1.0 Introduction

This report evaluates the performance of the groundwater remediation system at the Shiprock, New Mexico, Disposal and Processing Site for the period April 2009 through March 2010. The Shiprock site, a former uranium-ore processing facility under the Uranium Mill Tailings Radiation Control Act (UMTRCA), is managed by the U.S. Department of Energy (DOE) Office of Legacy Management.

The mill operated from 1954 to 1968; mill tailings were contained in an engineered disposal cell in 1986. As a result of milling operations, groundwater in the mill site area was contaminated with uranium, nitrate, sulfate, and associated constituents. In March 2003, DOE initiated active remediation of the groundwater using extraction wells and interceptor drains. At that time, a baseline performance report was developed (DOE 2003). That report established specific performance standards for the Shiprock groundwater remediation system and documented the site conditions that form the basis for comparisons drawn herein.

The Shiprock site is divided into two distinct areas, the floodplain and the terrace; an escarpment forms the boundary between the two areas. The floodplain remediation system consists of two groundwater extraction wells, a seep collection drain, and two collection trenches (Trench 1 and Trench 2). The terrace remediation system consists of nine groundwater extraction wells, two collection drains (Bob Lee Wash and Many Devils Wash), and a terrace drainage channel diversion structure. All extracted groundwater is pumped into a lined evaporation pond on the terrace. Figure 1–1 shows the site layout and the major components of the floodplain and terrace groundwater remediation systems. Figure 1–2 shows the locations of monitoring wells and surface water sampling locations at the site.

A detailed description of the Shiprock site conditions is presented in the Site Observational Work Plan (SOWP) (DOE 2000), and the compliance strategy is presented in the Groundwater Compliance Action Plan (GCAP) (DOE 2002). Since these initial reports were developed, DOE has undertaken additional evaluations, including the *Refinement of Conceptual Model and Recommendations for Improving Remediation Efficiency at the Shiprock, New Mexico, Site* (DOE 2005), and the more recent evaluation of the Trench 2 groundwater remediation system (DOE 2009b). DOE recently issued a midterm evaluation of the remediation strategy for both the floodplain and the terrace (DOE 2010a).

1.1 Remediation System Performance Standards

This performance assessment is based on an analysis of groundwater quality and groundwater level data obtained from site monitoring wells in addition to groundwater flow rates associated with the extraction wells, drains, and seeps. Specific performance standards established for the Shiprock floodplain groundwater remediation system in the Baseline Performance Report (DOE 2003) are summarized as follows:

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

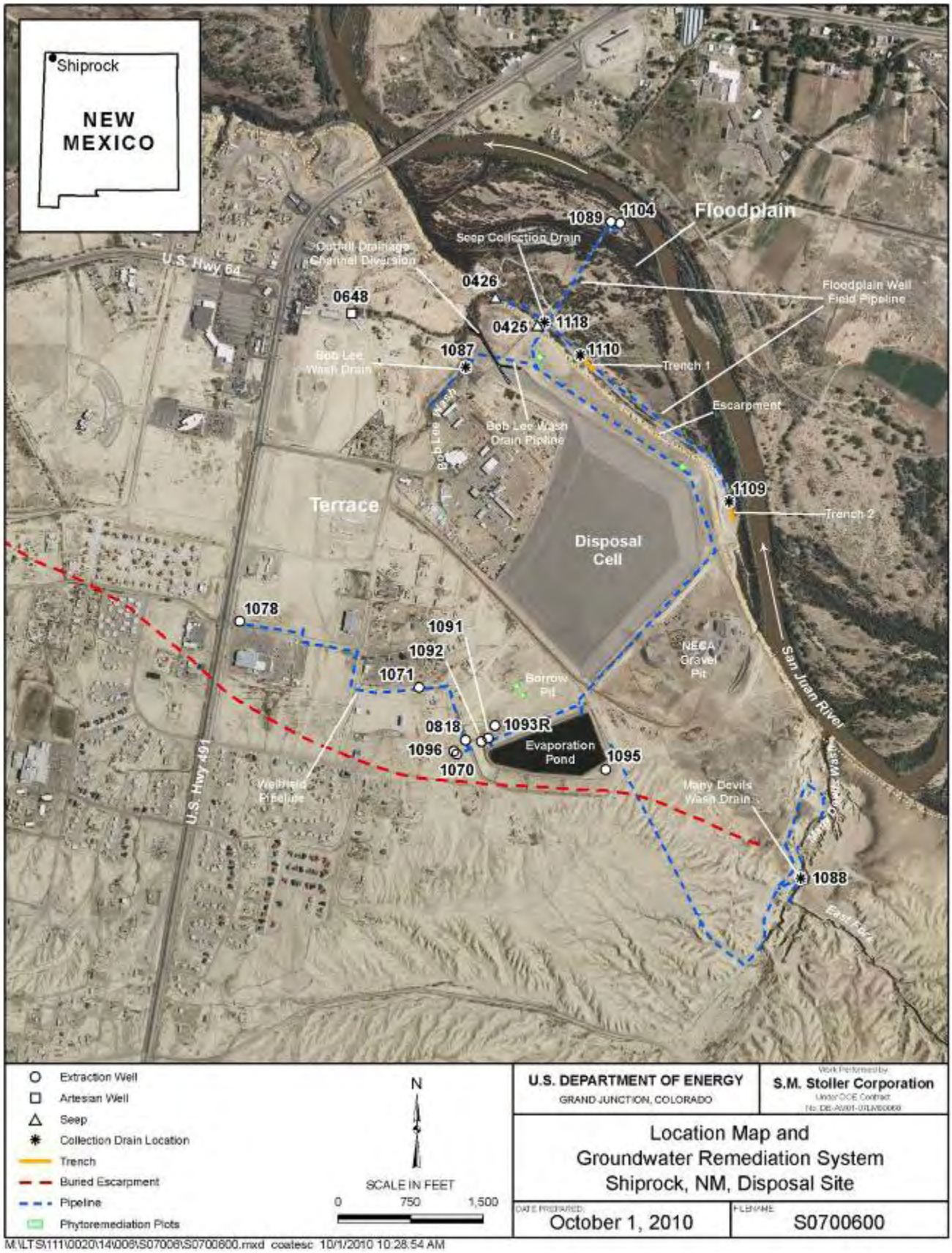

Figure 1–1. Location Map and Groundwater Remediation System

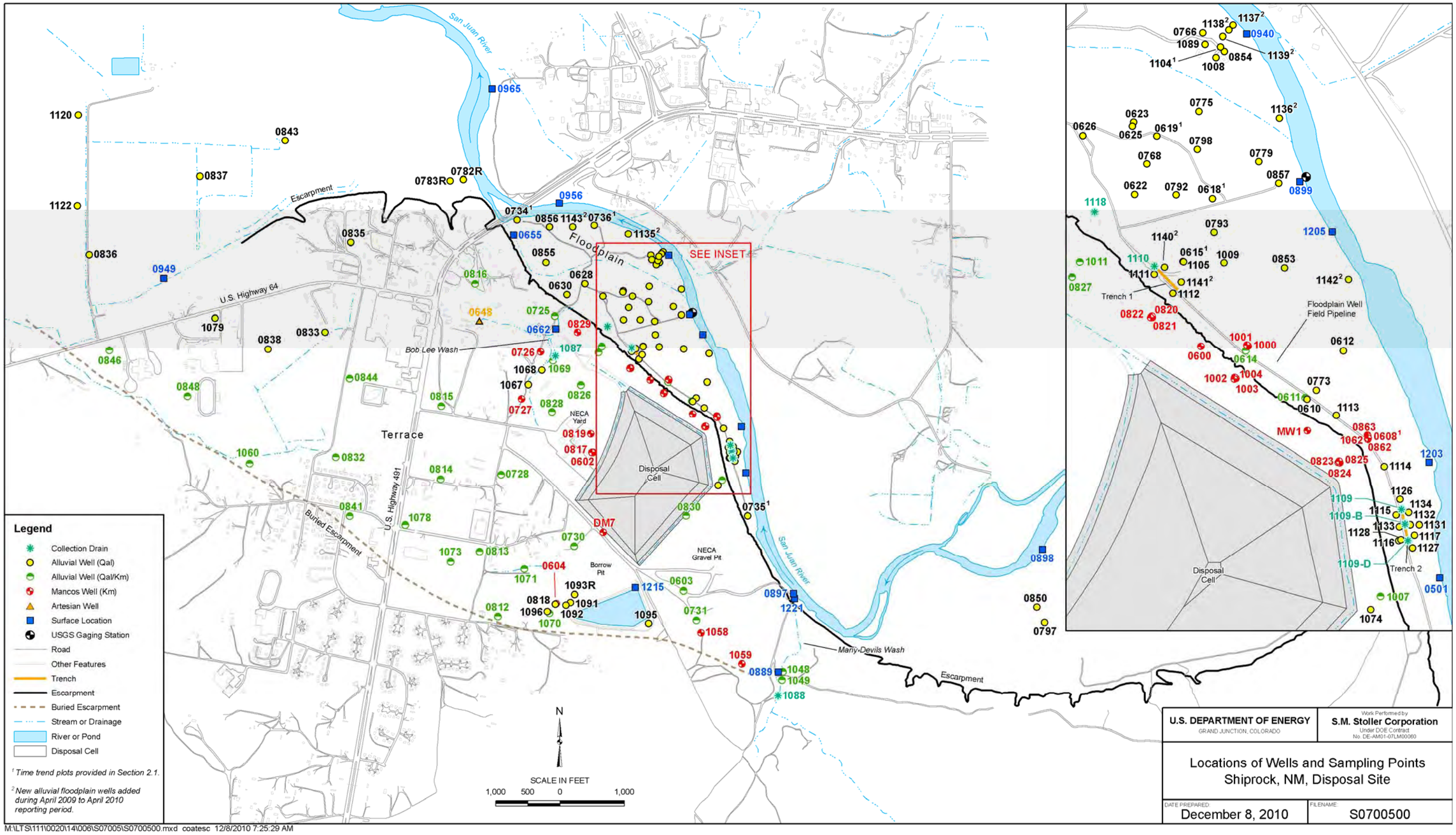

Figure 1–2. Locations of Wells and Sampling Points at the Shiprock Site

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Performance standards established for the terrace groundwater remediation system in the 2003 baseline report (DOE 2003) are:

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

1.2 Contaminants of Concern (COCs) and Remediation Goals

The COCs for both the floodplain and terrace, defined in the GCAP (DOE 2002) are ammonia (total as nitrogen); manganese; nitrate (nitrate + nitrite as nitrogen); selenium; strontium; sulfate; and uranium. These constituents are listed in Table 1–1 along with respective UMTRCA standards and, for comparison, corresponding floodplain background data. Background data are available only for the floodplain because, even after years of investigation and reconnaissance, groundwater reflective of background conditions has not been encountered in terrace areas near the disposal cell.

Table 1–1. Groundwater COCs for the Shiprock Site

Contaminant	40 CFR 192 MCL	SOWP Floodplain Background Value	Historical Range in Floodplain Background[a] (Mean)	Comment
Ammonia, as N (mg/L)	NA	0.045	Not detected (≤0.1)	
Manganese (mg/L)	NA	1.24	0.001–7.2 (1.3)	Maximum background level of 7.2 mg/L measured in March 2006 (well 0797).
Nitrate[b] (mg/L)	10	0.12	0.004–3.3 (0.16)	
Selenium (mg/L)	0.01	<0.001	0.0001–0.018 (0.001)	EPA Safe Drinking Water Act (SDWA) MCL standard is 0.05 mg/L.
Strontium (mg/L)	NA	2.3	1.0–10 (3.0)	Background maximum (10 mg/L) measured in September 2008 (well 0797). EPA risk-based value is 22 mg/L (see discussion at the conclusion of Section 1.2).
Sulfate (mg/L)	NA	1432	427–5200 (1983)	Because sulfate levels have historically been elevated in terrace artesian well 0648 (1870−2340 mg/L), the GCAP proposed an alternate cleanup goal of 2000 mg/L (DOE 2002).
Uranium[c] (mg/L)	0.044	0.007	0.004–0.12 (0.03)	In recent years, levels in both background wells, although variable, have been increasing slightly and have approached or exceeded the 0.044 mg/L standard.

[a] Floodplain background wells 0797 and 0850 (locations shown in Figure 1–2; also see Figure 2–10)
[b] Nitrate + nitrite as nitrogen (N)
[c] Equivalent to 30 picocuries per liter (pCi/L) U-234 + U-238, assuming secular equilibrium
40 CFR 192 = Title 40 *Code of Federal Regulations* Part 192; EPA = U.S. Environmental Protection Agency; MCL = Maximum concentration limit (applies to 40 CFR 192) or maximum contaminant level (EPA SDWA)
mg/L = milligrams per liter
NA = Not applicable (contaminant does not have an MCL in 40 CFR 192)

The compliance standards for uranium and nitrate in the floodplain are their respective 40 CFR 192 standards of 0.044 milligram per liter (mg/L) and 10 mg/L. A secondary standard of 250 mg/L for sulfate has been established under the U.S. Environmental Protection Agency (EPA) Safe Drinking Water Act (SDWA).[1] However, sulfate concentrations in floodplain background wells 0797 and 0850 have consistently been above this standard (427–5200 mg/L). Because sulfate levels have also been elevated in groundwater entering the floodplain from flowing artesian well 0648 (up to 2340 mg/L), the GCAP proposed an alternate cleanup goal for sulfate of 2000 mg/L (DOE 2002). This alternate goal is conservative given the elevated levels in floodplain background wells.

Relatively high selenium concentrations in the floodplain (originating on the terrace) make it unlikely that the 40 CFR 192 standard of 0.01 mg/L for this constituent can be met while contaminated water from the terrace is still providing a source.[2] Therefore, DOE has proposed an interim alternate concentration limit for selenium of 0.05 mg/L (DOE 2002), which is the EPA maximum contaminant level for drinking water.

Previous reports (e.g., DOE 2009a) have cited a cleanup objective for manganese based on the maximum background concentration for the floodplain. This level is currently 7.2 mg/L, the historical maximum measurement in well 0797 in March 2006.[3] The maximum background concentration of strontium was also detected in well 0797: 10 mg/L in September 2008. A cleanup standard has not been established for ammonia (EPA has not developed any toxicity values upon which to base an associated risk-based standard), and levels measured in background wells have been low ($\leq$0.1 mg/L).

Regulatory standards are also not available for strontium, a constituent typically not associated with uranium milling sites. Strontium was selected as a COC based on the Baseline Risk Assessment (DOE 1994); it was selected primarily because of concentrations measured in sediment (rather than groundwater) and a conservatively modeled agricultural uptake scenario. The form present at the Shiprock site is stable (nonradioactive) strontium, a naturally occurring element, and is distinguished from the radioactive and much more toxic isotope strontium-90, a nuclear fission product (ATSDR 2004). EPA has developed a risk-based screening level for stable strontium in groundwater of 22 mg/L (assuming groundwater is used for drinking water). As discussed later in this report, almost all historical groundwater results at Shiprock have been less than this risk-based value.[4]

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[1] Studies conducted by the Centers for Disease Control in conjunction with EPA have shown that no adverse effects from sulfate ingestion occur at concentrations of up to 1,200 mg/L (EPA 1999). The report notes that other studies have shown that concentrations of sulfate exceeding 2,000 mg/L may have little or no adverse effect on humans and animals.

[2] As acknowledged in the recently issued *Review and Evaluation of the Shiprock Remediation Strategy* (DOE 2010a), although concentrations are clearly elevated in some areas at the site, the extent to which selenium is attributable to former milling processes rather than natural sources is not clear. Selenium concentrations are highest in distal areas (e.g., the paleochannel south of the site and in Many Devils Wash; see Figures 1–6a and 1–6b) and evidence suggests that selenium could have been leached from the Mancos Shale or soils derived from the shale.

[3] At the time the GCAP (DOE 2002) was developed, the maximum background value for manganese was 2.7 mg/L; this 2009–2010 updated annual report reflects the most updated historical background range.

[4] http://www.epa.gov/reg3hscd/risk/human/rb-concentration_table/Generic_Tables/index.htm. Last revision May 2010; accessed October 27, 2010.

1.3 Hydrogeological Setting

This section presents a brief summary of the floodplain and terrace groundwater systems. More detailed descriptions are provided in the SOWP (DOE 2000), the refinement of the site conceptual model (DOE 2005), and the recent Trench 2 evaluation (DOE 2009b).

1.3.1 Floodplain Alluvial Aquifer

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

As discussed in the following section, most groundwater contamination in the floodplain lies close to the escarpment east and north of the disposal cell. This plume configuration is best characterized by elevated concentrations of sulfate and uranium. Contamination does not occur along the escarpment base in the northwest part of the floodplain because relatively uncontaminated surface water from Bob Lee Wash discharges to the floodplain, recharging local groundwater and then flowing to the north and west. Surface water in Bob Lee Wash originates primarily as deep groundwater from the Morrison Formation that flows to the land surface via artesian well 0648. Well 0648 flows at approximately 65 gallons per minute (gpm) and drains eastward into lower Bob Lee Wash. Background groundwater quality in the floodplain aquifer is defined by monitoring wells 0797 and 0850 installed in the floodplain approximately 1 mile upriver from the site.

1.3.2 Terrace Groundwater System

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

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

Mancos Shale in the terrace area is weathered several feet below its contact with the alluvium. Groundwater is known to occur in the weathered shale and, in some areas, appears to flow through deeper portions of the shale, within fractures and along bedding surfaces.

1.4 Contaminant Distributions

This section provides an overview of sitewide contaminant distributions. The floodplain remedial strategy focuses on reduction of COC concentrations and decreased contaminant mass discharging to the San Juan River. Therefore, subsequent discussions of contaminant distributions and temporal trends focus primarily on floodplain wells. Contamination trends on the terrace receive less focus in this annual report because the compliance strategy is based on hydrologic control—active remediation to reduce groundwater elevations, with the ultimate goal of eliminating potential exposure pathways (e.g., in seeps and washes). Therefore, concentration-driven performance standards for the terrace system have not been developed. However, as a best management practice, contaminant concentrations are measured at each extraction well, drain, and seep.

Whereas Section 2 (Section 2.1.2 in particular) focuses primarily on temporal trends for floodplain wells, this section presents a snapshot of current conditions and a comparison of that snapshot with baseline (pre-remediation) conditions.

1.4.1 Data Presentation and Visualization

Concentrations of COCs in terrace and floodplain groundwater, based on results of the most recent sampling event (September 2009 or March 2010), are shown in Figures 1–3 through 1–9. Detailed information and supporting quality assurance documentation is provided in the corresponding Data Validation Package (DVP) reports (DOE 2009c, DOE 2010b).

In Figures 1–3 through 1–9, each figure is presented as a pair (e.g., Figures 1–3a and 1–3b). Figures with an "a" suffix plot contaminant concentrations using graduated symbols defined for discrete categories. Categories (or interval classes) are based on defined increments above or below a regulatory criterion (e.g., 40 CFR 192 MCLs, if available), the floodplain background data listed in Table 1–1, and/or the sitewide contaminant distribution.[5] Companion figures (with a "b" suffix) plot the same data, but in an alternate form, using bar charts that reflect the actual (continuous vs. discrete) distribution of the data, overlying an aerial photograph. In these "b" series figures, each bar denotes the COC magnitude at a given location relative to the maximum detected concentration at the site for all sample types (e.g., alluvial well, Mancos well, surface water location, or treatment system sump locations).[6] The latter (bar chart) data visualization method is provided to facilitate identification of "hot spots" and, more importantly, to better depict the overall distribution of contaminants across the site (and across media).

Figures 1–5a and 1–5b, which plot nitrate concentrations, provide a good example of the two (spot plot vs. bar chart) data presentation methods. In Figure 1–5a, it is apparent that nitrate

[5] In some cases, distinctions between groupings are subtle and not significant. For example, in Figure 1–7a, the red symbols denote any strontium measurement exceeding the historical background maximum of 10 mg/L. However, in some areas (e.g., the area between the evaporation pond and Many Devils Wash), there is very little variability in the data despite differences in symbols (<10 mg/L vs. >10 mg/L), and no indication of contaminant levels significantly above the historical background range.

[6] Data values are not labeled in the "b" series figures because the purpose of these figures is to show the relative magnitude and overall distribution of contaminants rather than specific values. Although bar charts are considered a useful data visualization tool, for some adjacent or colocated data points (e.g., Mancos wells 0602 and 0817, located west of the disposal cell), if one datum (0817) is elevated, its neighbor (0602) may be obscured. In these cases, the reader is referred to the "a" version of the figure pair for clarification.

concentrations are elevated on the terrace in the radon borrow pit area in the paleochannel near the buried escarpment, in Many Devils Wash, and on the floodplain at the base of the escarpment and in the well 1089 area. But only by reviewing Figure 1–5b is it apparent how nitrate concentrations at most site locations (including the disposal cell area) pale in comparison to those measured in the radon borrow pit and paleochannel area. Also, nitrate concentrations in Many Devils Wash are higher than most on the floodplain.

Figure 1–10, a side-by-side comparison of relative contaminant distributions for the primary COCs, represents a compendium of the individual "b" series figures discussed above. Based on the detailed statistical summary provided in Appendix A, Figure 1–11 plots corresponding historical distributions of each COC shown in Figure 1–10 for floodplain wells. Strontium is not plotted in either of these figures because of its uniform distribution (i.e., no spatial variation; see Figures 1–7a and 1–7b).] Whereas Figure 1–10 represents the most recent "snapshot" for all terrace wells, the plots in Figure 1–11 reflect all historical measurements: the longer the box, the more historical variation. Alternatively, tight boxes indicate stable levels (i.e., little variation) and/or a small number of samples (e.g., in the case of the new floodplain wells).

Appendix A, the detailed basis for the summary plot in Figure 1–11, presents a sampling summary and descriptive statistics for site COCs in all floodplain monitoring wells. In this appendix, box plots (also called box-and-whisker plots) are used as a data visualization tool to show the historical distribution of COCs in all floodplain wells, organized by area, where area groupings are based on the categorizations defined in Table A–1 and Figure A–1. Detailed summary statistics are also provided.

As a final data visualization method, Figures 1–12 through 1–18 plot changes in the extent of the floodplain and terrace contaminant plumes and present interpolated data for wells sampled between 2000 and 2003 (representing baseline conditions) and the most recent result for this evaluation period (September 2009 or March 2010).[7] Because these interpolations consist of predicting concentrations of COCs at an unsampled site based on measurements made at the closest surrounding sites, these figures are most useful for examining changes in plume extent for floodplain monitoring wells, given the density of wells in this area. Interpolations for west terrace areas and/or areas where well density is sparse should be reviewed with some caution (and also noting actual data values).

1.4.2 Overview of Findings

As shown in Figure 1–2, the Shiprock well network is dense. For this reporting period, 118 monitoring wells were sampled (62 on the floodplain and 56 on the terrace). Surface water locations (e.g., at seeps and the San Juan River) are also routinely sampled. Given the density of the site sampling network and the distinct COCs evaluated, it is difficult to capture the essence of contaminant distributions both spatially and temporally. However, based on the plots in Figures 1–3 through 1–18, several global trends are apparent.

[7] In previous annual performance reports (e.g., DOE 2008), March 2003 data (corresponding to the onset of active groundwater remediation) were used to generate contaminant plume maps representing baseline conditions. However, because fewer alluvial wells were sampled in 2003 than in 2000–2001, baseline plume maps were developed using the most recent 2000–2003 measurement to optimize the number of wells with a corresponding 2009–2010 measurement and thus comparability of the two (baseline and current) plume snapshots.

As discussed in the recently issued 2010 site remediation strategy review (DOE 2010a; see Section 5.1.4), DOE has considered initiating a pilot groundwater hot-spot remediation study at locations where concentrations of one or more contaminants are elevated. However, as is evident in the figures provided in this section, a factor that confounds such an evaluation is the fact that maximum concentrations of individual COCs do not occur in the same location. Figure 1–10 (the merged version of the bar chart figures) demonstrates the differences in spatial distributions of individual contaminants. For example, uranium is highest around the disposal cell and on the floodplain, at the base of the escarpment and in the Trench 1 and well 1089 areas (also see Figure 1–11). In terms of relative magnitude, uranium concentrations at the remainder of the site are much lower. Alternatively, nitrate, which is most concentrated in the radon cover borrow pit and paleochannel area, has a very different distribution. Nitrate, like sulfate and selenium, is also elevated in Many Devils Wash.

Sulfate, in general the most evenly distributed of site-related contaminants, is most elevated in Many Devils Wash. The inability to find representative background concentrations for the terrace (to date, candidate locations have been dry) further complicates interpretation of these findings. Like uranium, ammonia is highest in wells screened in the Mancos Shale just west of the disposal cell (0602 and 0817). However, ammonia (like manganese) is also elevated in the evaporation pond area. Manganese, which is at or near background concentrations across much of the site, is elevated in the evaporation pond area, and in some of these wells levels have increased (e.g., see Figure 1–13).

Selenium, on the other hand, is most elevated along the buried escarpment on the terrace and is present at much lower concentrations on the floodplain. As mentioned above, selenium levels are also elevated in Many Devils Wash, and the extent to which this is attributable to the site or naturally occurring conditions is the subject of a recently initiated evaluation.

The extent to which the differing distributions discussed above reflect prior milling practices, differences in contaminant chemistry and mobility, and/or influences from background are not clear at this time. To address these unknowns, DOE plans to conduct more targeted characterization to address key issues and site areas, such as Many Devils Wash. Therefore, the current interpretation is likely to continue to evolve as ongoing and planned studies yield additional data.

The plume maps in Figures 1–12 through 1–18 (comparing baseline and current snapshots) demonstrate the success of the floodplain remediation, in particular for the primary COCs (nitrate, sulfate, and uranium). In these figures, an arcuate plume extends northward from the contaminated area at the base of the disposal cell, crosses the floodplain and approaches the San Juan River near the floodplain extraction wells. This plume configuration is best characterized by elevated concentrations of sulfate and uranium. In general, contamination does not occur along the escarpment base in the northwest part of the floodplain (Figure 1–10). Additional discussion of floodplain contaminant trends is provided in Section 2.1.2, which presents time-concentration plots of COCs for a representative subset of floodplain wells.

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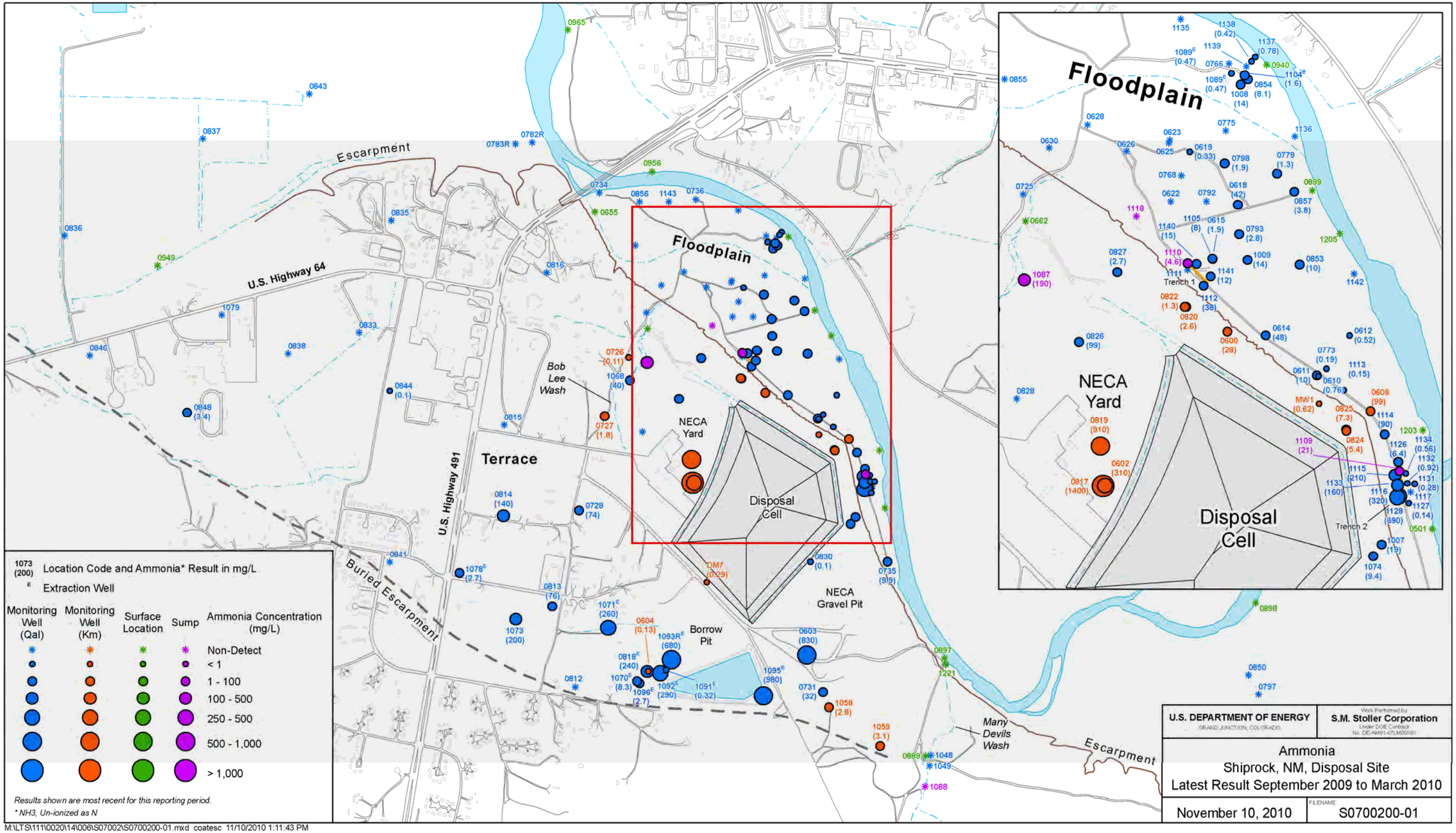

Figure 1–3a. Concentrations of Ammonia in Groundwater and Surface Water, September 2009–March 2010

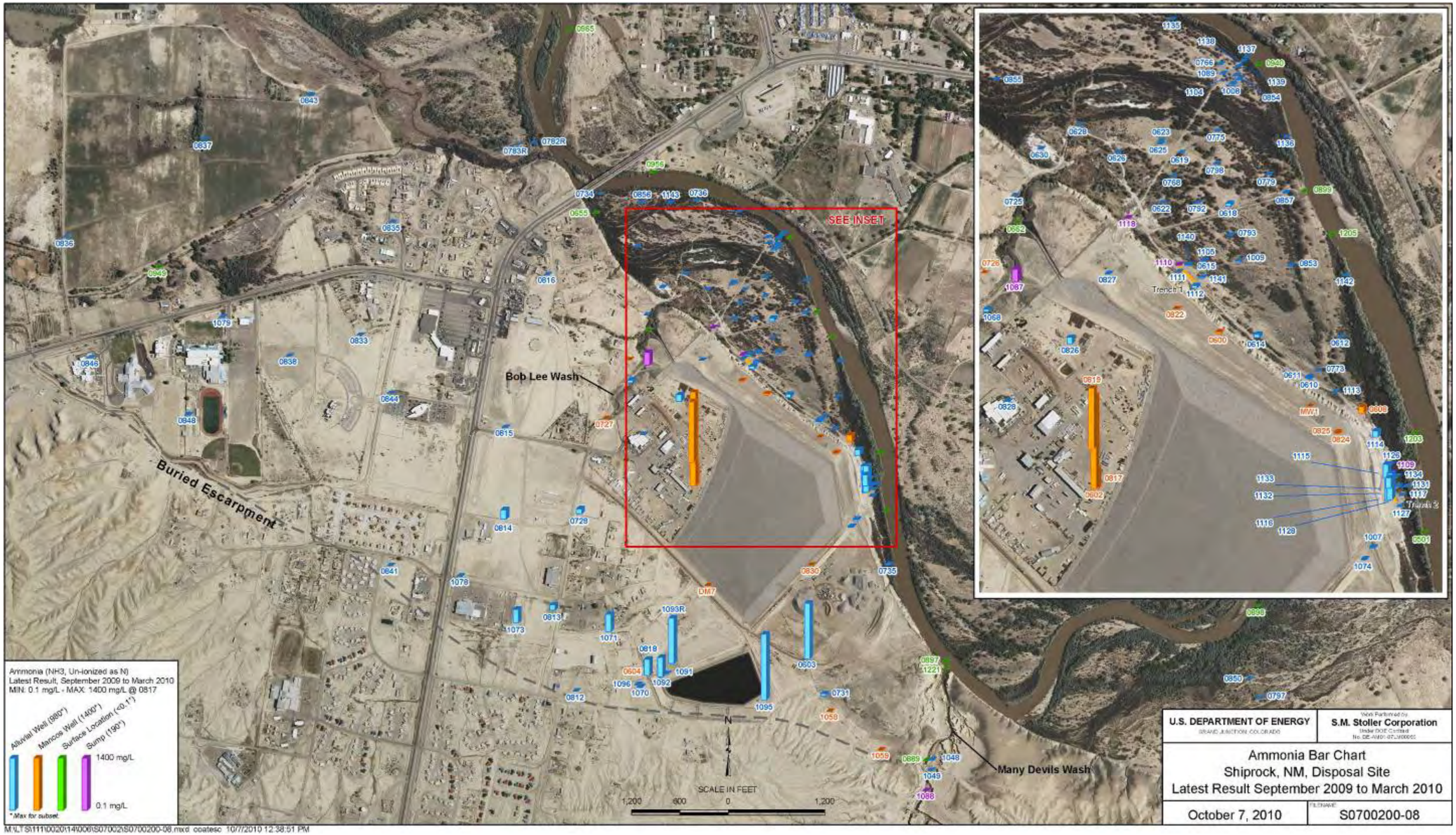

Figure 1−3b. Relative Distribution of Ammonia in Groundwater and Surface Water, September 2009–March 2010

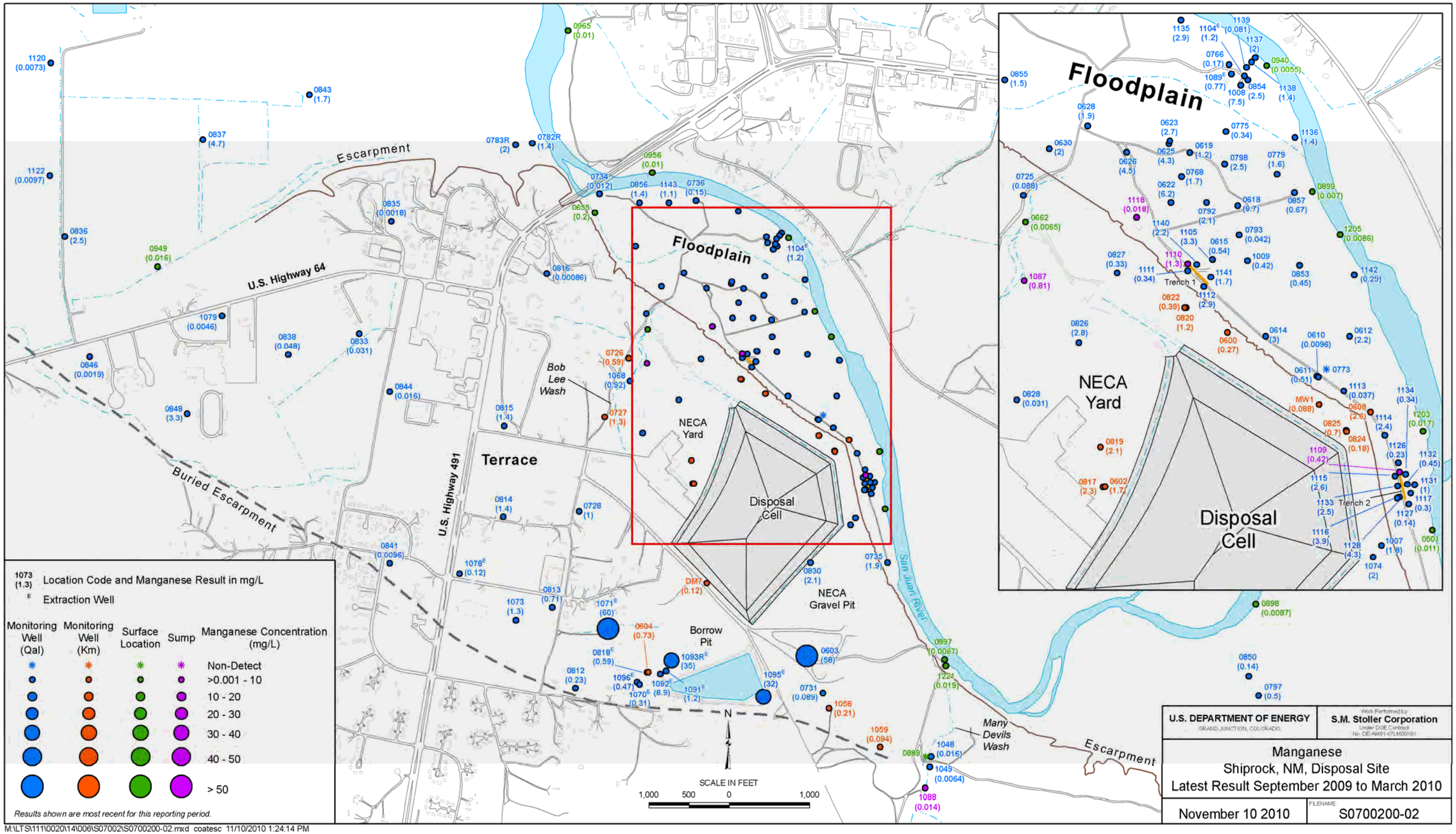

Figure 1–4a. Manganese Concentrations in Groundwater and Surface Water, September 2009–March 2010

Figure 1−4b. Relative Distribution of Manganese in Groundwater and Surface Water, September 2009–March 2010

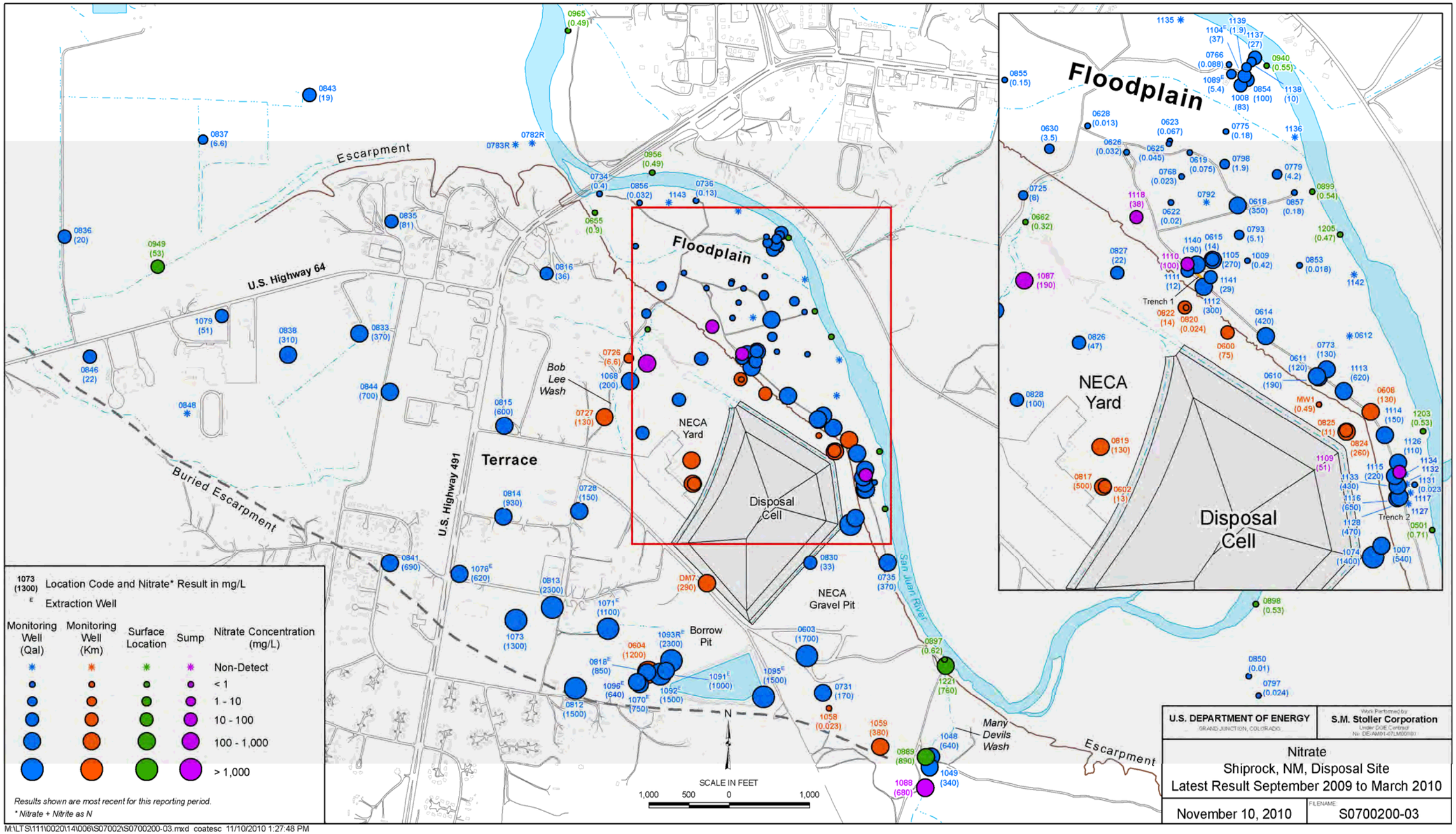

Figure 1–5a. Nitrate Concentrations in Groundwater and Surface Water, September 2009–March 2010

Figure 1−5b. Relative Distribution of Nitrate in Groundwater and Surface Water, September 2009–March 2010

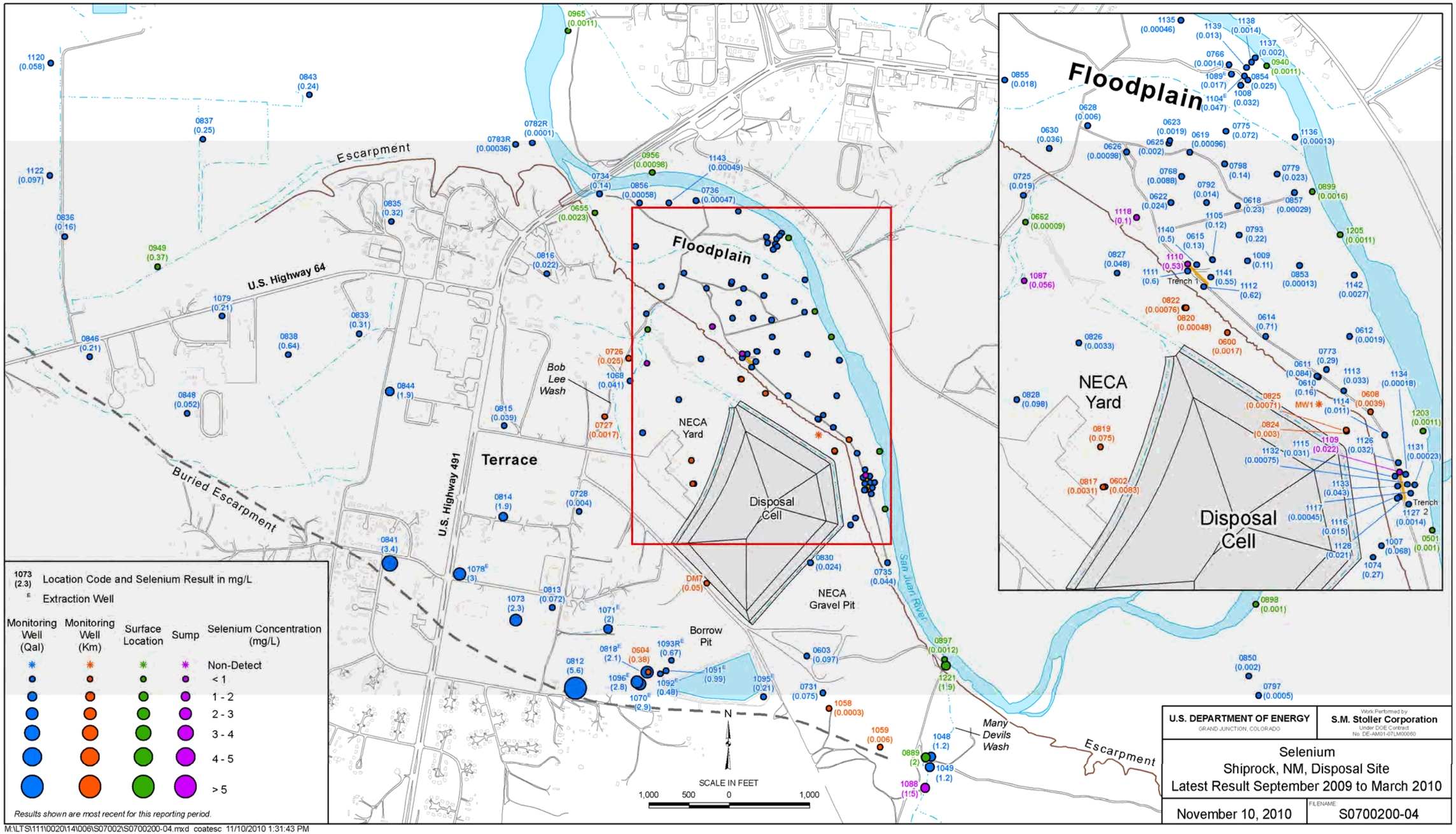

Figure 1–6a. Selenium Concentrations in Groundwater and Surface Water, September 2009–March 2010

Figure 1−6b. Relative Distribution of Selenium in Groundwater and Surface Water, September 2009–March 2010

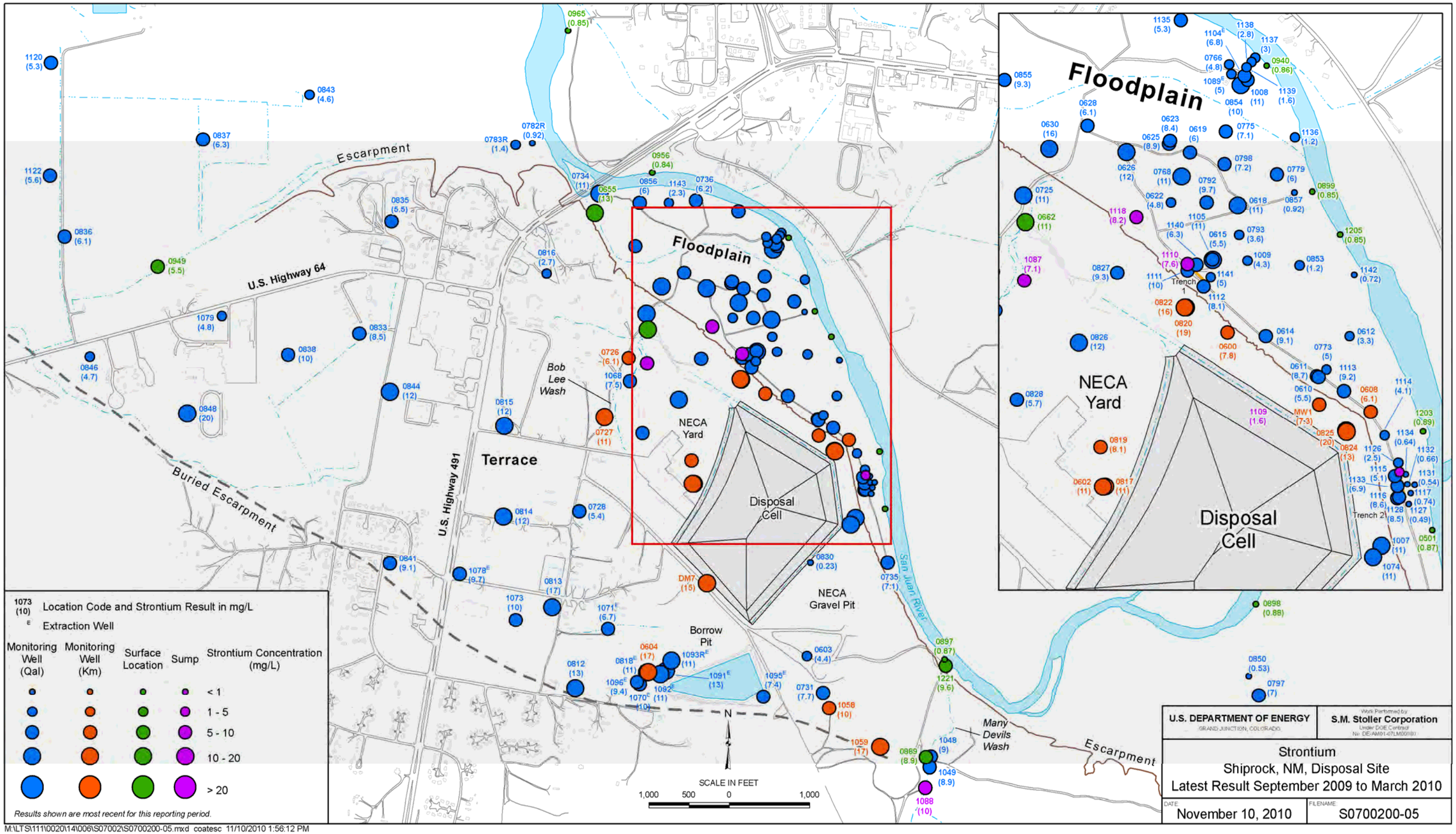

Figure 1–7a. Strontium Concentrations in Groundwater and Surface Water Samples, September 2009–March 2010

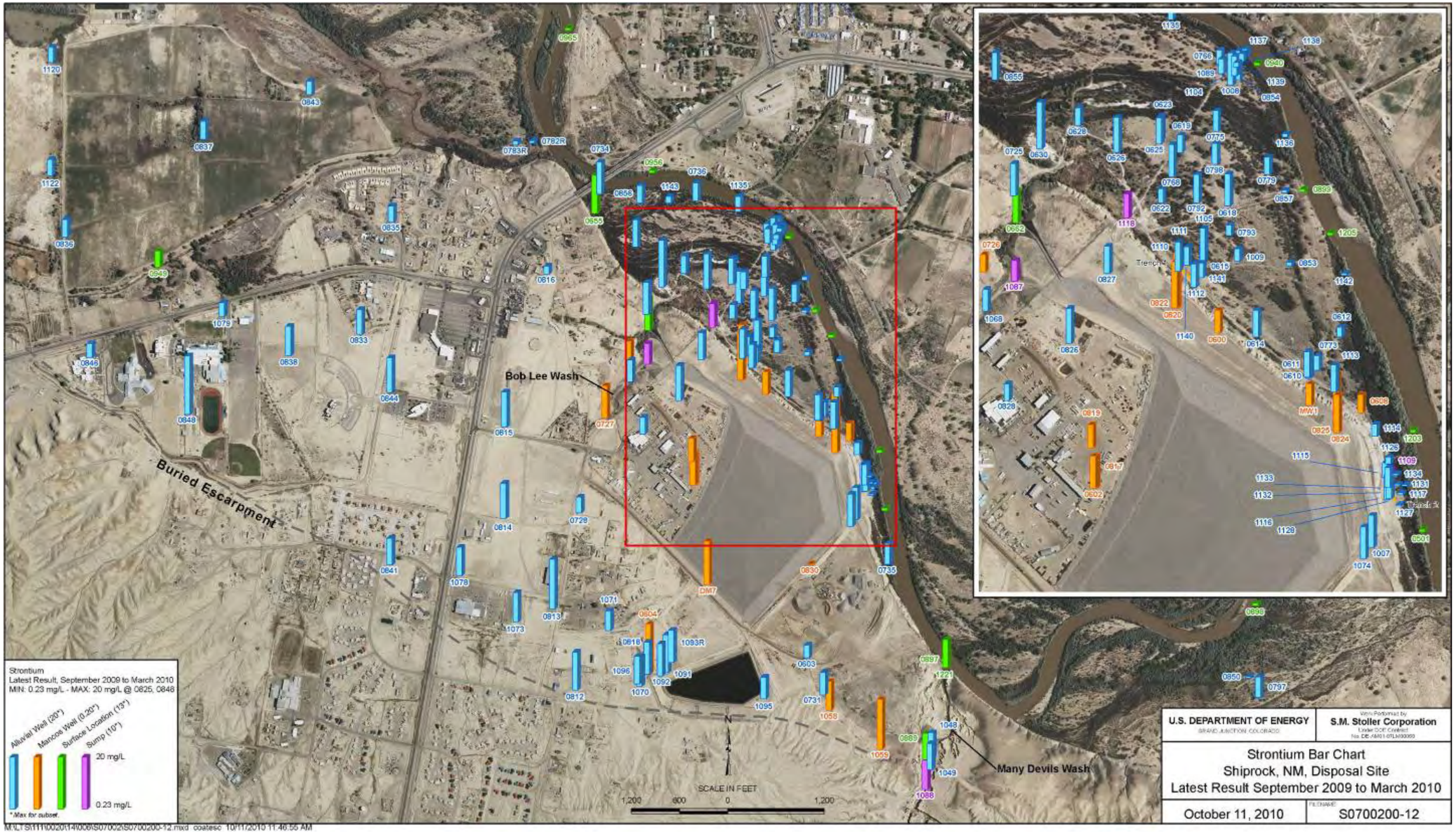

Figure 1−7b. Relative Distribution of Strontium in Groundwater and Surface Water Samples, September 2009–March 2010

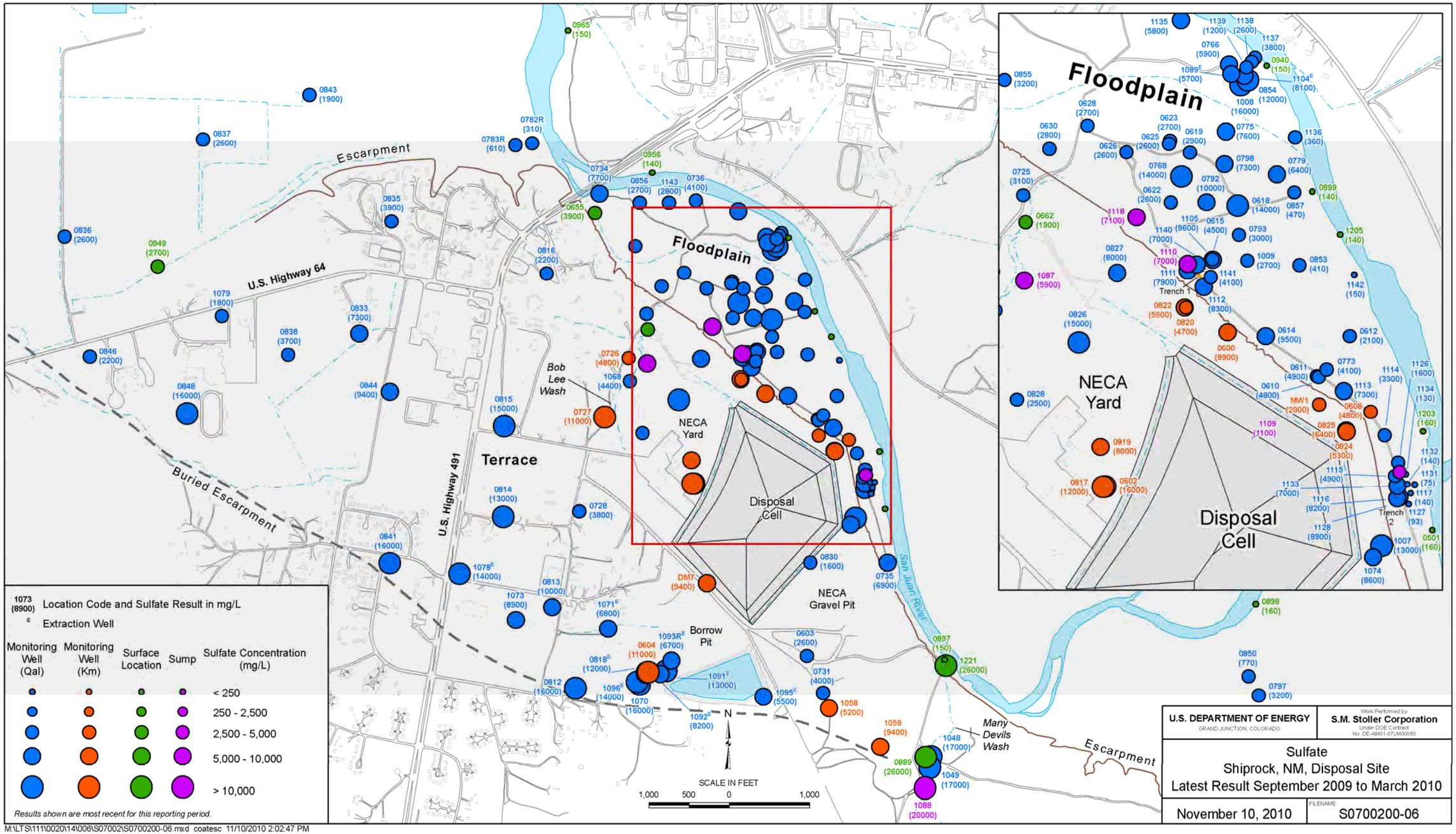

Figure 1–8a. Sulfate Concentrations in Groundwater and Surface Water Samples, September 2009–March 2010

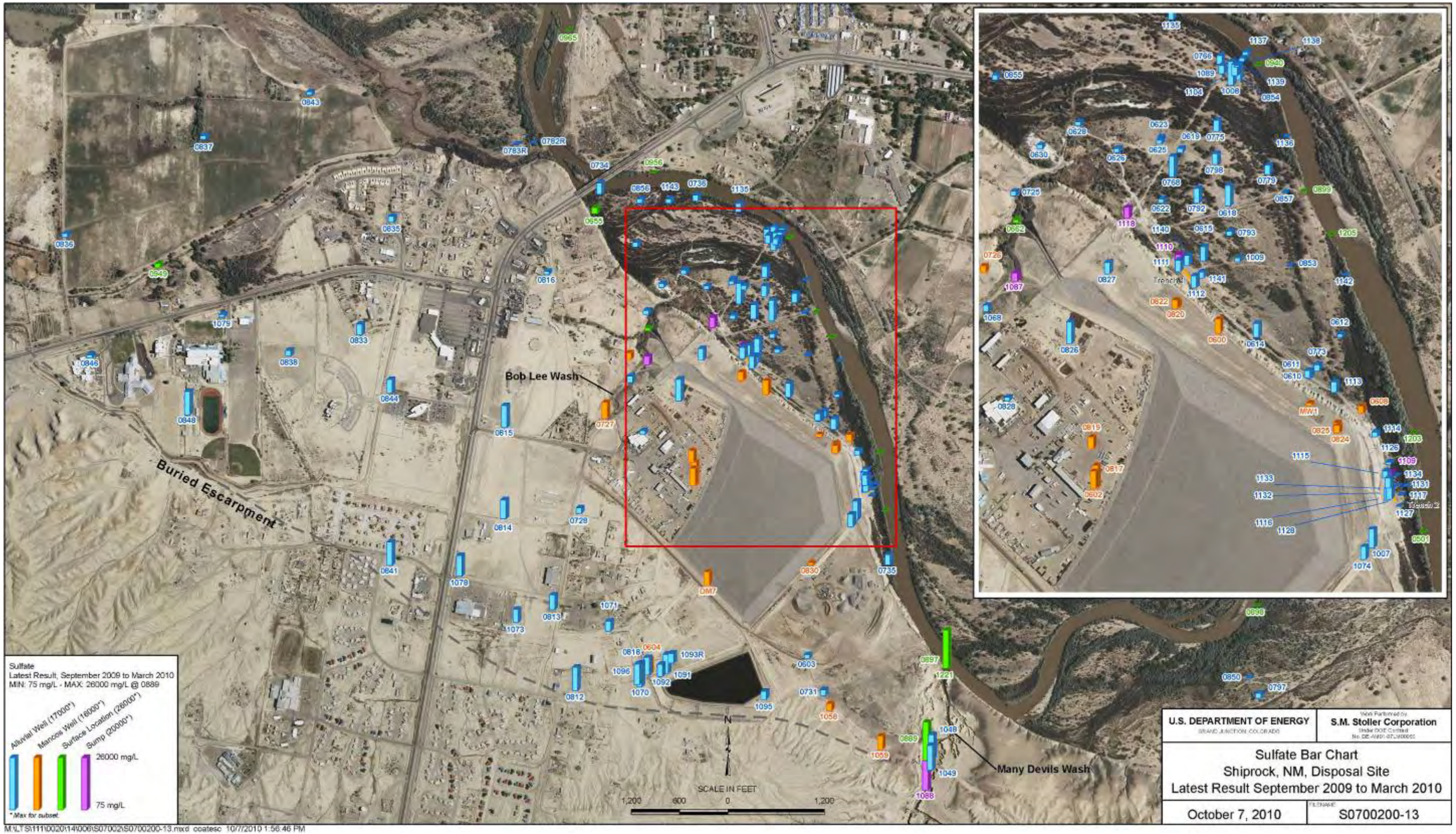

Figure 1−8b. Relative Distribution of Sulfate in Groundwater and Surface Water Samples, September 2009–March 2010

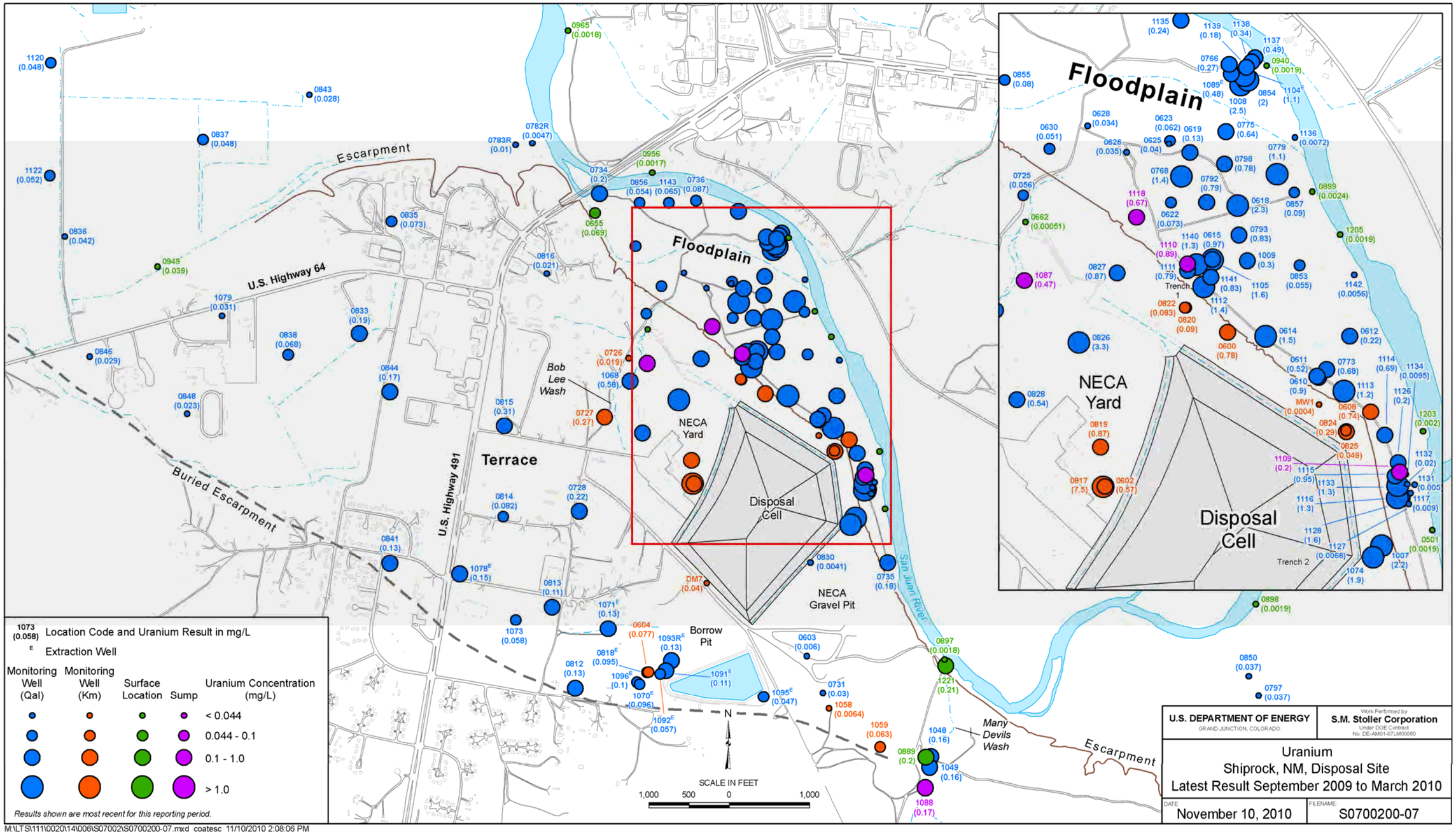

Figure 1–9a. Uranium Concentrations in Groundwater and Surface Water Samples, September 2009–March 2010

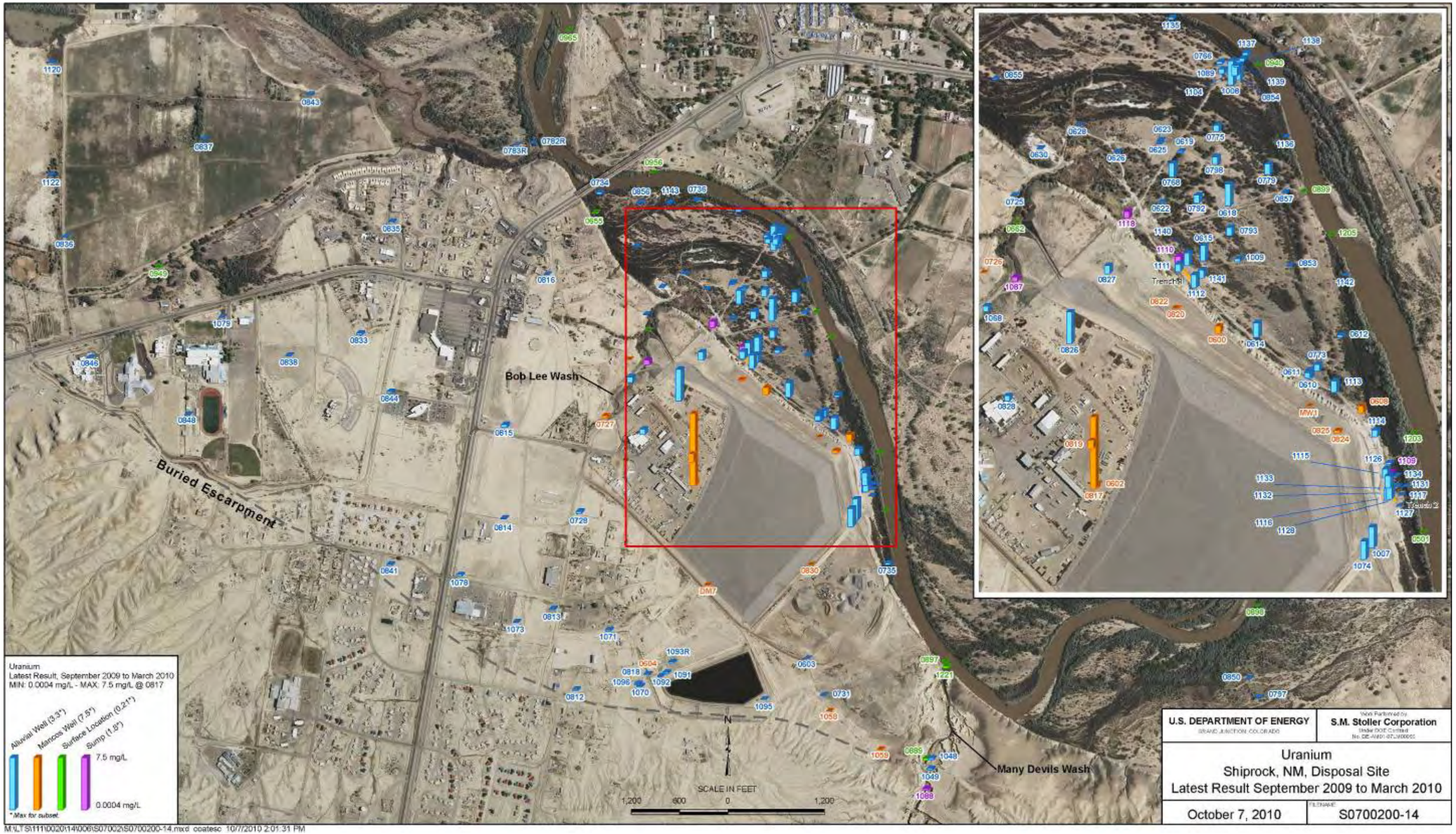

Figure 1−9b. Relative Distribution of Uranium in Groundwater and Surface Water Samples, September 2009–March 2010

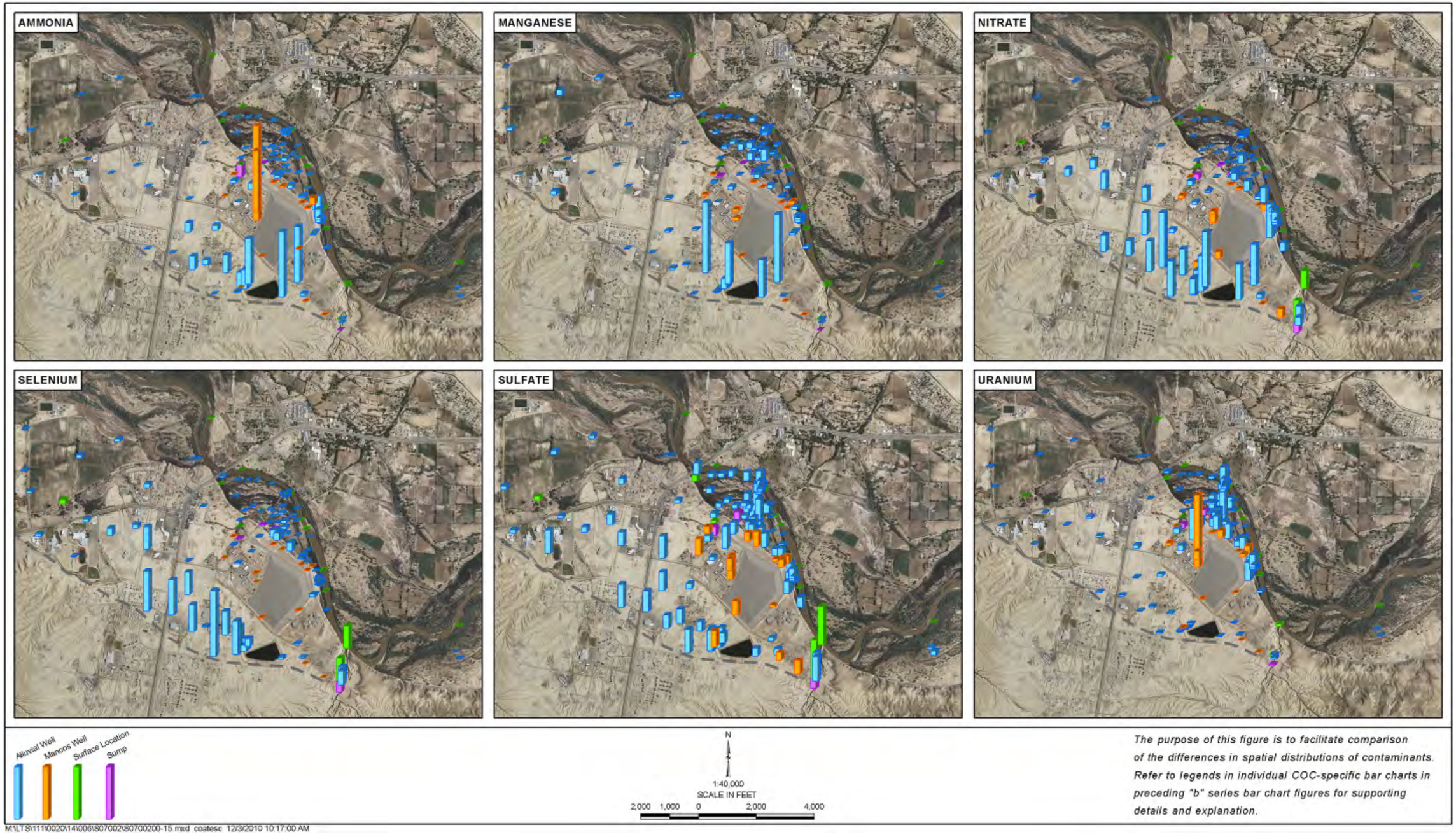

Figure 1–10. Side-By-Side Comparison of Relative Contaminant Distributions for the Primary COCs

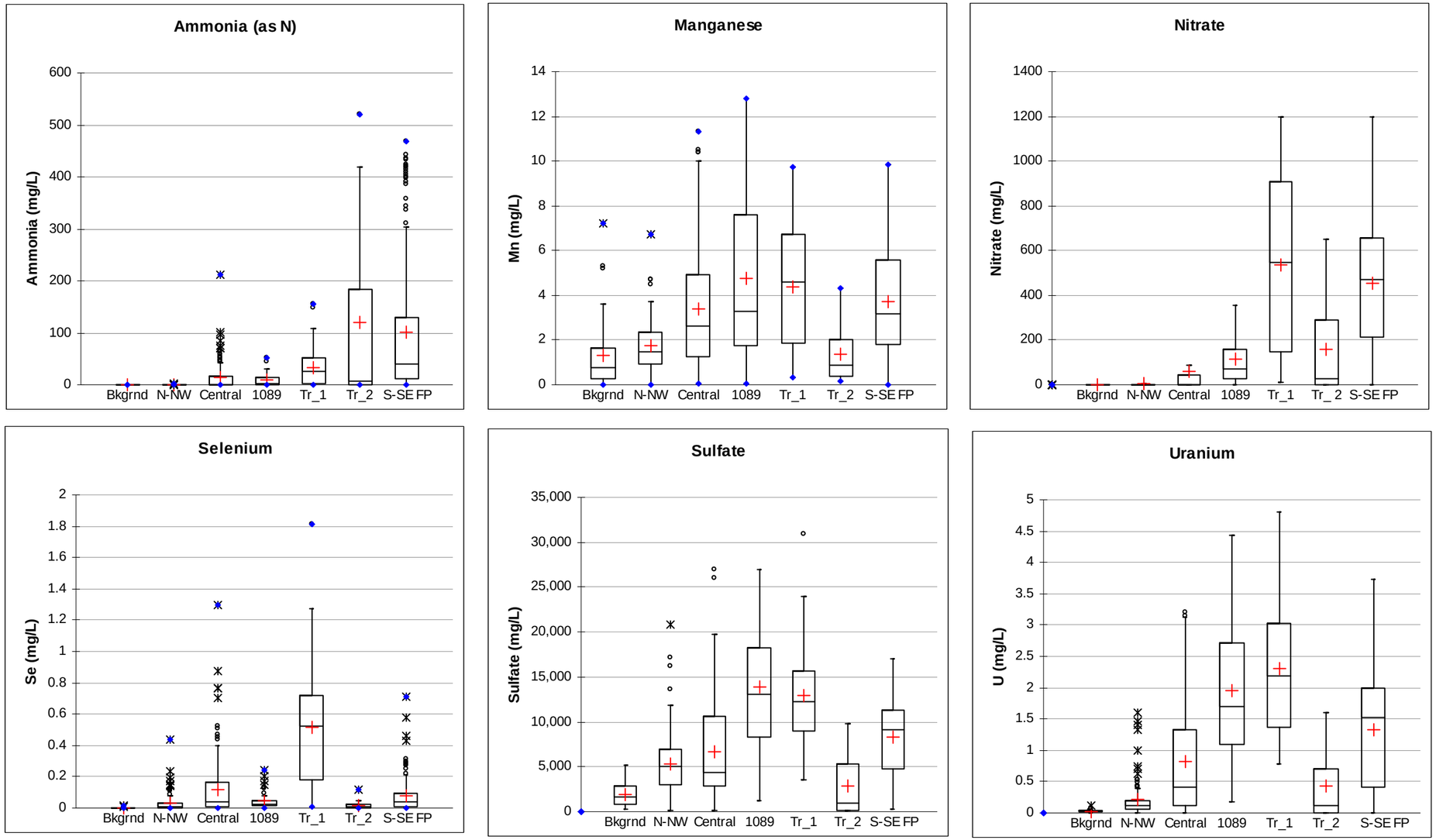

Figure 1–11. Historical Distribution of Shiprock Primary COCs in Floodplain Wells†

† The box plots shown above depict the median, the lower and upper quartiles, and the non-outlier range of floodplain COCs (excluding strontium) for the floodplain well subgroups defined in Appendix A; points plotted beyond these limits are outliers. The mean is denoted by +, whereas the median line bisects the box. In each plot above, "Bkgrnd" refers to background wells 0797 and 0850; "N-NW" refers to North-Northwest floodplain wells (see orange-coded wells in Appendix A, Figure A–1); "Central" refers to central floodplain wells; "1089" corresponds to the Well 1089 area (see uppermost portion of Figure 1–2 inset); "Tr_1" and "Tr_2" refer to Trench 1 and 2 area wells, respectively; and "S-SE FP" corresponds to south-southeastern floodplain wells (again, refer to Appendix A, Figure A–1). The combined plot above is a summary version of the COC-specific statistical summaries provided in Appendix A. This appendix also documents the number of data points corresponding to each box in the plots above (an important consideration in data interpretation).

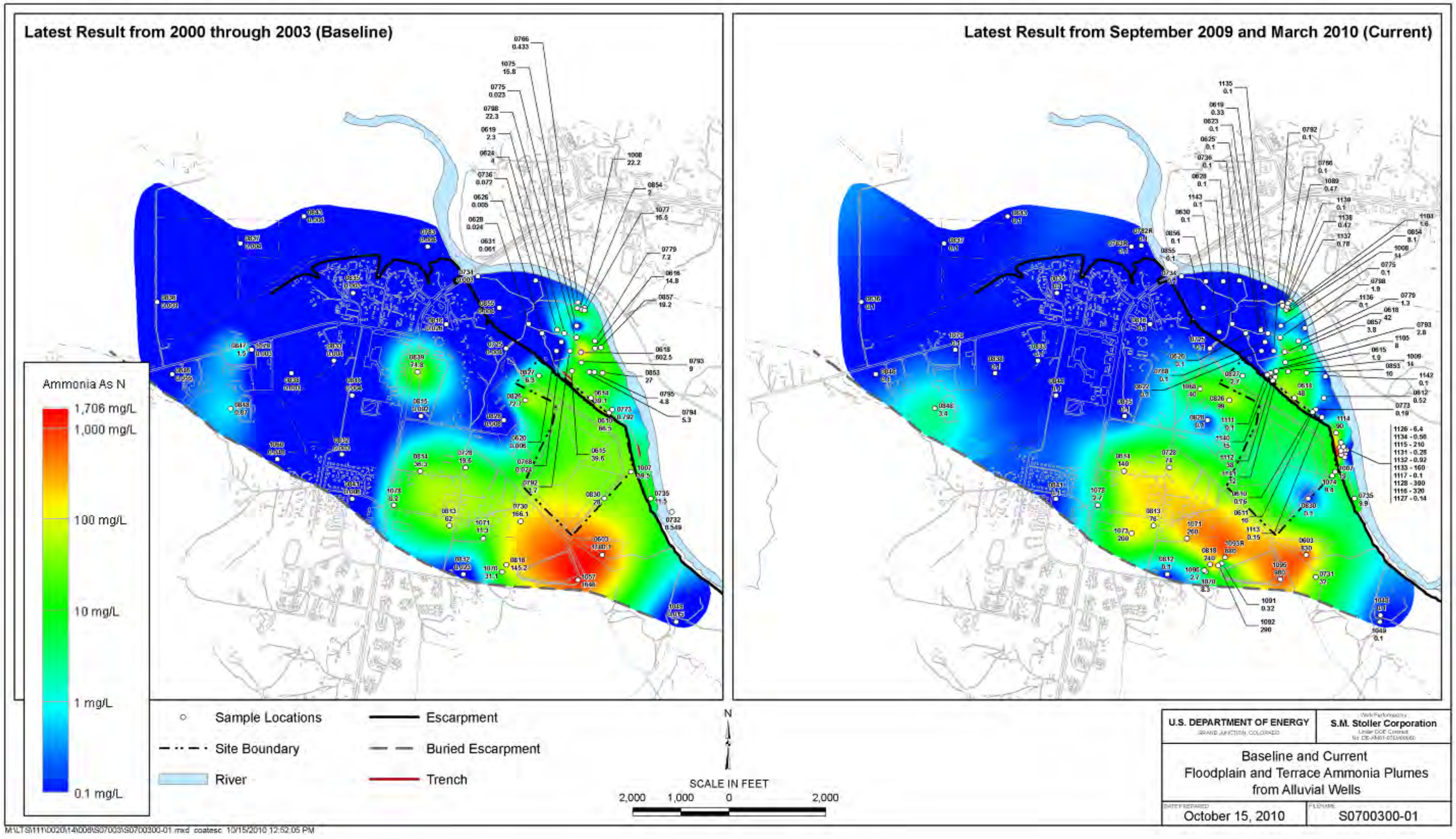

Figure 1–12. Baseline (2000–2003) and March 2010 Floodplain and Terrace Ammonia Plumes

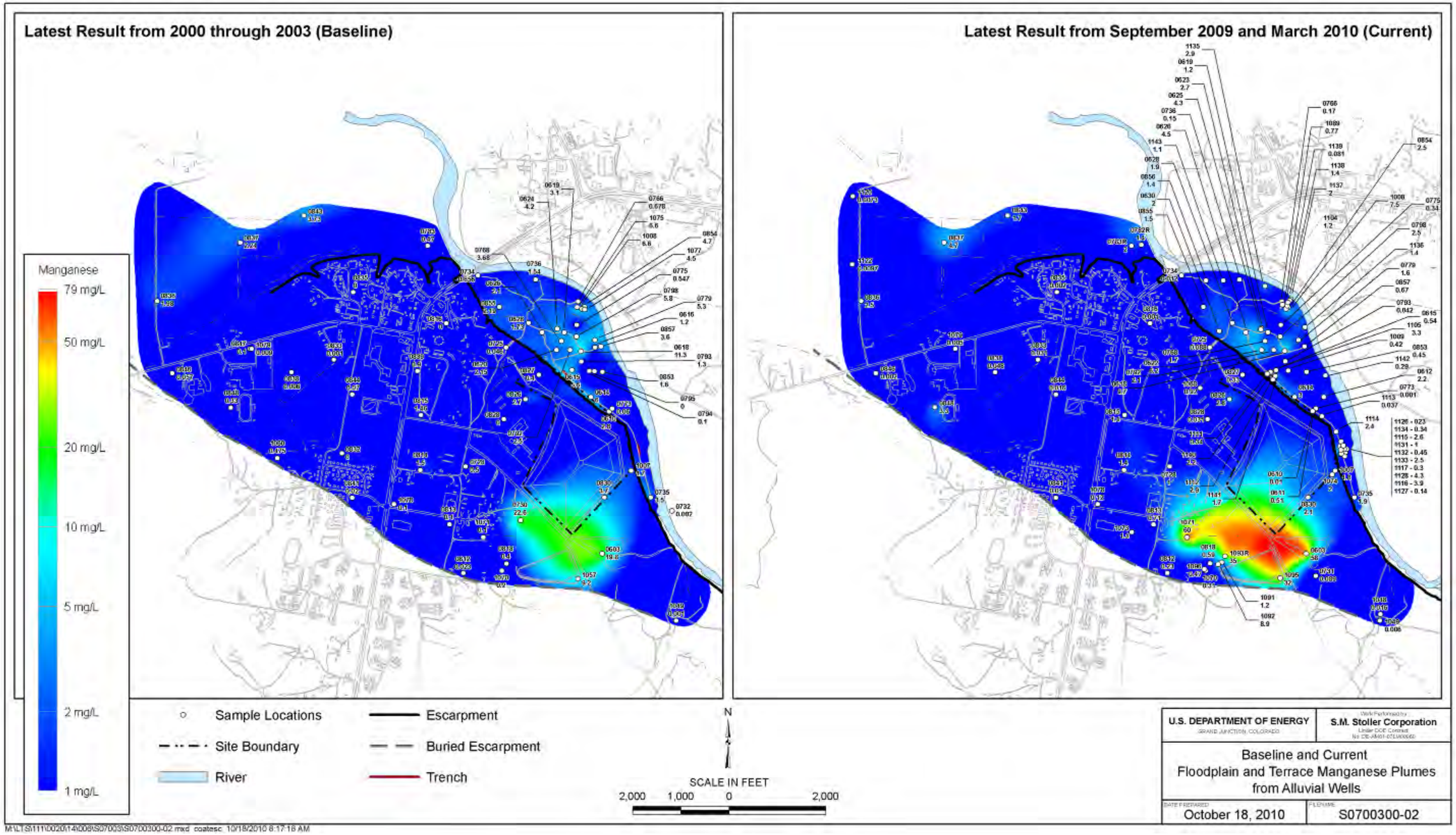

Figure 1–13. Baseline (2000–2003) and March 2010 Floodplain and Terrace Manganese Plumes

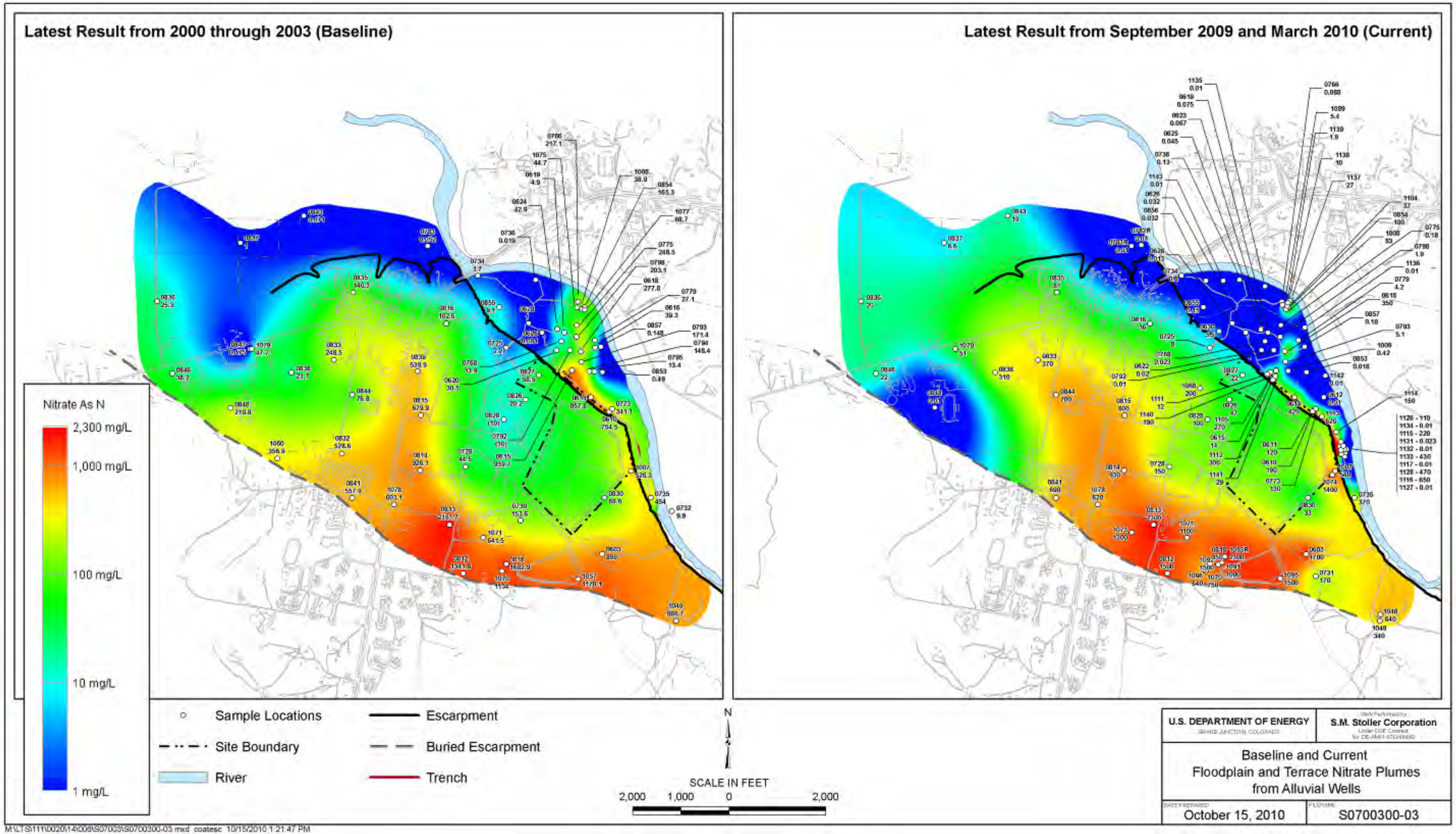

Figure 1–14. Baseline (2000–2003) and March 2010 Floodplain and Terrace Nitrate Plumes

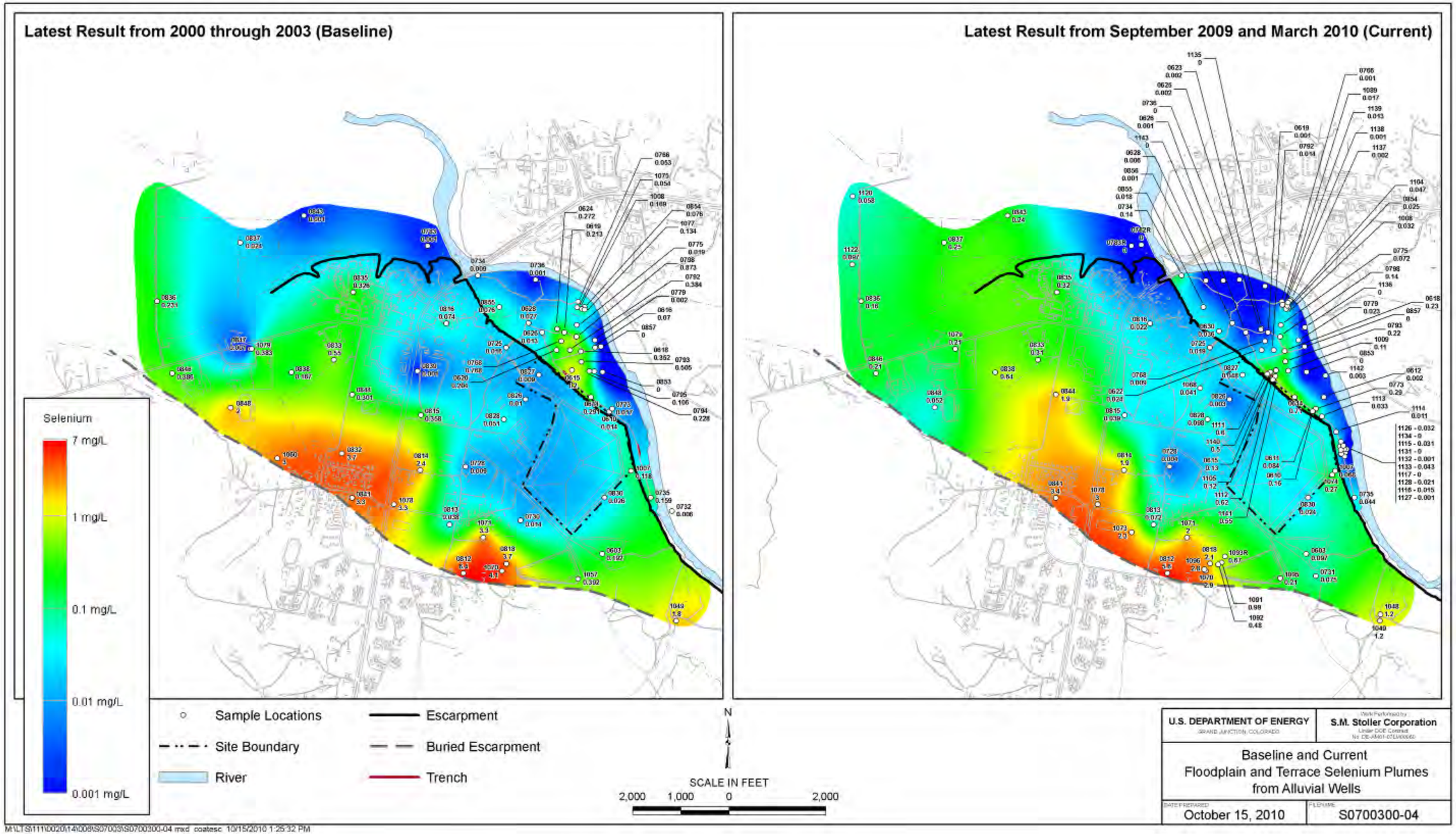

Figure 1–15. Baseline (2000–2003) and March 2010 Floodplain and Terrace Selenium Plumes

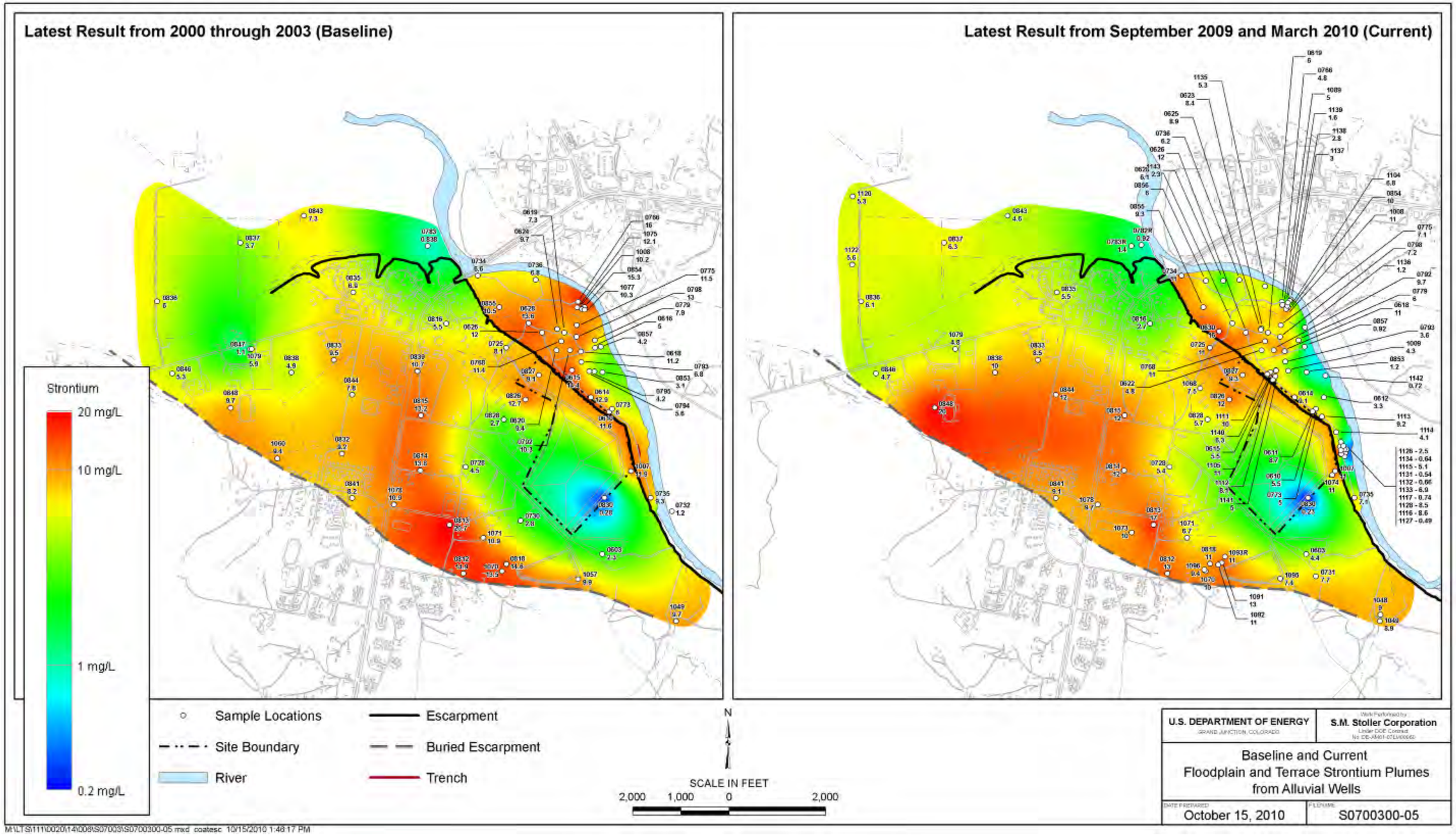

Figure 1–16. Baseline (2000–2003) and March 2010 Floodplain and Terrace Strontium Plumes

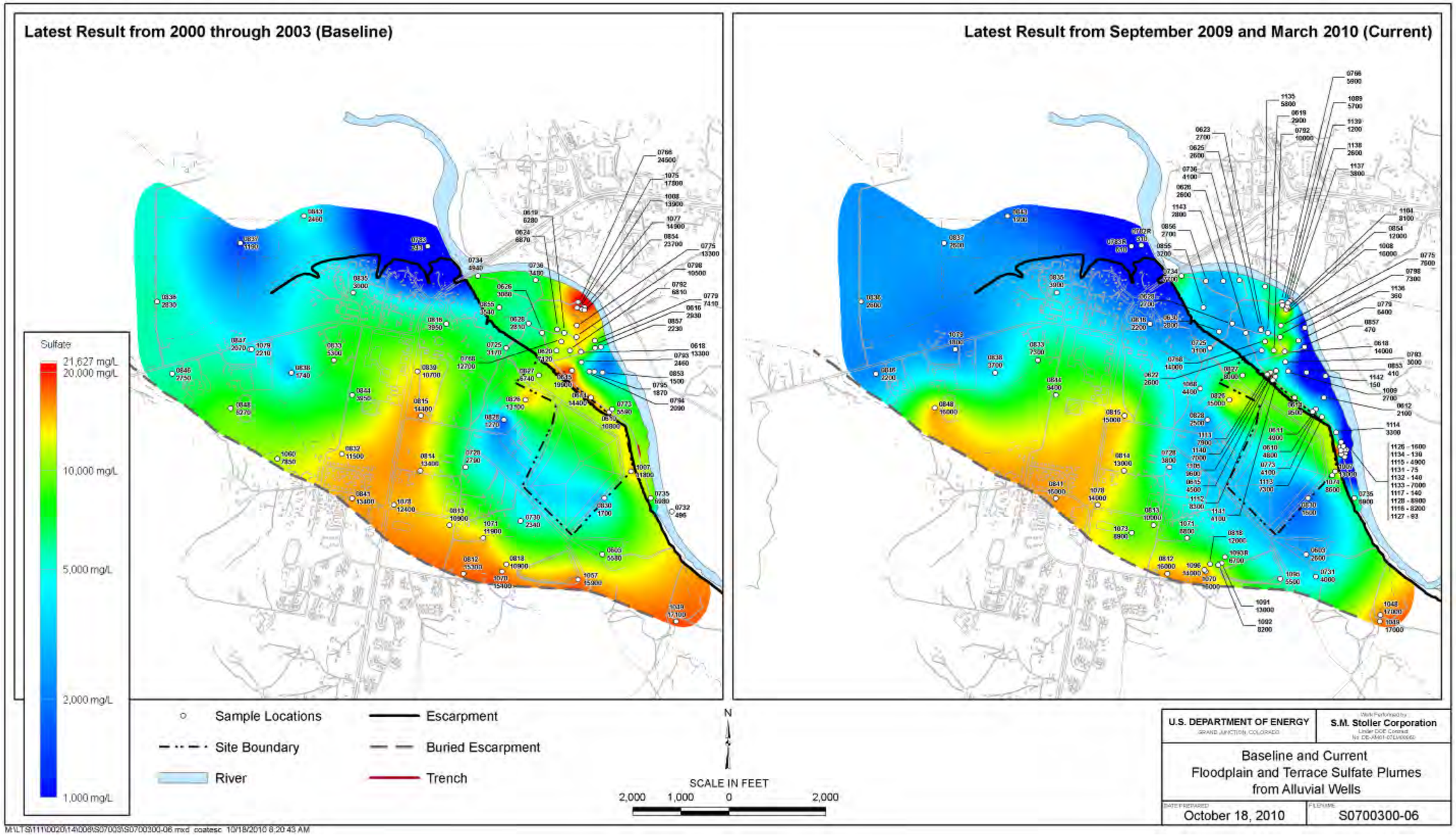

Figure 1–17. Baseline (2000–2003) and March 2010 Floodplain and Terrace Sulfate Plumes

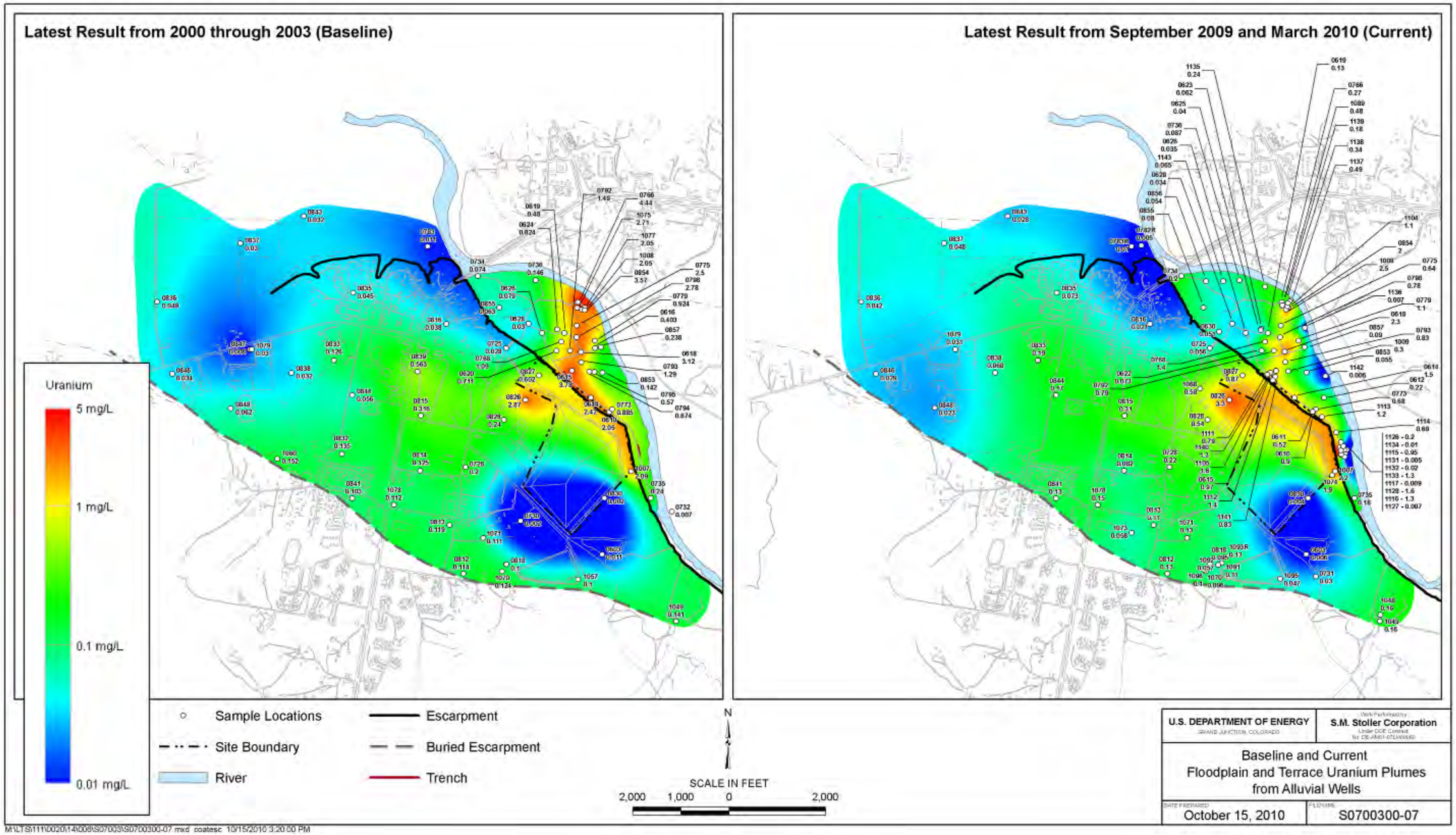

Figure 1–18. Baseline (2000–2003) and March 2010 Floodplain and Terrace Uranium Plumes

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