LMS/RVT/S09799

2012 Enhanced Characterization and Monitoring Report Riverton, Wyoming, Processing Site

June 2013

U.S. DEPARTMENT OF ENERGY | Legacy Management

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Contents

Abbreviations v
Executive Summary vii
1.0 Introduction 1
2.0 Verification Monitoring 1
2.1 Site Conditions 1
2.1.1 Uranium Mill Tailings Remedial Action (UMTRA) Site and Surface Remediation 1
2.1.2 Hydrogeology 3
2.1.3 Water Quality 3
2.1.4 Institutional Controls 4
2.1.4.1 Site Institutional Controls 4
2.1.4.2 Institutional Control Monitoring 7
2.2 Monitoring Program 8
2.3 Results of 2012 Monitoring 10
2.3.1 Groundwater 10
2.3.1.1 Groundwater Flow 10
2.3.1.2 Groundwater Quality 14
2.3.1.3 Domestic Wells 15
2.3.2 Surface Water 28
2.3.2.1 Surface Water Flow 28
2.3.2.2 Surface Water Quality 28
2.3.3 AWSS Monitoring 35
3.0 Enhanced Characterization 41
3.1 Purpose and Scope 41
3.2 Fieldwork Summary 41
3.3 Soil Characterization 42
3.3.1 Summary of Methods 42
3.3.2 Results and Interpretation 47
3.3.2.1 Batch Tests 47
3.3.2.2 Distribution Coefficients 50
3.3.2.3 Secondary Source in the Unsaturated Zone 55
3.4 Groundwater Characterization 57
3.4.1 Summary of Method 57
3.4.2 Interpretation and Results 57
3.4.2.1 Comparability of Data 57
3.4.2.2 General Water Chemistry 58
3.4.2.3 Manganese 60
3.4.2.4 Molybdenum 60
3.4.2.5 Sulfate 60
3.4.2.6 Uranium 61
3.5 Site Conceptual Model 61
3.5.1 Original Site Conceptual Model 70
3.5.1.1 Original Contaminant Sources 70
3.5.1.2 Groundwater 70
3.5.1.3 Surface Water 70
3.5.1.4 Groundwater Modeling/Natural Flushing Assessment 70

3.5.2 Revised Site Conceptual Model 71
3.6 Groundwater Modeling 71
3.6.1 Modeling Approach 71
3.6.2 Input Parameters, Assumptions, and Limitations 72
3.6.3 Transient Flow Model 73
3.6.3.1 Model Calibration 73
3.6.4 Transport Modeling and Forecasting 79
4.0 Compliance Strategy Assessment 83
5.0 Summary and Recommendations 87
6.0 References 91

Figures

Figure 1. Site Location Map 2
Figure 2. Institutional Control Boundary and 2012 Monitoring Locations at the Riverton Site 5
Figure 3. Warning Sign at the Oxbow Lake 7
Figure 4. June 2012 Groundwater Elevations in the Surficial Aquifer at the Riverton Site 11
Figure 5. February 1997 and December 2012 Groundwater Elevations in the Surficial Aquifer at the Riverton Site 12
Figure 6. Continuous Water Elevations in Selected Surficial Aquifer Wells. 13
Figure 7. Molybdenum Concentrations in Surficial Aquifer Wells within the Contaminant Plume 16
Figure 8. Molybdenum Concentrations in Surficial Aquifer Wells on the Edge of the Contaminant Plume 17
Figure 9. June 2012 Molybdenum Distribution in the Surficial Aquifer at the Riverton Site 18
Figure 10. December 2012 Molybdenum Distribution in the Surficial Aquifer at the Riverton Site 19
Figure 11. Uranium Concentrations in Surficial Aquifer Wells within the Contaminant Plume 20
Figure 12. Uranium Concentrations in Surficial Aquifer Wells on the Edge of the Contaminant Plume 21
Figure 13. June 2012 Uranium Distribution in the Surficial Aquifer at the Riverton Site 22
Figure 14. December 2012 Uranium Distribution in the Surficial Aquifer at the Riverton Site 23
Figure 15. Molybdenum Concentrations in Semiconfined Aquifer Wells 24
Figure 16. Uranium Concentrations in Semiconfined Aquifer Wells 25
Figure 17. Molybdenum Concentrations in Domestic Wells 26
Figure 18. Uranium Concentrations in Domestic Wells 27
Figure 19. Historical Maximum Stages of the Little Wind River 29
Figure 20. Molybdenum Concentrations in Creek and River Locations 30
Figure 21. Uranium Concentrations in Creek and River Locations 31
Figure 22. Molybdenum Concentrations in Ponds 33
Figure 23. Uranium Concentrations in Ponds 34
Figure 24. AWSS 1-Million-Gallon Tank 35
Figure 25. Location of Flushing Hydrants and Tap Monitoring Locations 37
Figure 26. Enhanced Characterization Geoprobe Locations 43

Figure 27. Installing a Borehole with a Geoprobe in August 2012 ... 45
Figure 28. Soil Samples Collected Using the Geoprobe ... 46
Figure 29. Results of Soil Kinetic Tests (0 to 18 Hours) ... 47
Figure 30. Results of Soil Kinetic Tests (Full Duration) ... 48
Figure 31. Distribution of Solid-Phase Uranium in Upper Zone (0–2.5 ft) vs. Lower Zone (2.5–5 ft) Samples ... 49
Figure 32. Uranium Distribution from Soil Batch Tests ... 51
Figure 33. Plot of Apparent Distribution Coefficients (K_d^*) ... 54
Figure 34. Piper Diagram of Major Anion and Cation Data ... 59
Figure 35. Graduated Symbol Plots of Manganese, Molybdenum, Sulfate, and Uranium in Groundwater: August 2012 ... 62
Figure 36. Box-and-Whisker Plots for Manganese, Molybdenum, Sulfate, and Uranium ... 63
Figure 37. Distribution of Manganese in the Surficial Aquifer: August 2012 Enhanced Characterization ... 65
Figure 38. Distribution of Molybdenum in the Surficial Aquifer: August 2012 Enhanced Characterization ... 66
Figure 39. Distribution of Sulfate in the Surficial Aquifer: August 2012 Enhanced Characterization ... 67
Figure 40. Distribution of Uranium in the Surficial Aquifer; August 2012 Enhanced Characterization ... 68
Figure 41. Original and Updated Site Conceptual Models ... 69
Figure 42. 2005 Water Levels versus Model Simulation: Well 0707 ... 74
Figure 43. 2009 Water Levels versus Model Simulation: Well 0707 ... 75
Figure 44. Hydraulic Conductivity Field Calculated Using Pilot Points and PEST ... 77
Figure 45. Initial Uranium Concentrations (µg/L) in the Surficial Aquifer from the Enhanced Characterization – August 2012 ... 80
Figure 46. Simulated Uranium Concentrations (µg/L) after 50 Years (i.e., in 2062) ... 81
Figure 47. Simulated Uranium Concentrations (µg/L) after 100 Years (i.e., in 2112) ... 82
Figure 48. Uranium Concentrations and Maximum Little Wind River Stage ... 84
Figure 49. Average Uranium Concentration in Plume Wells ... 85

Tables

Table 1. 2012 Sampling Network at the Riverton Site ... 9
Table 2. Riverton Vertical Gradients ... 14
Table 3. Discharge Statistics[a] from the Little Wind River. ... 28
Table 4. October 2012 Hydrant Flushing Summary ... 36
Table 5. Monitoring Results from the October 2012 AWSS Flushing Event ... 39
Table 6. Uranium K_d Values Calculated from Batch Test Data and Column Labile Fractions ... 50
Table 7. Comparison of June 2012 Results with August 2012 Results ... 58
Table 8. Summary of Groundwater Results ... 60
Table 9. Groundwater Model Inputs ... 73
Table 10. Groundwater Model Calibration Statistics ... 75
Table 11. Pilot Points Summary ... 77
Table 12. Pilot Points Details ... 77
Table 13. Stress-Period Setup for the Transient Flow Model ... 78
Table 14. Transient Flow Model Stress-Period Summary ... 78

Table 15. Comparison of Pre-Flood, 2010 Flood, and 2012 Results..... 83
Table 16. Recommendations for Potential Future Work 88

Appendixes

Appendix A Water Level Data
Appendix B Groundwater Quality Data – Verification Monitoring
Appendix C Domestic Well Data
Appendix D Surface Water Quality Data
Appendix E AWSS Data
Appendix F *Laboratory Analysis of Shallow Sediment Near a Former Uranium Mill: Riverton, Wyoming, Site*
Appendix G Groundwater Quality Data – Enhanced Characterization

Abbreviations

ASW	artificial site water
AWSS	alternate water supply system
bgs	below ground surface
cfs	cubic feet per second
COPC	contaminant of potential concern
DOE	U.S. Department of Energy
EPA	U.S. Environmental Protection Agency
ft	foot
ft/s	feet per second
g	grams
GCAP	Groundwater Compliance Action Plan
GV	Groundwater Vistas
IC	institutional control
K_d	distribution coefficient
LM	Office of Legacy Management
LTMP	*Long-Term Management Plan for the Riverton, Wyoming, Processing Site*
MCL	maximum concentration limit
µg/g	micrograms per gram
mg/L	milligrams per liter
mL	milliliters
mL/g	milliliters per gram
mL/min	milliliters per minute
mm	millimeters
NRC	U.S. Nuclear Regulatory Commission
pCi/L	picocuries per liter
PD	percent difference
SOWP	Site Observational Work Plan
UMTRA	Uranium Mill Tailings Remedial Action
UMTRCA	Uranium Mill Tailings Radiation Control Act

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Executive Summary

Verification monitoring in 2012 at the Riverton, Wyoming, Processing Site involved routine sampling of groundwater, surface water, and domestic wells, and a flushing and monitoring program of the alternate water supply system that was reinstituted in late 2011. Concentrations of uranium and molybdenum at the site remained above their respective groundwater standards in surficial aquifer wells; however, concentrations in 2012 decreased to near 2009 levels after spiking following the 2010 flood of the Little Wind River. Sampling results from domestic wells continued to indicate no impact from site-related contaminants, and the flushing program for the alternate water supply system was effective in controlling the buildup of radionuclides in the system.

An enhanced characterization of the surficial aquifer was conducted in 2012, which included installation of 103 boreholes along 9 transects with a Geoprobe, collection of 103 water samples and 65 soil samples, laboratory tests on the soil samples, and additional groundwater modeling. Analysis of groundwater samples resulted in a better understanding of the size and shape of contaminant plumes for manganese, molybdenum, sulfate, and uranium. Laboratory soil testing indicated that there is uranium in the soils above the water table that can be mobilized by flood events; however, the concentration of uranium in unsaturated zone samples alone does not appear to be high enough to have caused the spikes observed in the groundwater after the 2010 flood.

Several types of information, including uranium mobilized by flood events, current plume size and concentration, groundwater modeling results, historical data, and experience at other Uranium Mill Tailings Radiation Control Act (UMTRCA) sites, indicates natural flushing of the surficial aquifer is occurring at the Riverton site, but the rate at which it is occurring might not meet the 100-year regulatory time frame. Additional information will be needed and additional work conducted to gain a better understanding of the site before a final decision can be made regarding the natural flushing compliance strategy or before a selection of an alternate compliance strategy can be made.

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1.0 Introduction

This Riverton, Wyoming, Processing Site enhanced characterization and monitoring report does the following: presents data collected during calendar year 2012, presents and evaluates enhanced characterization efforts to update the site conceptual model, provides an update on the natural flushing compliance strategy, and provides recommendations for future work. Data from 2012 were generated from two routine groundwater and surface water sampling events conducted at the Riverton site during June and December, an enhanced characterization effort with the field investigation conducted in August, a flushing event of the alternate water supply system (AWSS) conducted in October, and soils testing and groundwater modeling in the fall and winter.

2.0 Verification Monitoring

The compliance strategy for the Riverton site is natural flushing in conjunction with institutional controls (ICs) (DOE 1998a). Monitoring required during the natural flushing period is referred to as verification monitoring because the purpose of the monitoring is to verify that the natural flushing strategy is progressing as predicted, and to verify that ICs are in place and functioning as intended. Data collected during verification monitoring are reported annually in a Verification Monitoring Report. These reports have been issued annually since 2001, and the reports from 2005 to 2011can be found on the U. S. Department of Energy's (DOE) Office of Legacy Management (LM) website at http://www.lm.doe.gov/Riverton/Sites.aspx. All water quality data for the Riverton site are archived in the LM's environmental database in Grand Junction, Colorado. Water quality data also are available for viewing with dynamic mapping via the Geospatial Environmental Mapping System (GEMS) website at http://gems.lm.doe.gov/imf/sites/gems_continental_us/jsp/launch.jsp.
The monitoring program at the Riverton site is specified in the *Long-Term Management Plan for the Riverton, Wyoming, Processing Site* (LTMP) (DOE 2009).

2.1 Site Conditions

2.1.1 Uranium Mill Tailings Remedial Action (UMTRA) Site and Surface Remediation

A uranium and vanadium-ore-processing mill operated from1958 to 1963 at the Riverton site. A tailings pile covered about 72 acres of the 140-acre site. In 1988 and 1989, the tailings pile was excavated down to an average depth of 4 feet (ft) below ground surface (bgs) based on a radium-226 soil standard. Surface remediation activities resulted in removal of about 1.8 million cubic yards of tailings and associated materials from the site, which were encapsulated at the Gas Hills East, Wyoming, Disposal Site (Figure 1) (DOE 1998b). Soils at and below the water table with elevated thorium-230 concentrations were left in place on portions of the former mill site by applying supplemental standards. An easement and covenant to restrict land use on the former mill site is in place to prevent exposure to and disturbance of the supplemental-standard areas.

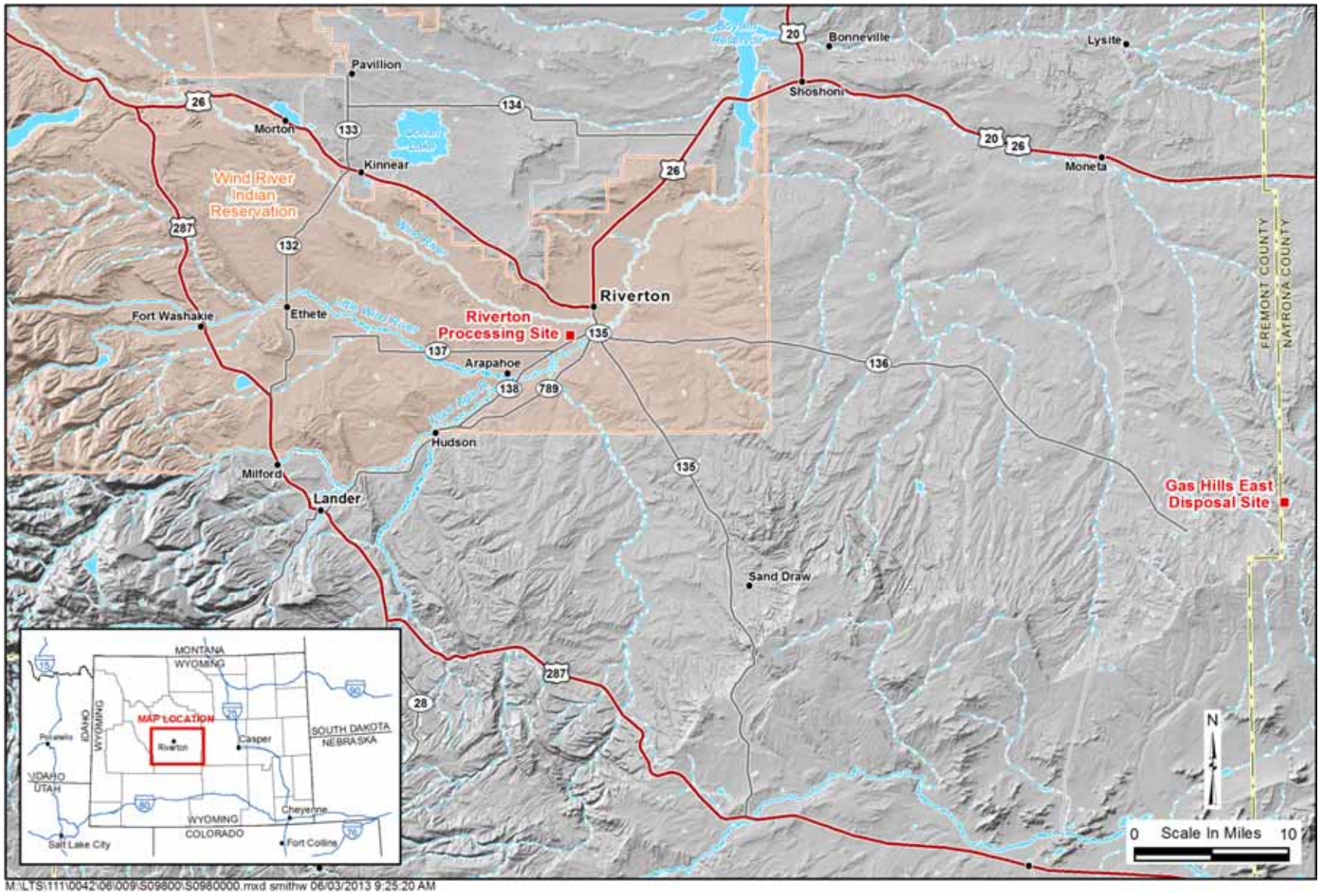

Figure 1. Site Location Map

2.1.2 Hydrogeology

The Riverton site is located on an alluvial terrace between the Wind River and the Little Wind River approximately 2.3 miles southwest of the town of Riverton, Wyoming (Figure 1). Groundwater is in three aquifers beneath the site: (1) a surficial unconfined aquifer (surficial aquifer), (2) a middle semiconfined aquifer, and (3) a deeper confined aquifer (DOE 1998b). The surficial aquifer consists of approximately 15 to 20 ft of unconsolidated alluvial material; the semiconfined and confined aquifers are composed of shales and sandstones of the upper units of the Eocene Wind River Formation, which is over 500 ft thick in the vicinity of the site. Depth to groundwater in the surficial aquifer is generally less than 10 ft bgs. For compliance purposes, the surficial aquifer and semiconfined aquifer comprise the uppermost aquifer, which is the aquifer where compliance with groundwater standards is assessed. Groundwater in the uppermost aquifer flows to the southeast.

Because the Riverton site is located on an alluvial terrace between the Wind River and the Little Wind River, site conditions have been influenced by periodic flooding of these rivers. Influence of river flooding on site conditions includes the following: formation of an oxbow lake in 1995; spikes in groundwater contaminant concentrations; high groundwater levels leaving contaminants in the unsaturated zone; and high groundwater levels that leached contaminants from the former tailings pile (White et al.1984). Significant floods of the Little Wind River that likely affected the site occurred in 1963, 1965, 1967, 1983, 1991, 1995, and 2010 when peak river discharge was greater than 8,000 cubic feet per second (cfs) (USGS 2012a). Significant floods of the Wind River that likely affected the site occurred in 1963, 1967, 1971, 1991, 1997, 1999, and 2011 when peak stream discharge was greater than 8,000 cfs (USGS 2012b). Discharge data and flood data from the Little Wind River are presented in Section 2.3.2.1.

2.1.3 Water Quality

Shallow groundwater beneath and downgradient from the site was contaminated as a result of uranium-processing activities from 1958 through 1963 (DOE 1998b). Contaminants of potential concern (COPCs) in the groundwater beneath the Riverton site are manganese, molybdenum, sulfate, and uranium. COPCs were selected using a screening process that compared contaminant concentrations with the maximum concentration limits (MCLs) in Title 40 *Code of Federal Regulations* Part 192 (40 CFR 192), as appropriate, and evaluated potential human health risks and ecological risks. (Note: The MCLs discussed in this document are not the same as the maximum contaminant levels that the U.S. Environmental Protection Agency (EPA) sets as drinking water standards.) The COPC-selection process is detailed in the *Environmental Assessment of Ground Water Compliance at the Riverton, Wyoming, Uranium Mill Tailings Site* (DOE 1998c). Molybdenum and uranium were selected as indicator contaminants for compliance monitoring in the *Final Ground Water Compliance Action Plan for the Riverton, Wyoming, Title I UMTRA Project Site* (DOE 1998a). These contaminants were selected as indicator contaminants because they are the most widely distributed and because they form significant aqueous plumes in the uppermost aquifer in the vicinity of the site. The MCLs for molybdenum and uranium are 0.10 milligram per liter (mg/L) and 30 picocuries per liter (pCi/L), respectively.

In order to provide a consistent comparison with historical data, uranium concentrations continue to be measured in mg/L; therefore, the uranium standard referenced in this report has been converted from 30 pCi/L to 0.044 mg/L (which assumes secular equilibrium of uranium isotopes) to allow direct comparison of uranium data to the standard.

2.1.4 Institutional Controls

To protect human health and the environment during the natural flushing period, ICs are required to control exposure to contaminated groundwater. An IC boundary has been established at the Riverton site (Figure 2), delineating the area that requires protection. The IC boundary was set to encompass the area of current groundwater contamination and a surrounding buffer zone to account for potential future plume migration.

2.1.4.1 Site Institutional Controls

All IC components have not been finalized, but there is an ongoing cooperative effort among DOE, the Northern Arapaho and Eastern Shoshone Tribes, and the State of Wyoming in order to final additional viable and enforceable ICs at the Riverton site. ICs currently in place include the following components:

- An AWSS, funded by DOE and currently operated by the Great Plains Utility Organization, supplies potable water to residents within the IC boundary to minimize use of groundwater.
- Warning signs installed around the oxbow lake (Figure 3) explain that the contaminated water is not safe for human consumption, with instructions not to drink from, fish in, or swim in the lake.
- A Tribal Ordinance places restrictions on well installation, prohibits surface impoundments, authorizes access to inspect and sample new wells, and provides notification to drilling contractors of the groundwater contamination within the IC boundary. Restrictions on well installation include a minimum depth of 150 ft bgs (approximately 50 ft below the top of the confined aquifer) and installation of surface casing through the contaminated upper aquifer.
- DOE will notify area drilling contractors of the existing groundwater contamination.
- A State of Wyoming Department of Environmental Quality notification of existing groundwater contamination will be provided to persons on privately owned land who apply for a gravel pit permit within the IC boundary.
- A U.S. Bureau of Indian Affairs notification of existing groundwater contamination will be provided to persons on tribal land applying for a surface impoundment within or adjacent to the IC boundary.
- The State of Wyoming State Engineer's Office will inform DOE when permit applications are received for wells or surface impoundments within or adjacent to the IC boundary, provide DOE with a copy of the application (so that DOE may comment on it), and incorporate DOE's comments on the permit, if approved.
- An easement and covenant to restrict land use and well drilling on the former mill site property was finalized on June 29, 2009, and the former mill site was purchased by Chemtrade Refinery Services Inc.

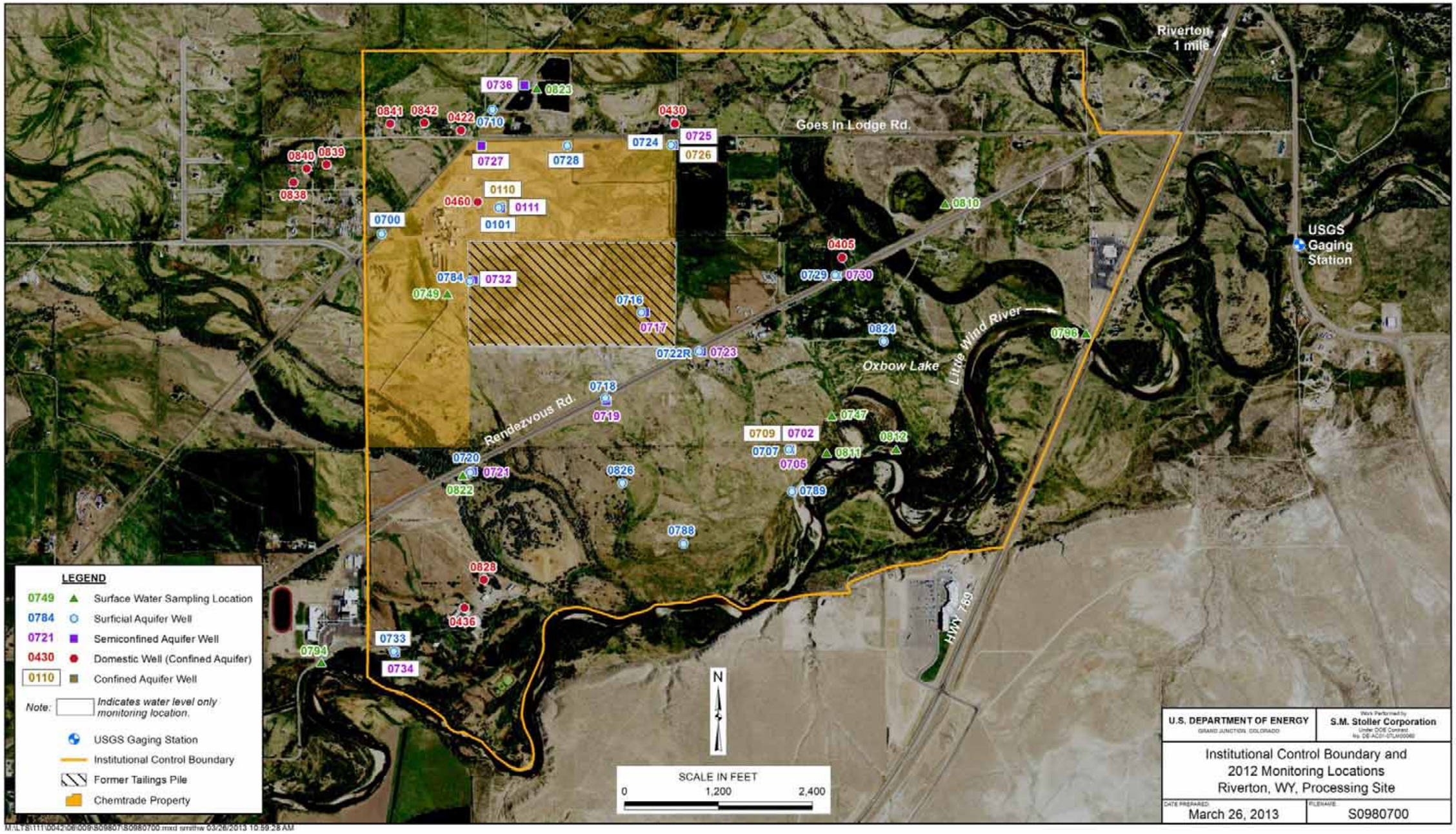

Figure 2. Institutional Control Boundary and 2012 Monitoring Locations at the Riverton Site

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Figure 3. Warning Sign at the Oxbow Lake

ICs that are in progress, but not finalized, include the following:

- A U.S. Bureau of Indian Affairs–provided notification of existing groundwater contamination will be provided to all residents on tribal land within or adjacent to the IC boundary.
- A notification of existing groundwater contamination will be provided to fee-land property owners within the IC boundary every 5 years.

2.1.4.2 Institutional Control Monitoring

The LTMP specifies ongoing IC monitoring to verify that ICs are in place and working, in order to ensure that potential exposure to contaminated groundwater is minimized during the natural flushing period. IC monitoring consists of two components: (1) sampling and (2) land and water use verification. The sampling component consists of sampling of domestic wells and the AWSS. The land and water use verification consists of periodic inspection of lands within the IC boundary to verify and document that no additional land or water uses expose or involve shallow groundwater, such as new wells, gravel pits, and recreational ponds.

All known domestic wells used as a potable water source within the IC boundary were sampled during June and December in 2012, and the results are presented in Section 2.3.1.3 and Appendix C.

The Great Plains Utility Organization is responsible for ensuring that the quality, safety, and quantity of the water in the AWSS are adequate. The Great Plains Utility Organization is also required to maintain compliance with EPA standards that regulate community water systems. To assist in this effort and to maintain the AWSS as a viable IC, DOE has a cooperative agreement with the Northern Arapaho Tribe to ensure cooperative efforts and funding for ongoing maintenance, flushing, sampling, and capital improvements on the AWSS.

An AWSS hydrant flushing program was restarted in October of 2011 as specified in the cooperative agreement with the Northern Arapaho Tribe. As a result of some erroneous laboratory results from the October 2011 hydrant flushing and sampling event that were disclosed to DOE prior to a public meeting on May, 6, 2012, DOE committed to managing the sampling and analysis portion of the hydrant flushing program to ensure samples were analyzed by an accredited and audited analytical laboratory. In 2012, flushing and sampling events were conducted in April and October. The April hydrant flushing event (prior to the public meeting) was conducted by the Great Plains Utility Organization and the Tribal Engineer's Office, and the October hydrant flushing event was conducted as a joint effort among the Great Plains Utility Organization, the Tribal Engineer's Office, and DOE. Results of the October hydrant flushing event are presented in Section 2.3.3 and Appendix E.

Verification that one component of the institutional controls is working as intended was received in 2012. DOE received a letter from the State Engineer's Office on December 18, 2012, requesting comments on a proposed well in the vicinity of the Riverton site. DOE reviewed the application for the well, and determined that the well installation could proceed because the proposed location of the well was outside of the IC boundary. A response letter was drafted and sent to the State Engineer's Office in early 2013.

Sampling crews inspected areas within the IC boundary during each semiannual sampling event and found no evidence of new land or water use that would expose groundwater.

2.2 Monitoring Program

The verification monitoring program for 2012 consisted of 18 monitoring wells, 11 domestic wells, and 9 surface water locations, which are listed in Table 1 and shown in Figure 2. In addition, 7 AWSS hydrant locations and 4 AWSS tap locations were sampled and are listed in Table 1 and discussed in Section 2.3.3. Domestic wells 0838, 0839, and 0840 were sampled only in June at the request of the homeowners; these wells are outside the IC boundary and will not be included in the long-term monitoring program. Water levels were measured at 15 additional monitoring wells. Sampling events were conducted in June (groundwater, surface water, and domestic wells), October (AWSS), and December (groundwater, surface water, and domestic wells). Samples collected in June and December were analyzed for manganese, molybdenum, selenium (June only), sulfate, and uranium, and field measurements of temperature, pH, specific conductance, oxidation-reduction potential, dissolved oxygen, alkalinity, and turbidity were measured at each sampling location. Samples collected in October were analyzed for radium-226, radium-228, and uranium and field measurements of chlorine, temperature, pH, specific conductance, oxidation-reduction potential, dissolved oxygen, alkalinity, and turbidity.

Table 1. 2012 Sampling Network at the Riverton Site

Location ID	Description	Sampling Event	Rationale
DOE Monitoring Wells			
0705	Semiconfined aquifer	June, December	Monitor semiconfined aquifer
0707	Surficial aquifer	June, December	Monitor centroid of plume
0710	Surficial aquifer	June, December	Background location
0716	Surficial aquifer	June, December	Monitor upgradient portion of plume
0717	Semiconfined aquifer	June, December	Monitor semiconfined aquifer
0718	Surficial aquifer	June, December	Monitor lateral plume movement
0719	Semiconfined aquifer	June, December	Monitor semiconfined aquifer
0720	Surficial aquifer	June, December	Monitor lateral plume movement
0721	Semiconfined aquifer	June, December	Monitor semiconfined aquifer
0722R	Surficial aquifer	June, December	Monitor centroid of plume
0723	Semiconfined aquifer	June, December	Monitor semiconfined aquifer
0729	Surficial aquifer	June, December	Monitor lateral plume movement
0730	Semiconfined aquifer	June, December	Monitor semiconfined aquifer
0784	Surficial aquifer	June, December	Monitor lateral plume movement
0788	Surficial aquifer	June, December	Monitor lateral plume movement
0789	Surficial aquifer	June, December	Monitor centroid of plume
0824	Surficial aquifer	June, December	Monitor lateral plume movement
0826	Surficial aquifer	June, December	Monitor lateral plume movement
Domestic Wells[a]			
0405	Private residence	June, December	Potential point of exposure
0422	Private residence	June, December	Potential point of exposure
0430	Private residence	June, December	Potential point of exposure
0436	St Stephens Mission	June, December	Potential point of exposure
0460	Chemtrade Refinery	June, December	Potential point of exposure
0828	St. Stephens Mission	June, December	Potential point of exposure
0838	Private residence	June	Homeowner request
0839	Private residence	June	Homeowner request
0840	Private residence	June	Homeowner request
0841	Private residence	June, December	Potential point of exposure
0842	Private residence	June, December	Potential point of exposure
Surface Water			
0747	Oxbow lake	June, December	Impacted by groundwater discharge
0749	Chemtrade Refinery discharge ditch	June, December	Effluent from sulfuric acid plant
0794	Little Wind River	June, December	Upstream of predicted plume discharge
0796	Little Wind River	June, December	Downstream of predicted plume discharge
0810	Pond—former gravel pit	June, December	Potential for impact—within IC boundary
0811	Little Wind River	June, December	Within area of predicted plume discharge
0812	Little Wind River	June, December	Within area of predicted plume discharge
0822	West side irrigation ditch	June, December	Potential for impact—within IC boundary
0823	Pond—former gravel pit	June, December	Upgradient of plume—within IC area
AWSS Hydrants			
0818	AWSS flushing hydrant	October	Verify effectiveness of flushing program
0819	AWSS flushing hydrant	October	Verify effectiveness of flushing program
0820	AWSS flushing hydrant	October	Verify effectiveness of flushing program
0821	AWSS flushing hydrant	October	Verify effectiveness of flushing program
0829	AWSS flushing hydrant	October	Verify effectiveness of flushing program
0830	AWSS flushing hydrant	October	Verify effectiveness of flushing program
0834	AWSS flushing hydrant	October	Verify effectiveness of flushing program

Table 1 (continued). 2012 Sampling Network at the Riverton Site

Location ID	Description	Sampling Event	Rationale
AWSS Taps			
0813	AWSS tap at house	October	Verify taps unaffected by flushing process
0815	AWSS tap at house	October	Verify taps unaffected by flushing process
0816	AWSS tap at house	October	Verify taps unaffected by flushing process
0837	AWSS tap at house	October	Verify taps unaffected by flushing process

[a] All domestic wells are completed in the confined aquifer, except for well 0841, which might be completed in the semiconfined aquifer

2.3 Results of 2012 Monitoring

2.3.1 Groundwater

2.3.1.1 Groundwater Flow

Water levels were measured at all wells in the monitoring network in June and December in order to verify groundwater flow direction and to assess vertical gradients throughout the IC area. Water level data are included in Appendix A.

Assessment of horizontal groundwater flow direction in the surficial aquifer is required to ensure that the monitoring network is adequate for assessing contaminant plume movement and to ensure that the IC boundary provides a sufficient buffer to prevent access to contaminated groundwater. As shown in Figure 4 and Figure 5, groundwater elevation contours for the surficial aquifer indicate a general flow direction to the southeast in June and December. Water levels have been historically consistent as shown in Figure 5, which compares December 2012 and February 1997 water levels. Contaminant plume configurations tend to have a more southerly axis than the measured groundwater flow direction, which may be explained by different flow patterns during milling operations caused by groundwater mounding in the tailings area coupled by irrigation practices to the east of the site. In addition to water levels measured during each sampling event, continuous water-level measurements recorded by pressure transducers installed in wells along the groundwater flow path demonstrate that, based on groundwater elevations, the groundwater flow does not reverse direction throughout the year (Figure 6).

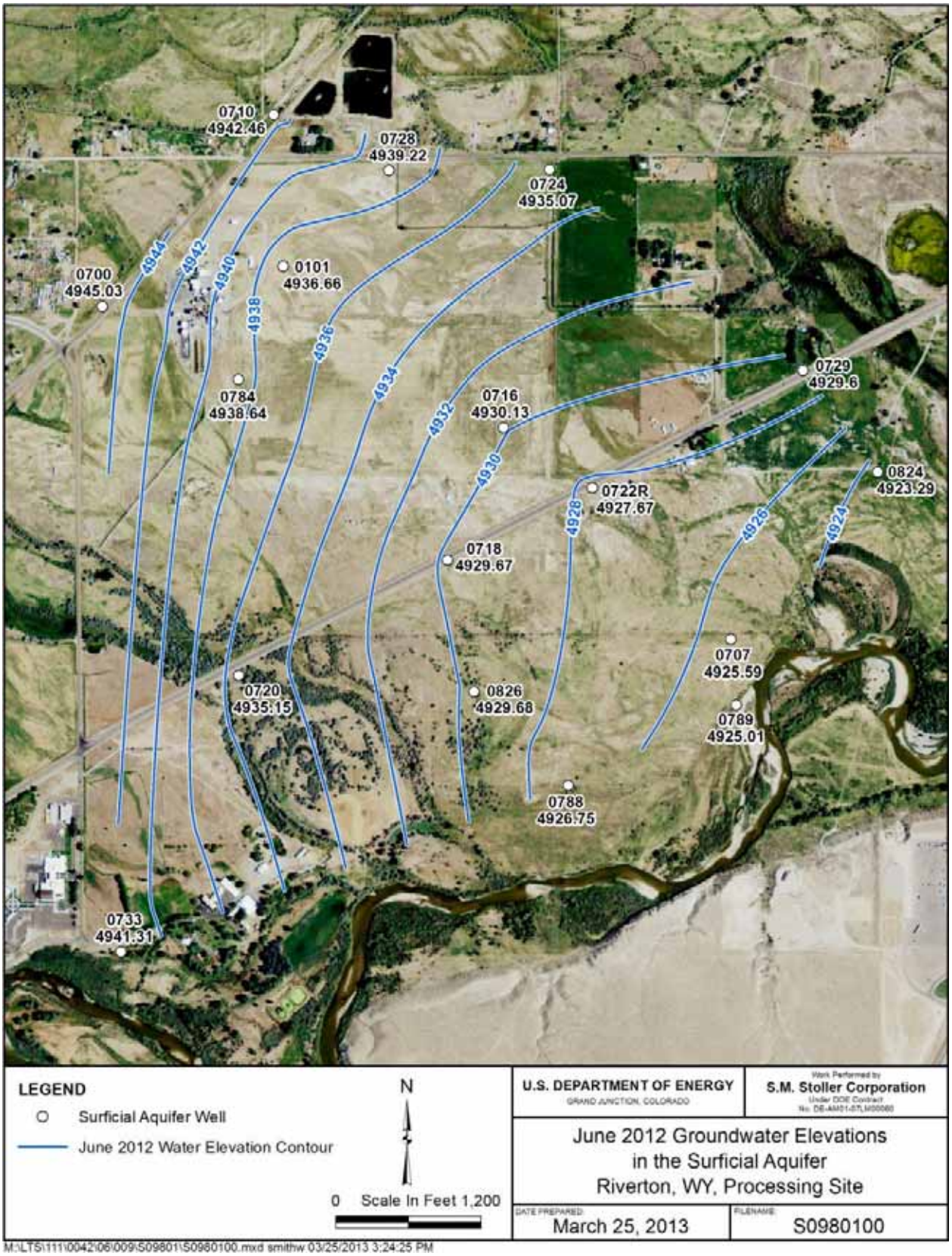


Figure 4. June 2012 Groundwater Elevations in the Surficial Aquifer at the Riverton Site

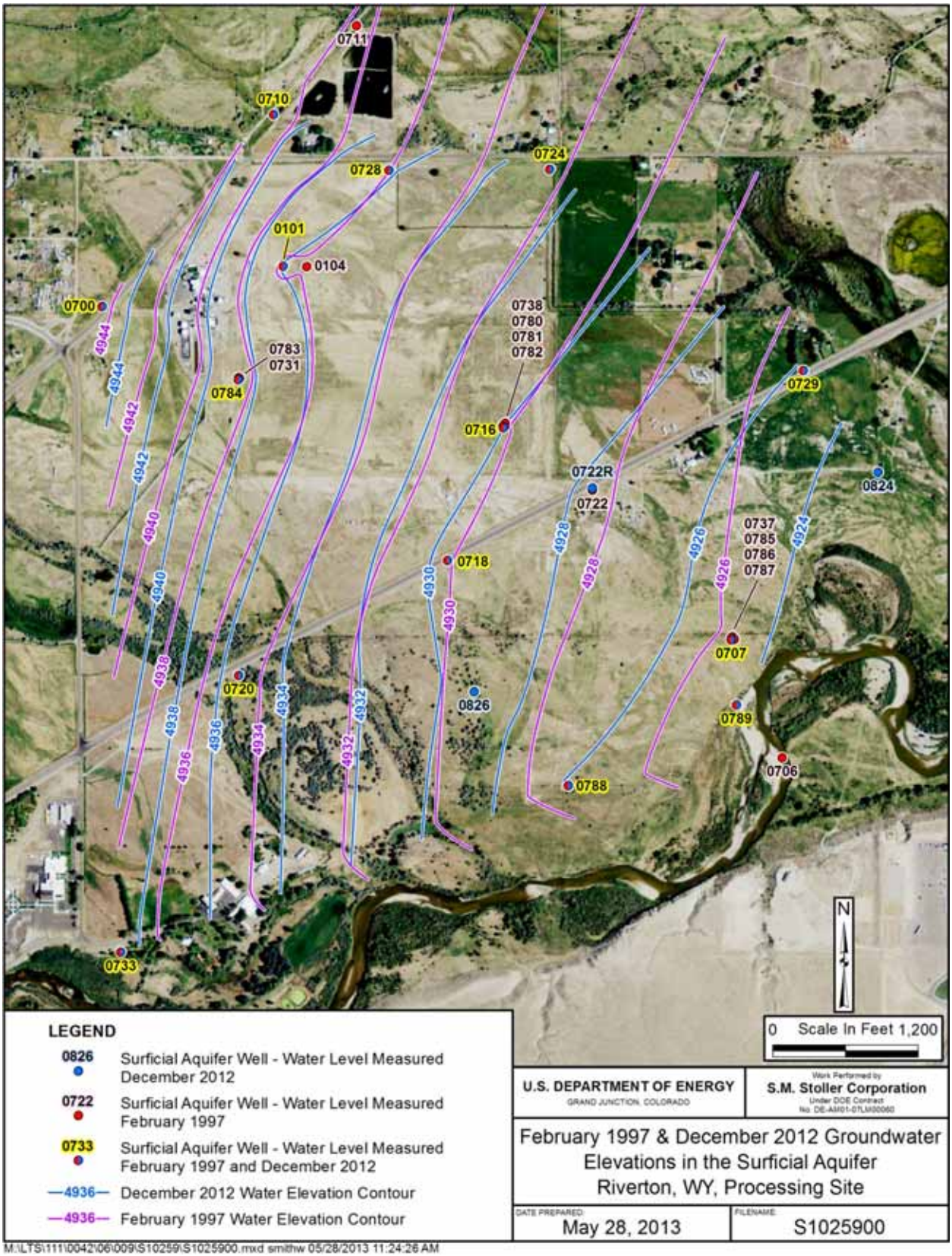


Figure 5. February 1997 and December 2012 Groundwater Elevations in the Surficial Aquifer at the Riverton Site

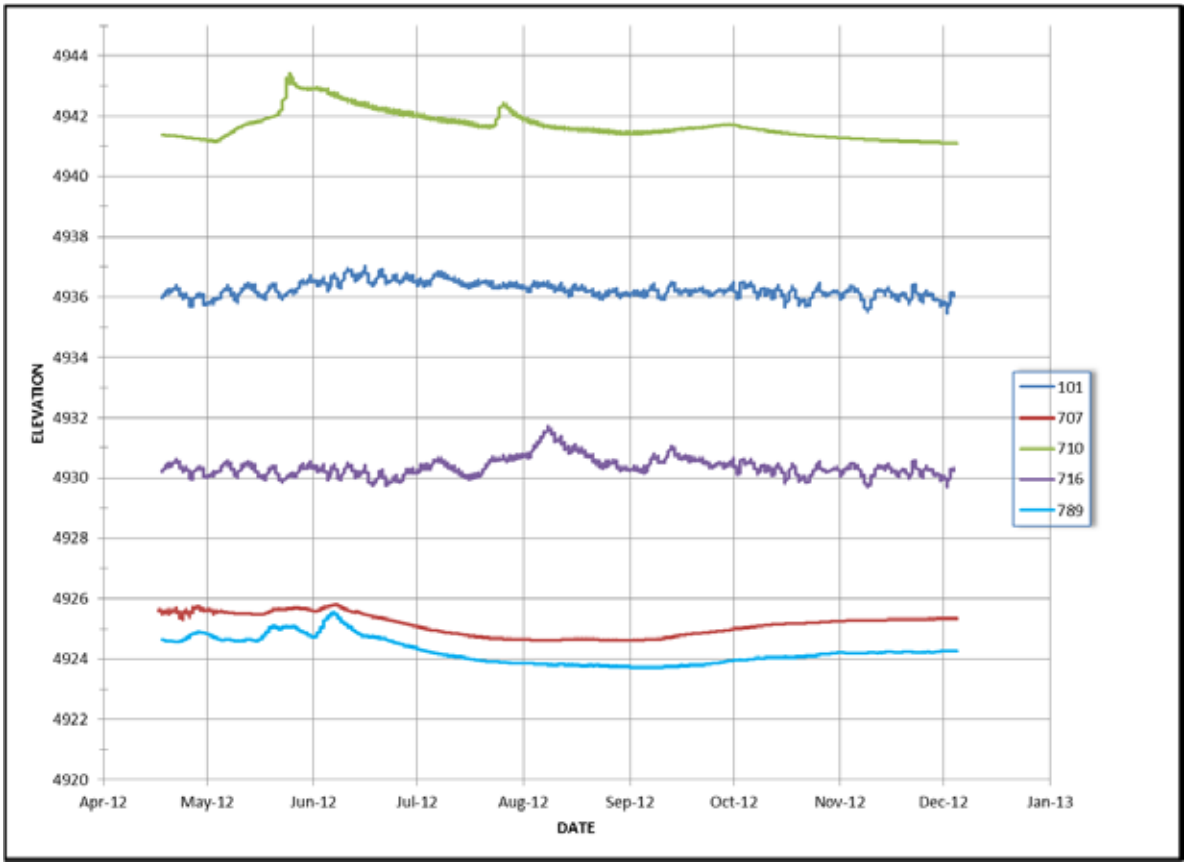


Figure 6. Continuous Water Elevations in Selected Surficial Aquifer Wells

Vertical gradients are used to assess the direction that groundwater will flow vertically. Using the methods that have traditionally been applied to assess vertical flow, a negative gradient indicates potential for upward groundwater flow, and a positive gradient indicates potential for downward groundwater flow. Regardless of the direction indicated by gradient, vertical migration of groundwater between the Riverton site aquifers is expected to be relatively minor because of the low vertical hydraulic conductivities of the confining layers separating aquifers. Vertical gradients are calculated from monitoring wells in an upper aquifer$_1$ and lower aquifer$_2$ using the following formula: $(GE_1\text{-}GE_2) \div (SE_1\text{-}SE_2)$, where GE = groundwater elevation and SE = screen elevation at the midpoint of the screen. Vertical gradients calculated from June and December data from grouped monitoring wells are shown in Table 2. General observations from Table 2 include the following:

- Vertical gradients in the confined aquifer are upward or 0 at two locations and mixed at one location.
- The well cluster adjacent to the sulfuric acid plant (0101, 0111, and 0110) typically shows downward vertical gradient between the confined aquifer and surficial aquifer, which is likely a reflection of continuous long-term pumping of the confined aquifer from the acid-plant production well; in 2012, the gradient was slightly upward in December.
- Although the well cluster adjacent to the sulfuric acid plant typically indicates a downward vertical gradient in the confined aquifer, an upward vertical gradient is indicated in the semiconfined aquifer, which confirms that the semiconfined and confined aquifers are hydrologically isolated.

- Vertical gradients between the surficial and semiconfined aquifer vary but tend to be downward near surface water features, and upward away from surface water features. Surface water is likely recharging the surficial aquifer, causing a localized increase in heads in the surficial aquifer and a resulting downward vertical gradient.

Table 2. Riverton Vertical Gradients

Well ID	Aquifer	Water Elevation June 2012	Water Elevation December 2012	Vertical Gradient[a] June 2012	Vertical Gradient December 2012
0724	Surficial	4935.07	4932.7		
0725	Semiconfined	4935.19	4932.68	-0.007	0.001
0726	Confined	4935.7	4933.83	-0.006	-0.010
0101	Surficial	4936.66	4935.88		
0111	Semiconfined	4937.82	4936	-0.043	-0.004
0110	Confined	4932	4935.99	0.089	-0.002
0784	Surficial	4938.64	4938.73		
0732	Semiconfined	4937.02	4936.84	0.061	0.072
0716	Surficial	4930.13	4929.98		
0717	Semiconfined	4930.17	4929.98	-0.001	0
0707	Surficial	4925.59	4925.25		
0705	Semiconfined	4924.48	4924.06	0.039	0.042
0709	Confined	4927.68	4925.25	-0.027	0
0718	Surficial	4929.67	4929.35		
0719	Semiconfined	4930.05	4929.66	-0.019	-0.016
0722R	Surficial	4927.67	4927.65		
0723	Semiconfined	4927.89	4927.86	-0.007	-0.007
0720	Surficial	4935.15	4935.09		
0721	Semiconfined	4932.56	4932.45	0.072	0.073
0729	Surficial	4929.6	4925.83		
0730	Semiconfined	4928.1	4925.44	0.065	0.017
0733	Surficial	4941.31	4938.52		
0734	Semiconfined	4938.92	4936.76	0.105	0.077

[a] The vertical gradient from the semiconfined aquifer is between the semiconfined aquifer and the surficial aquifer, and the vertical gradient from the confined aquifer is between the confined aquifer and the surficial aquifer. A negative value indicates an upward vertical gradient.

2.3.1.2 Groundwater Quality

Surficial aquifer data from the 2012 sampling events are summarized in the following plots and figures. Time-concentration plots for molybdenum in wells located within contaminant plumes and wells bordering the contaminant plumes in the surficial aquifer are shown in Figure 7 and Figure 8, respectively. The distribution of molybdenum in the surficial aquifer from the June

and December 2012 sampling events is shown in Figure 9 and Figure 10, respectively. Time-concentration plots for uranium in wells located within contaminant plumes and wells on the lateral edge of the contaminant plumes in the surficial aquifer are shown in Figure 11 and Figure 12, respectively. The distribution of uranium in the surficial aquifer, based on June and December 2012 sampling results, is shown in Figure 13 and Figure 14, respectively.

As shown in the plots and figures, concentrations of molybdenum and uranium in groundwater in the surficial aquifer are still above their respective MCLs. In June 2010, a dramatic increase in uranium concentrations was observed in wells 0707, 0788, 0789, and 0826 where flooding of the Little Wind River occurred. These increases in uranium concentrations included wells on the western edge of the plume (0788 and 0826), where sample concentrations exceeded the uranium standard, indicating lateral expansion of the plume. In addition, molybdenum concentrations increased dramatically in well 0707 during the June sampling event (Figure 7). In 2012, the concentration of uranium in sample collected from well 0707 in December was back to a pre-flood level.

Concentrations of molybdenum and uranium in groundwater in the semiconfined aquifer are still below corresponding MCLs in areas where the overlying surficial aquifer groundwater is contaminated, which indicate no significant impact from site-related contamination in this unit (Figure 15 and Figure 16).

Groundwater quality data by parameter for monitoring wells in the long-term monitoring network sampled during 2012 are provided in Appendix B.

In response to a review of groundwater quality data that was documented in the *Evaluation of Groundwater Constituents and Seasonal Variation at the Riverton, Wyoming, Processing Site* (DOE 2012a), samples collected from all wells were analyzed for selenium during the June sampling event. All selenium concentrations were one to two orders of magnitude below the selenium MCL of 0.01 mg/L, which confirms that this contaminant is not a concern at the Riverton site and will not be included in the long-term monitoring program. Selenium data are provided in Appendix B.

2.3.1.3 Domestic Wells

Domestic wells at residences within the IC boundary used as a potable water source and three wells outside the IC boundary were sampled in 2012; most of these wells are completed in the confined aquifer with the exception of well 0841, which is likely completed in the semiconfined aquifer. Results from domestic wells did not indicate any impacts from the Riverton site. Concentrations of molybdenum in samples collected from domestic wells were two orders of magnitude below the standard, and concentrations of uranium in samples collected from domestic wells were one to three orders of magnitude below the standard. Time-concentration graphs for molybdenum and uranium are shown in Figure 17 and Figure 18, respectively. Selenium concentrations measured in samples collected in June were low (below or near the detection limit) and two to three orders of magnitude below the MCL. Data obtained from sampling of domestic wells in 2012 are provided in Appendix C.

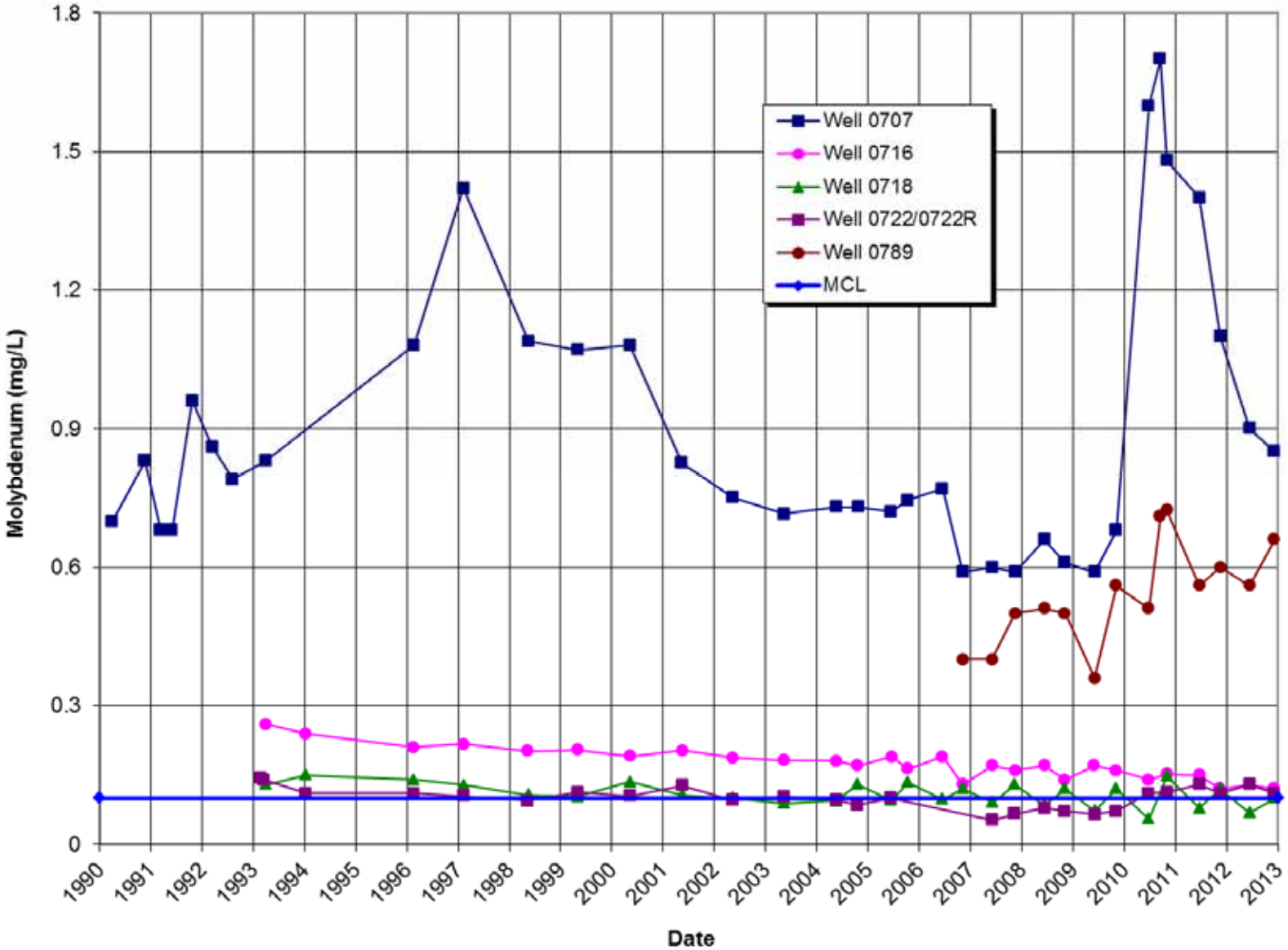
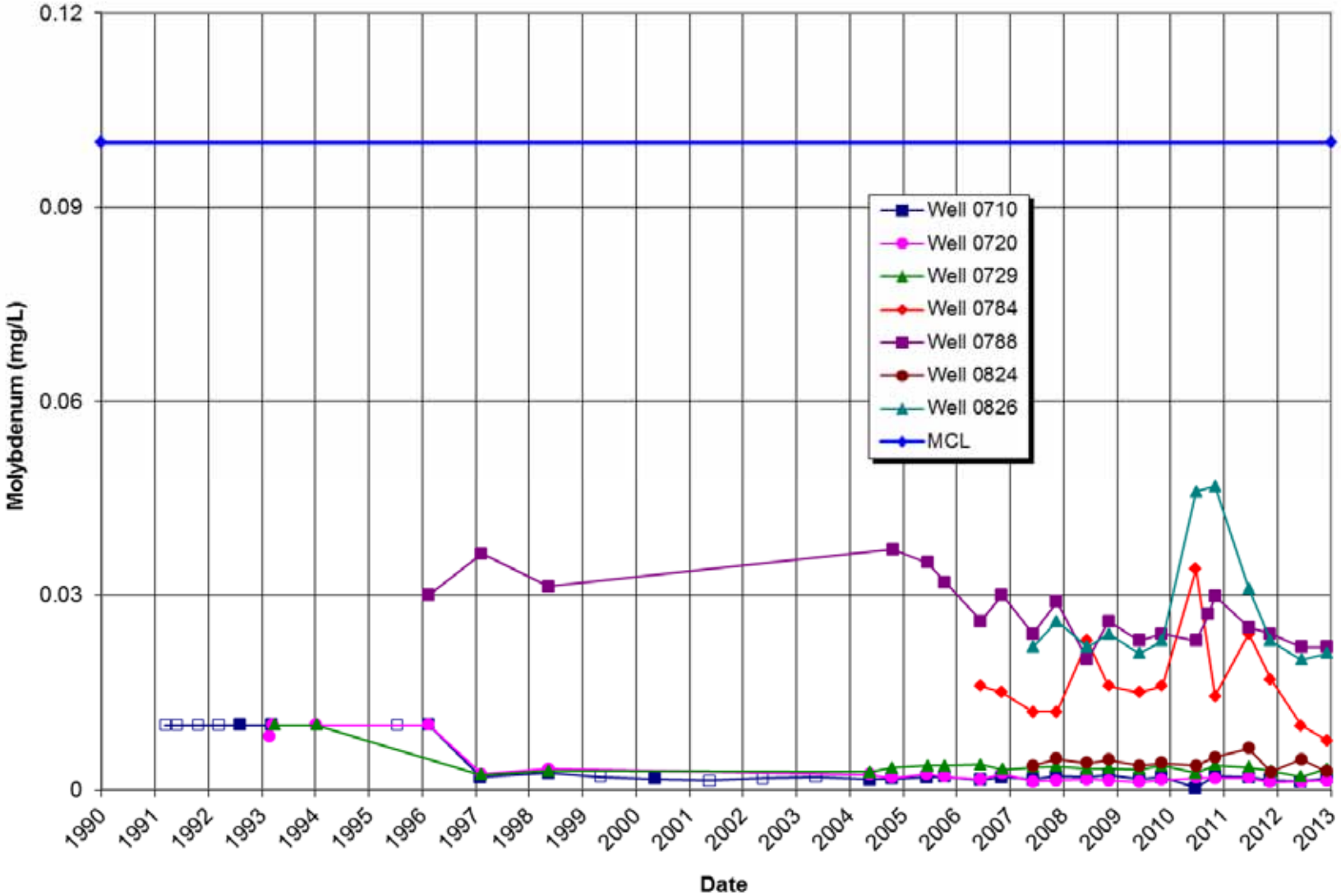


Figure 7. Molybdenum Concentrations in Surficial Aquifer Wells within the Contaminant Plume



Note: A hollow symbol denotes an analytical result below the detection limit.

Figure 8. Molybdenum Concentrations in Surficial Aquifer Wells on the Edge of the Contaminant Plume

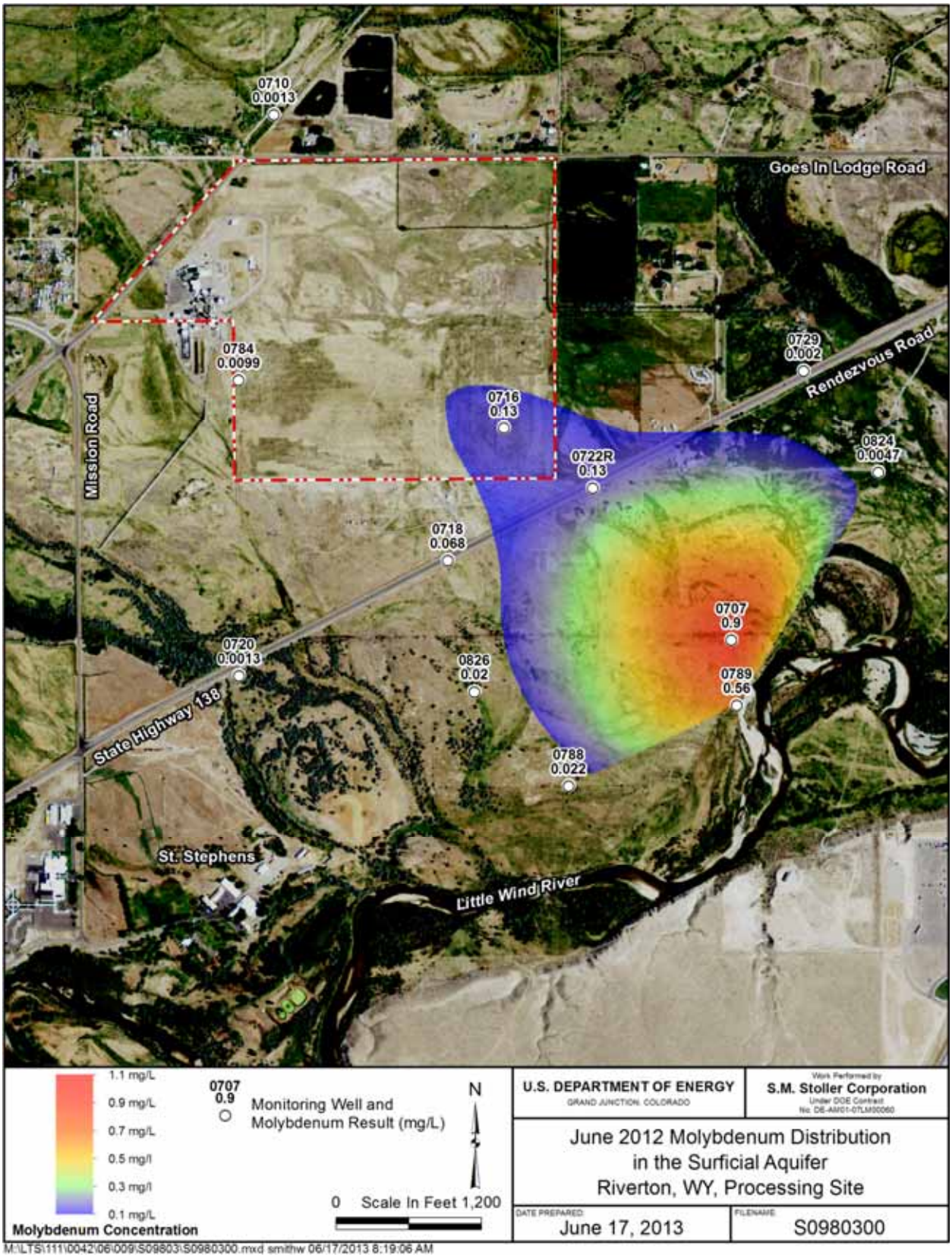


Figure 9. June 2012 Molybdenum Distribution in the Surficial Aquifer at the Riverton Site

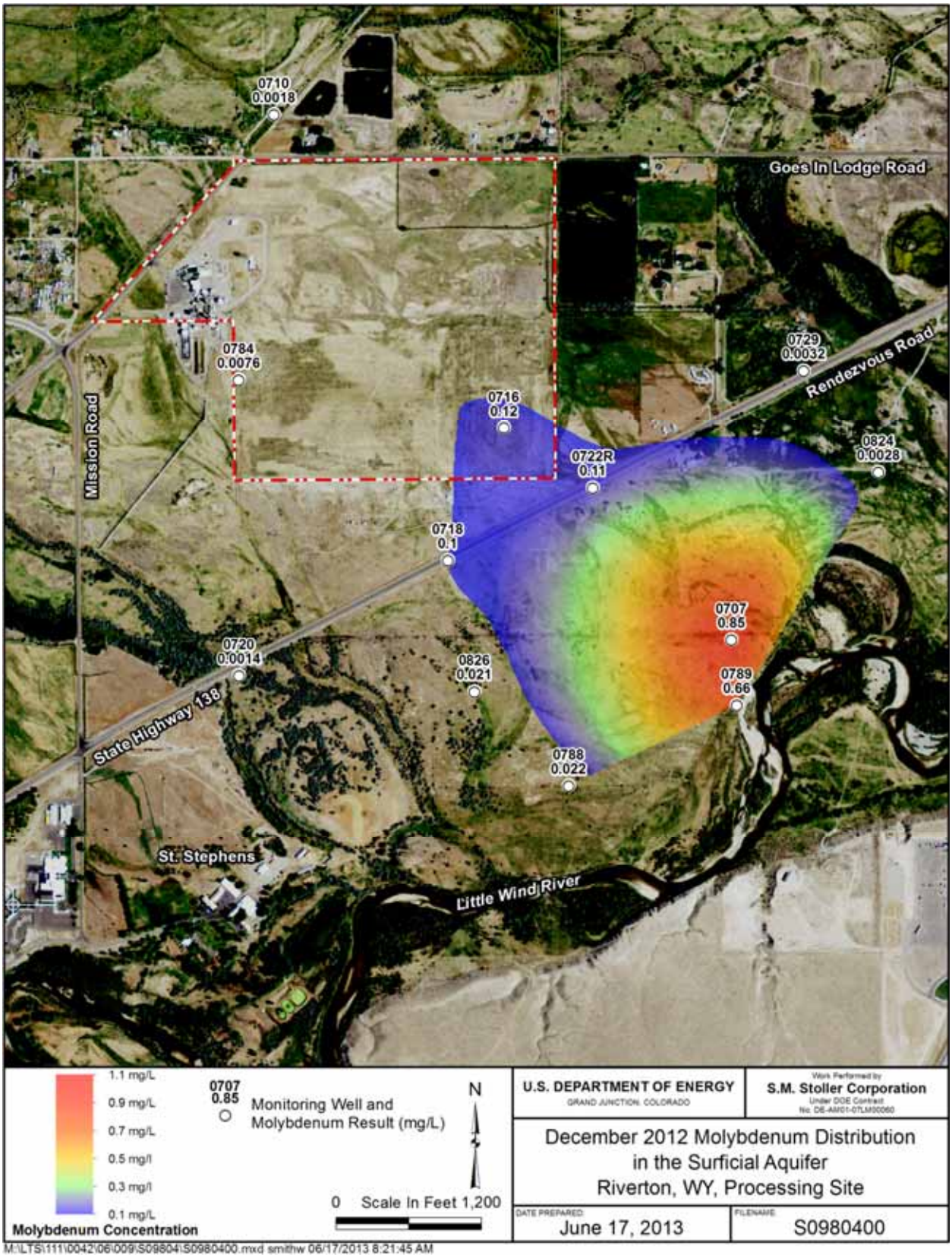


Figure 10. December 2012 Molybdenum Distribution in the Surficial Aquifer at the Riverton Site

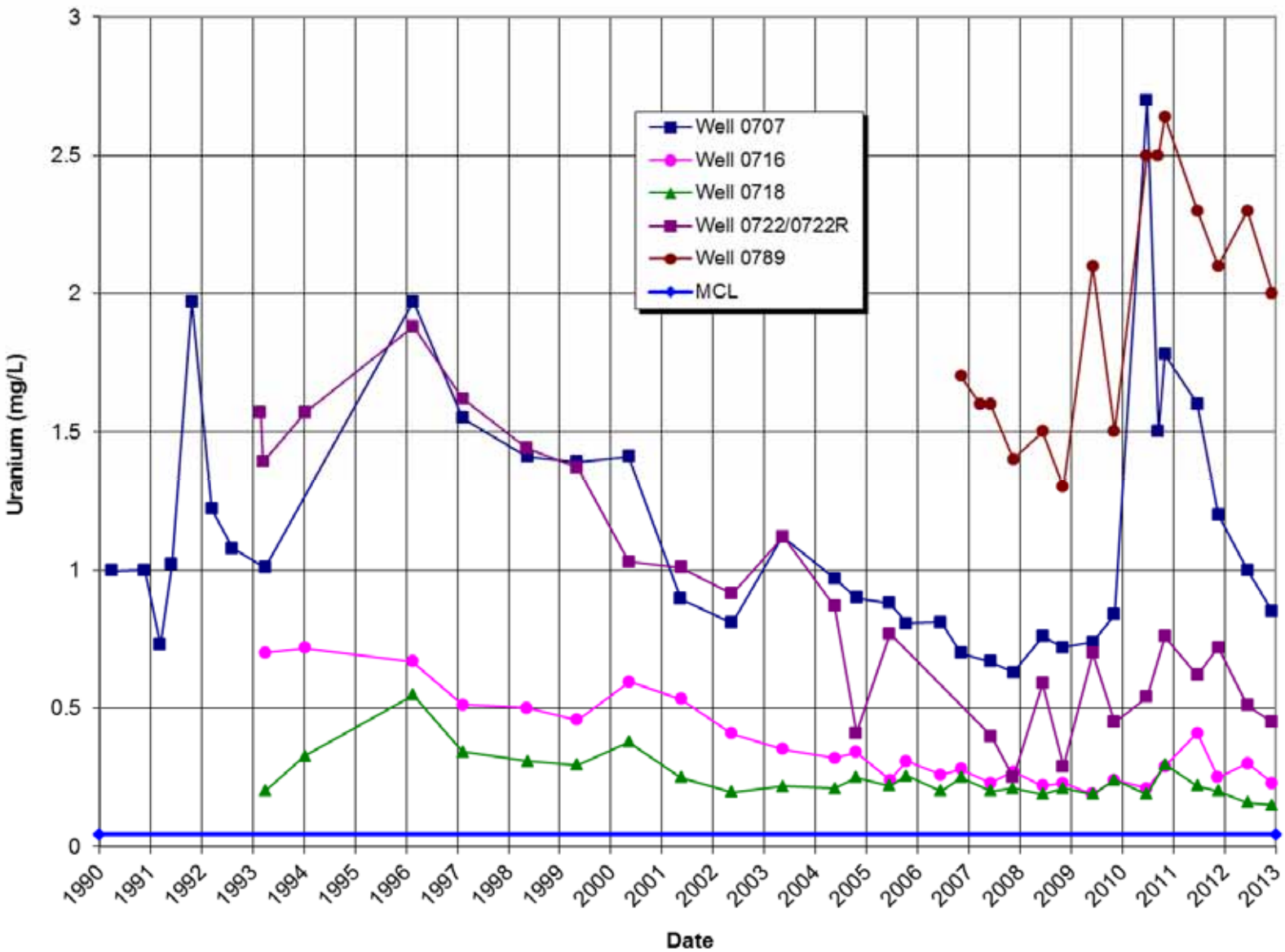
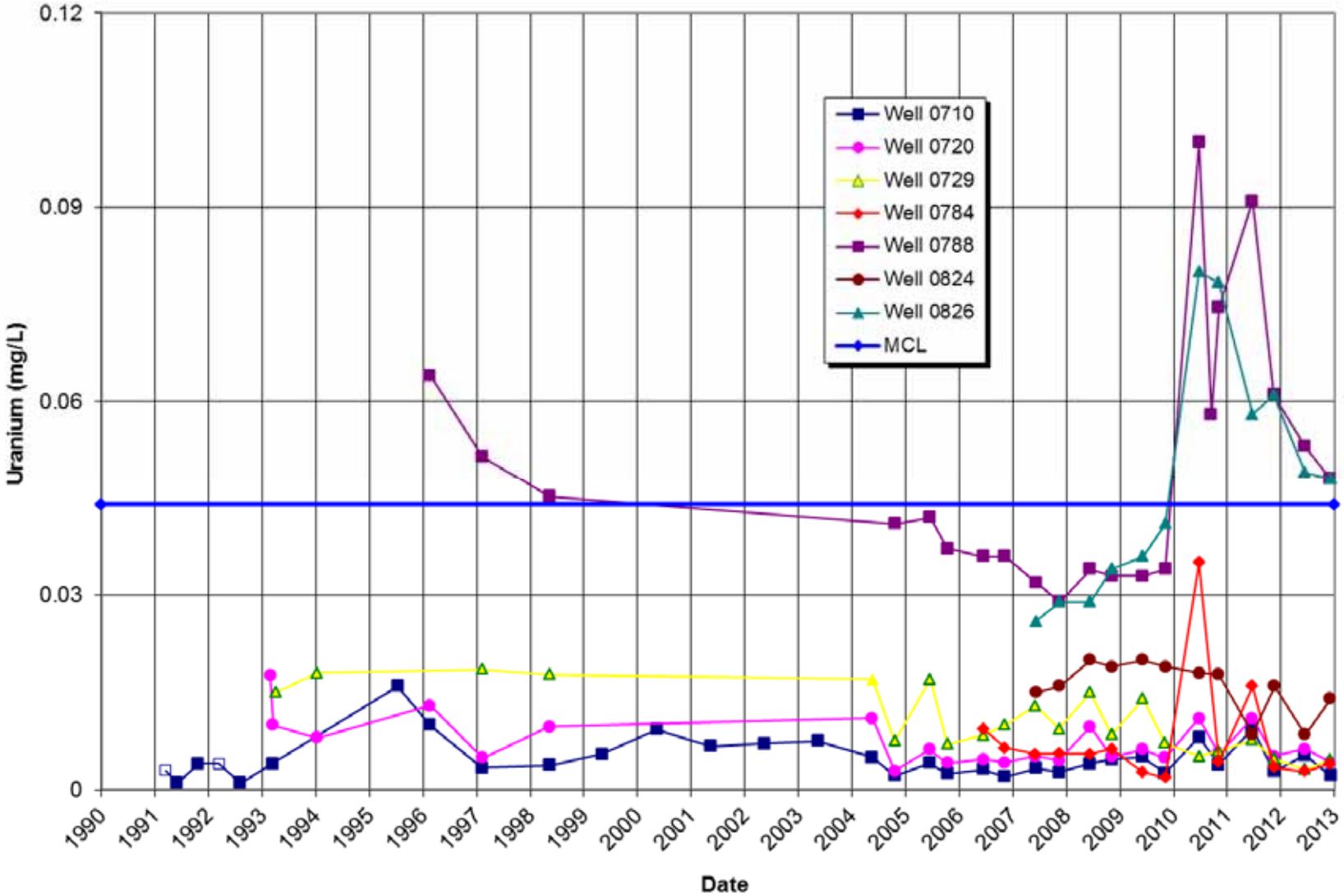


Figure 11. Uranium Concentrations in Surficial Aquifer Wells within the Contaminant Plume



Note: A hollow symbol denotes an analytical result below the detection limit.

Figure 12. Uranium Concentrations in Surficial Aquifer Wells on the Edge of the Contaminant Plume

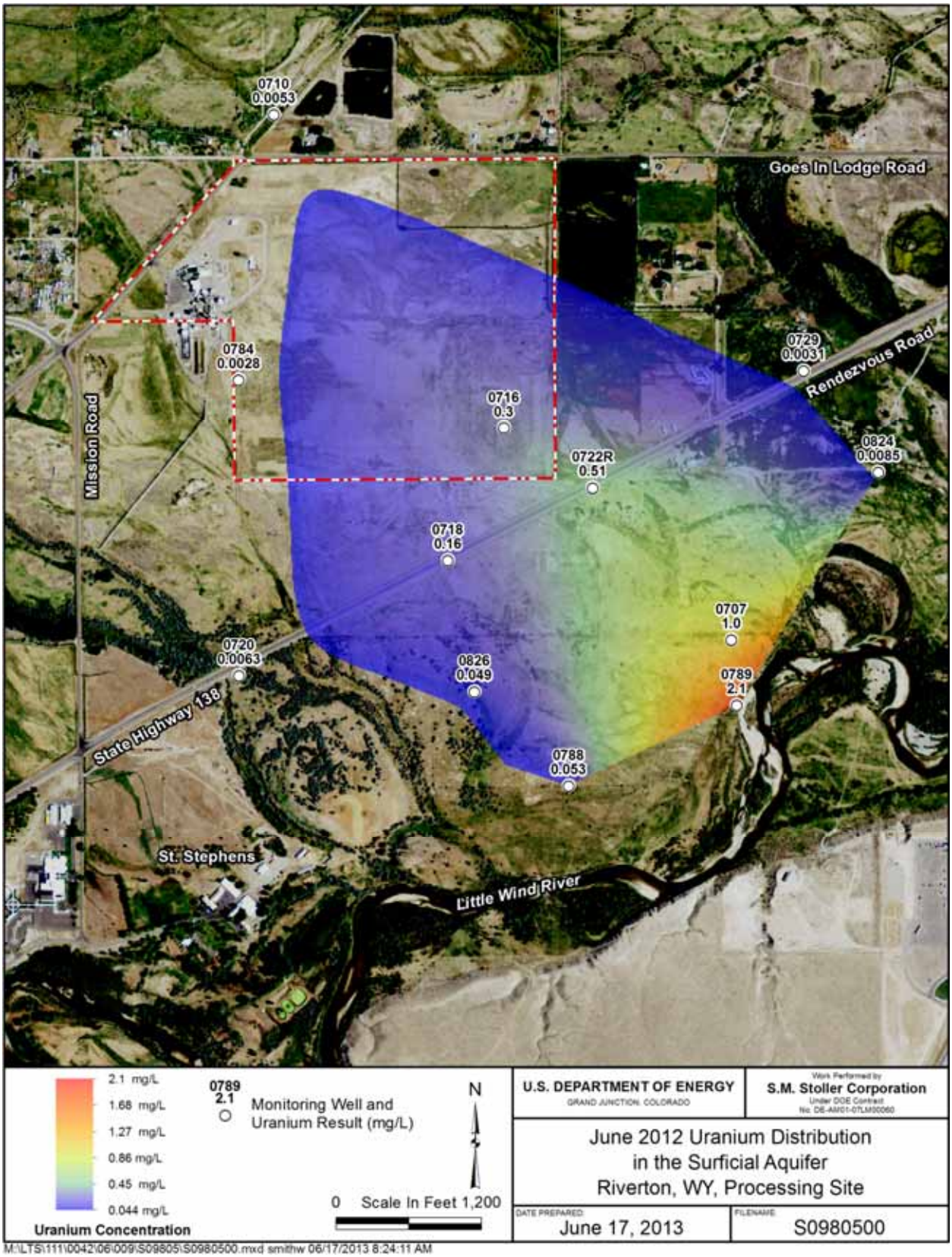


Figure 13. June 2012 Uranium Distribution in the Surficial Aquifer at the Riverton Site

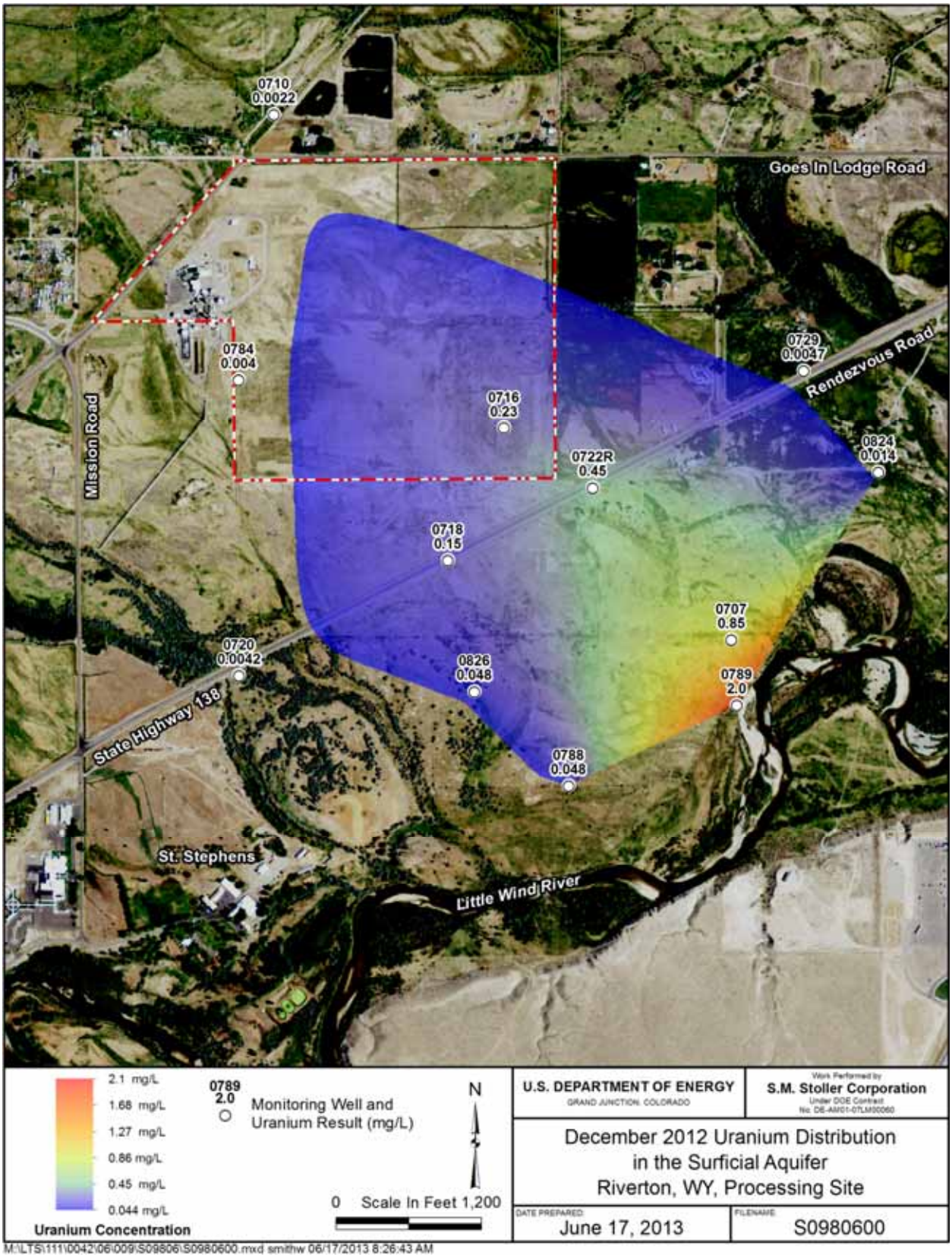
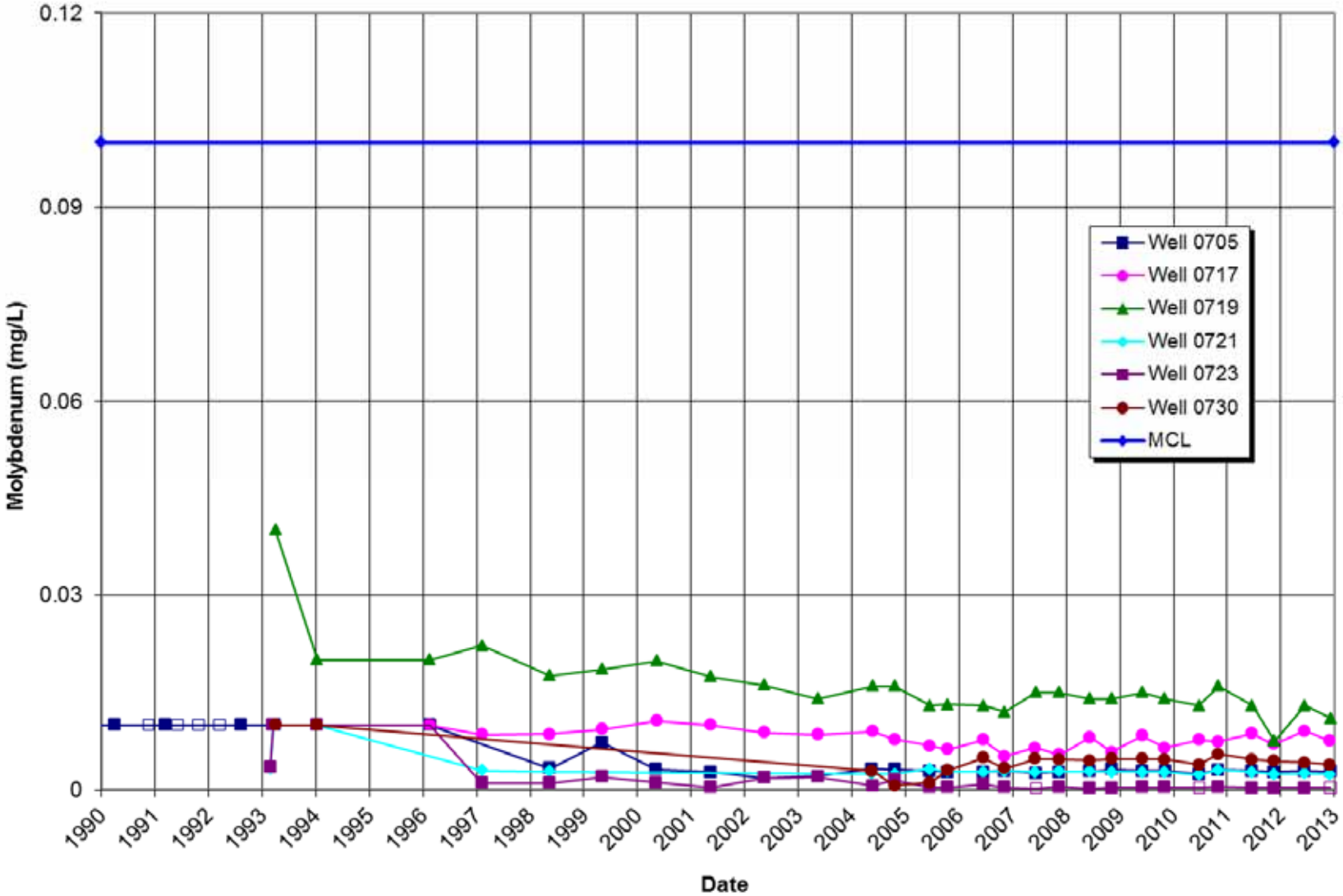
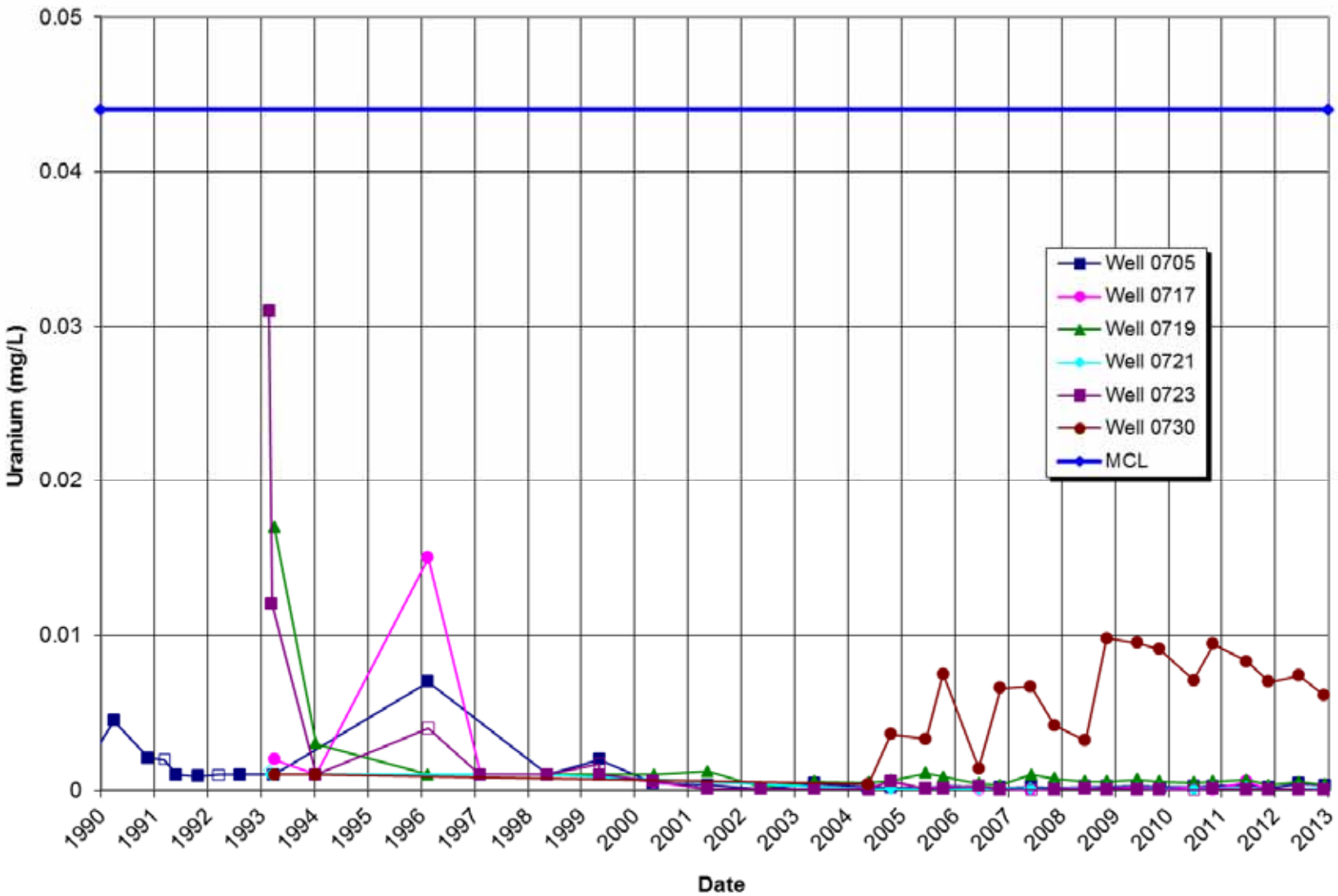


Figure 14. December 2012 Uranium Distribution in the Surficial Aquifer at the Riverton Site



Note: A hollow symbol denotes an analytical result below the detection limit.

Figure 15. Molybdenum Concentrations in Semiconfined Aquifer Wells



Note: A hollow symbol denotes an analytical result below the detection limit.

Figure 16. Uranium Concentrations in Semiconfined Aquifer Wells

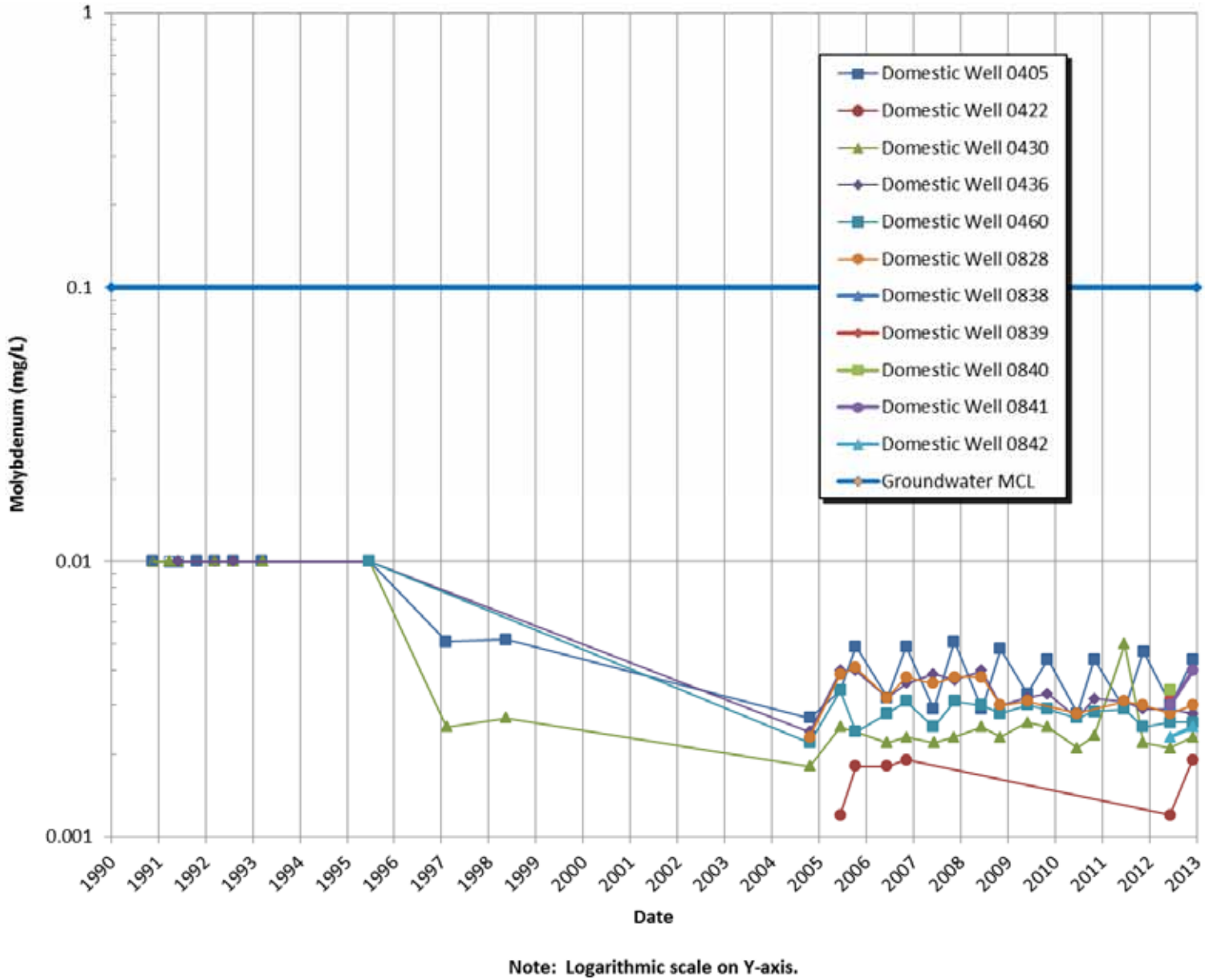


Figure 17. Molybdenum Concentrations in Domestic Wells

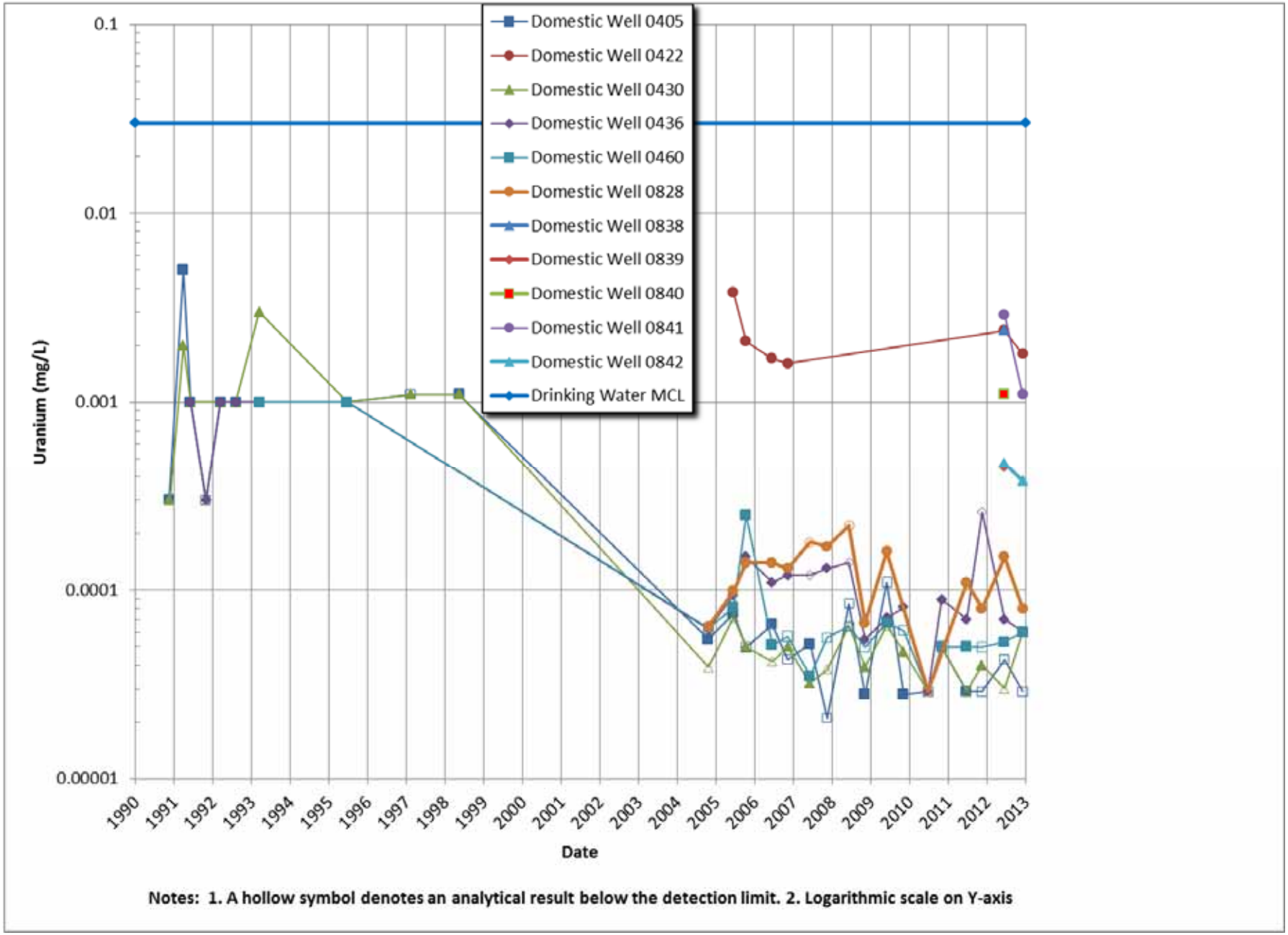


Figure 18. Uranium Concentrations in Domestic Wells

2.3.2 Surface Water

2.3.2.1 Surface Water Flow

The 2010 flood of the Little Wind River demonstrated a direct correlation between high discharge in the Little Wind River and increased contaminant concentrations in the surficial aquifer; therefore, it is likely that pre-2010 flooding of the river affected the concentration and configuration of contaminants in the saturated and unsaturated zones of the surficial aquifer. Figure 19 shows the highest peak discharges recorded since the start of milling operations (1958) at the U.S. Geological Survey gaging station (USGS 2012a) located approximately 1.6 miles east of the former mill site (the gaging station location is shown in Figure 2). In 2012, the highest discharge for the year was measured on June 6 at 1,610 cfs and at a river stage of 3.34 feet below flood stage. Discharge in the Little Wind River is statistically the highest in June, which reflects spring runoff from the Wind River Range. Most of the recharge of the alluvial aquifer likely occurs during these higher flows in the river. An assessment of June Little Wind River discharge data indicates that spring runoff/flow in the river was below normal in 2012, after being above normal for the previous three years (Table 3). Prior to 2009, mean spring runoff/flow in the river had been below normal since 2000.

Table 3. Discharge Statistics[a] from the Little Wind River

Year	Mean June Discharge (cfs)	Deviation from Normal[b] June Discharge (cfs)	Maximum Discharge (cfs)
2000	1,089	-1,231	2,720
2001	233.2	-2,087	2,090
2001	740.6	-1,579	1,930
2003	861.7	-1,458	2,490
2004	1,591	-729	4,120
2005	2,272	-48	4,520
2006	642.4	-1,678	1,710
2007	738.9	-1,581	1,910
2008	2,175	-145	3,730
2009	3,012	692	4,190
2010	5,829	3,509	13,300
2011	2,861	541	7,210
2012	594	-1,726	1,610

[a] U.S. Geological Survey gaging station statistics.
[b] Based on a mean June discharge of 2,320 cfs since 1941.

2.3.2.2 Surface Water Quality

Samples were collected at four locations on the Little Wind River (Figure 2), which flows generally from the southwest to the northeast adjacent to the site. Contaminated groundwater likely discharges to the Little Wind River, but there is no evidence that it impacts surface water quality in the river. Molybdenum and uranium concentrations measured in samples collected from river locations adjacent to and downstream of the groundwater plume (locations 0811, 0812, and 0796) are comparable to concentrations from river samples collected upstream of the groundwater plume (location 0794), as shown in Figure 20 and Figure 21, respectively.

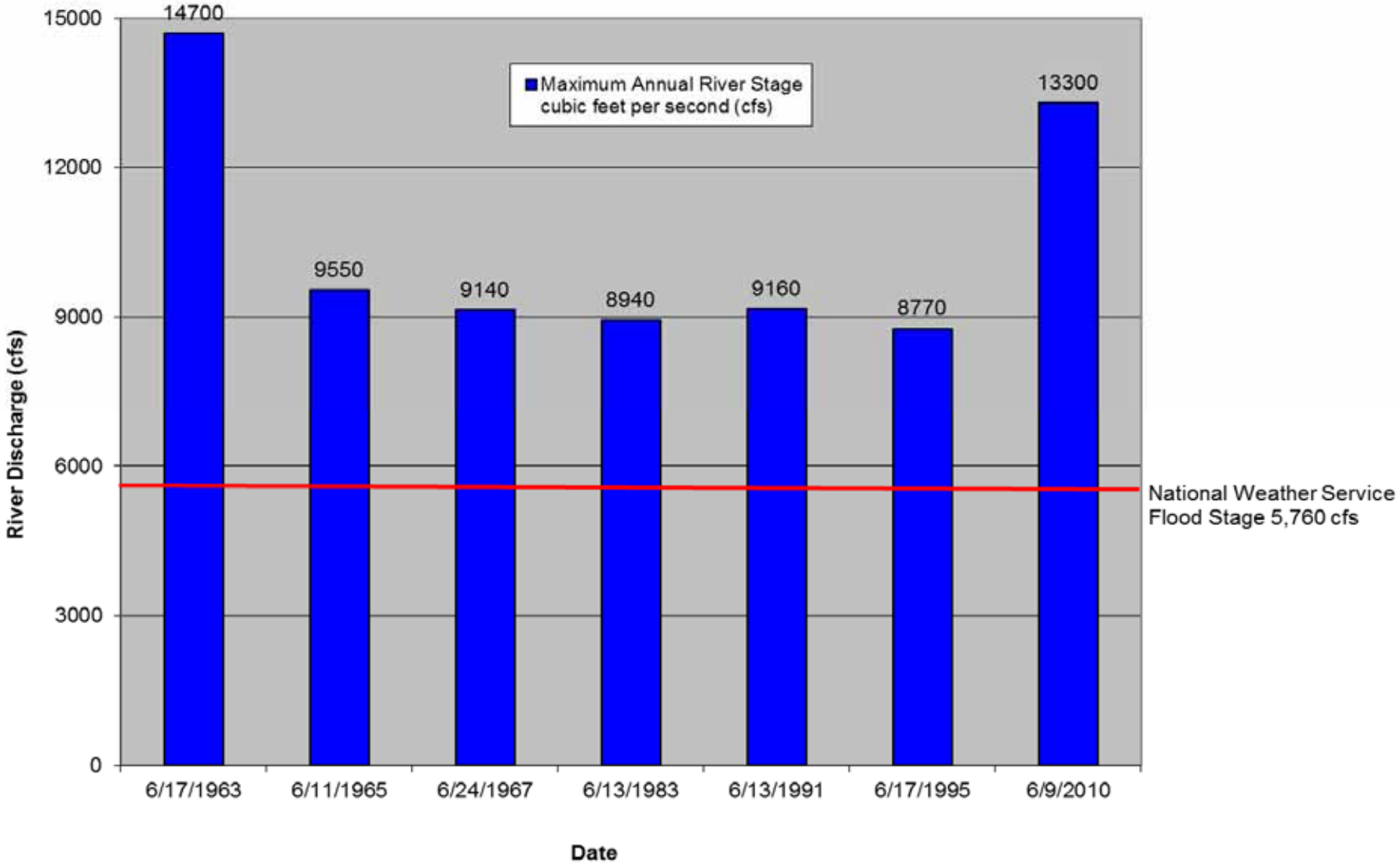
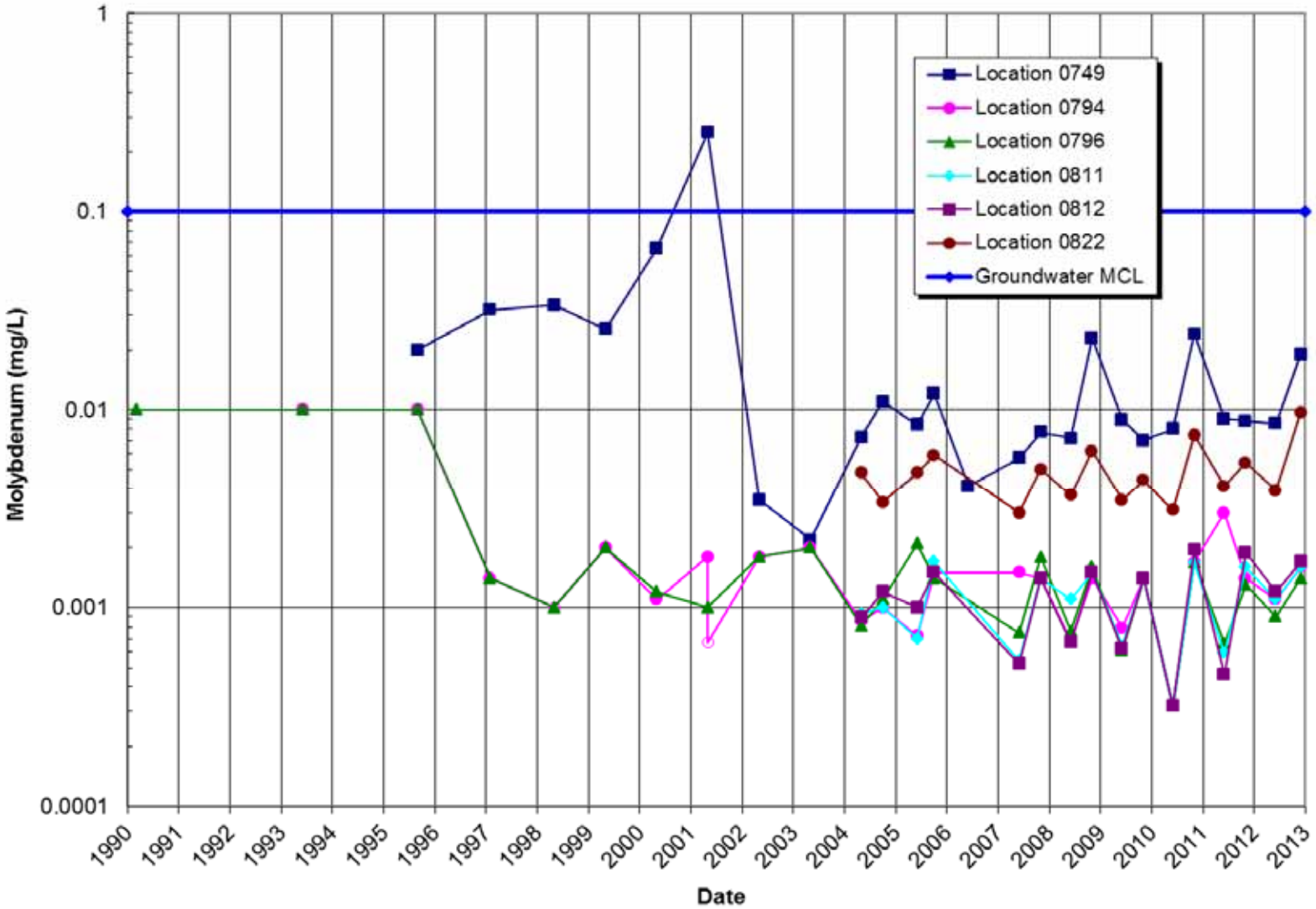
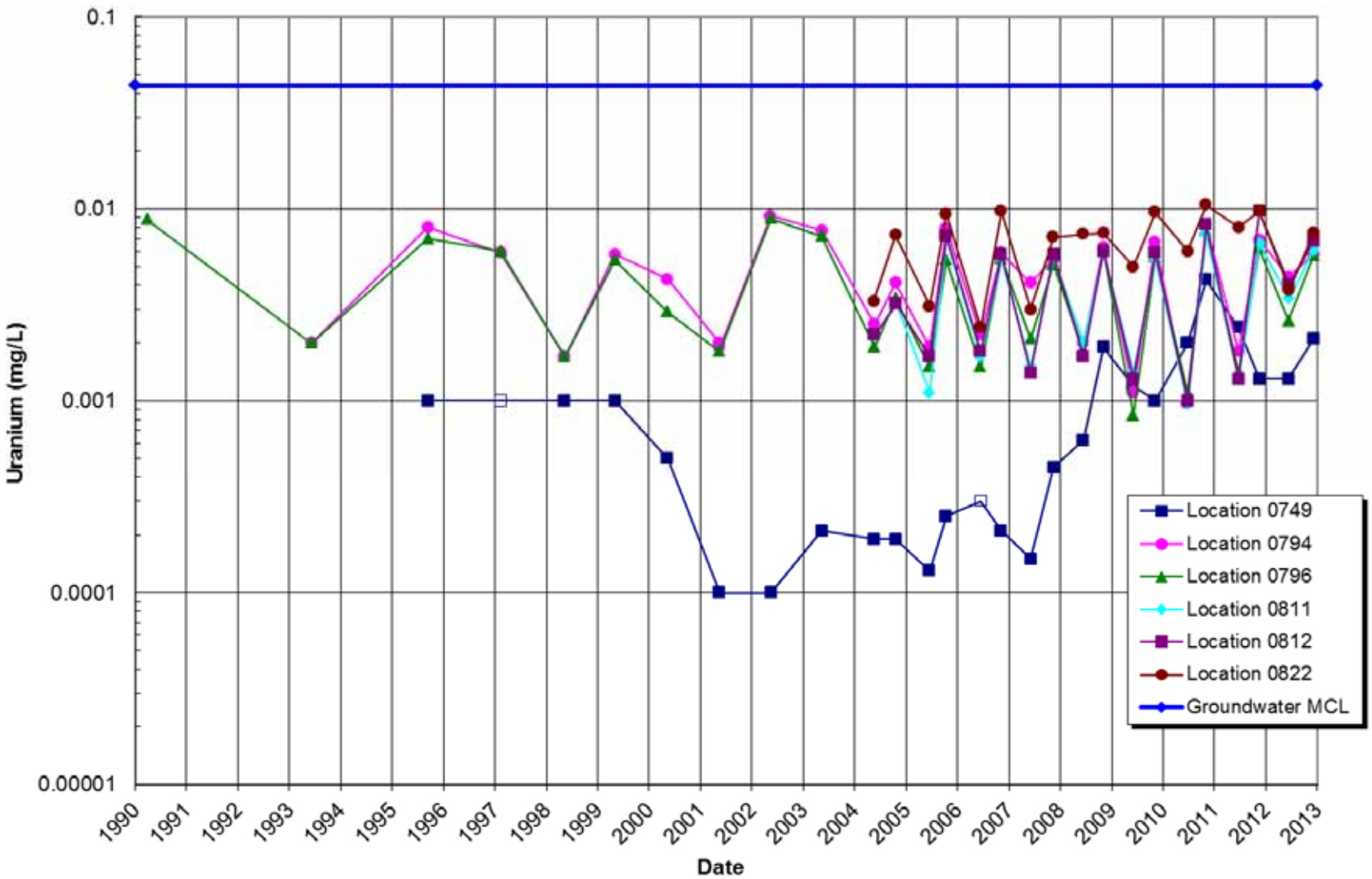


Figure 19. Historical Maximum Stages of the Little Wind River



Notes: 1. A hollow symbol denotes an analytical result below the detection limit. 2. Y-axis is a logarithmic scale.

Figure 20. Molybdenum Concentrations in Creek and River Locations



Notes: 1. A hollow symbol denotes an analytical result below the detection limit. 2. Y-axis is a logarithmic scale.

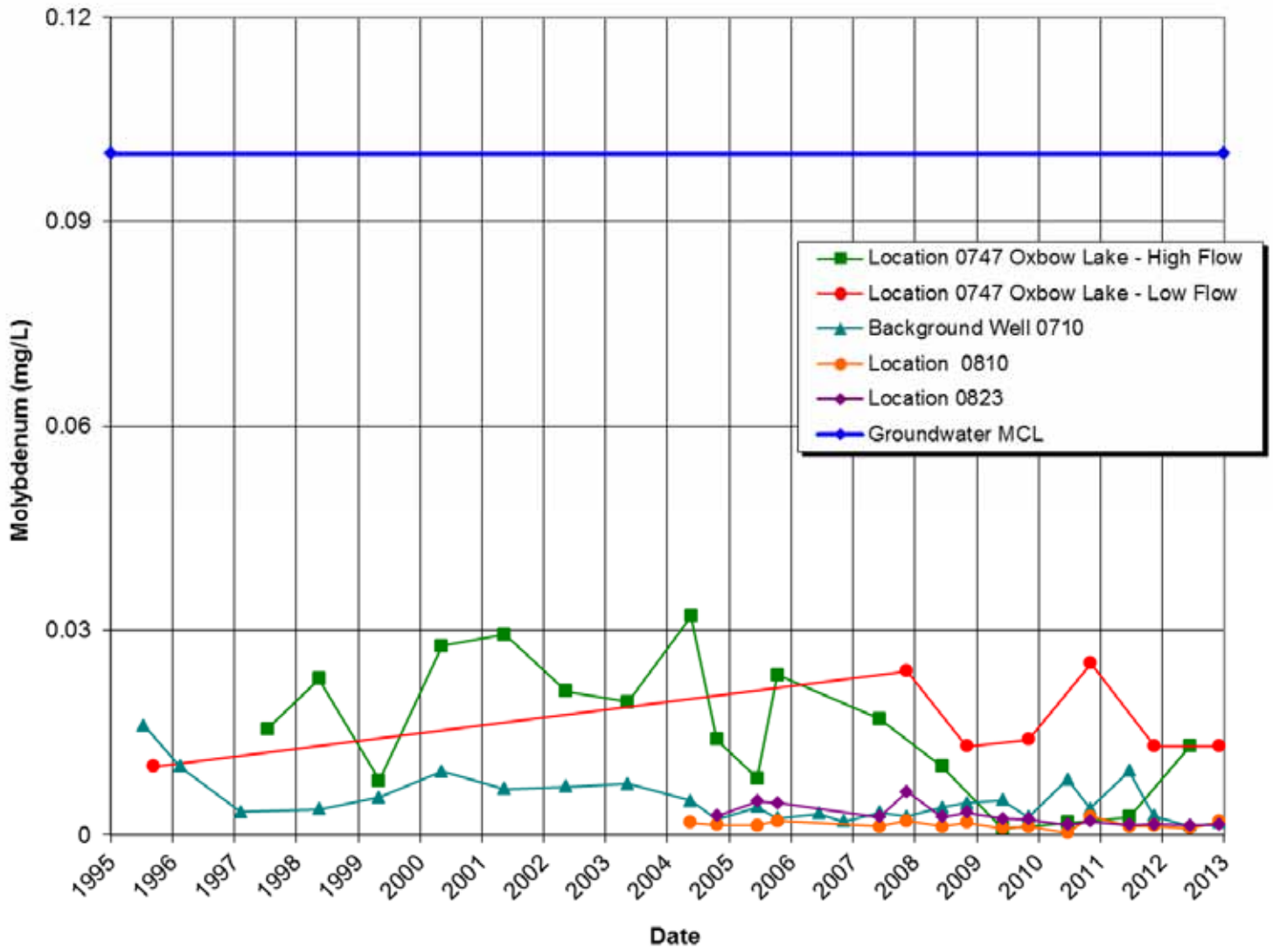
Figure 21. Uranium Concentrations in Creek and River Locations

Two ponds (locations 0810 and 0823) formed from groundwater discharge into former gravel pits were sampled as part of the long-term monitoring network. These ponds are primarily used for fishing and swimming. Samples collected from these ponds had concentrations of molybdenum and uranium that were below their respective groundwater MCLs and comparable to background, which indicates no discernible impacts from the site. Molybdenum and uranium concentrations over time in these pond locations are shown in Figure 22 and Figure 23, respectively.

The sample collected at the ditch that carries discharge water from the Chemtrade sulfuric acid refinery (location 0749) had elevated concentrations of sulfate in 2012 (2,000 mg/L in June). Discharge from the ditch is regulated through a National Pollutant Discharge Elimination System permit issued to Chemtrade and administered by EPA. Sulfate concentrations have been in the 1,800 to 3,000 mg/L range since 2004. The elevated sulfate concentrations in the Chemtrade ditch water have affected sulfate concentrations farther downstream in the west side irrigation ditch (e.g., 960 mg/L at location 0822 in June). Water samples from the west side irrigation ditch also have been analyzed for radium-226 and radium-228 in response to elevated concentrations of these contaminants in the sediments within the ditch. Radium concentrations in water samples collected from the ditch were low (<0.5 pCi/L) and either less than the detections limit (one sample) or near the detection limit (three samples), which indicates minimal impacts to water quality in the ditch from the sediments. Historically, radium concentrations have been below or near the detection limit, indicating no impact to water quality in the ditch. Uranium concentrations in samples collected from the west side irrigation ditch have been within the range of background uranium concentrations and correlate with uranium concentrations in the river (Figure 21), which indicates minimal site impacts to the water quality in the ditch.

Concentrations of molybdenum and uranium in the oxbow lake (location 0747) have varied over time. This variability is attributed to surface inflow (this does not occur every year; it depends on the river stage) to the lake from the Little Wind River during a high river stage, which causes a dilution of uranium concentrations. Hydraulic and water quality data indicate that the oxbow lake is fed by the discharge of contaminated groundwater; therefore, elevated concentrations are expected.

Figure 22 and Figure 23 split oxbow-lake sampling data into high-flow and low-flow events; the high-flow events reflect the potential for river inflow diluting analyte concentrations in the oxbow lake, and the low-flow events reflect a low potential for river inflow diluting analyte concentrations in the oxbow lake. In the June 2012 sampling event, the Little Wind River was not flowing into the oxbow lake and run-off was lower than normal; therefore, the uranium concentration in the sample collected from the oxbow lake was elevated. Uranium concentrations also were elevated in samples collected from the oxbow lake in December, as expected, because the river was not flowing into the lake at that time. Surface water quality data by parameter for locations sampled during 2012 are provided in Appendix D.



Note: A hollow symbol denotes an analytical result below the detection limit.

Figure 22. Molybdenum Concentrations in Ponds

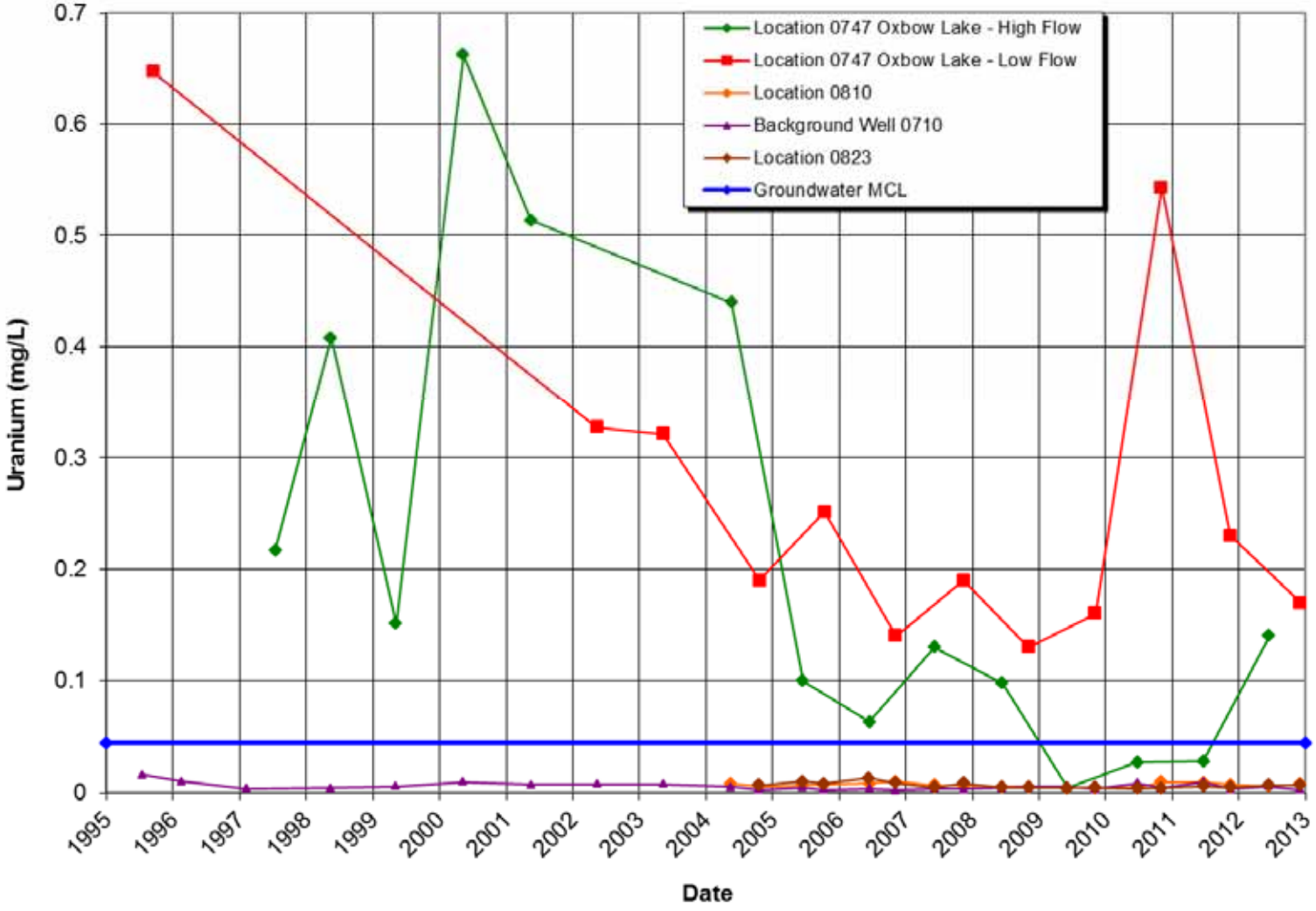


Figure 23. Uranium Concentrations in Ponds

2.3.3 AWSS Monitoring

The AWSS was installed in 1998 by the Indian Health Service. DOE provided $800,000 in funding, which included 25 percent of the cost of a new 1-million-gallon storage tank (Figure 24). As a component of ICs for the Riverton site, the AWSS is designed to supply drinking water to residents within the IC boundary in lieu of drinking groundwater that could potentially be impacted by the contaminated surficial aquifer. The AWSS is an addition to a pre-existing water supply system and consists of 8.5 miles of transmission pipeline running from the 1-million-gallon tank (Figure 25).

Figure 24. AWSS 1-Million-Gallon Tank

Elevated concentrations of radionuclides were identified in the AWSS in 2002 (Babits 2003), and these results were confirmed by DOE in 2004 (DOE 2005). In response to these findings, DOE funded an independent analysis of the AWSS, and the analysis recommended implementation of a flushing program to determine if flushing would reduce the radionuclide concentrations to acceptable levels (ASCG 2005). Based on the recommendation of the independent analysis, DOE implemented a 2-year flushing study to determine if flushing would reduce radionuclide concentrations and control radionuclide buildup in the AWSS (DOE 2006). Results of the study indicated that a unidirectional flushing program be implemented on a 6-month frequency (DOE 2008).

Flushing of the AWSS in 2012 consisted of two semiannual events. One event was conducted by the Great Plains Utility Organization and the Tribal Engineer's Office in April, and a second flushing event was conducted jointly among the Great Plains Utility Organization, the Tribal Engineer's Office, and DOE in October. Sampling was conducted in in accordance with the *Alternate Water Supply System Flushing Plan, Riverton, Wyoming* (DOE 2012b). Seven hydrant locations on the AWSS were flushed and sampled, and four tap locations were sampled. Two samples were collected at each of five hydrant locations – one sample 5 minutes into the flush and one sample at the end of the flush, as specified in the plan. Only end-of-flush samples were collected at hydrant locations 0820 and 0834 because of the short flushing time. A new hydrant (0843) was noted during the flushing event and added to the flushing network for subsequent events; a cursory flush was conducted on this hydrant during the October event, and samples were collected from this hydrant by the Wind River Environmental Quality Commission.

Monitoring of flow during each hydrant flush was required to ensure the calculated water volume of each section of pipe was removed. Flow meters were installed at each hydrant during flushing to measure the volume of water flushed from the pipe. Volume measurements also were used to calculate the velocity of the water moving through the pipe. Velocity data were used to determine if water movement within the pipeline was sufficient to remove sediment and debris, and to scour biofilm from the inside of the pipe. According to the independent analysis (ASCG 2005), flushing velocities of 2 to 3 feet per second (ft/s) are needed to remove sediment and loosely attached particles, while flushing velocities of greater than 5 ft/s are required to scour and remove buildup of biofilm and material adhering to the wall of the pipe. Water volume removed and velocities from each section are shown in Table 4.

Table 4. October 2012 Hydrant Flushing Summary

ID	Calculated Flushing Volume[a]	Section Volume Flushed (gallons)	Section Flush Time (minutes)	Section Average Flow Rate (gallons/minute)	Section Average Velocity (ft/s)
0829	20,252	20,400	41.5	492	3.14
0830	39,554	39,600	70	566	3.61
0818	20,738	20,800	42	495	5.62
0819	43,209	43,200	77	561	3.58
0821	13,973	14,000	33.6	417	4.73
0820	3,139	3,200	6.5	492	5.59
0834	918	1,000	2.13	469	5.33
		Total 142,200	**Total 273**	**Average 499**	**Average 4.51**

[a] Flushing volume calculated as 1.25 x pipe volume.

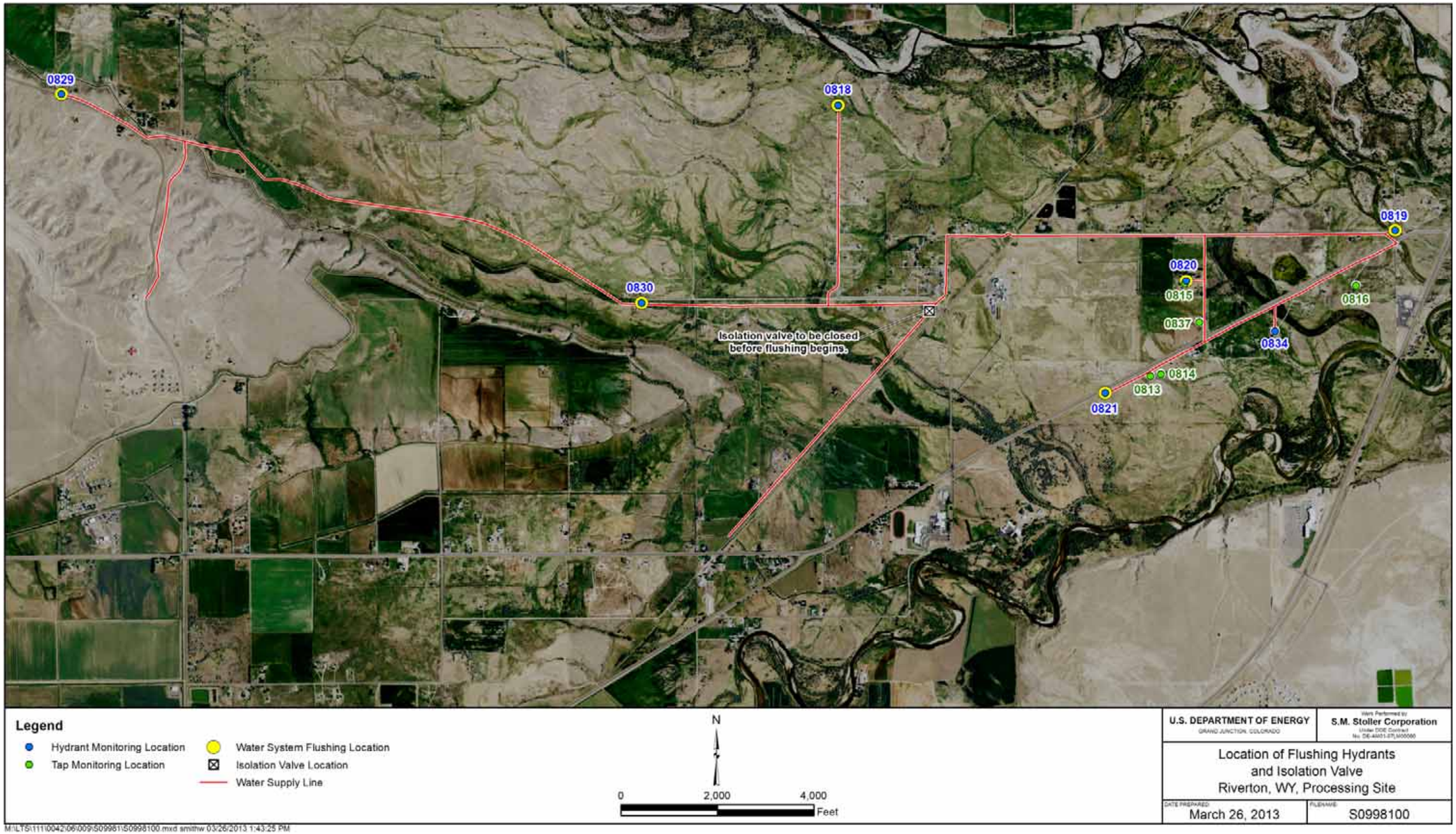


Figure 25. Location of Flushing Hydrants and Tap Monitoring Locations

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Monitoring of hydrant and tap locations was conducted to determine the effectiveness of the flushing program in reducing radionuclide concentrations and maintaining them at acceptable levels. The flushing program is successful when the combined radium-226 and radium-228 concentrations are below the federal drinking water MCL of 5 pCi/L, and the uranium concentrations are below the federal drinking water MCL of 0.03 mg/L. DOE was not involved in the April flushing event, so those results are not presented in this report; however, no issues were identified by the Great Plains Utility Organization or the Tribal Engineer's Office. Effectiveness of the flushing program was demonstrated in October with a maximum-observed combined radium-226 and radium-228 concentration of 2.52 pCi/L, and a maximum observed uranium concentration of 0.00011 mg/L. Results from samples collected from AWSS hydrant and tap locations in October are summarized in Table 5 and provided in Appendix E.

Table 5. Monitoring Results from the October 2012 AWSS Flushing Event

ID	Sample	Radium-226 +Radium-228 (pCi/L)	Radium-226 +Radium-228 MCL	Uranium (mg/L)	Uranium MCL (mg/L)
Hydrant Locations					
0818	5-minute	1.543	5 pCi/L	0.00011	0.03 mg/L
	End of flush	1.364		0.00009	
0819	5-minute	1.943		0.00009	
	End of flush	2.273		0.00009	
0820	5-minute	2.52		0.00011	
0821	5-minute	1.657		0.00008	
	End of flush	2.24		0.0001	
0829	5-minute	1.458		0.00009	
	End of flush	0.939		0.0001	
0830	5-minute	1.44		0.00008	
	End of flush	1.4		0.00008	
0834	5-minute	1.992		0.00008	
Tap Locations					
0813	After completion of flushing	0.776	5 pCi/L	0.0001	0.03 mg/L
0815	After completion of flushing	0.92		0.00009	
0816	After completion of flushing	0.771		0.00008	
0837	After completion of flushing	2.124		0.00009	

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3.0 Enhanced Characterization

3.1 Purpose and Scope

Results of the verification monitoring indicated that natural flushing was generally progressing as expected until June 2010, when significant increases in contaminant concentrations were measured in several wells. The June 2010 sampling event was conducted immediately after record flooding of the Little Wind River. During the flood, overbank flow was observed within a large area downgradient of the former mill site. Significant increases in contaminant concentrations occurred in monitoring wells where the flooding occurred. The spikes in contaminant concentrations were attributed to flood waters mobilizing residual contamination in the unsaturated zone (DOE 2011a).

The observations made in 2010 revealed that the existing site conceptual model and groundwater computer modeling did not account for the spikes in contaminant concentrations observed in the surficial aquifer groundwater. Consequently, the site conceptual model needed to be updated and a new groundwater flow and transport model developed to better simulate natural flushing processes. The enhanced characterization work in 2012 was designed to provide additional data to assist in accomplishing these goals.

The purpose of the enhanced characterization was to obtain additional data to further characterize the surficial aquifer (DOE 2012c). Specific objectives of the investigation were to:

- Provide enhanced definition of contaminant plumes, including the location of the centroid of each plume and the extent of groundwater contamination for each contaminant of concern
- Provide a detailed distribution of contaminants for input into the updated groundwater model.
- Provide data that will guide placement of new monitoring wells outside of the contaminant plumes to monitor lateral plume behavior.
- Provide a detailed and updated baseline of groundwater contamination for tracking plume configuration, movement, and size over time. This will be used to assess the progress of natural flushing if this study is repeated in the future.
- Provide information on soil characteristics, including the leachability of uranium.
- Estimate the mass of uranium remaining in the unsaturated zone of the surficial aquifer, which can be used to develop appropriate contaminant source terms in the transport modeling.

3.2 Fieldwork Summary

Fieldwork was conducted August 20–29, 2012. It was performed in accordance with the *Work Plan for the Enhanced Characterization of the Surficial Aquifer, Riverton, Wyoming, Processing Site* (Work Plan) (DOE 2012c). Fieldwork consisted of installing 103 boreholes along 9 transects (Figure 26) with a Geoprobe, which is equipment that is used to direct-push steel rods into the shallow soils and surficial aquifer material (Figure 27). Water samples were collected at each location, and soil samples were collected at 34 locations. To optimize the mapping of contaminant plumes (which may have a slightly different configuration for each contaminant),

transects were oriented northeast and southwest approximately perpendicular to the known southeast direction of groundwater flow and to the axis of the known contaminant plumes. Distance between transects was reduced and sampling density increased in the portion of the aquifer near the expected centroid of the contaminant plumes downgradient of the former mill site. The increase in sampling density was designed to enhance definition of the centroid of the plumes and to provide more soil data from the unsaturated zone above the contaminant plumes in areas where the 2010 flood had the largest effect on groundwater contaminant concentrations. Details of the fieldwork are found in the *Enhanced Characterization of the Surficial Aquifer, Riverton, Wyoming, Processing Site, Data Summary Report* (Data Summary Report) (DOE 2013a).

3.3 Soil Characterization

3.3.1 Summary of Methods

Soil samples were collected at 34 locations (Figure 26). Geoprobe rods were driven to 5 feet bgs at each location, and two soil samples (0–2.5 feet and 2.5–5 feet) were collected at most locations for a total of 65 samples. Soils typically consisted of a dry, pale-yellowish silt in the top 2 to 3 feet with some near-surface roots, and sand and gravels below the silt. Figure 28 (top) displays a typical soil-core retrieved from the Geoprobe with a dry silt at the top that grades to a moist clayey-silt and then to sand and gravel. Figure 28 (bottom) shows another soil sample in the process of being homogenized prior to placement into a sample bag. Full sample recovery was not obtained in any of the 2.5–5-foot samples, with a maximum recovery of 84 percent in that interval. No recovery was obtained, and therefore samples were not collected, from the 2.5–5-foot interval at three locations (T01-07, T04-12, and T08-02). Soil characteristics were described and recorded for each location and are documented in the Data Summary Report.

Soil samples were analyzed by the Grand Junction Environmental Laboratory using three different tests: batch tests, kinetic tests, and column tests. Methods used in the laboratory tests are detailed in the *Laboratory Analysis of Shallow Sediment Near a Former Uranium Mill: Riverton, Wyoming, Site* (DOE 2013b) (Appendix F). Samples were dried in air and weighed several times during drying to determine the rate of water loss. Dried samples were sieved through a 2 millimeter (mm) sieve. The proportion of less-than-2 mm fraction varied from 20.95 percent to 99.98 percent of the sample. Artificial site water (ASW) containing a composition similar to the Little Wind River was prepared in the laboratory and used as the primary leaching solution for the tests.

Kinetic tests were conducted to determine the agitation time required for uranium to reach a steady-state concentration. These tests were conducted on eight samples (from four locations) also using ASW. Ten aliquots from each sample were tested with end-over-end agitation times in the test ASW of 5 minutes, 15 minutes, 30 minutes, 1 hour, 2 hours, 4 hours, 8 hours, 16 hours, 48 hours, and 96 hours. After agitation of each aliquot, uranium analysis of the test solution was conducted using Environmental Laboratory analytical method AP (U-2), “Uranium Determination by Chemchek” (DOE 2011b). Soil concentrations in micrograms per gram were calculated from the uranium concentration measured in the test solution.

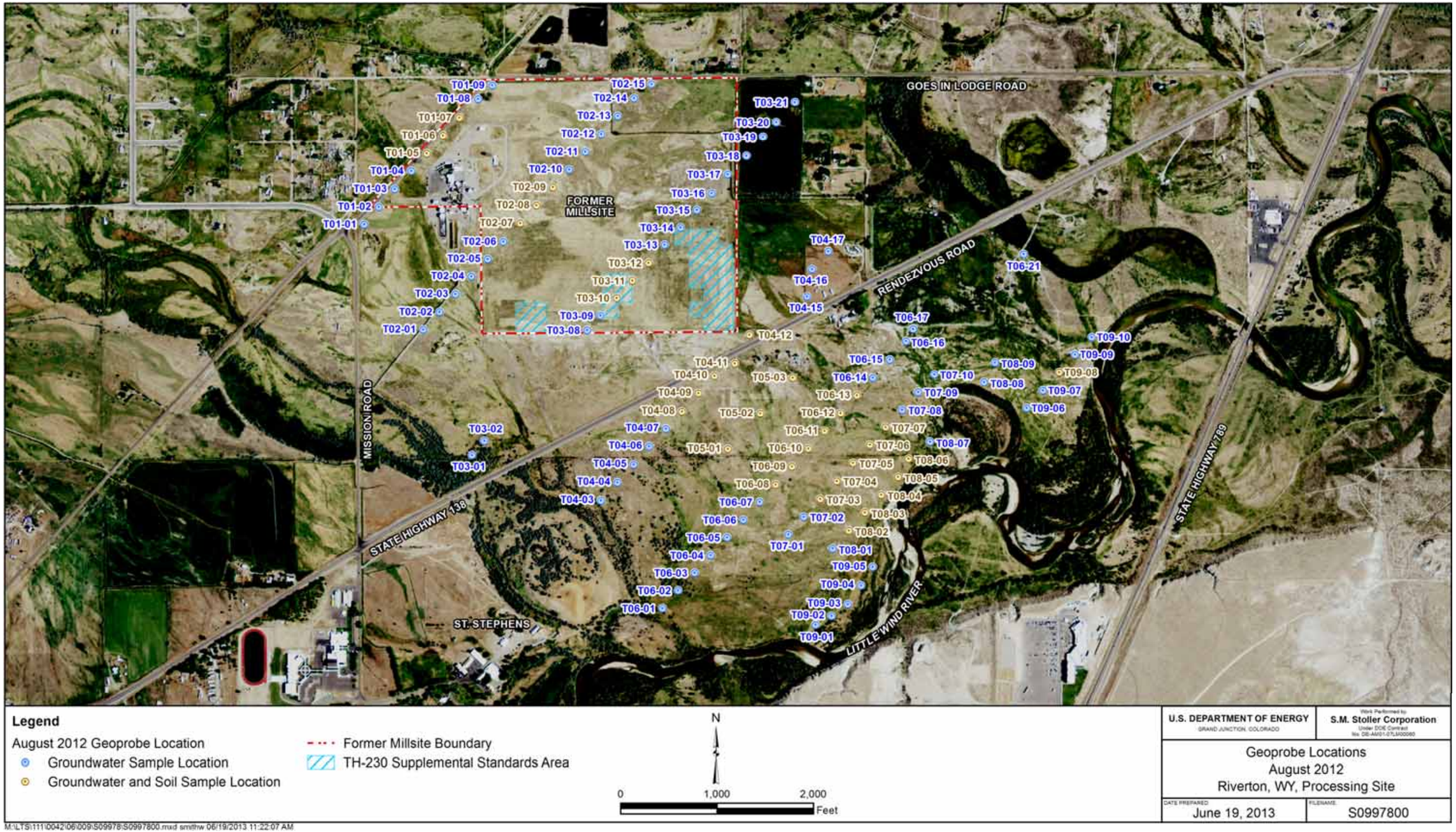

Figure 26. Enhanced Characterization Geoprobe Locations

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Batch tests were conducted on all 65 soil samples by leaching with a high water-to-rock ratio (200 milliliters [mL] of water to 2 grams [g] of soil) using ASW to simulate flood events that would remove uranium. Samples were agitated end-over-end for two separate 24-hour intervals with fresh test solution for each agitation event. Test solutions from the two events were combined and analyzed for uranium using analytical method AP (U-2).

Figure 27. Installing a Borehole with a Geoprobe in August 2012

Column tests were conducted on 16 samples (8 locations) to estimate the total uranium source materials remaining in the unsaturated zone. These tests were conducted by pumping ASW through a soil column at a rate of approximately 0.09 milliliters per minute (mL/min) for most columns. Effluent from the column was collected approximately every pore volume and analyzed for uranium using analytical method AP (U-2). Column tests were continued until uranium concentrations in the effluent stabilized, which resulted in completion of tests at various stages ranging from 48 to 93 pore volumes. After the conclusion of the column tests, an extractant solution of sodium bicarbonate ($NaHCO_3$) and sodium carbonate (Na_2CO_3) developed by Kohler et al. (2004) was used to extract the easily removable, or labile, uranium from the column sediments.

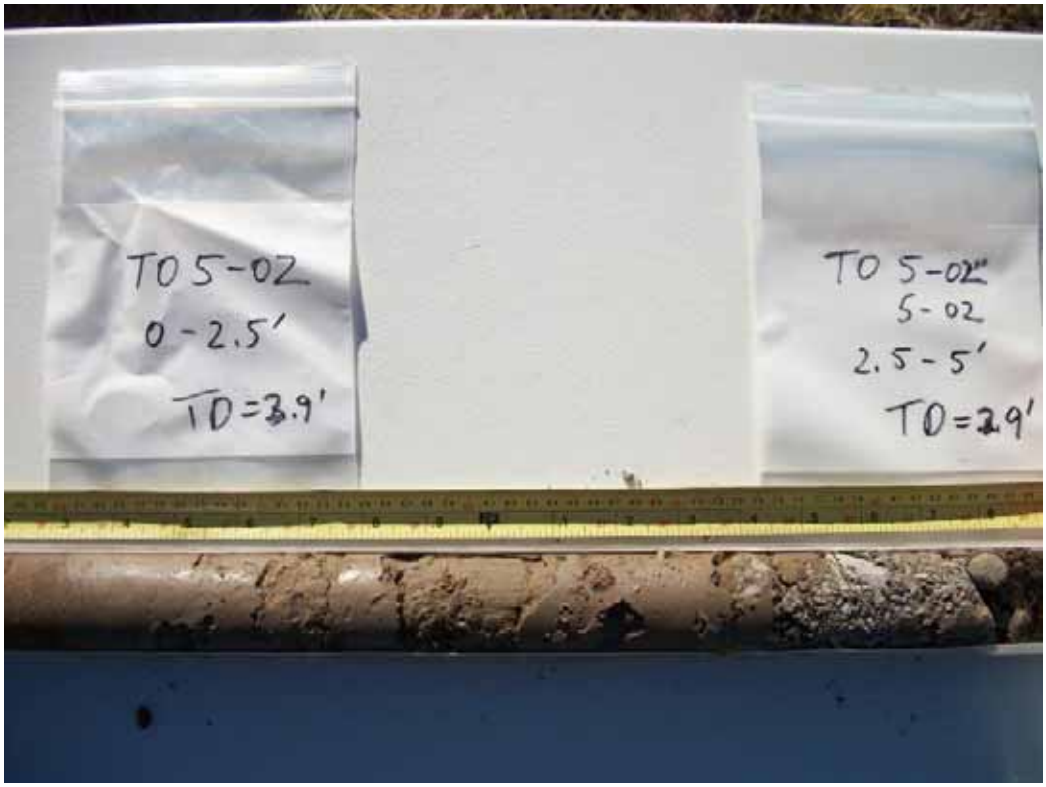
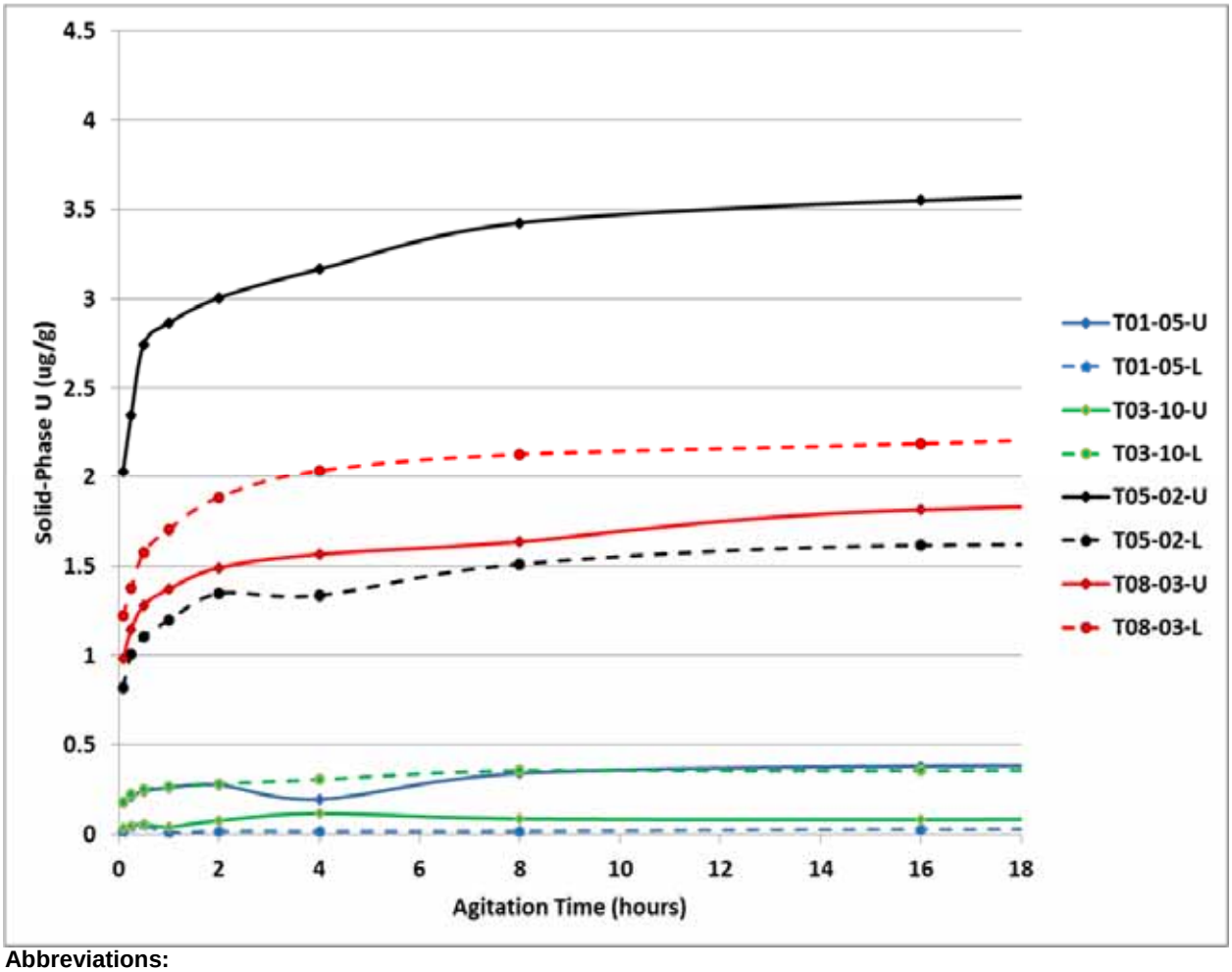


Figure 28. Soil Samples Collected Using the Geoprobe

3.3.2 Results and Interpretation

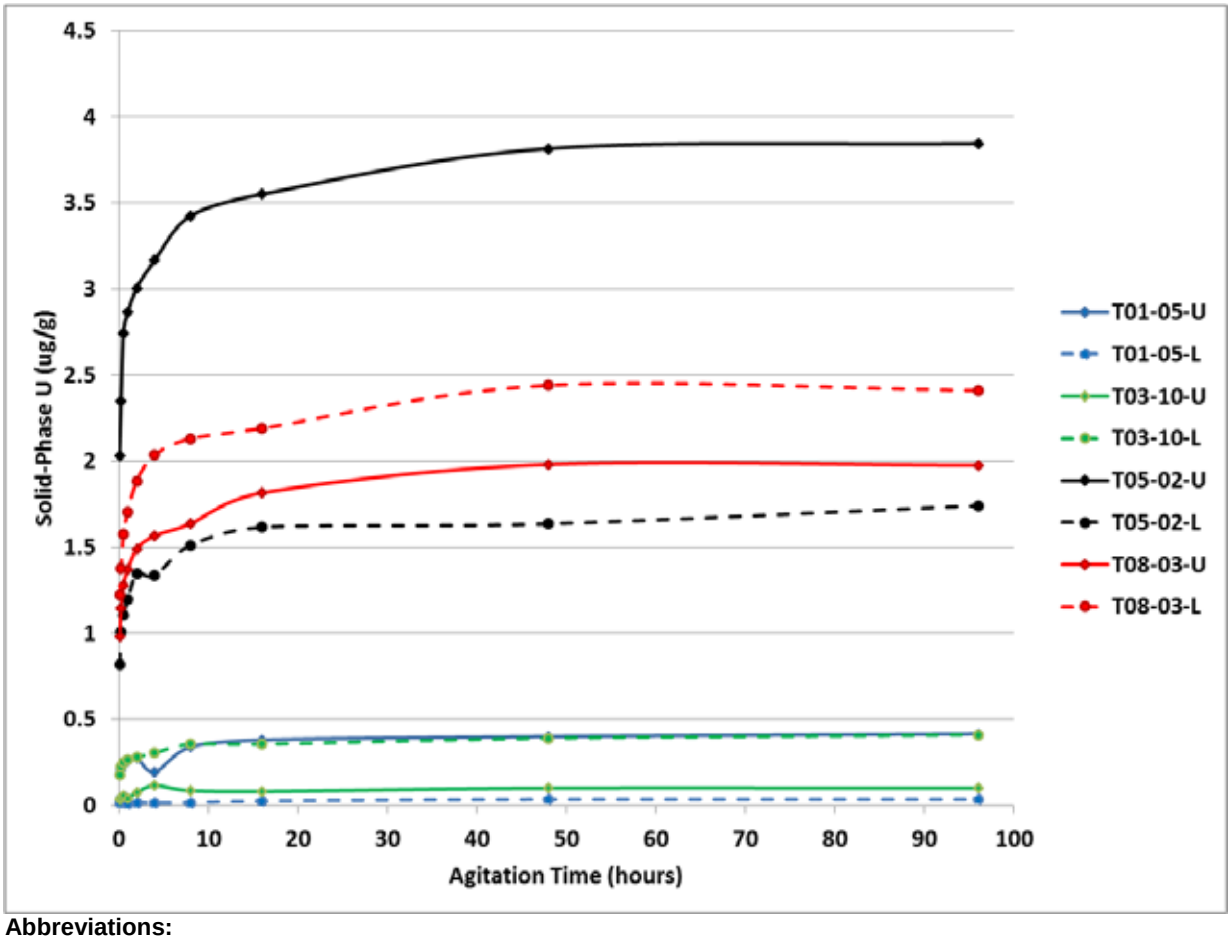
3.3.2.1 Batch Tests

Kinetic test results are shown in Figure 29 and Figure 30. As shown in these figures, the majority of the uranium is removed within the first 8 hours.



Abbreviations:
µg/g = micrograms per gram
U = uranium

Figure 29. Results of Soil Kinetic Tests (0 to 18 Hours)



Abbreviations:
µg/g = micrograms per gram
U = uranium

Figure 30. Results of Soil Kinetic Tests (Full Duration)

Results of the batch tests indicated a positive correlation between the abundance of fine-grained sediment (<2 mm) and the solid-phase uranium concentrations of the soil samples. The labile fraction is generally considered to be the mass that is weakly sorbed to mineral surfaces and is the fraction that most readily participates in interactions with groundwater. The concentrations of labile uranium measured in the soil samples were comparable to abundances of uranium in sedimentary rocks that make up the crust of the earth.

The concentrations of uranium in the <2 mm sediments that were removed by a 48-hour agitation with ASW were variable, ranging from 0.04 to 4.8 micrograms per gram (µg/g) with a median of 0.96 µg/g (Figure 31). In nearly all paired samples, the upper sample had a higher concentration of removable uranium than the lower sample. Median values for the upper and lower units were 2.10 and 0.34 µg/g, respectively (Figure 31). The distribution of soil concentrations at the Riverton site from batch tests are displayed in Figure 32. The concentrations were generally higher in the offsite (transects 04 through 08) samples than in the onsite (transects 01 through 03) samples.

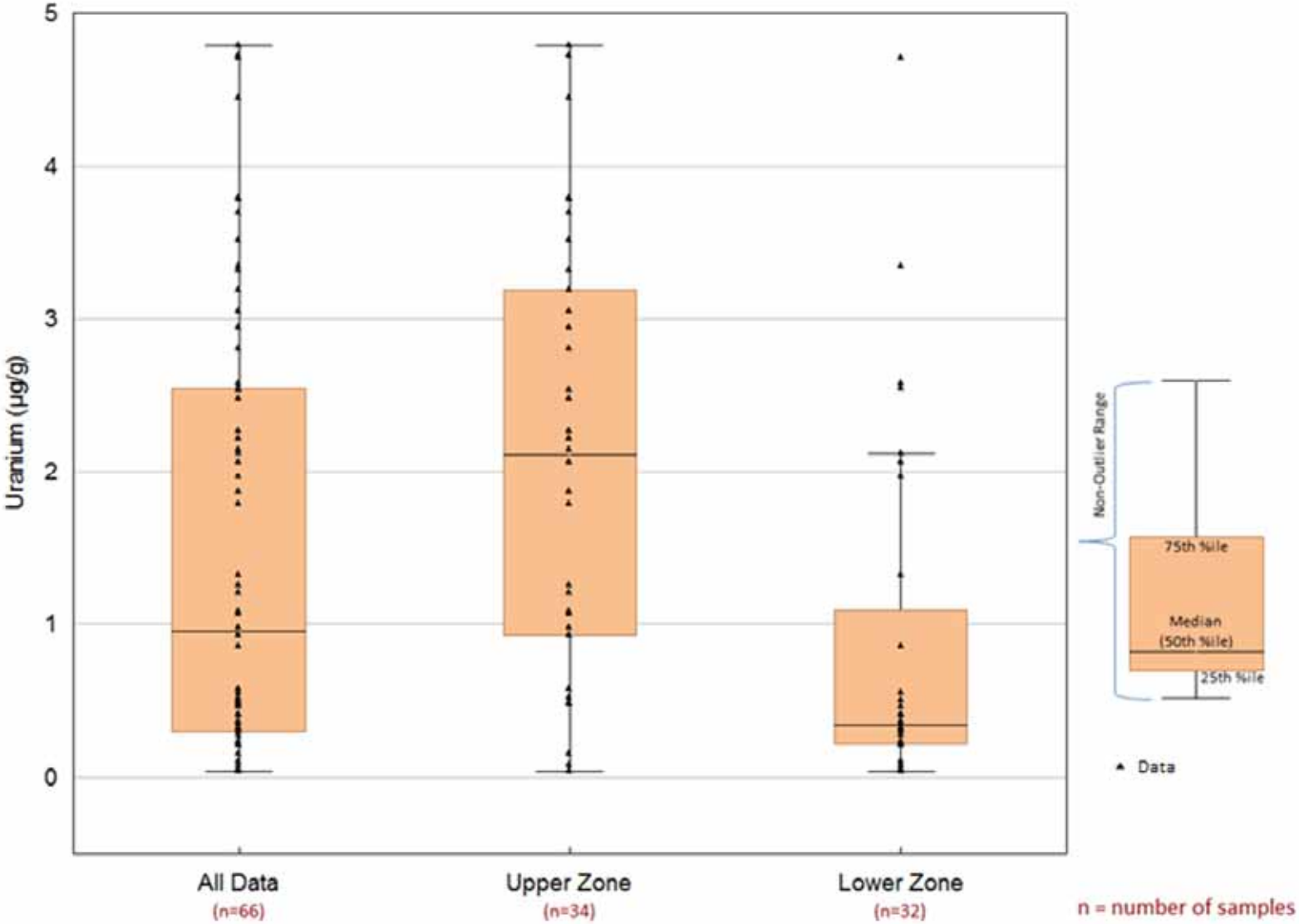


Figure 31. Distribution of Solid-Phase Uranium in Upper Zone (0–2.5 ft) vs. Lower Zone (2.5–5 ft) Samples

3.3.2.2 Distribution Coefficients

The transfer of uranium between sediments and groundwater is often modeled by assuming that the ratio of uranium concentration in the sediment to the concentration in the groundwater is constant. The ratio is called the distribution coefficient (K_d) and it is often used by groundwater modelers, in part because it is easily incorporated into numerical groundwater codes. It is well known that the actual partitioning of uranium concentrations between groundwater and sediment varies with chemical parameters, in particular the concentration of dissolved carbonate and pH. Thus, groundwater aquifers are likely to display variable K_d values over space and time. It is also known that the transfer of mass between aquifer solids and groundwater is controlled to some extent by rate-limited processes, such as slow diffusion from immobile pore fluid. These rate-limited processes are not typically considered in flow and transport models. Despite these uncertainties, it is instructive to examine the range of uranium K_d values that might be observed in the subsurface sediments.

The batch test data collected during the enhanced characterization study were not suitable for determining K_d values on their own because the concentration of labile uranium in the solid phase was not measured. However, assuming that the labile fractions measured on splits of the same samples used in column tests are representative of the labile fractions in the splits used for batch testing, K_d values can be calculated as shown in Table 6. K_d values calculated in this way ranged from 4.30 to 158.75 milliliters per gram (mL/g).

Table 6. Uranium K_d Values Calculated from Batch Test Data and Column Labile Fractions

Sample Number	24 Hour Batch Test Data		Column Labile	After Batch	
	U (µg/L)	U (µg/g)	U (µg/g)	U (µg/g)	K_d (mL/g)
T01-05U	4.8	0.48	0.657	0.177	36.88
T02-07L	0.8	0.08	0.136	0.056	70.00
T03-10U	0.8	0.08	0.207	0.127	158.75
T03-10L	4.7	0.47	0.715	0.245	52.13
T04-10U	25.4	2.54	3.761	1.221	48.07
T04-10L	5.1	0.51	0.729	0.219	42.94
T05-02L	13.2	1.32	1.921	0.601	45.53
T06-10U	17.9	1.79	2.033	0.243	13.58
T06-10L	2.2	0.22	0.329	0.109	49.55
T07-04U	12.1	1.21	1.262	0.052	4.30
T07-04L	2.4	0.24	0.312	0.072	30.00
T08-03U	20.7	2.07	2.265	0.195	9.42
T08-03L	25.8	2.58	2.716	0.136	5.27

µg/L = micrograms per liter

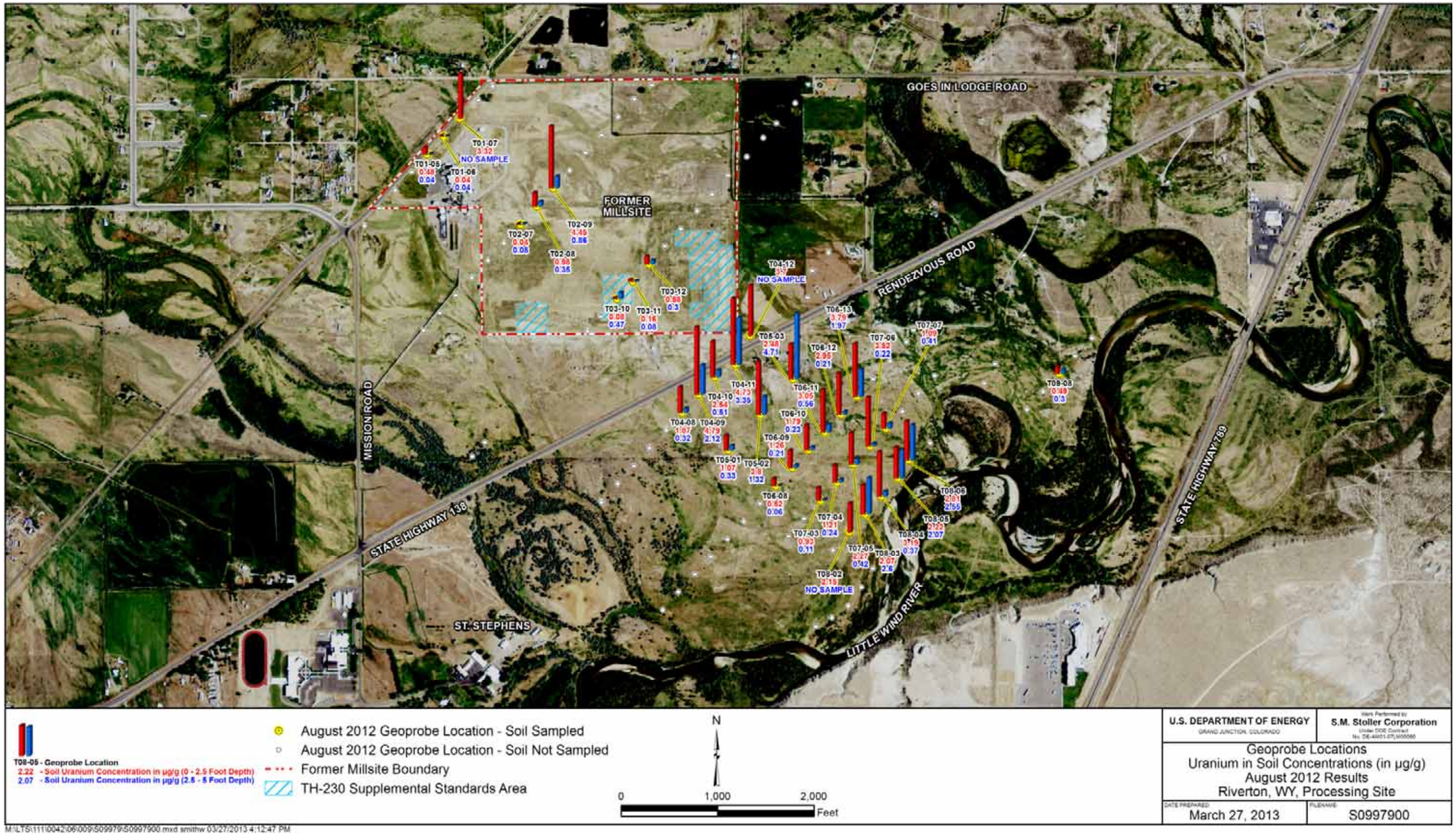


Figure 32. Uranium Distribution from Soil Batch Tests

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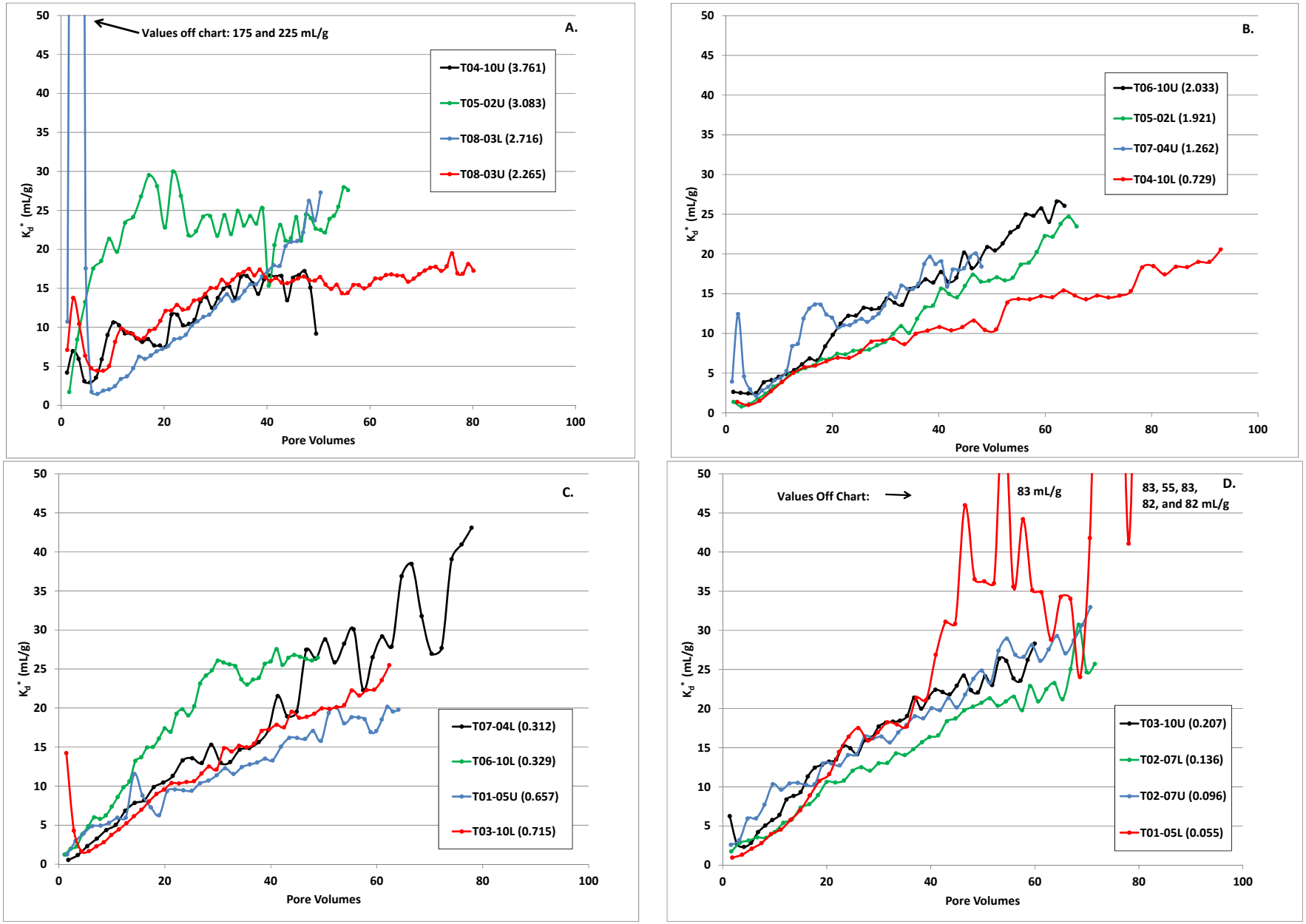
The column data can also be used to estimate K_d values. The apparent uranium distribution coefficient (K_d^*) was determined for each effluent sample collected from the column tests. Because the distribution of uranium in the columns is unknown, K_d^* is the ratio of the concentration of uranium in the effluent sample to the *average* concentration of uranium in the column sediment. To evaluate *true* K_d, the concentration of uranium in the column sediment at the top of the column would need to be used with the effluent dissolved concentration. Residence time also influences the estimated K_d values since the fluid is not in contact with the sediment long enough to come to equilibrium, as is indicated by batch test results measured at variable time intervals.

With the exceptions of fluctuations in the early stages (first 10 pore volumes), the uranium effluent concentrations in the column effluents demonstrated a monotonic decrease throughout the tests. K_d^* values are plotted on Figure 33, arranged in order of their total labile uranium concentrations in µg/g.

With only a few exceptions, the K_d^* values are low early on and gradually trend to higher values as more pore volumes are passed. The fluctuations observed in some columns (e.g., T05-02) during the early stages may be due to fluctuation in the dissolved inorganic and organic carbon concentrations. Some of the fluctuation observed in the later stages (e.g., in T01-05L) are due to imprecision in the uranium concentration analysis at the low dissolved concentrations present in some of the effluent samples.

The early values of K_d^* are typically less than 5 mL/g, with some as low as about 1 mL/g. Most of the K_d^* values observed after more than 40 pore volumes exceed 10 mL/g. Numerical models using K_d values of more than 10 mL/g should result in minimal plume movement (an example is provided in Freeze and Cherry 1979). Because uranium appears to be released and transported by groundwater at the Riverton site, it is likely that the K_d^* values measured in the column tests do not accurately reflect the nature of the uranium partitioning between sediment and groundwater.

Reasons for the wide distribution of K_d^* in the column tests are uncertain. Some of the variation is due to mobilization of organic carbon during the early stages of column operation and the possible influence of pH and dissolved inorganic carbon species. Conceptually, the use of the K_d approach in predictive modeling mandates that the system be maintained at chemical equilibrium. The condition of equilibrium may not be met during the column testing. The residence time of about 1 hour is insufficient for the system to reach an equilibrium state. The condition of equilibrium can be tested using a flow-interruption technique. After a flow-interruption, there should be no change in effluent concentrations if the system is at equilibrium; however, rate-limited reactions are indicated by higher concentrations following column restarts. There are many physical and chemical processes that could cause rate-limited mass transfer. A time lag can occur simply due to slow desorption from mineral surfaces. Slow diffusion from intraparticle pores can also limit uranium transfer. As sediment ages, uranium can migrate to internal portions of mineral crystal structures or to intracrystalline microfractures and pores where it becomes more recalcitrant to re-release. The Riverton sediments have had decades for these types of transformations to occur. Regardless of the exact processes involved, it is reasonable to speculate that the release of contaminants from these sediments is rate controlled.



Note: The labile uranium concentrations in µg/g are given in the parentheses following the sample name—e.g., T03-10U (0.207).

Figure 33. Plot of Apparent Distribution Coefficients (K_d^*)

3.3.2.3 Secondary Source in the Unsaturated Zone

Two scenarios were examined to determine if uranium concentrations measured in soil samples from the 2012 enhanced characterization were high enough to cause the spikes observed in samples collected from monitoring wells in 2010 after flooding of the Little Wind River. These two scenarios were: Scenario 1 – groundwater rising up into the unsaturated zone and mobilizing uranium during flood events, and Scenario 2 – flood waters infiltrating down from the surface and mobilizing uranium. It should be noted that soils collected during the 2012 investigation did not represent the entire unsaturated zone because the samples were only collected from 0 to 5 feet (the unsaturated zone extends deeper most of the year), and recovery ranged from 0 to 85 percent in the 2.5 to 5-foot interval.

Scenario 1 assumes that rising groundwater levels driven by an increasing river stage provide the sole mechanism for leaching of contaminants in the alluvial aquifer's unsaturated zone, and that the resulting leachate was the primary cause of the spikes in concentration observed at near-river wells 0707 and 0789 shortly after a river flood event in June 2010. The viability of this scenario can be assessed by examining flow and advective transport processes associated with this alternative and the results from preliminary modeling of those processes. The observed increase in uranium concentration at well 0707 in response to the 2010 flooding was from about 0.8 mg/L to 2.7 mg/L, and the corresponding increase at well 0789 was from about 1.5 mg/L to 2.64 mg/L (Figure 11).

It is assumed that the rising groundwater elevation was caused by pressure wave transmission inland (toward the Riverton site) from the river, and none of the increase in groundwater level was caused by infiltration of overbank flood water on the floodplain surface. This mechanism had the potential to be most effective at mobilizing contamination if the water table rose as high as the ground surface, so that a maximum amount of sediment was contacted by groundwater. Contaminant mobilization was also likely enhanced by longer contact time between the rising groundwater and the shallow contaminated sediment. The extent of groundwater rise and the contact time depended on aquifer hydraulic conductivity, the specific yield of the aquifer, and the magnitude and duration of the increased river stage during a flood.

Though leaching of uranium from the shallow floodplain sediments apparently increased concentrations in the uppermost part of the saturated zone, additional processes would have been required to transport the newly mobilized uranium to produce the concentrations observed in 2010. Accordingly, it would have been necessary that significant downward flow occurred in the saturated zone as groundwater levels gradually declined upon passage of the flood wave in the river. Downward advective transport of the uranium would have been particularly important for detecting uranium at a concentration of 2.7 mg/L in well 0707, as the top of the 5-foot screened interval for this well is located 9.8 feet bgs, which is about 4.5 feet below the lowest water table levels observed at this well.

Several numerical simulations were performed with a cross-sectional model to assess the likelihood that contaminants mobilized from shallow floodplain sediments in June 2010 migrated as deep as the top of the screened interval in well 0707. The model was designed to account for groundwater flow and advective transport along a 2,100-foot section of the alluvial aquifer aligned with axis of the uranium plume as mapped over the past nine years. The model was constructed using 16 layers, a single row representing a flow path extending northwestward from the river to Rendezvous Road, and 105 columns with a uniform length of 20 feet. Temporally

variable, prescribed-head boundary conditions were invoked on the downgradient end of the model to represent changing river levels associated with flows observed at the U.S. Geological Survey gaging station on the river near Riverton during the 2010 flood event. A general head boundary condition was applied to the upgradient boundary to account for groundwater flow in the vicinity of Rendezvous Road, which during non-flood conditions comprises inflows from the northwest. Advective transport was simulated using particle tracking.

Several simulations were conducted with the cross-sectional model, each with a different combination of aquifer hydraulic conductivity and specific yield, with the intent of accounting for a variety of possible groundwater flow conditions. In all cases, the particle tracking indicated that the downward flow associated with a falling water table after the flood event was insufficient for driving leached contamination as deep as the top-of-screen elevation at well 0707. Thus the cross-sectional modeling suggested that, though some mobilization of unsaturated-zone contamination was likely, it was not large enough to produce the spike in uranium concentration observed at well 0707 in 2010.

Scenario 2 invokes the possibility that, during the period of overbank flows that occurred in June 2010, infiltration of surface water on the floodplain augmented downward flow in the aquifer to the extent that uranium was carried as deep as the top-of-screen elevation at well 0707.

Review of principles of contaminant transport associated with this scenario is helpful for assessing its viability. For example, for scenario 2 to be true, it is a requirement that the leaching of shallow floodplain sediments in June 2010 produced aqueous-phase concentrations of uranium that exceeded the 2.7 mg/L peak concentration observed at well 0707, and that such large concentrations were maintained over a several-day period. Otherwise, it would have been impossible for the shallow sediments to be the source of the uranium levels observed at the well. None of the laboratory leach-tests on soil samples produced a dissolved uranium concentration as large as 2.7 mg/L, which raises questions of the viability of this scenario.

The validity of scenario 2 was also analyzed with multiple simulations of two-dimensional groundwater flow and transport in a large area surrounding the former Riverton site over a time period that spanned the 2010 flood event. The numerical model used for this purpose was assigned a single layer intended to represent the entire saturated thickness of the alluvial aquifer, the Little Wind River comprised the southeast boundary of the simulation domain, and the flow portion of the model was automatically calibrated with the pilot-point methods incorporated in PEST software. In simulations aimed at accounting for uranium mass mobilization from shallow floodplain sediments, prescribed hydraulic heads along the model's downgradient border were varied over time to reflect changing river stages associated with river flows in 2010. Thus simulated groundwater levels rose and fell accordingly, due to pressure wave transmission. Mass loading of contamination to the alluvial aquifer was modeled in all cases by simulating recharge with a specified uranium concentration to floodplain areas in the vicinity of and upgradient of wells 0707 and 0789. The recharge represented infiltration of overbank surface water, and was only invoked over the time span when the river apparently overflowed its banks.

Several different combinations of recharge rate and prescribed concentrations were applied in the multiple simulations. One of the findings from the various model runs was that it was necessary to limit the assigned recharge rate so that computed groundwater levels remained within a range that did not exceed the estimated surface-water elevation during the overbank flood stage. In addition, it was necessary to use prescribed uranium concentration in the recharge on the order of

10 mg/L or greater to achieve simulated concentrations in the well 0707 and well 0789 areas that were of the same general magnitude as those measured after passage of the 2010 flood wave. These results suggest it is unlikely that this scenario was the cause of the uranium concentrations spikes observed in wells 0707 and 0789.

3.4 Groundwater Characterization

3.4.1 Summary of Method

Groundwater samples were collected at all 103 borehole locations (Figure 26) according to the procedures specified in the Work Plan. Samples were collected after the Geoprobe rods were driven to 12 feet bgs or until rod refusal (see the Data Summary Report [DOE 2013a] for the locations where Geoprobe rods could not be driven to 12 feet), and 8 liters of water were purged from the rod. The 12-foot depth the Geoprobe rods were driven to approximated the average midpoint of the screened interval for the monitoring wells in the surficial aquifer that comprise the long-term monitoring network. Field measurements of pH, specific conductance, temperature, oxidation-reduction potential, total alkalinity, turbidity, and dissolved oxygen were made at each borehole, and samples were analyzed for the U.S. Nuclear Regulatory Commission (NRC)–approved contaminants of concern (manganese, molybdenum, sulfate, and uranium) (DOE 1998a), major cations (calcium, magnesium, potassium, and sodium), and an additional major anion (chloride). Samples were analyzed by ALS Laboratory Group in Fort Collins, Colorado, using standard EPA methods. Groundwater data were validated according to the "Standard Practice for Validation of Laboratory Data" in the *Environmental Procedures Catalog* (LMS/POL/S04325).

3.4.2 Interpretation and Results

3.4.2.1 Comparability of Data

An assessment of the comparability of the groundwater results obtained during the enhanced characterization to the results from the long-term monitoring network was conducted because sampling methodology was by necessity different for the temporary boreholes sampled during the enhanced characterization (DOE 2013a). The assessment was conducted by comparing (1) molybdenum, sulfate, and uranium results from monitoring well samples collected during the June 2012 routine sampling event with (2) results from the temporary boreholes collected in August 2012, as shown in Table 7. The temporary borehole closest to a monitoring well and within the same contour was used for the comparison.

As shown in Table 7, the mean percent difference (PD) ranged from −31.9 to 3.2 PD. This range of PD indicates good comparability of methods given the following considerations: (1) EPA guidance for acceptable precision for laboratory duplicates is 20 relative percent difference (LMS/POL/S04325), and one third of the comparisons met the laboratory criteria; (2) temporal variability between the June and August events; and (3) distance between the monitoring well and temporary borehole (up to 680 feet). Correlation between enhanced characterization results and long-term monitoring results was exceptional where uranium concentrations were high in monitoring wells 0707 and 0789.

Table 7. Comparison of June 2012 Results with August 2012 Results[a]

Monitoring Well Location	U June	U August	PD[b]	Mo June	Mo August	PD	SO_4 June	SO_4 August	PD
0707	1	1.1	−9.5	0.9	0.53	51.7	3100	2300	29.6
0716	0.3	0.22	30.8	0.13	0.11	16.7	460	440	4.4
0718	0.16	0.42	−89.7	0.068	0.21	−102.2	2600	2600	0.0
0720	0.0063	0.0028	76.9	0.0013	0.0058	−126.8	190	320	−51.0
0722R	0.51	0.18	95.7	0.13	0.15	−14.3	840	130	146.4
0729	0.0031	0.0096	−102.4	0.002	0.0046	−78.8	74	120	−47.4
0784	0.0028	0.0011	87.2	0.0099	0.018	−58.1	2300	2200	4.4
0788	0.053	0.029	58.5	0.022	0.02	9.5	1700	1200	34.5
0789	2.1	2.1	0.0	0.56	0.56	0.0	5900	3900	40.8
0824	0.0085	0.027	−104.2	0.0047	0.0057	−19.2	85	320	−116.0
0826	0.049	0.07	−35.3	0.02	0.027	−29.8	1800	2000	−10.5
		Mean	**0.7**		**Mean**	**−31.9**		**Mean**	**3.2**

[a] Units are in milligrams per liter (mg/L).
[b] Percent difference was calculated as $[(a - b) \div (a + b)/2)] \times 100$, where a = June concentration value from a monitoring well and b = August concentration value from a temporary borehole near the monitoring well.

3.4.2.2 General Water Chemistry

Major anion and cation data are displayed as a Piper diagram in Figure 34. Locations were divided into four areas of the aquifer—upgradient of the uranium plume, within the uranium plume, northeast of the uranium plume, and southwest of the uranium plume—and plotted on the diagram. General water chemistry varies spatially within the aquifer as shown in Figure 34:

- Upgradient locations (green) have no dominant cation type and are distributed between bicarbonate and sulfate types of water for anions.
- Locations within the uranium plume (red) tend to have no dominant cation type and are a sulfate type of water for anions.
- Locations northeast of the uranium plume (blue) are calcium type of water for cations and bicarbonate type of water for anions.
- Locations southwest of the uranium plume (black) are distributed between no dominant type and a sodium/potassium type of water for cations and are generally a sulfate type of water for anions.
- The difference between water types on each side of the uranium plume is likely due to the influence of sulfate in the discharge water from the sulfuric acid plant on the southwest side of the uranium plume that is recharging the surficial aquifer.

Groundwater summary statistics for all results are provided in Table 8, and a complete set of groundwater data collected during this characterization is provided in Appendix G.

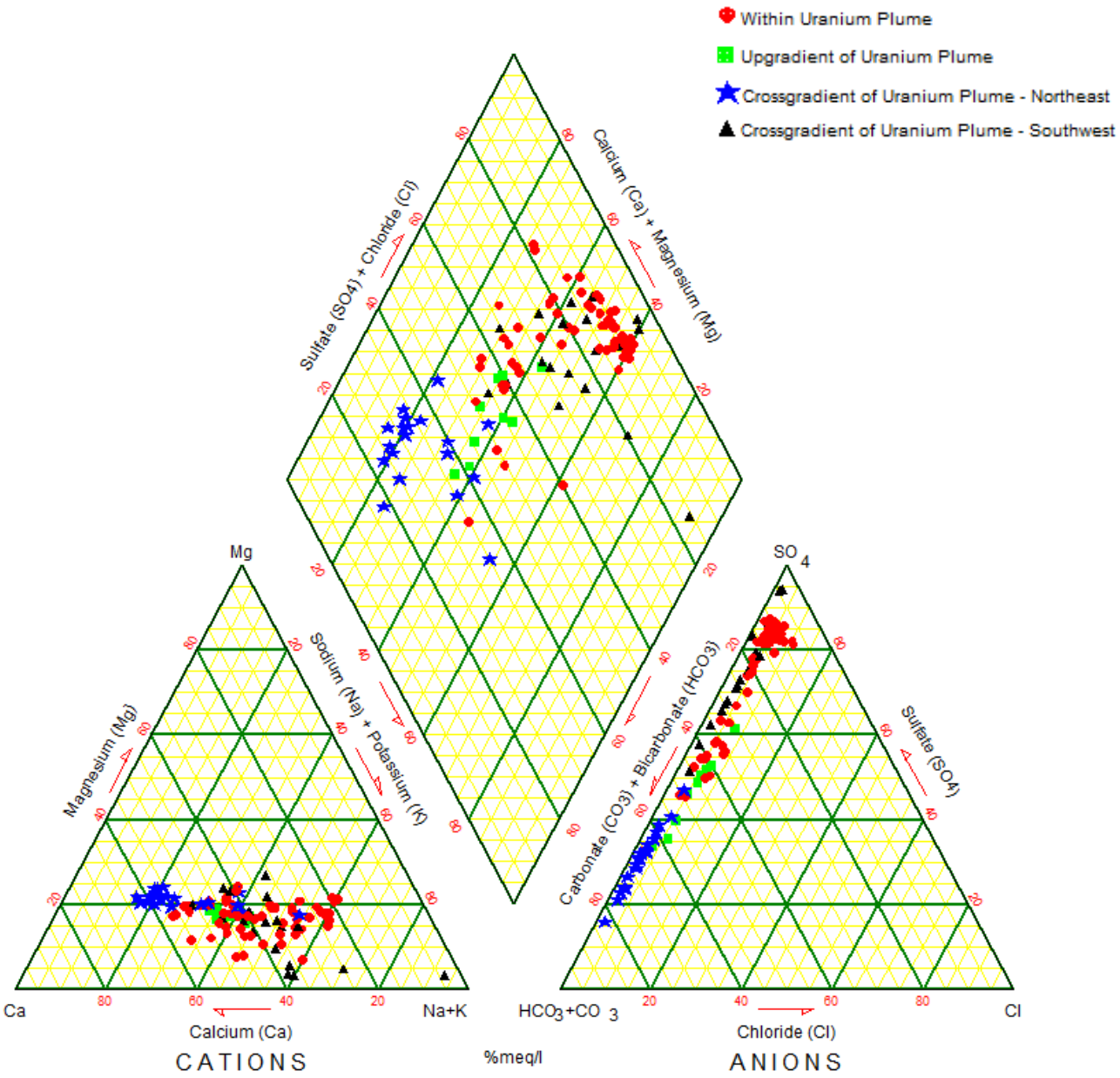


Figure 34. Piper Diagram of Major Anion and Cation Data

Table 8. Summary of Groundwater Results

Analyte	Benchmark[a,b]	Range[b]	Mean[b]	Area of Plume[c] (Acres)
Manganese	2.26	0.012–7.2	0.998	71
Molybdenum	0.1	0.004–1.1	0.165	182
Sulfate	400	39–5,900	1,431	465
Uranium	0.044	0.00081–2.1	0.277	323
Calcium	271	48–760	247	NA
Magnesium	25.5	7.7–390	76.4	NA
Potassium	4.1	2.6–28	8.8	NA
Sodium	167	16–2,000	429	NA
Chloride	73	3.4–570	72	NA

[a] Benchmark is either 40 CFR 192 MCL (molybdenum and uranium) or maximum background concentration (manganese, sulfate, calcium, magnesium, potassium, sodium, and chloride) (DOE 2012a).
[b] Units are in milligrams per liter (mg/L).
[c] Area of plume determined from outer contour of plume using Geographic Information System (GIS) software.

3.4.2.3 Manganese

Manganese concentrations in the surficial aquifer are relatively low, with the maximum concentration approximately four times the background concentration; therefore, manganese does not form a well-defined plume, as shown in Figure 37. Graduated symbol plots and box-and-whisker plots for all groundwater COPCs are shown in Figure 35 and Figure 36, respectively. Those figures show that higher manganese concentrations are skewed to the southwest and occur further upgradient than the molybdenum and uranium plumes.

3.4.2.4 Molybdenum

The molybdenum plume is narrow, well defined, and within the bounds of the long-term monitoring well network as shown in Figure 38. Figure 35 and Figure 36 confirm that elevated molybdenum concentrations occur within the narrow plume area and are evenly distributed along the axis of the plume. The current long-term monitoring network is adequate for monitoring molybdenum.

3.4.2.5 Sulfate

The sulfate plume (Figure 35, Figure 36, and Figure 39) is larger than the other plumes and is skewed upgradient and to the west, which is likely due to infiltration of water from the unlined ditch that carries discharge from the sulfuric acid plant. The outer boundary of the sulfate plume is defined as 400 mg/L, which is the maximum concentration observed in background wells (DOE 2012a). The ditch contained water with sulfate concentrations up to 2,000 milligrams per liter (mg/L) in 2012. Future work may be required to determine the contribution of sulfate to the surficial aquifer from the sulfuric acid plant versus the former mill; however, the high levels of sulfate in the centroid of the plume are likely mill-related.

3.4.2.6 Uranium

In general, the extent of the uranium plume (Figure 40) is similar to previous interpretations using monitoring data from the long-term monitoring program. The centroid of the plume is near the Little Wind River and located near monitoring well 0789, and the maximum uranium concentration found during this investigation is equal to the uranium concentration in monitoring well 0789.

However, two anomalous areas were revealed during the enhanced characterization. First, the uranium concentration measured in the sample collected at location T06-01 (furthest southwest location) was above the MCL in 40 CFR 192, which is anomalous for this area of the aquifer based on plume configurations and groundwater flow direction. This uranium concentration also stands out in Figure 35 and Figure 36. Although anomalous, this uranium concentration is considered valid as it correlates with the elevated sulfate concentration (1,200 mg/L) in T06-01 and elevated uranium concentration (above background) in samples collected from adjacent locations in the same transect (0.024 mg/L in T06-02, 0.02 mg/L in T06-03, and 0.029 mg/L in T06-04). Additional investigation work may be warranted in this area to determine the extent of uranium contamination.

Second, the uranium concentration at T03-08 (1.1 mg/L) on the south edge of the former tailings pile is higher than would be expected 23 years after the completion of surface remediation at the former mill site. This elevated concentration indicates more complex aquifer properties, geochemical controls, and/or additional sources/sinks, which enable recalcitrant uranium concentrations to remain upgradient of the main centroid of the plume. It is unknown if this is an isolated point, because other planned locations to the southwest on Transect 3 were not sampled due to owner access and cultural resource survey issues. Additional investigation work may be warranted in this area to determine the extent and possible causes of this high uranium concentration.

3.5 Site Conceptual Model

Limited empirical data indicates that surprises occur in 20 to 30 percent of conceptual models, with a surprise being defined as new data that renders the site conceptual model invalid (Bredehoeft 2005). The flood of the Little Wind River in 2010 due to rapid snowmelt and rainfall caused increases in dissolved contaminant concentrations in groundwater wells and provided a "surprise" related to the original site conceptual model as detailed in the Site Observational Work Plan (SOWP) (DOE 1998b). An update to the original model is needed. However, there continues to be aspects of the site that are not well understood, so the site conceptual model will continue to evolve as new data are collected (see Section 5.0, "Summary and Recommendations") and as alternative site conceptual models are tested. This section presents the major aspects of the original site conceptual model presented in the SOWP and presents aspects of an evolving site conceptual model that have been discovered since 2010. A generalized schematic of the original conceptual model and a revised (and evolving) site conceptual model are presented in Figure 41.

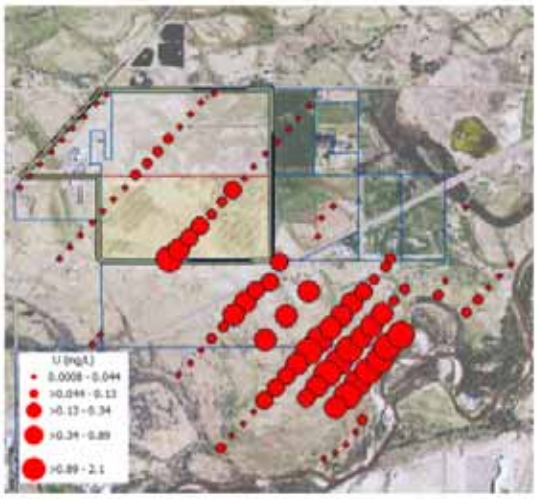


Figure a. Uranium (mg/L)

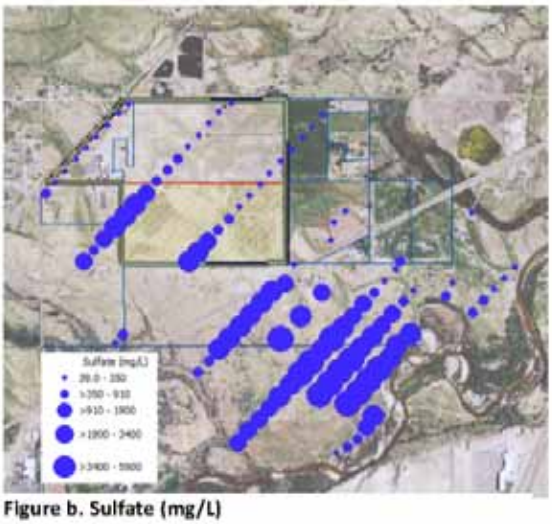


Figure b. Sulfate (mg/L)

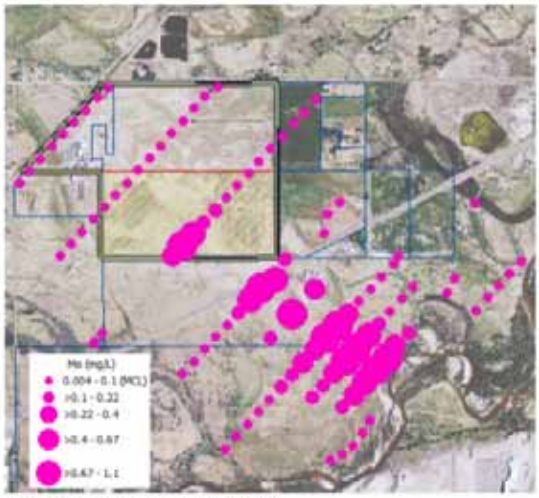


Figure c. Molybdenum (mg/L)

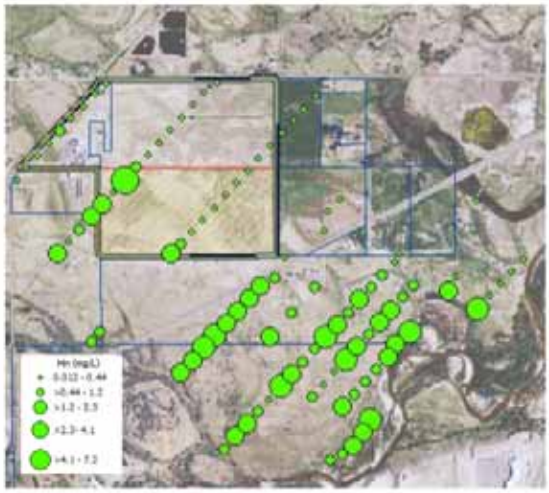


Figure d. Manganese (mg/L)

Symbol (magnitude) categories were established using the Natural Breaks (Jenks) classification method in ArcMap (version 10.0). Exceptions are the first category classes for U and Mo, which were modified slightly to correspond to MCLs (0.044 and 0.1 mg/L). (Initial Jenks-based ranges for these categories were 0.0008–0.037 and 0.004–0.075 mg/L for U and Mo, respectively.)

Figure 35. Graduated Symbol Plots of Manganese, Molybdenum, Sulfate, and Uranium in Groundwater: August 2012

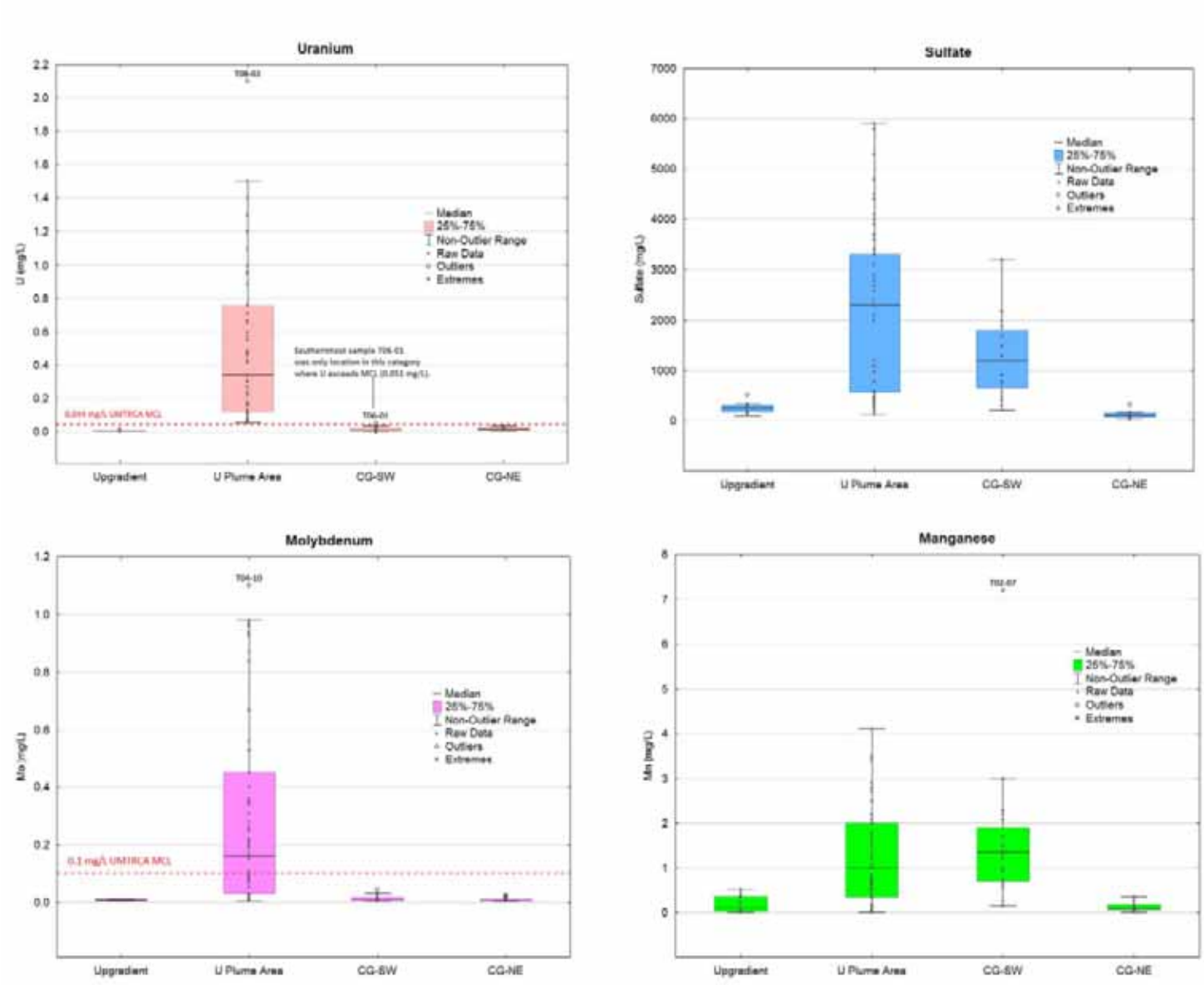


Figure 36. Box-and-Whisker Plots for Manganese, Molybdenum, Sulfate, and Uranium

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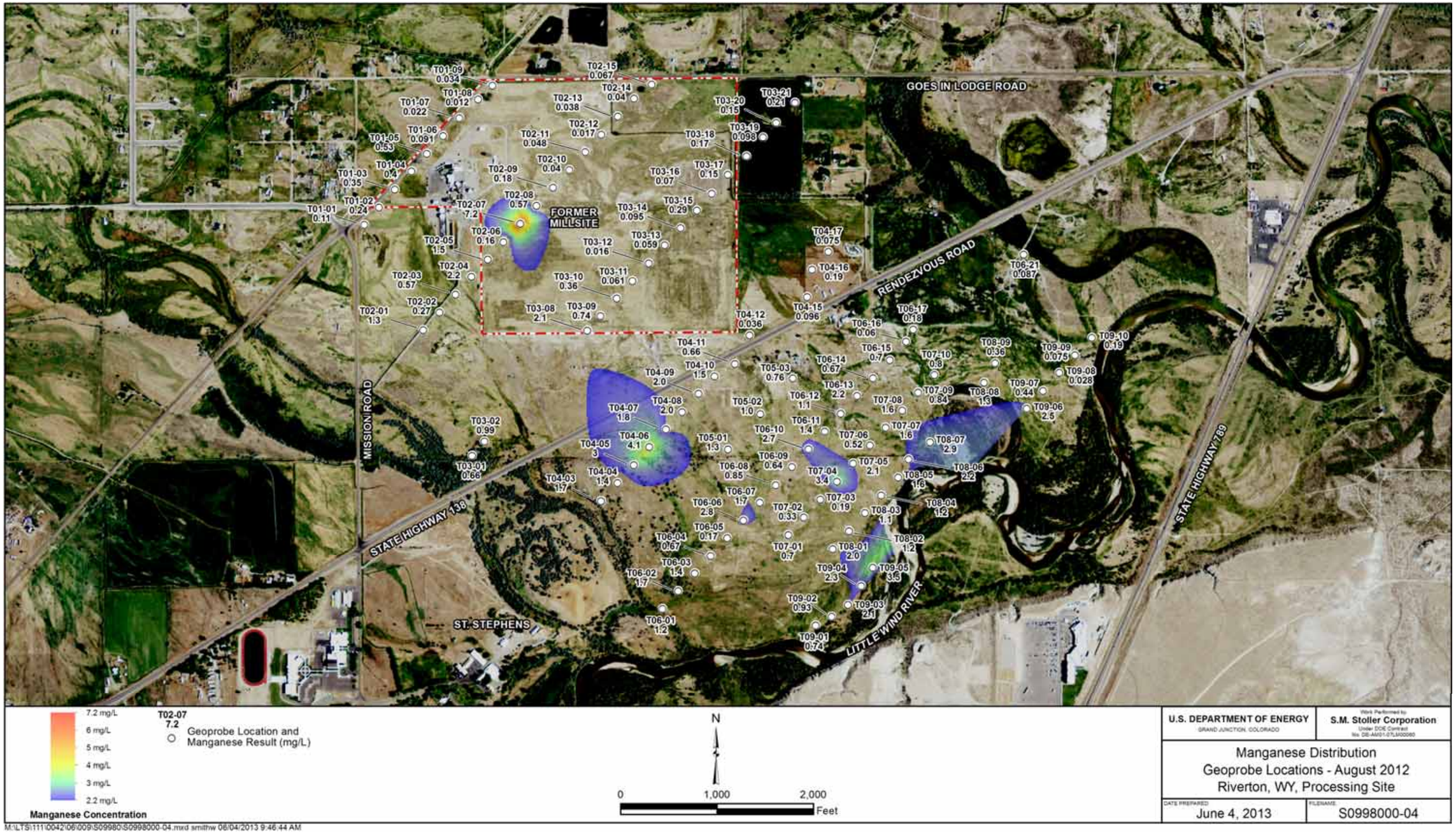

Figure 37. Distribution of Manganese in the Surficial Aquifer: August 2012 Enhanced Characterization

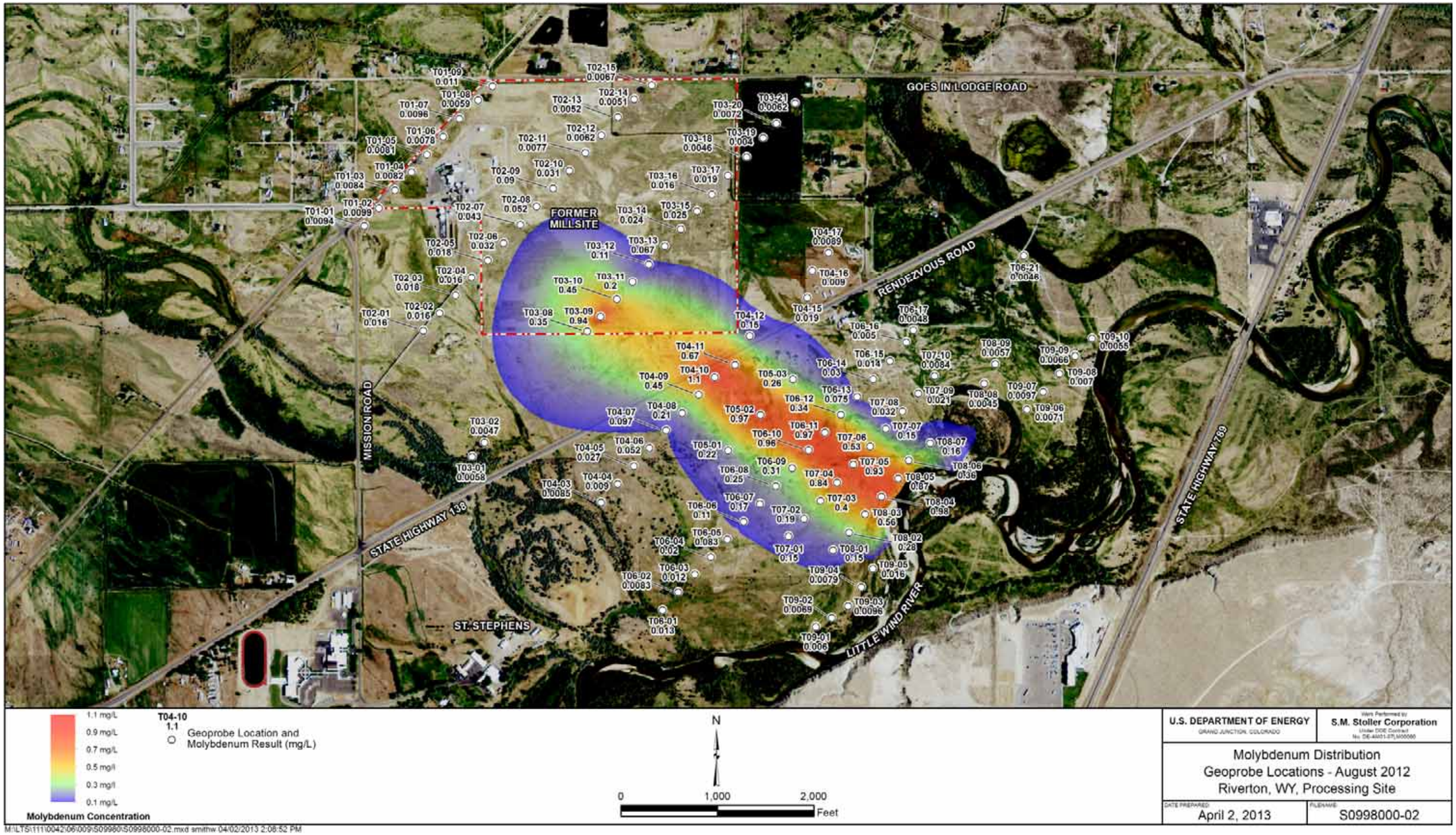

Figure 38. Distribution of Molybdenum in the Surficial Aquifer: August 2012 Enhanced Characterization

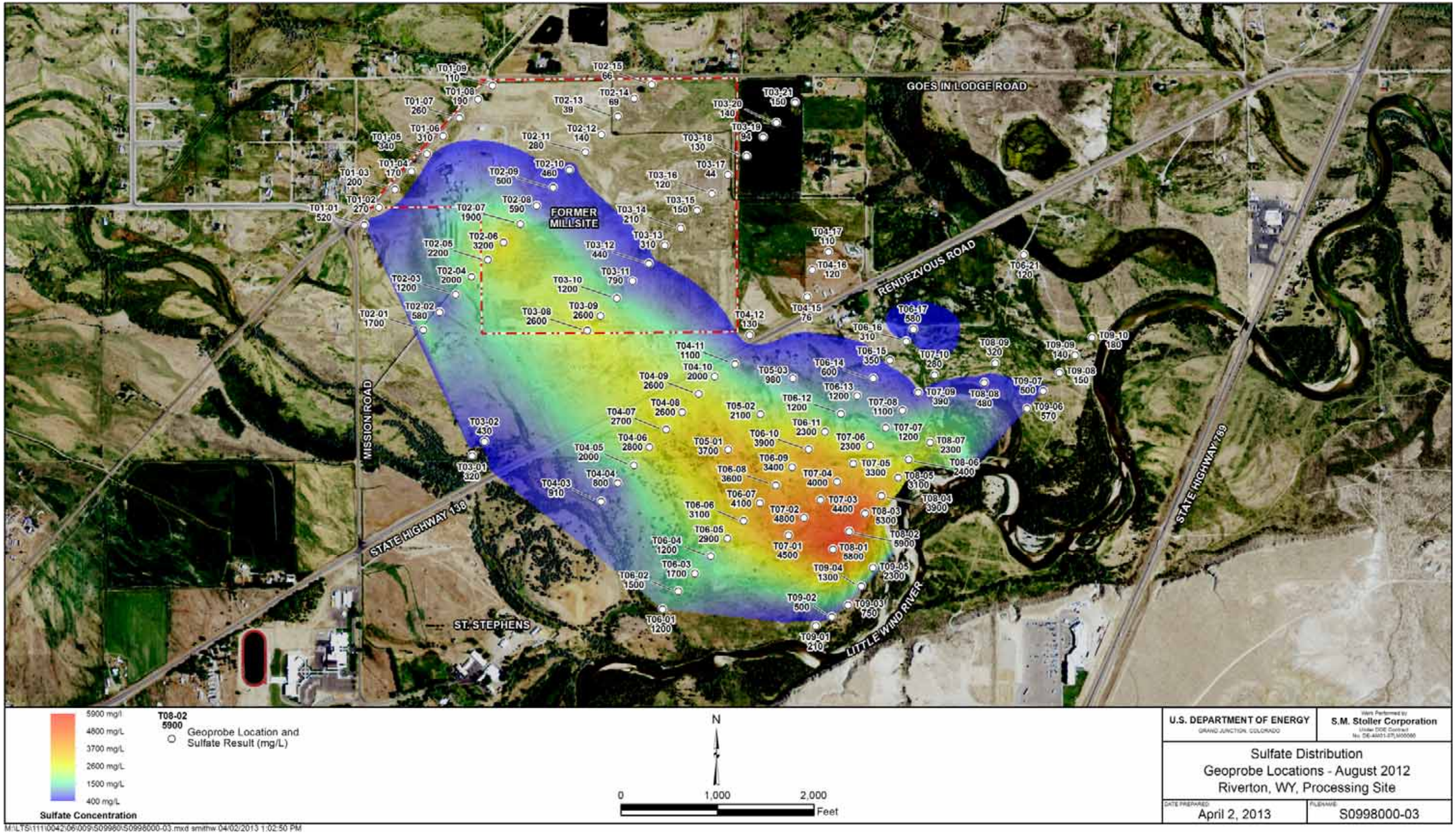

Figure 39. Distribution of Sulfate in the Surficial Aquifer: August 2012 Enhanced Characterization

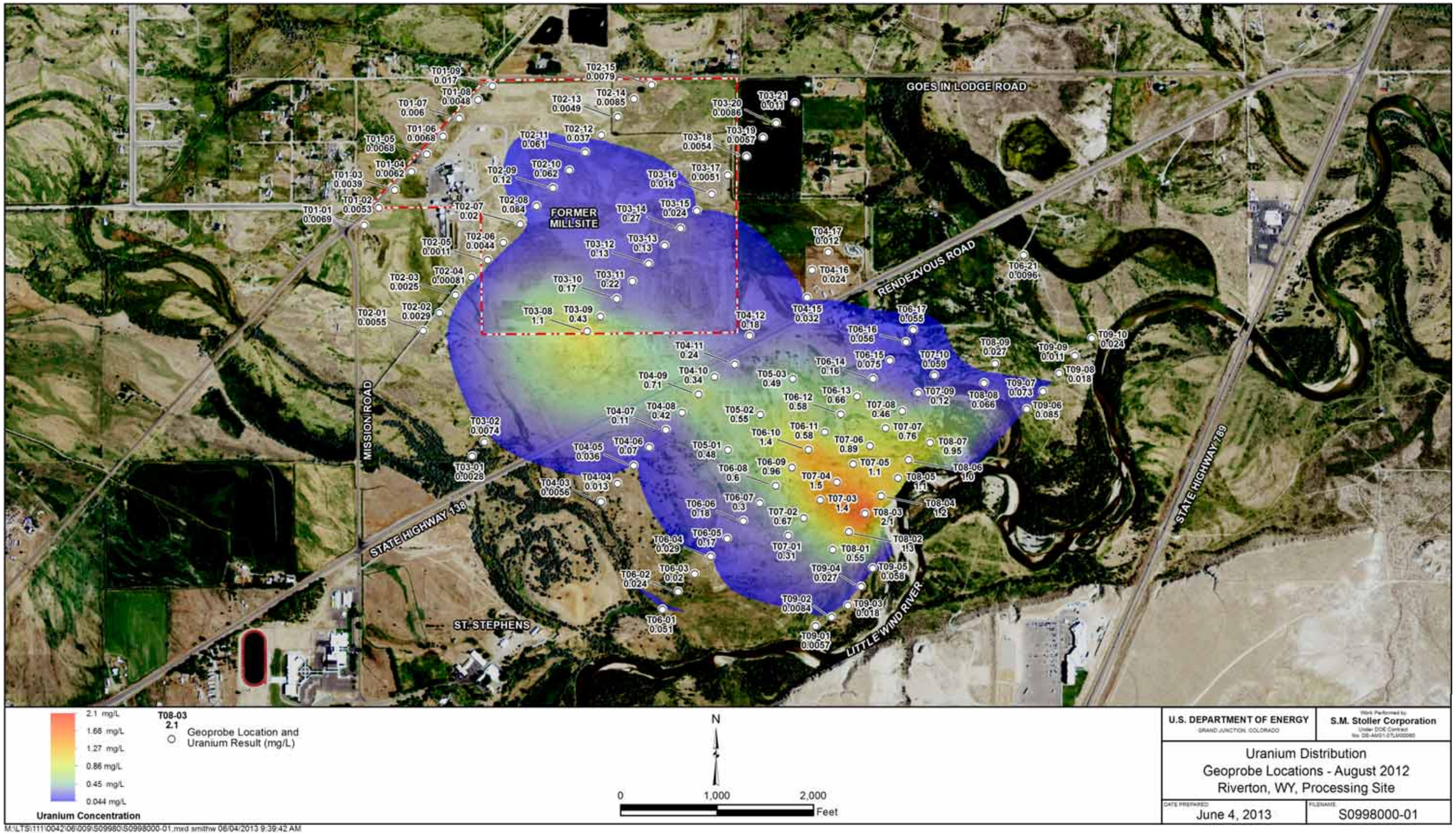

Figure 40. Distribution of Uranium in the Surficial Aquifer; August 2012 Enhanced Characterization

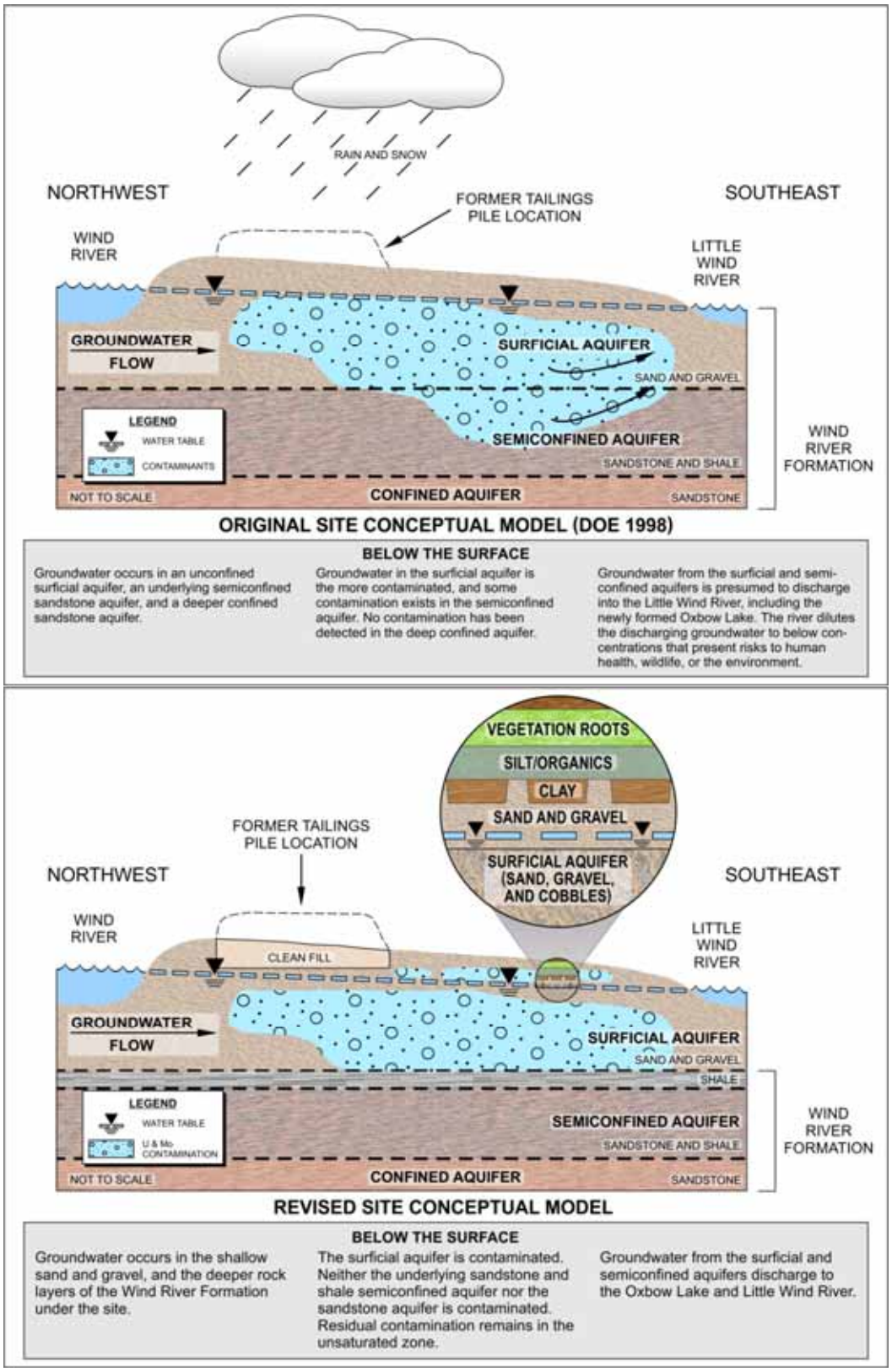

Figure 41. Original and Updated Site Conceptual Models

3.5.1 Original Site Conceptual Model

This section lists the major aspects of the original site conceptual model as described in the SOWP.

3.5.1.1 Original Contaminant Sources

- Groundwater in the surficial aquifer was originally contaminated by downward migration of leachates from the former mill tailing pile as a result of transient drainage from tailings and from infiltration of precipitation on the pile.
- Tailings were not considered a source of continuing contamination, as tailings were excavated down to 4 feet bgs in 1989.
- The excavation also included contaminated surface soils outside the site boundary, which might have resulted from windblown tailings.
- All original sources of groundwater contamination were removed.

3.5.1.2 Groundwater

- Groundwater flows in the surficial aquifer from the Wind River to the Little Wind River. Flow direction can change seasonally – east-southeast in March and south in June.
- The surficial aquifer is unconfined with a geometric mean of saturated hydraulic conductivity of 125 ft/day.
- A discontinuous shale layer separates the sand and gravels of the surficial aquifer from the semiconfined aquifer; the two aquifers are hydrologically connected.
- The surficial aquifer and semiconfined aquifer discharge to the Little Wind River.
- Both the surficial and semiconfined aquifers have been impacted by site contaminants.
- The confined aquifer is hydrologically isolated from the other two aquifers and has not been impacted by site contaminants.

3.5.1.3 Surface Water

- The oxbow lake receives discharge of contaminated groundwater from the surficial aquifer.
- The Little Wind River has not been impacted by site contaminants.
  - Average river flow is 579 ft^3/s and average groundwater discharge to the river 0.28 ft^3/s.

3.5.1.4 Groundwater Modeling/Natural Flushing Assessment

- A GANDT probabilistic groundwater model was used to simulate groundwater flow and transport of uranium and molybdenum, assuming linear, equilibrium sorption (i.e., a K_d approach).
- All of the transport simulations were based on steady-state flow fields under non-flooding conditions.
- Hydraulic conductivity fields were created using geostatistical simulation techniques; hydraulic conductivities were allowed to vary from 1 to 180 ft/day.
- Modeling predicted that molybdenum and uranium levels would be below standards within 75 years of the 1998 starting time.

3.5.2 Revised Site Conceptual Model

This section lists new major concepts derived from additional data collection and evaluation since 2010. These new concepts represent changes and omissions from the original site conceptual model. These new concepts will form the basis for new investigations, data collection, and evaluations that will be used to test alternative site conceptual models and to refine and develop a new site conceptual model.

- Recalcitrant sources of contamination, or secondary sources, remain in the saturated and/or unsaturated zone of the alluvial aquifer.
- Spikes in groundwater contaminant concentrations occur as a result of hydraulic phenomena associated with river flood events that mobilize the secondary sources.
- Magnitudes of the concentration spikes in groundwater vary depending on the peak river flow associated with each high flow event, and may also be dependent on the duration of the event.
- Although the shale layer that separates the sand and gravels of the surficial aquifer from the semiconfined aquifer is discontinuous, there are enough fine-grained sediments in the upper portion of the Wind River Formation to prevent further downward migration of contaminants to more permeable strata within the Wind River Formation. Based on the presence of fine-grained sediments and low concentrations of uranium and molybdenum in the semiconfined aquifer monitoring wells, the semiconfined aquifer has not been impacted by site contaminants.
- Original groundwater modeling (which used steady-state flow fields and linear, equilibrium sorption, or the K_d approach) was too simplistic. It did not account for the effects of transient phenomena, such as changing flow conditions between seasons and the occasional mobilization of contaminants induced by river floods. The original modeling also did not account for additional transport processes that can greatly impact contaminant fate. Such transport phenomena include water chemistry-dependent desorption, rate-limited mass transfer from fine-grained to coarser-grained sediments, preferential flow zones, rate-limited mass transfer from intragrain porosity, and potential redox reactions in near-river areas. The site conceptual model will continue to evolve as these factors are evaluated.
- Hydraulic parameters used to estimate surficial aquifer properties have been updated based on additional site characterization (see Section 3.6 for details).

3.6 Groundwater Modeling

3.6.1 Modeling Approach

Observations in 2010 revealed that the existing numerical groundwater computer modeling did not account for the spikes in contaminant concentrations observed in the surficial aquifer groundwater after flooding of the Little Wind River. Consequently, the Work Plan specified that a new groundwater flow and transport model was needed to better simulate site conditions. Initial efforts were conducted to model flow and uranium source term in the unsaturated zone; however, the complexities of modeling the unsaturated zone, and the limited data for the unsaturated zone, made this impractical. Although this model did not account for additional

uranium source term, there are other aspects of the model that were updated from the original SOWP model. These modifications included:

- Extensive initial groundwater-concentration data generated from the enhanced characterization using the Geoprobe.
- An improved accounting for transient conditions and the influence of the Little Wind River flooding on the water levels in the surficial aquifer.
- An improved calculation of hydraulic conductivities using pilot points and PEST software (Doherty 1994).

This new model was intended to be one aspect of assessing the viability of the natural flushing compliance strategy, and so it should be viewed in light of other empirical evidence before a final decision is made. The new flow and transport model was intended to provide a conservative estimate of flushing time because of the following:

- The new model did not account for any additional source mobilized by flood events; therefore, actual flushing time will be longer than predicted by the new model because groundwater concentrations are known to increase after significant flood events.
- The lowest average K_d was selected from the laboratory tests conducted on soils that were similar to surficial aquifer materials. If a higher K_d was selected, flushing time predicted by the model would increase.

Four flow and transport models were developed. Three steady-state flow and transport models were developed to simulate unchanging flow conditions and to assist in development of a fourth model, which was a transient flow and transport model that is presented in this section. The transient model is considered more representative of the Riverton site because it can represent changing flow/stage of the Little Wind River over time.

3.6.2 Input Parameters, Assumptions, and Limitations

Table 9 compares the input parameters in the new flow and transport model with the original GANDT model.

Using a groundwater flow and transport model has significant limitations, and the transport/forecasting aspect of the model should be viewed as a gross estimate, which should be interpreted only in conjunction with other lines of evidence. Data obtained from the enhanced characterization of the surficial aquifer revealed that concentrations of uranium were still high (1.1 mg/L) on the former mill site in 2012. This data, along with experience at similar sites and current literature (Zhu 2003), suggests that groundwater modeling using a linear, equilibrium sorption or K_d approach is too simplistic and does not account for fine-grained sediments and reducing zones (acting as variable sources/sinks in the aquifer) that make transport of contaminants erratic and unpredictable.

Table 9. Groundwater Model Inputs

Parameter	Units	New MODFLOW Model		Original GANDT Model	
		Value	Source	Value	Source
Hydraulic Conductivity	ft/day	6 to 433	Pilot points & PEST	57	DOE 1995, SNL 1996, and model trials
Recharge	ft/day	0.00016	Lasse 1998	0.0002	Expert judgment and general literature
Porosity	Decimal fraction	0.3	Lasse 1998	0.3	DOE 1995 and general literature
Dispersivity	ft	500	Expert judgment and general literature	160–230	Expert judgment and general literature
K_d	mL/g	1.04	Laboratory soil testing	0.1–0.2	DOE 1993 and general literature
Bulk Density	g/cm^3	2.5149	Lasse 1998	1.8	General literature
Initial Uranium Concentration	µg/L	0.81 to 2,100	August 2012 enhanced characterization	Not reported	DOE 1995
Background Uranium Concentration	µg/L	5	Mean from background well data	Not reported	DOE 1995

µg/L = micrograms per liter

3.6.3 Transient Flow Model

The new groundwater flow model is a single-layer, transient flow that was developed using MODFLOW 2000. Groundwater Vistas (GV) was used in conjunction with MODFLOW 2000. GV is a groundwater modeling environment for Microsoft Windows that couples a powerful model design system with comprehensive graphical analysis tools. GV is a model-independent graphical design system that can be used with MODFLOW and other similar models.

3.6.3.1 Model Calibration

This groundwater flow model was calibrated using continuous water level data from 2005 and 2009 obtained from a transducer installed in monitoring well 0707 along with water level data obtained from the monitoring well network during routine sampling events in 2004, 2007, 2009, 2010, and 2011. Model calibration for transducer data is illustrated in Figure 42 and Figure 43 by comparing actual water elevations in monitoring well 0707 with simulated water levels generated by the groundwater model in 2005 and 2009, respectively. Calibration statistics were generated by looking at the difference (residual) between the modeled versus actual water level at 551 targets, which is a substantial number of targets (Table 10). A good “rule of thumb” for model calibration is a sum of squares of residuals per target of 1.0 or less. As shown in Table 10, the sum of squares per target is 0.31, which indicates good model calibration.

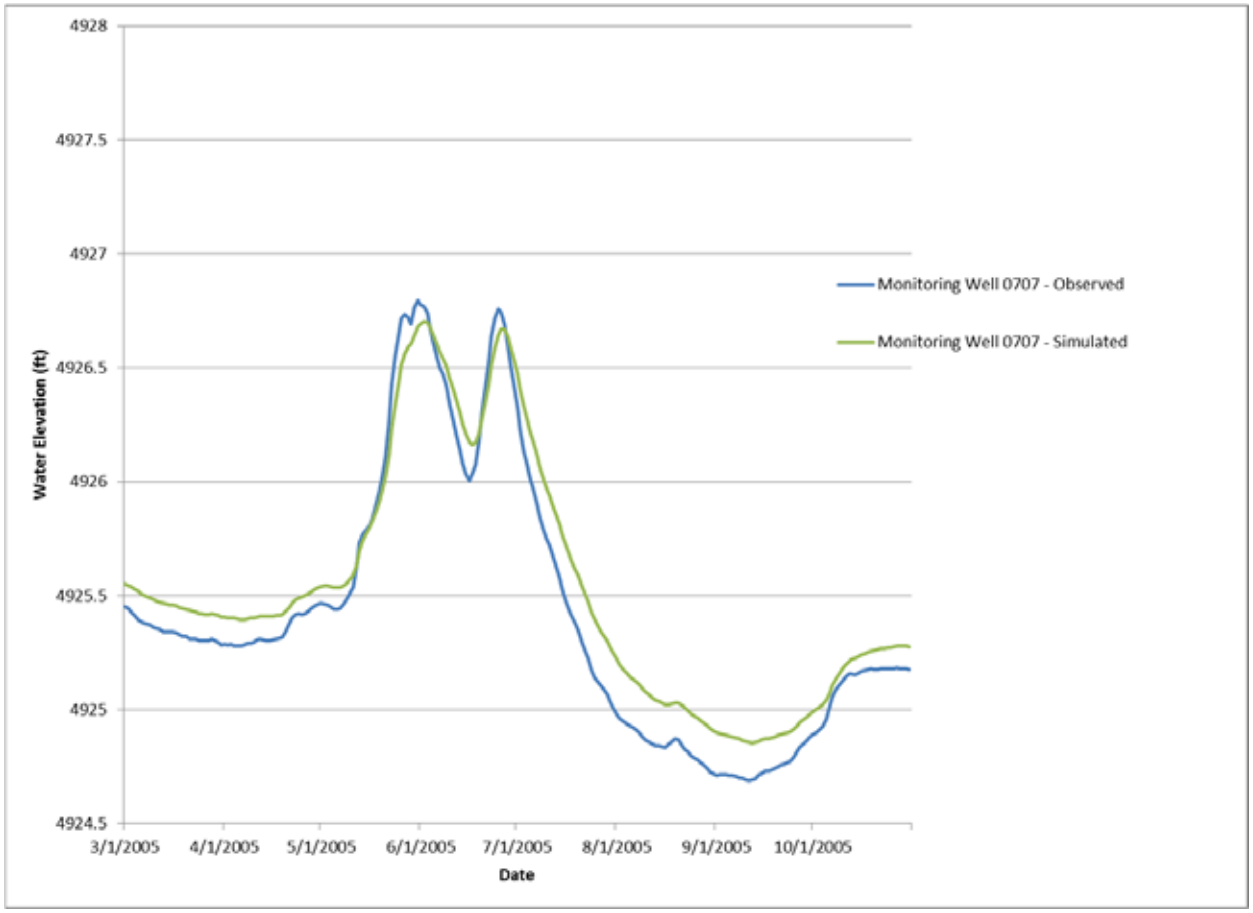

Figure 42. 2005 Water Levels versus Model Simulation: Well 0707

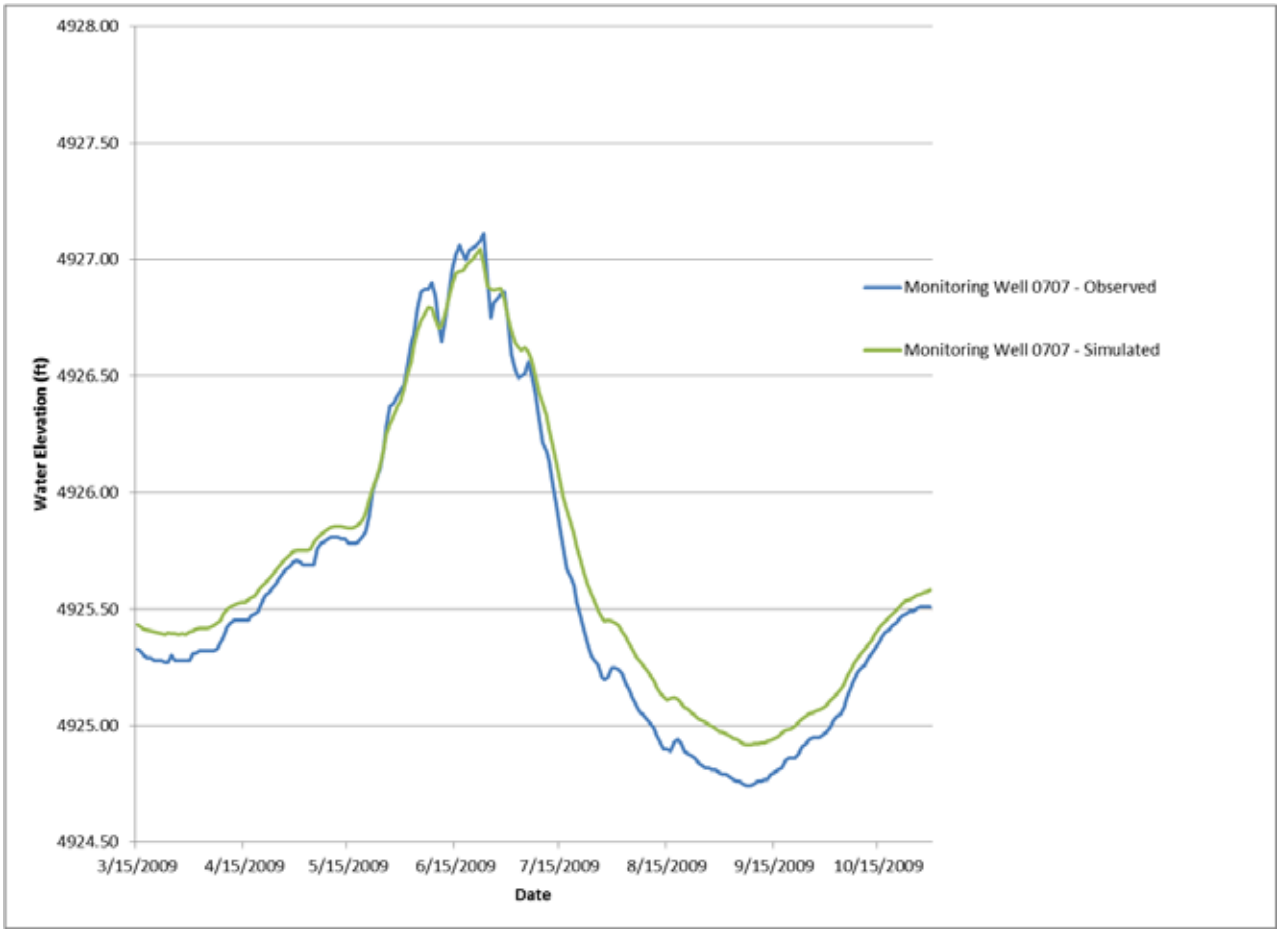

Figure 43. 2009 Water Levels versus Model Simulation: Well 0707

Table 10. Groundwater Model Calibration Statistics

Calibration Statistic	Value
Residual Mean	-0.087
Absolute Residual Mean	0.254
Residual Standard Deviation	0.553
Sum of Squares	172.7
Number of Targets	551
Sum of Squares per Target	0.31
RMS Error	0.560
Minimum Residual	-2.67
Maximum Residual	4.31
Range in Observations	24.15
Scaled Residual Standard Deviation	0.023
Scaled Absolute Residual Mean	0.011
Scaled RMS Error	0.023
Scaled Residual Mean	-0.004

Pilot points can be used for several parameters within GV in calibrating a model, including horizontal hydraulic conductivity (K_x), vertical hydraulic conductivity (K_z) specific storage (S_s) specific yield (S_y) recharge, and porosity. Sensitivity analysis indicated that the model was sensitive only to hydraulic conductivity, so pilot points were used for horizontal hydraulic conductivity to aid in the calibration of the Riverton model.

In conventional model calibration, the calibration process typically involves assigning one overall hydraulic conductivity value (or a separate hydraulic conductivity value to each hydraulic conductivity zone, if there are multiple zones), and adjusting this parameter (these parameters) until the fit between model-predicted and field-observation values is as good as possible. If the fit obtained on the basis of existing zones is not acceptable, then extra zones could be added into the model domain at locations where the modeler felt that they would "do the most good," which is arbitrary. This process would continue until the fit between model predicted and observed values are acceptable. There are a number of shortcomings associated with this approach, which include:

- The process is labor intensive and slow.
- Often there is no geological mapping to provide guidance on where to put additional zones, which makes the process subjective and non-unique.
- Characterization of heterogeneity by zones of piecewise uniformity is not consistent with the nature of geological material, so that any zonation that is finally decided upon is defensible only on the basis that it is better to employ a zonation scheme than to ignore heterogeneity altogether. In addition, piecewise uniformity as a method of characterizing heterogeneity lacks the flexibility required to explore the effects of small-scale variability on model predictive uncertainty.

These problems can be overcome using pilot points and PEST software. PEST is a model-independent calibration tool from Watermark Computing. PEST uses nonlinear least-squares techniques to calibrate virtually any type of model. Special software is included with GV to interface PEST with all models supported by GV.

In the transient flow model (i.e., the new model), the distribution of hydraulic conductivity within the model domain was described by a set of pilot points. Pilot points were located in the model domain, and PEST was used to estimate the hydraulic conductivity of the aquifer at each point. These "point hydraulic conductivities" are then spatially interpolated to all the active cells within the model domain using kriging. In estimating hydraulic conductivity values at pilot points, PEST effectively assigns parameter values to the whole model domain.

A total of 91 pilot points were introduced into the model domain. Pilot points are associated with different site activities (pumping and slug tests) or model features (calibration targets), as shown in the Table 11. Each pilot point is assigned an initial value and a range to restrict hydraulic conductivity to reasonable values. The initial value and range for the pumping and slug tests vary by location and are displayed in Table 12. The hydraulic conductivity field generated using pilot points and PEST is shown in Figure 44.

Table 11. Pilot Points Summary

Parameter	Number of Pilot Points	Description	Initial Value and Range (ft/day)
Pump Tests	3	Pump test locations	Varies (see Table 12)
Slug Tests	5	Slug test locations	Varies (see Table 12)
Calibration Targets	9	Target locations	125.0, 100.0–400.0
Target Triangle	46	Center of each calibration target triangle	125.0, 100.0–400.0
Filler	28	Placed in cells that do not have pilot points within 10 cells	125.0, 100.0–400.0

Table 12. Pilot Points Details

Location	Pilot Point Type	Initial Value (ft/day)	Range (ft/day)
0100	Pumping	104.0	101.0–400.0
0737	Pumping	158.0	155.0–400.0
0738	Pumping	119.0	116.0–400.0
0724	Slug	5.9	4.9–400.0
0728	Slug	16.9	11.9–400.0
0729	Slug	5.4	4.4–400.0
0783	Slug	128.1	74.1–400.0
0788	Slug	7.4	12.4–400.0

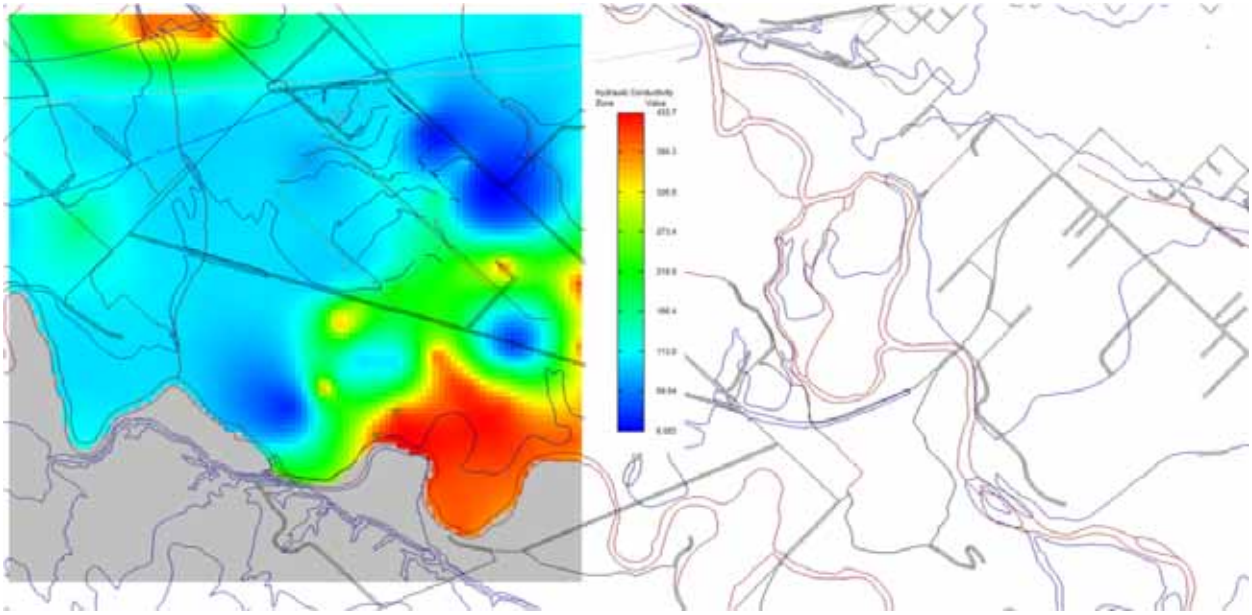

Figure 44. Hydraulic Conductivity Field Calculated Using Pilot Points and PEST

A statistical analysis of annual peak river flows in the Little Wind River was performed to develop perspective regarding the frequency with which the river could be expected to flood and help release contamination. The analysis, based on a record of annual peak flows extending from 1941 to 2011, revealed that the peak river discharge in 2010 (13,300 cfs) was likely to be equaled or exceeded once every 75 years (i.e., a 75-year return period). In addition, analysis of smaller flood events, such as the flood in June of 1965 (peak discharge of 9,550 cfs) had a return period for that peak flow of 15 years. These return periods of 15 and 75 years were used in the new transient flow model. In this model, the typical or average flow years were combined with a higher flow that occurs approximately every 15 years and an extreme flood flow that occurs approximately every 75 years. Constant head (representing river elevation) varies, based on typical or average flow, the 15-year flood event flow, and the 75-year flood event flow. The setup and summary of stress periods using these flood return periods are shown in Table 13 and Table 14, respectively.

Table 13. Stress-Period Setup for the Transient Flow Model

Year Type	Number of Stress-Periods	Stress-Period Length (days)	Cumulative Length (days)
Typical Year	1	90	90
	14	10	230
	1	135	365
15-Year Flood Event	1	125	125
	16	5	205
	1	160	365
75-Year Flood Event	1	125	125
	17	5	210
	1	155	365

Table 14. Transient Flow Model Stress-Period Summary

Flow Type	Number of Years	Date Range	Number of Stress-Periods per Year	Beginning Stress-Period	Ending Stress-Period
Typical	13	2012-2024	16	1	208
15 Yr. Flood	1	2025	18	209	226
Typical	14	2026-2039	16	227	450
15 Yr. Flood	1	2040	18	451	468
Typical	14	2041-2054	16	469	692
15 Yr. Flood	1	2055	18	693	710
Typical	14	2056-2069	16	711	934
15 Yr. Flood	1	2070	18	935	952
Typical	14	2071-2084	16	953	1176
75 Yr. Flood	1	2085	19	1177	1195
Typical	14	2086- 2099	16	1196	1419
15 Yr. Flood	1	2100	18	1420	1437
Typical	14	2101-2114	16	1438	1661
15 Yr. Flood	1	2115	18	1662	1679
Typical	14	2116-2129	16	1680	1903
Total	**118 Total**				

3.6.4 Transport Modeling and Forecasting

Transport simulations were conducted using MT3DMS software. Results of the new flow and transport model are presented below. This model was run for 118 years starting in 2012. Results indicate that the location of higher concentration is further east (downgradient) with increased river elevations during flood events. With higher river elevations, the gradient from the processing area toward the river in the vicinity of well 0707 is decreased. The flow direction likely shifts more to the southeast during 15-year flood and 75-year flood events, causing spreading of contamination in this direction. The change is clearly evident during a 75-year flood event. The initial concentration and transport simulations for 50-year and 100-year time frames are shown in Figure 45, Figure 46, and Figure 47, respectively. As shown in those figures, uranium concentrations are estimated to be above the standard after 100 years (in 2112). That will be 114 years since the Groundwater Compliance Action Plan (GCAP) was finalized in 1998. The GCAP predicted that natural flushing and other natural attenuation processes would reduce contaminant concentrations to MCL or background levels by the year 2098.

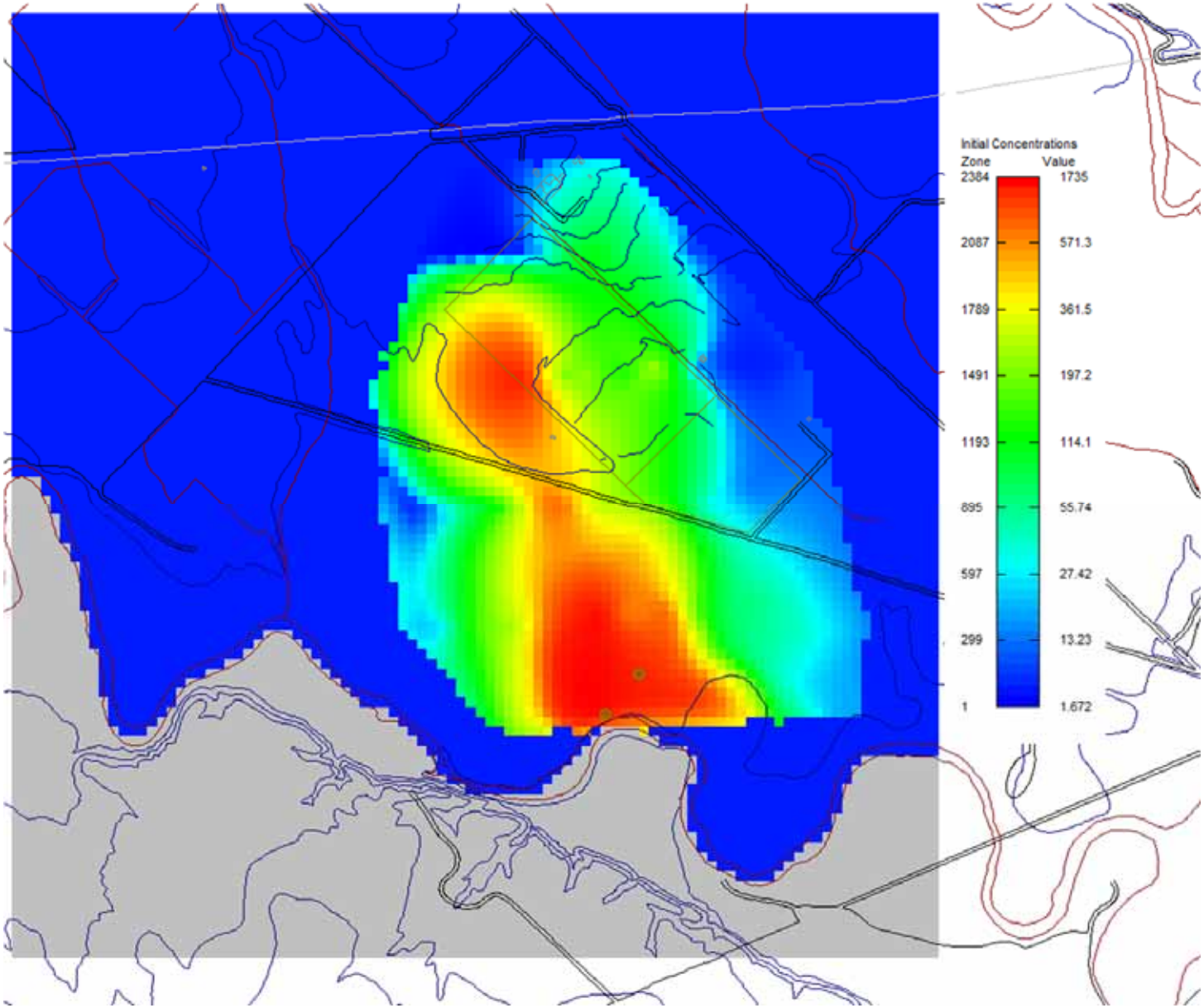

Figure 45. Initial Uranium Concentrations (µg/L) in the Surficial Aquifer from the Enhanced Characterization – August 2012

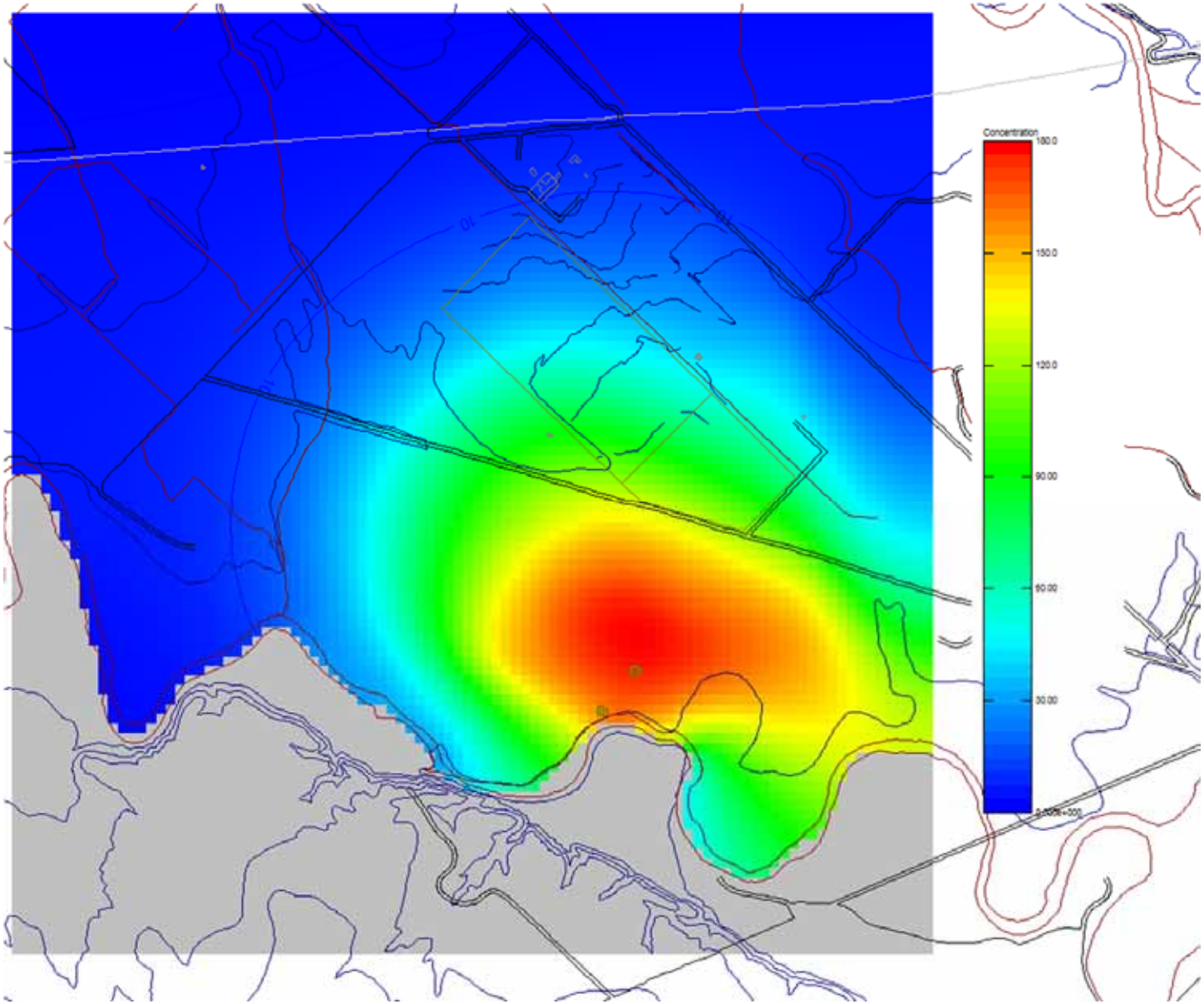

Figure 46. Simulated Uranium Concentrations (µg/L) after 50 Years (i.e., in 2062)

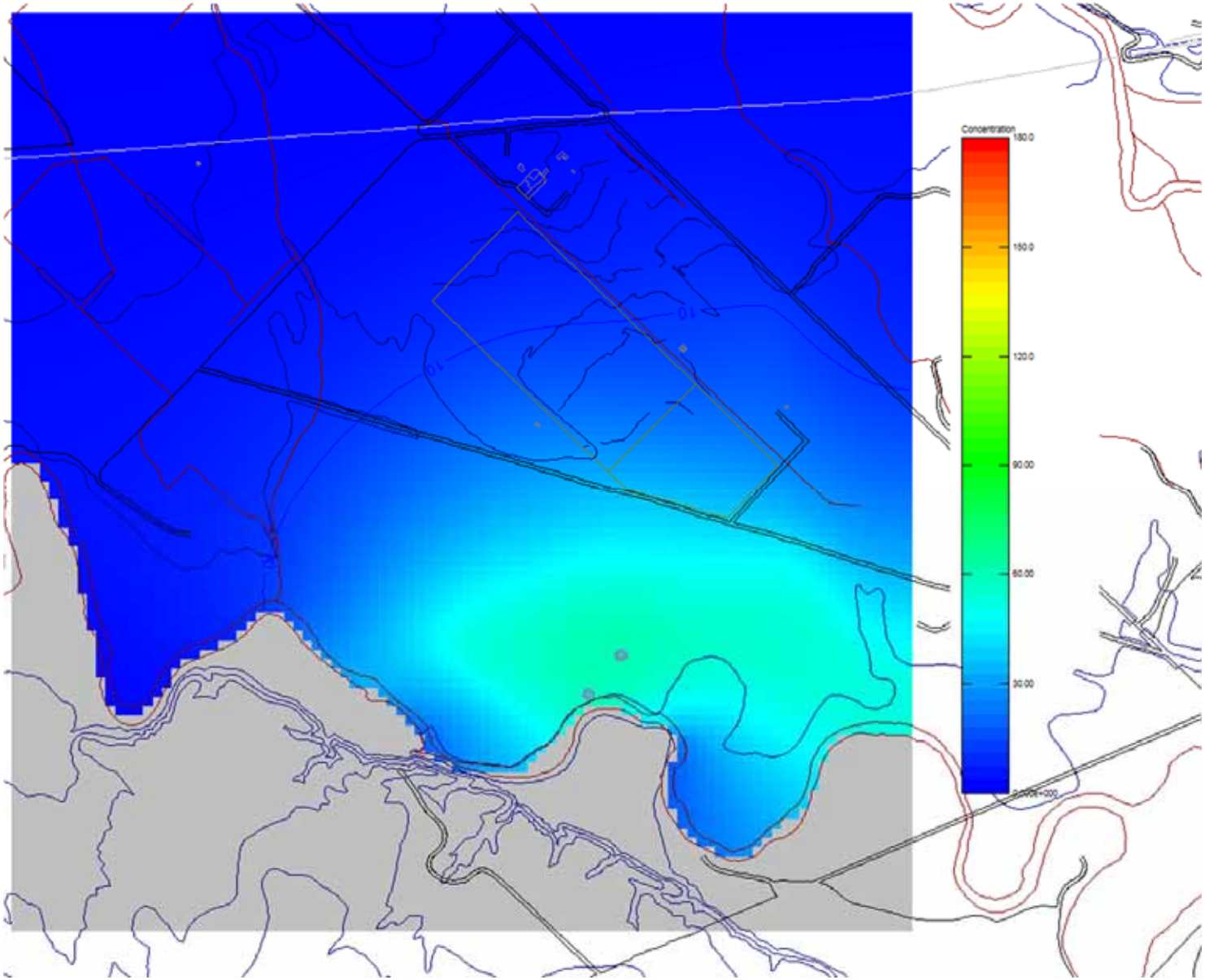

Figure 47. Simulated Uranium Concentrations (µg/L) after 100 Years (i.e., in 2112)

4.0 Compliance Strategy Assessment

After surface remediation was completed, groundwater numerical modeling in 1998 predicted that the alluvial aquifer will naturally flush contaminants to levels below applicable standards within the 100-year regulatory time frame. This modeling formed the basis for the natural flushing strategy that was approved in the *Final Ground Water Compliance Action Plan for the Riverton, Wyoming, Title I UMTRA Project Site* (DOE 1998a) in 1998. In previous years, the progress of natural flushing was assessed using three tools: comparison to hydrogeologic modeling predictions, trend analysis, and curve matching/interpolation techniques applied to temporal plots of contaminant concentrations at individual locations. These techniques were based on a site conceptual model of gradually declining contaminant concentrations after surface remediation of source material on the former mill site. Prior to 2010, these techniques indicated that natural flushing of the surficial aquifer was progressing toward applicable standards.

However, based on observations made in 2010 in context with historical data, the site conceptual model and groundwater computer modeling were too simplistic to account for the spikes in contaminant concentrations in the surficial aquifer groundwater. Spikes in contaminant concentrations are attributed to flooding of the Little Wind River in June 2010, which mobilized contaminants into the saturated zone of the surficial aquifer. Cross correlation of flood events in the Little Wind River with monitoring data reveal that uranium concentrations spiked in monitoring well 0707 in 1991, 1995, and 2010, which followed floods of Little Wind River (Figure 48).

Although the 2010 flood of the Little Wind River caused significant spikes in contaminant concentrations in the surficial aquifer, contaminant concentrations continue to decline and are generally approaching pre-flood levels, as shown in Table 15. Figure 49 shows the average uranium concentration in surficial aquifer wells with a long history that have always been above the MCL (0707, 0716, 0718, and 0722/0722R). As shown in this Figure, the average uranium concentration in these wells was below pre-flood levels in 2012. These data indicate that the effects of 2010 flood are relatively short-lived in context of the 100-year regulatory time frame.

Table 15. Comparison of Pre-Flood, 2010 Flood, and 2012 Results

Well	Molybdenum[a]			Uranium[a]			Sulfate[a]		
	Pre-Flood[b]	*2010 Flood*[c]	*2012*[d]	*Pre-Flood*	*Post-Flood*	*2012*	*Pre-Flood*	*2010 Flood*	*2012*
0707	0.68	1.6	0.85	0.84	2.7	0.85	1900	7000	3000
0788	0.024	0.023	0.022	0.034	0.1	0.048	630	4500	1500
0789	0.56	0.51	0.66	1.5	2.5	2	3900	9400	5300
0826	0.023	0.046	0.021	0.041	0.08	0.048	580	2400	2000

[a] Units are in mg/L.
[b] Pre-flood results are from the November 2009 sampling event.
[c] 2010 flood results from the June 2010 sampling event.
[d] 2012 results are from the December 2012 sampling event.

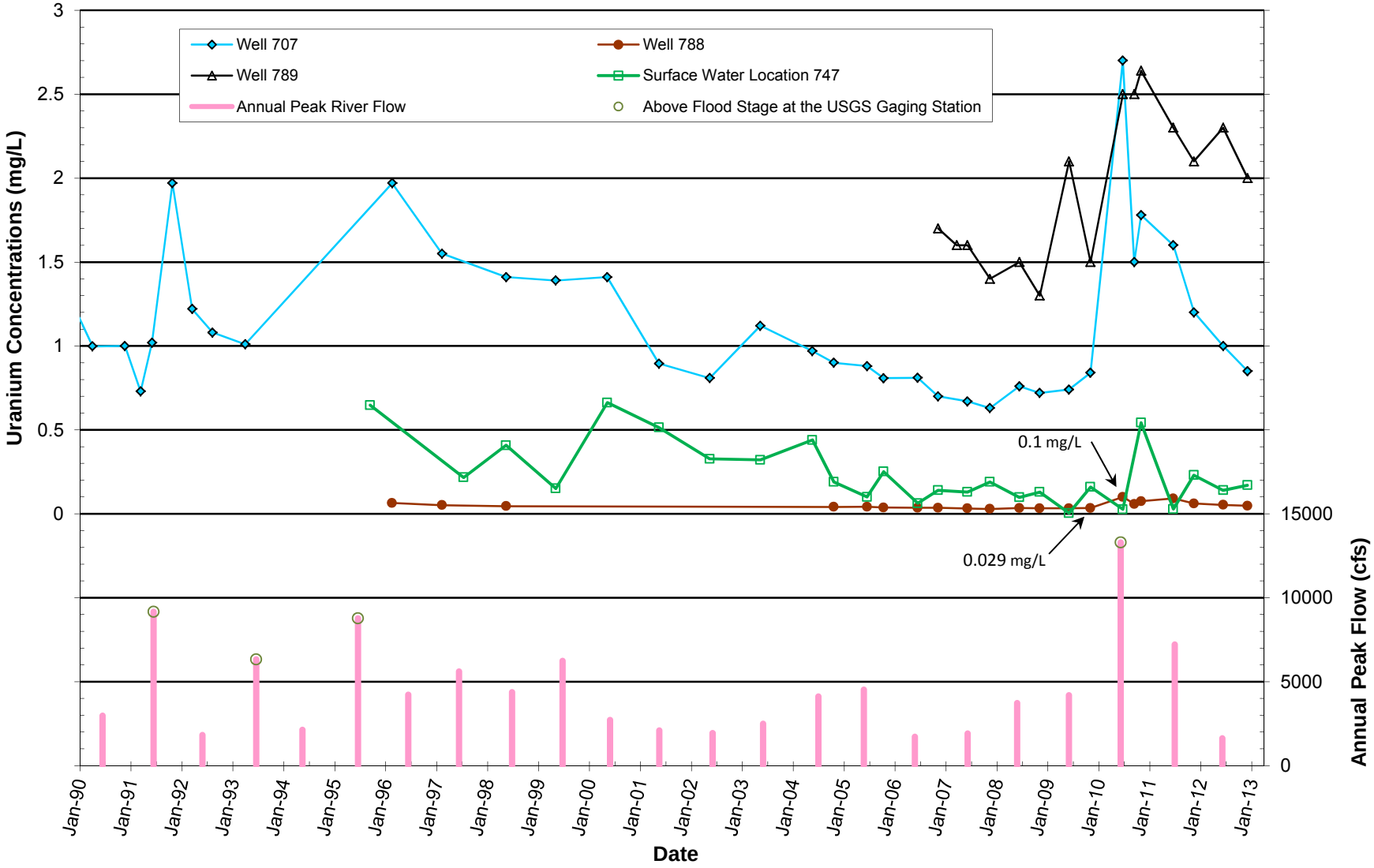

Figure 48. Uranium Concentrations and Maximum Little Wind River Stage

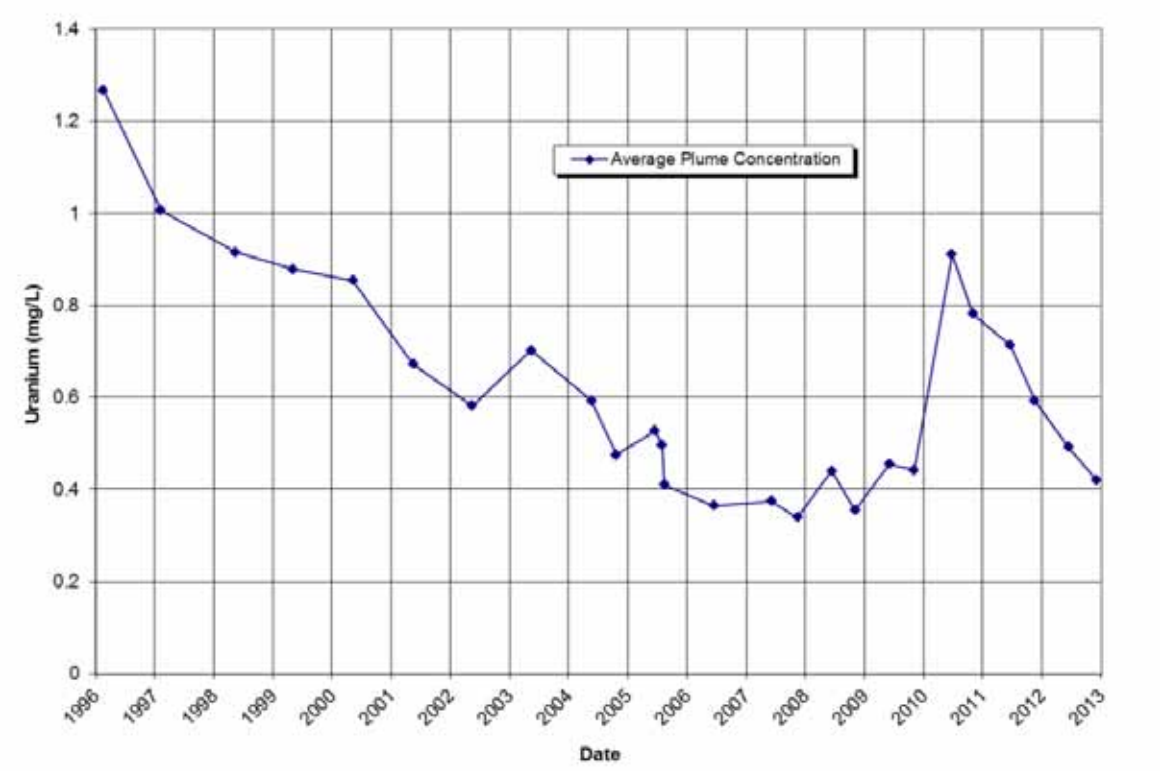

Figure 49. Average Uranium Concentration in Plume Wells

Overall, natural flushing (contaminant movement and removal via groundwater flow) in the surficial aquifer is occurring; however, the rate of flushing does not currently appear to be fast enough to restore the aquifer within the 100-year regulatory time requirement. Several lines of evidence indicate that the natural flushing compliance strategy may not meet the 2089 target date. These include:

- Current plume configurations and magnitude developed from the 2012 enhanced characterization.
  - Uranium concentrations of 1.1 mg/L still exist on the former mill site, which indicates contaminant plume movement is retarded by aquifer properties and/or influenced by additional source.
  - Uranium concentrations in the center of the plume adjacent to the Little Wind River are greater than 2 mg/L, which is very high compared to the uranium standard of 0.044 mg/L.
- Recently completed groundwater modeling indicates aquifer restoration will take longer than 100 years from the present.
- Other UMTRCA former uranium mill-sites with similar geology and contaminants are not cleaning up as predicted by groundwater modeling done to support a natural flushing compliance strategy.

- Time versus concentration graphs for average concentrations and for individual wells show that concentrations of contaminants are not declining as rapidly as in the past and/or have leveled out.
- Future flooding of the Little Wind River will likely cause an increase in contaminant concentrations in groundwater, even if the increase is relatively short-lived.
- Additional contaminants in the saturated and/or unsaturated zone may be acting as additional contaminant sources for elevated concentrations in groundwater.

Although the completion of natural flushing within the 100-year regulatory time frame is uncertain, additional information will be required to make a definitive decision on the natural flushing compliance strategy. A better understanding of the Riverton site, including aquifer properties, geochemistry, and potential additional contaminant sources, will be needed to support the natural flushing compliance strategy or to select a new compliance strategy. Some of this potential future work and information are identified in the Summary and Recommendations Section.

5.0 Summary and Recommendations

Verification monitoring results from 2012 verify that mill-related groundwater contamination continues to impact the surficial aquifer and oxbow lake, but institutional controls are in place and functioning as intended to protect human health and the environment from the groundwater contamination. In addition, verification monitoring results continue to verify that mill-related contamination has not impacted any potable domestic wells within the IC boundary, the semiconfined aquifer, the confined aquifer, the Little Wind River, gravel pit ponds, or the AWSS. Results from the AWSS flushing program provide evidence that the flushing program is effective in controlling the buildup of natural occurring radionuclides found in the source wells for the system.

The enhanced characterization conducted in 2012 resulted in a better understanding of uranium concentrations in the unsaturated zone soils and groundwater contaminant distributions. Uranium is present in higher concentrations in the unsaturated zone soils overlying the uranium plume than in the unsaturated zone soils overlying areas outside the contaminant plume. Although higher in the plume area, the range of labile uranium concentrations measured in the unsaturated soil are comparable to abundances of uranium in sedimentary rocks that make up the crust of the earth and may not be high enough to cause the increases that were observed in groundwater contaminant concentrations after the 2010 flood of the Little Wind River. Enhanced definition of groundwater plumes was obtained from the enhanced characterization effort, which also provided (1) evidence of the influence of the sulfuric acid plant discharge on the sulfate plume and (2) higher-than-expected uranium concentrations in the surficial aquifer on the south edge of the former tailings pile and in an area southwest of the primary uranium plume.

Although still above their respective MCLs, molybdenum and uranium concentrations in the surficial aquifer groundwater have returned to their pre-flood levels after spiking following the 2010 flood of the Little Wind River. However, numerous lines of evidence, including updated groundwater modeling, indicate that the rate of natural flushing is not rapid enough to meet the 100-year regulatory limit.

Although DOE obtained a better understanding of the site conceptual model, contaminant distributions, and properties of the unsaturated zone of the surficial aquifer at the Riverton site in 2012, additional work is needed to further define the conceptual model, to better understand geochemical processes that control contaminant fate and transport, to identify additional sources of uranium that are liberated during flood events, and to understand why uranium concentrations decline relatively quickly after flood events. This additional information will assist in making decisions for a path-forward compliance strategy. Recommendations for potential future work are listed in Table 16. DOE will prioritize the potential future work, will add medium- and high-effort work to future budgets, and will schedule the work. Low-effort work will be conducted under the current budget.

Table 16. Recommendations for Potential Future Work

Work Scope	Effort[a]	Purpose	Comments
Field Investigation			
Field observation of seeps.	Low	Assess groundwater discharge to the Little Wind River in accordance with the current site conceptual model.	Conduct during routine sampling.
Vertical measurements in wells and assessment of screened interval in the monitoring network.	Low	Determine if vertical contamination stratification exists and, if so, what are the impacts to the current understanding of the surficial aquifer contamination.	Vertical measurements of specific conductance can be conducted during routine sampling,
Additional water-level data loggers.	Low	Estimate irrigation infiltration impacts on groundwater flow and contaminant migration.	Wells 0826 and 0722R.
In situ measurements of groundwater flow direction.	Medium	Estimate flow direction in the surficial aquifer based on in situ measurements, and compare that with the flow direction based on water levels.	Research and purchase of equipment needed.
Install stilling well on the Little Wind River adjacent to well 0789.	Medium	Assess groundwater discharge to the Little Wind River in accordance with the current site conceptual model.	
Install stilling well on the Wind River with an adjacent monitoring well.	Medium	Evaluate interaction between the Wind River and the surficial aquifer.	
Additional field characterization with the Geoprobe; additional groundwater sampling around hot spots and the Little Wind River.	High	Better define the extent of groundwater contamination.	Work Plan required to define specific activities, objectives, and scope.
Additional field characterization with a drill rig, including soil/alluvial aquifer sampling below 5 ft, sampling of the clay/shale layer at the base of the alluvium. Perform lab experiments on samples.	High	Estimate the location of the sources of uranium and molybdenum that are mobilized during flood events. Determine the distribution of contaminants in saturated and unsaturated zone sediments.	Work Plan required to define specific activities, objectives, and scope.
Pilot tests or feasibility studies based on potential compliance strategy.	High	Determine feasibility of potential compliance strategies (if active remediation).	Work Plan required to define specific activities, objectives, and scope.
Laboratory Analyses			
Additional groundwater analyses: major cations/anions, total organic carbon, sulfide, and chloride.	Low	Better understand geochemical properties of the aquifers.	Can be conducted during routine sampling; analytical costs only.
Additional lab experiments on fine and coarse sediments in unsaturated zone.	Medium	Estimate source distribution in the unsaturated zone.	Perform tests on soil samples from 2012.
Assessment of sulfate in the semiconfined aquifer, including sulfur isotope analysis, additional chemical analyses.	Medium	Evaluate whether sulfate in the semiconfined aquifer is mill related.	Could be a High effort, depending upon the number and types of analyses.

Table 16 (continued). Recommendations for Potential Future Work

Work Scope	Effort[a]	Purpose	Comments
X-ray diffraction tests.	Medium	Identify clay and mineral types to assist in geochemical modeling, identifying contaminant sources, and assessing contaminant mobility.	Perform tests on soil samples from 2012.
Backscatter electron imaging and spectroscopy for mineralization analysis.	Medium	Identify mineral types to assist in geochemical modeling, identifying contaminant sources, and assessing contaminant mobility.	Perform tests on soil samples from 2012.
Data Evaluation			
Flood frequency analysis of Wind River.	Low	Predict future flooding of the Wind River.	
Assessment of chloride concentrations in groundwater as a conservative tracer.	Low	Estimate irrigation infiltration impact on groundwater flow and contaminant migration.	
White Paper detailing compliance strategy options.	Medium	Present feasibility, requirements, and data gaps for each compliance strategy option under UMTRCA to enhance communications with NRC and stakeholders.	Budgeted in 2013.
Geochemical and reaction path modeling.	High	Better understand geochemical processes that control fate and transport of site contaminants.	Work Plan required to define specific activities, objectives, and scope.
Additional groundwater modeling, coupled with geochemical modeling.	High	Better understand groundwater contaminant transport that includes groundwater flow and geochemical aspects.	Work Plan required to define specific activities, objectives, and scope.

[a] Low = less than 40 hours of labor or less than $1,000 of cost. Medium = between 40 and 160 hours of labor or less than $10,000 of cost.
High = greater than 160 hours of labor or greater than $10,000 cost.

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