset from the centerline of each wash to minimize infiltration of surface water. All water collected by these drains is pumped through a pipeline to the evaporation pond.

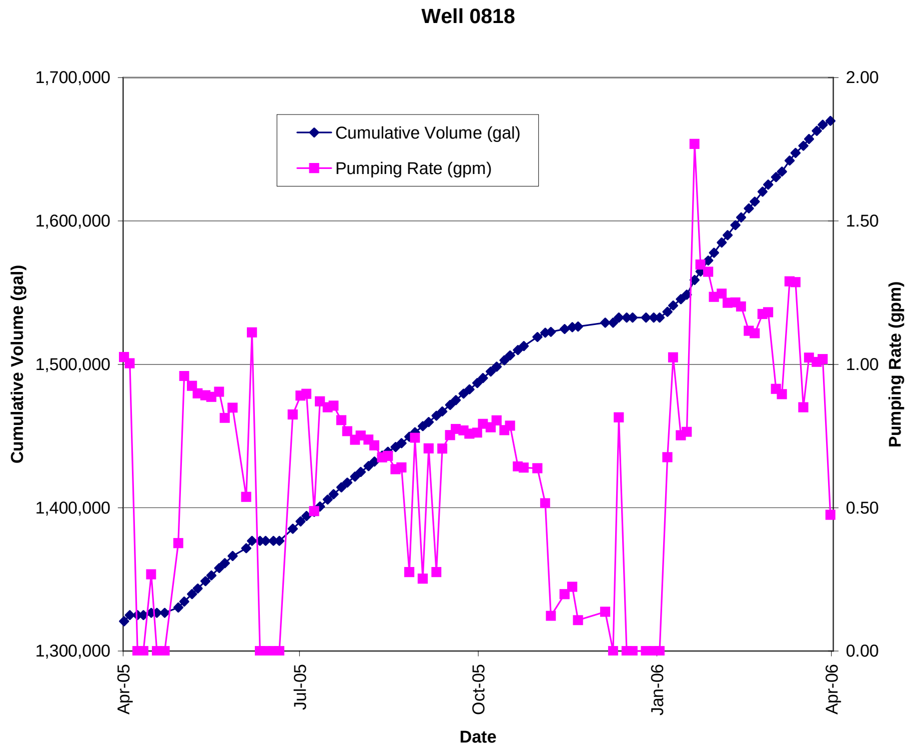


Figure 3–4. Well 0818 Pumping Rate and Cumulative Ground Water Volume Extracted

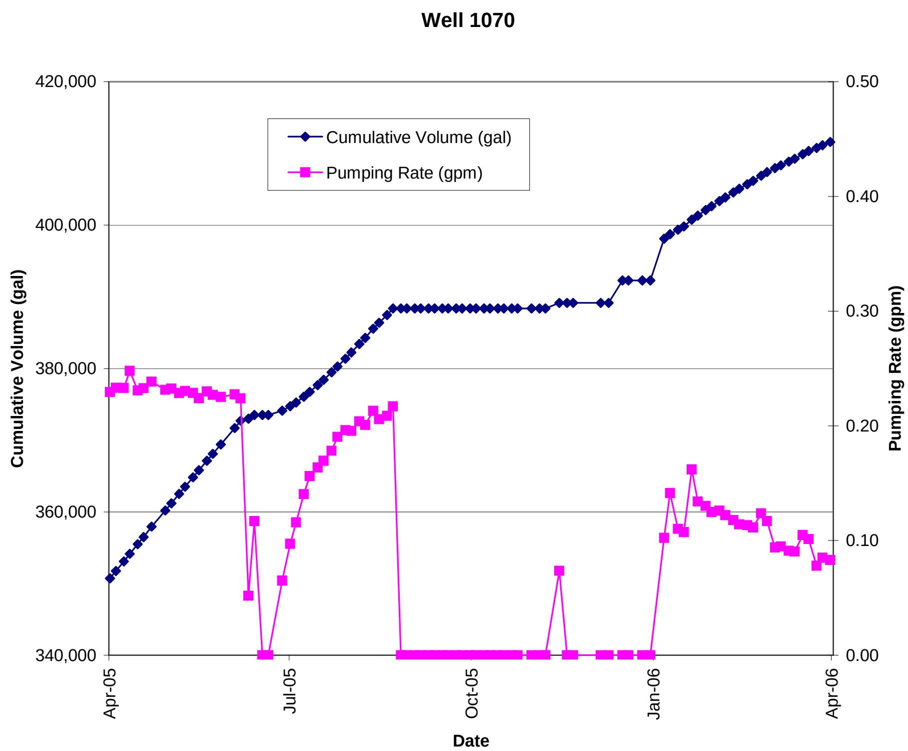


Figure 3–5. Well 1070 Pumping Rate and Cumulative Ground Water Volume Extracted

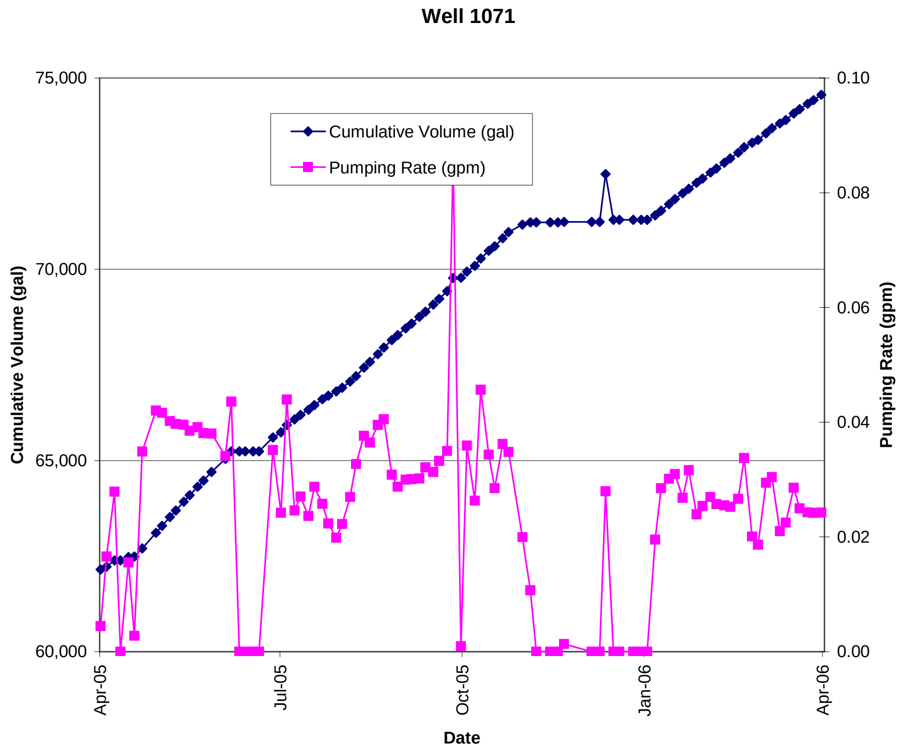


Figure 3–6. Well 1071 Pumping Rate and Cumulative Ground Water Volume Extracted

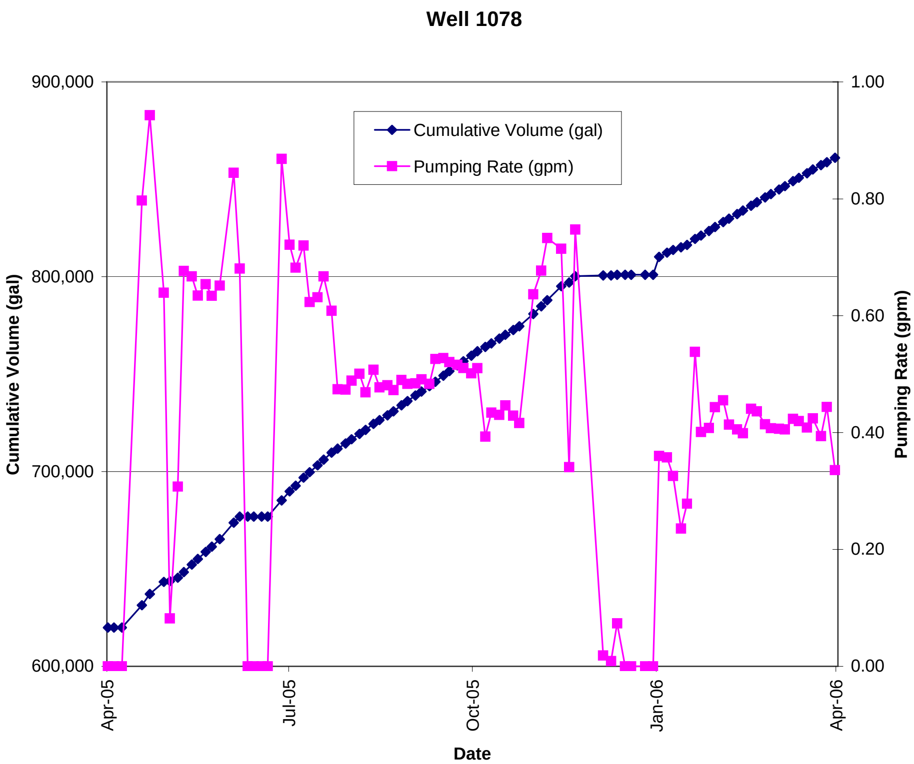


Figure 3–7. Well 1078 Pumping Rate and Cumulative Ground Water Volume Extracted

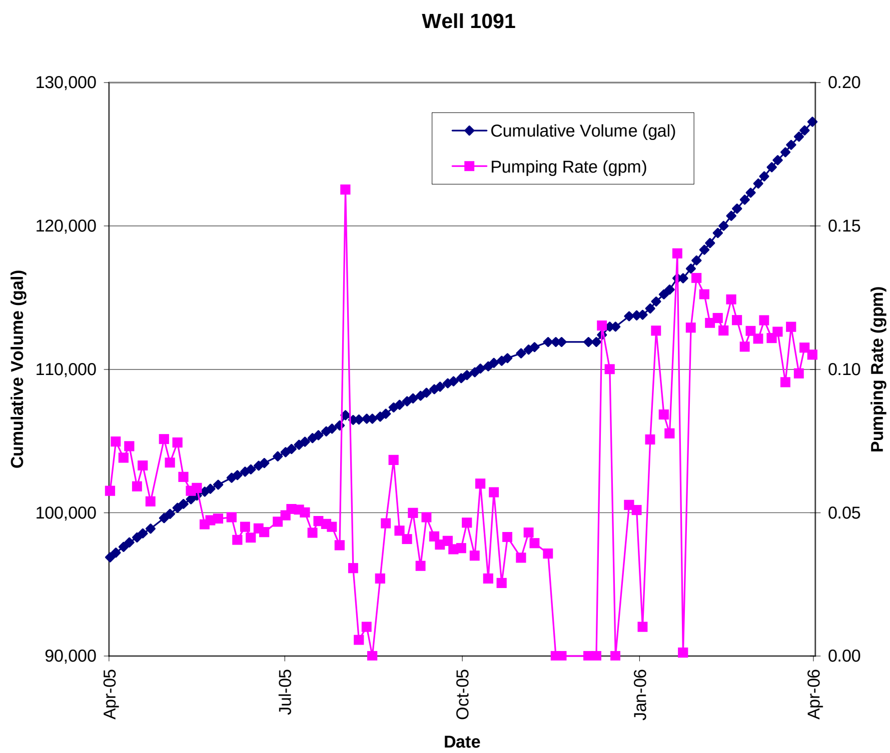


Figure 3–8. Well 1091 Pumping Rate and Cumulative Ground Water Volume Extracted

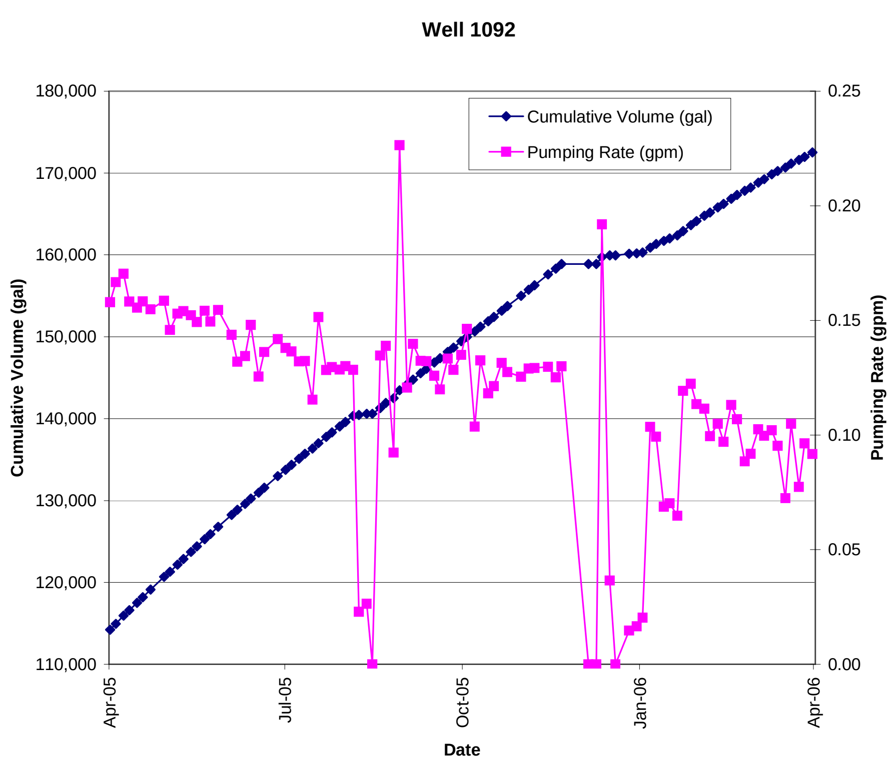


Figure 3–9. Well 1092 Pumping Rate and Cumulative Ground Water Volume Extracted

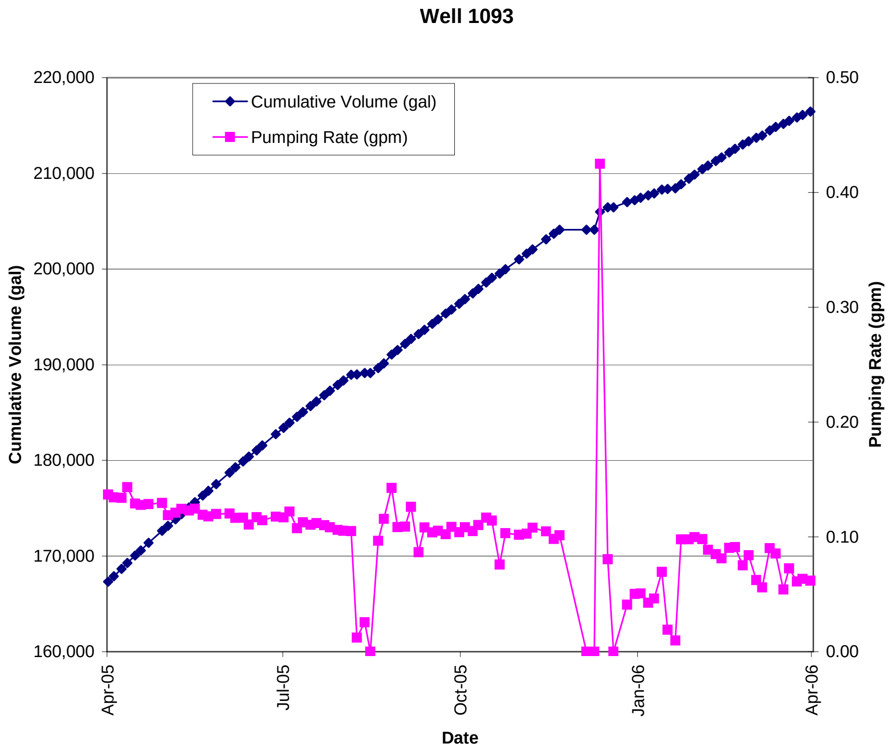


Figure 3–10. Well 1093 Pumping Rate and Cumulative Ground Water Volume Extracted

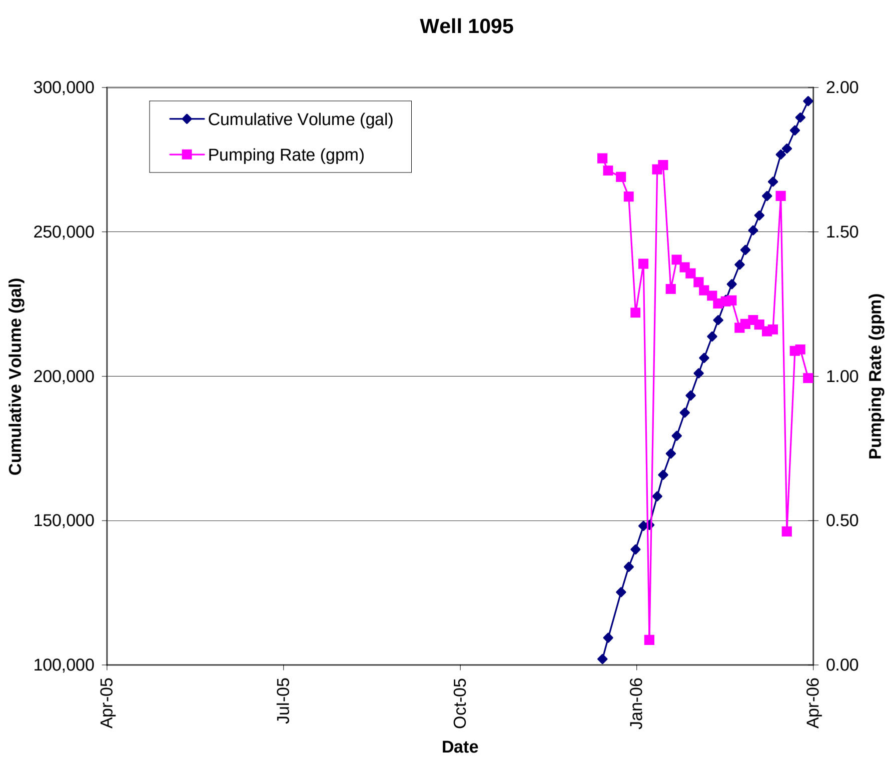


Figure 3–11. Well 1095 Pumping Rate and Cumulative Ground Water Volume Extracted

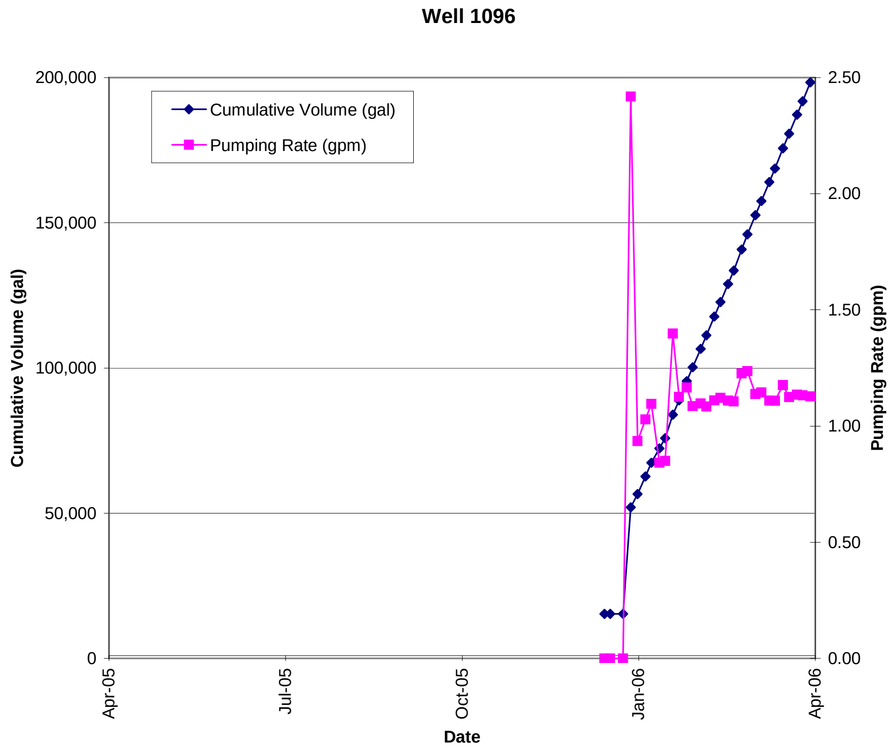


Figure 3–12. Well 1096 Pumping Rate and Cumulative Ground Water Volume Extracted

Extraction rates and cumulative flow volumes for the pump installed in the Bob Lee Wash (location 1087) drain are presented in Figure 3–13. During the current performance period, the average pumping rate from Bob Lee Wash was 3.34 gpm, and approximately 1,690,000 gallons of water were removed by the ground water interceptor drain.

The pumping rates and volume of water removed from the ground water interceptor drain in Many Devils Wash (location 1088) are presented in Figure 3–14. During the current performance period, the average pumping rate from Many Devils Wash was 1.21 gpm, and approximately 640,000 gallons of water were removed by the ground water interceptor drain.

3.2.3 Evaporation Pond

The selected method for treating ground water from the interceptor drains and extraction wells is solar evaporation. The contaminated ground water is pumped to a lined evaporation pond in the south part of the radon cover borrow pit area (Figure 1–1). Depth of water in this 11-acre pond was approximately 1 ft in March 2006, leaving approximately 7 ft of unfilled pond capacity.

Approximately 47 percent of the influent liquids entering the evaporation pond come from the floodplain aquifer, leaving approximately 53 percent of the inflow to come from the terrace ground water system. As of the end of this reporting period, approximately 20,000,000 gallons of water had been pumped to the evaporation pond from all sources. The terrace contribution includes the extraction wells, Bob Lee Wash, and Many Devils Wash. Figure 3–15 presents the total volume of water transported to the pond, and the relative contributions from the floodplain and terrace systems.

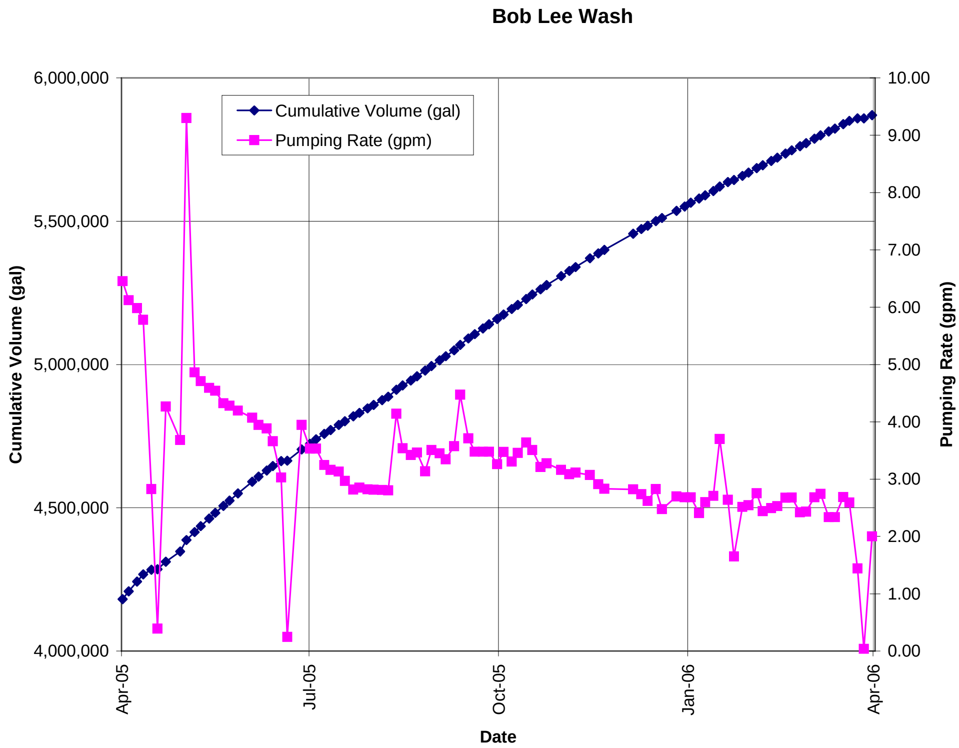


Figure 3–13. Bob Lee Wash Pumping Rate and Cumulative Ground Water Volume Extracted

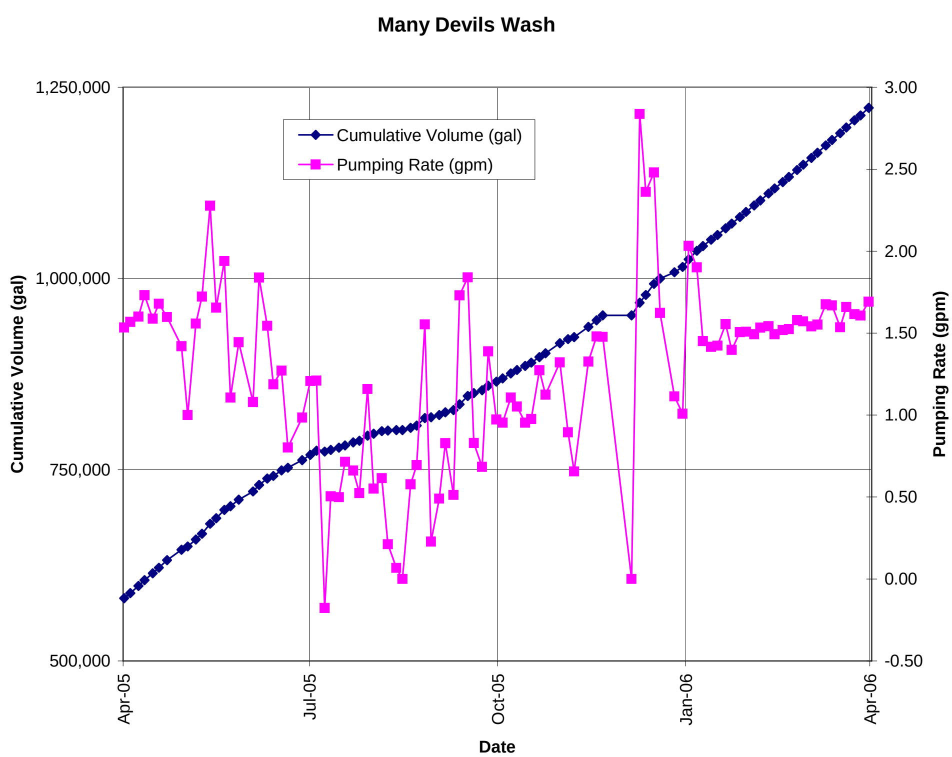


Figure 3–14. Many Devils Wash Pumping Rate and Cumulative Ground Water Volume Extracted

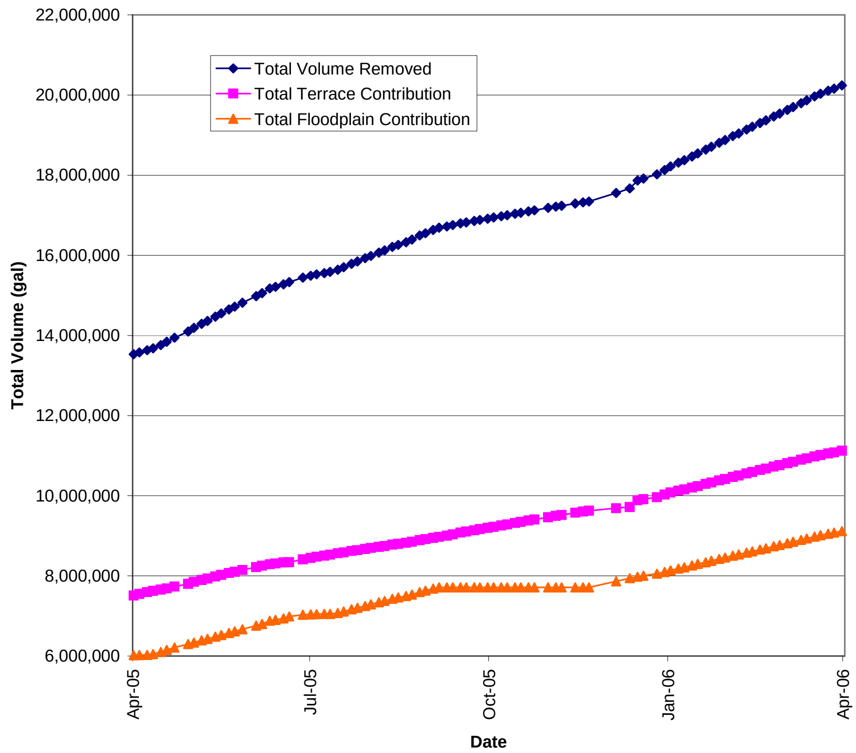


Figure 3–15. Total Ground Water Volume Transported to the Evaporation Pond

The estimated masses of sulfate, nitrate, and uranium entering the evaporation pond from the alluvial extraction wells and the terrace ground water extraction system (i.e., extraction wells and the ground water interceptor drains in Bob Lee Wash and Many Devils Wash) are summarized in Table 3–2. Because of its high concentration in both the alluvial and terrace ground water systems, sulfate is the dominant COC (in terms of mass) that enters the evaporation pond. During the current performance period the estimated mass of selected COCs pumped to the evaporation pond was 681,908 pounds of sulfate, 25,691 pounds of nitrate, and 46.6 pounds of uranium. This is the first performance report that includes an estimate of the mass of COCs entering the evaporation pond from the ground water extraction system. The estimate was computed from the average COC concentrations and the monthly flows at each well.

3.2.4 Terrace Drainage Channel Diversion

Storm-water runoff from the disposal cell is designed to drain northwest to a rock-lined energy dissipation area, eventually reaching upper Bob Lee Wash. The so-called "outfall drainage channel diversion" conveys surface water to the lower part of Bob Lee Wash from the energy dissipation area. The extent to which the energy dissipation area functions as a point source of recharge to the terrace is unclear.

Table 3–2. Estimated Total Mass of Selected Constituents Pumped from Terrace and Floodplain

Location	Annual cumulative volume (gal)	Percent contribution	Nitrate - average concentration (mg/L)	Nitrate mass contribution per location (mg/L)	Nitrate mass cumulative (kg)	Nitrate mass cumulative (lb)[a]	Sulfate - average concentration (mg/L)	Sulfate mass contribution per location (mg/L)	Sulfate mass cumulative (kg)	Sulfate mass cumulative (lb)	Uranium - average concentration (mg/L)	Uranium mass contribution per location (mg/L)	Uranium mass cumulative (kg)	Uranium mass cumulative (lb)
0818	348931	10	1600	2113	2113	4659	13000	17169	17169	37851	0.140	0.185	0.185	0.408
1070	60868	2	780	180	2293	5055	15000	3456	20625	45470	0.130	0.030	0.215	0.474
1071	12411	0	2350	110	2403	5298	3700	174	20799	45853	0.100	0.005	0.220	0.484
1078	241098	7	670	611	3015	6646	14000	12776	33575	74018	0.135	0.123	0.343	0.756
1091	30381	1	1650	190	3204	7064	12000	1380	34954	77061	0.120	0.014	0.357	0.786
1092	58285	2	1700	375	3579	7891	13000	2868	37822	83383	0.120	0.026	0.383	0.845
1093	49141	1	3350	623	4202	9265	5450	1014	38836	85618	0.079	0.015	0.398	0.877
1095	193204	6	1730	1265	5468	12054	10900	7971	46807	103191	0.110	0.080	0.478	1.054
1096	182918	5	1730	1198	6665	14694	10900	7547	54354	119828	0.110	0.076	0.554	1.222
1087 (blw)[b]	1689210	48	375	2398	9063	19980	7850	50190	104544	230477	0.590	3.772	4.327	9.539
1088 (mdw)[c]	641050	18	715	1735	10798	23805	19500	47314	151858	334786	0.185	0.449	4.776	10.528
1089	2632440	86	49	488	11286	24881	12500	124547	276405	609363	1.200	11.957	16.732	36.888
1077	238730	8	270	244	11530	25419	22000	19879	296284	653189	2.900	2.620	19.353	42.665
1104	181143	6	180	123	11653	25691	19000	13027	309311	681908	2.600	1.783	21.135	46.595
Total terrace	3507497	53												
Total floodplain	3052313	47												
Total pond	6559810													
Notes >>>														
(1) Annual cumulative volumes derived from data used to generate plots in Figures 3-1 through 3-14 >>> from 01 April 2005 through 31 March 2006.														
(2) Mass in kg derived >>> annual volume x 3.785 x average concentration x (1/1000000) >>> conversion to pounds = kg x 2.2046														
(3) No data available in SEEPro for 1095 and 1096 >> used average of terrace extraction wells for average concentration.														

[a]lb = pounds
[b]b/w = Bob Lee Wash
[c]mdw = Many Devils Wash

4.0 Performance Summary

This report contains an assessment of the ground water remediation system at the DOE−LM site in Shiprock, New Mexico, for the performance period of April 2005 through March 2006. The performance period marks the end of the third year of operation of the ground water remediation system. Findings from the April 2005 through March 2006 evaluation of the floodplain and terrace remediation systems at the site are as follows:

- Ground water in the floodplain system is currently being extracted by two wells adjacent to the San Juan River north of the disposal cell. Two collection trenches were recently added to the system to enhance extraction of contaminated ground water from the system.
- Approximately 3,000,000 gallons of ground water were extracted from the floodplain aquifer system during this performance period for a total of approximately 9,000,000 gallons extracted since March 2003.
- A significant mass of COCs is being intercepted by the remediation system that would otherwise discharge to the San Juan River. This contaminated ground water is being transported to the evaporation pond on the terrace just south of the disposal cell.
- Relative to baseline conditions, levels of some COCs in ground water in the floodplain aquifer appear to be decreasing, although there is a certain amount of periodic variation in concentrations of constituents that is not necessarily indicative of the overall longer-term trend. Concentrations of constituents in ground water in the floodplain alluvium are affected by seasonal changes in climate, river stage influence, discharge of ground water from the artesian well that flows into Bob Lee Wash and then onto the floodplain, and pumping rates of the extraction wells.
- Concentrations of nitrate (as NO_3) and uranium in surface water in the San Juan River adjacent to the site have remained below background benchmark levels during this period.
- Ground water in the terrace system is currently being extracted from nine wells and two drainage trenches in Bob Lee and Many Devils Washes.
- Approximately 3,600,000 gallons of ground water were extracted from the terrace system during this performance period for a total of approximately 11,000,000 gallons extracted since March 2003.
- Actual withdrawals of ground water from the terrace system are lagging behind model-projected ground water withdrawals. As identified in the GCAP (DOE 2002), the total pumping rate for the terrace well field was estimated to range from 4 gpm to 7.5 gpm and was assumed to require 3 to 4 extraction wells. As presented in Table 3–1 of this report, the average pumping rate for the well field during the current performance period was 4.26 gpm; during the previous period, the pumping rate was 2.04 gpm. Nine extraction wells are currently being used to produce these yields.
- Two new wells (1095 and 1096) were installed in the terrace east well field during March 2005 and came on line during December 2005. These wells have produced at a pumping rate of about 1.36 gpm each and have increased the total production rate close to the levels that were assumed in the GCAP design.

- The estimated dissolved masses of sulfate, nitrate, and uranium removed from the floodplain and terrace east well fields were 681,908 pounds, 25,691 pounds, and 46.6 pounds, respectively.
- Even though rates of ground water discharge at seeps 0425 and 0426 have significantly decreased during this performance period, measurements display considerable temporal variability and are not recommended indicators of long-term changes in flow rates. It is possible that spatially and temporally variable recharge on the terrace affects the varying seep rates.

5.0 Recommendations

The following recommendations are provided to help improve the performance and evaluation of the Shiprock remediation system:

- The floodplain extraction system appears to be functioning as anticipated. The addition of the two trenches at the base of the escarpment will enhance removal of contaminant mass from ground water in the alluvium. No additions to the floodplain system are deemed necessary at this time.
- The terrace extraction system is operating adequately with the addition of the two new extraction wells. Water levels are gradually declining over time. No additions to this system are recommended at this time.
- Presentation of three-point analysis of ground water level data have been discontinued, as they do not represent any additional value to interpretation and assessment of the performance standards for remediation at the site.
- To improve the analysis of ground water response to precipitation events, full functionality of the recording precipitation gauge at the Navajo Tribal Utility Authority trailer should be maintained.
- As the pumping capability of the remediation system increases, it will become more important to monitor the fluid level in the evaporation pond. A staff gauge or other means of monitoring water levels in the pond should be installed.
- The performance of the terrace remedial action is currently tied to the reduction of flow from springs 0425 and 0426 and perhaps the elimination of flow at these locations. As a consequence, the discharge from these springs should be monitored with totalizing flow meters. Records from the devices should be analyzed and included as part of the annual performance evaluation. Given the temporal variability in hydrologic conditions at the site, long-term trends in annual combined flow rates from the two seeps may be discernible.

End of current text

6.0 References

U.S. Department of Energy (DOE), 2000. *Final Site Observational Work Plan for the Shiprock, New Mexico, UMTRA Project Site*, Rev. 2, GJO−2001−169−TAR, MAC-GWSHP 1.1, U.S. Department of Energy Grand Junction Office, Grand Junction, Colorado, November.

———, 2002. *Final Ground Water Compliance Action Plan for Remediation at the Shiprock, New Mexico, UMTRA Project Site*, GJO−2001−297−TAR, MAC-GWSHP 1.9, U.S. Department of Energy Grand Junction Office, Grand Junction, Colorado, July.

———, 2003. *Baseline Performance Report for the Shiprock, New Mexico, UMTRA Project Site*, GJO−2003−431−TAC, U.S. Department of Energy Grand Junction Office, Grand Junction, Colorado, September.

———, 2004. *Refinement of Conceptual Model and Recommendations for Improving Remediation Efficiency at the Shiprock, New Mexico, Site*, GJO−2004−579−TAC, U.S. Department of Energy Grand Junction Office, Grand Junction, Colorado, March.

———, 2005. *Annual Performance Report April 2004 through March 2005 for the Shiprock, New Mexico, UMTRA Project Site*, DOE−LM/GJ933−2005, U.S. Department of Energy Grand Junction Office, Grand Junction, Colorado, September.

U.S. Environmental Protection Agency (EPA), 1999. *Health Effects from Exposure to High Levels of Sulfate in Drinking Water Study*, EPA 815-R-99-001, Office of Water, January.

End of current text