LMS/TUB/S07879

Annual Groundwater Report
April 2010 Through March 2011
Tuba City, Arizona, Disposal Site

July 2011

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Abbreviations

CFR	*Code of Federal Regulations*
DOE	U.S. Department of Energy
ft	feet
gpm	gallons per minute
lb	pounds
MCL	maximum concentration limit
mg/L	milligrams per liter
NNEPA	Navajo Nation Environmental Protection Agency
TDS	total dissolved solids

Executive Summary

This report evaluates the progress of groundwater remediation at the U.S. Department of Energy (DOE) Office of Legacy Management site near Tuba City, Arizona, for the period April 2010 through March 2011, and cumulatively since the start of remediation in 2002. The progress of water quality restoration is evaluated and reported annually.

The site is within the Navajo Nation and near Hopi Reservation land. A uranium-ore processing mill operated at the site from 1956 until 1966. DOE conducted surface remedial actions, consisting of encapsulating all solid waste within an on-site engineered disposal cell, between 1988 and 1990. A remnant plume of groundwater contamination, presumed to have originated from process water stored in solar evaporation ponds and slurry-impounded tailings during mill operation, extends beneath and off site approximately 1,500 feet to the south and southeast in the underlying sandstone aquifer.

The primary contaminants in groundwater are nitrate, uranium, and sulfate. DOE constructed a pump-and-treat (mechanical distillation) remediation system, operational by mid-2002, to remove these and other site-related contaminants from the aquifer and achieve water quality restoration goals established in the groundwater compliance action plan (DOE 1999). The plan indicated that removal of two pore volumes of groundwater within the contaminant plume, over 20 years of active remediation, would possibly suffice to meet those goals.

During the current review period (April 2010 through March 2011), close to 12 million gallons of contaminated groundwater were treated, yielding a total cumulative treatment volume of 350 million gallons, or about 29 percent of the total estimated volume of uranium-contaminated groundwater prior to remedial action. Major findings through the period are summarized below:

- Operation of the remediation system was suspended in October 2010 to allow for the upgrading and replacement of treatment system components (during this review period, the treatment system was operational for 79 days; extraction wells were periodically and briefly operated during the period to maintain a desired water level in the evaporation pond). The remediation system is scheduled to resume full operation in September 2011.
- Historically (excluding the recent shutdown period) the treatment plant has, overall, operated effectively and as intended. Treatment rate and efficiency, distillate quality, and return flow to the aquifer meet or exceed design objectives during normal operation.
- When the extraction system is fully operational, its current configuration captures the lateral region of maximum groundwater contamination and the full vertical extent to meet design objectives. Plume expansion into uncontaminated regions is not significant.
- Since plant shutdown, the water table has recovered by up to about 50 percent of the maximum drawdowns observed during active pumping.
- Groundwater monitoring results from February 2011, reflecting about 4 months without pumping, indicate no significant contaminant concentration rebound, expansion of the contaminant plume, or anomalous data in response to or before the suspension of remediation activity.
- Despite the measureable progress in groundwater treatment, as indicated by cumulative contaminant mass and volumes extracted from the aquifer, after 9 years of full-scale

operation, significant and widespread decreases in contaminant concentrations are not apparent.

- Groundwater monitoring results for nine new Navajo Nation monitoring wells installed in September 2010 indicate that the DOE site is not a contributor to alleged contamination at the non-DOE open dump site located about 5 miles west (crossgradient) of the site.
- Groundwater monitoring results from the nine new wells also indicate that groundwater beneath the non-DOE Highway 160 site, located immediately north (upgradient) of the DOE site, is not at risk from the DOE site.
- Groundwater samples collected from the seven Tuba City water supply wells in February 2011 indicated no impacts from the DOE site (iiná bá [Navajo Nation environmental consultant]/DOE 2011).
- Contamination at lower terrace wells (off site and farther downgradient) remains generally absent—with a few minor exceptions, constituent concentrations in these wells continue to be below restoration goals.

1.0 Introduction

1.1 Background Information

This report evaluates the progress of groundwater remediation at the U.S. Department of Energy (DOE) Office of Legacy Management site near Tuba City, Arizona, for the period April 2010 through March 2011, and cumulatively since the start of remediation in 2002. The progress of water quality restoration is evaluated and reported annually.

The site is located near Tuba City, Arizona, within the Navajo Nation and near Hopi Reservation land. A uranium-ore processing mill operated at the site from 1956 until 1966. DOE conducted surface remedial actions, consisting of encapsulating all solid waste within an on-site engineered disposal cell, between 1988 and 1990. A remnant plume of groundwater contamination, presumed to have originated from process water stored in solar evaporation ponds and slurry-impounded tailings during mill operation, extends beneath and off site approximately 1,500 feet (ft) to the south and southeast in the underlying sandstone aquifer.

The primary contaminants in groundwater are nitrate, uranium, and sulfate. DOE constructed a pump-and-treat (mechanical distillation) remediation system, operational by mid-2002, to remove these and other site-related contaminants from the aquifer with the objective of meeting water quality restoration goals established in the groundwater compliance action plan (DOE 1999). The action plan did not define a specific duration of active groundwater remediation to meet those goals.

1.2 Groundwater Remediation System

The groundwater remediation system currently comprises 37 extraction wells completed within the contaminated region of the aquifer. The extracted water is conveyed in underground piping to an on-site treatment plant, where it is distilled following ion exchange softener pretreatment. A lined solar evaporation pond receives the waste liquid (brine) and the softener regeneration waste. An infiltration trench located upgradient of the contaminant plume receives the treated water (distillate), where it is returned to the aquifer.

Operation of the remediation system was suspended in October 2010 to allow upgrading and replacement of treatment system components. DOE updated the preventive maintenance program and operating procedures to improve on-stream time. The remediation system is scheduled to resume operation in September 2011.

Six injection wells (wells 1003 through 1008; see Figure 2 for well locations), originally intended to create a hydraulic barrier downgradient of the contaminant plume by injecting a portion of the treated water, remain unused for that purpose because contamination does not extend to the area of those wells. Of the 37 extraction wells, eight wells (wells 1126 through 1133) were installed in summer 2004 to expand the capture zone of the original 25 wells (wells 1101 through 1125, installed in 1999). Monitoring wells 935, 936, 938, and 942 were converted to extraction wells in summer 2005.

Numerous groundwater monitoring wells that are used to track water quality and water level trends are situated within and surrounding the network of extraction wells. Figures 2a through 2c

depict the locations of extraction and monitoring wells and the primary features of the site. Figure 2a shows all well locations, Figure 2b shows monitoring wells only, and Figure 2c shows treatment system wells only. (These figures are referred to collectively as Figure 2.) Corresponding well completion information is provided in Appendix A.

Figures 2a and 2b also show the locations of monitoring wells installed by the Navajo Nation Environmental Protection Agency (NNEPA) in September 2010 (iiná bá/DOE 2011). DOE sampled six of these wells (wells NMW-1A, -6S, -7D, -8S, -9D) in February, along with the regularly scheduled biannual sampling of the site well network. NNEPA wells NMW-2A, -3A, and -4A were not sampled by DOE.

1.3 Groundwater Compliance Strategy

The groundwater compliance strategy for the Tuba City site, as defined in the *Phase I Ground Water Compliance Action Plan for the Tuba City, Arizona, UMTRA Site* (DOE 1999), is to achieve applicable cleanup levels through active remediation of those portions of the aquifer affected by previous site activities. Cleanup levels for the aquifer consist of restoration standards (requirements of Title 40 *Code of Federal Regulations* Part 192 [40 CFR 192], "Health and Environmental Protection Standards for Uranium and Thorium Mill Tailings") and restoration goals (cleanup levels requested by the Navajo Nation but not required by 40 CFR 192).

Groundwater contaminants requiring active remediation at the site are molybdenum, nitrate, selenium, sulfate, and uranium (DOE 1999). The focus of the figures and data analyses presented in this report are nitrate, uranium, and sulfate, because these contaminants are most widespread and contribute most to potential risk. Restoration standards correspond to a maximum concentration limit (MCL) in groundwater as established by Subpart A of 40 CFR 192. Sulfate is not regulated by 40 CFR 192; however, a restoration standard was adopted for this constituent because it is present in site groundwater at concentrations that could cause excess potential risk (DOE 1999). Groundwater remediation targets for the site are presented in Table 1.

Table 1. Groundwater Remediation Targets

Constituent/Property	Cleanup Level	Baseline Concentrations in Plume
Nitrate[a] as NO_3	44 mg/L as NO_3	840–1,500 mg/L as NO_3
Molybdenum[a]	0.10 mg/L	0.01–0.58 mg/L
Selenium[a]	0.01 mg/L	0.01–0.10 mg/L
Uranium[a]	30 pCi/L (0.044 mg/L) U-234 + U-238	0.3–0.6 mg/L
Sulfate[a]	250 mg/L	1,700–3,500 mg/L
Total Dissolved Solids (TDS)[b]	500 mg/L	3,500–10,000 mg/L
Chloride[b]	250 mg/L	20–440 mg/L
pH[b]	6.5–8.5	6.3–7.6
Corrosivity[b]	not corrosive	not applicable

[a] Restoration standard
[b] Restoration goal
mg/L = milligrams per liter
pCi/L = picocuries per liter

Source: DOE 1999

1.4 Performance Monitoring and Reporting

The effectiveness of the remediation system in removing contaminants from the aquifer and progressing toward cleanup levels is evaluated yearly, mainly on the basis of groundwater monitoring conducted in July or August and February of each year. During these events, samples are collected at monitoring wells for water quality analysis, and water levels are measured. The data are then compared to baseline conditions determined between 1998 and March 2002 (DOE 2003) to evaluate the capture zone of the extraction system, to evaluate plume movement within the aquifer, and to evaluate contaminant concentration trends.

Most of the extraction wells are sampled only during the July–August events. This is also the case for several distal monitoring wells that have no history of contamination. Other information used in evaluating the effectiveness of the groundwater remediation system includes monitoring data collected during routine operation of the treatment plant, such as (1) continuous flow metering for each extraction well, (2) continuous flow metering of the bulk influent and all outflow streams, (3) approximately weekly determination of bulk inflow and distillate composition through composite sampling, and (4) approximately monthly analysis of groundwater composition at each extraction well.

1.5 Hydrogeologic Setting

1.5.1 Site Conceptual Model and Groundwater Flow

The Tuba City site lies on the middle of three alluvial terraces formed during ancestral flow in Moenkopi Wash. The wash is located about 1.5 miles southeast of the former processing site (see Figure 2 for location of Moenkopi Wash). The terraces are composed of thin (≤20 ft) surface deposits of coarse, semi-indurated, Quaternary alluvium. Loose dune sand and silt mantle the terraces at most locations. The terrace and dune deposits unconformably overlie the regionally extensive Navajo Sandstone, a massively cross-bedded, friable, fine-grained to very fine grained sandstone and siltstone of Jurassic age. Escarpments that separate the terraces are formed by cliffs of the Navajo Sandstone. The regional dip of the bedrock is about 1 degree to the northeast.

At about 200 ft below ground, the massive eolian dune deposits typifying "classic" Navajo Sandstone become interbedded with fine-grained alluvium more typical of the deeper Kayenta Formation. This "intertonguing interval" is 400 to 450 ft thick. Occasional thin (≤2 ft), resistant limestone beds, which are deposits from relict playa lakes, are interspersed throughout both the classic and intertonguing intervals. The Kayenta Formation consists primarily of 100 ft or more of less-resistant, thin-bedded, red silt and fine sand and lacks the characteristic cross-beds of the Navajo Sandstone. Figure A–1 in Appendix A depicts a conceptual model of the site hydrogeology to illustrate the relationship of surface topography, subsurface geology, and groundwater flow.

Groundwater beneath the Tuba City site occurs in the regionally extensive "N" multiple-aquifer (Cooley et al. 1969), which in the site area comprises the classic and intertonguing intervals of the Navajo Sandstone. Because of the fine-grained composition of the Kayenta Formation locally, it is not water bearing and is considered the base of the N-aquifer in the site area. The local water table occurs within the Navajo Sandstone; the terrace and dune deposits in the site area are not saturated. Groundwater saturation extends from the water table, about 50 to 60 ft

below ground surface on the upper and middle terraces, to the contact with the Kayenta Formation, accounting for a saturated thickness on the order of 500 ft.

Except for the local effects of groundwater withdrawal at the site, groundwater flow is south to southeast to Moenkopi Wash. There, regional aquifer discharge is expressed as a laterally extensive (miles) spring zone near the exposed base of the intertonguing interval. Local discharge of groundwater from higher in the formation occurs in some areas, as evidenced by scattered bands of desert phreatophytes that typically occur near the base of the escarpment between the middle and lower terraces. One such area is noted in Figure 2 as the "greasewood area," where the depth to water is only about 20 ft.

1.5.2 Vertical Discretization of the N-Aquifer

In the absence of laterally continuous marker beds in the Navajo Sandstone, for this project the subsurface is discretized into 50-ft intervals, or "horizons," each with a letter designation. This designation is a convenient reference for evaluating site hydrogeology and depth of contamination. Ground surface of the middle terrace, nominally 5,050 ft in elevation, marks the top of the uppermost horizon, Horizon A (Figure A–1). Horizons A, B, C, and possibly D span the interval of classic Navajo Sandstone beneath the site. The depths of Horizons E through J include the regions of the intertonguing interval.

Horizons K, L, and M include the lower intertonguing interval and possibly the upper portion of the Kayenta Formation. Because of surface topography, the uppermost horizon on the lower terrace progresses from Horizon C to D, north to south. The steep topography at Moenkopi Wash intersects Horizons E through G. Contamination of the aquifer is limited in depth; therefore, groundwater remediation at the site focuses primarily on the upper 250 ft of the bedrock aquifer (Horizons A through E).

The stratigraphic relationships to aquifer horizons are shown in Figure A–1 of Appendix A. In Figure 2, color-coding identifies the corresponding horizon in which the midpoint of the well screen is located for extraction wells (round symbols) and monitoring wells (square symbols). Well screen depth in relation to aquifer horizon and elevation for all project wells is shown schematically in Figure A–2 of Appendix A. Table A–1 of Appendix A includes additional well completion information such as screen length and screen intake elevations.

2.0 Treatment and Extraction Systems

2.1 Bulk Treatment Parameters

During the current review period of April 2010 through March 2011, the treatment plant operated for 79 of 365 total days[1], yielding a net on-stream factor of 21.6 percent. This on-stream percentage decreased from 64 percent (235 operational days) reported for 2009–2010. The decrease in the net on-stream factor is due to a number of factors, the primary one being the plant

[1] Operational days include only the days when the plant was fully in service and returning treated water to the aquifer. The plant is not considered to be operational on startup days, when equipment is bringing the plant up to operating conditions and is not treating water for reinjection.

shutdown in October 2010 (which extended through the remainder of this reporting period). Continued problems with fouling in the evaporator vessel, power failures, and scheduled maintenance accounted for the remainder of the downtime.

Approximately 11.9 million gallons of water were treated during this period, resulting in an average operating rate of 104.6 gallons per minute (gpm), about 87 percent of the 120 gpm treatment plant capacity. The effective rate (downtime included) was 22.6 gpm. Aquifer yield generally limits the extraction rate to about 90 to 100 gpm. For comparison, corresponding values reported for 2009–2010 were 31.7 million gallons treated, and average operating and effective rates of 94 gpm and 60 gpm, respectively.

Total groundwater treatment as of April 1, 2011, was approximately 350.3 million gallons, equivalent to about 29.2 percent of the total estimated volume of uranium-contaminated groundwater prior to remedial action (see Section 4.0 for discussion of contaminant removal rates). (Corresponding values reported for 2009–2010 were 338.4 million gallons [cumulative treated volume], corresponding to 28.2 percent of the total contaminated groundwater volume.)

Figures 3 and 4 show the feed rate to the treatment plant and the corresponding concentration of nitrate, sulfate, and uranium determined from weekly composite samples since the start of remediation. These figures indicate that the bulk extraction rate (represented by inflow) has been relatively steady over time for periods when the plant has been operating. As has been the case historically, weekly inflows sometimes vary considerably, and this variability has been greater in the last several years (reflecting greater downtime—e.g., the plant shutdown in October 2010). Concentrations of nitrate entering the treatment system at typical inflows have been relatively stable (Figure 3). Sulfate and uranium concentrations in the feed, although generally stable in the first 4–5 years of plant operation, have increased slightly in the last several years (Figures 3–4).

Contaminant masses extracted during the current review period were about 0.4 times those reported last year, largely due to the plant shutdown in October 2010. Extracted masses of nitrate, sulfate, and uranium, estimated from the weekly monitoring of bulk inflow to the treatment plant, were 43,119 pounds (lb), 127,747 lb, and 30 lb, respectively (Table 2).

Table 2. Treatment System Performance Summary, April 2010–March 2011

Contaminant	Mass Removed During Review Period (lb)	Typical Feed Concentration (mg/L)	Average Distillate Concentration (mg/L)
Nitrate (as NO_3)	43,119	428	3.8
Sulfate	127,747	1,269	15.4
Uranium	30	0.29	0.002

mg/L = milligrams per liter
The masses removed in 2010–2011 were 105,000 lb; 283,000 lb; and 70 lb for nitrate, sulfate, and uranium, respectively. Typical feed concentrations for 2009–2010 were 409 mg/L; 1,158 mg/L; and 0.3 mg/L; average distillate concentrations were 3.8 mg/L; 13.2 mg/L; and 0.002 mg/L.

2.2 Distillate Quality

Figures 5a and 5b plot average weekly concentrations of nitrate, sulfate, uranium, chloride, and total dissolved solids (TDS) in the distillate over time. Except for increases in 2007 and 2008[2], distillate quality has remained relatively stable since 2005. During this review period, concentrations of nitrate, sulfate, and uranium in the distillate averaged 3.8, 15.4, and 0.002 milligrams per liter (mg/L), respectively. These averages are nearly the same as those reported last year (Table 2; also see DOE 2010).

During this review, chloride concentrations in the distillate ranged from 0.8 to 33.9 mg/L (12.8 mg/L average), and TDS concentrations ranged from 20 to 95 mg/L (46 mg/L average). Although chloride levels in the distillate increased this period (Figure 5b), they are still well below the 250 mg/L remediation target. For all parameters, the distillate quality results indicate highly effective contaminant removal and a quality of water returned to the aquifer in most cases well below the remediation targets listed in Table 1.

2.3 Treatment System Water Budget

About 10.3 million gallons (86 percent) of the total feed to the treatment system was returned to the aquifer at the infiltration trench. Treatment system wastewater sent to the evaporation pond normally comprises about 5 percent of the total inflow as brine and about 4 percent as loss for softener regeneration. Water levels in the evaporation pond continue to remain safely below the maximum operating level. Additional feed water was added to the pond during this review period due to treatment system operating issues and to maintain a minimum level in the pond.

2.4 Extraction Well System Description

In Figure 2c, the extraction wells labeled 1101 to 1125 are constructed of 6-inch-diameter Schedule 40 PVC solid casing and 6-inch, continuous V-wrap stainless-steel screen (0.017-inch slot). A filter pack of 20–40 mesh silica sand fills the 2-inch annulus to 30 or 40 ft above the screen slots. Screen lengths are 150 ft, extending from the bottom half of Horizon B to the mid-depth of Horizon E, except for wells 1116, 1117, and 1118, which have 100-ft screens to a depth near the base of Horizon D. Extraction wells 1126 to 1133 are constructed of 4-inch-diameter casing and screen. These wells have a 30-ft to 50-ft screen that is placed across most of Horizon B. These wells became operational in August 2005, as did former monitoring wells 935, 936, 938, and 942 (4-inch wells). The extraction well pumps are generally positioned 10 to 15 ft above the bottom of the well. Pumps in wells 935, 936, 938, and 942 are at the bottom of the well because these wells are much shallower and so have much less potential drawdown. Refer also to Table A–1 and Figure A–2 in Appendix A for well completion details.

[2] As addressed in the last annual report (DOE 2010), the increases in contaminant concentrations in the distillate observed in 2007–2008 were attributable to the need for replacement of the treatment system heat exchanger bags.

3.0 Groundwater Capture Analysis

3.1 Extent of Groundwater Contamination

Figures 6a through 14a illustrate the concentrations of nitrate (as NO_3), sulfate, and uranium in groundwater in the respective aquifer horizons before the start of remediation (baseline period). Figures 6b through 14b show contaminant distribution in July 2010 or February 2011 for the respective contaminant and aquifer horizon. Corresponding analytical results are tabulated in Appendix B for July 2010, February 2011, and the baseline period. Most of the baseline period data are from sample collection in March 2002, but data for some locations are from 1999 or 2001. In addition to the primary contaminants, Appendix B also documents analytical results for molybdenum and selenium. Additional information, including time-concentration graphs for all site monitoring and extraction wells, is provided in the Data Validation Packages for the July 2010 and February 2011 sampling events (DOE 2011a; DOE 2011b).

To facilitate review of Figures 6 through 14, although each well location sampled for the respective period is shown, a concentration value is posted only where the applicable remediation goal or standard was exceeded. In comparing the "a" series figures (representing baseline conditions) with the "b" series counterparts (plotting the most recent results), the area of contamination in the various horizons does not appear significantly different from that established for baseline conditions, indicating no lateral spreading of the contaminant plume (additional information regarding contaminant concentration trends is provided in Section 4.1).

As has been the case since groundwater treatment began, the depth of groundwater contamination is generally limited to Horizons A, B, and C beneath the middle terrace. Except for nitrate and sulfate in lower terrace well 1003 (see discussion below), contamination of Horizon D is confined to the disposal cell and evaporation pond area where groundwater extraction is most focused (Figures 7b, 10b, and 13b). Apparent contamination in Horizon D in these areas may be an effect of downward migration of contaminated groundwater from upper horizons in response to groundwater withdrawal at nearby extraction wells. Contamination in Horizon E (see Figures 8b, 11b, and 14b) is still limited to the occurrence of nitrate in well 268 (last two measurements were 75.3 and 83.3 mg/L). Contamination is absent in the deeper horizons (Horizons F, G, and I).

In general, contamination of lower terrace wells is absent—with few exceptions, constituent concentrations in these wells are still below remediation goals (as was the case for baseline conditions; see "a" series figures). However, nitrate continues to exceed the 44 mg/L (as NO_3) restoration standard at several locations (Figures 7a and 7b)—nominally at Horizon C wells 0903 (48.7 mg/L) and 0930 (65.6 mg/L), and more significantly in Horizon C well 0691 (277 mg/L) and paired (Horizon D) well 1003 (270 mg/L; refer to Section 4.0 for a discussion of corresponding time trends). These paired wells are the only locations on the lower terrace where the sulfate restoration goal has been and is presently exceeded (480–505 mg/L; Figure 10b).

Historically, uranium has exceeded the 0.044 mg/L restoration standard on the lower terrace only at well 0691. Exceedances have been slight (historical maximum of 0.066 mg/L); 0.05 mg/L uranium was measured in both the July 2010 and February 2011 samples. As discussed in Section 4.1, time-concentration trends in wells 0691 and 1003 have not been stable for all key site contaminants (see Section 4.1 for additional trending information).

Figures C–1, C–2, and C–3 in Appendix C show the distributions of nitrate, sulfate, and uranium during the current period of review. As has been the case for the last several reporting periods, the plume geometry and magnitude of the contour intervals has not changed significantly—for all constituents, contamination is still generally confined to the middle terrace.

Some of the conclusions drawn above regarding contaminant plume containment and geometry were recently confirmed in an independent investigation conducted by NNEPA (iiná bá/DOE 2011). In September 2010, in cooperation with DOE, NNEPA installed nine groundwater monitoring wells (shallow and deep) into the local groundwater aquifer west and north of the site; six of these wells (wells NMW-1A, -6S, -7D, -8S, and -9D; immediately adjacent to the site to the west) were also sampled by DOE in February 2011. Results of this sampling indicate that no site-related contaminants exceeded respective MCLs or NNEPA aquifer restoration goals and that water quality at those locations is consistent with background conditions. These results confirm closure of the western margin of the contaminant plumes. Very similar results were obtained at wells NMW-2A, -3A, and -4A for samples collected by iiná bá at that time. Groundwater samples from the seven Tuba City water supply wells, sampled in February 2011, also indicated no impacts from the site.

3.2 Water Table Configuration

3.2.1 Water Table Contours

Figure 15 shows the estimated water table for the baseline period (August 2001) using water levels in Horizons A and B monitoring wells for the middle terrace and Horizon C wells for the lower terrace. On the middle terrace, water levels at deeper wells are not representative of water table conditions because of pronounced vertical hydraulic gradients (see Section 3.5) and so are not appropriate for constructing a water table map. On the lower terrace, the water table occurs within Horizon C within the area of interest. The horizontal direction of groundwater flow was predominantly south during the baseline period. A steeper hydraulic gradient at the escarpment (Figure 15) mimics ground surface topography.

Figure 16 shows the estimated water table for February 2011. The monitoring wells and corresponding water table elevations used to generate the water table contours are identified in the figure. In previous annual reports, prior to the temporary cessation of active groundwater treatment in October 2010, comparison of Figures 15 and 16 indicated that operation of the extraction wells had significantly depressed the water table within the central regions of extraction to the south and east of the disposal cell. Also evident in Figure 16 of the previous annual reports was an elongate groundwater mound and increased hydraulic gradients along the north edge of the disposal cell. These features were caused by infiltration of the distillate at the trench. Although still apparent, the groundwater mounding and increased gradients have diminished in magnitude since operation of the remediation system was discontinued in October 2010. Water table rebound since groundwater withdrawal was suspended is addressed further in Section 3.3.

3.2.2 Infiltration Trench

The infiltration trench is constructed into bedrock along the north side of the site (see Figure 2 for location of the infiltration trench). As reported in previous annual reports, distribution of the distillate was adjusted on occasion through 2005 to result in uniform infiltration and a symmetrical groundwater mound along the trench. The annual report for 2010 indicated a uniform and symmetric groundwater mound at the infiltration trench. Dissipation of the groundwater mound since remediation was suspended has also resulted in a symmetrical shape of the water table at the infiltration trench. Wells 284 and 285 are paired with wells 946 and 943, respectively, to monitor water table conditions at the contact between the terrace deposits and the Navajo Sandstone immediately downgradient of the trench (see Figure 2b). Wells 284 and 285, completed with screen intakes that straddle the alluvium/sandstone contact, have remained dry since installation in 2004, indicating that mounding has not over-topped the trench to saturate the alluvium. The water table before groundwater treatment was suspended was closest to alluvium/sandstone contact at well 946, within about 6 ft of the contact. The water table elevation at this location has since decreased by about 5 ft since October 2010. Water level hydrographs for wells completed in the aquifer in the area of the trench are presented as Figure D−1 in Appendix D.

3.3 Water Level Drawdown

Figure 17 illustrates the effect of groundwater extraction and infiltration by showing the difference in water levels in Horizons A and B between the baseline period and February 2011. Figures 18 and 19 plot the water level differences between the same periods for the deeper horizons. Positive values identify locations where the water level in February 2011 is less than the baseline value. Negative values, such as those at the wells surrounding the infiltration trench (Figure 17), indicate that water levels at the respective locations are presently higher than during the baseline period.

Prior to October 2010 when active treatment was suspended, and as presented in previous annual reports, the pattern of water level drawdown in the area of groundwater extraction reflected three-dimensional converging flow to the extraction wells. The greatest drawdown (as much as 70 ft) was observed at the monitoring wells closest to or within the east and south areas of extraction and which are screened in the same horizons spanned by the extraction well intakes (Horizon C, D, or E). Drawdown was observed to decrease with vertical and horizontal distance from the extraction well intakes. Well hydrographs in Appendix D provide an additional view of water level variation over time at selected monitoring wells. Leading up to October 2010, the predominantly downward trend in groundwater levels indicated an expanding capture zone.

Recent increases in water levels of approximately 10 to 20 ft at most locations reflect the periods of plant downtime since October 2010. Rising water levels shortly prior to October 2010 were attributed in the 2010 annual report to earlier, short-term shutdowns of the remediation system. Current water levels at most monitoring wells indicate that the water table has recovered by as much as 50 percent since October 2010. The rate of water table recovery since then may be augmented by a regional rise in the water table, as exhibited at background wells 901, 910, and 947.

3.4 Horizontal Capture

Figure 20 depicts the estimated zone of groundwater capture in lateral extent in Horizons A and B, where the bulk of contamination resides. In this depiction, generated using groundwater elevation data obtained before October 2010 when the remediation system was shut down, all groundwater within the blue line, the approximate extent of plume capture, is predicted to ultimately flow to an extraction well. This prediction is based on slope analysis of the water table using the computer program SURFER. The analysis calculates a vector that describes the direction and magnitude of the water table slope within each user-specified grid cell used in computing the water table contours. The capture line in Figure 20 corresponds to a horizontal flow divide between the vectors that converge on the extraction wells and those that do not.

The slope analysis indicated that the full width of the contaminant plume along the south edge of the disposal cell was within the capture zone, suggesting that flow of contaminated groundwater from the site was eliminated by the remediation system. The capture zone encompasses the region of greatest contamination; however, the area encompassing extraction wells 1126 through 1129 apparently escapes capture. As reported in 2010 and previously, water level drawdown in this area is significant and was increasing before the remediation system was shut down (Figures D–4, D–5, and D–6 in Appendix D). These data indicated an expanding cone of depression and an expanding capture zone in this area. Contamination in this area is limited in vertical extent to Horizons A and B and is generally at lower concentrations than within the primary capture zone shown in Figure 20.

3.5 Vertical Capture

Hydrographs included in Appendix D for selected sets of co-located monitoring wells illustrate that at a given location, the hydraulic head in the aquifer is a function of well-intake depth. This relationship identifies vertical flow components throughout the monitored thickness of the aquifer, both before and since the start of groundwater remediation, and during the recent period of plant shutdown. With few exceptions, vertical flow potentials were downward during the baseline period. Since that time, until the remediation was suspended in October 2010, the magnitude of downward flow in Horizons A, B, and C generally increased, as exemplified by the greater vertical separation in the hydrographs for the respective locations of well pairs 263/264, 265/266, 909/932, and 908/912 since about mid-2002 (see Figures D–4 through D–7 in Appendix D). In the main region of contamination, the increased gradients during active remediation imply capture of groundwater from the upper, most contaminated horizons of the aquifer (Horizons A, B, and C).

In the deeper horizons, vertical gradients are generally upward to the extraction well intakes in response to groundwater extraction. For example, the vertical flow potentials reversed to upward between Horizons M, I, and E at co-located wells 268/256/257 (Figure D–8; wells 256 and 257 were decommissioned in August 2005). A similar trend for Horizons E and I is apparent at the location of wells 251/252 (see Figure D–9) until active remediation was suspended in October 2010, at which time pre-remediation gradients resulted.

A downward flow potential was present between Horizon I and M into 2005 at paired wells 254/255 (Figure D–10; wells 254 and 255 were decommissioned in August 2005). Groundwater elevation data for well 273, installed in August 2004 near the location of former

wells 254 and 255, implies vertically upward flow from Horizon I to D (Figure D–10). Groundwater extraction has reduced but not reversed the downward flow gradient between Horizons D and G at wells 915 and 916 (Figure D–11); however, this region of the aquifer is not contaminated.

Because the observed vertical influence of the extraction wells extends deeper than the presumed depth of contamination (Horizons A, B, and C, and to a lesser extent Horizon D), it is likely that the remediation system captures the full vertical extent of the contaminant plume. Flow potentials in lower terrace groundwater remain strongly downward, extending possibly through Horizon I, as indicted at the lower terrace well cluster identified in Figure D–12. The effect of pumping at that location has been to increase the downward hydraulic gradient between Horizons C and E and decrease the potential between Horizons E and I (Figure D–10). Despite the downward flow potential remaining on the lower terrace, the slight amount of contamination in lower terrace groundwater is limited primarily to Horizon C.

4.0 Remediation Progress

4.1 Contaminant Concentration Trends at Monitoring Wells

Appendix E contains time series graphs of nitrate, sulfate, and uranium concentrations in groundwater at selected monitoring wells located throughout the project area. In the main region of groundwater contamination (Horizons A and B), nitrate concentrations have risen since the baseline period (see Figure E–1). Similar trending is not apparent for sulfate or uranium, for which consistent trending is generally absent (Figures E–2 and E–3). Some of the highest uranium concentrations have been measured in wells 0262 and 0906, where trends have been erratic (Figure E–3; also see Figure 12b). In general, however, persistent and widespread contaminant trending, upward or downward, is not evident.

Horizon A, B, and C wells 271, 683, 684, 914, and 929 are located beyond but near the downgradient or crossgradient extent of contamination (Figure 2). At most of these "sentinel" wells (271, 683, 684, and 914), groundwater has not been contaminated since monitoring began in 1999 (Figures E–4 through E–6). However, minor nitrate contamination of about 1.5 to 2 times the remediation target remains at well 929; nitrate levels have increased in this well in the last several years. Toward the downgradient (south) margin of the plume (e.g., wells 271 and 929), sulfate and uranium concentrations have been relatively stable and generally consistent with baseline concentrations (Figures E–5 and E–6).

On the middle terrace, contaminant concentrations remain stable and below remediation standards in Horizons C and D, as indicated at wells 264, 266, 914, 915, and 932 (Figures E–7 through E–9). These results indicate that the plume is not expanding southward at this depth in the aquifer. In Figures E–7 and E–8, historically elevated nitrate and sulfate concentrations at well 912 (Horizon C) have trended downward over time, which also indicates that contamination is not spreading farther downgradient to the south of the disposal cell.

As presented in Section 3.1, groundwater contamination beneath the lower terrace is sparse and limited to concentrations that do not greatly exceed the remediation standards. Figures E–10 through E–12 show time-series plots for nitrate, sulfate, and uranium at selected lower-terrace

wells. Concentrations of these constituents are shown to be relatively stable before and after the start of groundwater remediation, except at paired well 691 and 1003 (discussed previously), where contaminant concentrations are highly erratic.

Contaminant concentrations at monitoring wells screened below Horizon D on both the middle and lower terrace remain stable and below remediation standards, except at well 268 (refer to Appendix E, Figures E–13 through E–15). At well 268 (Horizon E), located in an area of extensive water level drawdown (see Figures 16 and 19), contaminant concentrations increased between 2004 and 2006, presumably in response to groundwater withdrawal associated with the remediation system. The trend has since stabilized at this location, and only nitrate has exceeded the remediation standard. The previous rise in contaminant concentrations at well 268 may be explained by the downward movement of contaminated groundwater from upper horizons to deeper horizons intercepted by the nearby extraction wells. Also, well 268 is located in an area of pronounced drawdown.

4.2 Breakthrough from the Infiltration Trench

The arrival of water from the infiltration trench to the extraction wells may eventually be important in evaluating the flushing process and time requirement for restoration of the aquifer. Breakthrough of clean water from the infiltration trench is expected to be evident as a relatively abrupt decline in contaminant and dissolved solids concentrations at monitoring and extraction wells nearest the downgradient side of the disposal cell. Such trending is not yet apparent.

Darcy's Law predicts that the travel time from the infiltration trench to well 940 is about 17 years, based on the inferred water table gradient beneath the disposal cell (0.04 ft/ft), a hydraulic conductivity of 1 ft per day (from DOE 1998), and 25 percent porosity (computes to an average linear flow velocity of about 60 ft/yr). The estimated travel time (17 years) exceeds the cumulative remediation period to date, so breakthrough of the distillate is not yet expected.

4.3 Contaminant Concentration Trends at Extraction Wells

Figures 21 to 23 illustrate concentration trends at the extraction wells for nitrate, sulfate, and uranium. Each figure comprises three separate time series plots to show the trends in different areas of the extraction well field. The well field is separated into the area east of the disposal cell (figure "a"), the area immediately south of the disposal cell (figure "b"), and the area encompassing the southernmost portion of the plume (figure "c").

Figures 21a and 22a indicate no evident temporal trends for nitrate or sulfate in the eastern area of the extraction well field. This is not the case for uranium, however, which is generally trending downward (Figure 23a). As has been the case historically, concentration trending is much more variable in the area immediately south of the disposal cell (Figures 21b, 22b, and 23b). In this area, concentrations at some wells are observed to be static over time, while at other wells, trends may be slightly upward or downward. Nitrate and sulfate concentrations rose slightly in the southernmost portion of the extraction field at the onset of remediation. Concentrations have since been relatively stable. Uranium concentrations did not show a similar rise at the onset of remediation, and concentrations remain relatively stable. Concentration trends in southernmost extraction wells (Figures 21c, 22c, and 23c) have also been relatively stable.

Table 3 was prepared on the basis of Figures 21 to 23 to list the extraction wells where a primary contaminant concentration was below the remediation standard in the extract during this reporting period. For this review period, 1125 was the only extraction well where all three primary contaminants were below corresponding remediation standards.

Table 3. Pumping Wells Where a Contaminant Concentration Is Below the Remediation Standard in the Extract, as of February 2011

Extraction Well[a]	Nitrate[b]	Sulfate[b]	Uranium[b]
1112		X	
1113		X	X
1116			X
1117			X
1125	X	X	X
1133		X	

[a] Only those extraction wells where the remediation standard was not exceeded for at least one contaminant are listed above.
[b] Nitrate continues to exceed the remediation standard in all extraction wells except 1125. Results for sulfate and uranium are the same as those reported for 2009–2010.

4.4 Contaminant Mass Removal and Restoration Progress

Table 4 lists the cumulative amounts of nitrate, sulfate, and uranium removed from the aquifer through March 2011, about 9 years into full-scale groundwater extraction and treatment. For comparison, Table 4 also provides the estimated quantities of contamination initially present in the aquifer and the amount of contaminant removed as a percent of the initial quantity. Calculation methods for these estimates of initial contaminant mass are provided in Appendix G as Calculation Set 1 of previous annual reports (e.g., see DOE 2010). An estimate of the initial volume of contaminated groundwater is also presented in Table 4 based on these calculation sets.

Table 4. Summary of Cumulative Mass and Volume Recovery as of April 1, 2011

Contaminant	Initial Mass (lb)	Cumulative Mass Removed (lb)	Cumulative Percent Mass Reduction	Initial Volume (gallons)	Volume Treated (gallons)	Percent Plume Volume Reduction
Nitrate	9,500,000	1,178,768	12.4	1.2×10^9	3.5×10^8	29.2
Sulfate	20,150,000	2,990,273	14.8	1.2×10^9	3.5×10^8	29.2
Uranium	2,300	751	32.6	1.2×10^9	3.5×10^8	29.2

Masses are rounded above, but percent mass reduction and plume volume reduction calculations used non-rounded values. For the preceding review period (ending April 1, 2010), cumulative mass reductions were 12.0, 14.2, and 31.3 percent, respectively, for nitrate, sulfate, and uranium. The volume treated was 3.4×10^8 gallons, and the percent plume volume reduction was 28.2 percent. Twelve million gallons were treated this reporting period; this is less than volumes reported previously due to the plant shutdown in October 2010.

Table 5 summarizes similar information (cumulative masses and volumes removed), but for all preceding review periods and for uranium only. Restoration projections previously documented (e.g., see calculation sets in Appendix G of DOE 2010) have predicted complete mass removal of uranium within 25 years of active remediation. The corresponding volume of groundwater extracted after 25 years, assuming constant withdrawal of 85 gpm (equivalent to about a

3.6 percent reduction in plume volume per year), is 1 billion gallons, which is slightly less than one estimated pore volume of the contaminant plume.

Table 5. Historical Annual Cumulative Mass and Volume Recovery of Uranium

Year Ending (April)[a]	Cumulative Mass Removed, Uranium[b] (lb)	Cumulative Percent Mass Reduction	Cumulative Volume Treated[b] (million gallons)	Percent Plume Volume Reduction
2003	132	6	50	4
2004	234	10	92	8
2005	325	14	136	11
2006	412	18	180	15
2007	493	21	224	19
2008	574	25	266	23
2009	650	28	307	26
2010	721	31	338	28
2011	751	33	350	29

[a] Values reported from the end of each annual reporting period (all are rounded).
[b] Initial mass: 2,300 lb; initial volume: 1,200 million gallons

Review of historical biannual monitoring data indicates that trends in contaminant concentrations at monitoring wells and extraction wells are generally absent. This suggests that despite an extraction system that effectively targets the main region of contamination, approximately 9 years of aggressive groundwater capture, treatment, and reinjection has not significantly improved groundwater quality. The progress of water quality restoration may be limited by matrix and geochemical effects (dual-domain mass transfer and kinetically controlled release mechanisms in the subsurface). These effects could explain why—despite the measureable progress in extracting contaminant mass (e.g., see Table 5)—persistent and significant downward trending in contaminant concentrations at monitoring locations is not apparent.

5.0 Year in Review Summary

During the current review period of April 2010 through March 2011, close to 12 million gallons of contaminated groundwater were treated, yielding a total cumulative treatment volume of 350 million gallons, or about 29 percent of the total estimated volume of uranium-contaminated groundwater prior to remedial action. Major findings are summarized below:

- Operation of the remediation system was suspended in October 2010 to allow upgrading and replacement of treatment system components (during this review period, the system was operational for only 79 days). The remediation system is scheduled to resume operation in September 2011. Groundwater monitoring results from February 2011, reflecting about 4 months of no pumping, indicate no contaminant rebound or expansion of the contaminant plume.
- Historically (excluding the recent shutdown period), although occasional problems with fouling have caused periodic declines in plant efficiency, overall the treatment plant has operated effectively and as intended. Distillate quality, return flow to the aquifer, and infiltration capacity of the infiltration trench and groundwater mounding have all met or exceeded design objectives.

- The current configuration and operation of the extraction system effectively captures the lateral region of maximum groundwater contamination and the full vertical extent. Plume expansion into uncontaminated regions is not significant on either the middle or lower terrace. This conclusion was verified in a report recently issued by NNEPA, summarized below (iiná bá/DOE 2011).
- In September 2010, in cooperation with DOE, NNEPA installed nine groundwater monitoring wells (shallow and deep) into the local groundwater aquifer west and north of the site; DOE sampled six of these wells (immediately adjacent to the site to the west) in February 2011. Results of this sampling indicate that no site-related contaminants exceeded respective MCLs or NNEPA aquifer restoration goals. Groundwater samples from the seven Tuba City water supply wells also indicated no impacts from the site (iiná bá/DOE 2011).
- As has been the case since groundwater treatment began, the depth of groundwater contamination is generally limited to Horizons A, B, and C beneath the middle terrace. Contamination of lower terrace wells (off site and farther downgradient) is generally absent—with few exceptions, constituent concentrations in these wells continue to be below remediation goals. No temporal trends are evident in most site monitoring and extraction wells.
- Despite the measureable progress in groundwater treatment, as indicated by cumulative contaminant mass and volumes extracted, after 9 years of full-scale groundwater extraction and treatment, significant and widespread decreases in contaminant concentrations are not apparent.
- Recent increases in water levels of approximately 10 to 20 ft at most well locations reflect the plant downtime since October 2010. These increases are in contrast to sometimes significant water level drawdowns observed in the area of groundwater extraction during system operation.

6.0 References

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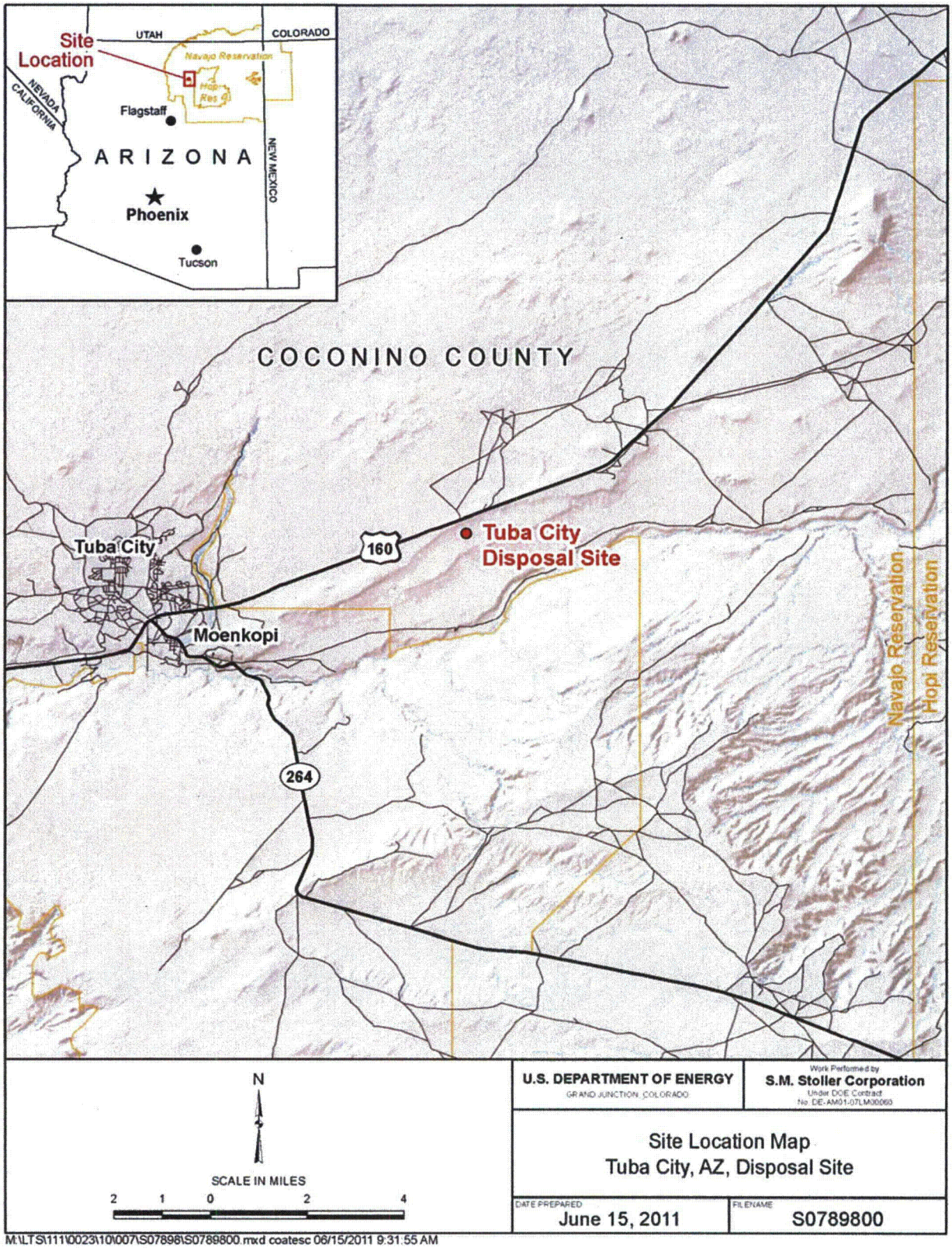

Figure 1. Tuba City Site Location

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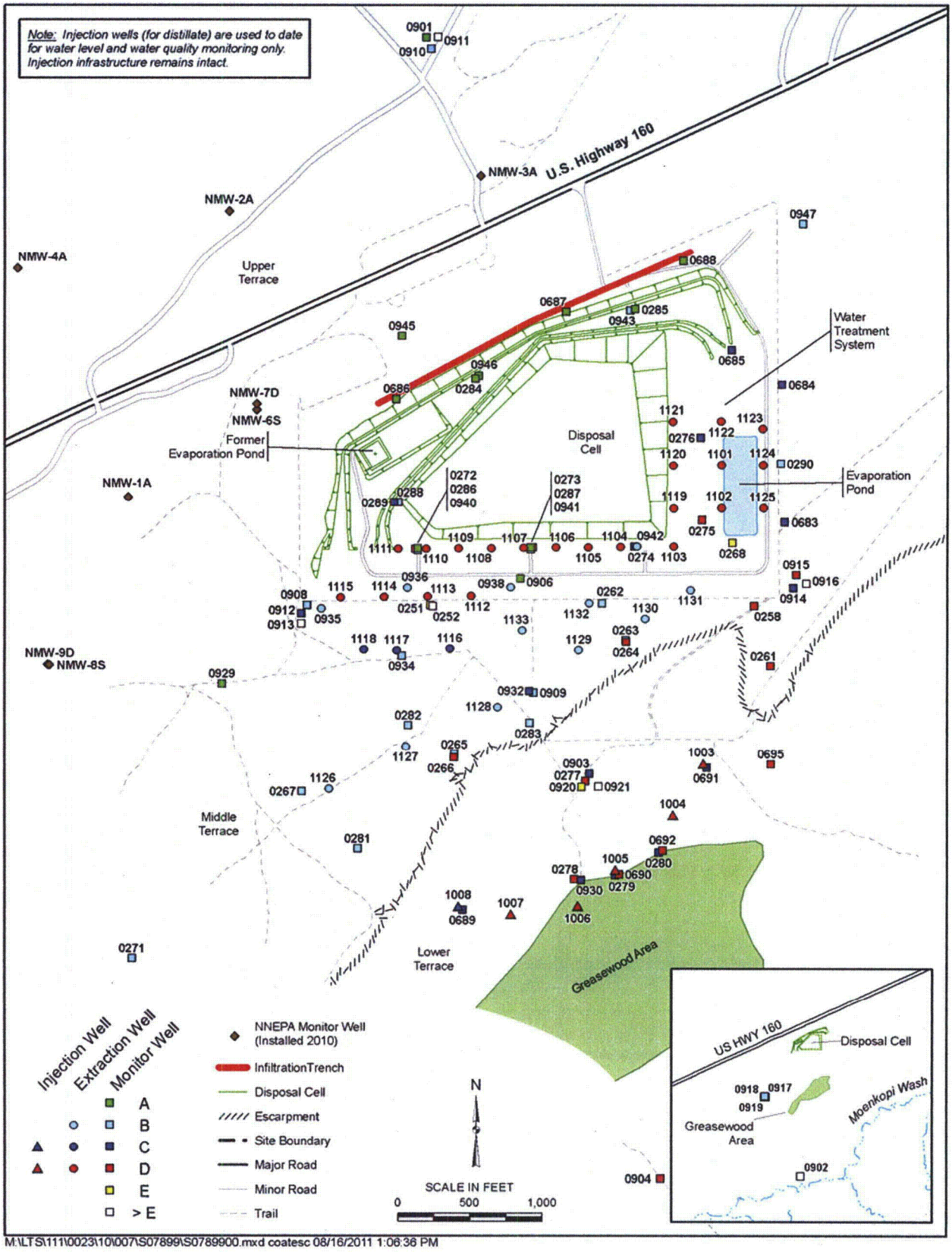

Figure 2a. Tuba City Site Features and Well Locations

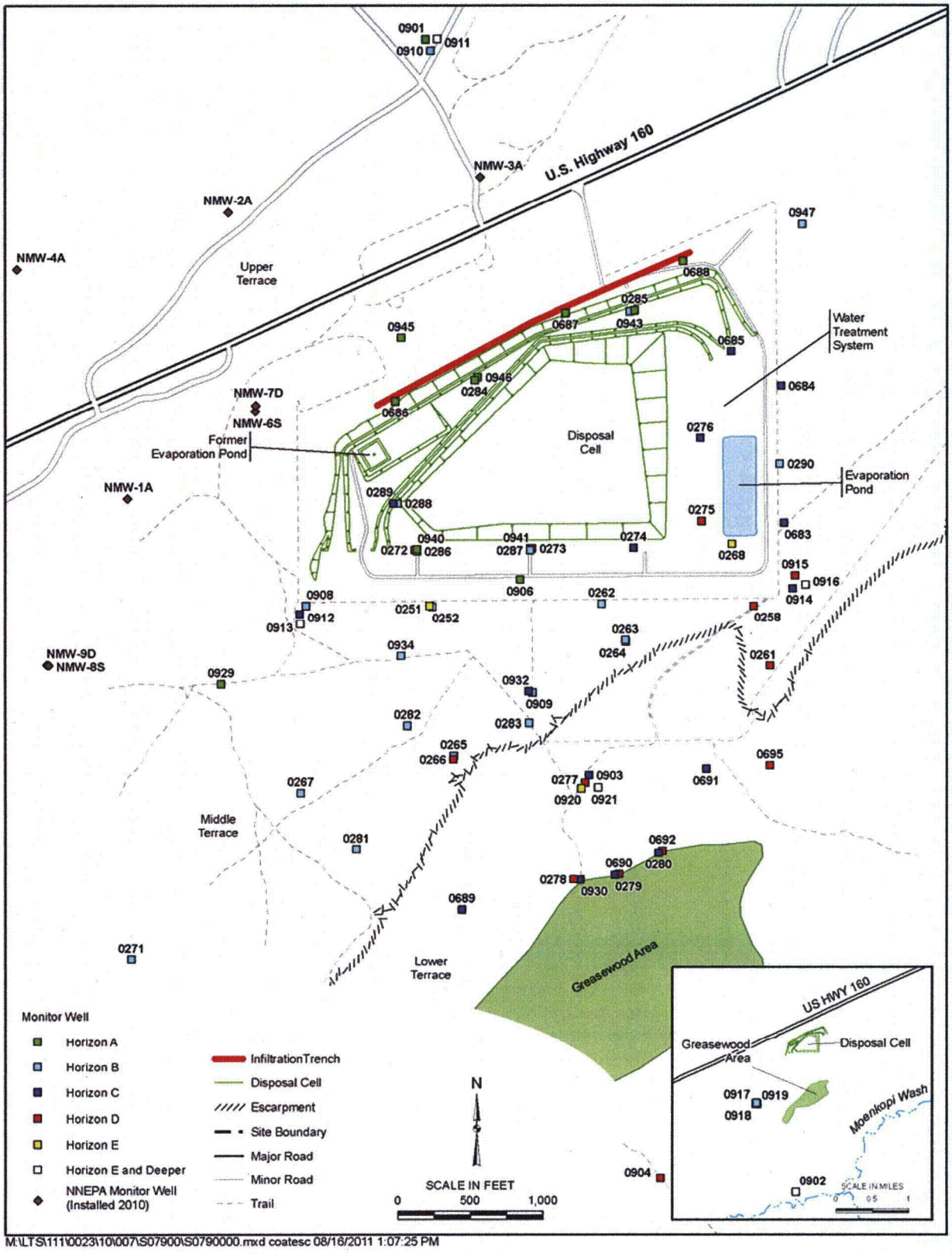

Figure 2b. Tuba City Site Features and Well Locations—Monitoring Wells Only

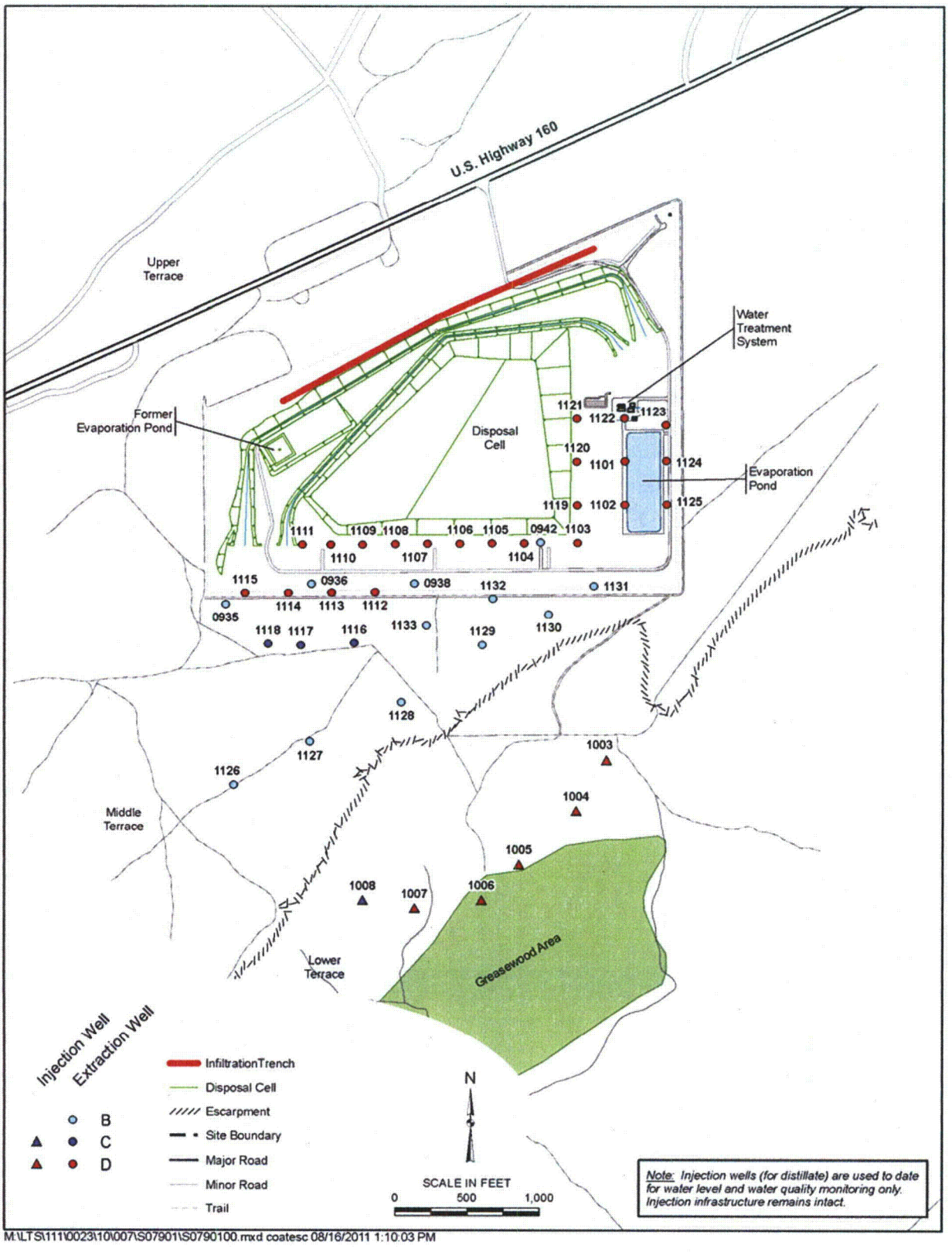

Figure 2c. Tuba City Site Features and Well Locations—Treatment System Wells Only

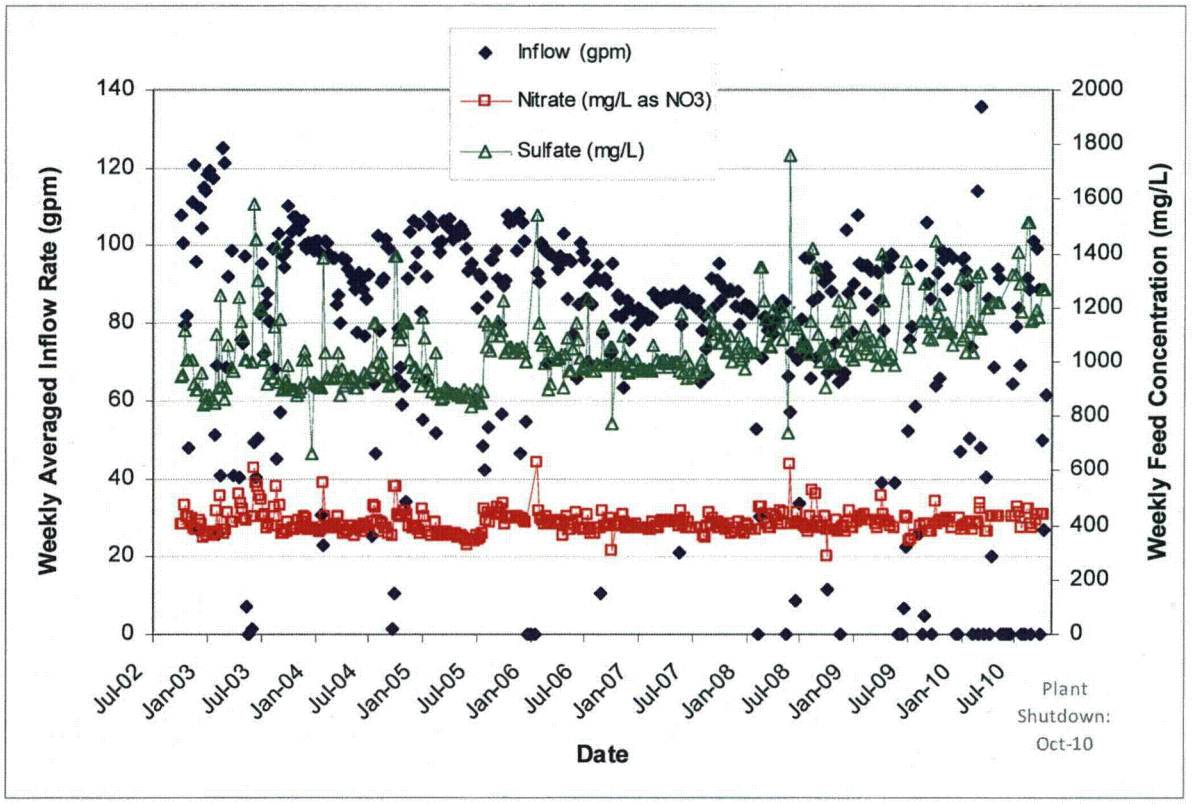

Figure 3. Treatment Plant Inflow Rate and Nitrate and Sulfate Concentrations

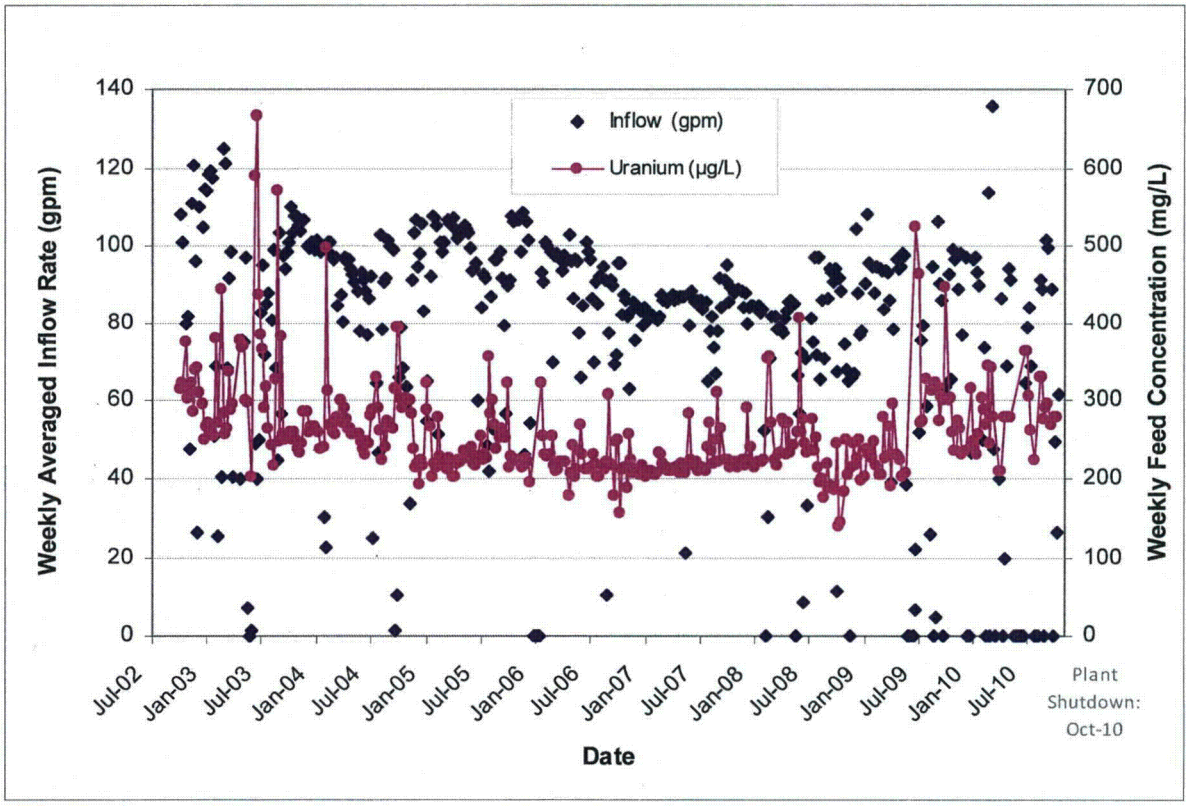

Figure 4. Treatment Plant Inflow Rate and Uranium Concentration

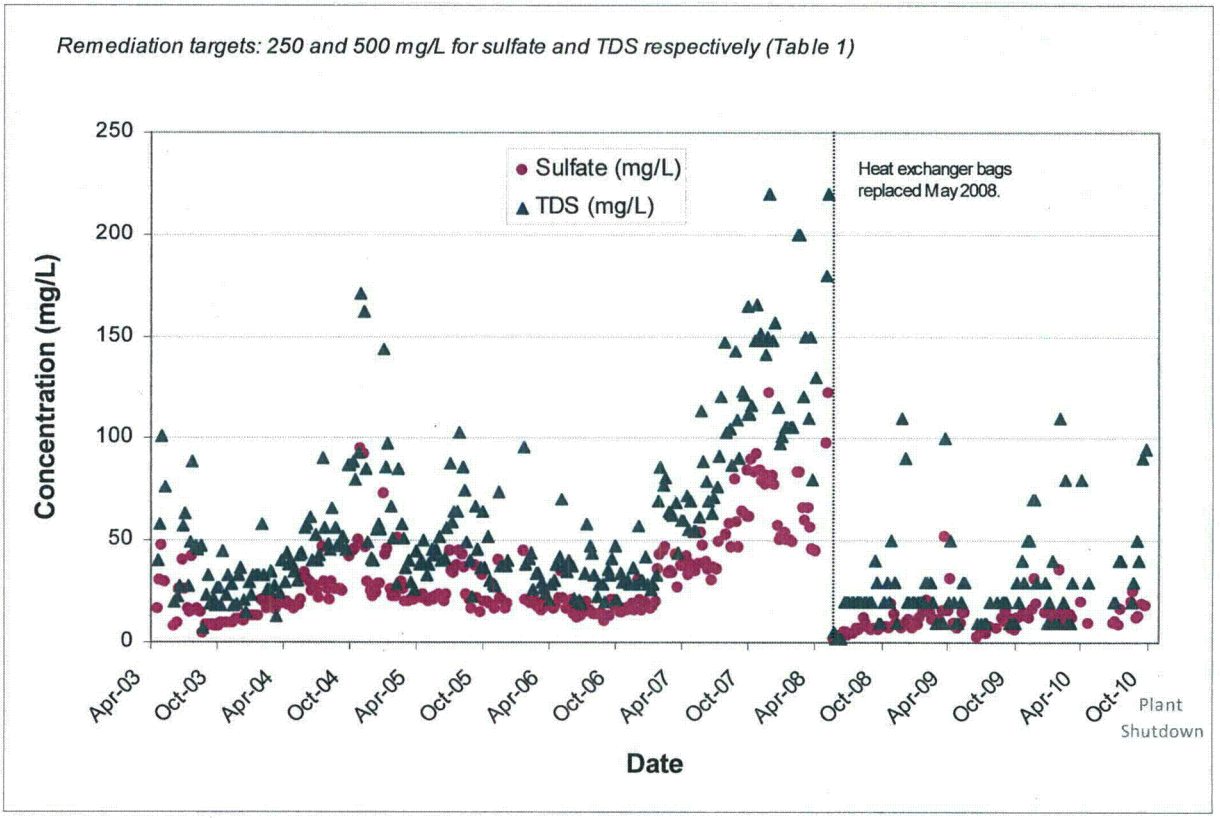

Figure 5a. Treatment Plant Distillate Quality—Sulfate and TDS

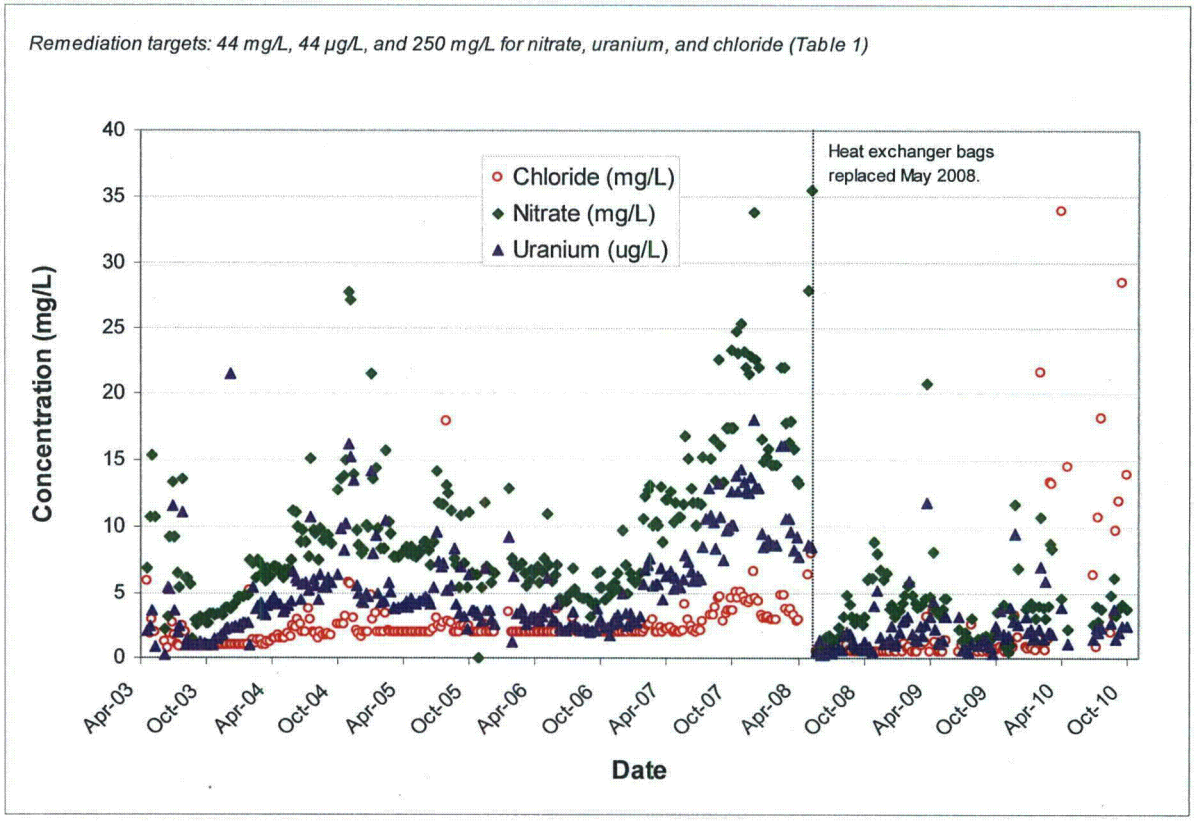

Figure 5b. Treatment Plant Distillate Quality—Nitrate, Uranium, and Chloride

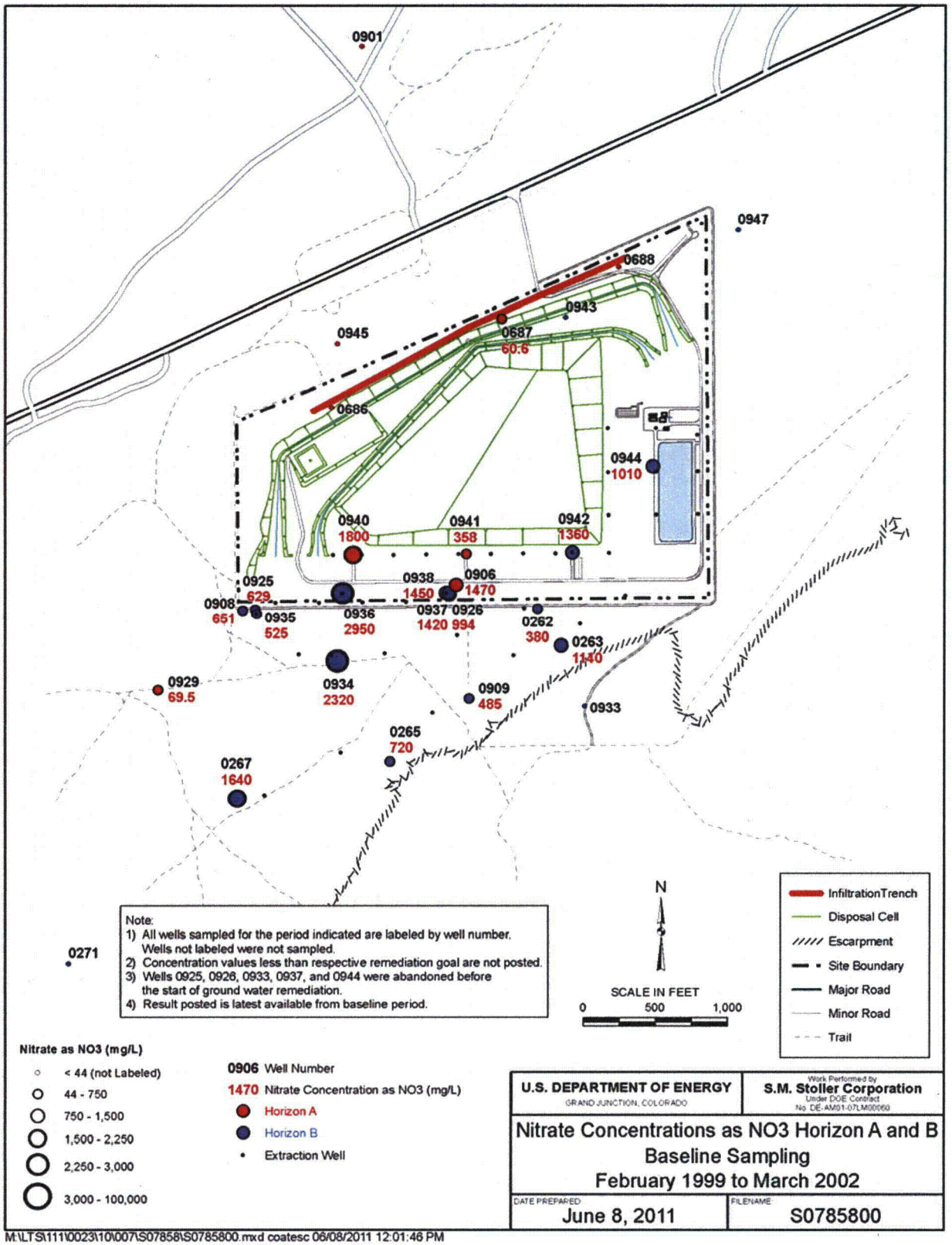

Figure 6a. Nitrate Concentrations as NO_3, Horizons A and B, Baseline Period

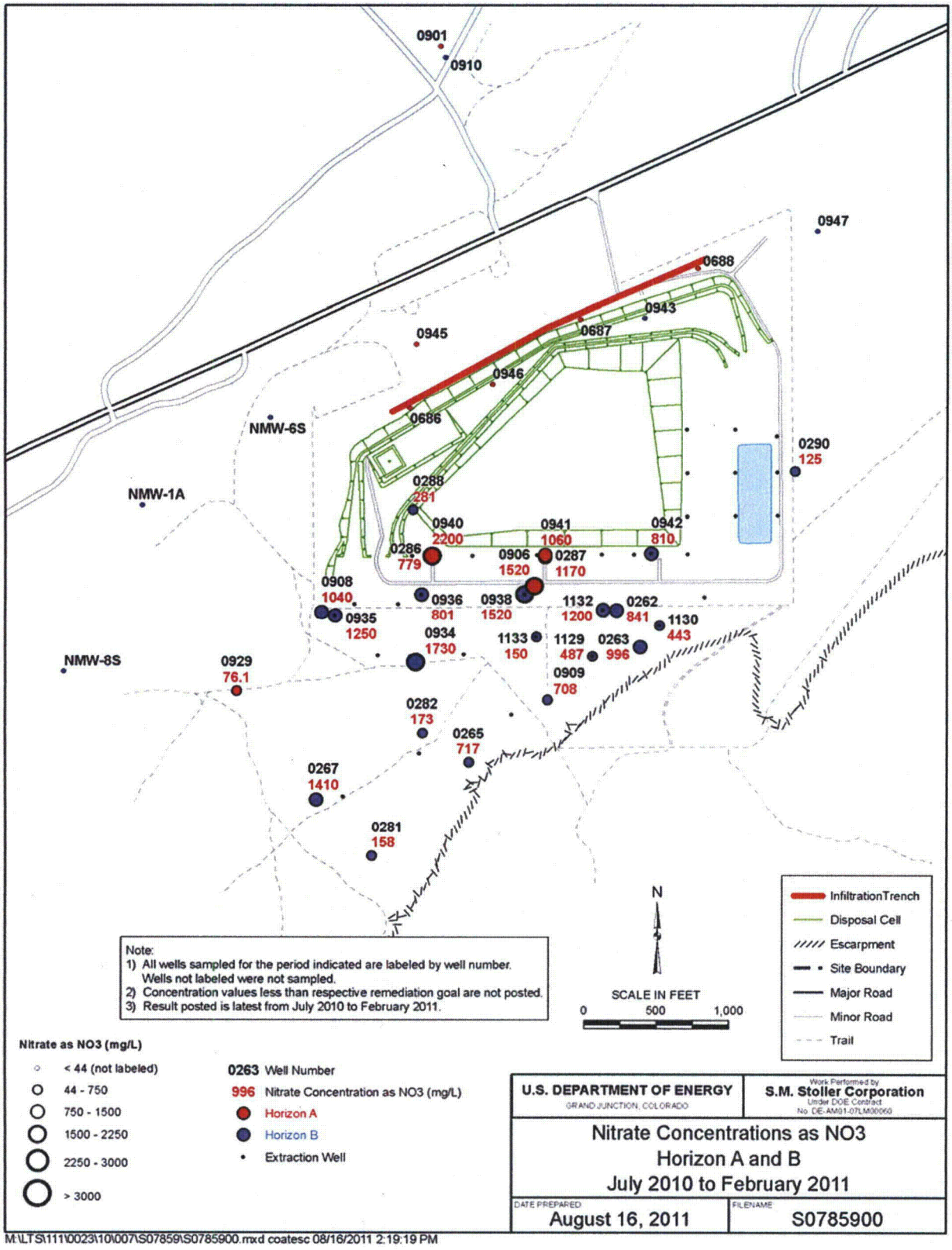

Figure 6b. Nitrate Concentrations as NO_3, Horizons A and B, February 2011

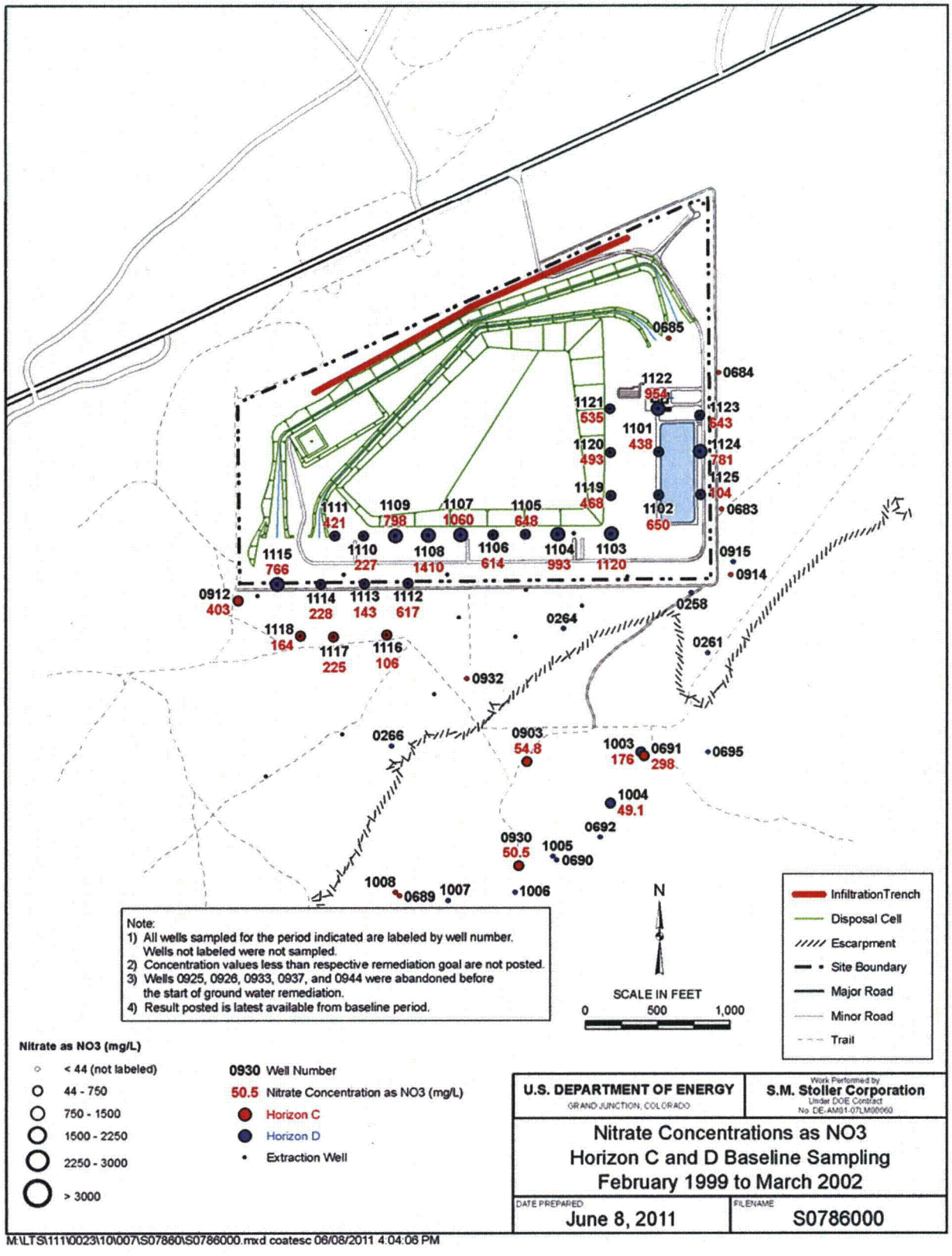

Figure 7a. Nitrate Concentrations as NO_3, Horizons C and D, Baseline Period

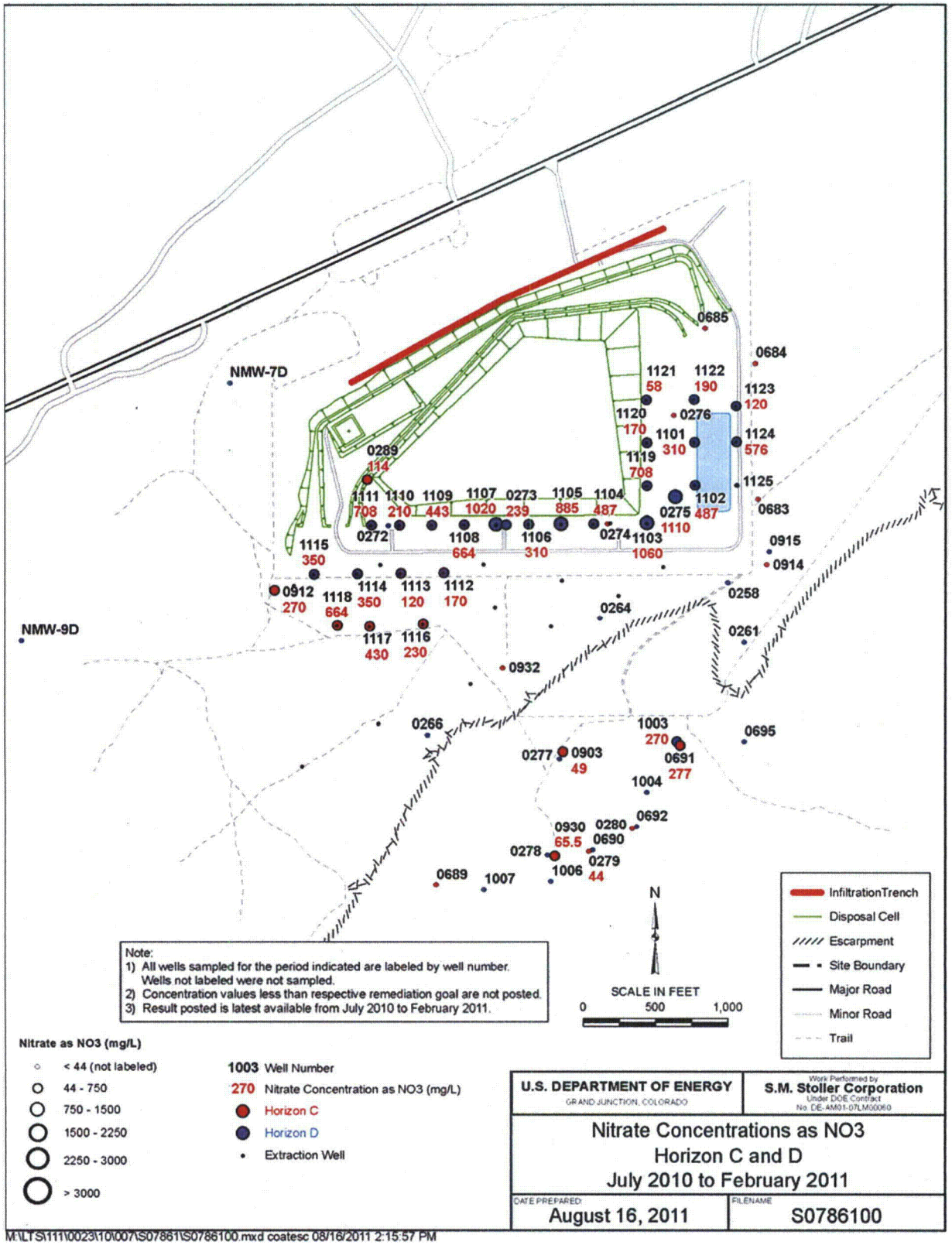

Figure 7b. Nitrate Concentrations as NO_3, Horizons C and D, February 2011

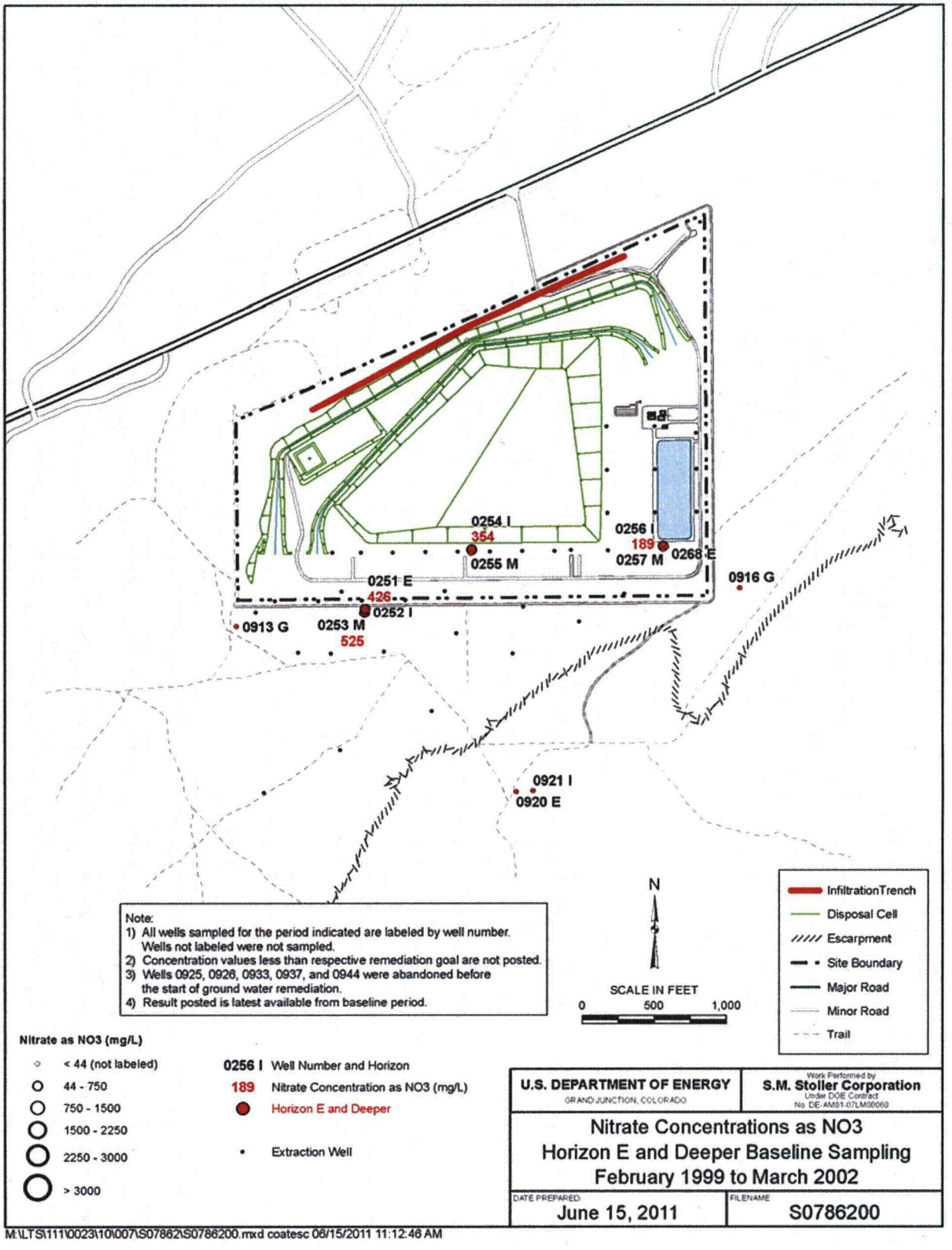

Figure 8a. Nitrate Concentrations as NO_3, Horizons E and Deeper, Baseline Period

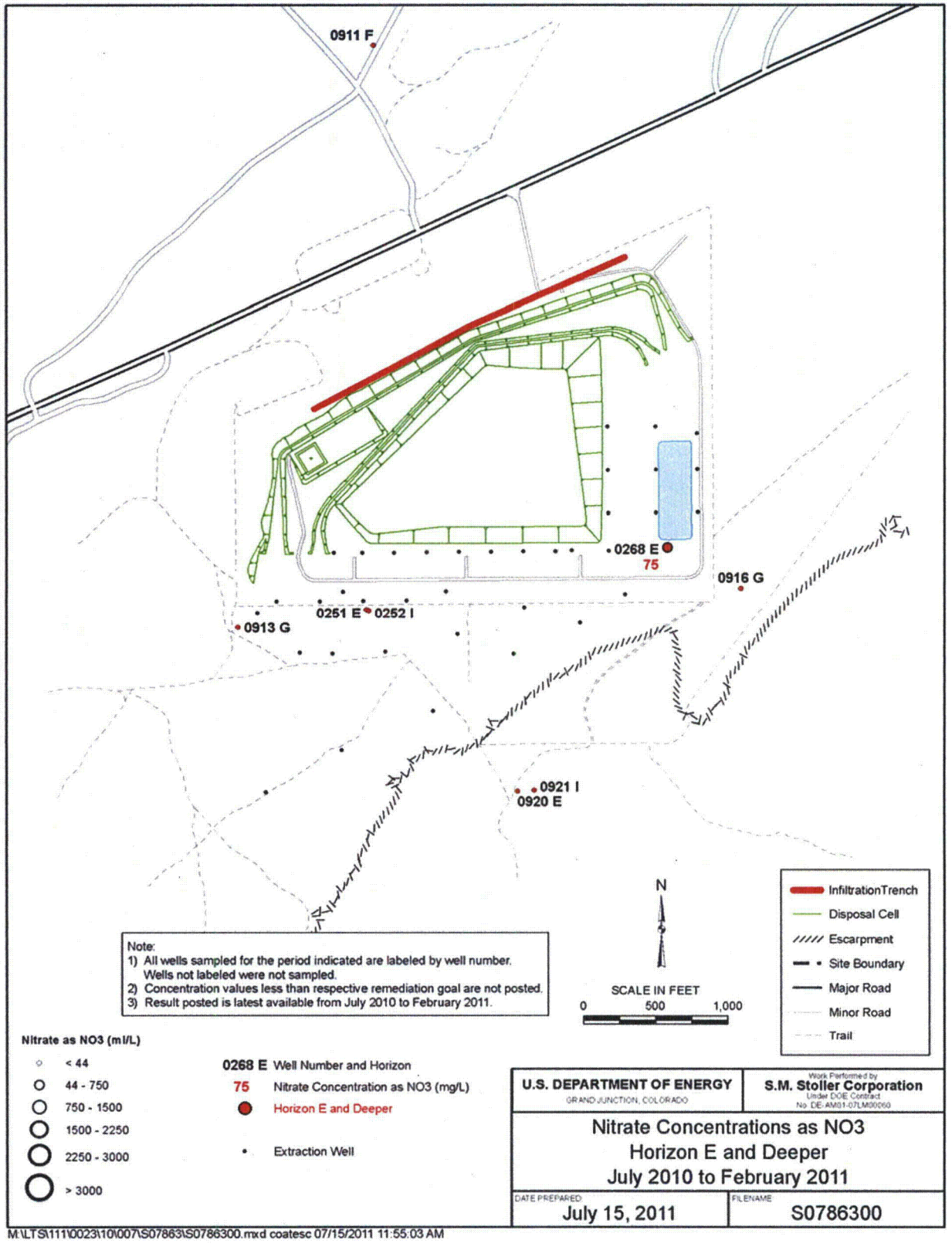

Figure 8b. Nitrate Concentrations as NO_3, Horizons E and Deeper, February 2011

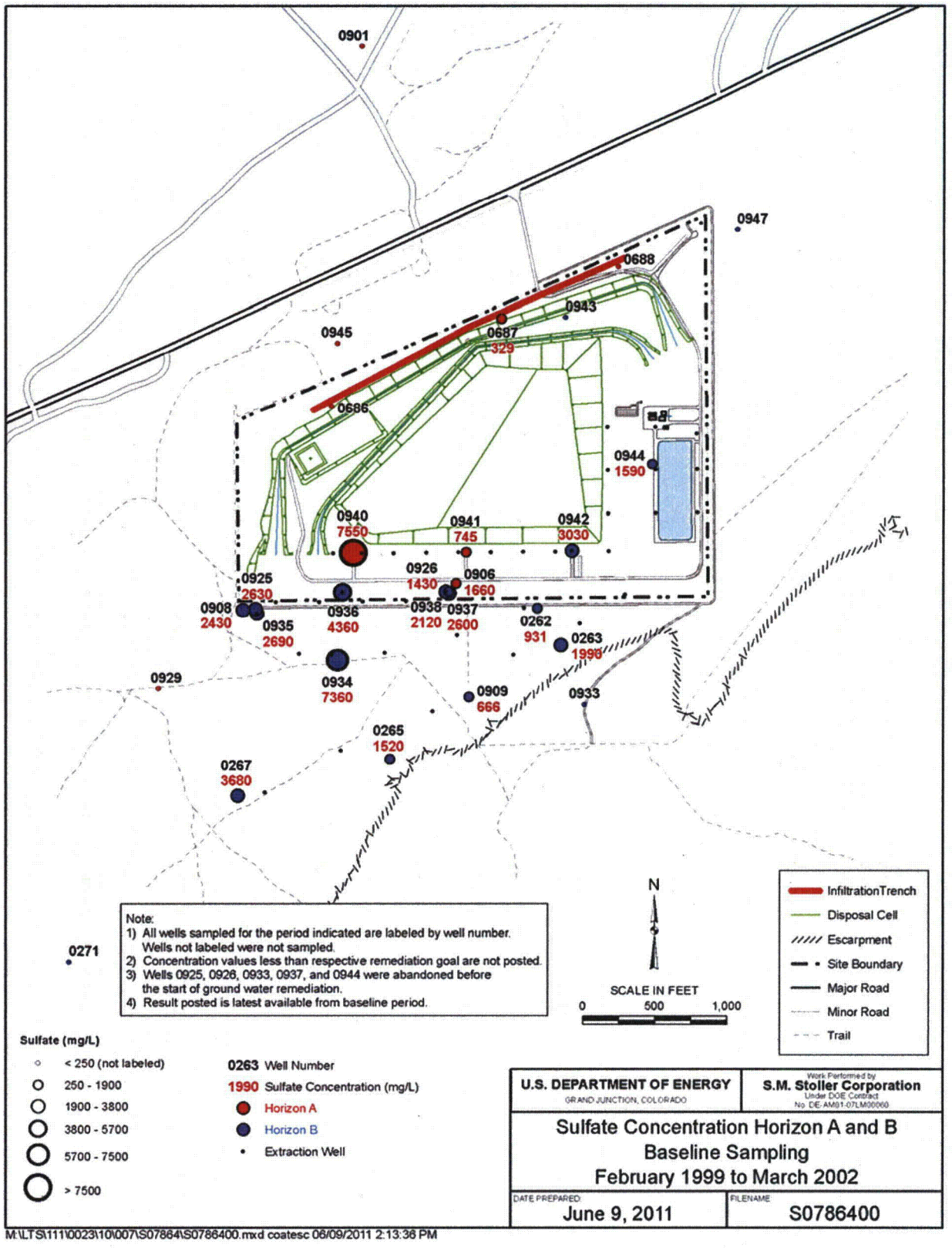

Figure 9a. Sulfate Concentrations in Groundwater, Horizons A and B, Baseline Period

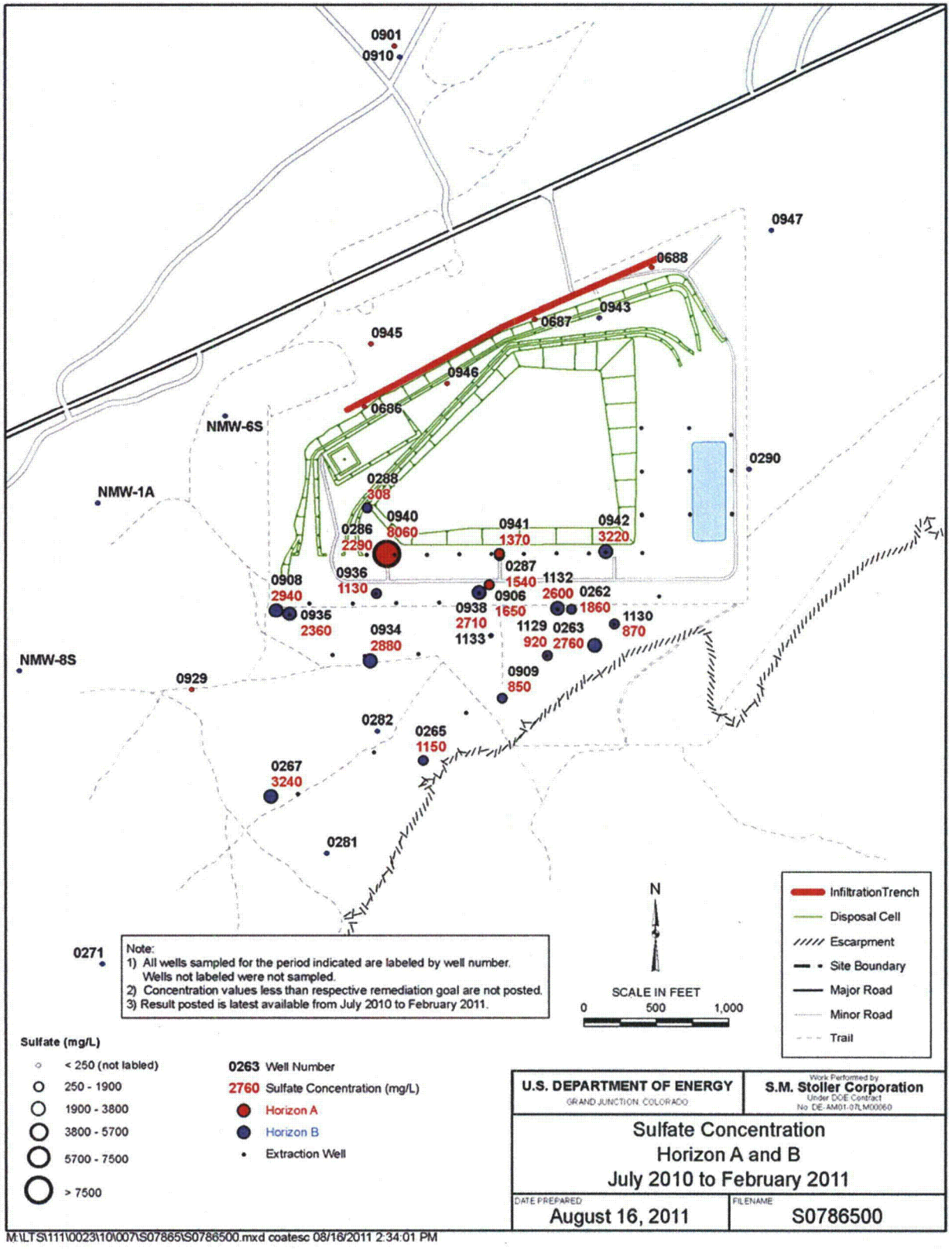

Figure 9b. Sulfate Concentrations in Groundwater, Horizons A and B, February 2011

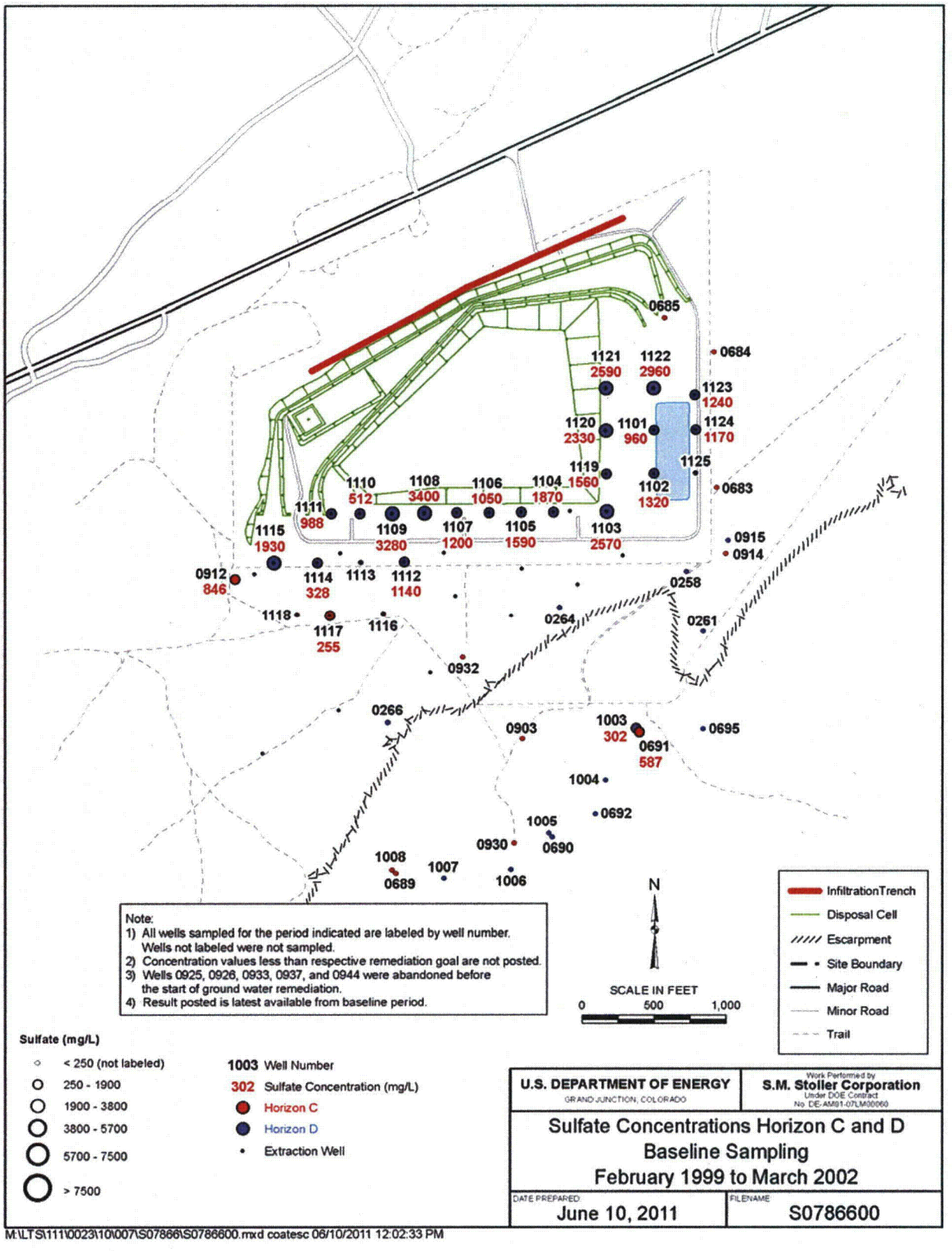

Figure 10a. Sulfate Concentrations in Groundwater, Horizons C and D, Baseline Period

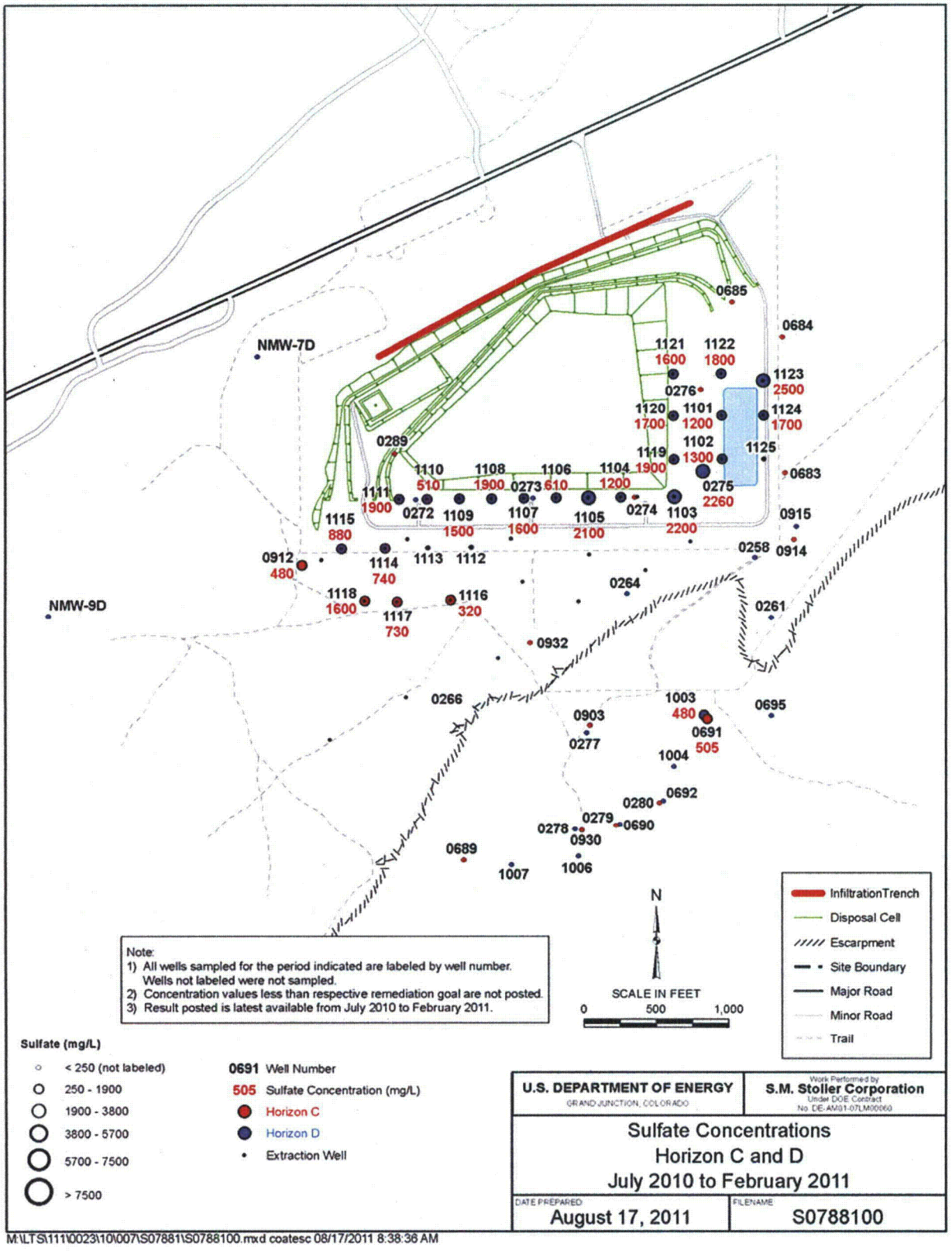

Figure 10b. Sulfate Concentrations in Groundwater, Horizons C and D, February 2011

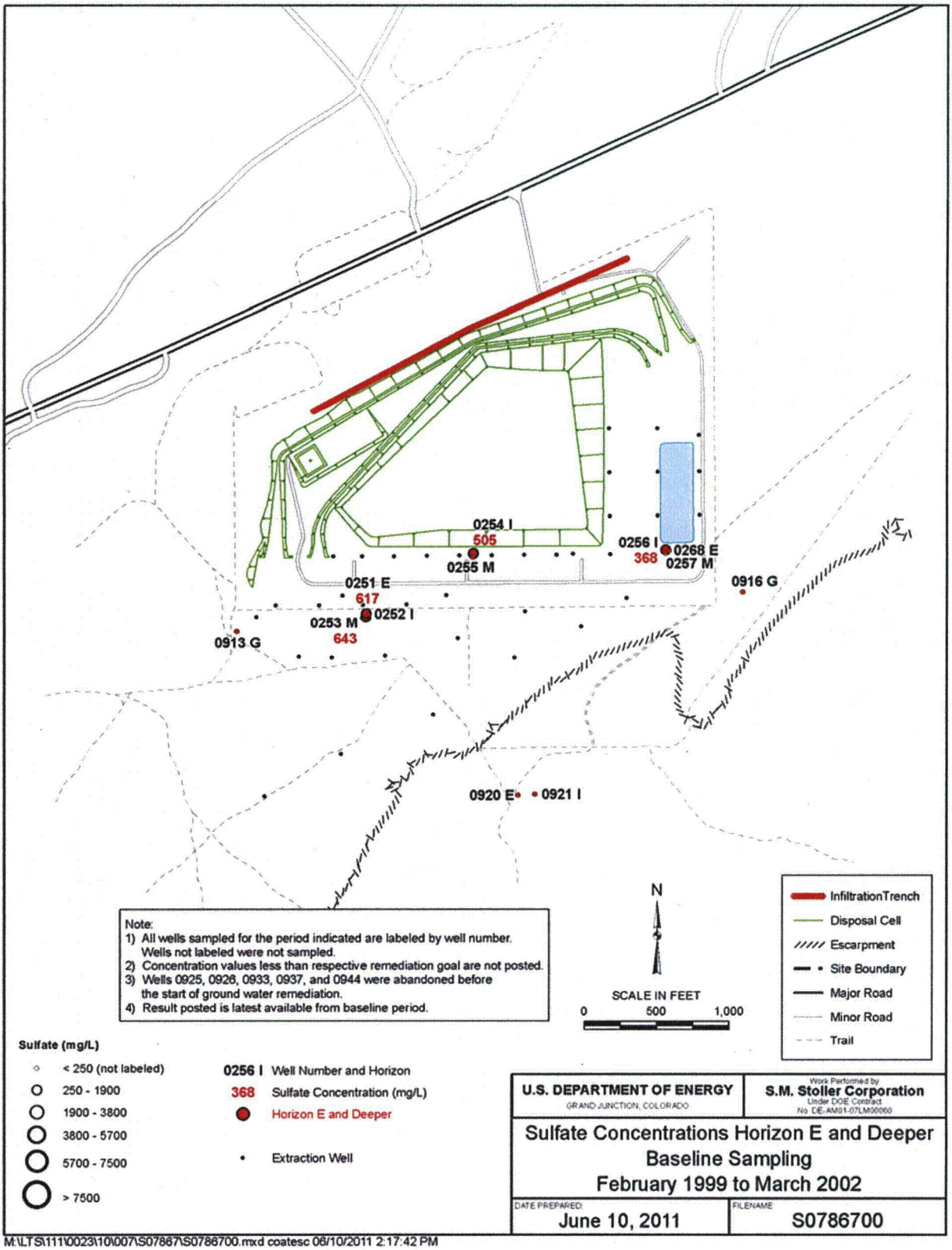

Figure 11a. Sulfate Concentrations in Groundwater, Horizons E and Deeper, Baseline Period

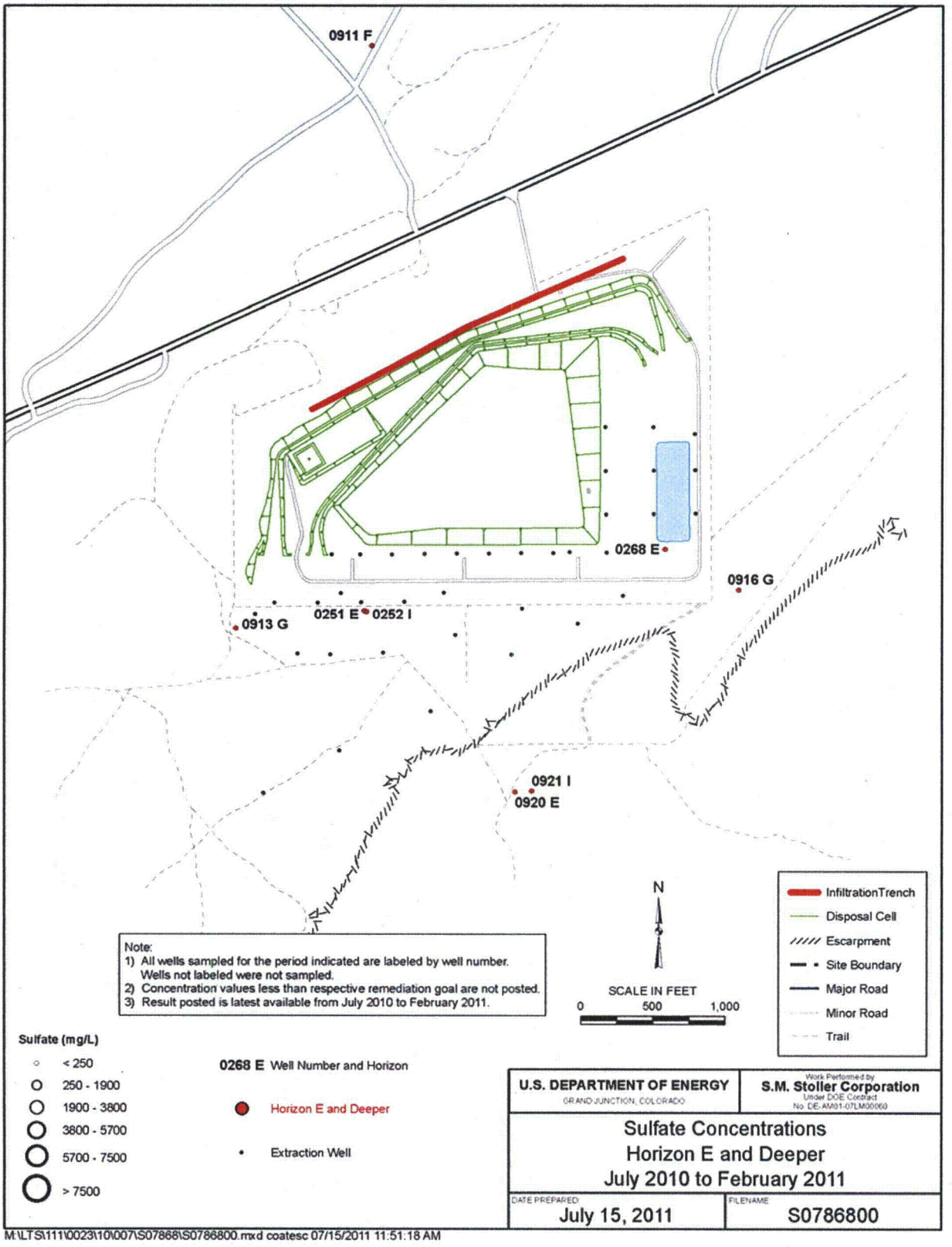

Figure 11b. Sulfate Concentrations in Groundwater, Horizons E and Deeper, February 2011

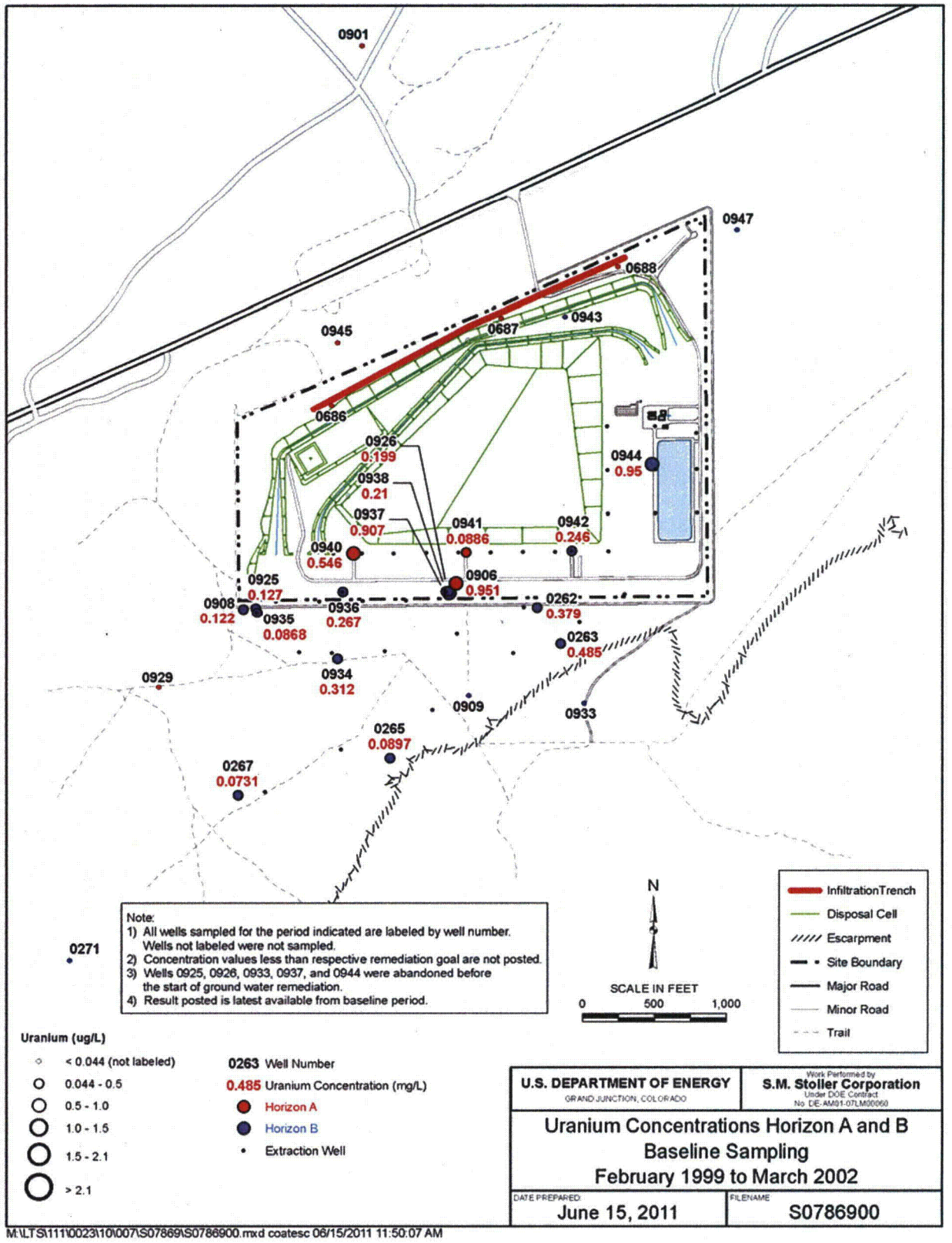

Figure 12a. Uranium Concentrations in Groundwater, Horizons A and B, Baseline Period

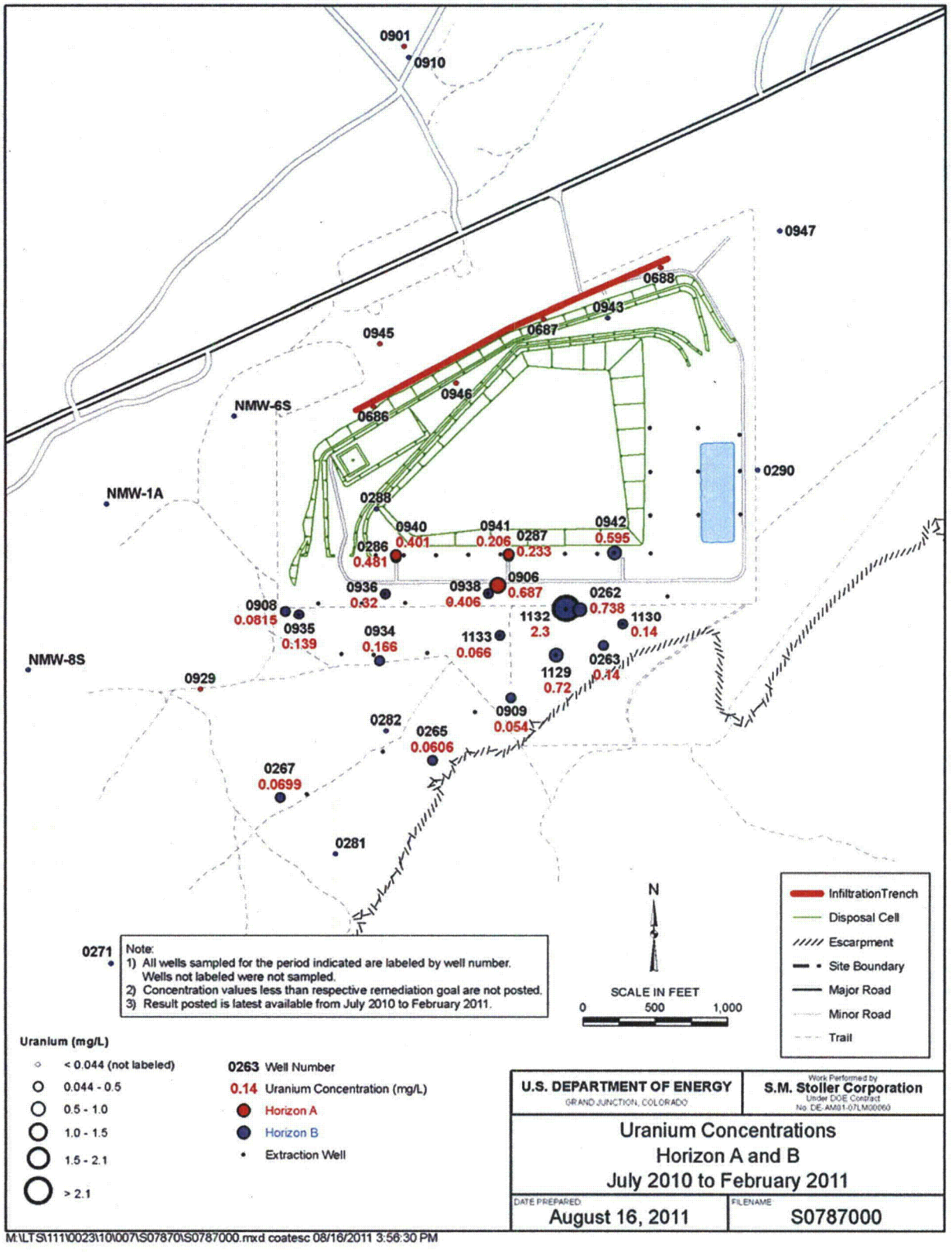

Figure 12b. Uranium Concentrations in Groundwater, Horizons A and B, February 2011

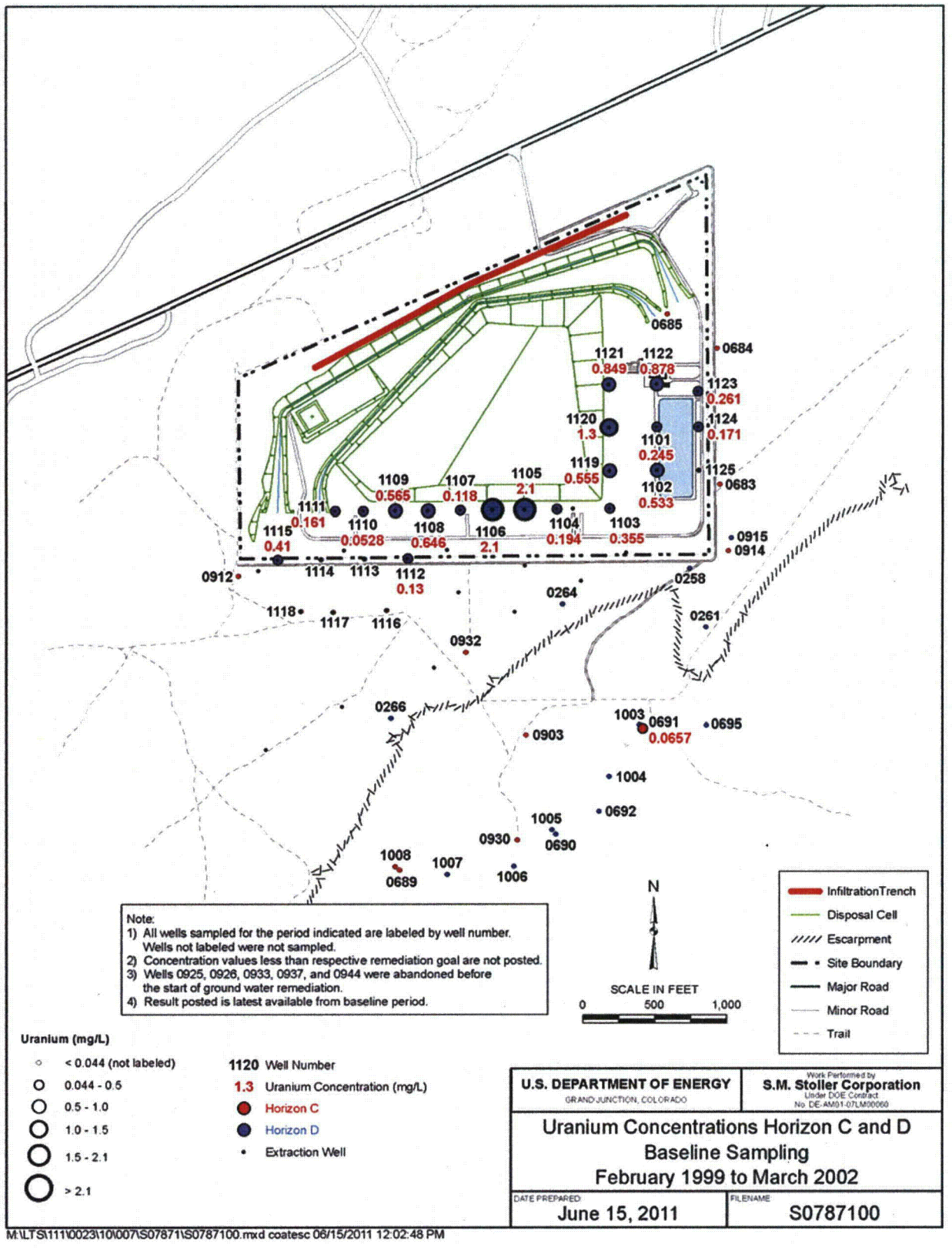

Figure 13a. Uranium Concentrations in Groundwater, Horizons C and D, Baseline Period

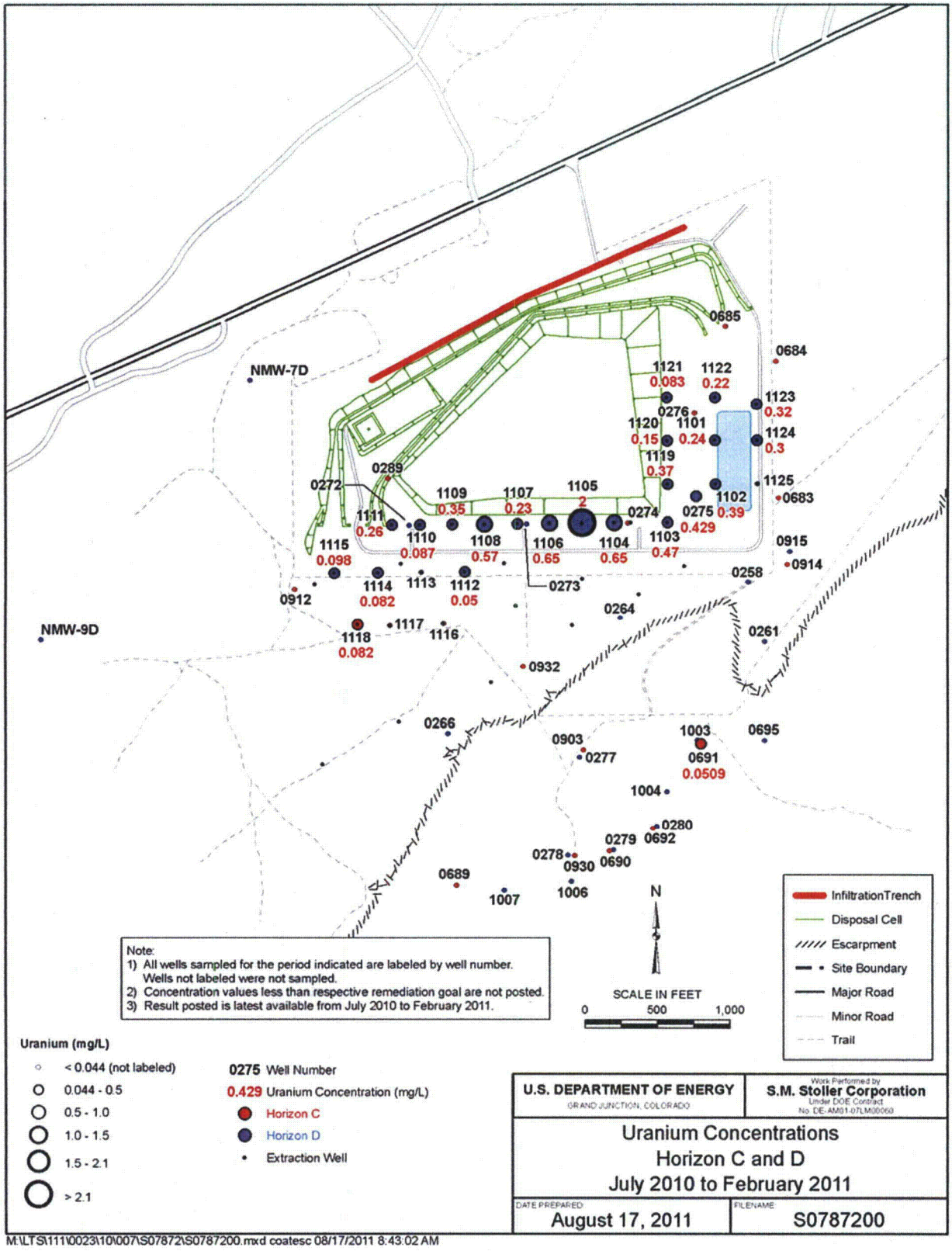

Figure 13b. Uranium Concentrations in Groundwater, Horizons C and D, February 2011

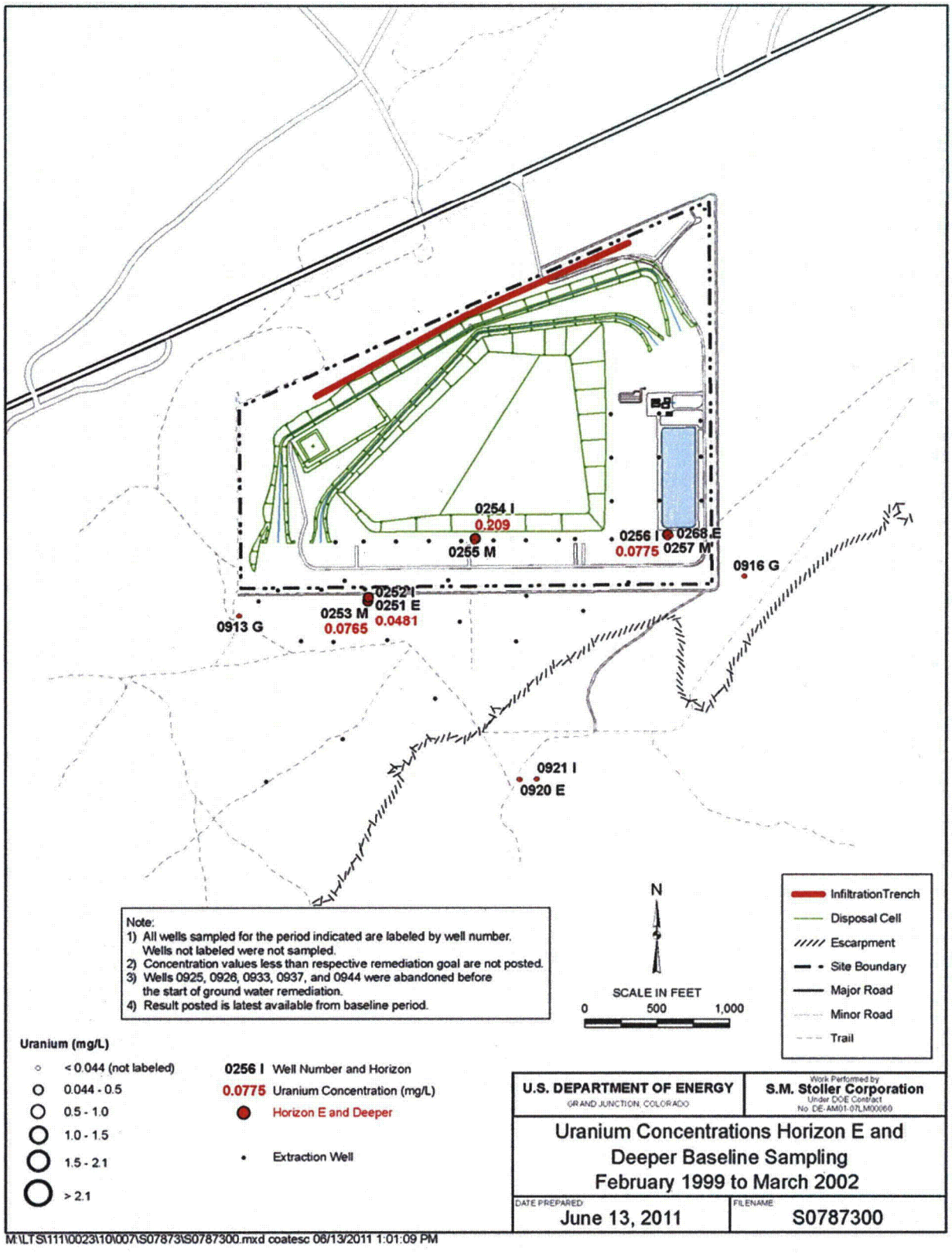

Figure 14a. Uranium Concentrations in Groundwater, Horizons E and Deeper, Baseline Period

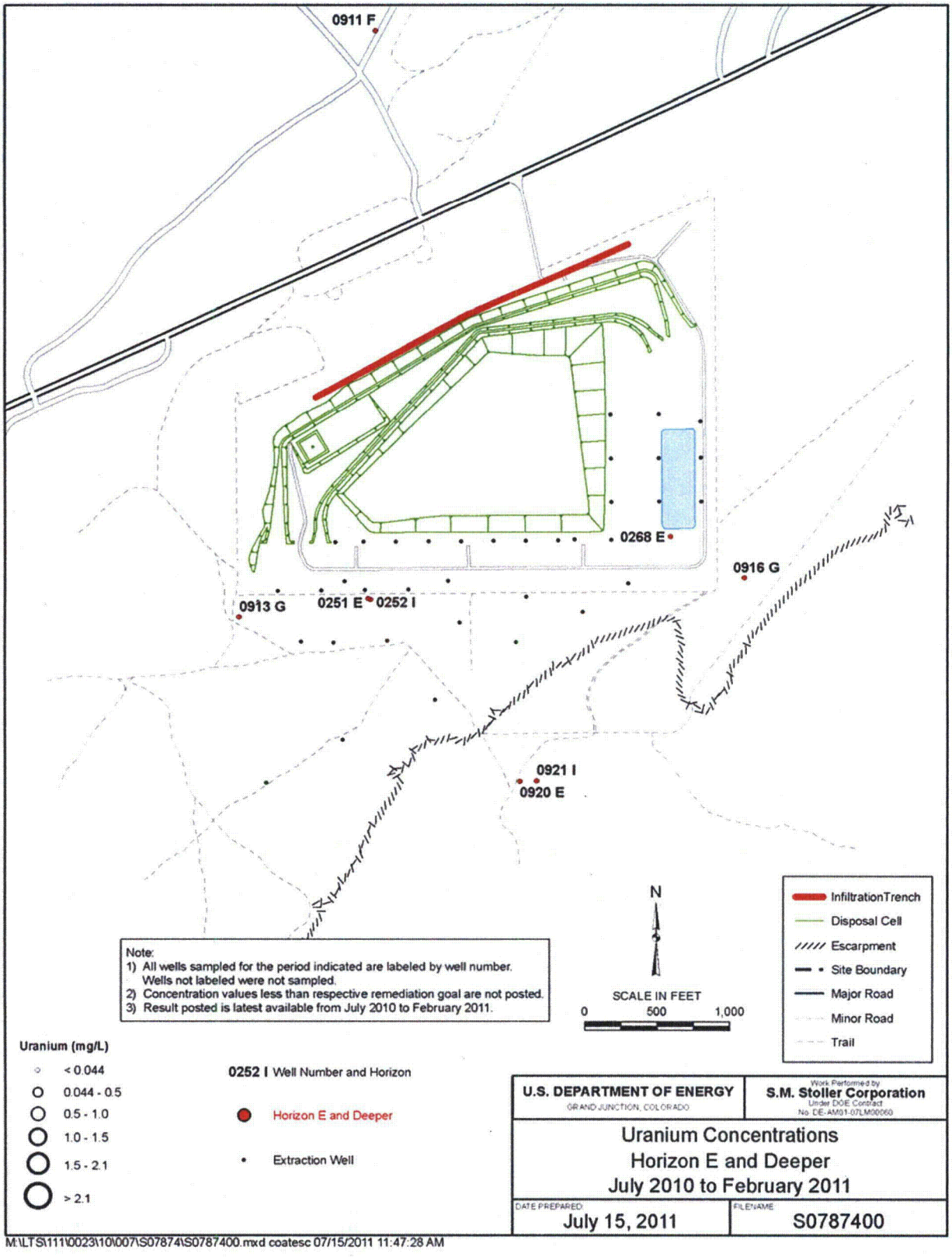

Figure 14b. Uranium Concentrations in Groundwater, Horizons E and Deeper, February 2011

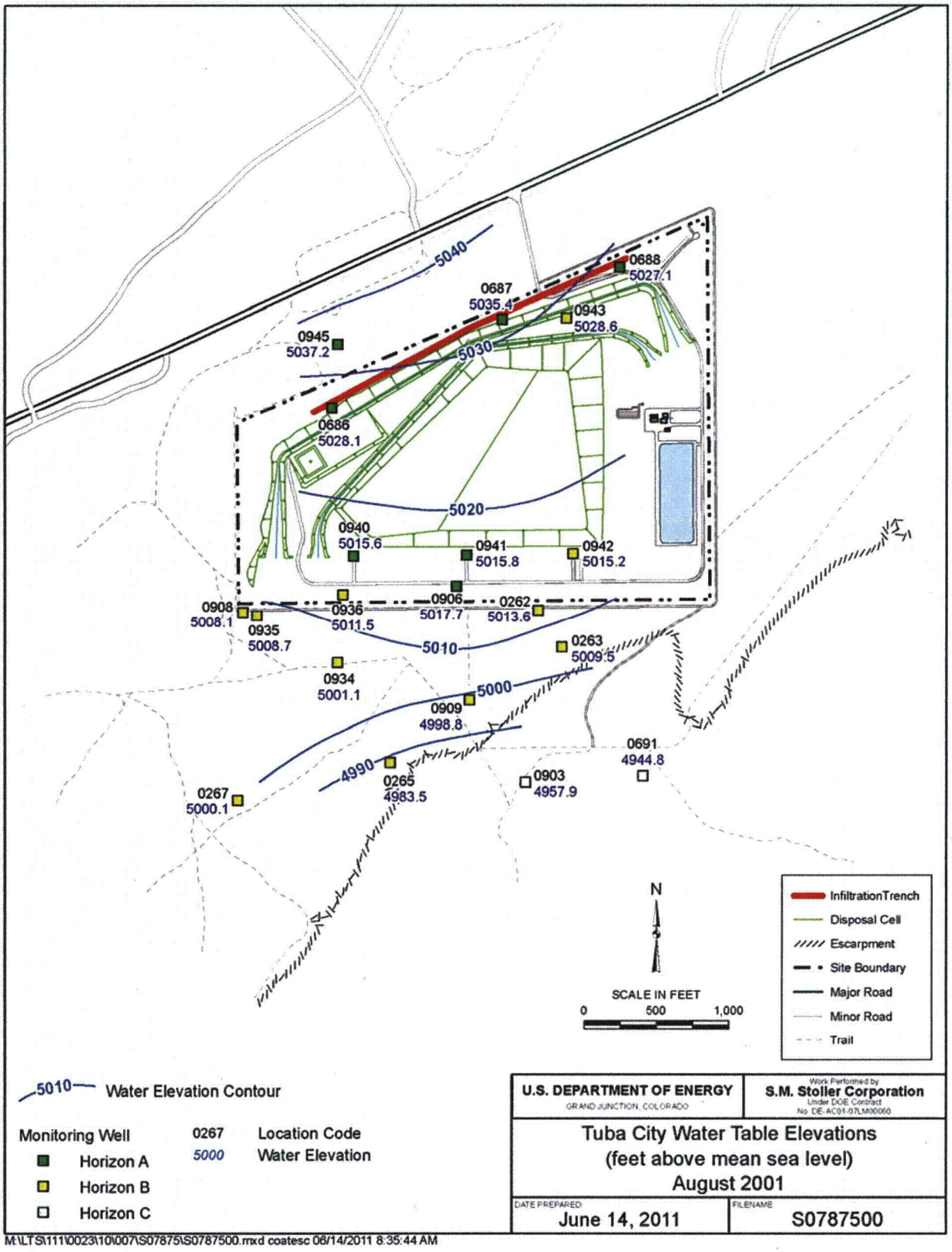

Figure 15. Water Table Elevations, Tuba City Site, August 2001

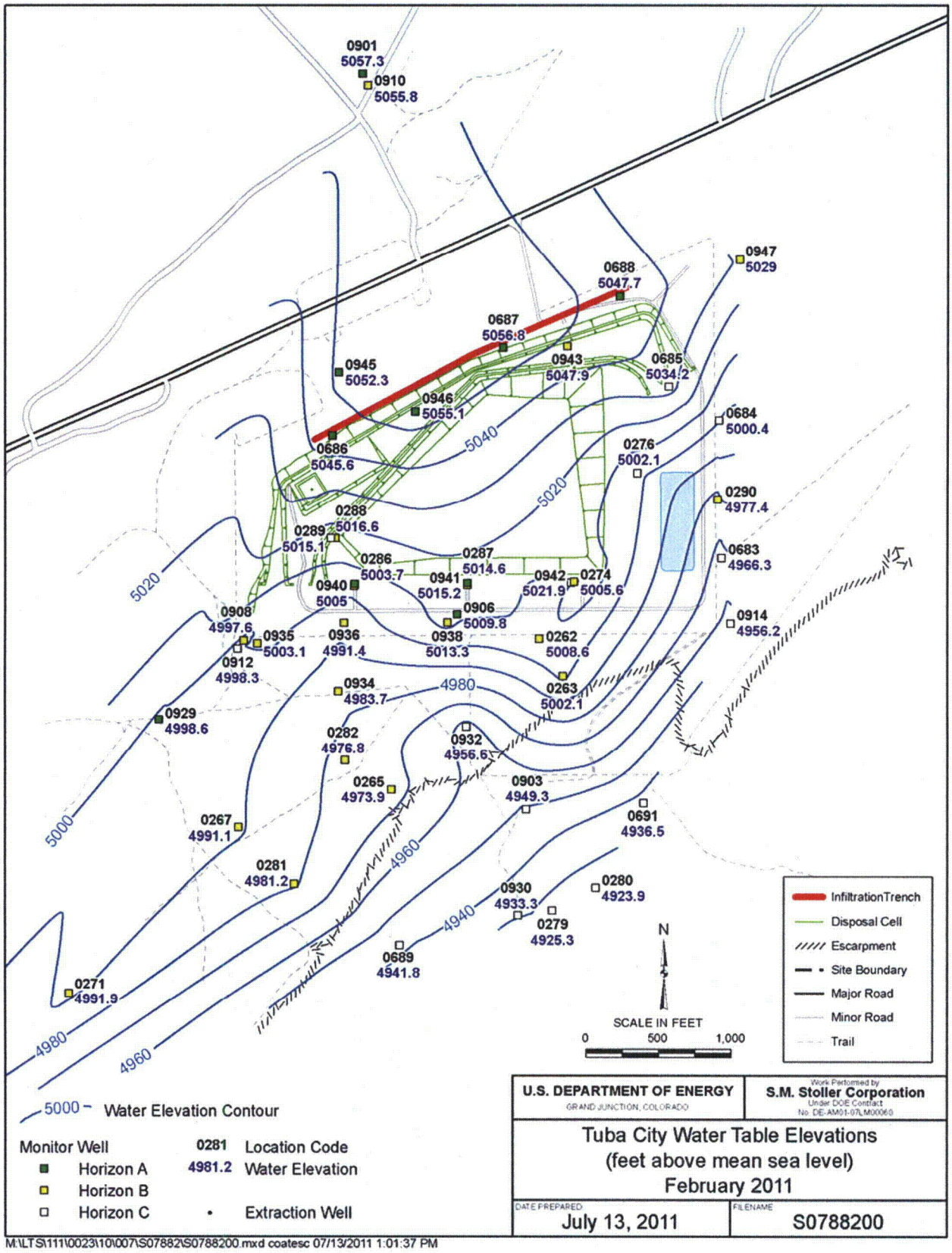

Figure 16. Water Table Contour Map, Tuba City Site, February 2011

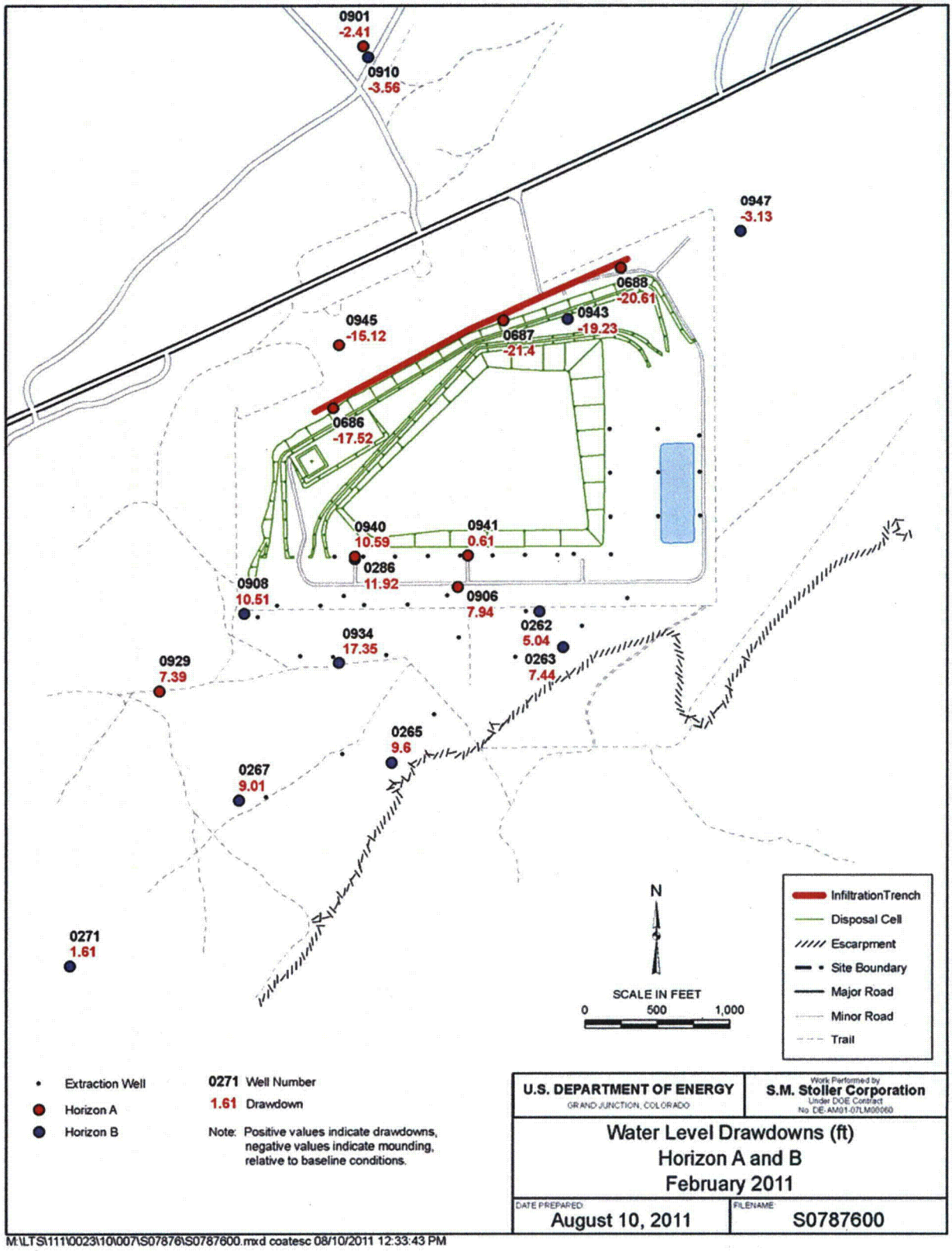

Figure 17. Water Level Drawdowns, Horizons A and B, February 2011

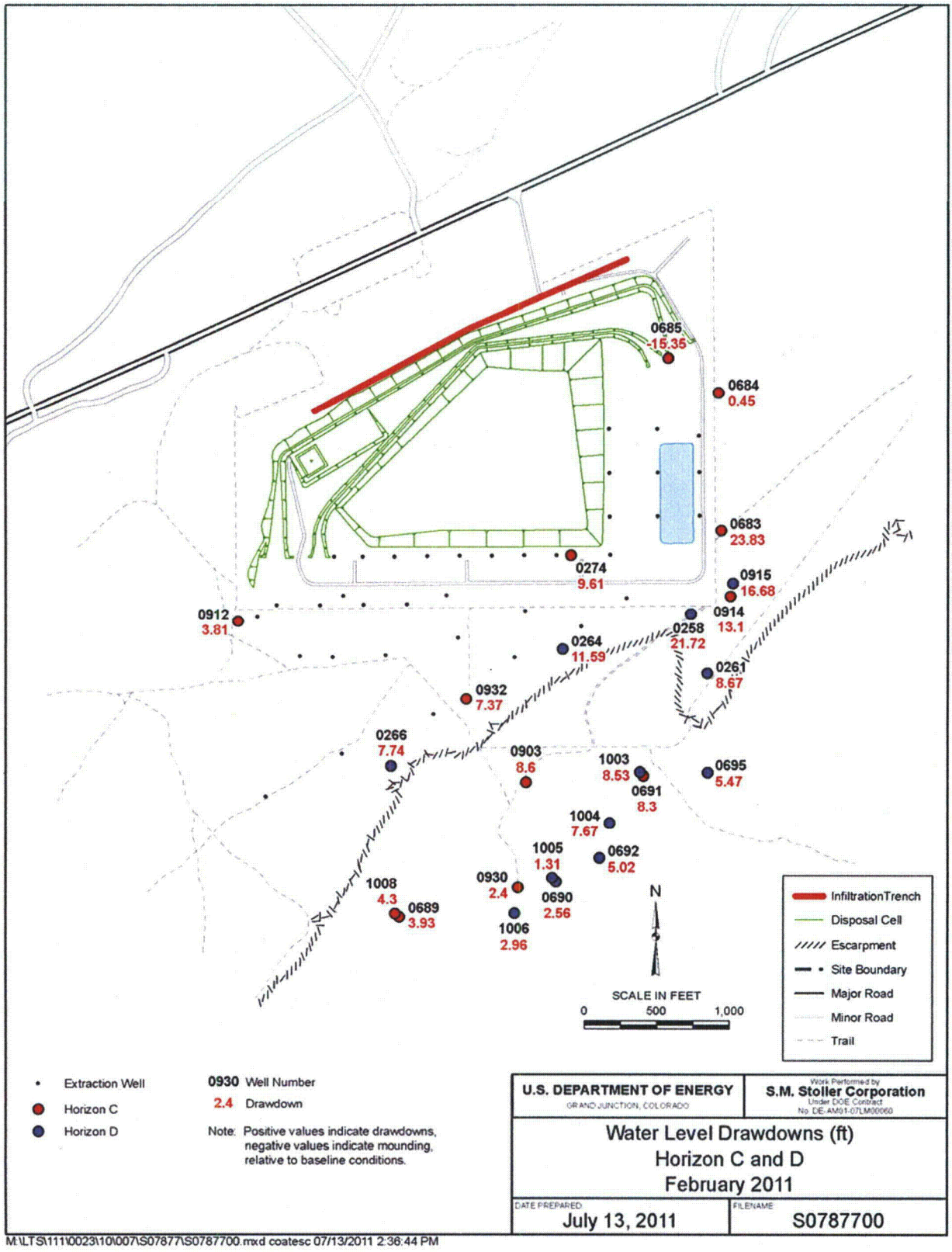

Figure 18. Water Level Drawdowns (Feet), Horizons C and D, February 2011

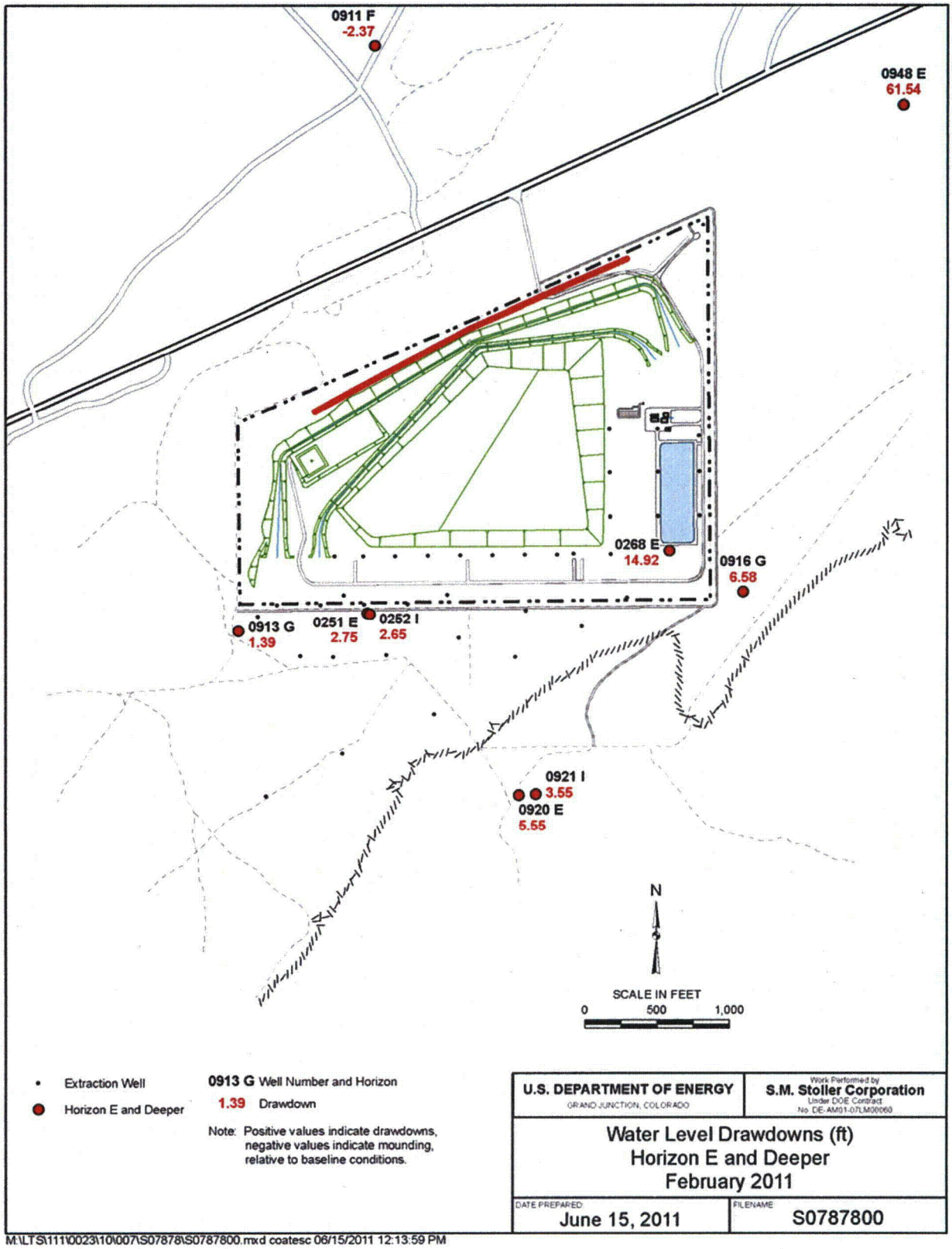

Figure 19. Water Level Drawdowns, Horizons E, F, G, I, and M, February 2011

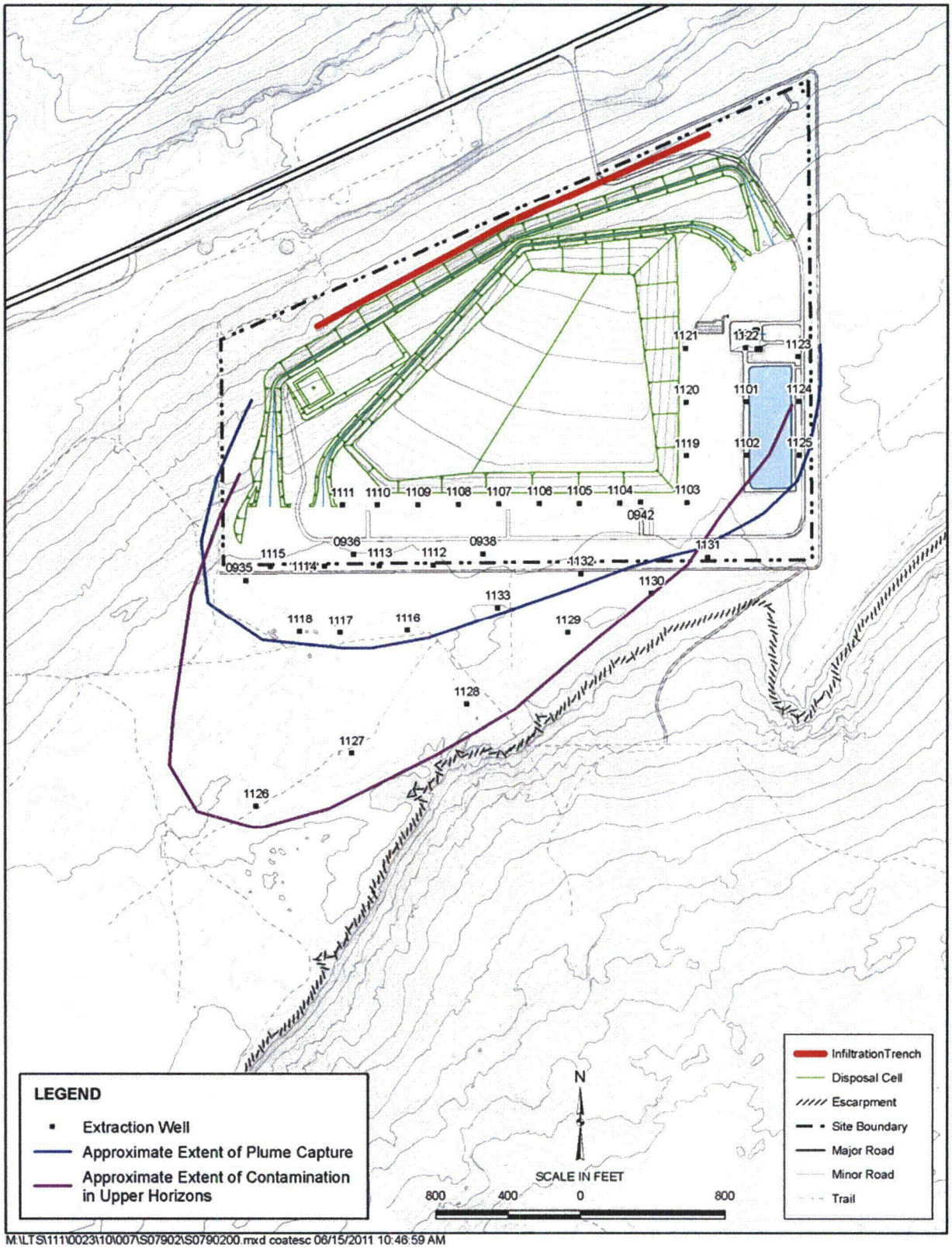

Figure 20. Approximate Extent of Groundwater Contamination and Extraction System Capture Zone, Horizons A and B

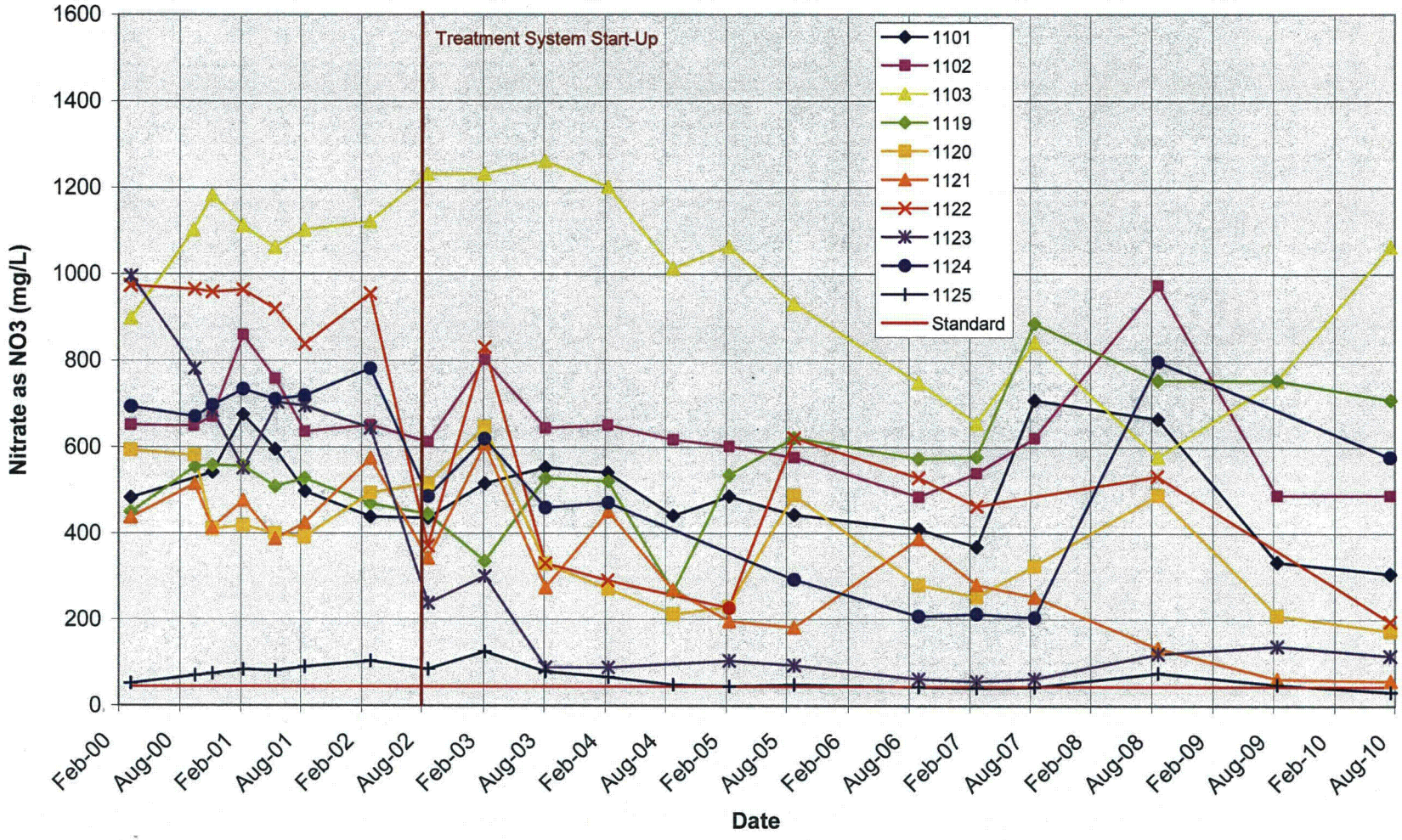

Figure 21a. Nitrate Concentration Trends at Extraction Wells 1101–1103, 1119–1125 (East of Disposal Cell)

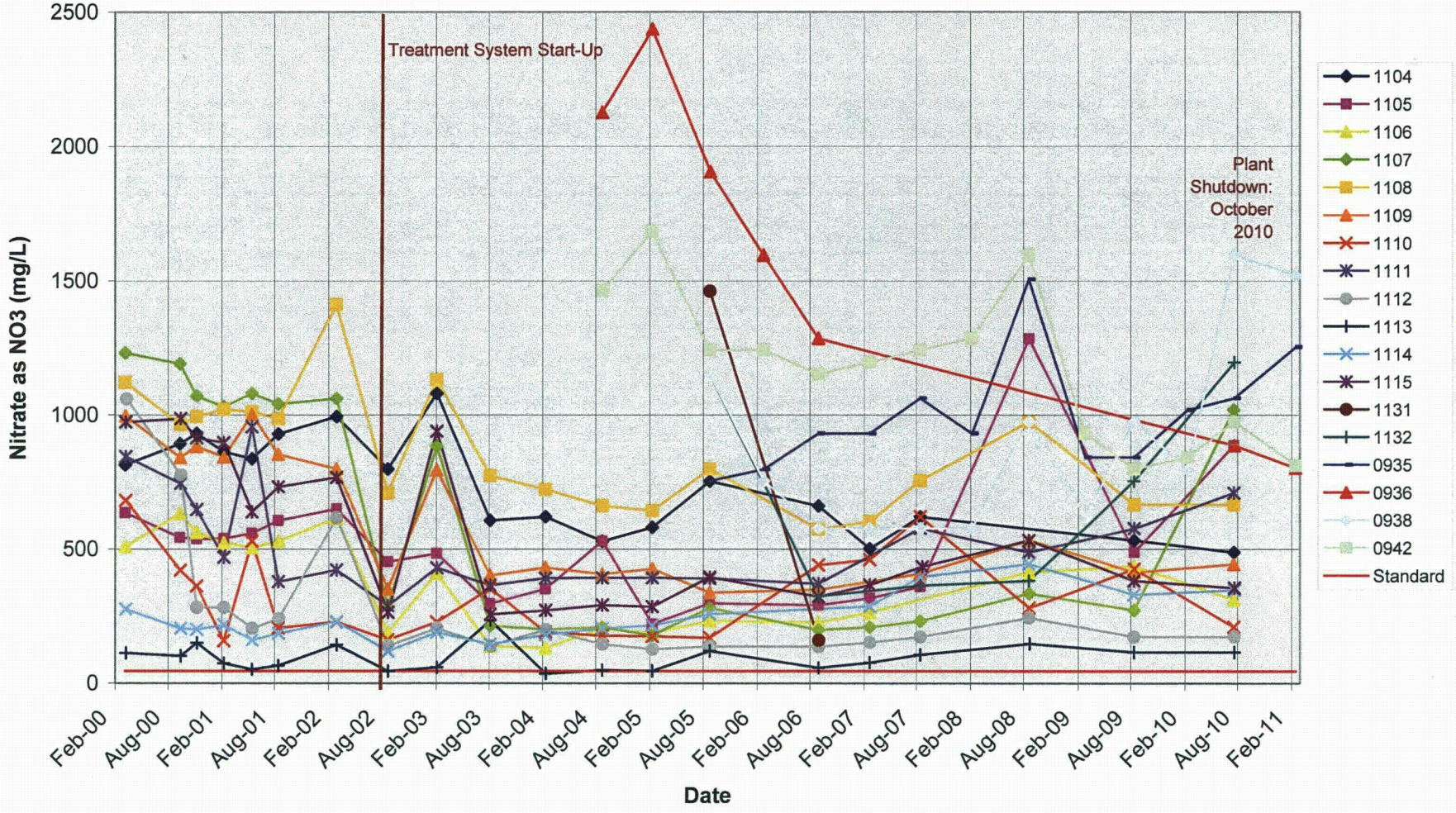

Figure 21b. Nitrate Concentration Trends at Extraction Wells 1104–1115, 1131–1132, 935, 936, 938, 942 (South of Disposal Cell at or within Site Boundary)

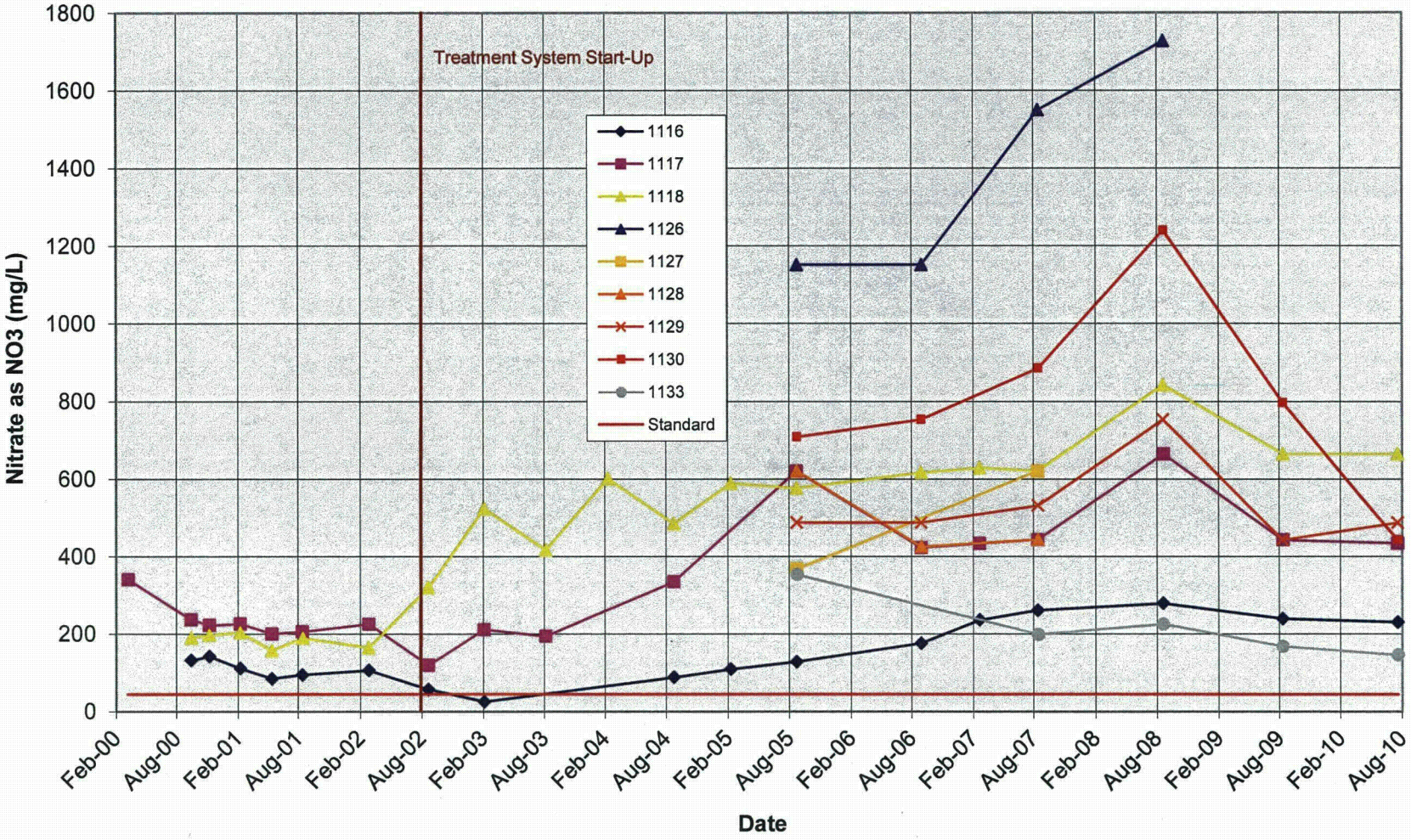

Figure 21c. Nitrate Concentration Trends at Southernmost Extraction Wells 1116–1118, 1126–1130, 1133

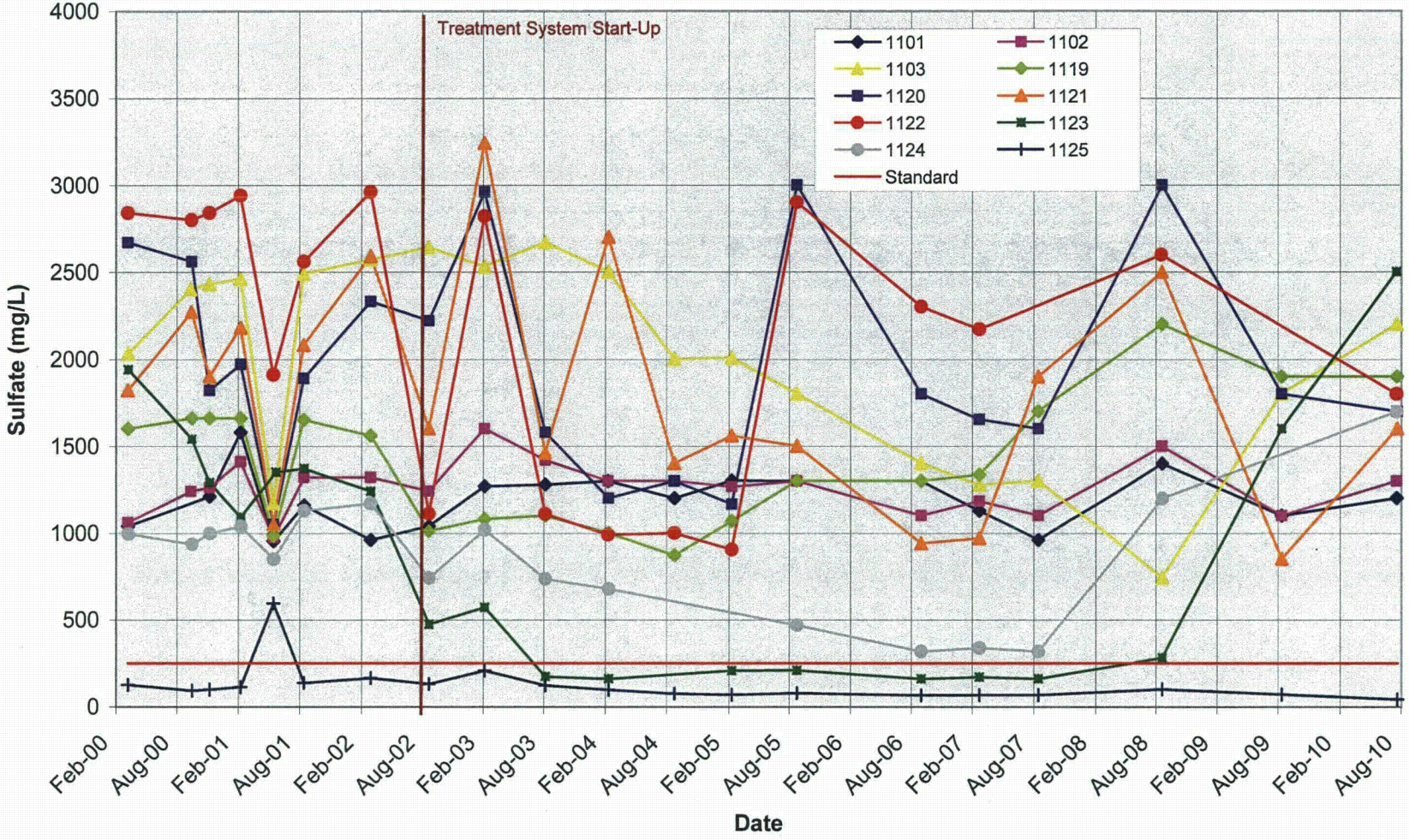

Figure 22a. Sulfate Concentration Trends at Extraction Wells 1101–1103, 1119–1125 (East of Disposal Cell)

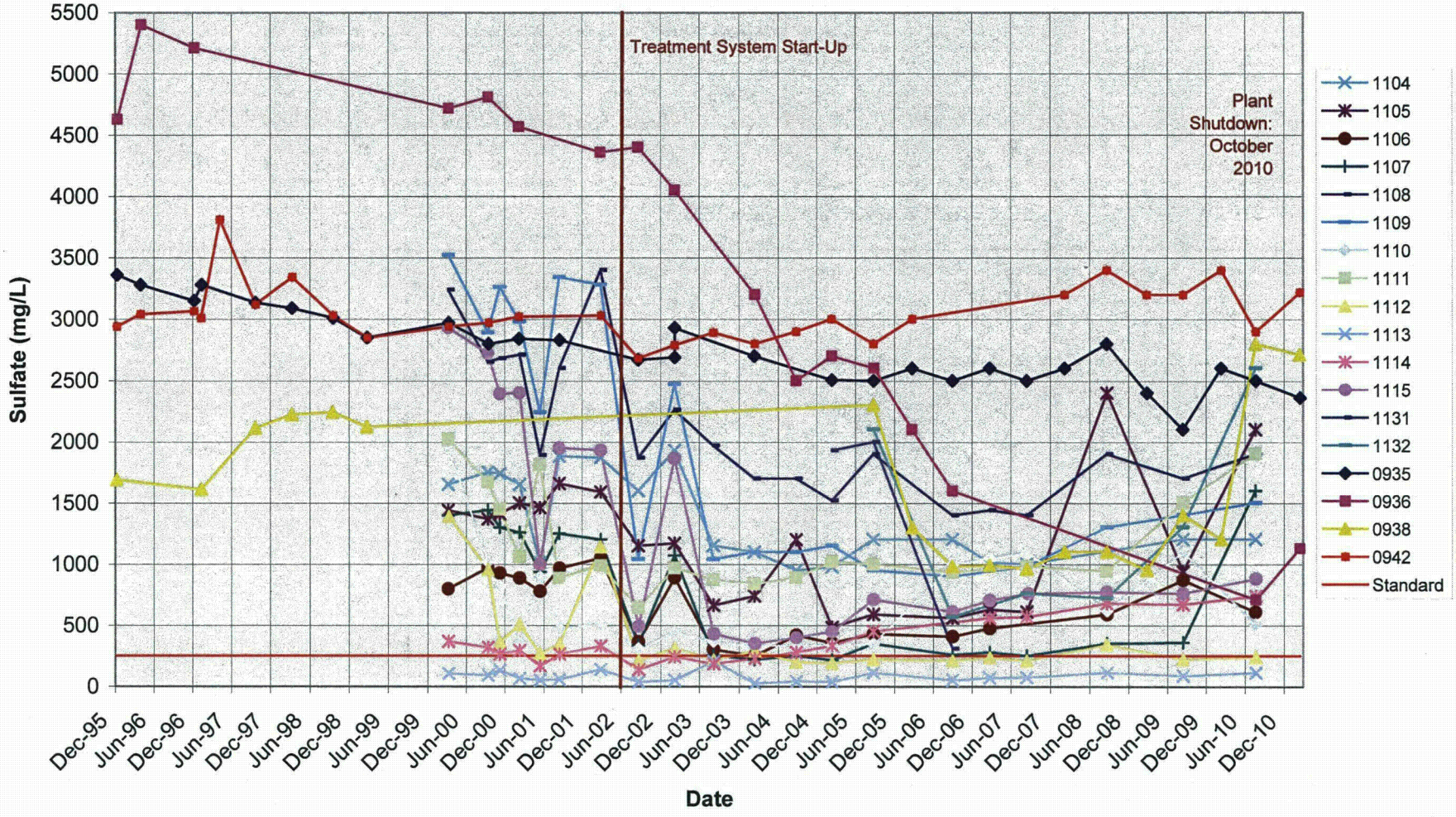

Figure 22b. Sulfate Concentration Trends at Extraction Wells 1104–1115, 1131–1132, 935, 936, 938, 942 (South of Disposal Cell at or within Site Boundary)

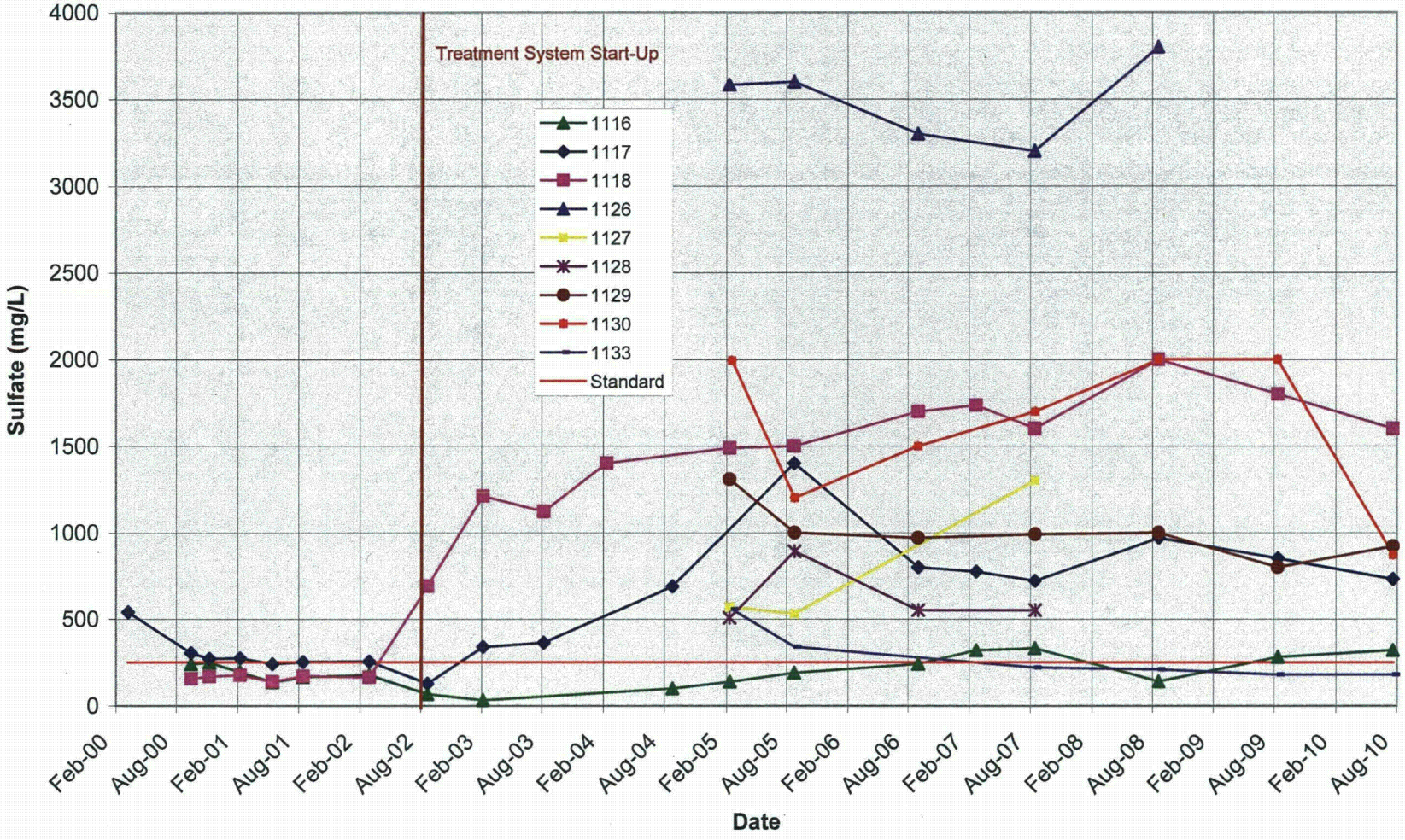

Figure 22c. Sulfate Concentration Trends at Southernmost Extraction Wells 1116–1118, 1126–1130, 1133

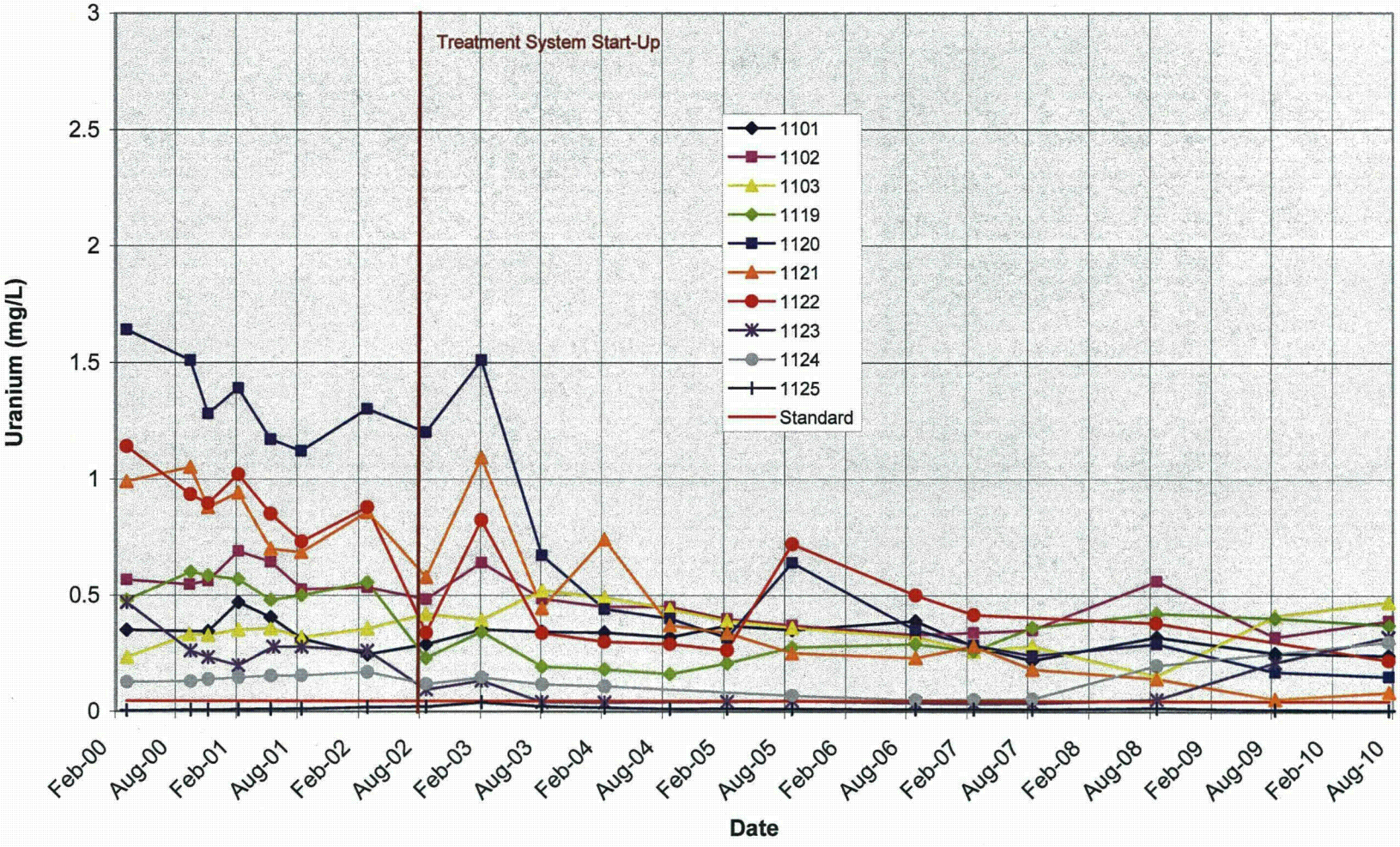

Figure 23a. Uranium Concentration Trends at Extraction Wells 1101–1103, 1119–1125 (East of Disposal Cell)

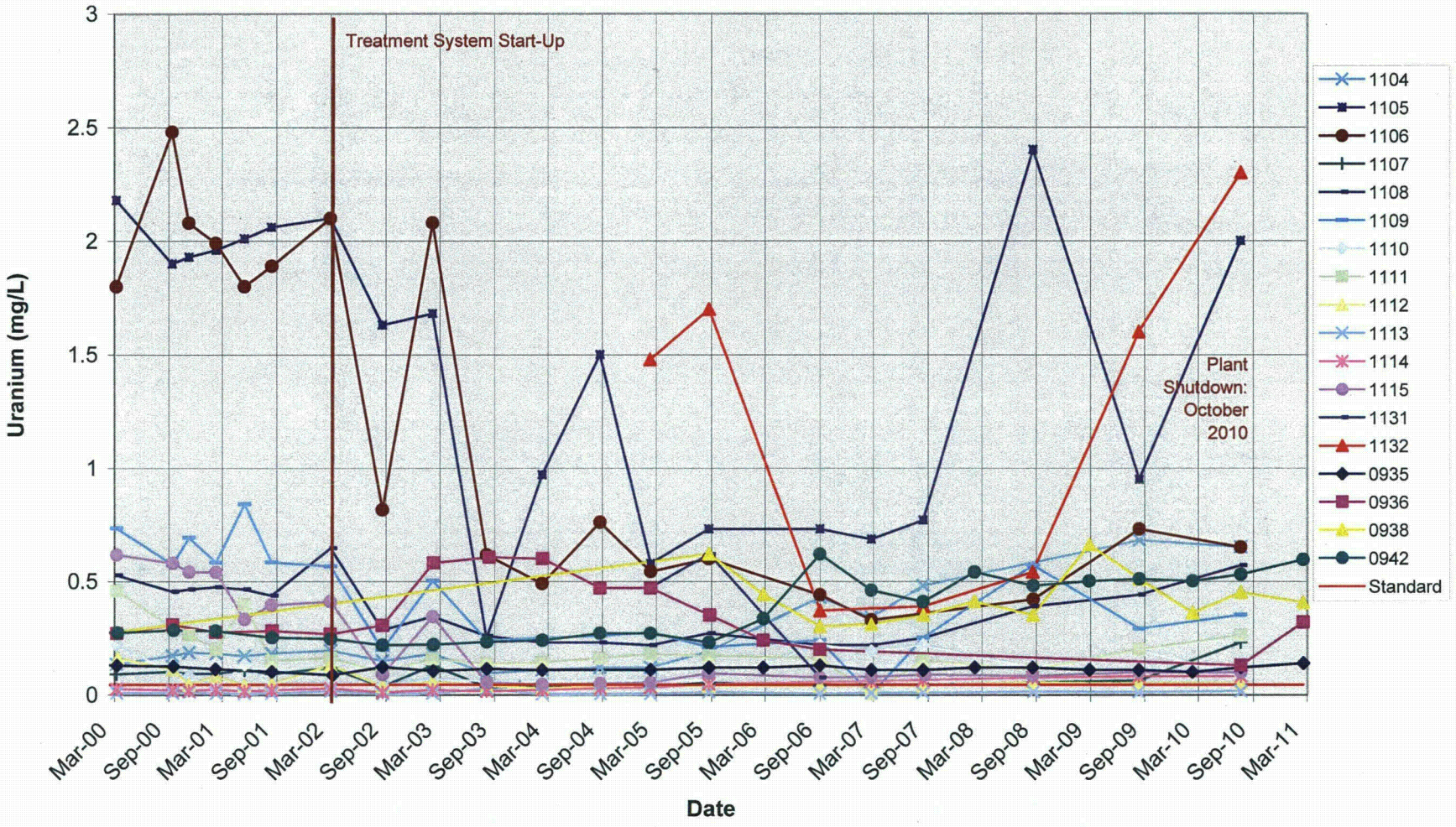

Figure 23b. Uranium Concentration Trends at Extraction Wells 1104–1115, 1131–1132, 935, 936, 938, 942 (South of Disposal Cell at or within Site Boundary)

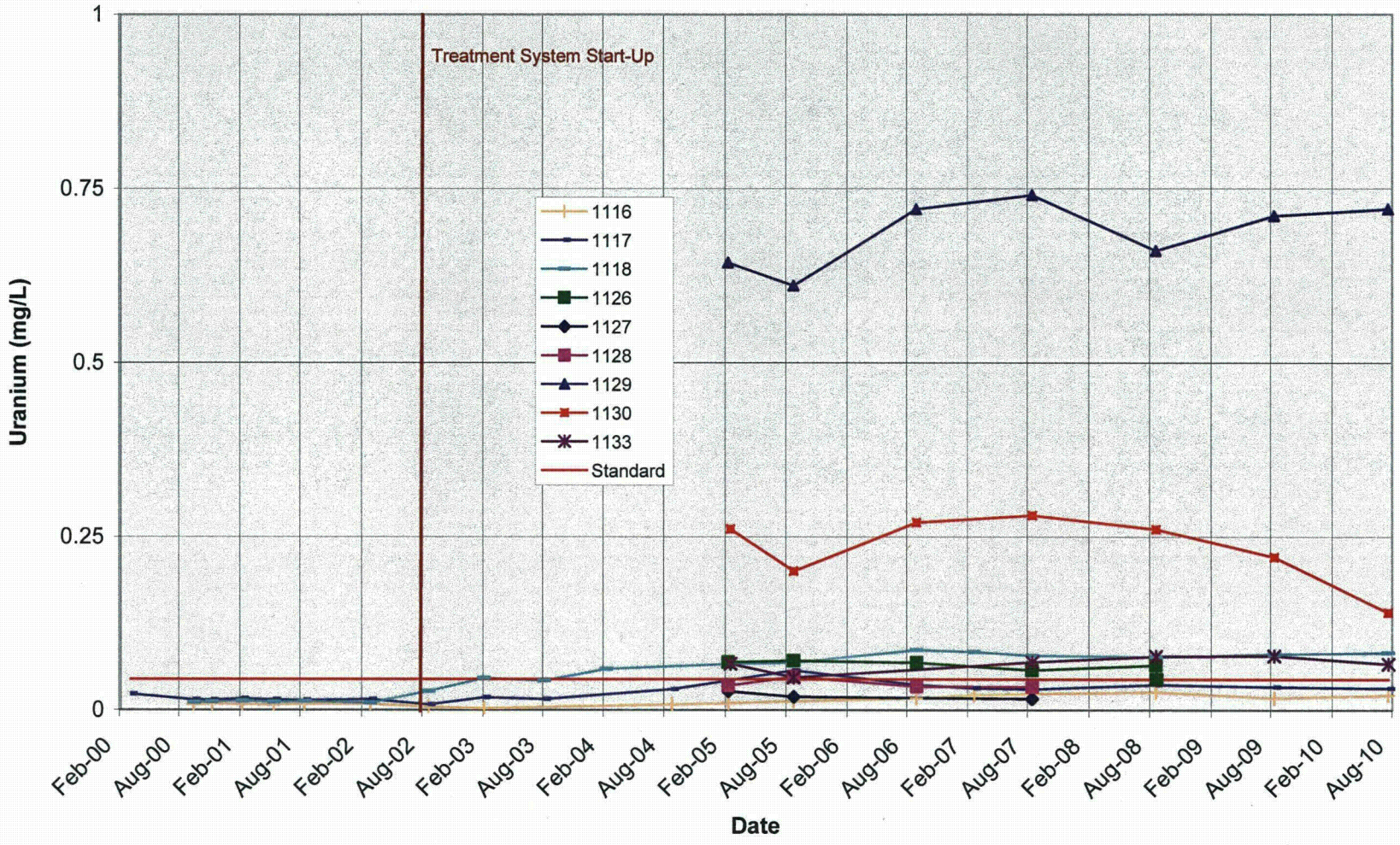

Figure 23c. Uranium Concentration Trends at Southernmost Extraction Wells 1116–1118, 1126–1130, 1133