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Annual Groundwater Report April 2007 through March 2008 Tuba City, Arizona, Disposal Site

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1.0 Introduction

1.1 Background Information

This report evaluates the performance of the groundwater remediation system at the U.S. Department of Energy (DOE) Office of Legacy Management site near Tuba City, Arizona, for the period April 2007 through March 2008, and cumulatively. The site is located in Coconino County, Arizona, within the Navajo Nation and near Hopi Reservation land (Figure 1). A former uranium-ore 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 evaporation ponds and slurry-emplaced tailings during mill operation, extends off site to the south and southeast in the underlying bedrock sandstone aquifer. The primary site contaminants in groundwater are nitrate, uranium, and sulfate. DOE constructed a pump-and-treat remediation system, operational by mid-2002, to remove contamination from the aquifer and restore groundwater quality. The progress of water quality restoration is evaluated and reported annually.

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 mechanically distilled following ion exchange pretreatment. An engineered solar evaporation pond receives the waste liquid (brine), and an infiltration trench located upgradient of the contaminant plume receives the treated water (distillate), where it is returned to the aquifer to promote the restoration process. Six injection wells (wells 1003 through 1008) originally intended to create a hydraulic barrier at the downgradient limit of contamination remain unused for that purpose. 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). Wells 935, 942, 936, and 938, used formerly for monitoring purposes only, were converted to extraction use in summer 2004. Numerous other groundwater monitor wells used to track water quality and water level trends are situated within and surrounding the network of extraction wells. The locations of extraction and monitor wells and the primary features of the site are depicted in Figure 2.

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 comprise 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). Restoration standards (see Table 1) for these

constituents, except sulfate, correspond to a maximum concentration limit in groundwater established in Table 1 of 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 groundwater at the site at concentrations that cause excess potential risk (DOE 1999). The Navajo Nation also requested that the distillate not exceed 20 milligrams per liter (mg/L) of sodium.

Table 1. Groundwater Remediation Targets
(source: DOE 1999)

Constituent/Property	Cleanup Level	Baseline Concentrations in Plume
Nitrate[a]	10 mg/L as N (44 mg/L as NO_3^-)	840–1,500 mg/L
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
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
pCi/L = picocuries per liter

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 partly on the basis of groundwater monitoring conducted in August and February of each year. During these events, samples are collected at monitor 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, plume movement within the aquifer, and concentration trends. The extraction wells are sampled during the August events. The February events also exclude monitoring of several distal wells and lower terrace wells that have no history of contamination.

Other information used in evaluating the effectiveness of the groundwater remediation system includes the 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) 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

The Tuba City site lies on the middle of three alluvial terraces formed during ancestral flow in Moenkopi Wash, located about 1.25 miles southeast of the site. The terraces are composed of thin (≤ 20 feet [ft]) surface deposits of coarse, semi-indurated, Quaternary alluvium. Loose dune

sand and silt mantle the terraces and terrace gravels 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 one 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, relicts of former playa lakes, are interspersed throughout both the classic and intertonguing intervals. The Kayenta Formation consists primarily of 100 ft or more of less resistant, fine-bedded, red silt and fine sand, lacking the characteristic cross-beds of the Navajo Sandstone.

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 nature of the Kayenta Formation locally, it is not water bearing and is considered as the base of the “N” aquifer in this 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. Groundwater flow beneath the site is 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 typically 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. Figure A−1 in Appendix A depicts a conceptual model of the site hydrogeology.

1.5.1 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. These designations are convenient for evaluating the site hydrogeology and depth of contamination. The top of the middle terrace, nominally 5,050 ft in elevation, marks the top of the uppermost horizon, Horizon A.

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. Because contamination of the aquifer is limited in depth, 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 horizon are shown in Figure A−1 of Appendix A. In Figure 2, color-coding identifies the corresponding horizon in which the mid-point of the screen

of each well is located for extraction wells (round symbols) and monitor 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 includes additional well completion information such as screen length and elevations.

2.0 Treatment and Extraction Systems

2.1 Bulk Treatment Parameters

During the current review period of April 2007 through March 2008, the treatment plant operated for about 352 of 365 total days, for a net on-stream factor of 96 percent. Power failures and scheduled maintenance requiring plant shutdown account for the majority of downtime. About 41 million gallons of water were treated during this period, resulting in an average operating rate of 81 gallons per minute (gpm) and an effective rate (downtime included) of 78 gpm. The operating capacity of the treatment plant is about 120 gpm. This rate is not attained because of limited formation yield to the extraction system. Figure 3 indicates that the bulk extraction rate has decreased over time; possibly because a quasi-steady-state cone of depression is yet to be attained, as the aquifer thickness continues to decrease in response to dewatering. Total groundwater treatment as of April 1, 2008, was approximately 266 million gallons, equivalent to about 22.5 percent of the total estimated volume of uranium-contaminated groundwater prior to remedial action (see Section 4.0 for discussion of contaminant removal rates).

Figure 3 shows the feed rate to the treatment plant and the corresponding concentration of nitrate and sulfate determined from weekly composite samples since the start of remediation. This figure indicates relatively stable concentrations of these constituents entering the treatment system at typical inflows. As seen in Figure 4, uranium concentration in the bulk feed shows a slight downward trend over the same period (concentration trends are further addressed in Section 4.0). The masses of nitrate, sulfate, and uranium extracted during the current review period, estimated from the weekly monitoring of bulk inflow to the treatment plant, are 137,162 pounds (lbs); 358,893 lbs; and 82 lbs, respectively (Table 2).

Table 2. Treatment System Performance Summary

Contaminant	Typical Feed Concentration (mg/L)	Average Distillate Concentration (mg/L)	Mass Removed During Review Period (lbs)
Nitrate (as NO_3)	350	17	137,162
Sulfate	1,000	59	358,893
Uranium	0.24	0.01	82

2.2 Distillate Quality

Concentrations of nitrate, sulfate, and uranium in the distillate averaged 17, 59, and 0.01 mg/L, respectively, during the review period (Table 2 and Figure 5). Total dissolved solids (TDS) ranged between 54 and 220 mg/L (114 mg/L average), and chloride concentrations were

generally about 3 mg/L with little variation. These results indicate highly effective contaminant removal and very high quality of water returned to the aquifer.

2.3 Treatment System Water Budget

About 38 million gallons, or 91 percent, of the total feed to the treatment system was returned to the aquifer at the infiltration trench over the past year. Treatment system wastewater sent to the evaporation pond comprised about 4 percent of the total inflow as brine and about 5 percent as loss for softener regeneration. Water levels in the evaporation pond continue to remain safely below the maximum operating level.

2.4 Extraction Wells

In Figure 2, 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 completes 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 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 monitor 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.

The operational history of each extraction well for the evaluation period is included in Appendix A, Table A−2. Extraction well data are not available for July 26 to August 16, 2007, and for February and March 2008. Pumping is generally continuous at wells 1101 to 1125. Among these wells, steady pumping rates range between about 1 and 6 gpm and average about 3.5 gpm. The contribution from wells 1101 to 1125 is 96 percent of total production. Continuous pumping is not sustained at wells 1126 to 1133 because of low aquifer yield. The on-stream time for these wells is indicated to be less than 5 percent. During the remaining time, the pumps are off to allow water level recovery. Pumping is discontinuous at wells 935, 936, 938, and 942 because the well screens intercept only 2 or 3 ft of the water table.

3.0 Groundwater Capture Analysis

3.1 Extent of Groundwater Contamination

Figures 6a through 14a illustrate the concentrations of nitrate, sulfate, and uranium in groundwater in the respective aquifer horizons before the start of remediation. Most of the information is from sample collection in March 2002, but data for some locations is from 1999. Figures 6b through 14b show contaminant distribution in August 2007 or February 2008 for the respective contaminant and aquifer horizon (some locations where contamination is absent are not sampled in February events).

Although each well location sampled for the respective period is shown, a concentration value is posted in Figures 6 through 14 only where the applicable remediation goal or standard was exceeded. In map view, the area of contamination in the various horizons does not appear significantly different from the baseline condition, indicating no lateral spreading of the contaminant plume (see also Section 4.1).

The depth of groundwater contamination is generally limited to Horizons A, B, and C beneath the middle terrace. Contamination of Horizon D does not appear widespread or continuous in distribution (see Figures 7b, 10b, and 13b), and the concentration is generally of lesser magnitude than in overlying horizons. Contamination in Horizon E (see Figures 8b, 11b, and 14b) is limited to the occurrence of nitrate in well 268. Nitrate concentrations at this location have risen over the past several years from about 15 mg/L as NO_3 to present values of about 100 mg/L as NO_3. Rising concentrations of sulfate and uranium are also observed at this location but do not approach the remediation goals. These rising trends may be explained by drawdown of contaminated groundwater from upper horizons to the horizons of the extraction well intakes.

On the lower terrace, nitrate continues to exceed the restoration standard at several locations (Figures 7a and 7b), currently at concentrations between 49 and 160 mg/L as NO_3 (restoration standard is 44 mg/L as NO_3). As of 2006, sulfate concentrations had decreased to levels below the restoration goal of 250 mg/L and continue to remain below the goal at all lower terrace locations (Figures 10a and 10b). Prior to 2005, uranium was present at several lower terrace wells in concentrations that exceeded the restoration standard of 0.044 mg/L. Uranium concentrations have since remained less than the standard at all lower terrace locations.

Appendix B provides "plume" maps of the contaminant distributions during the current period of review (Figures B−1, B−2, and B−3). The contours shown in the figures were computer generated using the "natural neighbor" interpolation method based on the posted concentration values. This method provides continuous contours, in contrast to the "bull's-eye" effect of other interpolators, from data sets containing areas of sparse and dense data, and does not generate contours in areas beyond the data range. One outcome of this method is that contours do not extend far beneath the disposal cell where no data are available. Analytical results for each contaminant requiring remediation are tabulated in Appendix C for August 2007, February 2008, and the baseline period.

3.2 Water Table Configuration

Figure 15 shows the estimated water table for the baseline period using water levels in Horizons A and B monitor wells for the middle terrace and Horizon C wells for the lower terrace. On the middle terrace, water levels from 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 local 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) may correspond to the decreased thickness of the aquifer at this feature.

Figure 16 shows a similarly constructed water table for August 2006. Comparison of Figures 15 and 16 indicates that operation of the extraction wells has significantly depressed the water table, with a significant drawdown cone centered on both the south and east bank of extraction wells.

The water table underlying the escarpment and lower terrace appears unaffected by groundwater extraction. Additional analysis of groundwater flow directions, as influenced by groundwater extraction, is provided in Sections 3.4 and 3.5. Also evident in Figure 16 is the development of an elongate groundwater mound and increased hydraulic gradients along the north edge of the disposal cell caused by infiltrating distillate at the trench.

3.2.1 Infiltration Trench

The infiltration trench is constructed into bedrock along the north side of the site (see Figure 2 for trench location). Distillate enters the trench at its mid-point from where it can flow in either direction in perforated pipe embedded in a 3-ft-thick gravel pack. Through mid-2003, nonuniform infiltration caused greater than 20 ft of groundwater mounding beneath the southwest section of the trench but only about 1 ft of mounding beneath the northeast section. The groundwater mound progressively became more symmetrical after November 2003 when flow valves were installed, and all inflowing water was diverted to the northeast segment of the trench. In April 2005, the valves were again adjusted to redirect some flow back to the southwest section of the trench, which has resulted in comparatively greater mounding in that section. Water levels have risen at well 946 to historical maximums to within about 30 ft of ground surface (water level hydrographs for wells completed in the aquifer in the area of the trench are presented as Figure D−1 in Appendix D). Monitor wells 284 and 285 (see Figure 2 for location), screened across the contact of the terrace deposits and Navajo Sandstone immediately downgradient of the trench, remain dry, indicating that mounding has not over-topped the trench to saturate the alluvium, although the current water level at well 946 is very close to the bedrock/alluvium contact.

3.3 Water Level Drawdown

Figure 17 further 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 2008. 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 2008 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.

In the area of groundwater extraction, the overall pattern of water level drawdown illustrated in Figures 17 through 19 reflects three-dimensional converging flow to the extraction wells. The greatest drawdown (30 to 40 ft) is observed at the Horizon E wells (wells 251 and 268) located within the extraction field. The intakes of these particular monitor wells are nearest to the interval of groundwater extraction among all monitor wells for which baseline data are available (extraction wells are screened across Horizons C to E and centered in Horizon D). Drawdown is 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 monitor wells. The predominantly downward trend in groundwater levels indicates an expanding capture zone and that the groundwater setting has not attained the condition of steady-state flow since the start of groundwater remediation.

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. All groundwater within the blue line is predicted to ultimately flow to an extraction well. This prediction is based on slope analysis of the water table depicted in Figure 20 using a computerized grid-based contouring application (SURFER). The analysis calculates a vector (direction and magnitude) for the slope of the water table in each grid cell. The capture line in Figure 20 corresponds to the horizontal flow divide separating the vectors that converge on the extraction wells from those that do not. Several conditions were imposed to obtain this result. First, because extraction well water levels are not monitored, the groundwater level at each extraction well was assigned a uniform value of 4,990 ft. This value is consistent with the water table elevation observed at several monitor wells located within the extraction field. In addition, to mimic the regional water table gradient, prescribed water table elevations were assigned at several locations in a line upgradient of the site near well 901 and along Moenkopi Wash east and west of well 902.

The slope analysis indicates that the full width of the contaminant plume along the south edge of the disposal cell is within the capture zone, suggesting that flow of contaminated groundwater from the site has been eliminated. The capture zone encompasses the region of greatest contamination; however, much of the area encompassing extraction wells 1126−1129 apparently escapes capture. Water level drawdown in this area is significant (Figures 17 and 18) and continues to increase (Figures D−4, D−5, and D−6). These data indicate an expanding cone of depression and expanding capture zone in this area with continued operation of the extraction wells. Contamination in this area is limited in vertical extent to Horizons A and B. Concentrations in this part of the plume currently range from about 180 to 1,400 mg/L nitrate as NO_3; 100 to 3,400 mg/L sulfate; and <0.044 to 0.7 mg/L uranium (at extraction well 1129), and average about 775 mg/L nitrate, 1,500 mg/L sulfate, and 0.06 mg/L uranium.

3.5 Vertical Capture

Hydrographs included in Appendix D for selected sets of co-located monitor wells illustrate that at a given location, the hydraulic head in the aquifer is a function of well-intake depth. This relationship clearly identifies vertical flow components throughout the entire monitored thickness of the aquifer, both before and since the start of groundwater remediation. With few exceptions, the vertical potentials were downward during the baseline period. Since that time, the magnitude of downward flow in Horizons A, B, and C has increased, as exemplified by the greater vertical separation in the hydrographs for the respective locations of well pairs 265/266, 263/264, 908/912, and 909/932 since about mid-2002 (see Appendix D, Figures D−4 through D−7). In the main region of contamination, these increased gradients likely 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 now 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 result between Horizons E, I, and possibly M is apparent at the location of wells 251/252/253 (see Figure D−9, monitoring well 253 was decommissioned in 2001). A downward flow potential remained 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 Horizon D under the current regime.

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. Although groundwater extraction has had no effect on downward flow between Horizons D and G at wells 915 and 916 (Figure D−11), this region of the aquifer is not contaminated. Downward flow potentials in lower terrace groundwater also remain unaffected by groundwater extraction (Figure D−12), but contamination there is minor and limited to the shallowest horizon. Also, there is no evidence of vertical or lateral spreading of contamination in the lower terrace groundwater.

4.0 Remediation Progress

4.1 Contaminant Concentration Trends at Monitor Wells

Appendix E contains time-series graphs of nitrate, sulfate, and uranium concentrations in groundwater at selected monitor wells located throughout the project area. In the main region of groundwater contamination, obvious or pronounced upward or downward trending is not apparent at most monitor wells (Figures E−1 to E−3). Uranium concentrations in wells 262 and 942 have increased in recent years (Figure E−3), possibly owing to capture zone expansion with time into areas of relatively high contamination. Toward the downgradient (south) margin of the plume, contaminant concentrations are relatively stable or slightly decreasing (see Figures E−4 through E−6). Horizons A, B, and C wells 271, 683, 684, 914, 921, and 929 are located beyond but near the downgradient or crossgradient extent of contamination. These “sentinel” wells remain uncontaminated, with the exception of minor nitrate contamination of about 1.5 times the remediation standard at well 929, indicating no significant lateral expansion of the contaminant plume.

Contaminant concentrations remain stable and below remediation standards in Horizons C and D wells 264, 266, 915, and 932 (Figures E−7 through E−9). These results indicate that no southward expansion of the plume is occurring at this depth in the aquifer. In Figures E−7 and E−8, 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.

As presented in Section 3.1, in groundwater beneath the lower terrace, uranium and sulfate concentrations have recently decreased to levels below the respective restoration objectives at all locations. The current extent of contamination on the lower terrace is limited to nitrate at well 930 (66 mg/L as NO_3), well 903 (58 mg/L as NO_3), well 691 (160 mg/L as NO_3), and well 1004 (49 mg/L as NO_3). Nitrate concentrations have remained relatively stable at wells 903, 930, and 1004; definitive trending is not recognized at well 691 and co-located well 1003 unless to indicate the recent passage of a very localized pulse of relatively low-level nitrate, sulfate, and uranium contamination. Contaminant concentration plots for lower terrace monitor wells are included in Appendix E, Figures E−10 through E−12.

4.1.1 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 concentration accompanied by changes in other indicator parameters such as rise in pH and decrease in dissolved silica. Such trending is not yet apparent at monitor wells located along the south side of the disposal cell. Darcy's Law predicts a travel time from the infiltration trench to well 940 of about 17 years, using the observed water table gradient (Figure 16) and a hydraulic conductivity of 1 ft/day (from DOE 1998). This amount of time exceeds the cumulative remediation period to date.

4.2 Contaminant Concentration Trends at Extraction Wells

Figures 21 to 23 illustrate concentration trends at the extraction wells for nitrate, sulfate, and uranium. For each contaminant, the trend at most wells is of decreasing concentration as contaminant mass is removed from the aquifer. Appendix F contains individual concentration plots for each extraction well based on the monthly on-site sampling and analysis.

On the basis of those figures, Table 3 identifies that contaminant concentrations in the extracted groundwater are below the remediation standards for all three primary contaminants at extraction well 1125. Although the extraction well samples are likely composites of groundwater from several horizons of variable contamination, it is noted that the region of the aquifer east of the evaporation pond and encompassing well 1125 is approaching cleanup goals.

Table 3. Pumping Wells Where a Contaminant Concentration Is Below the Remediation Standard in the Extract, as of February 2008

Nitrate	Sulfate	Uranium
--	--	1107
--	1112	1112
--	1113	1113
--	--	1116
--	--	1117
--	1123	1123
1125	1125	1125
--	--	1127
--	--	1128
--	1131	--
--	1133	--

4.3 Contaminant Inventory and Removal Rates

Table 4 lists the cumulative amounts of nitrate, sulfate, and uranium removed from the aquifer through March 2008, about 6 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.

By these estimates, at current mass recovery rates of between 1.6 (nitrate) to 4.2 percent per year (uranium), groundwater restoration will require about 23 to 63 years to complete since the inception of active remediation in mid-2002 (see also Figure 24, which projects current mass removal rates to future years), assuming total plume capture. The corresponding volume of groundwater extracted at 23 years, assuming constant withdrawal of 85 gpm (equivalent to about 3.8 percent reduction in plume volume per year [see Table 4]), is 1 billion gallons, or approximately one estimated pore volume of the contaminant plume.

Table 4. Summary of Cumulative Mass and Volume Recovery as of April 1, 2008

Contaminant	Initial Mass (lbs)[a]	Cumulative Mass Removed (lbs)	Cumulative Percent Mass Reduction	Initial Volume (gal)[a]	Volume Treated (gal)	Percent Plume Volume Reduction
Nitrate	9,500,000	891,600	9.4	1.2×10^9	2.7×10^8	22.5
Sulfate	20,150,000	2,214,500	11.0	1.2×10^9	2.7×10^8	22.5
Uranium	2,300	574	25.0	1.2×10^9	2.7×10^8	22.5

[a]Source: see Appendix G

4.3.1 Aquifer Restoration Index

An alternate approach to estimate the restoration period is based on concentration trending over time and is independent of mass and volume calculations. By this approach, an average concentration of a contaminant is computed for each sampling event from a selected group of monitor wells. The composition of the groundwater plume is thus represented by a single concentration value, or index, for a given contaminant and time. A time series plot of the index can then provide a measure of bulk trending and restoration progress. Figures 25 and 26 illustrate respectively how the sulfate and uranium indices vary since the start of active remediation. The selected monitor wells in this analysis are those located throughout the contaminant plume and sampled most regularly. Appendix G provides calculation information for this performance metric as Calculation Sets 3 and 4.

Despite the small increment of change and the relatively brief period of observation, the results presented in Figures 25 and 26 suggest a developing trend showing the effects of remediation in reducing the bulk concentration of uranium and sulfate (nitrate results have not yet been analyzed by this method). The recent increase in the index is explained by relatively large increases in uranium concentration at wells 262 and 906 in the past year. The increases are probably more indicative of internal plume movement in response to pumping rather than plume movement from beneath the disposal cell. Linear projection of the sulfate and uranium indices, disregarding any possible desorption or concentration tailing effects, predict restoration times of about 30 and 60 years, respectively, since the inception of active remediation in mid-2002. This compares to an estimated 27 years to remove one pore volume of the initial contaminant plume (Table 4) at the current cumulative extraction rate of about 3.8 percent per year by volume.

5.0 Year in Review Summary

- On-stream extraction and treatment flow rates meet design objectives.
- Distillate quality meets or exceeds design objectives.
- Return flow to the aquifer as a percentage of extracted water meets design objectives.
- The current configuration and operation of the extraction system effectively captures the region of maximum groundwater contamination.
- The current configuration and operation of the extraction system likely captures the full vertical extent of groundwater contamination.
- Plume expansion is not significant on either the middle or lower terrace.
- Uranium and sulfate concentrations have decreased to levels less than the restoration standard at all lower terrace monitoring locations. Only minor nitrate contamination remains on the lower terrace.
- Bulk concentration trends indicate measurable progress in water quality restoration.
- Projected cleanup times range between about 25 and 60 years since mid-2002. These projections assume total plume capture, which currently is not achieved.
- Five new monitor wells were installed in March 2007. Two wells (wells 286 and 287) replace wells 940 and 941, which have gone dry or will do so soon; nested wells 288 and 290 are to monitor the arrival of treated water from the trench; and well 290 closes the plume boundary east of the eastern extraction wells.

6.0 Recommendations

- Develop and implement a protocol of pumping and fallow time to evaluate contaminant rebound at well 1125.
- Divert a small increment of the distillate to the northwest section of the infiltration trench.
- Consider implementing injection of distillate at the existing but unused injection wells if trends of rising water levels at the infiltration trench continue.
- Use February as the more comprehensive groundwater monitoring event rather than August to improve annual data reporting.

7.0 References

Cooley, M.E., J.W. Harshbarger, J.P. Akers, and W.F. Hardt, 1969. *Regional Hydrogeology of the Navajo and Hopi Indian Reservations, Arizona, New Mexico and Utah,* U.S. Geological Survey Professional Paper 521-A.

DOE (U.S. Department of Energy), 1998. *Final Site Observational Work Plan for the UMTRA Project Site Near Tuba City, Arizona,* MAC-GWTUB1.1, U.S. Department of Energy Grand Junction Office, Grand Junction, Colorado, September.

DOE (U.S. Department of Energy), 1999. *Phase I Ground Water Compliance Action Plan for the Tuba City, Arizona, UMTRA Site*, GJO−99−99−TAR. U.S. Department of Energy Grand Junction Office, Grand Junction, Colorado, June.

DOE (U.S. Department of Energy), 2003. *Tuba City UMTRA Site Baseline Performance Evaluation*, GJO−2002−370−TAC, GJO-GWTUB 30.13.2-1. U.S. Department of Energy Grand Junction Office, Grand Junction, Colorado, May.

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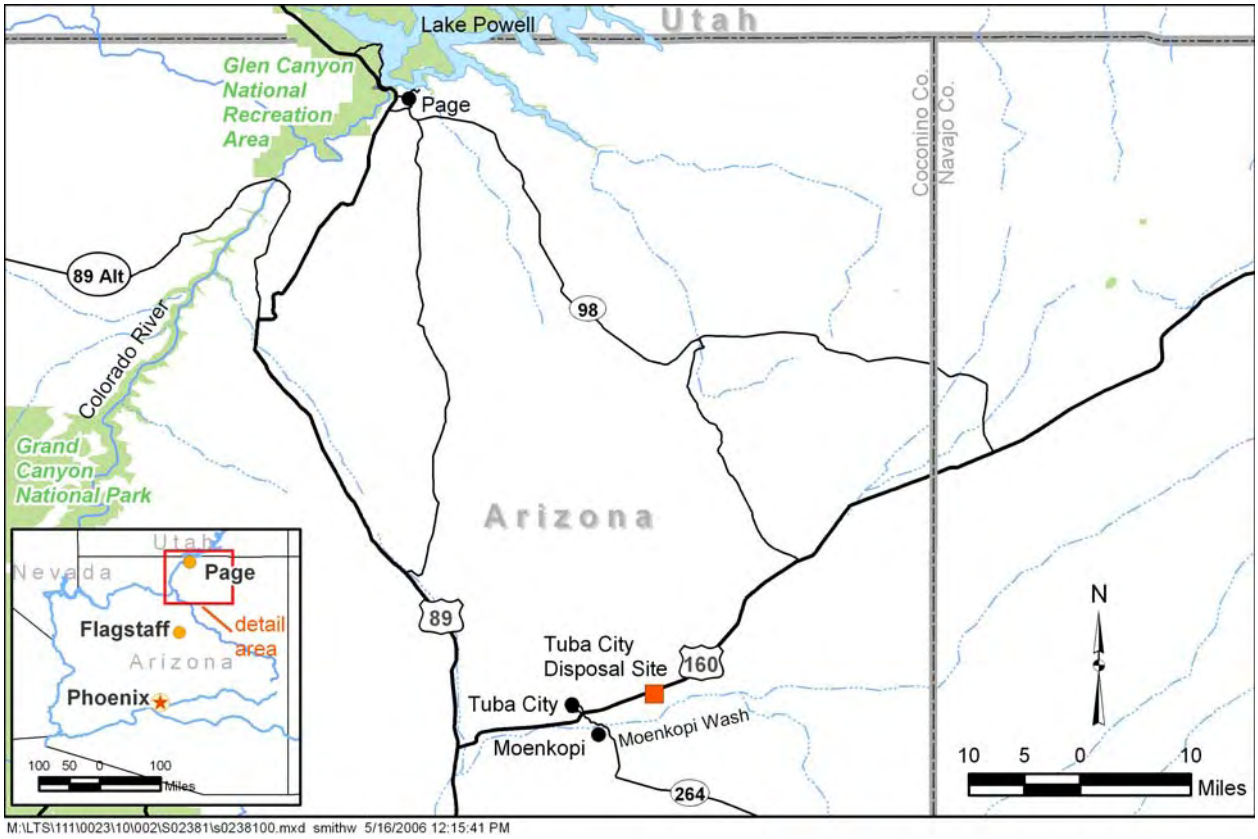

Figure 1. Tuba City Site Location

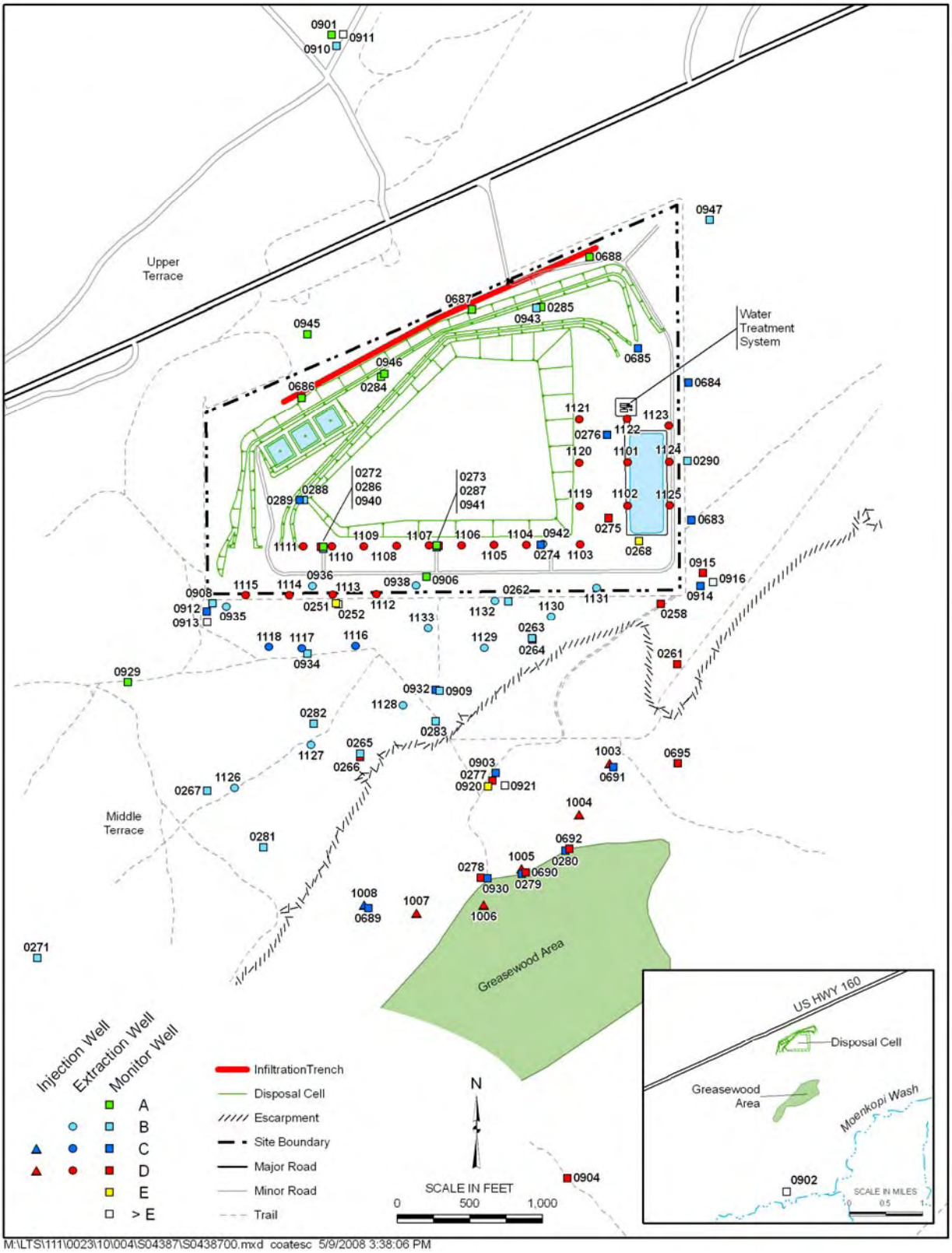

Figure 2. Tuba City Site Features and Well Locations

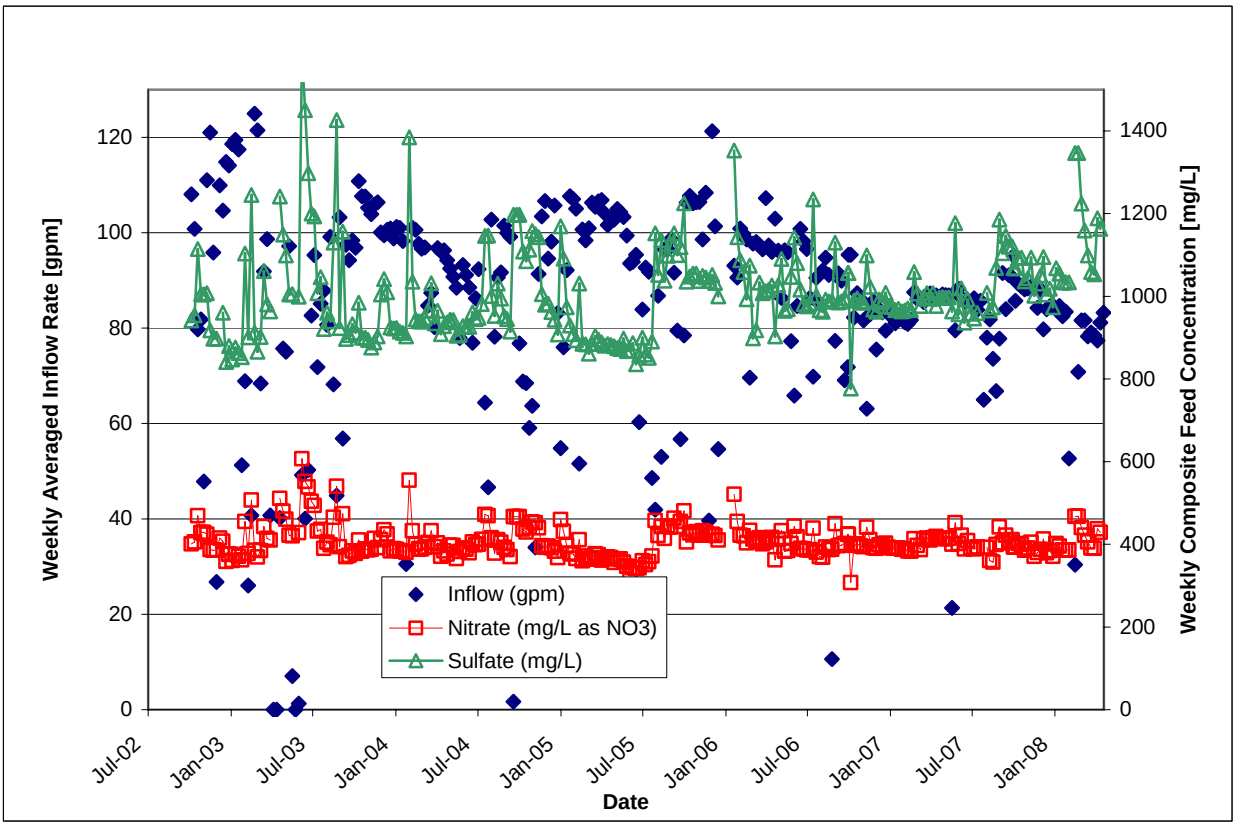

Figure 3. Treatment Plant Inflow Rate and Nitrate and Sulfate Concentration

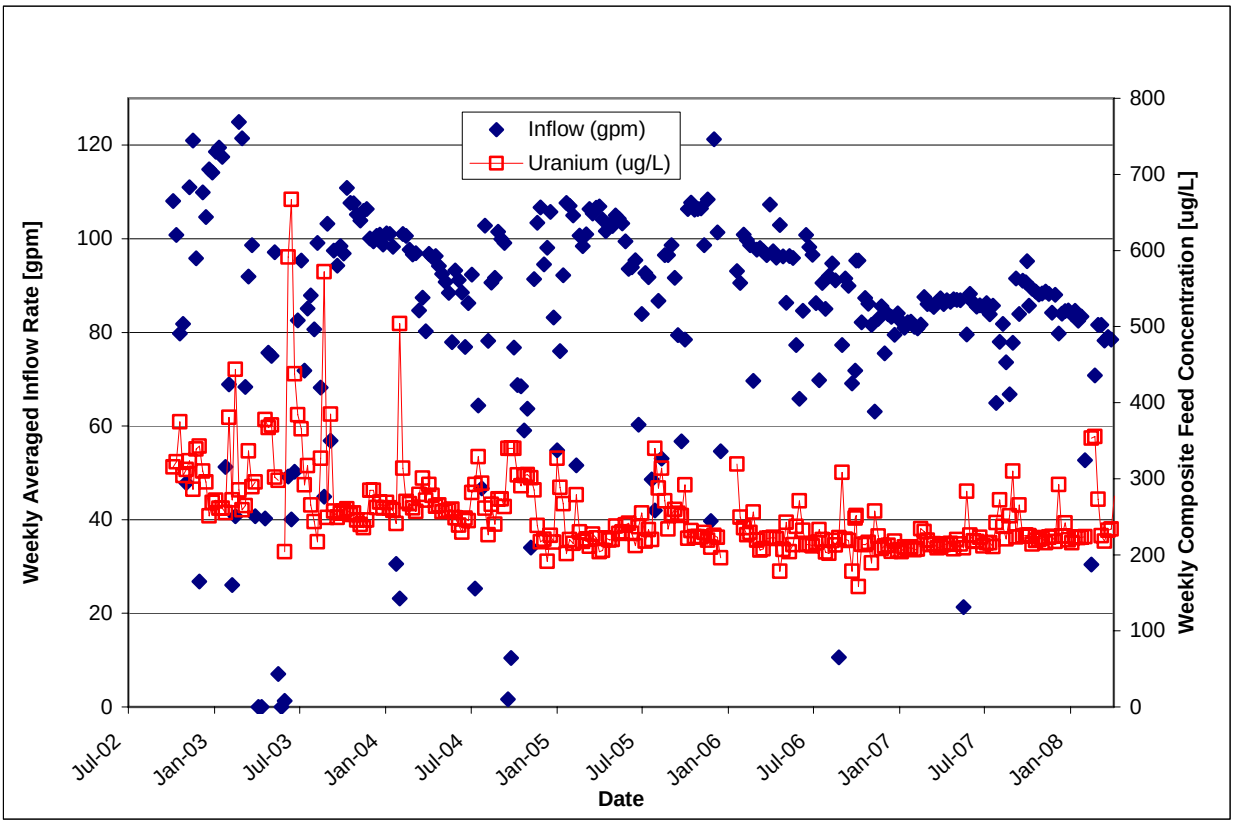

Figure 4. Treatment Plant Inflow Rate and Uranium Concentration

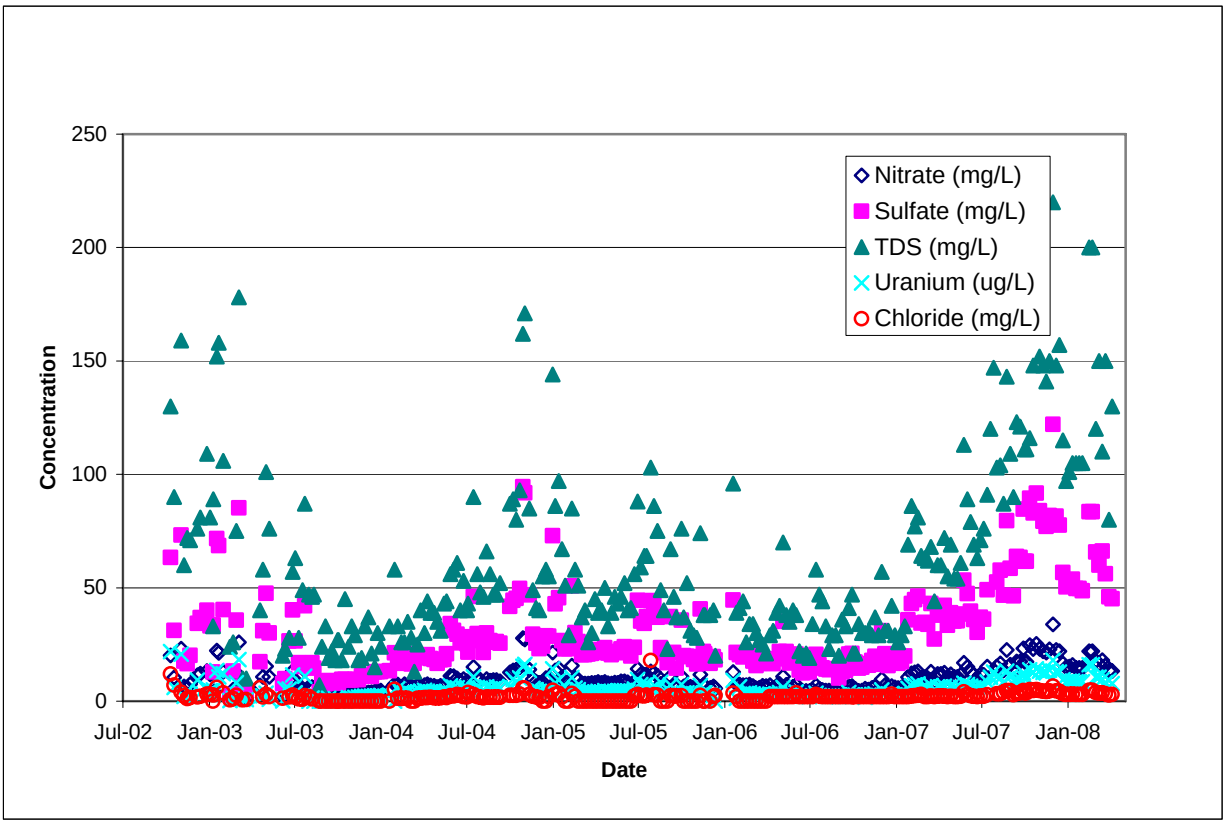

Figure 5. Treatment Plant Distillate Quality

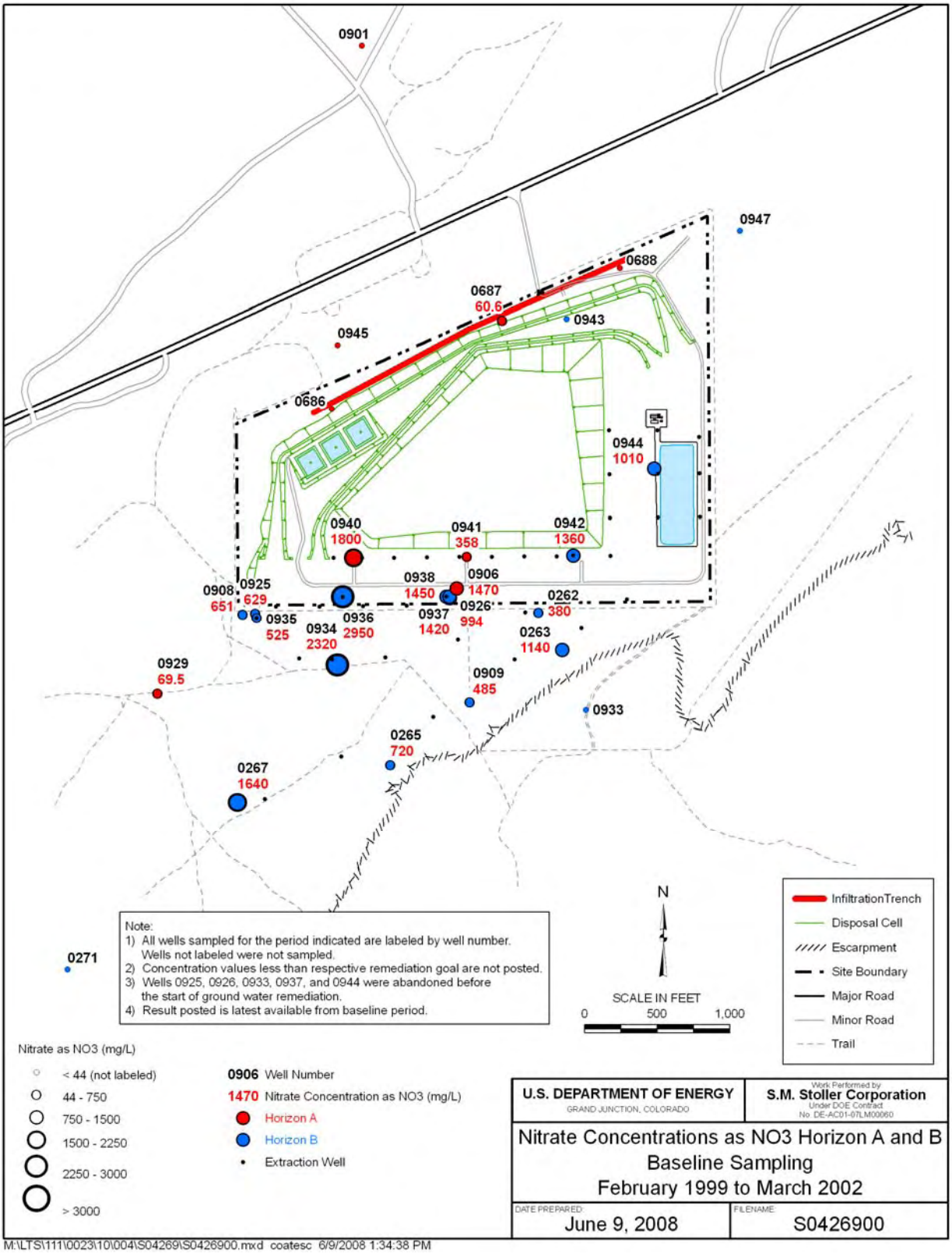

Figure 6a. Nitrate Concentrations as NO_3, Horizons A and B, Baseline Period

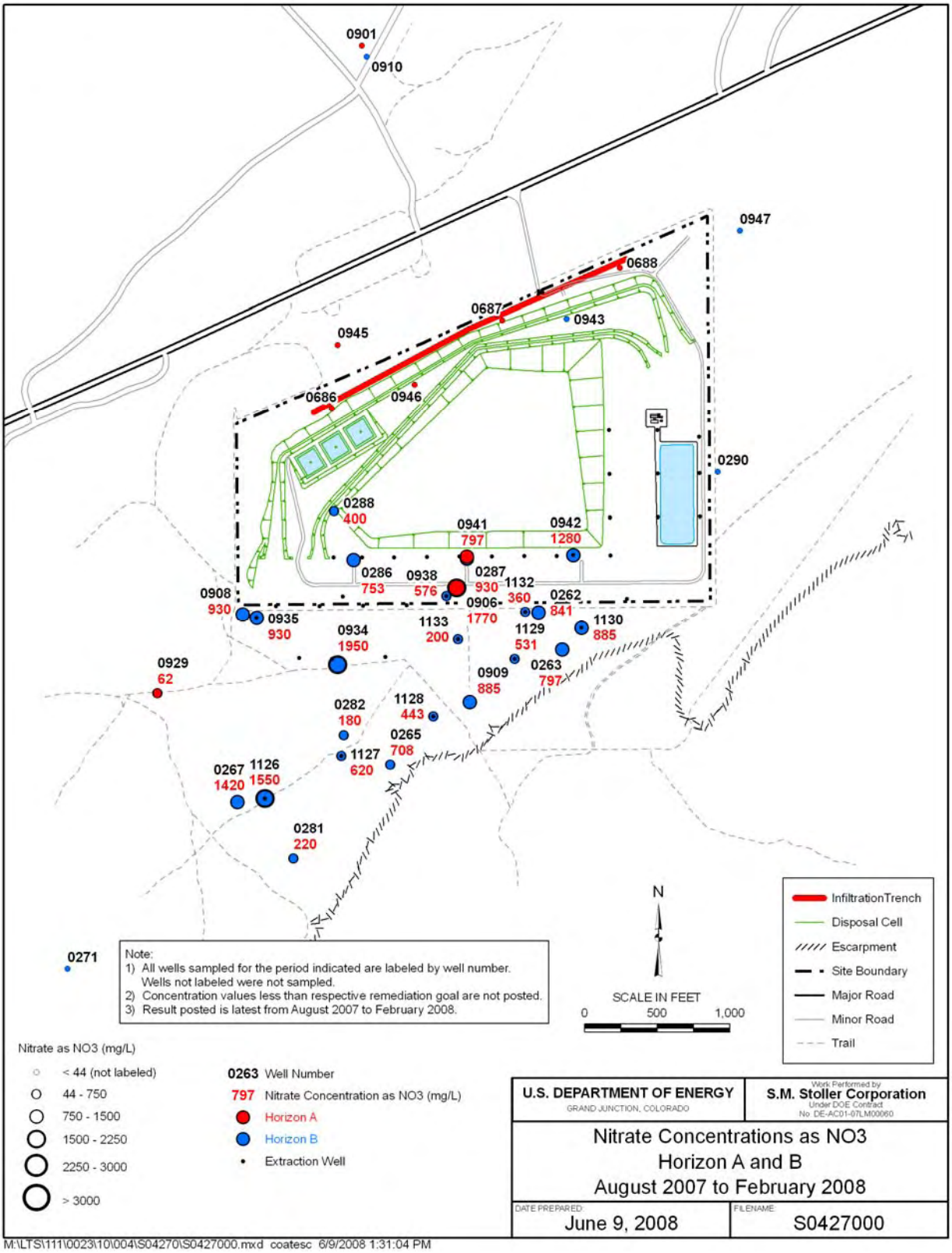

Figure 6b. Nitrate Concentrations as NO_3, Horizons A and B, February 2008

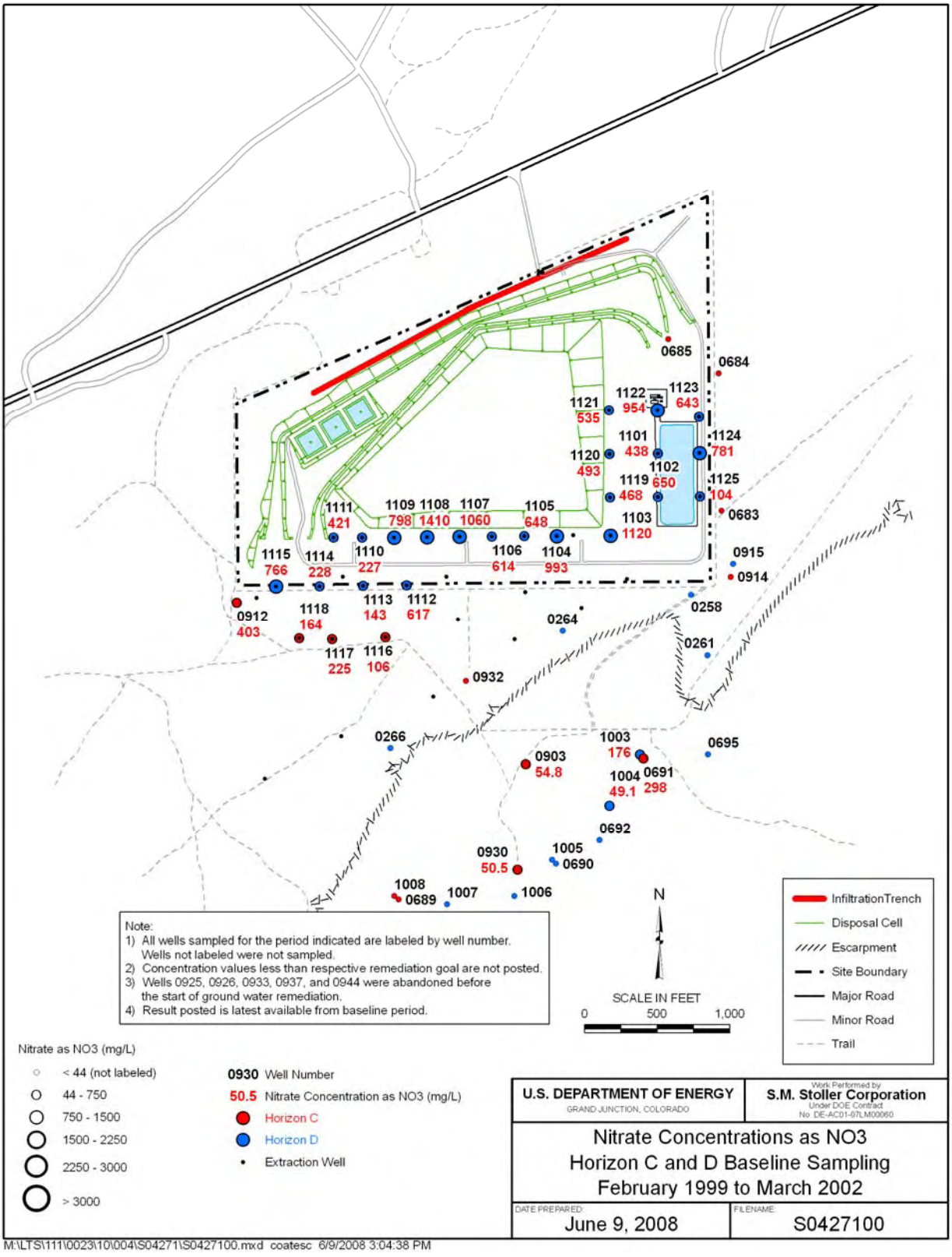

Figure 7a. Nitrate Concentrations as NO_3, Horizons C and D, Baseline Period

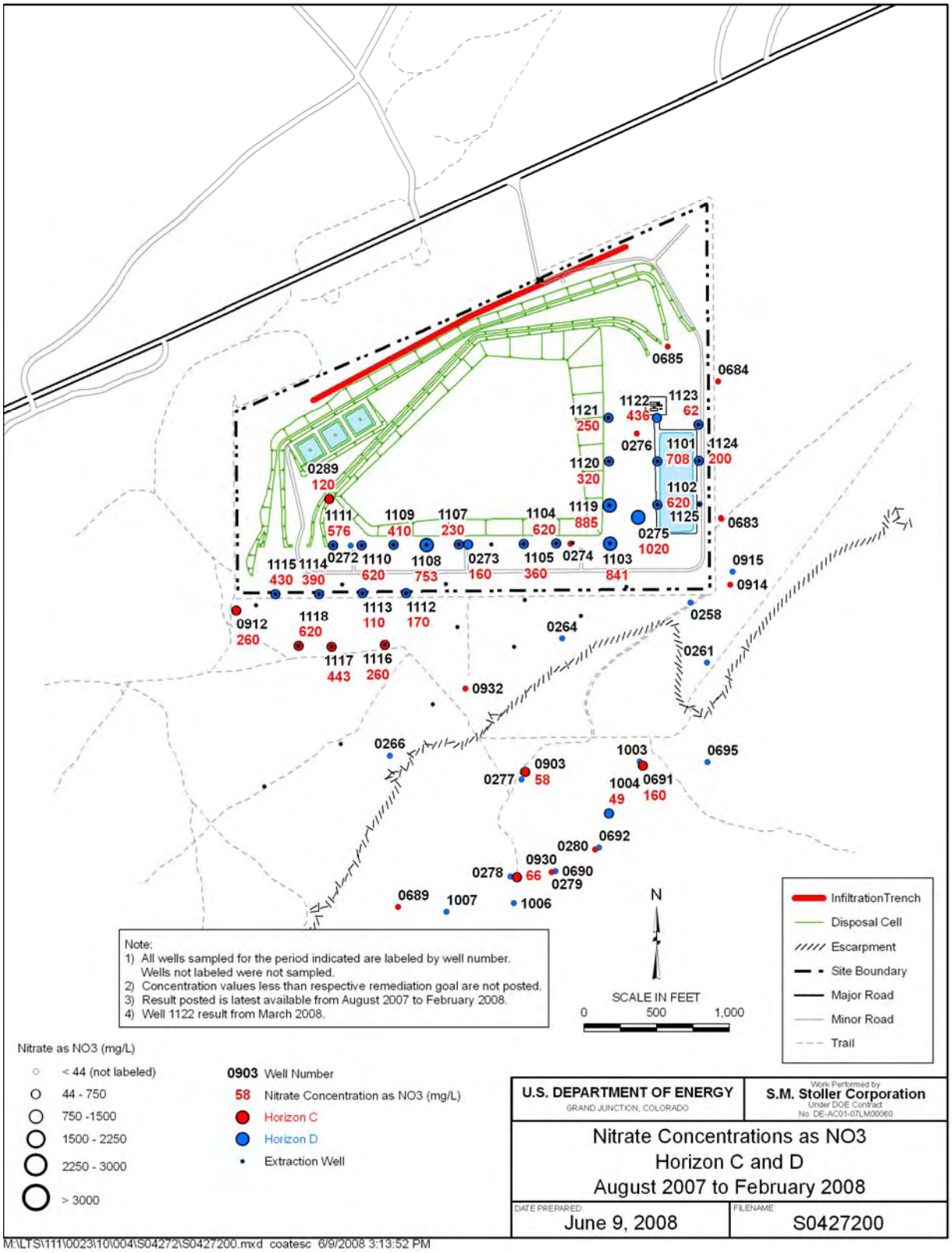

Figure 7b. Nitrate Concentrations as NO_3, Horizons C and D, February 2008

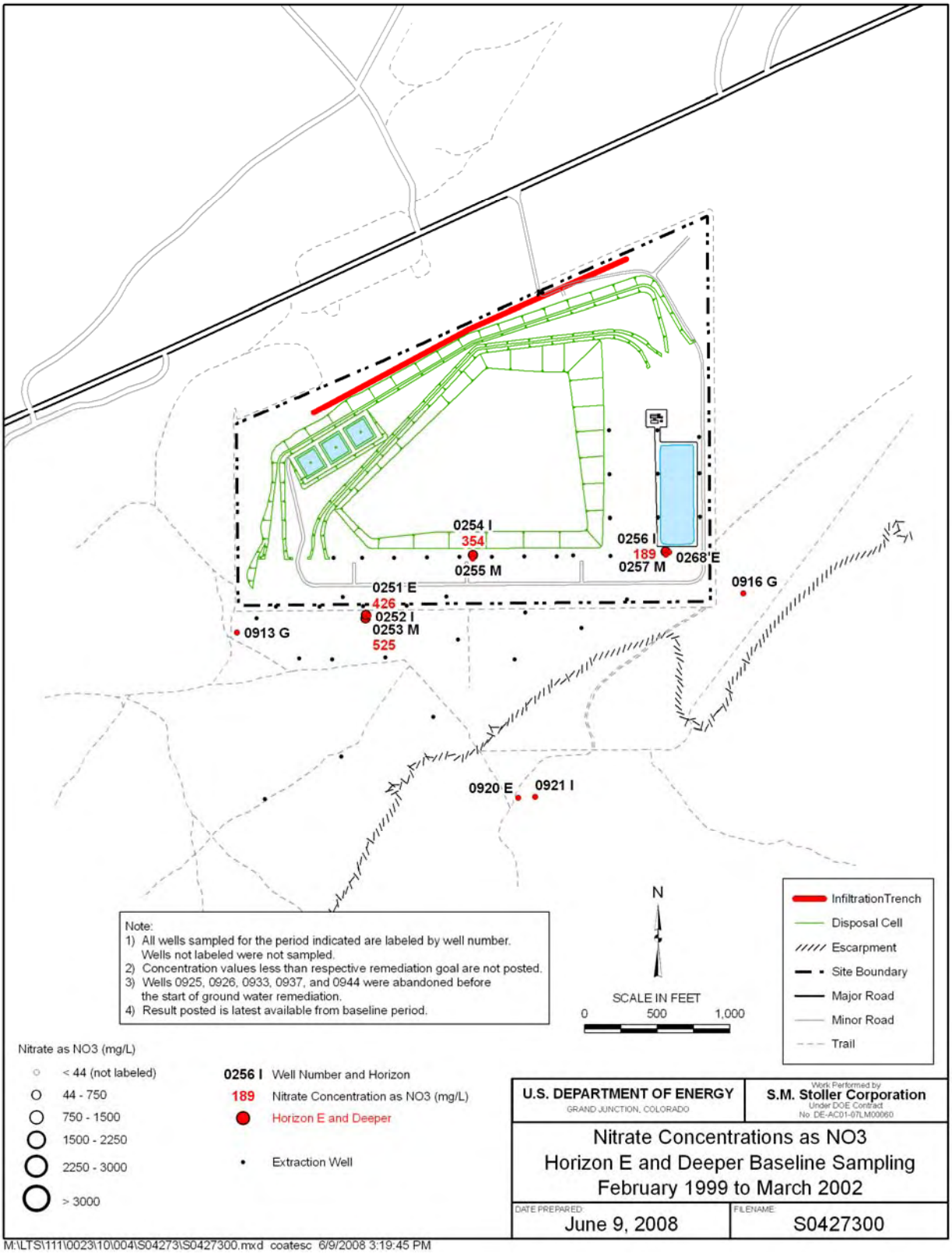

Figure 8a. Nitrate Concentrations as NO_3, Horizons E and Deeper, Baseline Period

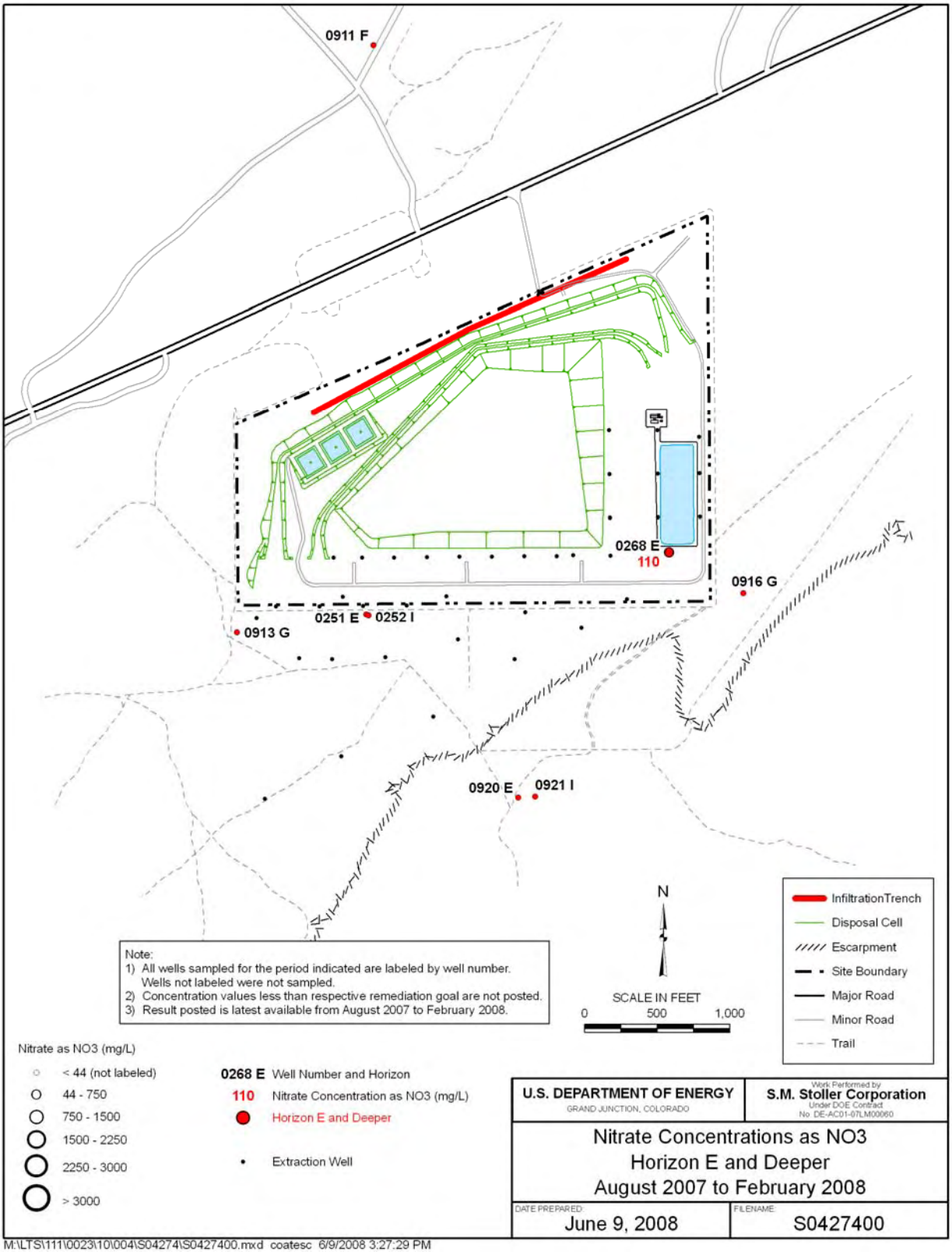

Figure 8b. Nitrate Concentrations as NO_3, Horizons E and Deeper, February 2008

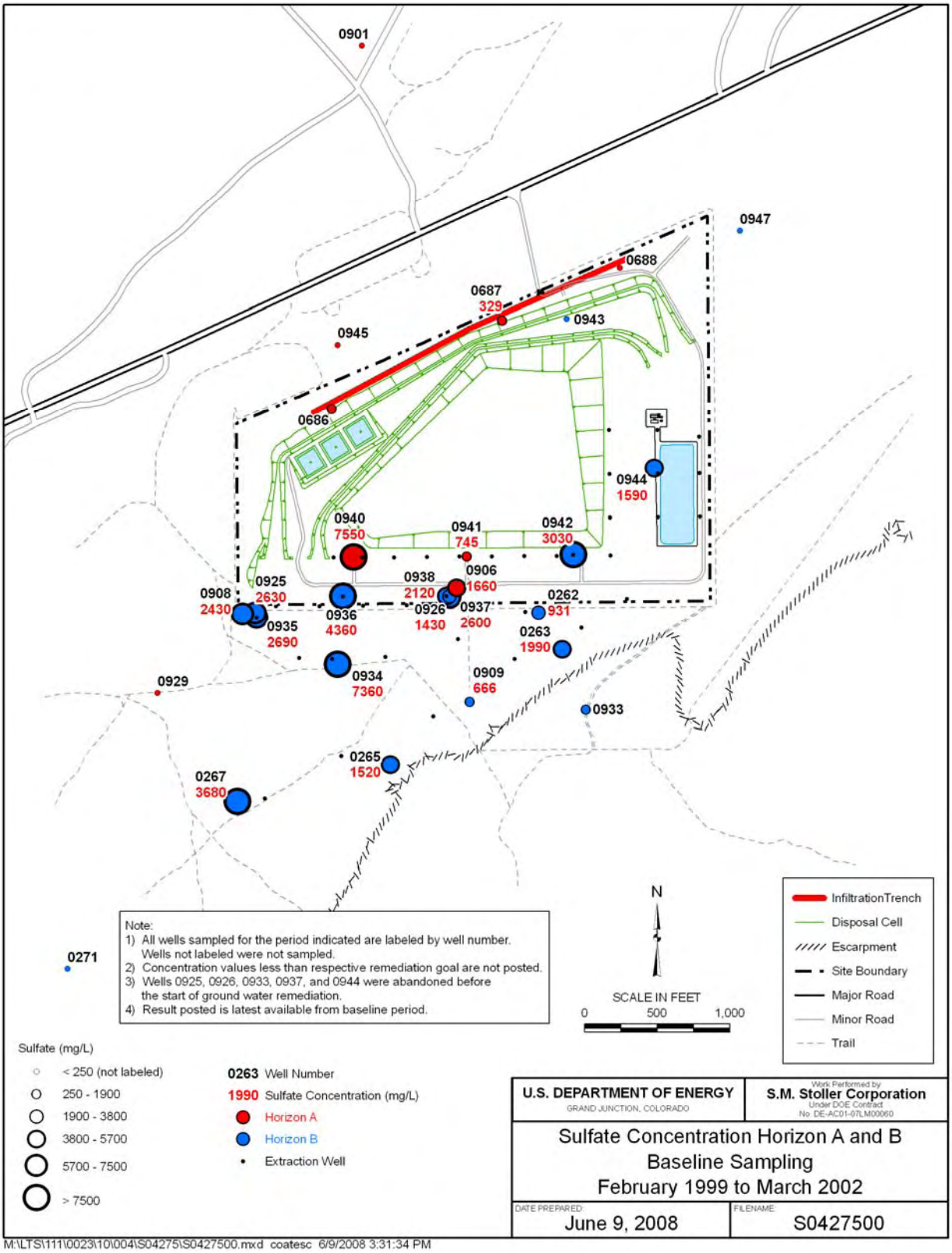

Figure 9a. Sulfate Concentrations in Groundwater, Horizons A and B, Baseline Period

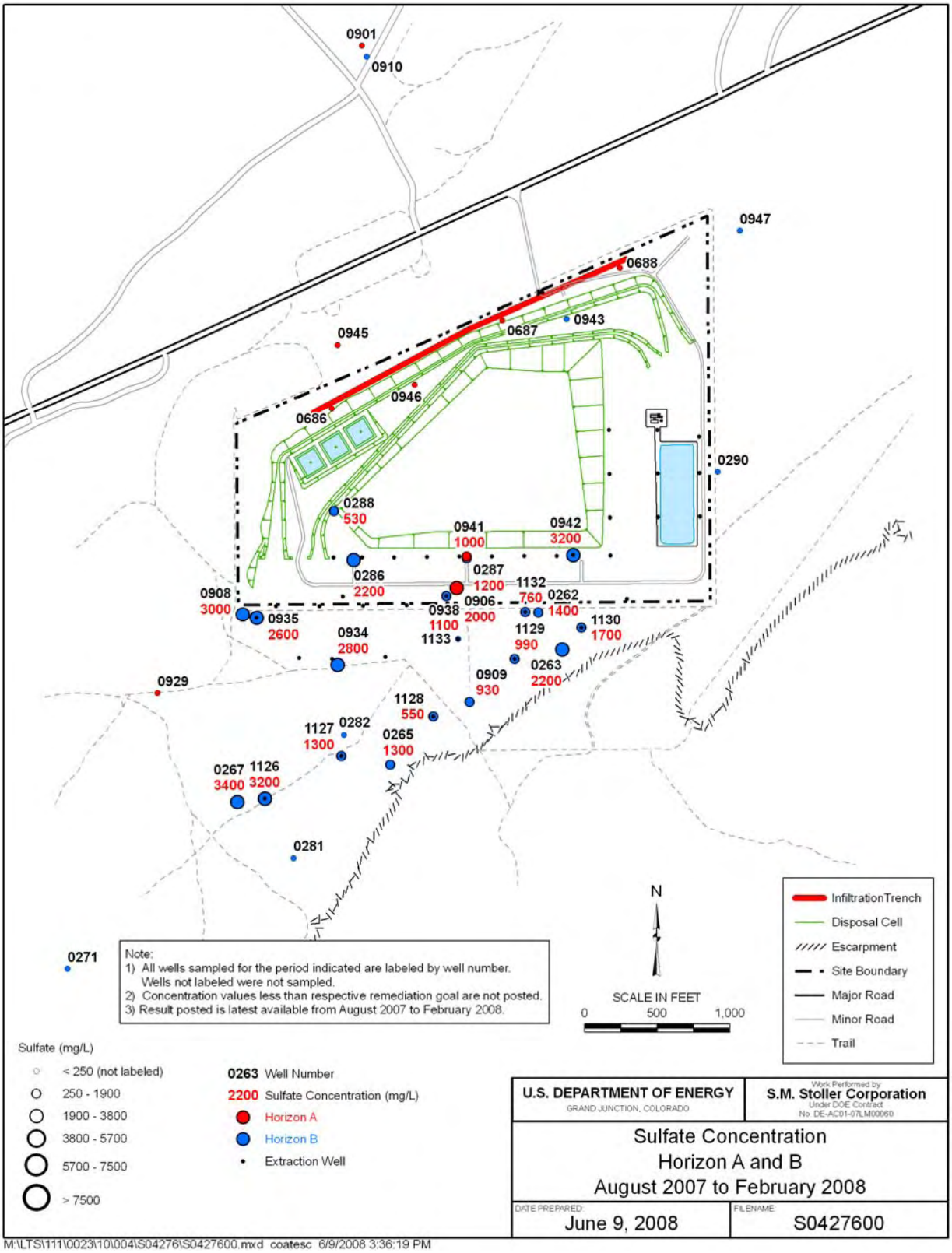

Figure 9b. Sulfate Concentrations in Groundwater, Horizons A and B, February 2008

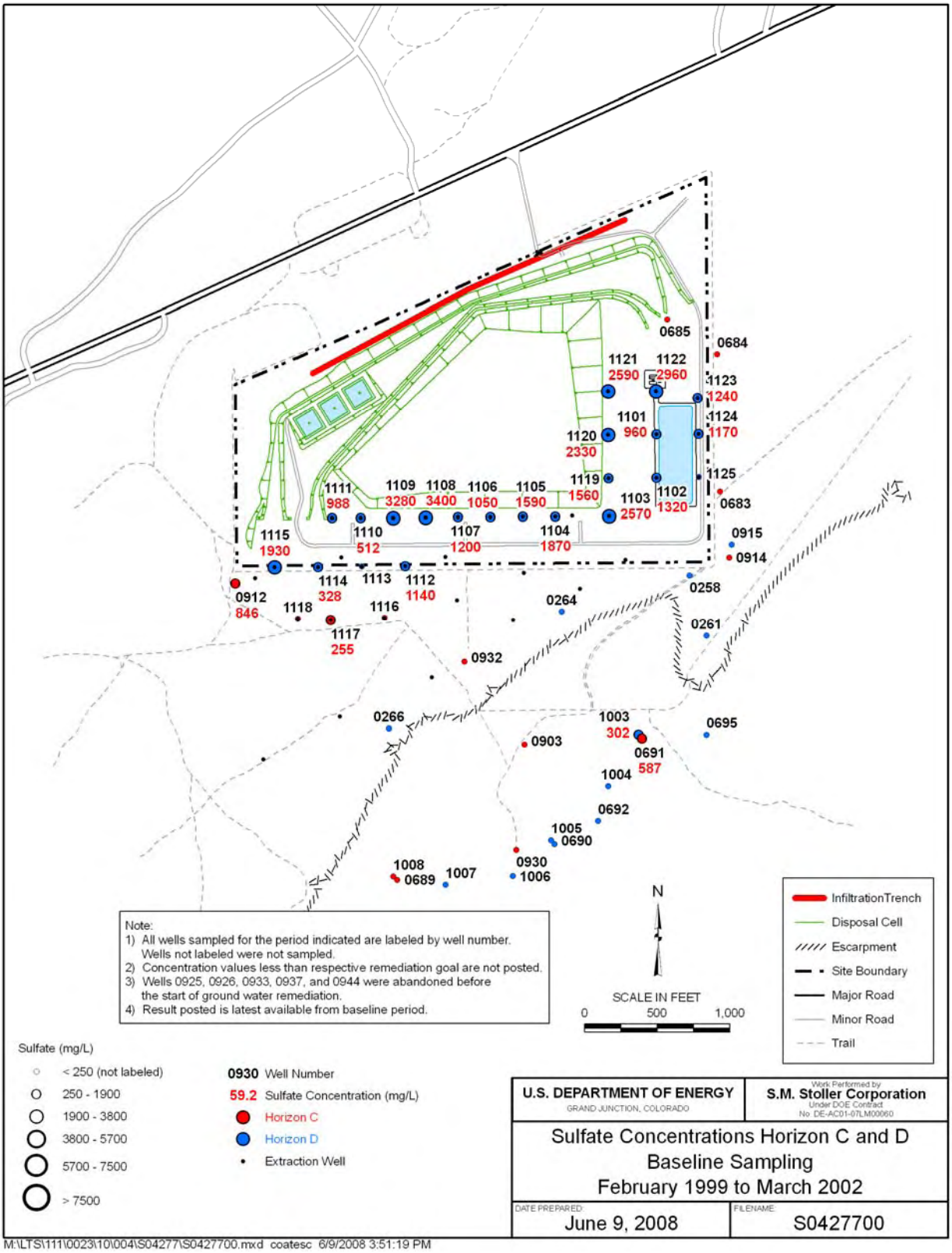

Figure 10a. Sulfate Concentrations in Groundwater, Horizons C and D, Baseline Period

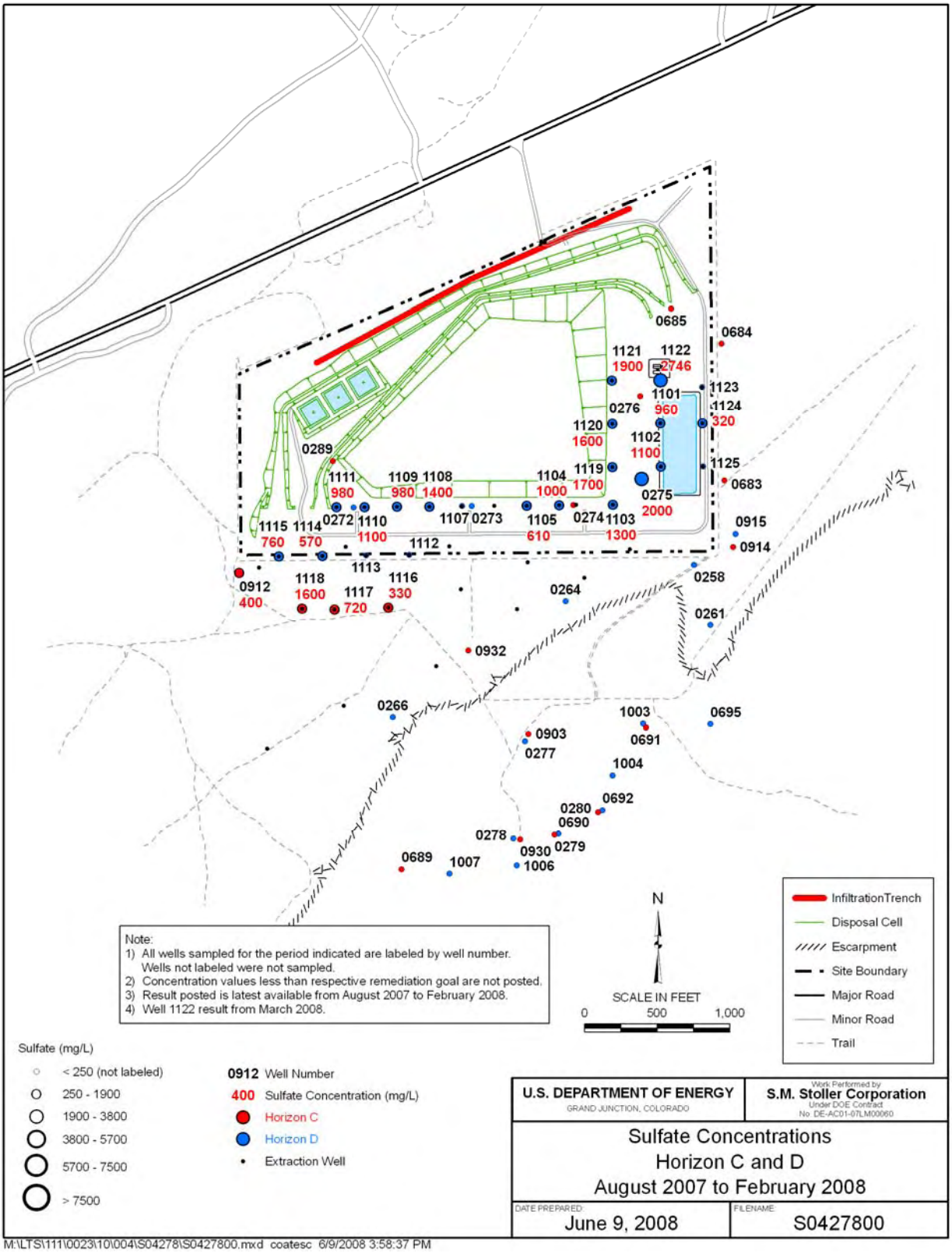

Figure 10b. Sulfate Concentrations in Groundwater, Horizons C and D, February 2008

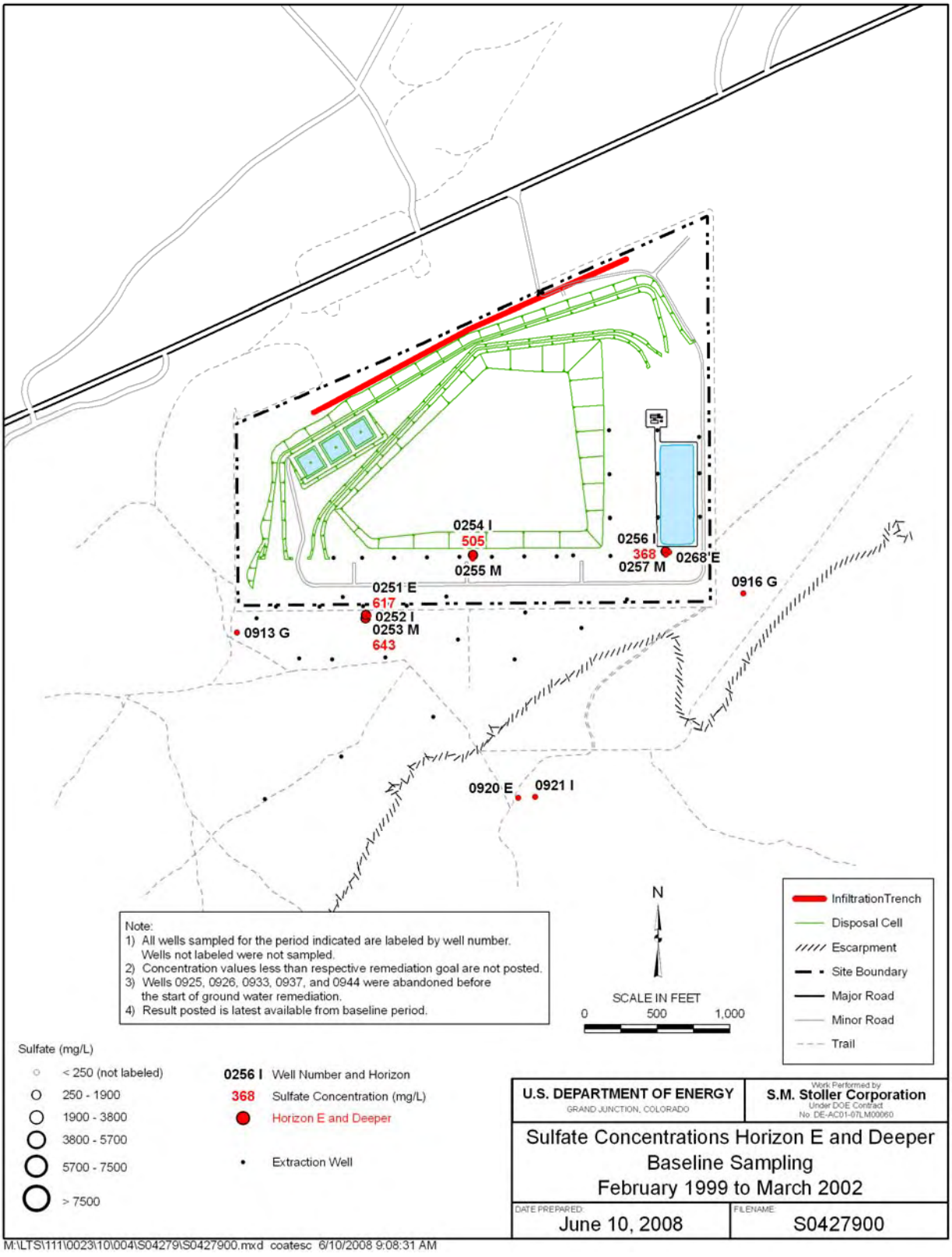

Figure 11a. Sulfate Concentrations in Groundwater, Horizons E and Deeper, Baseline Period

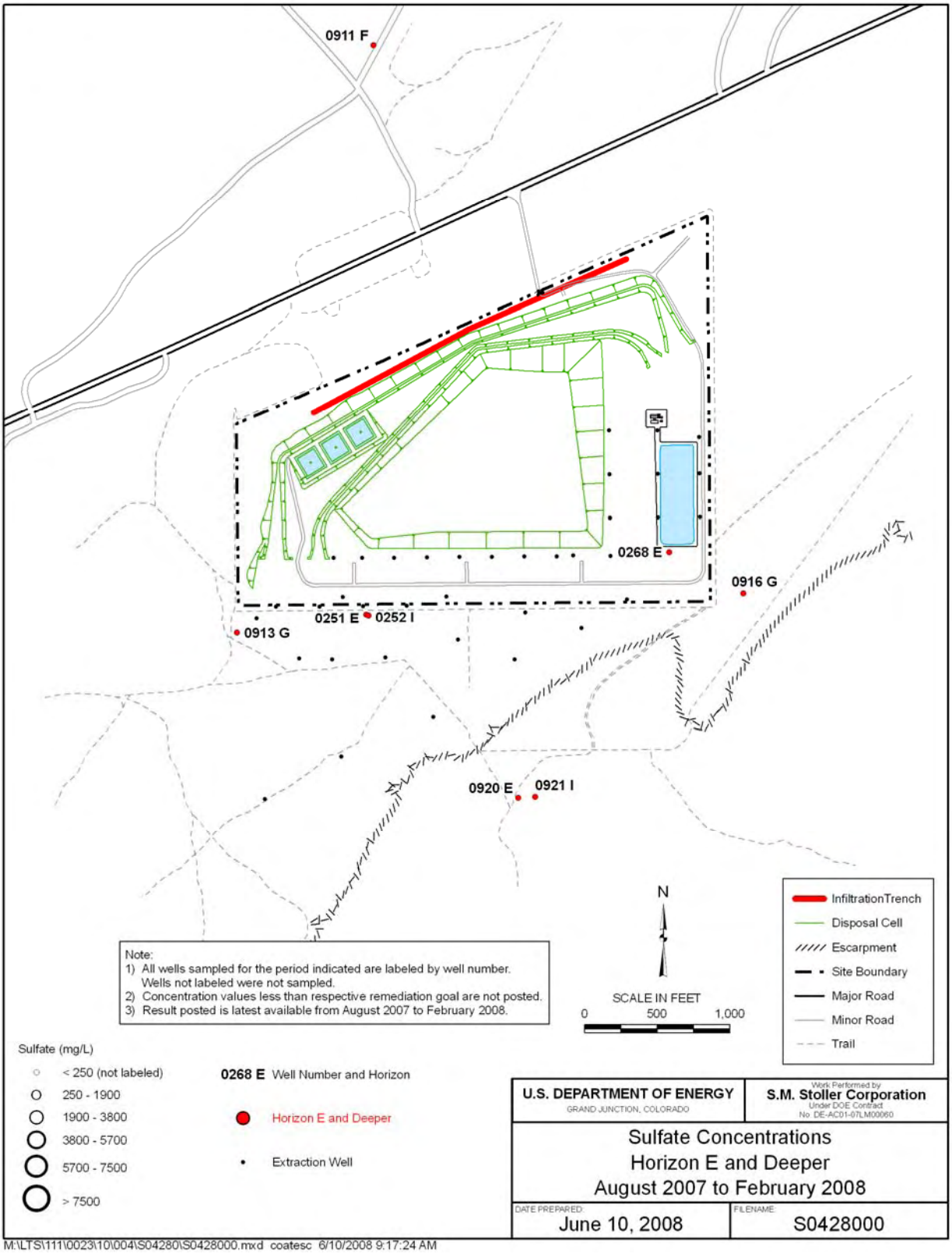

Figure 11b. Sulfate Concentrations in Groundwater, Horizons E and Deeper, February 2008

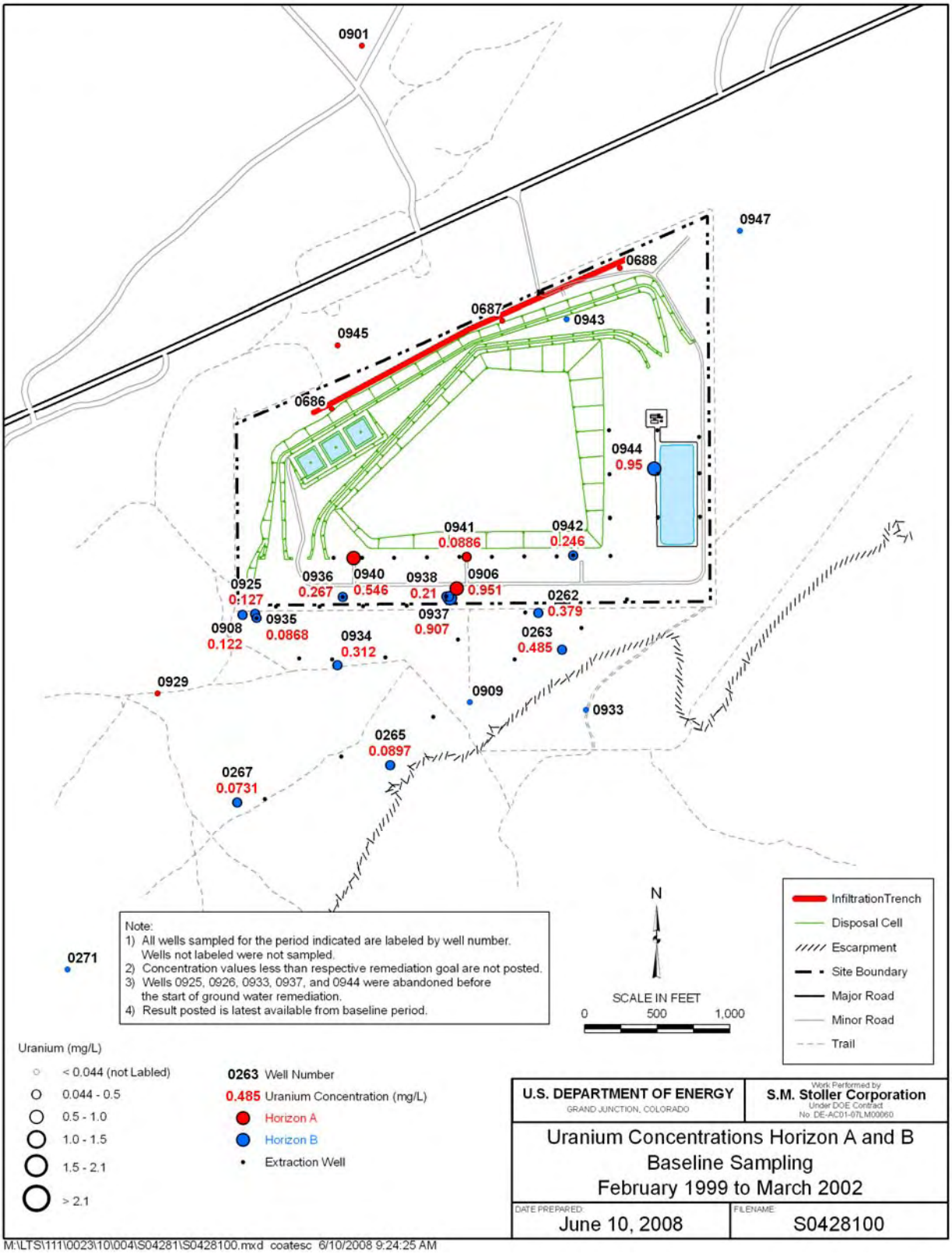

Figure 12a. Uranium Concentrations in Groundwater, Horizons A and B, Baseline Period

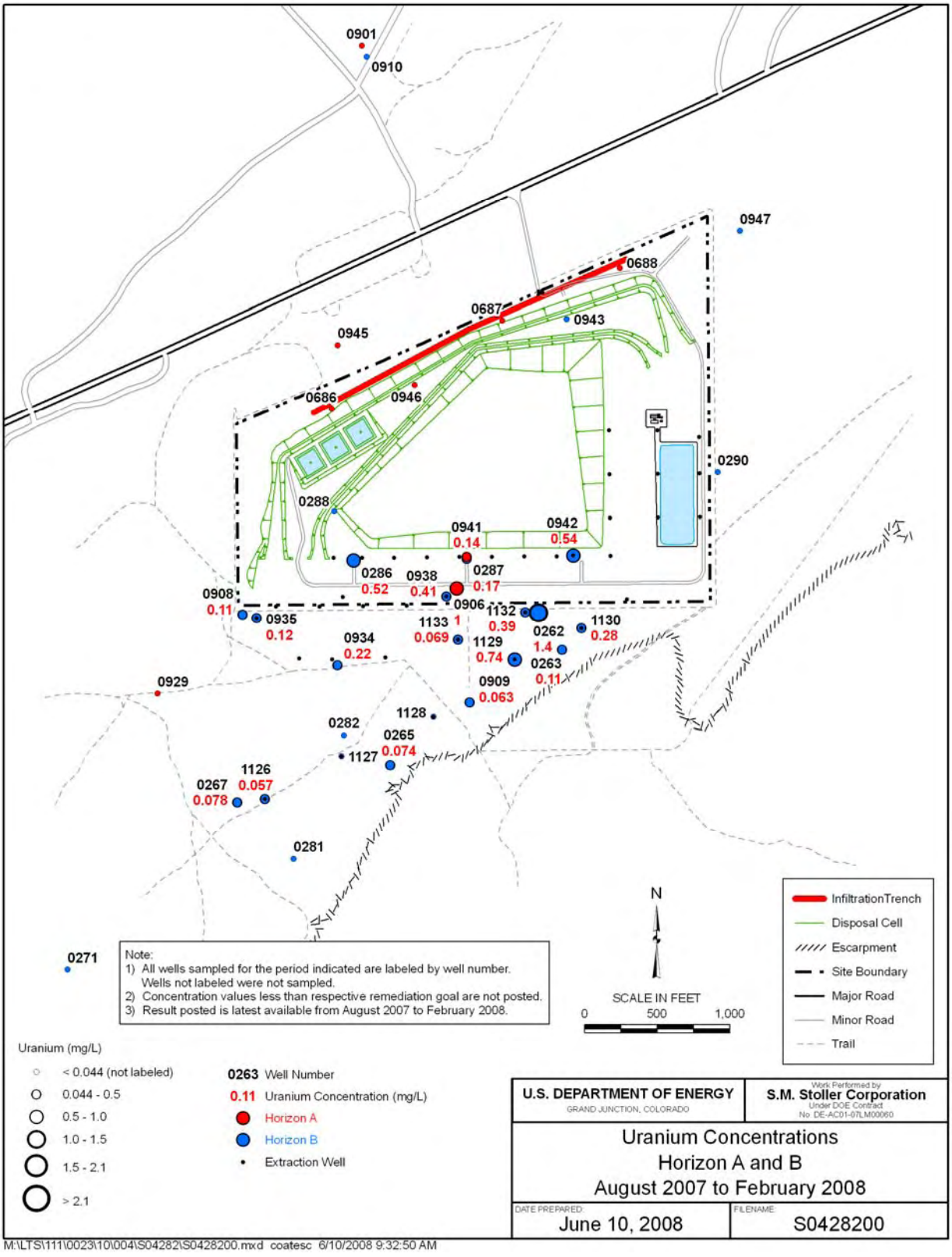

Figure 12b. Uranium Concentrations in Groundwater, Horizons A and B, February 2008

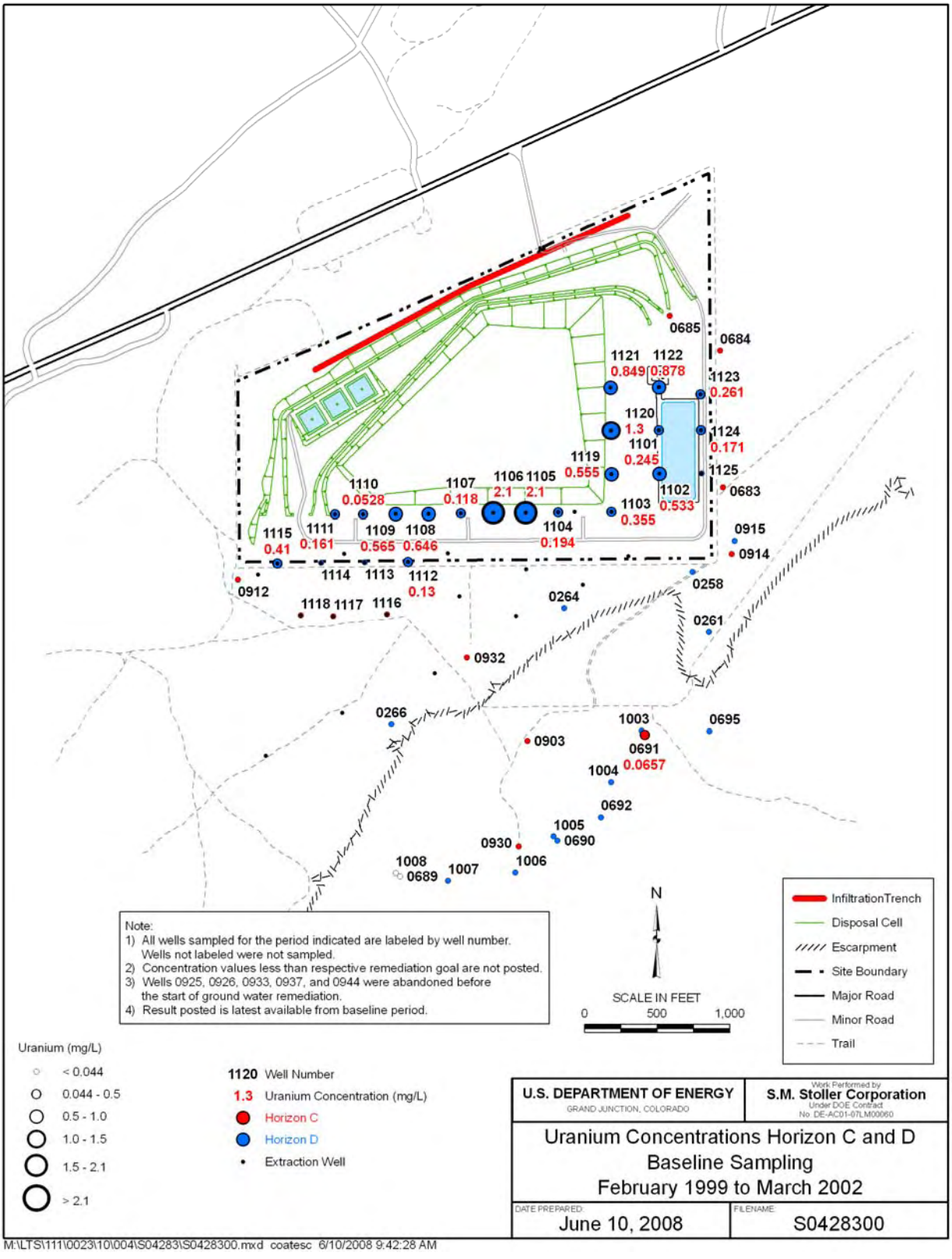

Figure 13a. Uranium Concentrations in Groundwater, Horizons C and D, Baseline

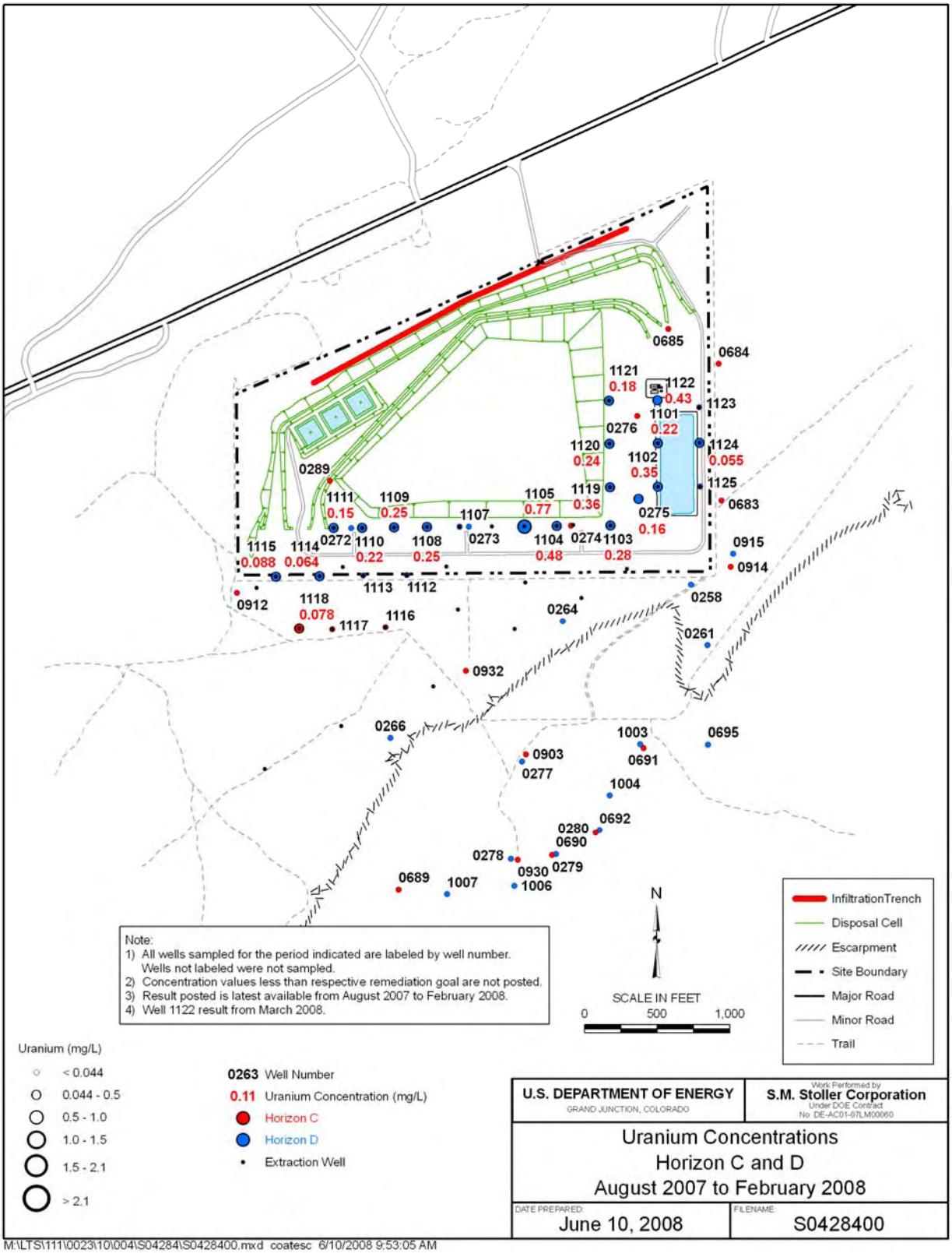

Figure 13b. Uranium Concentrations in Groundwater, Horizons C and D, February 2008

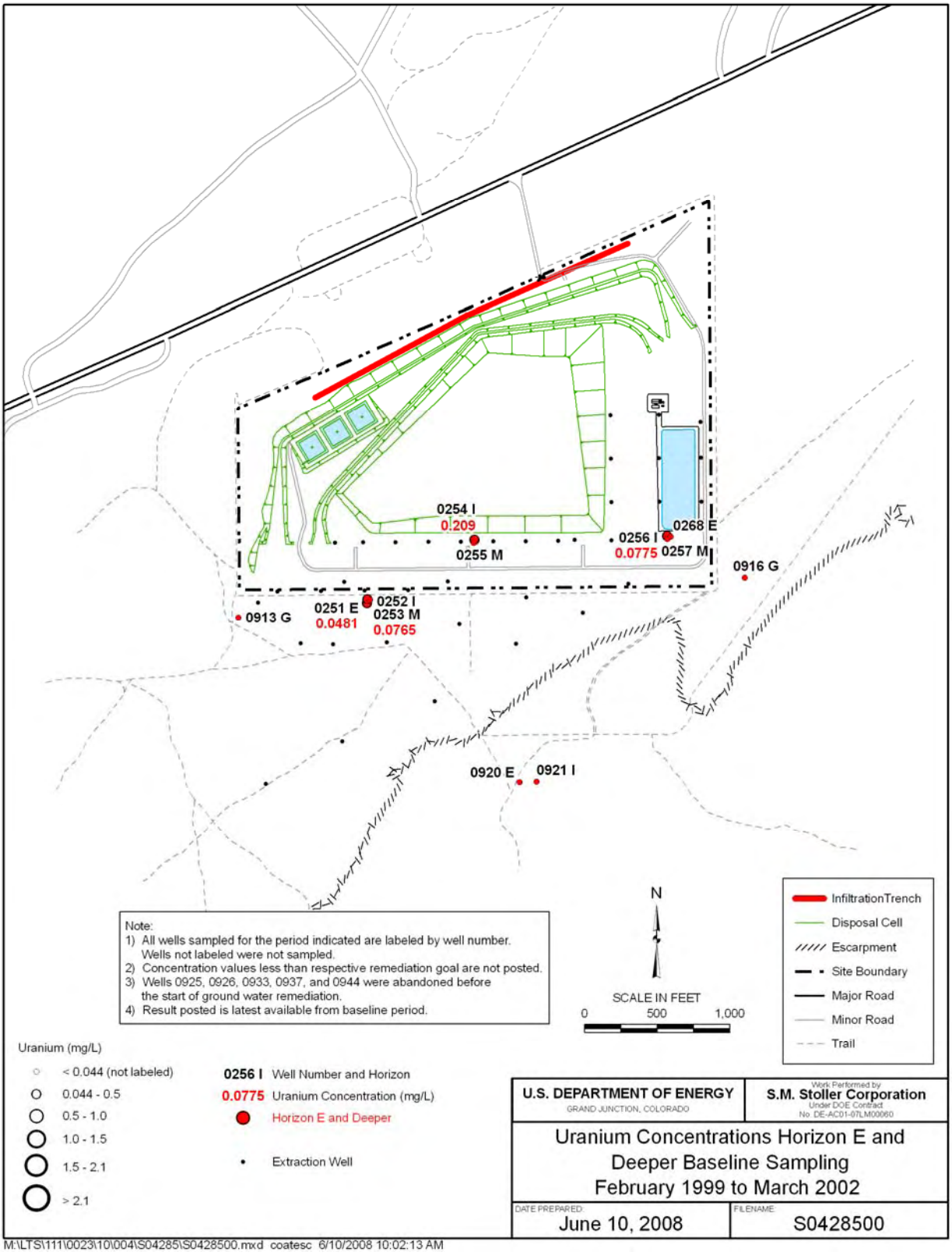

Figure 14a. Uranium Concentrations in Groundwater, Horizons E and Deeper, Baseline Period

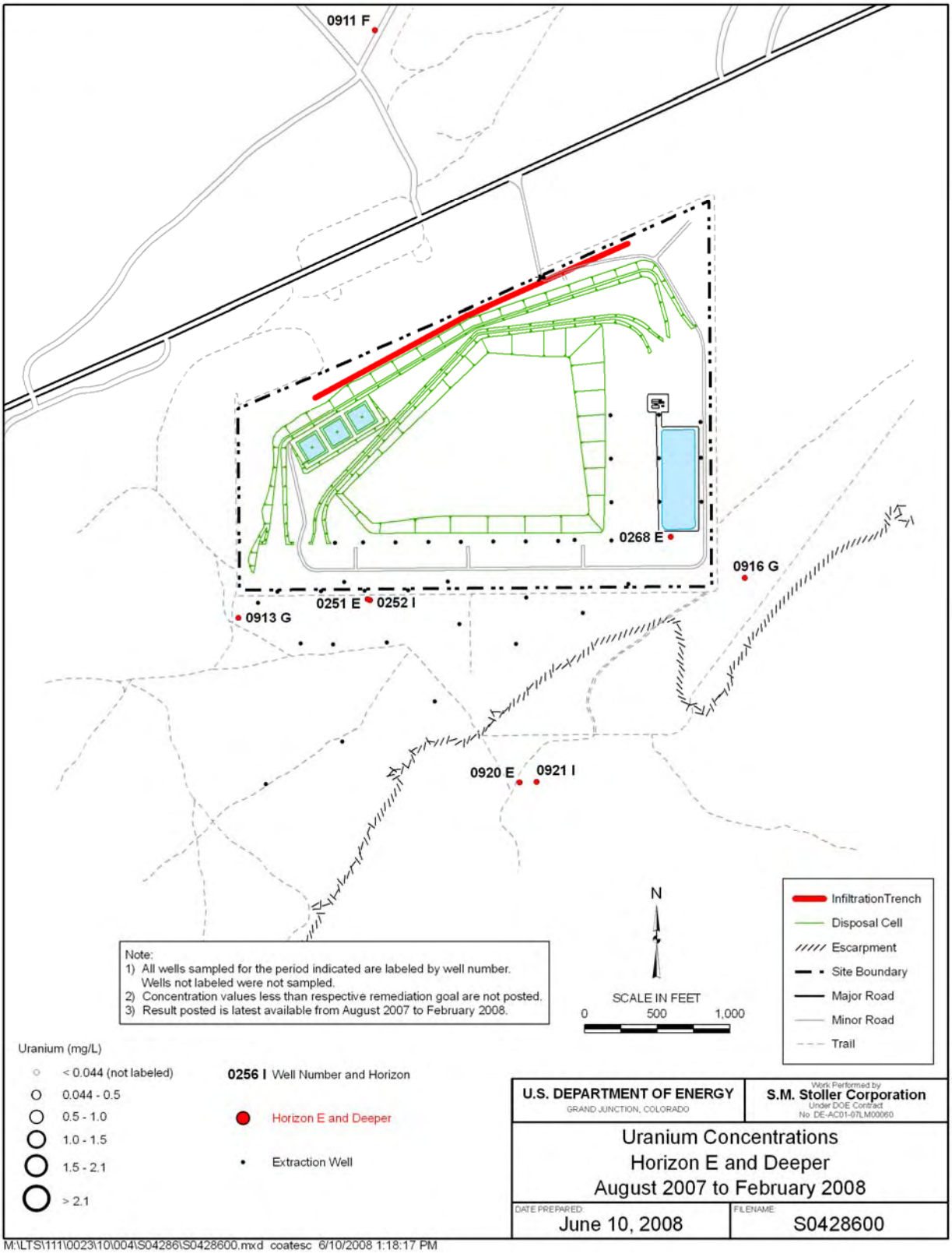

Figure 14b. Uranium Concentrations in Groundwater, Horizons E and Deeper, February 2008

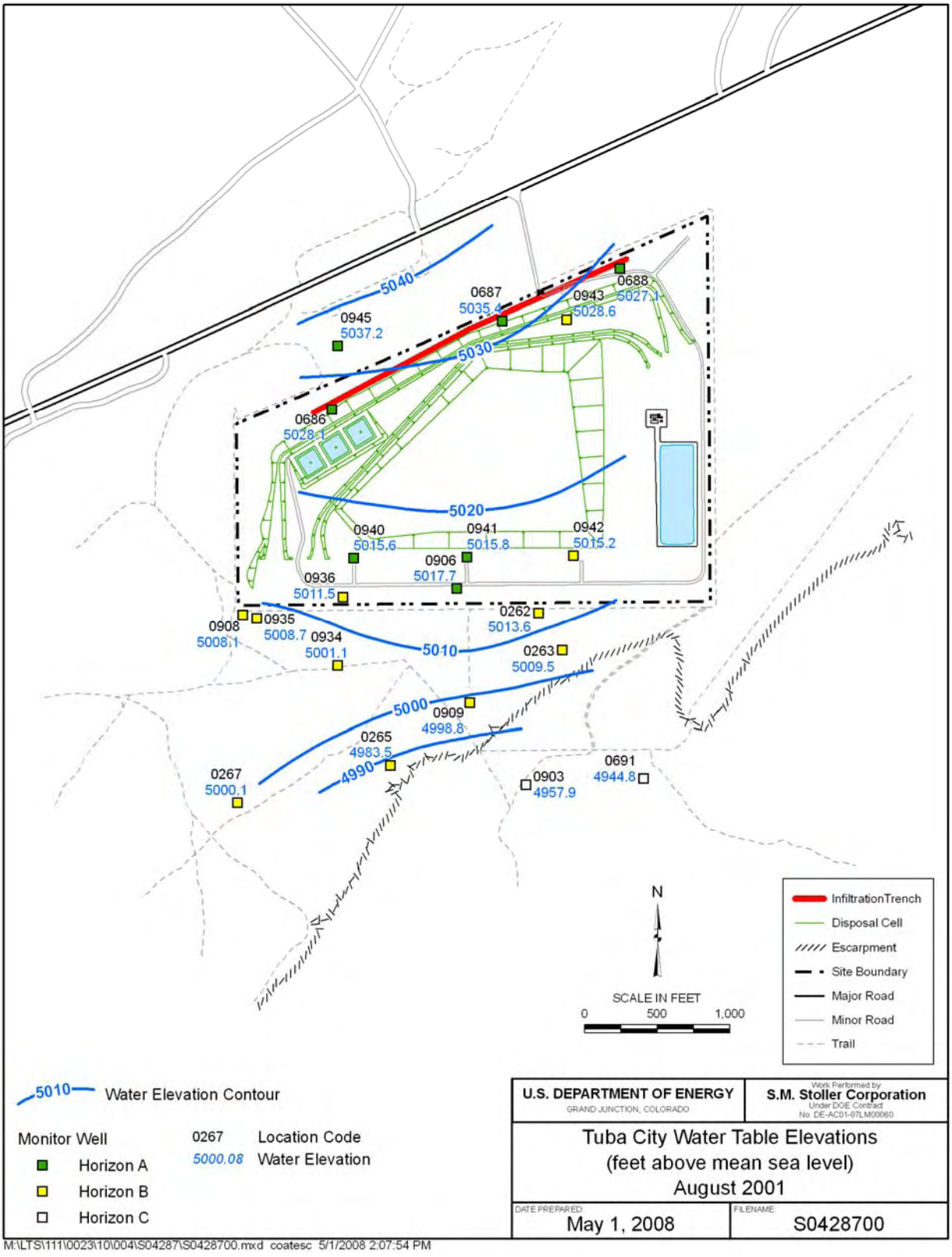

Figure 15. Water Table Elevations (feet above mean sea level), Tuba City Site, August 2001

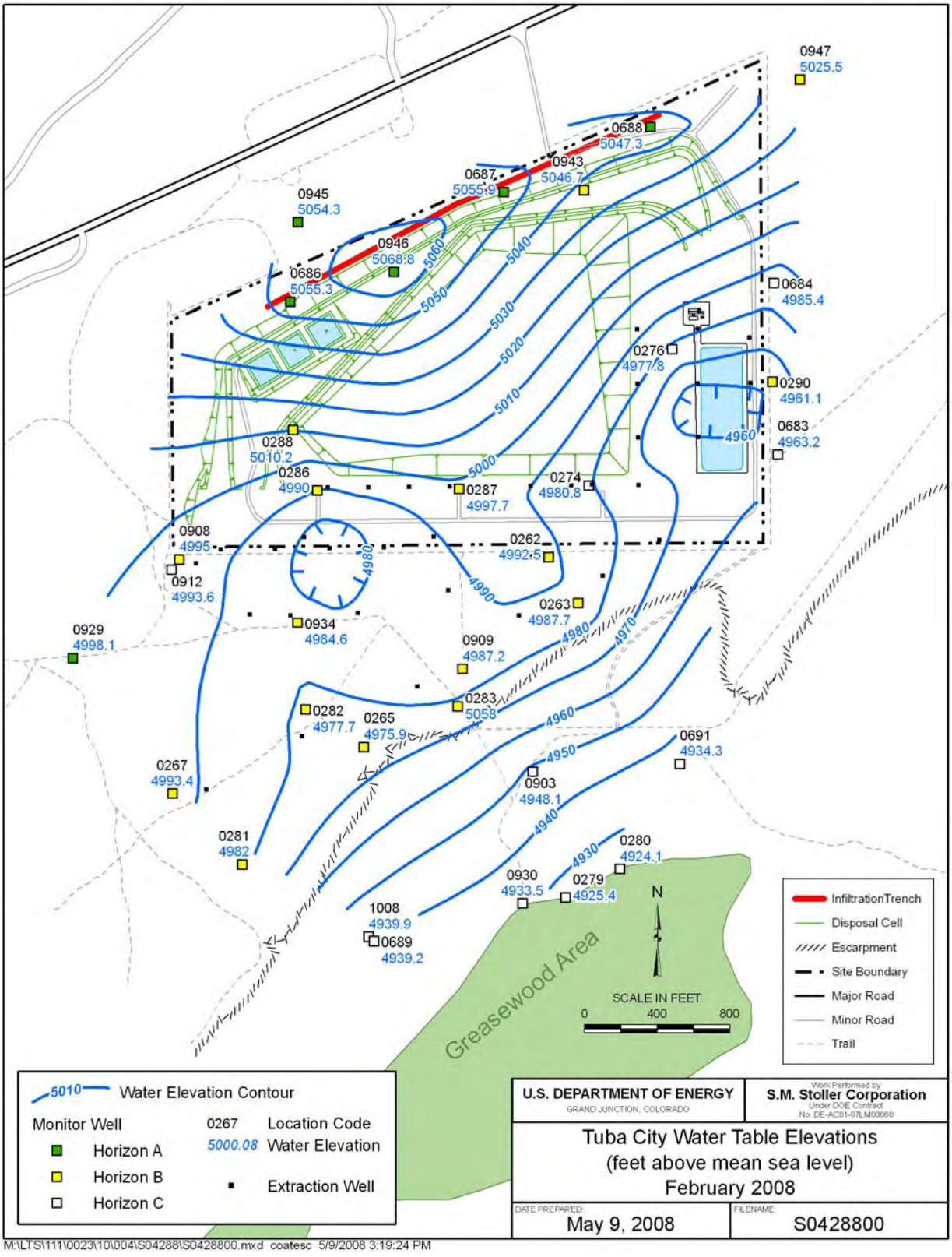

Figure 16. Water Table Contour Map, Tuba City Site, February 2008

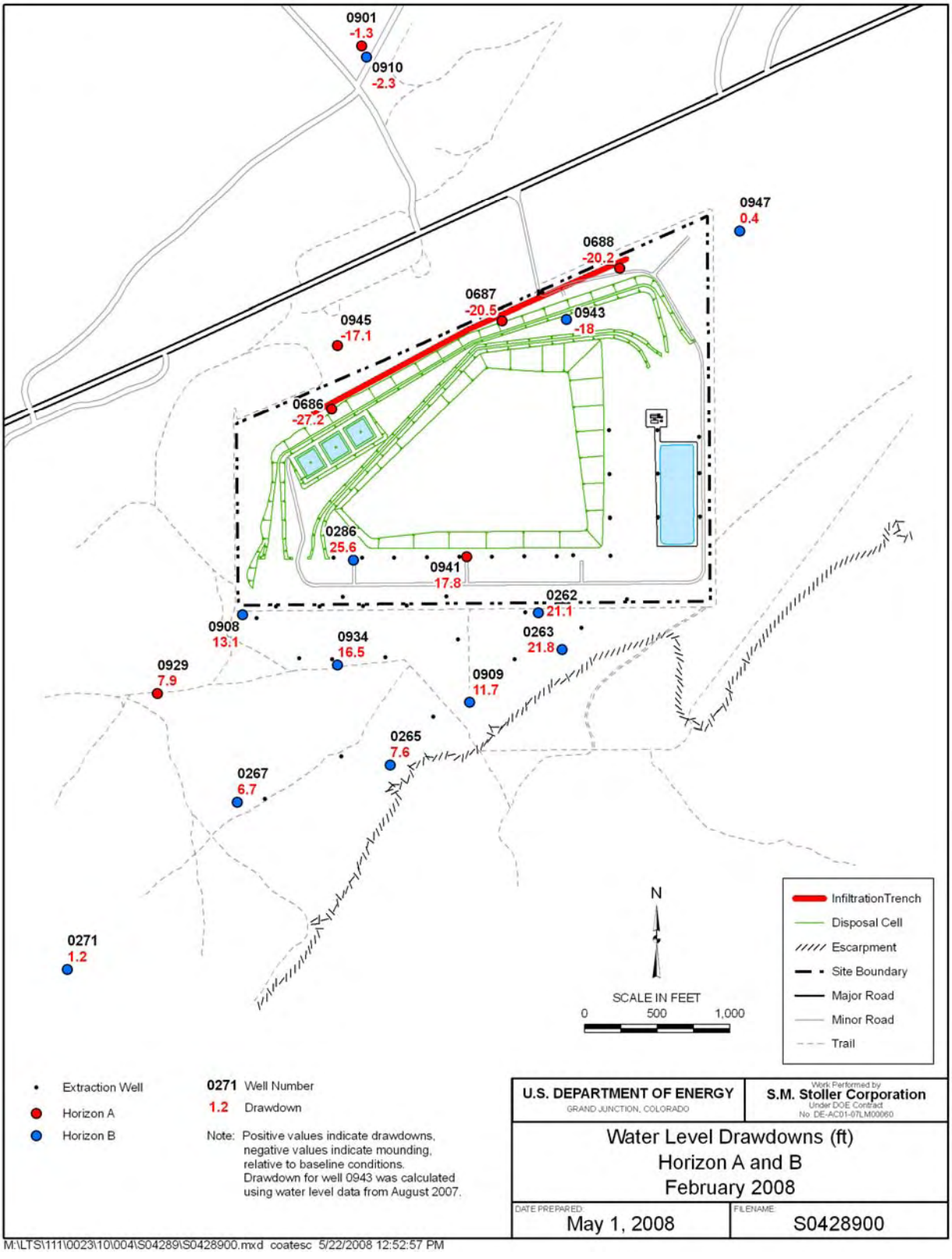

Figure 17. Water Level Drawdowns (feet), Horizons A and B, February 2008

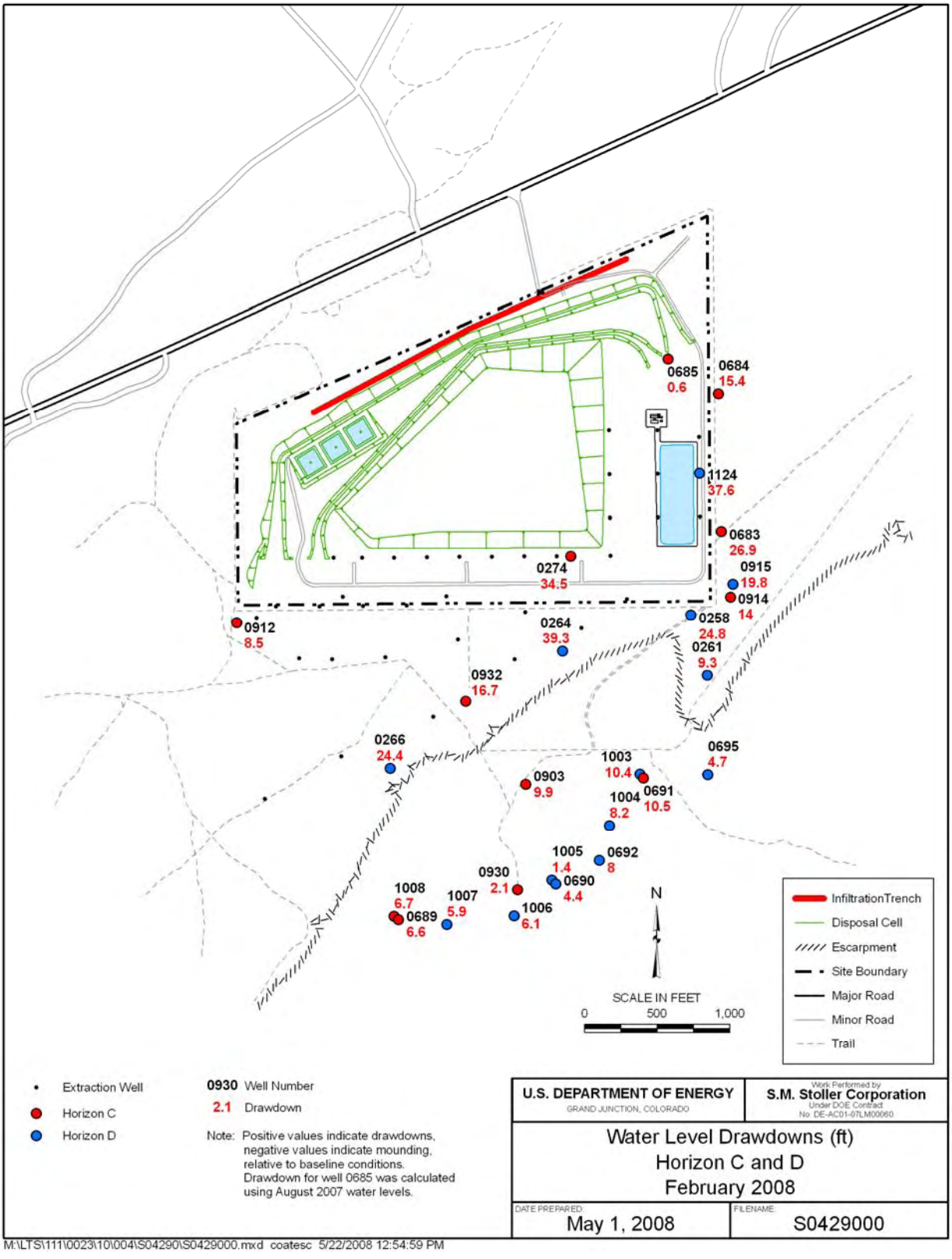

Figure 18. Water Level Drawdowns (feet), Horizons C and D, February 2008

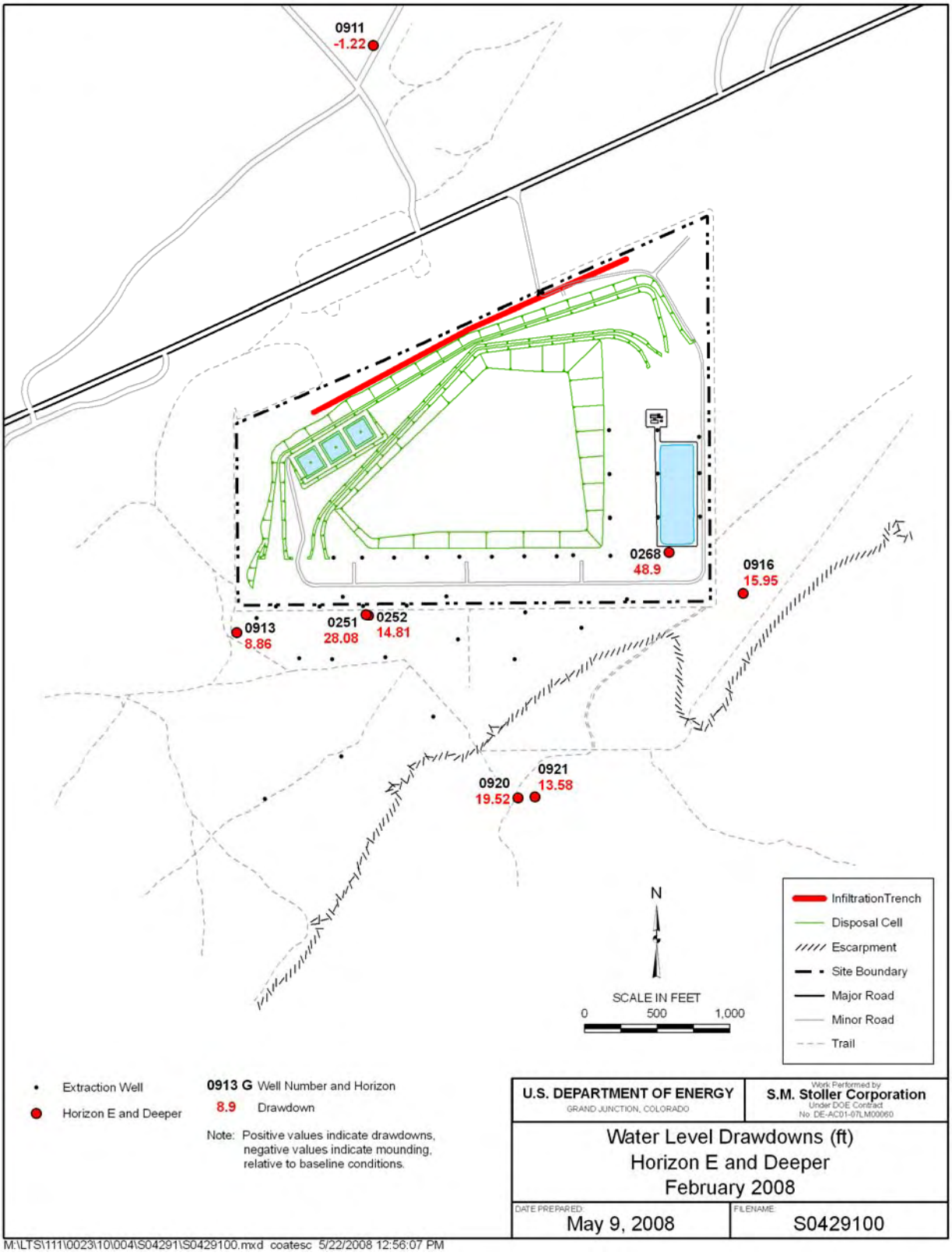

Figure 19. Water Level Drawdowns (feet), Horizons E, F, G, I, and M, February 2008

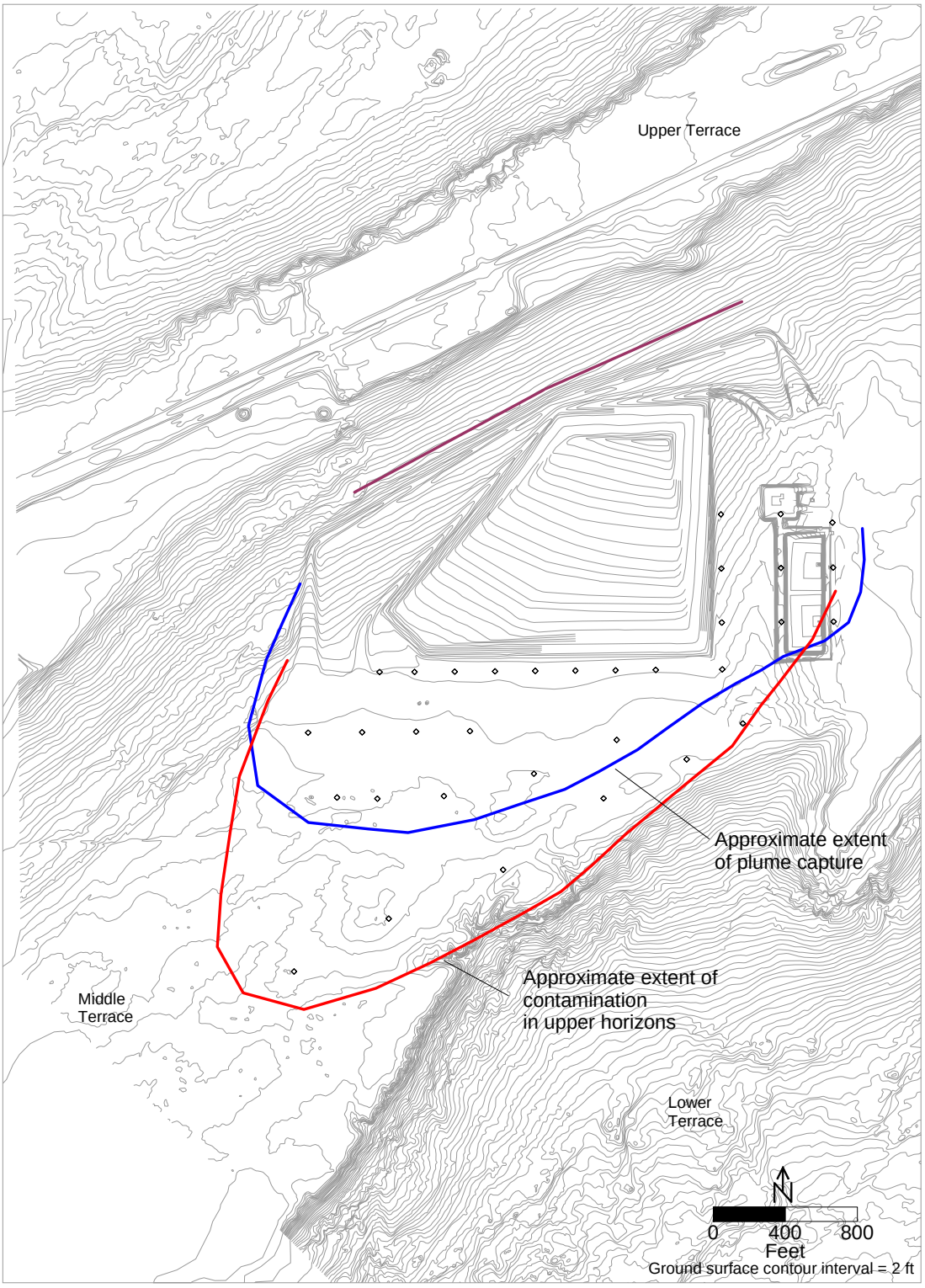

Figure 20. Extent of Groundwater Contamination and Extraction System Capture Zone: Horizons A and B

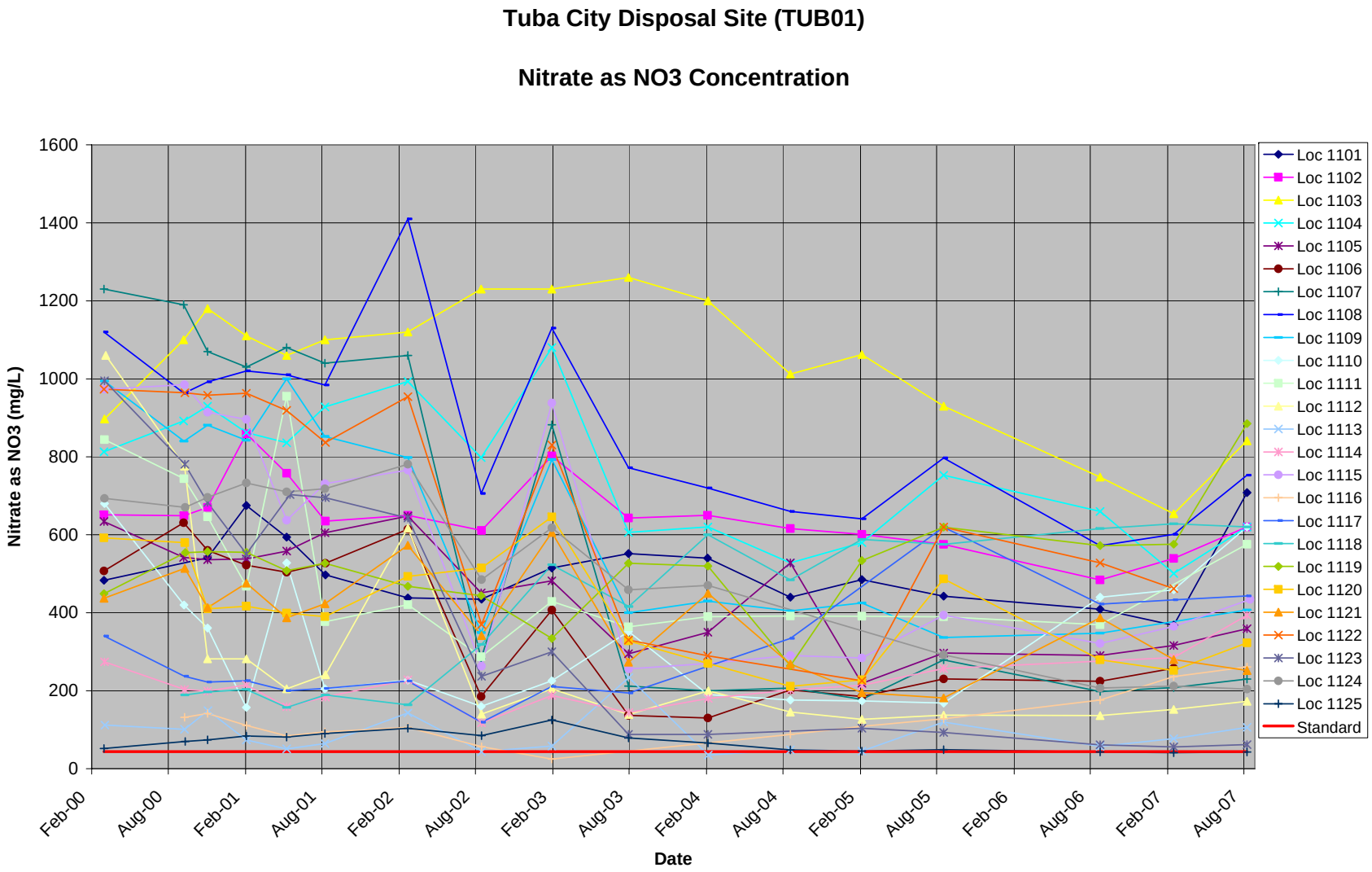

Figure 21a. Nitrate Concentration Trends at Extraction Wells 1101–1125

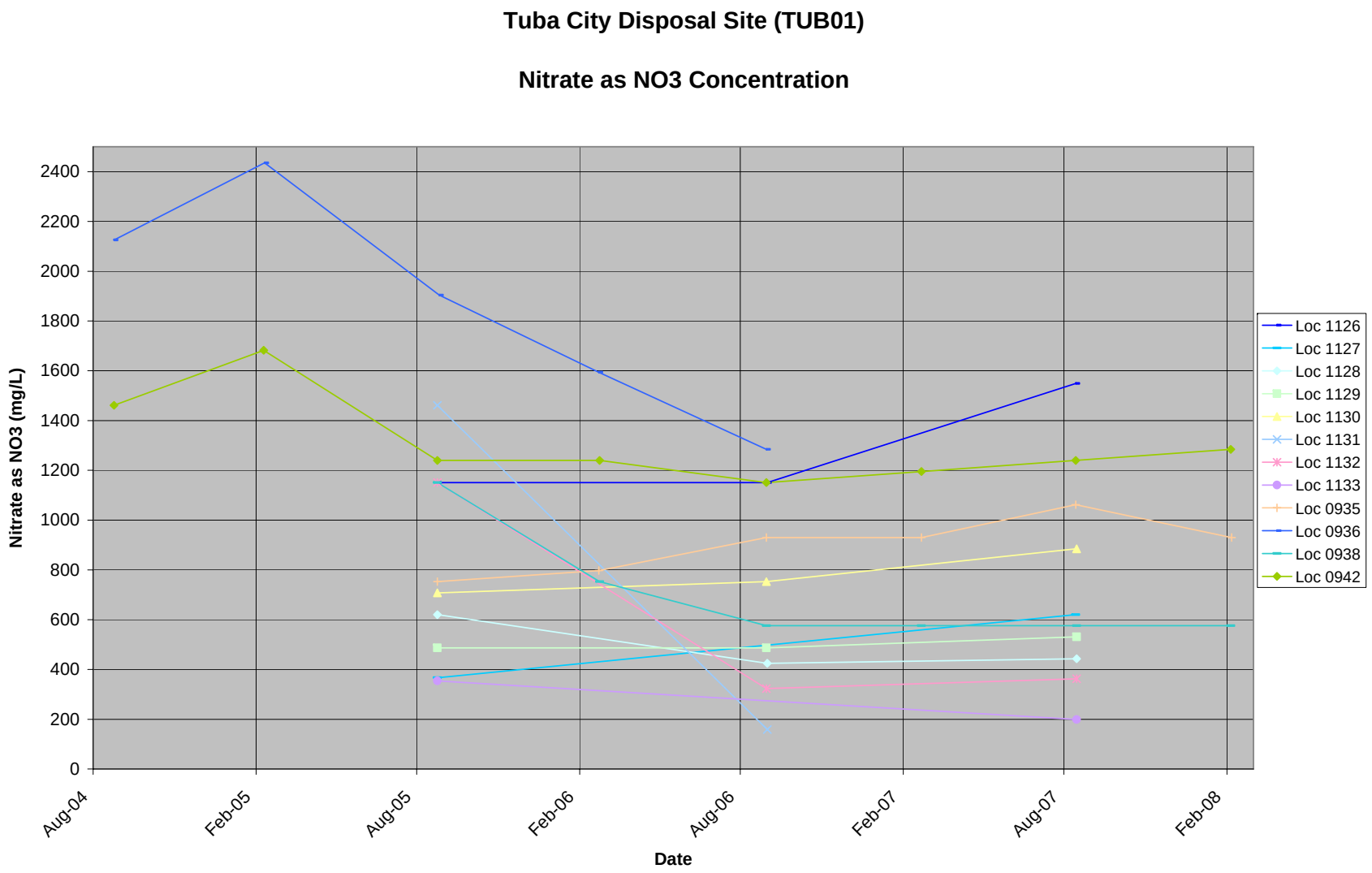

Figure 21b. Nitrate Concentration Trends at Extraction Wells 1126–1133, 935, 936, 938, 942

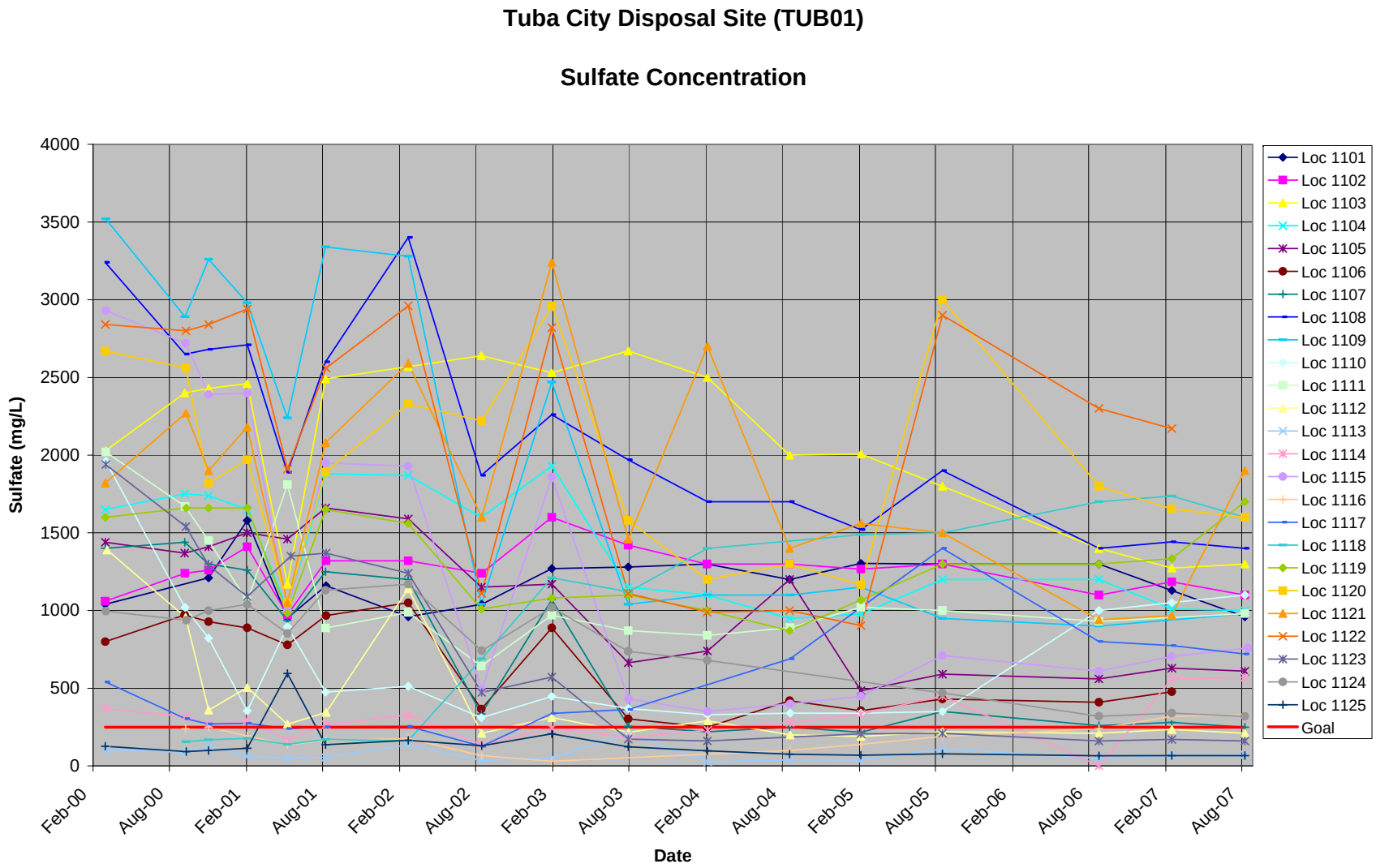

Figure 22a. Sulfate Concentration Trends at Extraction Wells 1101–1125

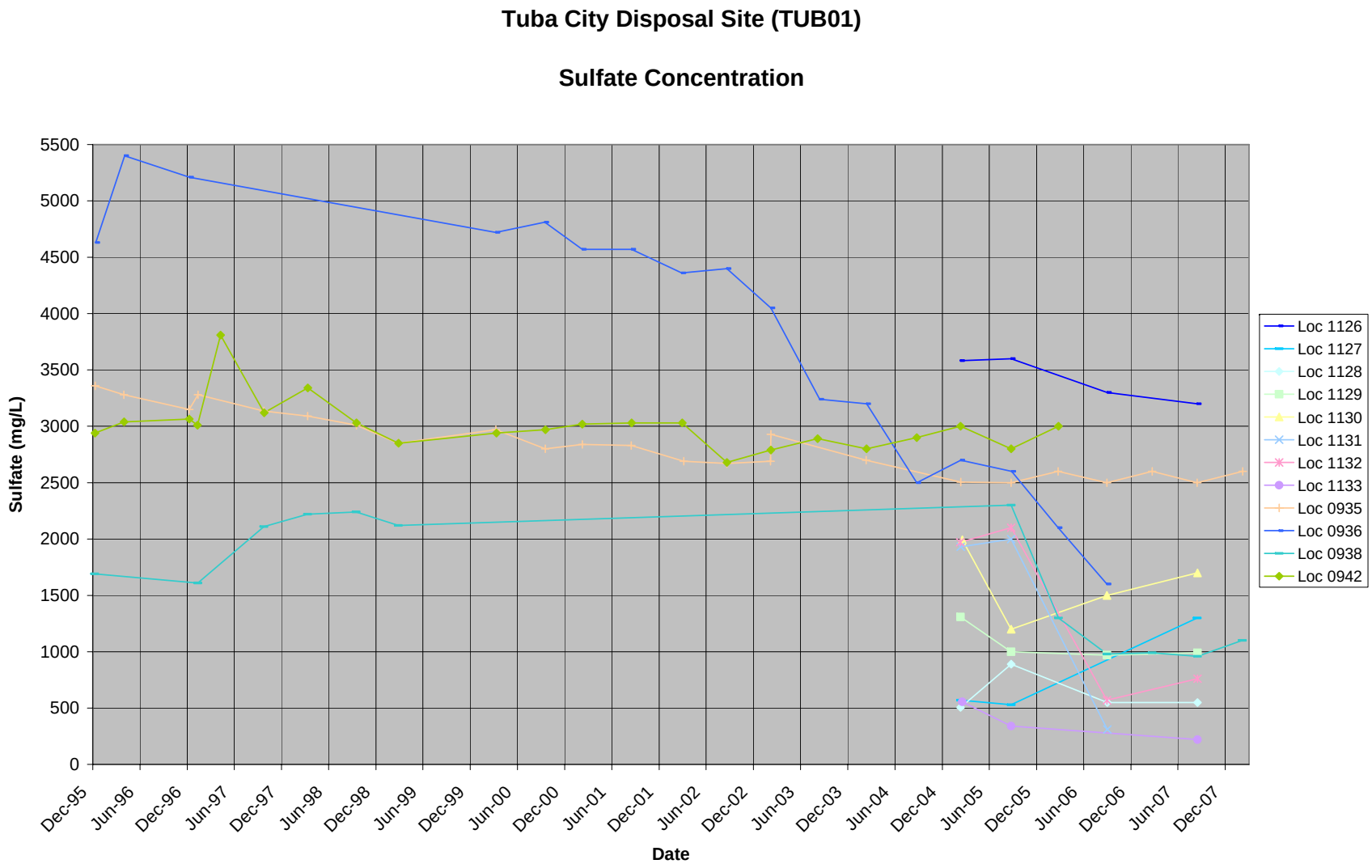

Figure 22b. Sulfate Concentration Trends at Extraction Wells 1126–1133, 935, 936, 938, 942

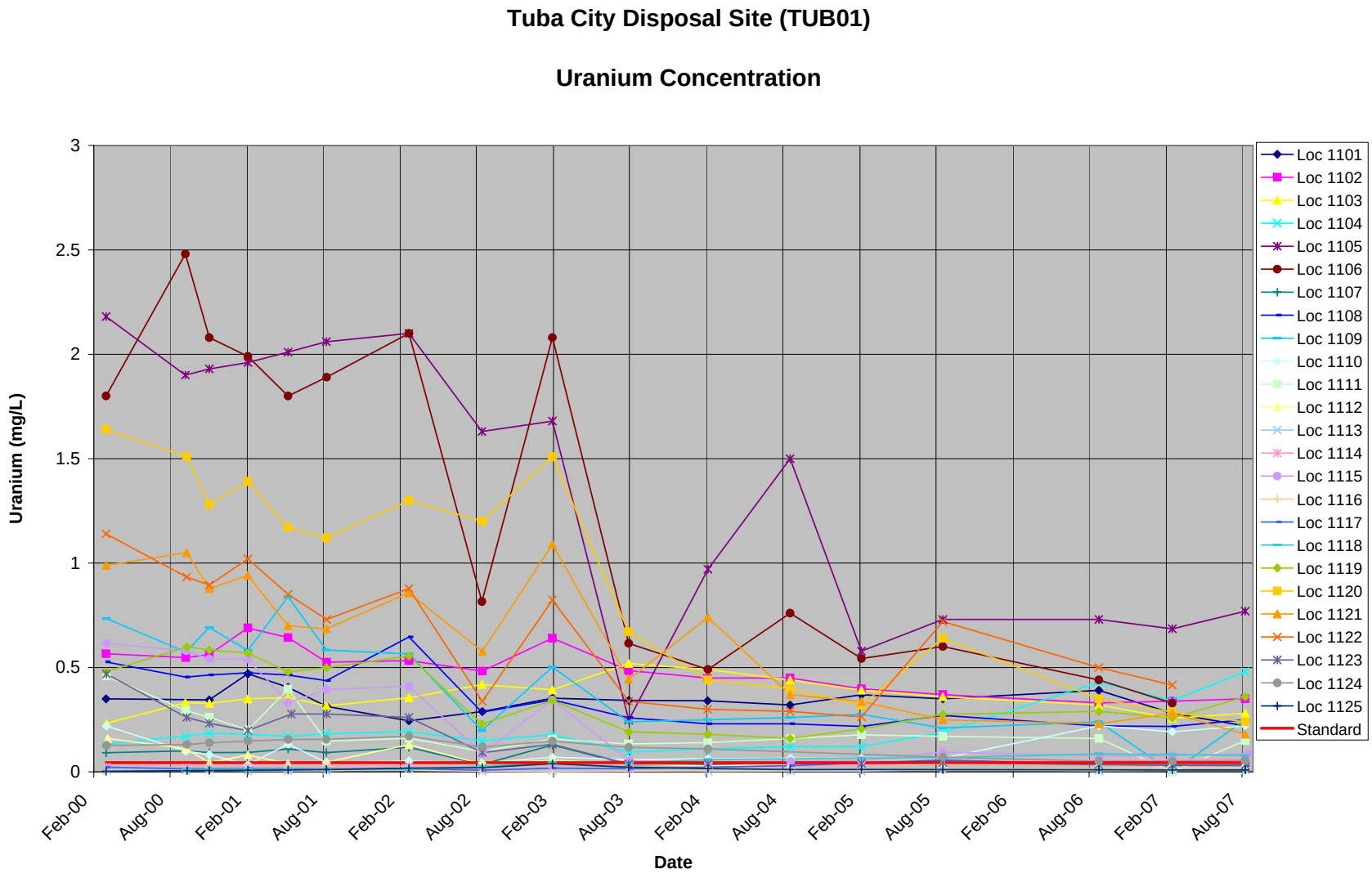

Figure 23a. Uranium Concentration Trends at Extraction Wells 1101–1125

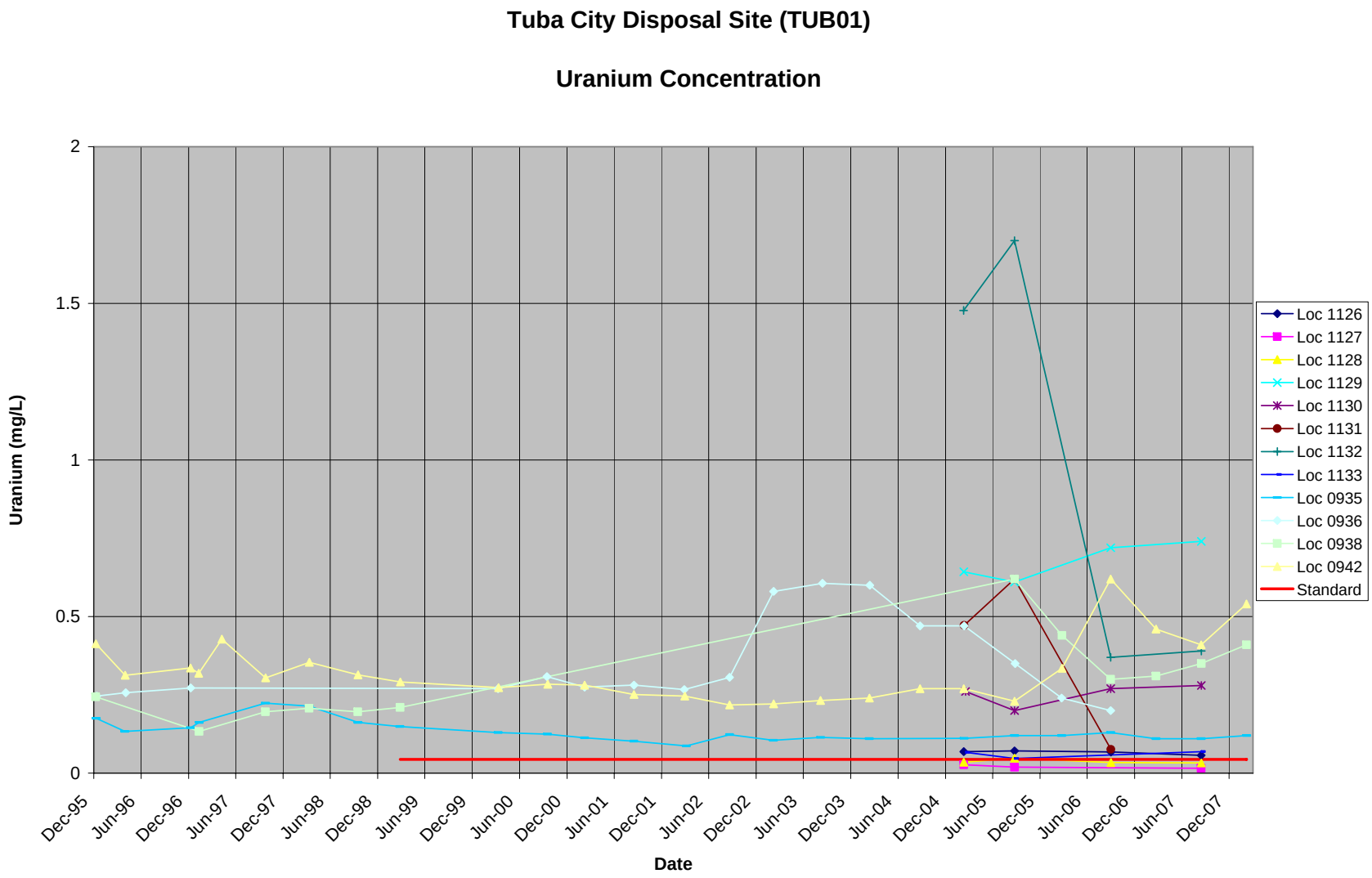

Figure 23b. Uranium Concentration Trends at Extraction Wells 1126–1133, 935, 936, 938, 942

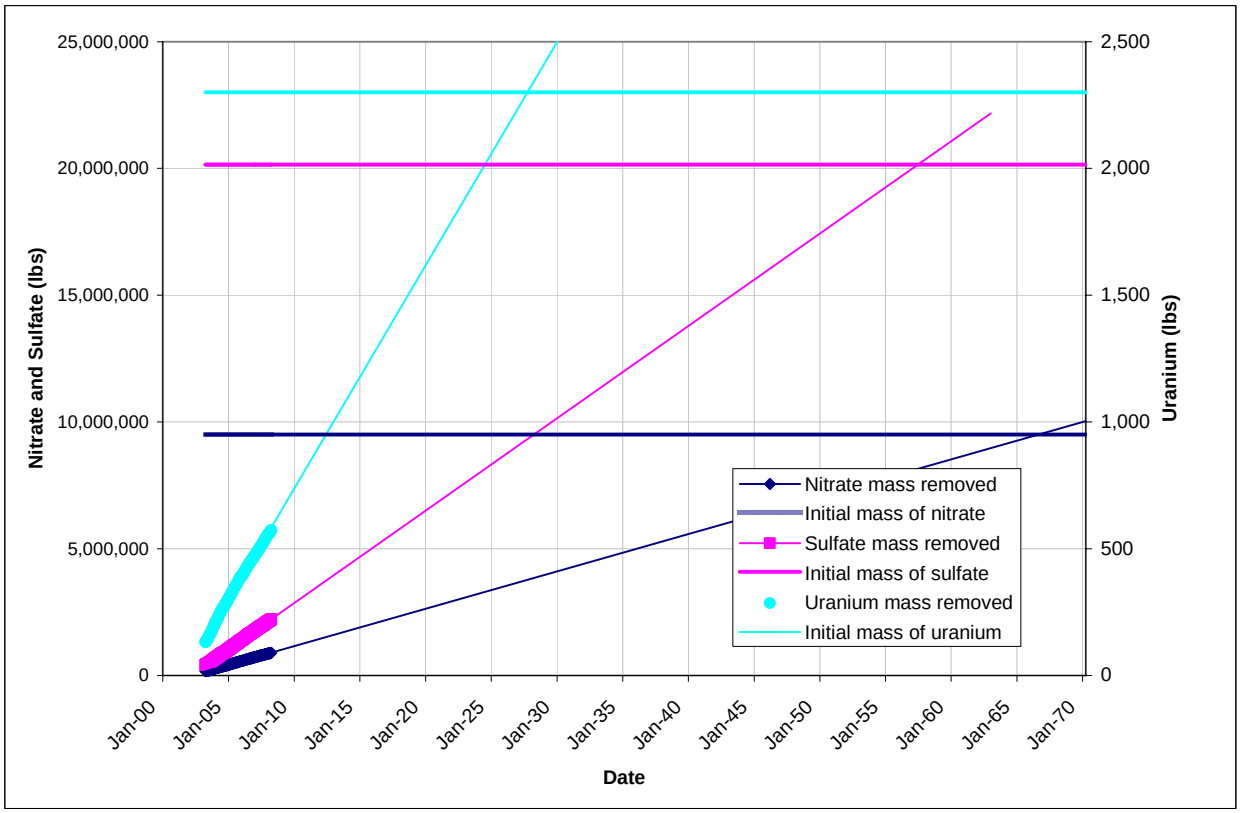

Figure 24. Nitrate, Sulfate, and Uranium Mass Removal Rate Projections

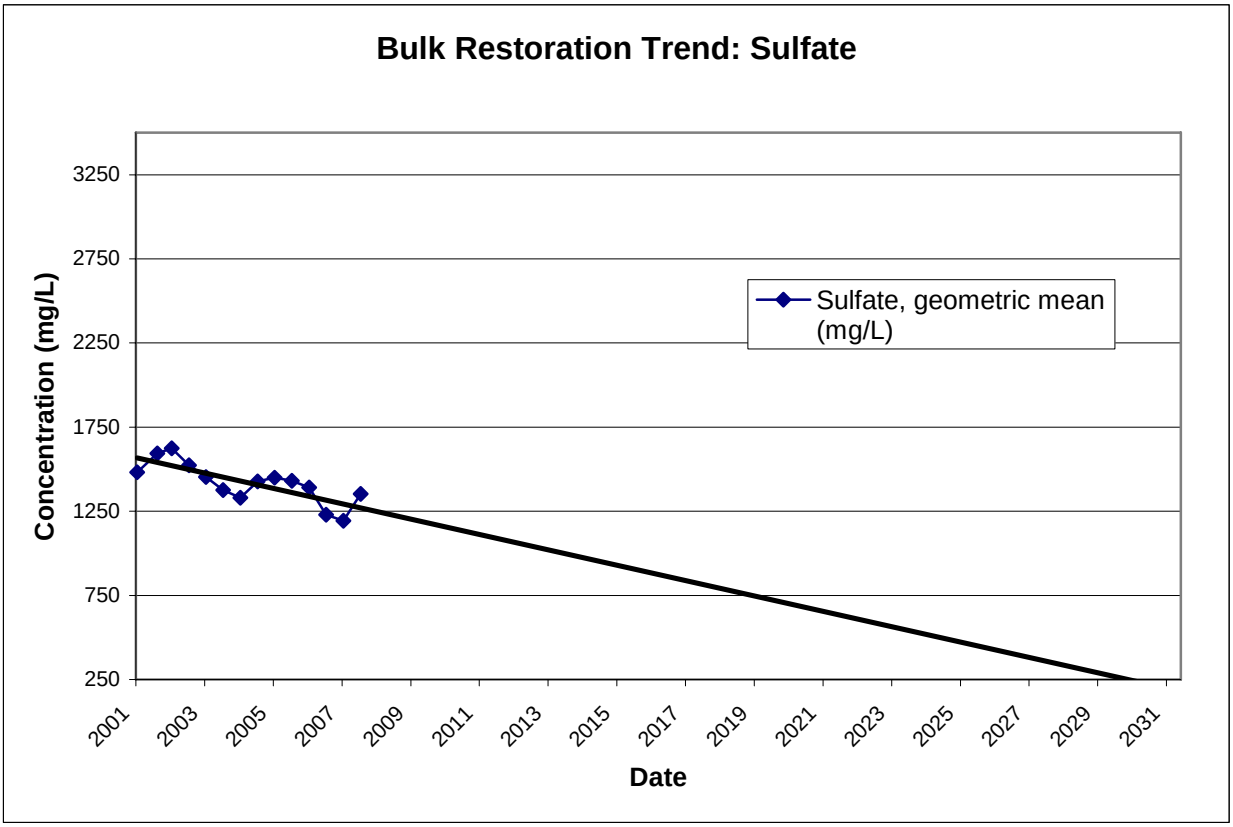

Figure 25. Bulk Restoration Trend for Sulfate

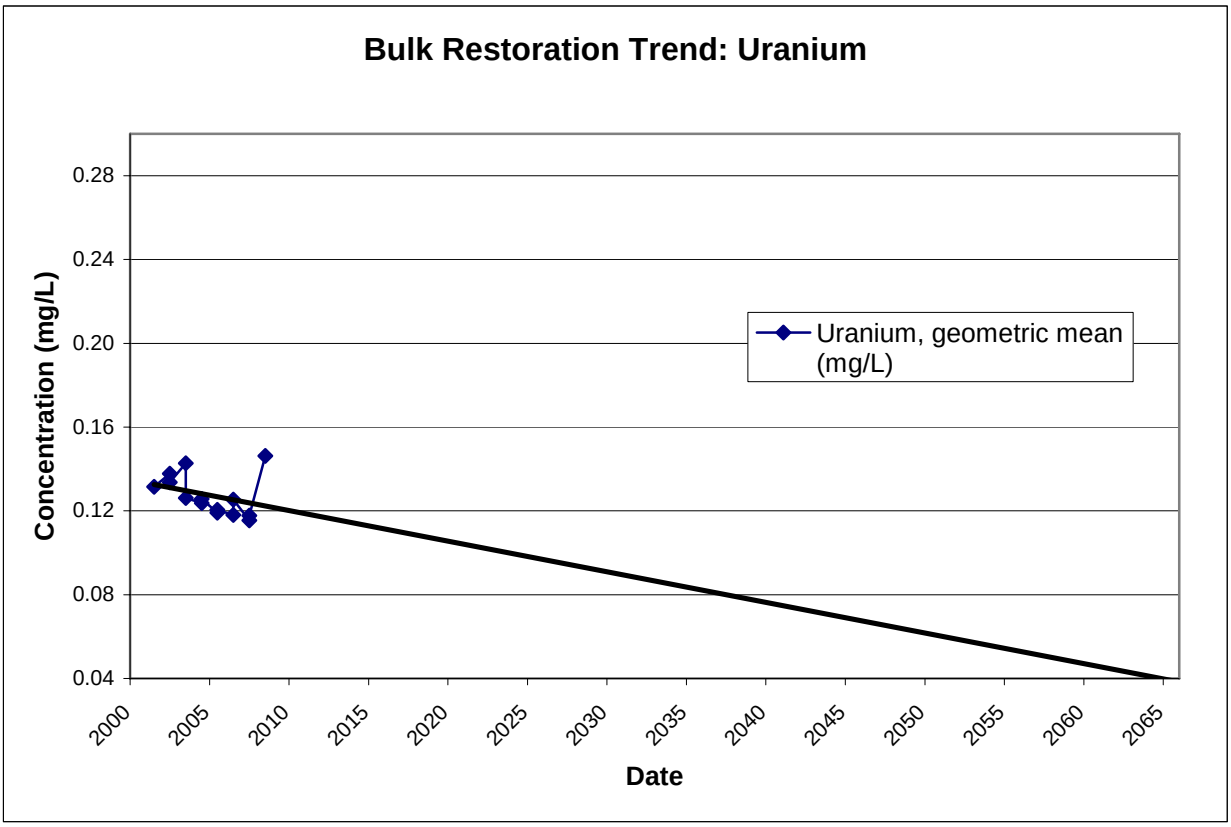

Figure 26. Bulk Restoration Trend for Uranium