Department of Energy
Washington, DC 20585

May 1, 2012

ATTN: Document Control Desk
U. S. Nuclear Regulatory Commission
Main Stop T8F5
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Subject: Transmittal of *Draft Groundwater Compliance Action Plan for the Old Rifle, Colorado, UMTRCA Title I Processing Site*

To Whom It May Concern:

Enclosed are three copies of the *Draft Groundwater Compliance Action Plan for the Old Rifle, Colorado, UMTRCA Title I Processing Site*. This draft Groundwater Compliance Action Plan presents the most recent characterization information and a new compliance strategy for groundwater cleanup at the Old Rifle, Colorado, former uranium-ore processing site.

The proposed groundwater compliance strategy will continue to be protective of human health and the environment. A recommendation of —no remediation with the application of supplemental standards based on technical impracticability—is provided. To support this strategy, new internal characterization efforts were combined with information gained from studies by national laboratory scientists working at the Old Rifle site to produce a new site conceptual model. Technical impracticability guidance from the U.S. Environmental Protection Agency and the U.S. Nuclear Regulatory Commission was used in developing the revised compliance strategy.

Please call me at (970) 248-6073 if you have any questions. Please send any correspondence to:

U.S. Department of Energy
Office of Legacy Management
2597 Legacy Way
Grand Junction, CO 81503

Sincerely,

Richard P. Bush
Site Manager

Enclosure

FSME20
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N. Orlando, NRC
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cc w/o enclosure:
A. Gil, DOE (e)
C. Carpenter, Stoller (e)
R. Dayvault, Stoller (e)
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Draft

Groundwater Compliance Action Plan for the Old Rifle, Colorado, UMTRCA Title I Processing Site

March 2012

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Draft

Groundwater Compliance Action Plan for the Old Rifle, Colorado, UMTRCA Title I Processing Site

March 2012

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Abbreviations

ACLs	alternate concentration limits
CDPHE	Colorado Department of Public Health and Environment
CFR	*Code of Federal Regulations*
COCs	contaminants of concern
cy	cubic yards
DOE	U.S. Department of Energy
EC	environmental covenant
EPA	U.S. Environmental Protection Agency
ft	feet
GCAP	Groundwater Compliance Action Plan
ICs	institutional controls
IFRC	Integrated Field Research Challenge
LM	(DOE) Office of Legacy Management
LTS&M	Long-Term Surveillance and Maintenance
MCLs	maximum concentration limits
mg/kg	milligrams per kilogram
mg/L	milligrams per liter
mL/g	milliliters per gram
NRC	U.S. Nuclear Regulatory Commission
pCi/g	picocuries per gram
PEIS	*Final Programmatic Environmental Impact Statement for the Uranium Mill Tailings Remedial Action Ground Water Project*
Ra-226	radium-226
RAP	*Final Remedial Action Plan and Site Design for Stabilization of the Inactive Uranium Mill Tailings Sites at Rifle, Colorado*
RCRA	Resource Conservation and Recovery Act
SOPs	standard operating procedures
SOWP	*Final Site Observational Work Plan for the UMTRA Project Old Rifle Site*
TI	technical impracticability
UMTRA	Uranium Mill Tailings Remedial Action (Project)
UMTRCA	Uranium Mill Tailings Radiation Control Act
VMRs	Verification Monitoring Reports

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Executive Summary

The Old Rifle site is a former ore-processing facility located approximately 0.3 mile east of the city of Rifle in Garfield County, Colorado. The site is situated on a low-lying erosional meander of the Colorado River—the river bounds the site on the south, and the alluvial aquifer discharges groundwater to the river along most of the site extent.

In 2001, the U.S. Department of Energy (DOE) received concurrence from the U.S. Nuclear Regulatory Commission (NRC) on the *Ground Water Compliance Action Plan (GCAP) for the Old Rifle, Colorado, UMTRA Project Site*. The compliance strategy for the Old Rifle processing site was a combination of natural flushing for uranium, the primary contaminant in terms of plume extent, and no remediation with the application of alternate concentration limits (ACLs) for vanadium and selenium, the other two site contaminants of concern. Flow and transport modeling of contaminants in alluvial groundwater conducted in support of early (1998–1999) site characterization activities predicted that uranium concentrations would decrease to 0.044 milligram per liter or background, whichever is greater, within 10 years. However, monitoring of aqueous uranium concentrations in the alluvial aquifer for the past 10 years indicates that concentrations are not decreasing as predicted. This prompted DOE to initiate new characterization activities at the site in 2010 and to conduct an extensive review of information produced by scientists working on the Integrated Field Research Challenge (IFRC) at the Old Rifle site. This new information was integrated into the August 2011 *Review of the Natural Flushing Groundwater Remedy at the Old Rifle Legacy Management Site, Rifle, Colorado*, provided in Attachment 1. The new site conceptual model proposed in the review of the natural flushing report, along with additional geochemical information, guided decisions to propose a new compliance strategy resulting in this 2012 GCAP revision. This new strategy for uranium, vanadium, and selenium is no remediation, application of supplemental standards based on technical impracticability, and application of institutional controls (ICs). The proposed revision was developed in collaboration with staff from the Colorado Department of Public Health and Environment (CDPHE).

Recent characterization efforts and review of Rifle IFRC data resulted in a new understanding of local groundwater flow processes, water sources recharging the alluvial aquifer, the impacts to groundwater from mill-related contaminants left in the substrate after surface remediation, and background biogeochemical processes in the subsurface. Collectively, the data, reports, and papers reveal that processes affecting the fate and transport of uranium in the site's subsurface system are more complex than had been previously assumed. Significant physical and biogeochemical heterogeneity and temporally variable flow and transport processes characterize the subsurface. Complex phenomena that potentially contribute to persistently elevated uranium concentrations in Old Rifle site alluvium include slow diffusion of uranium from low-permeability sediments, occasional mobilization of uranium in the vadose zone, and natural inflow of uranium in recharge sources north of the site. Such complexities not only limit the usefulness of existing technologies to adequately characterize local subsurface media but also severely hamper reliable modeling of contaminant transport in the alluvial aquifer on a sitewide scale. Consequently, natural flushing of uranium contamination cannot be reliably predicted at this time with data and modeling codes accepted by the regulatory community. Further, it was concluded in the attached evaluation that gathering more data and rerunning the model would not likely result in a more reliable prediction supporting a natural flushing compliance strategy.

Title 40 *Code of Federal Regulations* Part 192 (40 CFR 192) provides three basic options for groundwater remediation at designated processing sites—no remediation (if appropriate cleanup standards are already met), natural flushing (if standards can be met through natural processes within 100 years), or active remediation. Cleanup standards that can be applied are background concentrations, maximum concentration limits (MCLs, which are established in 40 CFR 192), ACLs, or supplemental standards. Because of the persistence of source materials within the aquifer at the Old Rifle site, it is unlikely that any form of remediation short of removal of all aquifer materials can meet background concentrations or MCLs. Although ACLs could theoretically be established in lieu of more stringent standards, the use of numerical cleanup standards is not necessary because ICs are in place that restrict any use of groundwater at the site (Appendix A). These ICs are expected to remain implemented, monitored, and enforced in perpetuity. Furthermore, any contaminant concentrations that could plausibly occur in the groundwater system would have no measureable impact on water quality at the only point of exposure (the Colorado River) due to the rapid dilution that occurs upon discharge. Any residual contamination that remains at the site due to former ore-processing activities will pose no unacceptable risk as long as use restrictions are maintained. Current concentrations are as low as reasonably achievable with regard to producing accompanying reductions in risk at the site. Significant reductions in contaminant concentrations would only be likely through the use of remediation methods that would likely result in the partial or complete destruction of the aquifer. Therefore, the use of supplemental standards based on the technical impracticability of groundwater cleanup is justified.

Three rigorous ICs are in place at the Old Rifle site that address the entire area of contamination. These overlapping measures restrict a number of activities at the site and limit access to the subsurface and groundwater without written permission from CDPHE and DOE. The only point of exposure is the Colorado River, and constituent concentrations in samples of river water collected upstream of the former mill site cannot be distinguished from those in samples collected downstream of the site. Geologic barriers prevent the spread of contamination in any direction except the adjacent river. Human health and the environment are protected by a combination of favorable geological conditions and ICs.

No numerical groundwater standards or monitoring are required for the strategy of technical impracticability (EPA 1993); however, DOE proposes to continue monitoring for the next 5 years in support of ongoing research at the site. Monitoring of ICs will occur on an annual basis. Analytical results and IC monitoring results will be reported annually in the Verification Monitoring Report that is distributed to NRC and CDPHE.

1.0 Introduction

1.1 Purpose

This revised Groundwater Compliance Action Plan (GCAP) serves as a stand-alone modification to Section E.3.6 of the *Final Remedial Action Plan and Site Design for Stabilization of the Inactive Uranium Mill Tailings Sites at Rifle, Colorado* (RAP) (DOE 1992) and is the concurrence document for compliance with Subpart B of Title 40 *Code of Federal Regulations* Part 192 (40 CFR 192) for the former Old Rifle, Colorado, processing site.

The proposed compliance strategy for the Old Rifle site is based on the compliance strategy selection framework following the steps prescribed in Section 2.1 of the *Final Programmatic Environmental Impact Statement for the Uranium Mill Tailings Remedial Action Ground Water Project* (PEIS) (DOE 1996) (Figure 1).

1.2 Regulatory Framework

The Old Rifle site was designated for cleanup under Title I of the Uranium Mill Tailings Radiation Control Act (UMTRCA). Surface remediation was completed according to the RAP. The PEIS provides the general compliance strategy selection framework for site groundwater and identifies three basic compliance strategies for attaining groundwater standards: no remediation, natural flushing, and active remediation. A combination of natural flushing and active remediation is also permitted. This compliance strategy selection framework has been concurred to by the U.S. Nuclear Regulatory Commission (NRC) and is included in their standard review plan for UMTRCA Title I sites with contaminated groundwater (NUREG-1724; NRC 2000). The groundwater cleanup standards that are applicable to Title I sites (including Old Rifle) are at 40 CFR 192 Subpart B. These regulations allow the use of background levels, maximum concentration limits (MCLs), alternate concentration limits (ACLs), or supplemental standards as the cleanup standards. Additionally, the regulations specify an extended period of 100 years for achieving compliance with those standards if natural flushing is relied on in full or in part.

The U.S. Department of Energy (DOE) is required by the PEIS to follow the groundwater compliance strategy selection framework summarized in Figure 1 in selecting the appropriate compliance strategy to clean up groundwater in the surficial aquifer (uppermost aquifer) affected by former processing activities at the Old Rifle site. The surficial aquifer at the site is defined as the alluvial aquifer and the upper, weathered Wasatch Formation that is hydraulically connected with the alluvium. The deeper Wasatch Formation is not contaminated at the Old Rifle site and is therefore not considered in the development of a compliance strategy.

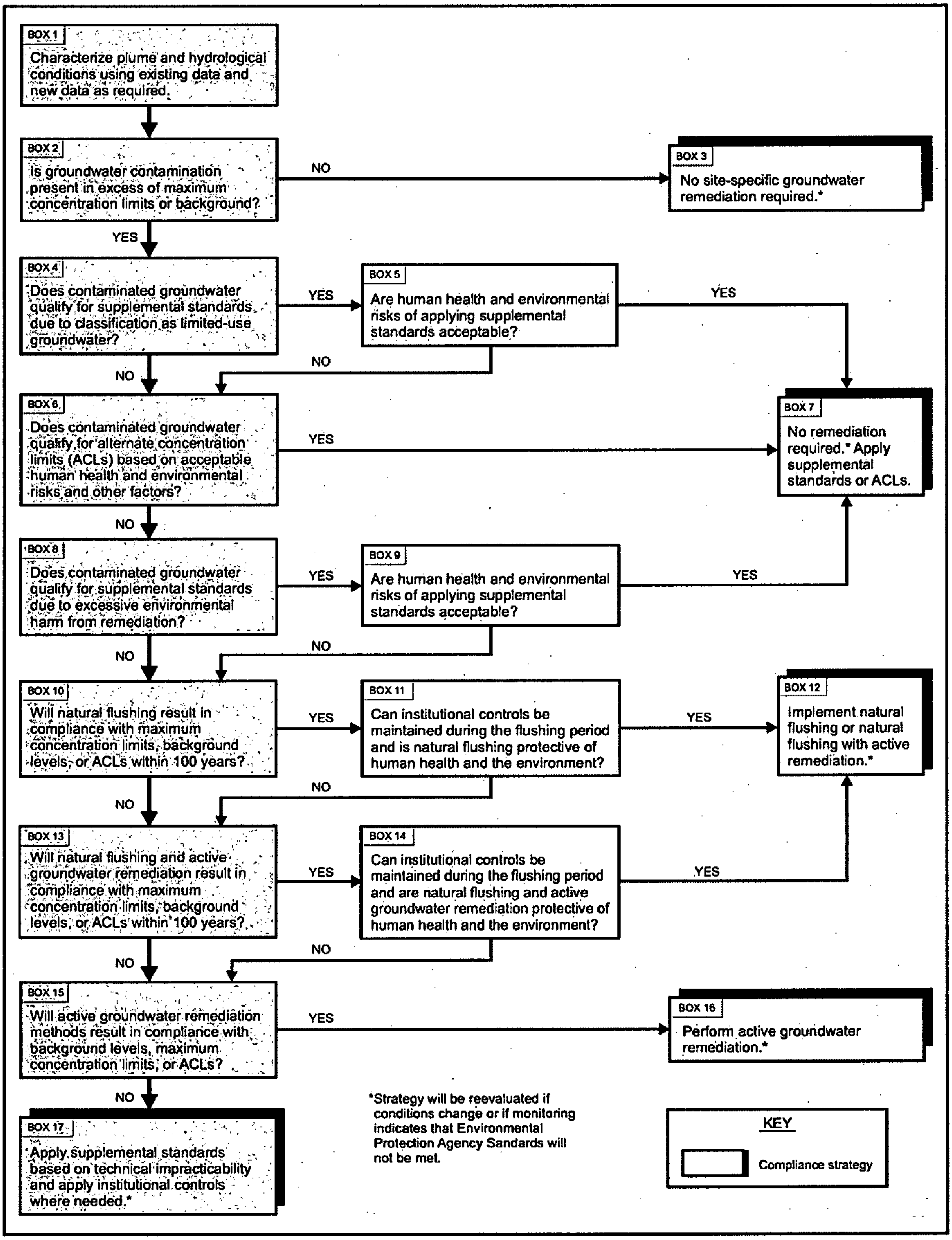

Figure 1. Compliance Selection Framework for the Old Rifle Site (The preferred path is shaded.)

DOE previously determined that natural flushing of the uppermost aquifer would result in meeting the MCL for uranium of 0.044 milligram per liter (mg/L) or the background value within a 10-year period (starting in 1998). (Average and maximum background values established at that time for uranium in the alluvial aquifer were 0.38 and 0.06 mg/L, respectively [DOE 1999].) ACLs were established for selenium (0.05 mg/L) and vanadium (0.33 mg/L); it was determined that those levels would be achieved within a 100-year period. Institutional controls (ICs) were selected as an additional component of the compliance strategy to restrict groundwater use at the site during the natural flushing period. The compliance strategies focused on contaminants of concern (COCs) retained after completion of the updated human health and ecological risk assessment screening processes (DOE 1999). Although arsenic was also identified as a COC in the Site Observational Work Plan (SOWP; DOE 1999) and in the initial GCAP (DOE 2001), it was not addressed in the site compliance strategy because concentrations were below the 0.05 mg/L MCL.

The natural flushing compliance strategy was selected following the decision framework (Figure 1, Box 12) while site-specific studies were being conducted to evaluate the feasibility of achieving standards by using active remediation. Based on the results of those studies (discussed in Section 2.3.2 and documented extensively in Attachment 1), the conceptual model for the Old Rifle site has changed significantly and sheds doubt on the ability of any remediation approach to achieve the uranium MCL. DOE has determined that (1) aquifer remediation to meet the uranium MCL is not feasible by either natural flushing or active remediation, (2) ACLs are not necessary, and (3) no remediation with the application of supplemental standards based on technical impracticability (TI) is the appropriate compliance strategy for the site.

Section 2.0 provides site information, the previous and revised site conceptual models, and an assessment of the remediation potential of the surficial aquifer. Based on this information, Section 3.0 details the revised compliance strategy and its implementation.

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2.0 Site Information

Extensive site characterization data are presented in a number of site documents, including the RAP (DOE 1992), the SOWP (DOE 1999), annual verification monitoring reports, and numerous research papers based on studies conducted at the site. A report entitled *Review of the Natural Flushing Groundwater Remedy at the Old Rifle Legacy Management Site, Rifle, Colorado* (DOE 2011a) was recently prepared based largely on the results of research conducted since the selection of the natural flushing compliance strategy. That report is included as Attachment 1 to this GCAP, as it provides the detailed technical basis for the revised compliance strategy proposed herein. This GCAP provides a summary of the key findings from the above-referenced documents and literature sources that support the revised compliance approach.

2.1 Physical Setting and Summary of Historical Site Operations

The Old Rifle site is located along a low-lying erosional meander of the Colorado River. The alluvial floodplain consists of a complex interfingering of fine- and coarse-grained materials that range in size from clay to boulders, with a uniform thickness of approximately 20 to 25 feet (ft). Well logs from across the site commonly show distinct, fine-grained layers interspersed with coarser sand and gravel horizons (DOE 2011a). Depth to groundwater ranges from 5 to 15 ft below land surface. The alluvium directly overlies an 8 to 13 ft thick zone of weathered Wasatch Formation claystone that appears to be hydraulically connected to the unconsolidated alluvium, thereby constituting the "uppermost aquifer" at the site. The resistant, cliff-forming beds of the Wasatch Formation control the western, northern, and eastern extent of the alluvium at the site. Groundwater beneath the site generally flows in a southwest direction with a hydraulic gradient ranging from approximately 0.003 to 0.006 ft/ft. Recharge to the alluvial aquifer occurs mostly as infiltration of precipitation, leakage from the drainage ditches north of U.S. Highway 6&24, and leakage from the open ditch that extends north to south across the site. The Colorado River bounds the site on the south, and the alluvial aquifer discharges groundwater to the river along most of the site extent. Figure 2 shows the key current and historical features of the Old Rifle site. Figure 3 provides a corresponding 3-dimensional schematic depicting the main physiographic features of the Old Rifle site.

The Old Rifle site operated from 1924 to 1932 and from 1942 to 1958; the mill was idle between 1932 and 1942. The western portion of the site was used for tailings storage, and the mill and ore storage area occupied the eastern part of the site. By the time processing activities ceased, the tailings pile covered a little more than half of the site. Old photos show that during operations, ponds occupied different portions of the site, and it is clear that the entire site was disturbed (Figure 4). Most of the tailings were moved to the New Rifle site after 1958 for reprocessing. Approximately 13 acres of tailings were stabilized at the site in 1967 in accordance with State of Colorado regulations. Stabilization consisted of covering the pile with approximately 6 inches of soil and installing a sprinkler system to promote the growth of grasses. River water was used for irrigation (DOE 1992).

Surface remediation started in spring 1992 and was completed in October 1996. This resulted in the removal and offsite disposal of all mill tailings and contaminated soils from the entire site to meet the 40 CFR 192 activity standard of 5 picocuries per gram (pCi/g) radium-226 (Ra-226). Because removal of soils generally stopped at the water table due to difficulties in excavating

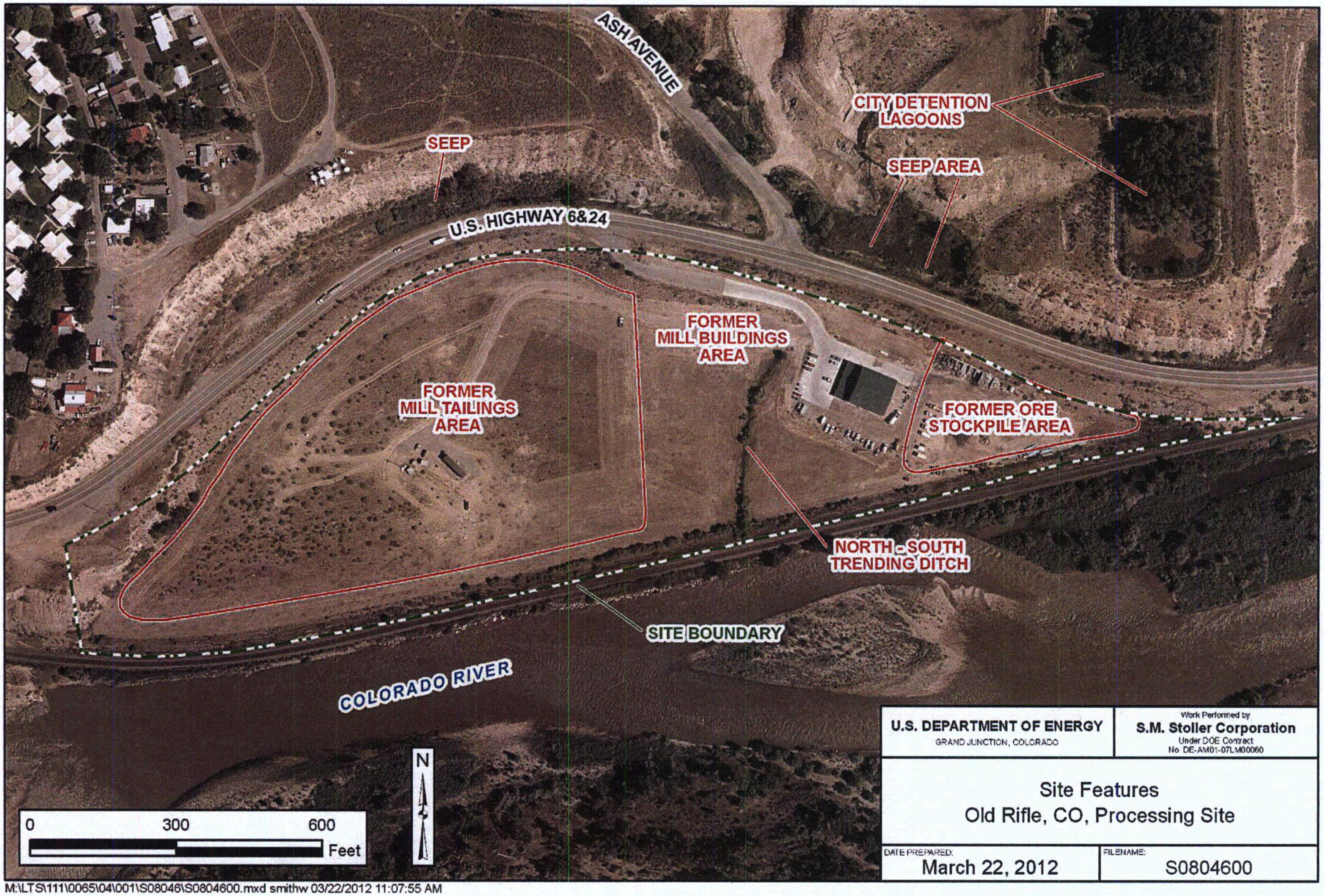

Figure 2. Site Features, Old Rifle, Colorado, Processing Site

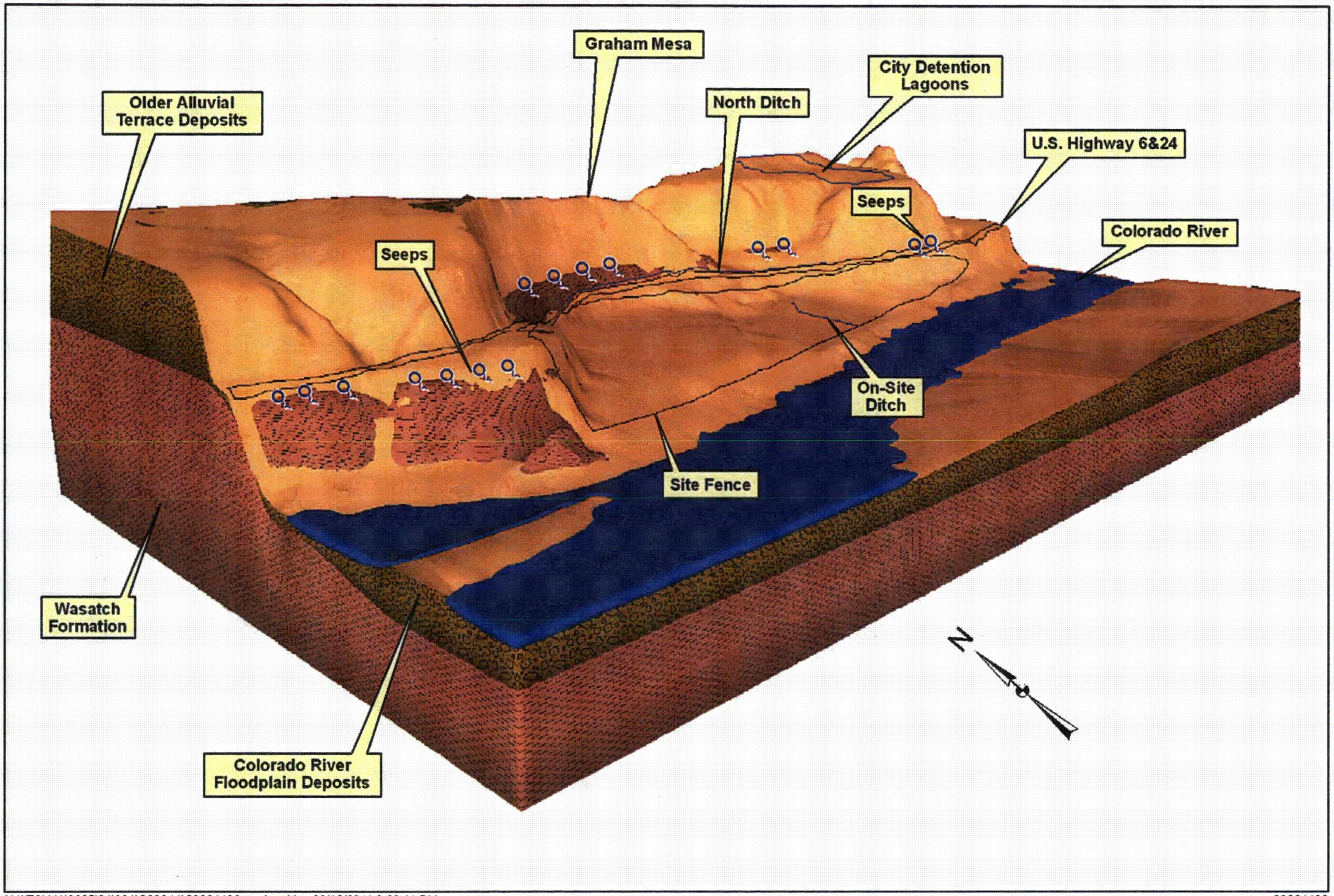

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Figure 3. Depiction of Physiographic Features at the Old Rifle Site

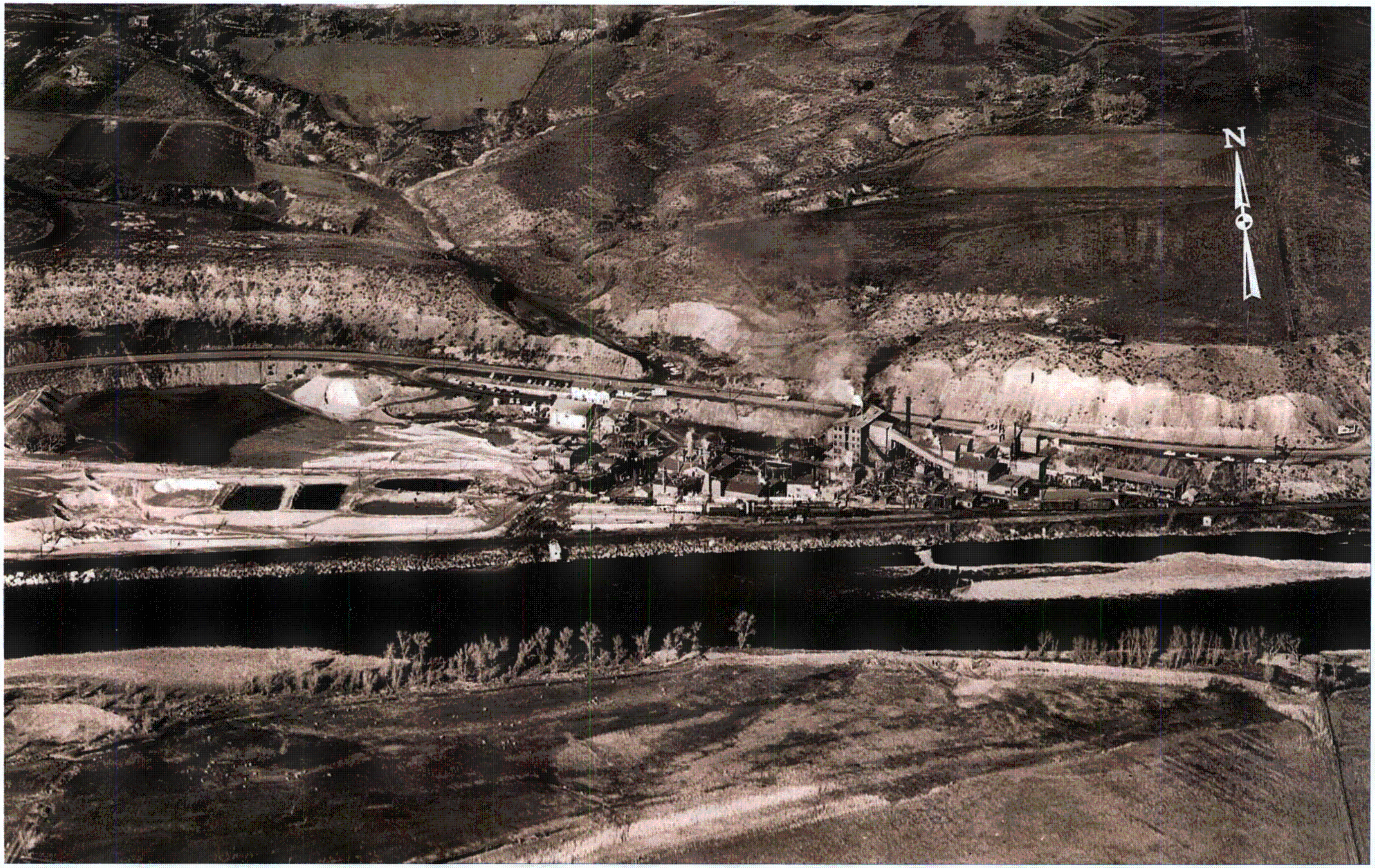

Figure 4. Old Rifle Site During Operations
(Tailings and raffinate ponds occupy the west side, mill buildings the east. Circa 1955, Union Carbide photo.)

below this level, some contamination from other metals (e.g., uranium) was left in place. In addition, an estimated 24,000 cubic yards (cy) of tailings qualified for supplemental standards because of concerns about worker safety and was left in place on adjoining vicinity properties north of the site boundary on the embankment adjacent to Highway 6&24 (Figure 5; DOE 1997). Other supplemental standards areas exist under the railroad right-of-way and along the riverbank south of the site. Residual contamination in these supplemental standards areas ranged up to 1,320 pCi/g Ra-226; the average concentration was reported to be 150 pCi/g. Residual uranium concentrations in soils in the former ore stockpile area ranged up to 12 milligrams per kilogram (mg/kg); however, the average residual uranium concentration was generally less than 2 mg/kg. Fine-grained fill was applied across most of the site and makes up the uppermost 5 to 10 ft of surficial material.

2.2 Groundwater Contaminants

The SOWP identified three constituents—uranium, selenium, and vanadium—as having elevated concentrations in groundwater and requiring the selection of a cleanup compliance strategy. Uranium is the most prevalent site-related contaminant occurring in the alluvial groundwater. With the exception of well 0309 located at the southwestern corner of the site (Figure 6), samples from all locations have had uranium concentrations that exceeded the 40 CFR 192 groundwater standard of 0.044 mg/L (assuming secular equilibrium) over the last several years (Figure 7). Uranium concentrations in samples from well 0304 have fluctuated around the standard, and concentrations in wells 0305, 0310, 0655, and 0656 have been consistently elevated.

In contrast, selenium and vanadium concentrations have exceeded their cleanup levels in only two wells—0305 and 0655, located in the center of the former mill processing area (Figure 8 and Figure 9). Selenium concentrations in well 0305 fluctuated widely between 1998 and 2006 (often exceeding the 0.05 mg/L ACL) but have since decreased to levels below 0.05 mg/L. An opposite trend is apparent in well 0655, where selenium concentrations more than doubled (to levels exceeding the ACL) in 2010 (Figure 8). However, as of November 2011, selenium concentrations in all wells were below the ACL (note recent marked reduction in well 0655 [Figure 8]). Vanadium concentrations have been slightly above the risk-based value of 0.33 mg/L in well 0655 for the last several years (Figure 9). Concentrations in well 0305 have varied considerably and have been consistently elevated. However, average concentrations for selenium and vanadium at the site do meet their respective standards.

A comparison of pre-surface-remediation groundwater data for uranium with recent concentrations indicates that remediation resulted in about an order-of-magnitude reduction in groundwater concentrations. Maximum uranium concentrations reported in the RAP for the 1987–1990 time period are on the order of 1 to 2 mg/L (DOE 1992) compared with current maximum concentrations of around 0.1 to 0.2 mg/L (Figure 7). Wells in the vicinity of existing well 0309 had concentrations of 0.11 to 0.13 mg/L (DOE 1992), compared with recent concentrations around 0.02 mg/L (Figure 7). It therefore appears that source control (i.e., removal of the tailings and other residual radioactive materials) resulted in rapid and significant improvements in water quality of the alluvial aquifer. However, the uranium plume at the site has remained largely unchanged since those initial reductions, as data from 1998 and 2007 show (Figure 10 and Figure 11). Figure 12 plots more recent data from 2011, supplementing DOE monitoring results with data from wells installed as part of the Rifle

LEGEND

Approximate Area of Supplemental Standards

Site Boundary

Aerial photograph from August 2008.

N

SCALE IN FEET

400 200 0 400

U.S. DEPARTMENT OF ENERGY
GRAND JUNCTION, COLORADO

Work Performed by
S.M. Stoller Corporation
Under DOE Contract
No. DE-AM01-07LM00060

Approximate Area of Supplemental Standards
Rifle Old, CO, Processing Site

DATE PREPARED: August 19, 2011

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Figure 5. Supplemental Standards Areas Remaining after Surface Cleanup

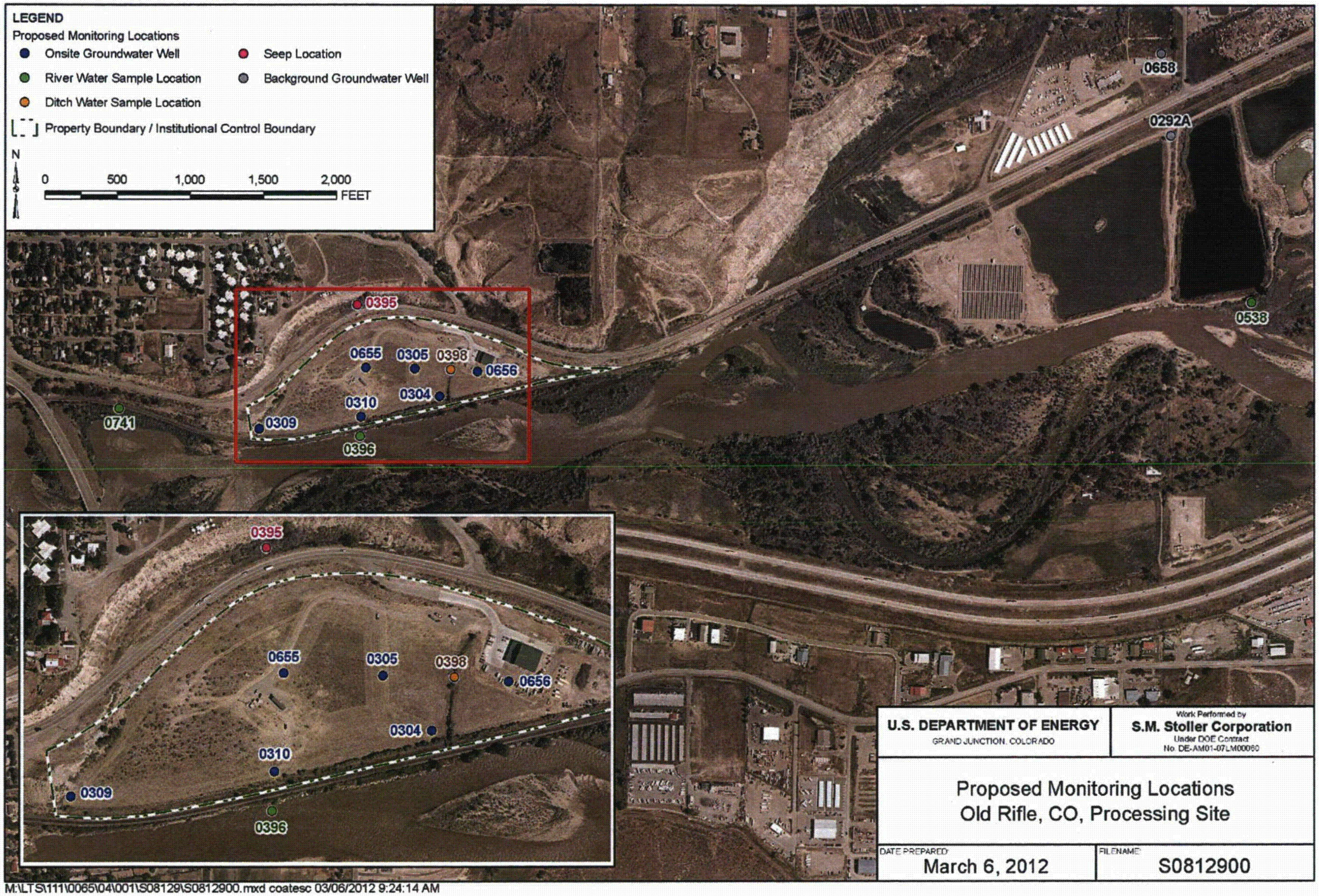

Figure 6. Monitoring Locations for the Old Rifle Site

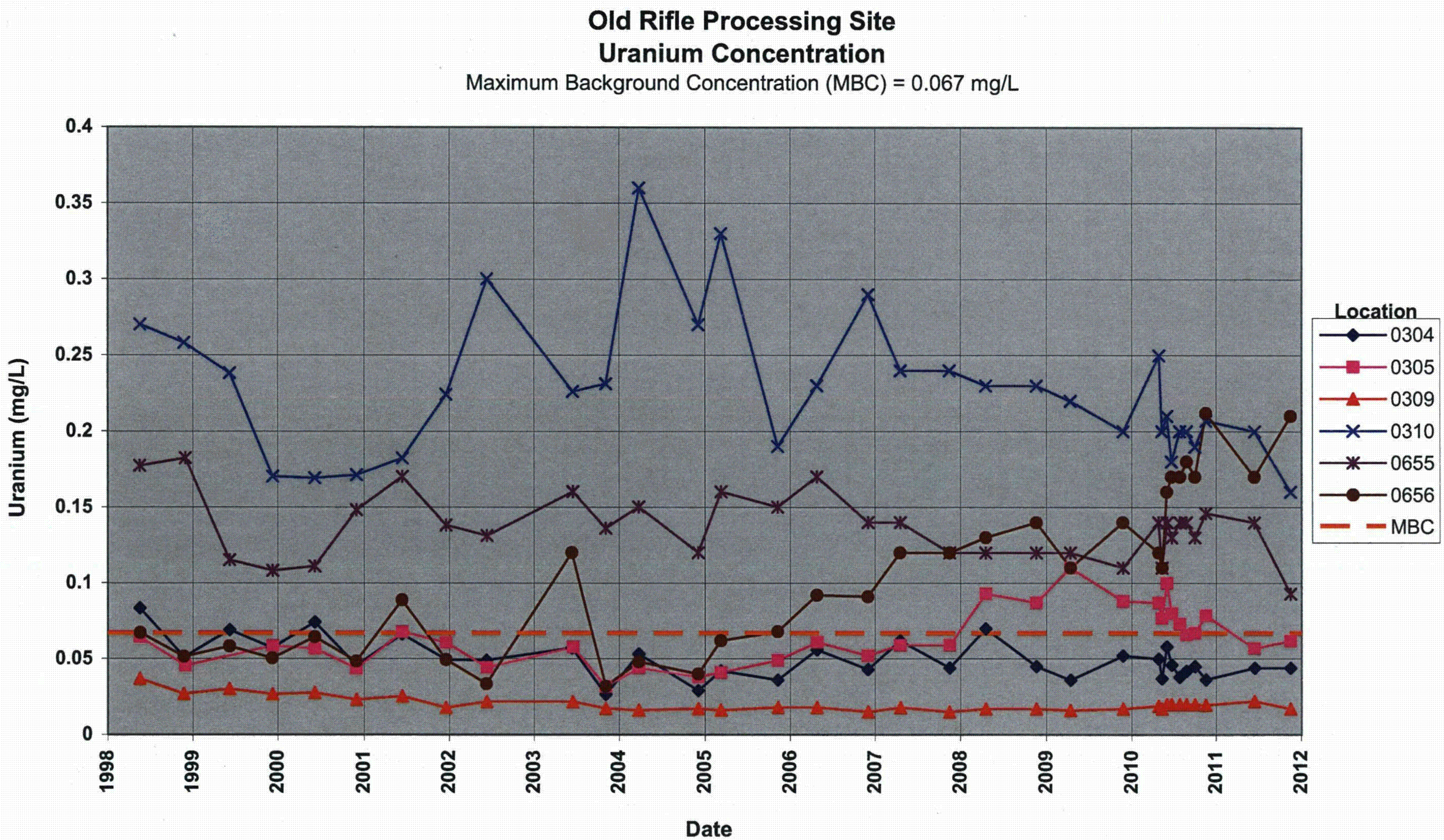

Figure 7. Uranium Time-Concentration Plots

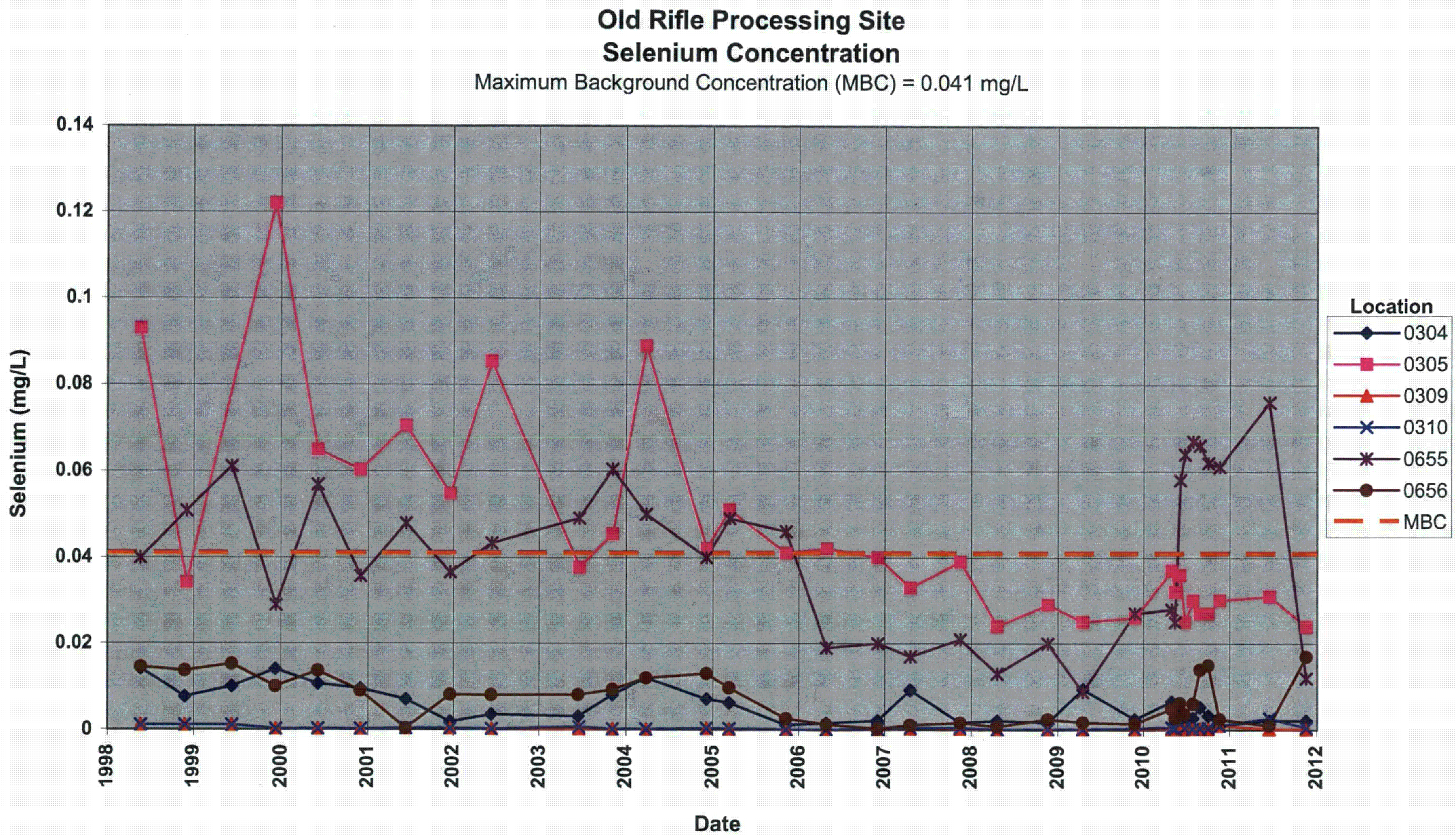

Figure 8. Selenium Time-Concentration Plots

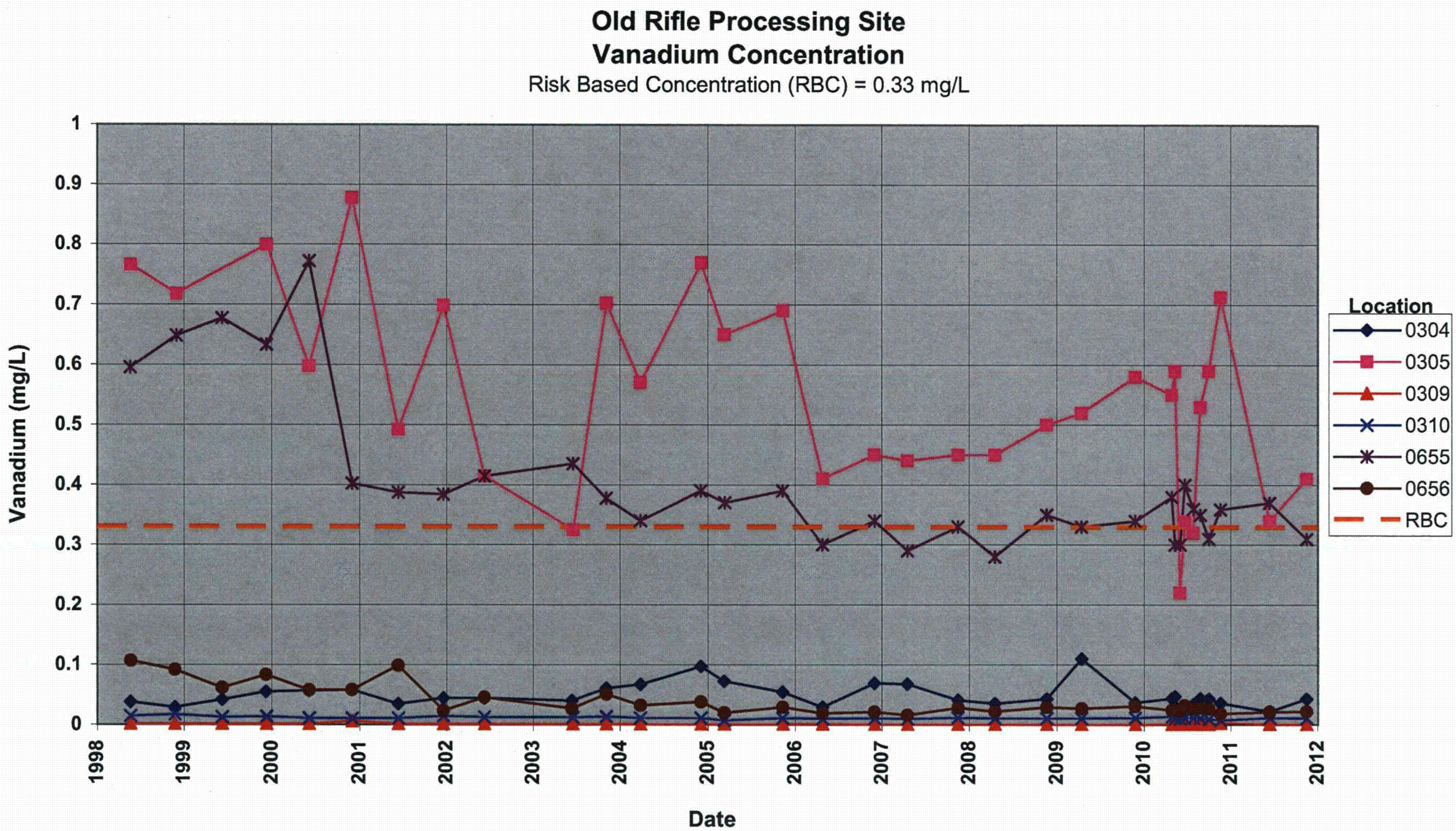

Figure 9. Vanadium Time-Concentration Plots

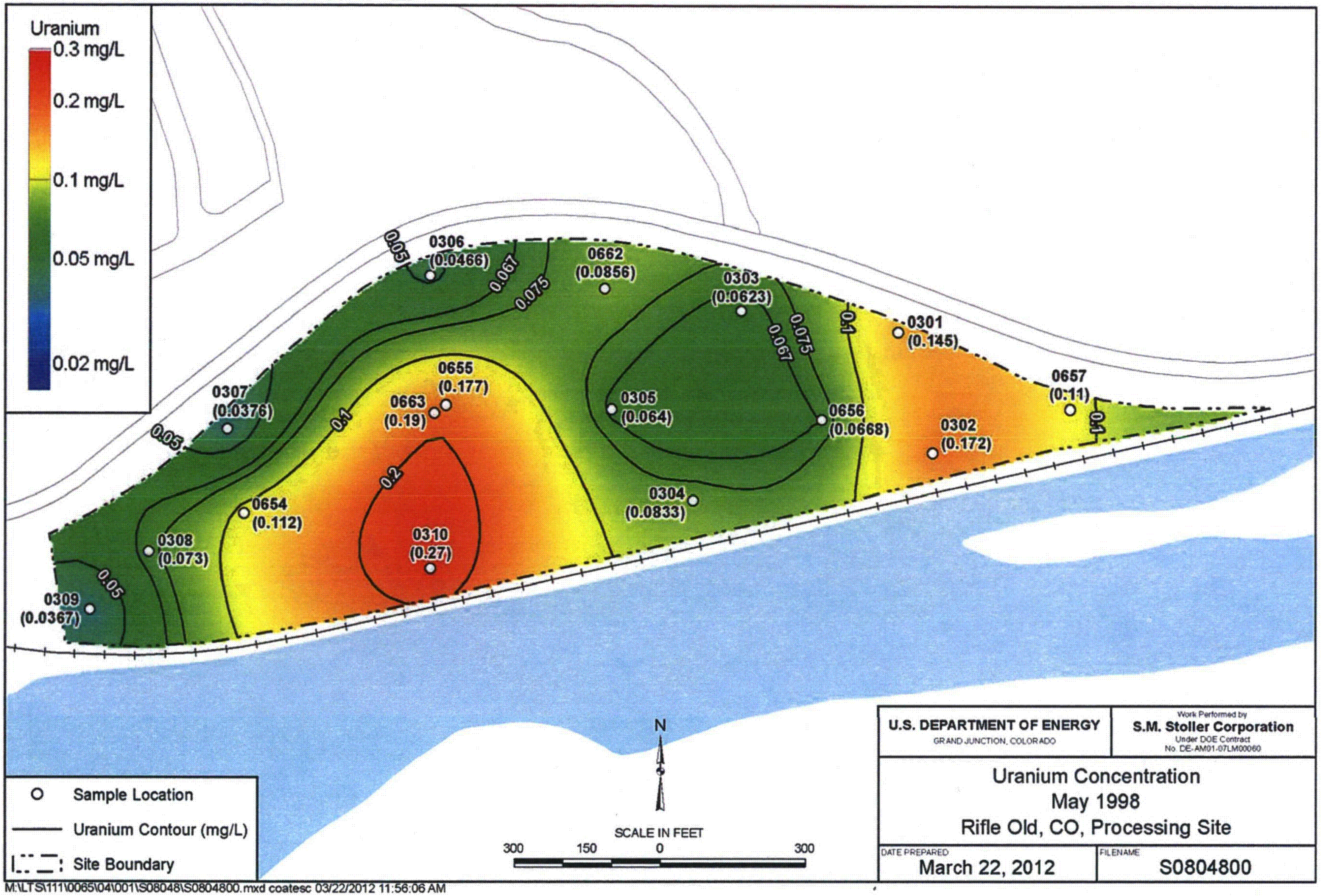

Figure 10. Uranium Concentrations, May 1998

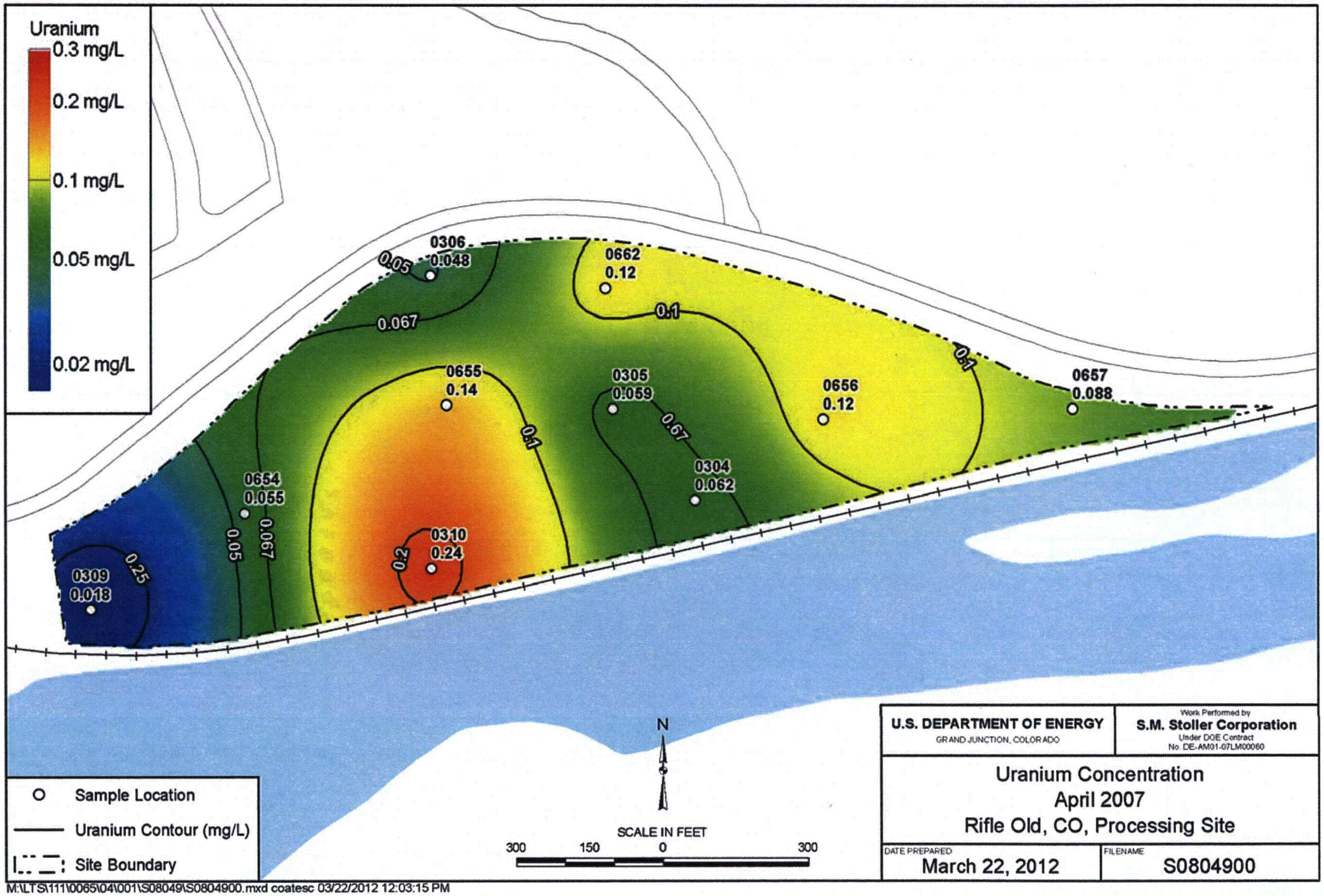

Figure 11. Uranium Concentrations, April 2007

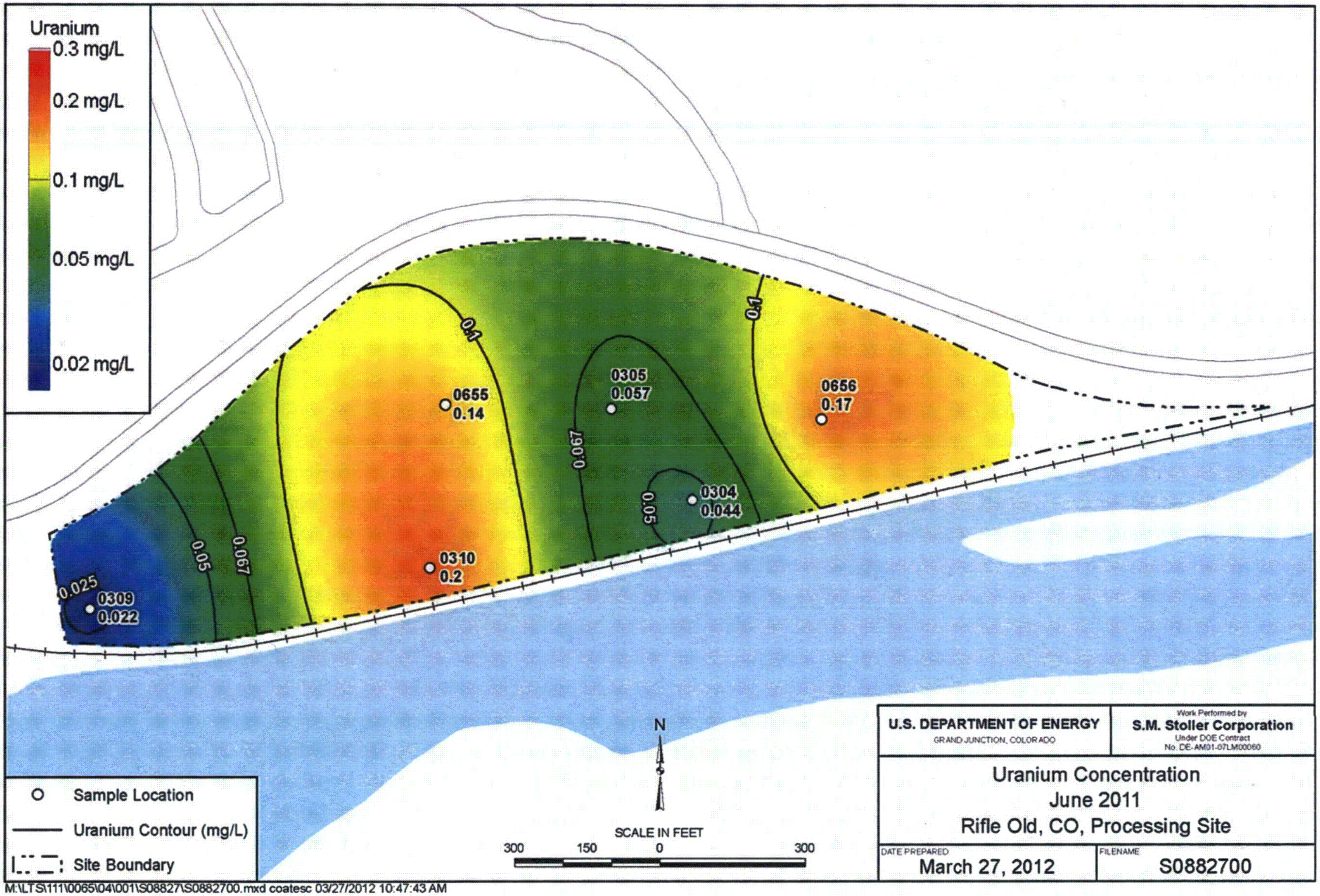

Figure 12. Uranium Concentration, June 2011

Integrated Field Research Challenge (IFRC) studies (see Section 2.3.2). While there is no well control along the northern site boundary, 2011 data from the rest of the site do not appear significantly different from 1998 and 2007 values.

The discussion in the remainder of this GCAP will focus on uranium, which has been the main subject of research at the site. Moreover, uranium is likely to be the most limiting constituent at the site from a groundwater remediation standpoint due to its demonstrated persistence and distribution. Therefore, a compliance strategy that ensures protectiveness with respect to uranium will also be protective with regard to the other site constituents.

2.3 Site Conceptual Model

2.3.1 SOWP Modeling

The SOWP (DOE 1999) presented detailed descriptions of the earlier site conceptual model and associated groundwater numerical simulations; that discussion is not repeated in this document. However, several simplifying assumptions that were made in the earlier modeling are mentioned here because they bear directly on the applicability and effectiveness of the natural flushing compliance strategy.

- The transport processes that were assumed to affect uranium fate in groundwater were limited to advection, mechanical dispersion, and sorption of uranium on aquifer sediments. The first two processes are controlled by the hydraulic characteristics of the alluvial aquifer, leaving sorption as the only chemical process that had the potential to impact aqueous-phase and solid-phase uranium concentrations.
- It was assumed that uranium sorption was an equilibrium phase-partitioning process that could be accurately modeled using a linear soil-water distribution coefficient, or K_d. It was also assumed that the partitioning coefficient remained constant with time and that it maintained a uniform value throughout the aquifer. A series of 100 probabilistic simulations were conducted as part of the numerical modeling in which the K_d was assigned a relatively low value in each model run; the assigned K_ds ranged between 0.0 and 0.2 milliliter per gram (mL/g). These low values were based on a finding in the SOWP that dissolved uranium sparingly sorbs to aquifer sediments and is, therefore, highly mobile in site groundwater. Accordingly, uranium migration through the aquifer was only mildly retarded in the numerical simulations.
- A uniform value of hydraulic conductivity representative of the coarser sediments in the alluvial aquifer (gravels and sands) was adopted in each of the simulations in the probabilistic modeling. This approach treated the aquifer as a homogeneous medium that transmitted groundwater from the most upgradient portions of the aquifer to discharge locations along the Colorado River within periods of less than 5 years. Aquifer heterogeneity and the lower hydraulic conductivities, water velocities, and slow contaminant migration occurring in finer-grained portions of the aquifer (silts and clays) were not taken into account.
- Steady-state flow conditions were assumed in each model run. Seasonal changes in groundwater elevation, flow direction, flow velocity, and aquifer recharge were not simulated.

- Initial concentrations of uranium employed in each model run were based on a plume map generated from concentrations measured at several site wells in May 1998. The total inventory of uranium (dissolved and sorbed) in the aquifer at the start of each simulation (in 1998) was dictated by this set of initial concentrations and the K_d value used in the simulation, with larger K_d values signifying a larger inventory.
- Inflow of uranium mass at concentrations less than the MCL from areas hydraulically upgradient of the site (north of Highway 6&24) was simulated in the model runs. The model assumed that the overlying vadose zone contributed no uranium to groundwater.

All of the probabilistic model runs conducted for the SOWP (DOE 1999) indicated that dissolved uranium concentrations in the aquifer would decrease to levels less than the MCL (0.044 mg/L) within 10 years of the 1998 starting time. As discussed above, such declines of uranium have not been observed, and average dissolved concentrations of uranium are actually higher in 2011 than at the beginning of the natural flushing period (DOE 2011c). While this may partly be a function of differences in past and present monitoring well networks, all indications are that dissolved uranium concentrations in the alluvial system are not declining.

2.3.2 Revision of the Site Conceptual Model

DOE's Office of Science has conducted research at the Old Rifle site since the early 2000s. Individual projects conducted under this research are collectively referred to in this document as the IFRC studies. A primary thrust of this research has been to evaluate the feasibility of immobilizing uranium in the subsurface using enhanced bioremediation techniques. The enhanced bioremediation makes use of biostimulation, in which organic carbon in the form of acetate is injected into the site's alluvial aquifer to promote a chemical oxidation-reduction (redox) reaction that leads to precipitation of uranium as a solid. The redox process is facilitated by indigenous iron-reducing bacteria that reside in the aquifer. The IFRC research has involved numerous experiments and subsurface characterization activities focused on understanding the physical, geochemical, and biological processes in the aquifer, both under background conditions and as a result of the biostimulation.

The IFRC studies have mostly been carried out on the west half of the site within several rectangular areas. Typically, multiple experiments are performed in each area, and individual biostimulation experiments are conducted in small test plots that encompass less than 0.1 acre. Tens of wells are located within each biostimulation plot, with some of the wells being used for acetate injection and others for monitoring the results of the experiment (see Section 4 of the evaluation report; DOE 2011a, Attachment 1). Figure 13 shows the locations of the rectangular areas, the names of many of the individual experiments conducted within them, and the density of wells that have been installed to facilitate the biostimulation experiments and other research experiments. Throughout the IFRC studies, numerical models of uranium transport have been developed and validated using experimental results in an effort to synthesize the multiple hydraulic, chemical, and microbial processes that affect uranium behavior in groundwater.

The IFRC studies differ from the site characterization and modeling performed in support of the SOWP in that the experiments are conducted in a manner that allows researchers to observe groundwater system behavior at a relatively fine scale and over short time intervals. The distances separating monitoring wells in the biostimulation experiments tend to range between 6 and 24 ft, and water samples are collected at intervals ranging from a few weeks to a few

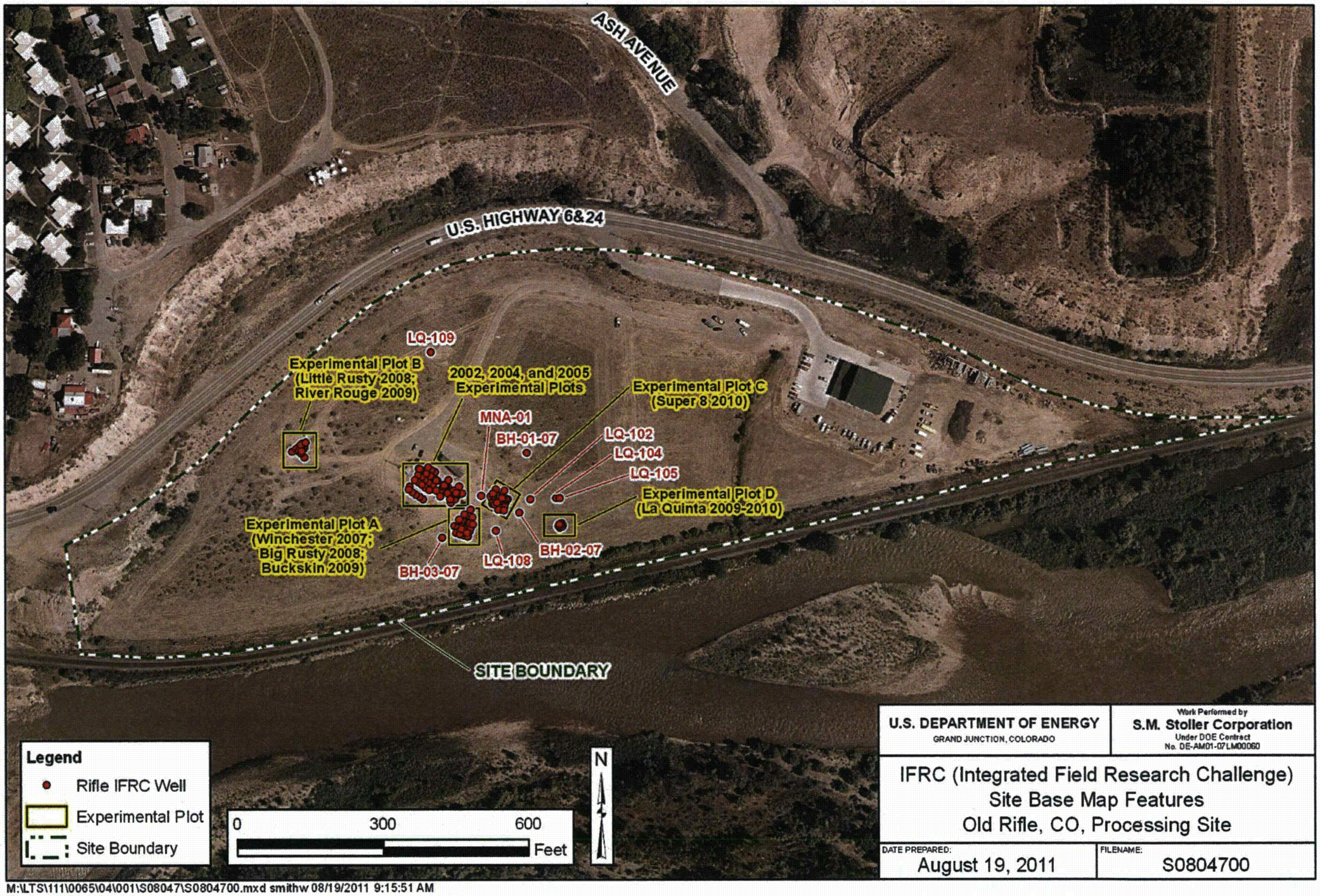

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Figure 13. Integrated Field Research Challenge (IFRC) Site Base Map Features

months. In addition, samples of aquifer sediment have often been collected, during both pre- and post-test phases of individual experiments, and subsequently analyzed for the purpose of better understanding the solid-phase chemistry of the aquifer. Similarly, the various indigenous microbial populations that influence aqueous-phase and solid-phase chemistries have been extensively characterized. Researchers have attempted to more thoroughly describe and quantify the interrelationships between all subsurface processes under both background and stressed (biostimulated) conditions. As a result of this focused work, IFRC researchers have developed a much clearer understanding of site phenomena affecting uranium fate than was possible during characterization phases of the SOWP investigation.

Using both the findings of the IFRC research and continued site monitoring results since initiation of the natural flushing remedy (i.e., since 1998), DOE has reevaluated the potential for natural flushing to meet the proposed groundwater cleanup goals. This reevaluation has led to the development of a revised conceptual model for the site, as presented in Section 6 of the attached natural flushing evaluation report (DOE 2011a, Attachment 1). Using the numerous components of the new model, DOE has also developed a list of potential causes of persistently high uranium concentrations at the site, which are discussed in Section 7 of the evaluation report. Some key elements of the revised site conceptual model include the following:

- The alluvial aquifer at the site is much more heterogeneous than previously assumed. Physical heterogeneities impact groundwater flow and contaminant transport in a variety of ways that cannot be accounted for by assuming the aquifer is homogeneous and dominated by flow in the coarser sediments in the subsurface.
- Complex biogeochemical processes in the aquifer that vary greatly in space and with time play a much more significant role in governing uranium fate than was recognized during SOWP (DOE 1999) investigations. A variety of microbial processes occurring in the aquifer, along with several different abiotic chemical processes, significantly impact uranium concentrations in groundwater.
- The groundwater flow system is dynamic, with groundwater levels rising about 5 to 6 ft in late spring and early summer months in response to high Colorado River levels due to snowmelt runoff. In addition to causing temporary changes in groundwater flow direction, the seasonal high-water levels potentially enable periodic entrainment of uranium that would normally reside in the vadose zone. Similarly, the possibility exists that occasional infiltration and downward percolation of rainfall and snowmelt on the site will leach vadose zone contaminants prior to recharging the aquifer.
- Uranium has the capacity to occur naturally in the aquifer in a chemically reduced form that exists in the solid phase, a phenomenon that is analogous to the uranium reduction induced through biostimulation. The naturally reduced uranium augments the solid-phase uranium sorbed to aquifer sediments, thus adding to the total uranium inventory in the subsurface.
- Sorption of uranium to aquifer sediments cannot be accurately characterized or modeled using a constant, uniform value of K_d because the values of this phase-partitioning coefficient can actually range over an order magnitude or more and change with time. K_d values derived from analysis of IFRC experiments (0.5 to 20 mL/g for hexavalent uranium; see Attachment 1) indicate that uranium is much less mobile (i.e., its transport is more retarded) than was assumed in the SOWP modeling (assumed K_d was 0.2 mL/g).

The new conceptual model indicates that there are likely multiple uranium sources other than those accounted for in the original conceptual model, which assumed that total uranium inventory was governed solely by observed uranium concentrations in groundwater in 1998 and an estimated value of K_d. Several new sources of uranium have been posited, including leaching from vadose zone sediments and supplemental standards areas, chemically reduced zones that occur naturally in the aquifer, and lower-permeability zones within the aquifer. Additionally, inflow of uranium-containing groundwater from offsite areas near the site's north boundary (from background sources and/or supplemental standards areas) is likely of higher concentrations (exceeding the MCL) than accounted for in the SOWP model. Most of these additional sources have the potential to affect the aquifer on a sitewide basis, though such a widespread impact has yet to be demonstrated in detail.

In contrast to a mostly homogeneous, uniformly behaving system (assumed in the SOWP), the alluvial aquifer likely functions as a dual-domain system, in which preferential pathways (mobile domain) are interspersed with less-permeable (immobile domain) zones. Preferential pathways of the coarser-grained materials can have hydraulic conductivities that are as much as 3 or 4 orders of magnitude larger than the conductivities of fine-grained sediments that constitute the immobile domain (DOE 2011a). In addition to causing local groundwater flow paths that are more convoluted than previously assumed, the dual-domain phenomenon leads to disparate contaminant transport rates, with uranium migration being relatively rapid in high-permeability zones and significantly slower in low-permeability sediments. In parts of the groundwater system where contaminant migration is so slow that it is effectively dominated by diffusion rather than advection, the low-permeability zones can act as long-lived contaminant sources that slowly bleed uranium into the mobile domain over time. The naturally occurring, chemically reduced zones typically coincide with low-permeability sediments, particularly those containing clay and significant quantities of natural organic matter. The naturally reduced zones appear to result from background biogeochemical processes in the aquifer and are thought to play a significant role in controlling uranium behavior at the site, though their exact role remains somewhat unclear. IFRC researchers have suggested that these zones may act as contaminant sinks or sources, or possibly both.

As noted previously, elevated levels of uranium have been observed in groundwater in areas upgradient of the site, as manifested in seeps just north of Highway 6&24 (Figure 6). Though not discussed in the attached natural flushing evaluation report, the potential for tailings left in place on the vicinity property along the upgradient edge of the site in the supplemental standards areas (Figure 7) to act as a long-term source of uranium contamination cannot be discounted. Occasional leaching of uranium from these offsite tailings has the capacity to augment the inflow of dissolved, naturally occurring uranium from north of Highway 6&24. Given that dissolved uranium concentrations exceeding the uranium MCL have been observed in wells in the alluvial aquifer at the base of the Highway 6&24 embankment, the combination of natural and tailings-related uranium from offsite sources constitutes a significant contaminant source in the revised conceptual model.

The interplay between numerous physical, chemical, and biological processes at the site, along with the potential for natural and offsite sources of uranium to augment uranium contamination stemming from former milling operations, has likely contributed to the persistence of uranium in site groundwater. Because of these complexities and observed uranium concentrations since the late 1990s, it is unlikely that sitewide compliance with the uranium MCL can be achieved within the 100-year period allowed in 40 CFR 192. Given the lack of uranium attenuation over the last

13 years, the natural flushing evaluation report (DOE 2011a; Attachment 1) also noted that remodeling the site with more complex numerical flow and transport models to better reflect the current understanding of complex processes in the subsurface would be unlikely to yield a different conclusion.

Further evidence of the recalcitrant behavior of uranium in groundwater at the site is presented in Figure 10 and Figure 11, which depict the spatial distribution of dissolved uranium in 1998 and 2007, respectively. These sampling events provided the most complete monitoring coverage immediately following surface remediation and recently. The 2007 plume map is less complete than the earlier one because some of the wells that were sampled in 1998 were subsequently abandoned. Though the 2007 map suggests that concentrations may have declined in portions of the uranium plume between the two sampling events, uranium levels at most uranium plume locations included in the 2007 monitoring event remain far above the MCL of 0.044 mg/L. For example, high concentrations have persisted in the vicinity of wells 0310 and 0656. While only two wells were still present along the northern edge of the site in 2007 (wells 0306 and 0662), it is notable that uranium concentrations at these wells were actually slightly higher in 2007 than in 1998, suggesting that "flushing" of the system by recharge with clean water was not occurring in these locales. It is unclear whether concentrations in alluvial wells near the site's northern boundary are caused by relict contamination in the saturated zone, impacted by natural inflows from groundwater north of Highway 6&24, derived from tailings leachate in supplemental standards areas (Figure 5), or some combination thereof. Wells in those areas were abandoned after the 2007 sampling event, so more recent data are not available. Figure 12 is a plume map based on June 2011 sampling results, which has fewer sampling locations than plume maps shown in Figure 10 and Figure 11. It is noteworthy that results from the most recent (2010–2011) sampling events at well 0656 have yielded the highest uranium values ever detected at this location [(0.17–0.21 mg/L); see Figure 7 and Figure 12.

An element of the original site conceptual model that remains valid is that virtually all groundwater migrating across the site eventually discharges to the Colorado River. Monitoring data for river water samples collected adjacent to the site since the late 1990s has confirmed that this discharge does not increase the surface water concentrations of site-related contaminants above background levels. Figure 6 shows surface water sampling locations along the river; Table 1 summarizes results of the river sampling since 1998.

Table 1. Summary of Colorado River Sampling Results for the Old Rifle Site

Constituent (mg/L)	Location 0538 (Upgradient)	Location 0396 (Adjacent)	Location 0741 (Downgradient)
Selenium	0.0001–0.0007	0.0001–0.0008	0.0001–0.0007
Uranium	0.001–0.0079	0.0008–0.0028	0.0009–0.0027
Vanadium	< 0.0001–0.0011	0.0004–0.0026	< 0.0001–0.0011

Figure 14 shows the complete record of Colorado River sampling results for uranium in the vicinity of the Old Rifle site. It can be seen that background sample location 0538 displayed the highest concentrations and greatest variability. The reason for this is unclear, though the magnitude of total variation in concentration is quite small (within a range of 0.007 mg/L), and all concentrations are well below any water quality benchmarks. These data support the conclusion that discharge of groundwater from the Old Rifle site has no measurable impact on water quality in the Colorado River.

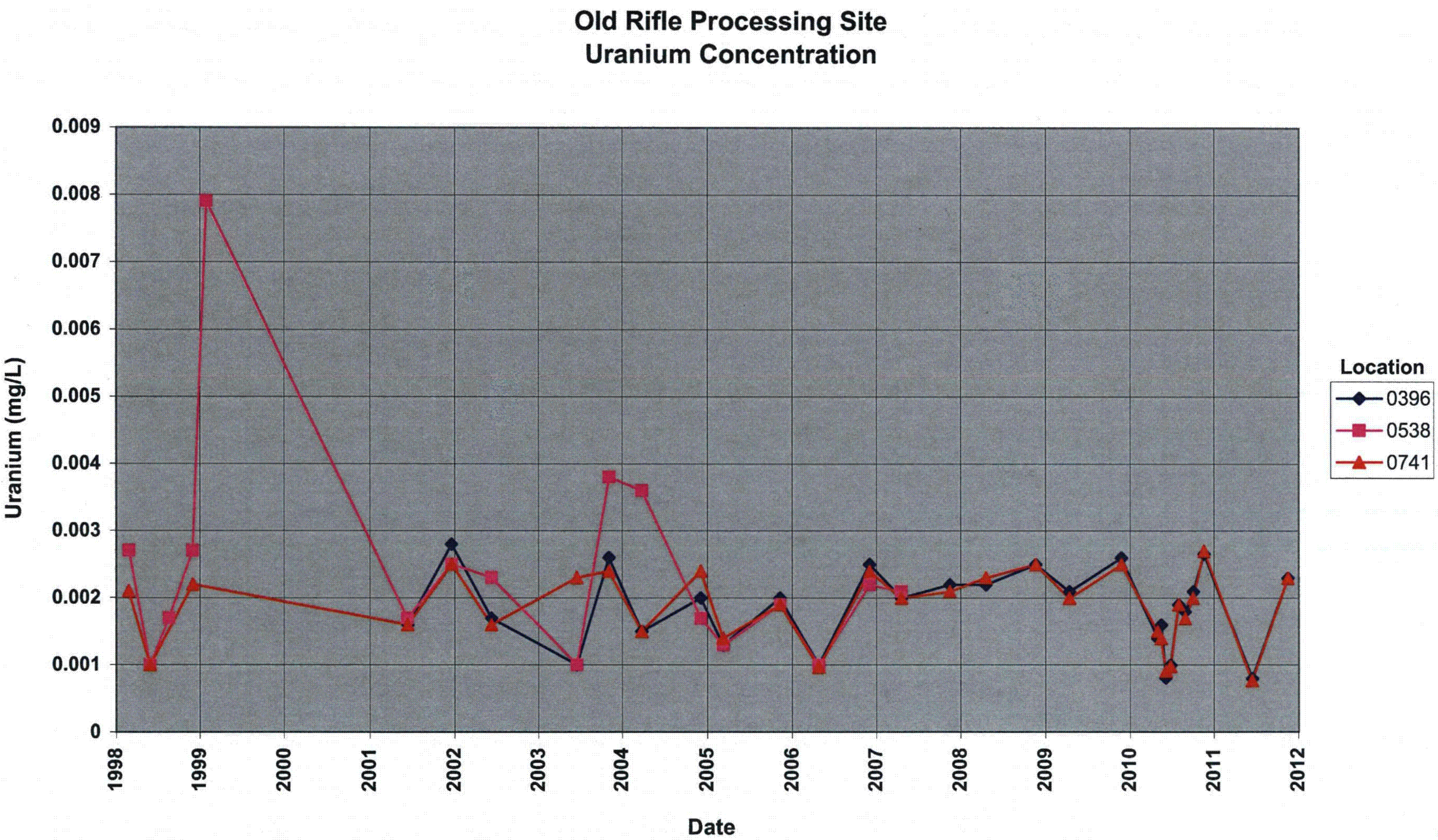

Figure 14. Results of Surface Water Sampling for Uranium

2.4 Assessment of Groundwater Restoration Potential

The potential for fully remediating the aquifer at the Old Rifle site can be further evaluated by examining the new conceptual model for the site from the perspective of guidance developed by the U.S. Environmental Protection Agency (EPA) for evaluating groundwater response strategies (EPA 1993,1996). DOE has adopted this guidance for evaluating the applicability of technical impracticability determinations for groundwater at Comprehensive Environmental Response and Liability Act and Resource Conservation and Recovery Act (RCRA) sites (DOE 1998)[1]. Because groundwater regulations in 40 CFR 192 are patterned after RCRA groundwater regulations, this guidance should also be applicable for groundwater at UMTRCA sites.

The guidance identifies five factors (Figure 15) that should be examined at groundwater contamination sites to assess the relative difficulty of achieving remediation objectives:

- Site use
- Chemical properties
- Contaminant distribution
- Geology
- Hydraulics/flow

Although these are treated as distinct factors in EPA guidance, they are fact interrelated. For example, the chemical properties of a groundwater system are affected by local geology, groundwater flow through the system, the contaminants that have historically impacted the groundwater, and site activities (site use) that led to the release of contaminants in the subsurface. Conversely, chemical reactions in the subsurface (e.g., biologically mediated precipitation of minerals) have the potential to influence groundwater flow by affecting local hydraulic properties of the aquifer such as hydraulic conductivity and porosity. Sections 2.4.1 through 2.4.5 describe multiple features of the Old Rifle site from the perspective of these five guidance factors.

2.4.1 Site Use

Operations at the site started in 1924, and the site operated for 24 years before closing in 1958. Most of tailings were removed at that time for reprocessing at the New Rifle site; materials that remained at the site sat largely uncontrolled before tailings were stabilized in place in 1967 (DOE 1992). That is how the site remained until surface remediation commenced in 1992. The site was covered at various times with tailings piles, ore stockpiles, and several ponds, such that the entire property was disturbed by milling-related activities at some time or another (Figure 4). Surface cleanup under the Uranium Mill Tailings Remedial Action (UMTRA) Project required remediation to meet only the Ra-226+Ra-228 standard, but even that standard could not be met for materials in an adjacent vicinity property located along the northern site boundary adjacent to the highway embankment (and possibly below the water table). Similarly, subpile soil sampling at the site as part of the characterization effort for the SOWP (DOE 1999) identified residual uranium contamination in solid-phase materials remaining at the site. As mentioned in

[1] CERCLA: Comprehensive Environmental Response, Compensation, and Liability Act
RCRA: Resource Conservation and Recovery Act

Examples of Factors Affecting Groundwater Restoration

Certain site characteristics may limit the effectiveness of subsurface remediation. The examples listed below are highly generalized. The particular factor or combination of factors that may critically limit restoration potential will be site specific.

Generalized Remediation Difficulty Scale
Increasing Difficulty →

	Contaminant Characteristics		→	
Site Use	Nature of Release	Small Volume Short Duration Slug Release	→	Large Volume Long Duration Continual Release
Chemical Properties	Biotic/Abiotic Decay Potential	High	→	Low
	Volatility	High	→	Low
	Contaminant Retardation (Sorption) Potential	Low	→	High
Contaminant Distribution	Contaminant Phase	Aqueous, Gaseous → Sorbed → LNAPLs	→	DNAPLs
	Volume of Contaminated Media	Small	→	Large
	Contaminant Depth	Shallow	→	Deep

	Hydrogeologic Characteristics			
Geology	Stratigraphy	Simple Geology (e.g., Planar Bedding)	→	Complex Geology (e.g., Interbedded and Discontinuous Strata)
	Texture of Unconsolidated Deposits	Sand	→	Clay
	Degree of Heterogeneity	Homogenous (e.g., well-sorted sand)	→	Heterogeneous (e.g., interbedded sand, silts, clays, fractured media, karst)
Hydraulics/Flow	Hydraulic Conductivity	High (>10^{-2} cm/s)	→	Low (<10^{-4} cm/s)
	Temporal Variation	Little/None	→	High
	Vertical Flow	Little	→	Large Downward Flow Component

Note: DNAPLs = dense nonaqueous-phase liquids, LNAPLs = light nonaqueous-phase liquids, cm/s = centimeters per second

Figure 15. Factors Affecting Groundwater Restoration

Section 2.1, soil concentrations of up to 12 mg/kg uranium remained in the former ore stockpile area, although the average concentration observed was generally less than 2 mg/kg total extractable uranium.

Contaminant releases at the site involved large volumes of tailings and ore, both of which were located on site for long durations (decades). Leaching of these sources and subsequent downward migration to the water table provided continual mass loading of contaminants to the alluvial aquifer during the many years leading up to the beginning of surface remediation in 1992. This type of release ranks at the high end of the difficulty scale for groundwater restoration (Figure 15).

2.4.2 Chemical Properties

Uranium is not volatile, its radioactive isotopes decay very slowly, and biodegradation of this inorganic element is not possible. IFRC studies (e.g., Williams et al. 2010; Williams et al. 2011) have shown that uranium has the potential to occur in solid forms within the aquifer, through both biologically mediated precipitation of dissolved uranium and sorption onto aquifer sediments. Though the solid-phase uranium is relatively immobile, groundwater migrating through the aquifer can release it into the mobile domain under certain conditions. Thus, the reservoir of uranium within and sorbed to aquifer sediment grains provides continuing sources of groundwater contamination over time.

Though chemical-constituent transport processes in the naturally reduced zones at the site have yet to be fully characterized, IFRC researchers consider the reduced zones and other low-permeability parts of the aquifer to be significant reservoirs of solid-phase uranium and potentially capable of releasing uranium to groundwater for many years. The transport processes leading to dissolution of the solid-phase uranium are complex, varying both spatially and temporally. Short of removing all aquifer materials at the site, as well as any underlying rock in the Wasatch Formation that may have also been contaminated, it is difficult to envision how persistent uranium releases from aquifer sediments can be stopped.

2.4.3 Contaminant Distribution

Uranium is distributed throughout most of the alluvial aquifer. Two distinct uranium plumes, located on either side of a north-south-trending ditch that bisects the property, appear to contain a majority of the subsurface inventory of uranium at the site (Figure 11; ditch apparent in Figure 12). In addition to containing most of the local dissolved uranium inventory, these plume areas also likely contain substantial quantities of solid-phase (sorbed and precipitated) uranium mass. It is difficult, if not impossible, to quantify the solid-phase uranium mass in the two plume areas, let alone identify specific zones within them that exhibit properties conducive to accumulation of uranium solids (e.g., low-permeability clays and silts, chemically reducing conditions). Release of uranium into the dissolved phase in these locales has been persistent enough since the completion of surface remediation in 1996 to either maintain aqueous uranium concentrations at constant levels or gradually increase them at most onsite wells. This observation suggests that such solid-phase uranium source areas, though not uniform throughout the aquifer, are widespread. These apparently long-term sources of aqueous uranium contamination present obstacles to remediation that are similar to those associated with dense nonaqueous-phase liquids that are often found at sites contaminated by organic chemicals.

Though the effects of their presence can be obvious (persistently high contaminant concentrations), their exact locations in the subsurface are difficult to pinpoint, and their removal is extremely challenging, particularly in environments where they are widespread.

Further evidence of the widespread distribution of contaminant mass in the alluvial aquifer is seen in historical uranium concentrations in monitoring wells near the north border of the site, at the base of the Highway 6&24 embankment. Though some of these wells have been abandoned since the late 1990s, all have at some time point had uranium concentrations that exceeded the uranium MCL. As mentioned in Section 2.3.2, the uranium concentrations at two of these wells (0306 and 0662) were greater than the MCL in 2007. Since the monitoring wells located at the base of the Highway 6&24 embankment are reflective of the water feeding the uranium plumes dominating both sides of the on-site ditch, the likelihood that upgradient portions of those plumes would soon exhibit significant concentration decreases due to an influx of "fresh water" appears low.

2.4.4 Geology

On first glance, the geology of the Old Rifle site appears to be relatively simple, with groundwater appearing to flow primarily within a shallow aquifer composed of alluvial sediments that are mostly sands and gravels. However, the revised conceptual model for the site, based on both IFRC findings and DOE's reassessment of local groundwater processes, indicates that the subsurface is quite heterogeneous. Single cores obtained from the subsurface typically contain several alternating layers of fine-grained and coarse-grained sediments. Similarly, it is common for the geologic log for individual site wells to show distinct layers of clays and silts interspersed with large sand and gravel horizons, and many of the more gravelly layers are often described as having clay or silt composing the matrix between the coarser materials. Such heterogeneity contributes to the dual-domain phenomenon described in Section 2.3.2 as playing a significant role in delaying the flushing of dissolved-phase uranium from the aquifer.

Adding to the complexity of the alluvium's composition is the fact that fine-grained fill, with typical thickness of 5 to 10 ft, was placed over the entire site after removal of tailings during surface remediation. The fine-grained fill influences infiltration of precipitation and groundwater recharge processes at the site, but its influence on the local hydrogeology is unclear. Though it is also uncertain whether the underlying Wasatch Formation bedrock plays a role in the fate of remnant uranium contamination, the geologic complexities affecting any groundwater remediation at the site would certainly increase if contamination were detected in this hydrogeologic unit.

The natural chemically reduced zones in the alluvial aquifer further illustrate the degree to which geologic heterogeneity might impact groundwater cleanup at the site. The organic materials in these zones, which were deposited syngenetically with fine-grained suspended loads carried by the ancestral Colorado River, are the apparent drivers for the microbially mediated redox processes that produce significant localized quantities of solid-phase uranium mass. Given that the naturally reduced zones are not detected throughout the alluvial aquifer, and their extents are uncertain, it stands to reason that the river deposition processes leading to their current, uncertain spatial distribution were quite complex, as is their apparent role as long-term contributors to aqueous uranium in groundwater.

2.4.5 Hydraulics/Flow

As emphasized in the revised site conceptual model, the heterogeneity of the alluvial aquifer results in a groundwater system in which hydraulic conductivities can vary by as much as 3 to 4 orders of magnitude over relatively short distances (tens of feet). This observation, when combined with the fact that the groundwater system is subject to temporally varying stresses, particularly during late-spring and early-summer runoff months, suggests that full aquifer remediation would be difficult or impossible. This conclusion is unavoidable even though groundwater flow through the aquifer is predominantly horizontal and directed entirely toward discharge locations along the Colorado River (latter component rated low on difficulty scale in Figure 15). Contaminant releases at the site involved large volumes of tailings and ore, both of which were located on site for long durations (decades). Leaching of these sources and subsequent downward migration to the water table provided continual mass loading of contaminants to the alluvial aquifer during the many years leading up to the beginning of surface remediation in 1992. This type of release ranks at the high end of the difficulty scale for groundwater restoration (Figure 15).

2.4.6 Overall Restoration Potential

The original flow and transport modeling that formed the basis for selection of a natural flushing compliance strategy assumed that site characteristics could be simplified in a manner that favored full restoration of the alluvial aquifer (left side of the difficulty scale in Figure 15). Because IFRC research during the past 9 years and DOE's reassessment of the site conceptual model indicate that flow and transport processes are much more complex than earlier thought (right side of the difficulty scale), restoration of the aquifer will be more difficult than originally conceived. Though the possibility that some form of remediation could eventually succeed cannot be ruled out, the methods used to accomplish aquifer cleanup would have to be robust enough to overwhelm the large variety of hydraulic, chemical, and biological processes that currently control uranium behavior on a sitewide scale.

Experience at other DOE sites has shown that remediation of uranium is more problematic than anticipated. The "tailing" effect, in which concentrations of uranium tend to remain above applicable standards over many tens of years, has been observed at a number of UMTRCA Title I and Title II sites. Examples of such sites include those at Tuba City, Arizona (DOE 2010), and Split Rock, Wyoming (WNI 1999), both of which have undergone active remediation. Though uranium concentrations at those locations showed significant decreases during the first few years of remediation, they then leveled off to relatively constant values that remained above applicable standards. However, unlike at the Old Rifle site, the primary sources of uranium (i.e., tailings piles) at these and other former mill sites have been stabilized in place in disposal cells, and gradually decreasing remnant seepage from the cells might still be impacting underlying groundwater systems.

At another uranium mill tailings site—the Monticello, Utah, Operable Unit III Superfund site—concentrations of uranium have not declined according to model predictions after a number of years of active remediation coupled with monitored natural attenuation (DOE 2011b). As at Old Rifle, mill tailings at the Monticello site were removed. In addition, secondary source materials (alluvial sediments) located beneath the tailings were completely removed down to bedrock, leaving only uranium in downgradient portions of the affected aquifer as a potential contaminant source. While removal of the tailings and contaminated alluvial materials produced significant decreases in uranium contamination, continued remediation of groundwater through use of a permeable reactive barrier coupled with extraction and treatment of groundwater has been ineffective in further reducing uranium concentrations. As with the Old Rifle site, concentrations have leveled off in the 0.1 to 0.2 mg/L range. The proposed reason for the recalcitrant contamination is slow release of uranium bound up in aquifer materials through adsorption or other, unknown mechanisms (DOE 2011b).

Assessments of subsurface remediation at the Monticello site and UMTRCA sites suggest that remediation of uranium in groundwater in alluvial aquifer settings is much more difficult than previously expected. Short of completely removing all affected aquifer materials at a site, both active and passive remediation efforts face significant limitations.

Despite a better understanding of the site conceptual model, it does not appear that alternatives to the natural flushing remedy (e.g., pump-and-treat, in situ chemical manipulation) would improve the potential for restoring the aquifer at Old Rifle. As with natural flushing, active remediation approaches would face serious limitations in removing uranium from a heterogeneous aquifer containing persistent long-term contaminant sources. The same factors that would limit active remediation would also limit more-passive, in situ methods for either immobilizing or mobilizing uranium.

EPA guidance (EPA 1993) notes that if TI is applied, an alternative remedial strategy then becomes appropriate. There are three main objectives in implementing an alternative remedial strategy—exposure control, source control (removal or containment), and remediation of the aqueous plume outside the containment area. As discussed in Section 2.5, exposure control at the Old Rifle site has been achieved through the implementation of ICs. Primary source control at the site was addressed by surface remediation, but secondary sources persist, likely throughout the alluvial aquifer. However, these sources are isolated and confined to the site boundary by the geologic characteristics of the site. Additionally, there is no dissolved plume beyond the source areas that requires remediation. Current site conditions therefore satisfy requirements for an alternative remedial strategy.

2.5 Human Health and Environmental Risks

Baseline risks associated with the Old Rifle site were assessed in the SOWP (DOE 1999). The risk assessment concluded that use of groundwater as a drinking water source was unacceptable. It was also determined that site conditions presented no complete pathways by which site-related contamination could adversely affect ecological receptors.

Site conditions can be summarized as follows:

- The alluvial aquifer is isolated—bounded both laterally and vertically.
- For groundwater compliance purposes, the entire site would be considered the "facility." There is no hydraulically connected aquifer downgradient of the facility; the aquifer ends at the facility boundary.
- ICs prohibit any use of site groundwater.

- Water from the aquifer discharges to the Colorado River (the only potentially complete point of exposure to site-related constituents), where any site-related contamination rapidly mixes with river water; river water quality adjacent to the site is indistinguishable from background surface water quality. The estimated dilution factor for the river is on the order of 3×10^{-5} under average flow conditions (DOE 1999).
- Uranium concentrations in the site groundwater since completion of surface remediation have consistently been less than 1 mg/L. Given these relatively low groundwater concentrations and the high degree of dilution with discharge to the river, it is virtually impossible for site-related contamination to have an adverse impact on river water quality. The surface water quality standard for the river is 0.03 mg/L based on its use as a source of drinking water (CDPHE Regulation No. 31).

Based on restrictions prohibiting groundwater use, it can be concluded that current site conditions are protective of human health and the environment. In most wells, contaminant concentrations in groundwater have been stable for more than a decade, and those conditions are expected to continue. No adverse site-related effects have ever been observed in the Colorado River (the only point of exposure). Therefore, protectiveness will be maintained as long as ICs restrict groundwater use. The alluvial aquifer at the Old Rifle site has never been used for beneficial purposes. With the Colorado River as a plentiful and high-quality source of water, the need for alluvial groundwater use in the future, particularly from an aquifer that is so limited in areal extent, is highly unlikely.

2.6 Institutional Controls

Residual contamination will remain in the groundwater for an extended period; therefore, it is critical that ICs be maintained to ensure protectiveness of the remedy. Groundwater contamination at the Old Rifle processing site has not migrated into any offsite aquifers; it discharges directly into the Colorado River where it rapidly mixes with river water. ICs correspond to the site boundary, thus simplifying their monitoring and verification. Multiple layers of ICs restricting groundwater use have been established for the Old Rifle site. Copies of all ICs are provided in Appendix A, "Institutional Controls for the Old Rifle Site."

This section describes the three ICs—transfer of title with the Quitclaim Deed restrictions, environmental covenant (EC), and UMTRA Overlay Zone District—and the general requirements for verifying their performance.

Transfer of Title to the City of Rifle with the Quitclaim Deed (2003): Along with transfer of the property to the Grantee (City of Rifle), eight requirements were agreed upon as listed in the last paragraph of the deed. As stated in the deed, the City agrees:

(i) to comply with applicable provisions of UMTRCA, 42 U.S.C. #7901 as amended;

(ii) not to use ground water from the site for any purpose, and not to construct wells or any means of exposing ground water to the surface unless prior written approval for such use is given by the Grantor [State of Colorado] and U.S. Department of Energy;

(iii) not to sell or transfer the land to anyone other than a government entity within the state;

(iv) that any sale or transfer of the property described in this deed shall have prior written approval from the Grantor and the U.S. Department of Energy; and that any deed or other document created for such sale or transfer and any subsequent sale of transfer will include information stating that the property was once used as a uranium milling site and all other information regarding the extent of residual radioactive materials removed from the property as required by Section 104(d) of the Uranium Mill Tailings, 42, U.S.C. sec. 7014(d), and as set forth in the Annotation attached hereto;

(v) not to perform construction and/or excavation or soil removal of any kind on the property without permission from the Grantor and the U.S. Department of Energy unless prior written approval of construction plans is given by the Grantor and the U.S. Department of Energy;

(vi) that any habitable structures constructed on the property shall employ a radon ventilation system or other radon mitigation measures;

(vii) that its use of the property shall not adversely impact groundwater quality, nor interfere in any way, with groundwater remediation under UMTRCA activities, and

(viii) to use the property and any profits or benefits derived therefrom only for public purposes as required by UMTRCA sec 104 (e)(1)(C), 42 U.S.C. 7914 (e)(1)(C).

Verification that the City has upheld these conditions will be an ongoing process, accomplished throughout each year by (1) discussions with City officials about construction projects and possible incursions of groundwater that could result from these activities, (2) physical inspection of the site by State and/or DOE contractor staff, usually at the time of the annual disposal site inspection, and (3) observations by groundwater sampling staff at other times of the year; those observations will be included in their trip reports.

Environmental Covenant (2004): The Colorado Department of Public Health and Environment (CDPHE) executed an EC pursuant to section 25-15-321, C.R.C. It reiterates requirements *(i)* to *(viii)* in the Quitclaim Deed and provides guidance for modification or termination of the stipulations, all of which require protection of human health and the environment.

According to Section 10 of the EC, the owner of the EC (City of Rifle) is required to submit to CDPHE an annual report of site activities. The report is due on the date that the EC was executed by the City. The annual report details the owner's compliance, and any lack of compliance, with the terms of the covenant.

UMTRA Overlay Zone District, Ordinance No. 9 Series of 2008: The City of Rifle created the UMTRA Overlay Zone District and included in the district the Old (East) and New (West) Rifle sites. The purpose of the district was to establish procedures and restrictions governing development of the properties in a new municipal code (Section 16-3-540). The new ordinance reiterated requirements *(i)* to *(viii)* in the Quitclaim Deed and provided eight standard operating procedures (SOPs) for conducting activities within the UMTRA Overlay Zone District (i.e., the Old and New Rifle sites).

The SOPs require the City to secure written permission from the State and DOE when intrusive work is planned for the site, to formalize training for subcontractors working on the site, to include a Materials Handling Plan as needed, and to submit a Completion Report to the State for all projects. In addition, the city manager is required to provide an annual summary of activities to City officials regarding these SOPs, deed restrictions, and ECs. While neither CDPHE nor DOE are signatories to a zone overlay, the restrictions it contains are covered in the Quitclaim Deed, and the Quitclaim Deed mandates both CDPHE and DOE approval for proposed actions at the site.

Verification is required Under No. 8 of Subsection (d), the SOPs. The city manager shall annually inform all City department heads of the SOPs, deed restrictions, and environmental covenants affecting the UMTRA sites.

Reporting Verifications of ICs

At a minimum, verifications that ICs remain protective will be reported in the annual Rifle Verification Monitoring Reports (VMRs) that DOE submits at the end of each fiscal year.

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3.0 Groundwater Compliance

The groundwater compliance selection process follows the decision framework outlined in the PEIS (Figure 1). Characterization data for the site (Figure 1, Box 1 of the framework) was presented in the surface remedial action plan (DOE 1992), the SOWP (DOE 1999), and the natural flushing evaluation report (DOE 2011a, Attachment 1), as well as annual verification monitoring reports for the site. Those data are summarized in this document and are sufficient for selecting the appropriate groundwater standards for the site and the compliance strategy for achieving those standards.

3.1 Compliance Strategy Selection

The selection of a compliance strategy involves the identification of both the appropriate groundwater standard and the mechanism for achieving that standard. As specified in 40 CFR 192.12 (c), four basic groundwater cleanup standards can be applied at Title I sites:

- Background concentration limits (40 CFR 192 [c][3][i][A])
- Maximum concentration limits (Table 1 of 40 CFR 192, Subpart A)
- Alternate concentration limits (40 CFR 192.02[c][3][ii])
- Supplemental standards (40 CFR 192.21 and 192.22)

The mechanisms for achieving one of those standards are no remediation (if the standards are already met), natural flushing (if the standards can be met within 100 years through passive remediation), active remediation (if passive remediation alone is not sufficient to meet standards), and some combination of active remediation and natural flushing.

The compliance strategy selection process for the Old Rifle site uses the decision framework presented in Figure 1. It is necessary to revisit the compliance strategy because concentrations of uranium, which were predicted to decrease below the MCL in a 10-year period, still persist at levels exceeding both the MCL and background ("YES" to Box 2).

The initial steps in the framework examine the possibility of achieving compliance without requiring the consideration of any form of remediation. According to Figure 1, DOE must first consider whether groundwater qualifies for supplemental standards based on "limited use" (40 CFR 192.119[e]; Box 4). As was the case during the original compliance strategy selection, Old Rifle site groundwater does not consistently meet any of the limited use criteria (i.e., ambient contamination unrelated to milling, <150 gallons/day aquifer yield, natural total dissolved solids levels >10,000 mg/L). However, since that time, additional monitoring has affirmed that background levels of uranium can be elevated above the groundwater standard (see Section 2.3.2). This alone cannot explain the persistently elevated uranium concentrations observed at the site and is not sufficient grounds to qualify groundwater as "limited use" ("NO" to Box 4).

Next in the decision framework, DOE must consider if groundwater qualifies for ACLs. EPA noted in its preamble to the final rule (60 FR 2857) that it retained the provision for applying ACLs to accommodate (1) minor projected seepage from a disposal cell and (2) cleanup situations involving pollutants for which no MCLs exist. EPA references its ACL guidance document (OSWER Directive 9481.00; EPA 1987), as well as NRC's technical position on the use of ACLs at UMTRCA Title II sites (NRC 1996), as being consistent with EPA's intended approach for the use of ACLs at Title I sites. In both of these guidance documents, ACLs are intended to apply at points of compliance at the downgradient edge of a "disposal facility" or "disposal unit." The ACLs serve as a "trigger level" for commencing corrective action if releases from the disposal unit have the potential to negatively impact the downgradient aquifer system.

As discussed in previous sections, contamination remaining at the Old Rifle site is mainly secondary contamination that has been sequestered in small pockets throughout the aquifer materials. This situation is unlike an engineered disposal unit where monitoring is required to confirm/assess the performance of the containment system and ensure that no releases are occurring. Additionally, there is no hydraulically connected aquifer downgradient of or beneath the Old Rifle site that requires protection; the source of continuing groundwater contamination at the site is effectively geologically isolated. It has been demonstrated that dilution of groundwater discharging to the Colorado River is so high that it would be impossible for site-related contaminants to have an adverse impact on surface water quality based on the quantities of uranium that remain in the alluvial aquifer system. Therefore establishment of a numerical ACL for uranium in groundwater at the site is unnecessary ("NO" to Box 6).

Supplemental standards may also be applied to groundwater at a site if remediation would result in "excessive environmental harm" (Box 8). No particularly sensitive environments are present at the Old Rifle site, and there are various methods of groundwater remediation that would not result in excessive environmental harm if implemented ("NO" to Box 8). Supplemental standards on these grounds cannot be justified.

According to Figure 1, it is next necessary to consider whether natural flushing can be effective at the site. Considerable discussion in this document has been devoted to demonstrating that it is unlikely that either background levels or the MCL can be achieved for uranium at the Old Rifle site through natural flushing alone ("NO" to Box 10). Site subsurface complexity has rendered natural attenuation ineffective, as average groundwater uranium concentrations have remained nearly constant over the 15 years since surface remediation was completed. The same factors that impede natural attenuation processes are likely to make background or the MCL unattainable through more aggressive remedial methods as well (i.e., active remediation with or without natural flushing; "NO" to Box 13 and 15). This leads to a consideration of whether groundwater remediation is "technically impracticable from an engineering perspective" (40 CFR 192.21[f]; Box 17 on Figure 1).

As discussed in Section 2.4, the alluvial aquifer at the Old Rifle site does have numerous characteristics that negatively affect the restoration potential of the system. In the preamble to the final groundwater rule, EPA provided some insight into situations in which groundwater restoration is considered to be technically impracticable: "For example, there may not be enough water available in a very small aquifer to carry out remediation and retain the groundwater resource, or, in other cases, some contaminants may not be removable without destroying the aquifer. EPA believes that DOE should not be required to institute active measures that would completely restore groundwater at these sites if such restoration is technically impracticable" (60 FR 2862). They further specify that use of supplemental standards should "...come as close to meeting the otherwise applicable standards as is reasonably achievable under the circumstances..." (60 FR 2861).

It is DOE's position that groundwater at the Old Rifle site is technically impracticable to restore and qualifies for supplemental standards on these grounds. It has already been shown that natural flushing is not likely to result in compliance with MCLs or background. It is also DOE's position that for any active remediation approach to be effective, it would likely require destruction of the aquifer in order to remove secondary source material. Less aggressive remedial actions could be implemented that would probably remove additional mass, but these actions would be unlikely to have a significant impact on overall groundwater concentrations based on the fact that concentrations have been largely static for the last 15 years. Technologies that immobilize uranium could result in concentration reductions, but this would likely not be a permanent phenomenon, and future contaminant releases would be considered likely, as evidenced by selenium behavior at the site. Surface remediation achieved an order-of-magnitude reduction in groundwater contaminant concentrations, but little further attenuation has been realized since then due to the likely presence of continuing sources of uranium in tailings remaining in supplemental standards areas, secondary contamination of aquifer materials (adsorbed or precipitated), and incoming background groundwater. Therefore, for all practical purposes, current contaminant levels at the site are considered as low as reasonably achievable.

Site conditions already meet the objectives of an alternate remediation strategy as described by EPA (1993)—exposure control, source containment, and restoration outside of the containment area. The RAP for the site (DOE 1992) estimated that the volume of material requiring removal was 501,000 cy from the Old Rifle site and 2,790,000 cy from the New Rifle site. Figures are not available for final volumes removed from each site. However, the total volume removed from both sites was 4,135,000 cy (GAO 1995). It is therefore likely that the actual volume of material removed from the Old Rifle site equaled or exceeded the original estimate. Further removal of soils, if possible by regulation, would effectively destroy the alluvial aquifer in the area of excavation.

Conditions are currently protective and will remain so as long as ICs are maintained. Three layers of IC currently exist at the site, and these controls will be maintained into the foreseeable future. Natural processes might further attenuate contamination in the aquifer, but these processes are not relied upon to achieve more stringent cleanup levels with the proposed compliance strategy. The remaining sources of groundwater contamination at the site (i.e., aquifer materials, supplemental standards areas) are naturally contained by geologic barriers and the Colorado River. There is no aquifer beyond the boundary of the site that is hydraulically connected to groundwater at the site; any groundwater discharged to the river (the point of exposure) is diluted to the point of being indistinguishable from background.

Based on the conditions described above, DOE is proposing a compliance strategy for the Old Rifle site of "no remediation with the application of supplemental standards based on TI." No numerical groundwater standards are required, as past and likely future groundwater conditions have been demonstrated to be protective of human health and the environment. This compliance strategy is applicable to all remaining contaminants at the site. Based on average concentrations at the site, selenium and vanadium already comply with standards agreed upon in the 2001 GCAP. While it is possible that concentrations in all wells could eventually meet their standards for these constituents through continued natural attenuation (selenium standards were met at all wells for a period of time), those constituents are irrelevant as long as uranium concentrations are sufficiently high to require ICs.

Since there are no risks to human health and the environment, DOE's Office of Legacy Management (LM) intends to allow for continued floodplain-wide study by IFRC personnel for the next few years. Information gained would provide enhanced methods of characterization, sampling, and monitoring and could help refine modeling of the fate and transport of COCs. This information could be applicable to the understanding of similar processes at other DOE sites and UMTRCA sites in particular. The continued use of the site as a field laboratory of the Office of Science and LM's continued monitoring at the site for some time to come will help ensure the appropriateness and protectiveness of the proposed TI remedy.

Table 2 summarizes the groundwater compliance strategy selection process for the Old Rifle site.

Table 2. Explanation of Compliance Strategy Selection Process

Box	Action or Question	Result or Decision
1	Characterize plume and hydrological conditions.	Revised site conceptual model described in DOE 2011a; Attachment 1 to the GCAP. Move to Box 2.
2	Does groundwater contamination exceed UMTRA MCLs or background?	Uranium exceeds the UMTRA MCL and site background. Move to Box 4.
4	Does contaminated groundwater qualify for supplemental standards due to limited use groundwater?	Alluvial groundwater does not consistently meet the criteria for limited use groundwater, though some background samples have exceeded the MCL for uranium. Supplemental standards based on limited use cannot be justified. Move to Box 6.
6	Does contaminated groundwater qualify for ACLs based on acceptable human health and environmental risk and other factors?	The use of ACLs is not warranted based on site-specific conditions. There is no disposal cell on site and no downgradient aquifer system. Contamination is geologically isolated and confined to the Old Rifle site. Discharge to the Colorado River has no discernible effect on surface water quality. Move to Box 8.
8	Does contaminated groundwater qualify for supplemental standards due to excessive environmental harm from remediation?	Although the applicability has not been formally assessed, it is unlikely that remedial action would cause excessive harm to the environment. Move to Box 10.
10	Will natural flushing result in compliance with UMTRA MCLs, background, or ACLs within 100 years?	There has been no overall decline in uranium concentrations in groundwater in the 15 years since surface remediation was completed. Natural flushing has not achieved MCLs as predicted by the transport model. Future declines are unlikely. Move to Box 13.
13 and 15	Will natural flushing and active groundwater remediation result in compliance with MCLs, background, or ACLs within 100 years?	Research studies at the Old Rifle site and remediation implemented at other uranium mill tailings sites indicate that active remediation and natural flushing have significant limitations with respect to uranium remediation. Concentrations undergo a "tailing off" before MCLs are met. Move to Box 17.
17	Apply supplemental standards based on TI and apply ICs where needed.	As with any other remediation strategy, this strategy may be reevaluated if conditions change.

Note: Explanation of Compliance Strategy Selection Process (Table 2) uses the Compliance Selection Framework (Figure 1).

3.2 Long-Term Surveillance and Maintenance Requirements

3.2.1 Monitoring Strategy

Under a compliance strategy in which supplemental standards are selected, monitoring is not required because groundwater standards are already met, and compliance has been attained. However, limited monitoring is proposed for the Old Rifle site to augment monitoring conducted through IFRC and LM research studies and to increase the understanding of the aquifer system. Monitoring will continue for approximately five years. The network consists of monitoring wells 0292A, 0304, 0305, 0309, 0310, 0655, 0656, and 0658; surface locations 0538, 0396, and 0741 on the Colorado River ; and seep surface location 0395 (Figure 6), to be augmented by other groundwater and surface locations as needed.

In addition, monitoring of ICs will continue according to guidance in Section 2.6, "Institutional Controls," of this report. Verification that requirements listed in the three ICs for this site are followed and that issues are addressed will be recorded in the annual VMR for the Rifle sites.

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4.0 References

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Appendix A

Institutional Controls for the Old Rifle Site

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UNITED STATES
NUCLEAR REGULATORY COMMISSION
WASHINGTON, D.C. 20555-0001

January 12, 2000

JAN 18 2000

Ms. Donna Bergman-Tabbert, Manager
U.S. Department of Energy
Grand Junction Office
2597 B 3/4 Road
Grand Junction, CO 81503

SUBJECT: TRANSFER OF FORMER URANIUM PROCESSING SITE AT OLD RIFLE, COLORADO

Dear Ms. Bergman-Tabbert:

By letter dated December 20, 1999, the U.S. Department of Energy (DOE) provided information related to the request from the Colorado Department of Public Health and Environment (CDPHE) for DOE and U.S. Nuclear Regulatory Commission (NRC) concurrence to transfer the Old Rifle former uranium processing site to the City of Rifle for perpetual public use. In this regard, Section 104(e)(1) of the Uranium Mill Tailings Radiation Control Act of 1978 (UMTRCA) requires DOE and NRC concurrence in the final disposition of processing sites acquired by the cooperating state, and DOE has indicated it concurs with the CDPHE request to transfer the Old Rifle site to the City of Rifle, Colorado.

The NRC staff has reviewed the Old Rifle land transfer information provided by DOE, including the "Quit Claim Deed" and attached "Land Annotation" which will be used to effect the transfer of the property. The staff finds that the "Quit Claim Deed" and attached "Land Annotation" appropriately reflect the requirements of UMTRCA Section 104. Accordingly, NRC concurs with the CDPHE request to transfer the Old Rifle site to the City of Rifle, Colorado.

If you have any questions regarding this letter, please contact the NRC Project Manager, Rick Weller, at (301) 415-7287.

Sincerely,

Thomas H. Essig, Chief
Uranium Recovery and
Low-Level Waste Branch
Division of Waste Management
Office of Nuclear Material Safety
and Safeguards

cc: R. Edge, DOE-GJO
J. Deckler, CO

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Facsimile: (303) 825-3997

*(Please direct all correspondence to our Glenwood Springs Office)

October 22, 2002

Jeffrey Deckler
Remedial Programs Manager
Colorado Department of Public Health and the Environment
4300 Cherry Creek Drive South
Denver, Colorado 80246-1530

Re: City of Rifle East UMTRA Site Deed and Environmental Covenant

Dear Jeff:

Enclosed are the Quitclaim Deed and Environmental Covenant for the East UMTRA Site, both of which have been executed by the City of Rifle. Please have the appropriate State officials execute these documents and let me know as soon as possible if there are any other documents required for this transaction. Please also let me know how you wish to handle the recording of the documents. We would be happy to assist with recording them with the Garfield County Clerk and Recorder's Office. If your office records them, please ensure that this office ends up with the original Deed.

Thank you for your assistance throughout this matter.

Very truly yours,

LEAVENWORTH & KARP, P.C.

James S. Neu

JSN:
Enclosures
cc: Selby Myers (w/o enc.)
Don Metzler (w/o enc.)

619021 01/21/2003 04:29P B1428 P982 M ALSDORF
1 of 6 R 31.00 D 0.00 GARFIELD COUNTY CO

Recorder 982

QUIT CLAIM DEED

The Colorado Department of Public Health and the Environment ("Grantor"), whose address is 4300 Cherry Creek Drive South, Denver, Colorado, 80222-1530, City and County of Denver, State of Colorado, pursuant to 42 U.S.C.§ 7914 (e) (1) (B) and C.R.S. § 25-11-303, hereby donates and quit claim(s) to the City of Rifle ("Grantee"), whose address is 202 Railroad Avenue, Rifle, Colorado, 81650, City of Rifle, County of Garfield, State of Colorado, the following real property in the County of Garfield, State of Colorado, to wit: A parcel of land described as follows:

Beginning at a point on the South right-of-way line of the U.S. Highway 6 & 24, said point more particularly described as being South 0°18' West 1415 feet more or less, from the northeast corner of the NW-1/4 of the NW-1/4 of Section 15, Township 6 South, Range 93 West, 6th P.M. and running then South 0°18' West 36.5 feet to the North right-of-way line of the D&RGW Railroad, thence South 76°36' West 1891.8 feet along said right-of-way, thence continuing along said right-of-way line the following courses and distances. South 79°2' West, 194.9 feet; South 85°35' West 194.1 feet; North 87°20' West 193.9 feet; North 80°23' West 194.0 feet; North 79°32' West 26.7 feet; thence North 74.5 feet to the said South right-of-way line of the U.S. Highway 6 & 24, and a point on a 673 foot radius curve to the left, thence Northeasterly along said curve an arc distance of 453.5 feet (chord bears north 69°26'30" East 445 feet); thence North 50°07' East 655.7 feet to a point on a 472.98 foot radius curve to the right, thence Northeasterly along said curve an arc distance of 223.16 feet (chord bears North 63°38' East 221.1 feet); thence North 80°51'30" East 293.9 feet; thence South 79°33' East 157.7 feet to a point on a 2825 foot radius curve to the right, thence Southeasterly along said curve an arc distance of 460.21 feet (chord bears South 74°53' East 459.7 feet); thence South 70°13' East 306.5 feet to a point on a 1081.8 foot radius curve to the left, thence Easterly along said curve an arc distance of 348.81 feet (chord bears South 79°24' East 347.2 feet) to the point of beginning.

EXCEPTING therefrom those portions of the above described property conveyed to the Denver and Rio Grande Western Railroad Company in deed recorded May 8, 1978 in Book 509 at Page 551 and that part conveyed to the City of Rifle in deed recorded January 18, 1971 in Book 416 at Page 257.

Subject to: (i) any coal, oil, gas, or other mineral rights in any person; (ii) existing rights-of-way for roads, railroads, telephone lines, transmission lines, utilities, ditches, conduits, or pipelines on, over, or across said lands; (iii) court liens, judgments, or financial encumbrances such as deeds of trust for which a formal consent or order has been obtained from a court for the lien holder; (iv) other rights, interests, easements, reservation or exceptions of record; and the following terms, conditions, rights, reservations and covenants:

Grantor reserves to (i) itself, the U. S. Department of Energy, their employees, agents and contractors the right of access to the property as may be necessary to complete activities under the Uranium Mill Tailings Radiation Control Act of 1978, 42 U.S.C. § 7901 et seq. ("UMTRCA") and for other lawful purposes, until such time as Grantor and the U.S. Department of Energy determine that all remedial activities are complete; and (ii) to itself any non-tributary groundwater underlying this parcel, the right to develop tributary groundwater, and the right to surface access for groundwater development.

Grantee covenants to hold harmless the Grantor and the Department of Energy for any liability associated with disruption of any public purpose ventures on the property conveyed by this deed, the disruption of any improvement on said property made by the Grantee, its successors and assigns, and any temporary or permanent limitations to the use of the property, should the Grantor and the Department of Energy be required to perform additional surface remedial activities on the property conveyed by this deed.

Grantee covenants (i) to comply with the applicable provisions of UMTRCA, 42 U.S.C. #7901 et. seq., as amended; (ii) not to use ground water from the site for any purpose, and not to construct wells or any means of exposing ground water to the surface unless prior written approval for such use is given by the Grantor and the U.S. Department of Energy; (iii) not to sell or transfer the land to anyone other than a governmental entity within the state; (iv) that any sale or transfer of the property described in this deed shall have prior written approval from the Grantor and the U.S. Department of Energy; and that any deed or other document created for such sale or transfer and any subsequent sale or transfer will include information stating that the property was once used as a uranium milling site and all other information regarding the extent of residual radioactive materials removed from the property as required by Section 104(d) of the Uranium Mill Tailings, 42 U.S.C. sec. 7014(d), and as set forth in the Annotation attached hereto; (v) not to perform construction and/or excavation or soil removal of any kind on the property without permission from the Grantor and the U.S. Department of Energy unless prior written approval of construction plans (e.g., facilities type and location), is given by the Grantor and the U.S. Department of Energy; (vi) that any habitable structures constructed on the property shall employ a radon ventilation system or other radon mitigation measures; and (vii) that its use of the property shall not

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After recording, please return to:
Leavenworth & Karp, P.C.
P. O. Drawer 2030
Glenwood Springs, CO 81602

adversely impact groundwater quality, nor interfere in any way, with groundwater remediation under UMTRCA activities; and (viii) to use the property and any profits or benefits derived therefrom only for public purposes as required by UMTRCA sec. 104(e)(1)(C), 42 U.S.C. 7914 (e)(1)(C).

These covenants are made in favor and to the benefit of Grantor, shall run with the land and be binding upon Grantee and its successors and assigns, and shall be enforceable by Grantor;

Grantee acknowledges that the property was once used as a uranium milling site, and that the Grantor makes no representations or warranties that the property is suitable for Grantee's purposes;

619021 01/21/2003 04:29P B1428 P983 M ALSDORF
2 of 6 R 31.00 D 0.00 GARFIELD COUNTY CO

IN WITNESS WHEREOF:

APPROVED AS TO FORM:

David Kreutzer, Assistant Attorney General

GRANTOR:

STATE OF COLORADO
Bill Owens, Governor
Acting by and through
The Department of Public Health and Environment

By: ______________________
Acting Executive Director

By: ______________________
Program Approval

ACCEPTANCE OF DEED
AND COVENANTS

GRANTEE:

CITY OF RIFLE
(Full Legal Name of Agency)

By: ______________________
Name. Keith Lambert

Title: Mayor

Signed this 9th day of January ~~19~~ 2003.

STATE OF COLORADO, } ss.
County of Garfield

The foregoing instrument was acknowledged before me this 9th day of January, 2003 , ~~19~~ , by Keith Lambert, Mayor, City of Rifle, Colorado.

My commission expires. 12/18/06

Witness my hand and official seal

____
Notary Public.

NOTARY PUBLIC
BRENDA S. LADD
STATE OF COLORADO

619021 01/21/2003 04:29P B1428 P984 M ALSDORF
3 of 6 R 31.00 D 0.00 GARFIELD COUNTY CO

No. ____________

QUIT CLAIM DEED

TO

STATE OF COLORADO, } ss.
County of

I hereby certify that this instrument was filed for record in my office, at ____________ o'clock _M., __________, 19_ and is duly recorded in book ____________ page ____________.

Film No. ______ Reception No. ______

____________ Recorder.

By ____________ Deputy.

Fees, $ ____________

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ATTACHMENT A

LAND ANNOTATION

OLD RIFLE, COLORADO PROCESSING SITE

The Uranium Mill Tailings Radiation Control Act (Public Law 95-604), Section 104, requires that the State notify any person who acquires a designated processing site of the nature and extent of residual radioactive materials removed from the site, including notice of the date when such action took place, and the condition of the site after such action. The following information is provided to fulfill this requirement.

The Old Rifle Colorado processing site consists of one land parcel which contained a large tailings pile. The site was operated by Standard Chemical company and later the U.S. Vanadium Corporation, over the period from 1924 to 1946 as a uranium processing facility. Approximately 597,000 cubic yards of contaminated materials which included 1) tailings; 2) subpile soils; 3) surficial materials in the mill yard; and 4) windblown materials; were removed from the mill site from 1992-1996. The remediation was conducted in accordance with regulations promulgated by the U.S. Environmental Protection Agency, in 40 CFR 192. These regulations require that the concentration of radium-226 in land averaged over any area of 100 square meters shall not exceed the background level by more than: 5 pCi/g (picocuries per gram), averaged over the first 15 cm (centimeters) of soil below the surface, and 15 pCi/g averaged over 15 cm thick layers of soil more than 15 cm below the surface. Verification measurements were conducted at the site by dividing the site into approximately 30-foot by 30-foot grids. A soil sample was collected and analyzed for contaminants from each grid to verify that the standards had been met. All verification grids on the site met the EPA standards for radium and thorium.

After remediation was complete the site was backfilled with clean fill material, graded for drainage and revegetated. Backfill materials were routinely analyzed for radium-226 and were determined to have concentrations near background (1.5 pCi/g).

Excavation of residual radioactive material was also conducted for thorium-230 beneath the tailings pile in the subpile soils. For thorium-230, the cleanup standard was determined as a projected 1,000 year radium-226 concentration based on the eventual decay of the thorium to radium. The average thorium in-growth at depth was calculated to be 3.8 pCi/g.

The EPA standards also allow for contamination to be left in place where removal would present a risk of injury to workers, would result in environmental harm, or where the cost of removal clearly outweighs the benefit in terms of risk reduction. At the Old Rifle site, these areas where contamination was left (called "supplemental standards") are the following:

1) an area 1,600 feet long, along the steep slopes at the northern edge of the property. This deposit extends under U.S. Highway 6 & 24;

2) under the railroad right of way extending the length of the site off the southern boundary; and

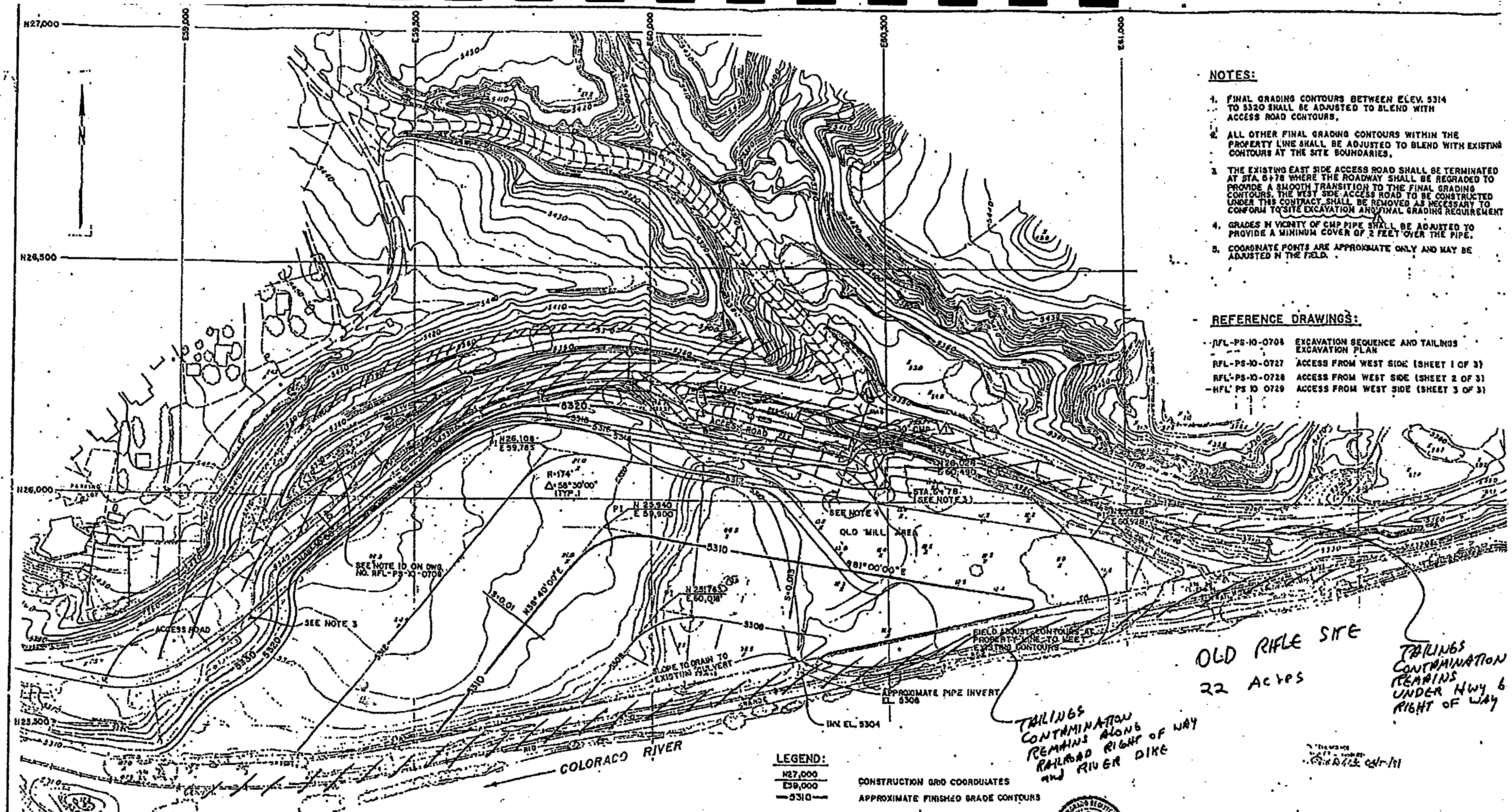
3) along the riverbank to the south of the site.

The supplemental standards areas are shown on the attached map. These deposits have been covered with clean fill and pose no risk unless disturbed. The average gamma exposure is 11 microroentgen per hour at waist height, which is equivalent to background.

The groundwater beneath the Old Rifle mill site remains contaminated and will be addressed during Phase II of the Uranium Mill Tailings Remedial Action Project. Several groundwater monitor wells are present on and downgradient of the site and will remain in place until the U.S. Department of Energy determines that they can be removed.

Any person who acquires a designated processing site shall apply for any permits, including U.S. Army Corps of Engineers Section 404 permits regarding construction in or near wetlands, as required by law.

Additional information concerning the remedial action, and groundwater conditions is available from the Colorado Department of Public Health and Environment, Hazardous Materials and Waste Management Division.



NOTES:

1. FINAL GRADING CONTOURS BETWEEN ELEV. 5314 TO 5320 SHALL BE ADJUSTED TO BLEND WITH ACCESS ROAD CONTOURS.
2. ALL OTHER FINAL GRADING CONTOURS WITHIN THE PROPERTY LINE SHALL BE ADJUSTED TO BLEND WITH EXISTING CONTOURS AT THE SITE BOUNDARIES.
3. THE EXISTING EAST SIDE ACCESS ROAD SHALL BE TERMINATED AT STA. 6+78 WHERE THE ROADWAY SHALL BE REGRADED TO PROVIDE A SMOOTH TRANSITION TO THE FINAL GRADING CONTOURS. THE WEST SIDE ACCESS ROAD TO BE CONSTRUCTED UNDER THIS CONTRACT SHALL BE REMOVED AS NECESSARY TO CONFORM TO SITE EXCAVATION AND FINAL GRADING REQUIREMENT
4. GRADES IN VICINITY OF CMP PIPE SHALL BE ADJUSTED TO PROVIDE A MINIMUM COVER OF 2 FEET OVER THE PIPE.
5. COORDINATE POINTS ARE APPROXIMATE ONLY AND MAY BE ADJUSTED IN THE FIELD.

REFERENCE DRAWINGS:

RFL-PS-10-0706	EXCAVATION SEQUENCE AND TAILINGS EXCAVATION PLAN
RFL-PS-10-0727	ACCESS FROM WEST SIDE (SHEET 1 OF 3)
RFL-PS-10-0728	ACCESS FROM WEST SIDE (SHEET 2 OF 3)
RFL PS 10 0729	ACCESS FROM WEST SIDE (SHEET 3 OF 3)

LEGEND:

N27,000 / E59,000	CONSTRUCTION GRID COORDINATES
—5310—	APPROXIMATE FINISHED GRADE CONTOURS

SCALE 100 0 100 200 FEET

	△								
	△								
	△								
	△	12-18-90	ADDED 30 INCH CMP & MODIFIED NOTE 3						
	△	3-15-90	ISSUED FOR CONSTRUCTION	—	—	—	—	—	—

U. S. DEPARTMENT OF ENERGY
ALBUQUERQUE, NEW MEXICO

OLD RIFLE PROCESSING SITE
RIFLE, COLORADO
PHASE II CONSTRUCTION

FINAL GRADING PLAN

MORRISON-KNUDSEN ENGINEERS, INC.

PROJECT NO. DE-AC04-83AL18796

619022 01/21/2003 04:30P B1428 P988 M ALSDORF
1 of 5 R 26.00 D 0.00 GARFIELD COUNTY CO

988

This property is subject to an Environmental Covenant held by the Colorado Department of Public Health and Environment pursuant to section 25-15-321, C.R.S.

ENVIRONMENTAL COVENANT

By this deed, the City of Rifle grants an Environmental Covenant ("Covenant") this 16th day of October, 2002 to the Colorado Department of Public Health and the Environment ("the Department") pursuant to § 25-15-321 of the Colorado Hazardous Waste Act, § 25-15-101, *et seq*. The Department's address is 4300 Cherry Creek Drive South, Denver, Colorado 80246-1530.

WHEREAS, The City of Rifle is the owner of certain property commonly referred to as the Old Rifle Uranium Mill site in Rifle, Colorado in Garfield County, more particularly described in Attachment A, attached hereto and incorporated herein by reference as though fully set forth (hereinafter referred to as "the Property"); and

WHEREAS, Union Carbide, disposed of uranium mill tailings at the Old Rifle Mill site, and as a result of this disposal, groundwater under the property is contaminated; and

WHEREAS, pursuant to the Site Observational Work Plan for the Old Rifle Mill Site, the Property is the subject of remedial action pursuant to the Uranium Mill Tailings Radiation Control Act, 42 U.S.C. § 7901 *et seq.*; and

WHEREAS, the purpose of this Covenant is to ensure protection of human health and the environment by restricting surface disturbance and groundwater use as further described below; and

WHEREAS, The City of Rifle desires to subject the Property to certain covenants and restrictions as provided in Article 15 of Title 25, Colorado Revised Statutes, which covenants and restrictions shall burden the Property and bind The City of Rifle, its heirs, successors, assigns, and any grantees of the Property, their heirs, successors, assigns and grantees, and any users of the Property, for the benefit of the Department.

NOW, THEREFORE, The City of Rifle hereby grants this Environmental Covenant to the Department, with the U.S. Department of Energy as a third party beneficiary, and declares that the Property as described in Attachment A shall hereinafter be bound by, held, sold, and conveyed subject to the following requirements set forth in paragraph 1 below, which shall run with the Property in perpetuity and be binding on the City of Rifle and all parties having any right, title or interest in the Property, or any part thereof, their heirs, successors and assigns, and any persons using the land. The City of Rifle and all parties having any right, title or interest in the Property, or any part thereof, their heirs, successors and assigns shall hereinafter be referred to in this covenant as OWNER.

After recording, please return to:
Leavenworth & Karp, P.C.
P. O. Drawer 2030
Glenwood Springs, CO 81602

1. Use restrictions

A. No habitable structure may be constructed on the property without properly designed radon mitigation as approved by the Department.

B. Wells completed in the alluvuial aquifer or the Entrada formation may not be used for domestic or potable water supplies.

C. No tilling, excavation, grading, construction, or any other activity that disturbs the ground surface is permitted on the Property, without the express written consent of the Department and the U.S. Department of Energy.

D. No activities that will in any way damage any monitoring or remedial wells installed by the Department of Energy, or interfere with the maintenance, operation, or monitoring of said wells is allowed, without the express written consent of the Department and the U.S. Department of Energy.

2. Purpose of this covenant The purpose of this Covenant is to ensure protection of human health and the environment by minimizing the potential for exposure to any residual radioactive material or contaminated groundwater that remains on the Property. The Covenant will accomplish this by restricting groundwater use, minimizing those activities that result in disturbing the ground surface, and by creating a review and approval process to ensure that any such intrusive activities are conducted with appropriate precautions to avoid or eliminate any hazards.

3. Modifications This Covenant runs with the land and is perpetual, unless modified or terminated pursuant to this paragraph. OWNER or its successors and assigns may request that the Department approve a modification or termination of the Covenant. The request shall contain information showing that the proposed modification or termination shall, if implemented, ensure protection of human health and the environment. The Department shall review any submitted information, and may request additional information. If the Department determines that the proposal to modify or terminate the Covenant will ensure protection of human health and the environment, it shall approve the proposal. No modification or termination of this Covenant shall be effective unless the Department has approved such modification or termination in writing. Information to support a request for modification or termination may include one or more of the following:

a) a proposal to perform additional remedial work;
b) new information regarding the risks posed by the residual contamination;
c) information demonstrating that residual contamination has diminished;
d) information demonstrating that the proposed modification would not adversely impact the remedy and is protective of human health and the environment; and
other appropriate supporting information.

4. Conveyances OWNER shall notify the Department at least fifteen (15) days in advance of any proposed grant, transfer or conveyance of any interest in any or all of the Property.

5. Notice to Lessees OWNER agrees to incorporate either in full or by reference the restrictions of this Covenant in any leases, licenses, or other instruments granting a right to use the Property.

6. Notification for proposed construction and land use OWNER shall notify the Department simultaneously when submitting any application to a local government for a building permit or change in land use.

7. Inspections The Department shall have the right of entry to the Property at reasonable times with prior notice for the purpose of determining compliance with the terms of this Covenant. Nothing in this Covenant shall impair any other authority the Department may otherwise have to enter and inspect the Property.

8. No Liability The Department does not acquire any liability under State law by virtue of accepting this Covenant, nor does any other named beneficiary of this Covenant acquire any liability under State law by virtue of being such a beneficiary

9. Enforcement The Department may enforce the terms of this Covenant pursuant to §25-15-321. C.R.S. The City of Rifle and any named beneficiaries of this Covenant may file suit in district court to enjoin actual or threatened violations of this Covenant.

10. Owner's Compliance Certification OWNER shall submit an annual Report to the Department, on the anniversary of the date this Covenant was signed by The City of Rifle, detailing OWNER's compliance, and any lack of compliance, with the terms of this Covenant.

11. Notices Any document or communication required under this Covenant shall be sent or directed to:

Jeffrey Deckler
Remedial Programs Manager
Colorado Department of Public Health and the Environment
4300 Cherry Creek Drive South
Denver, Colorado 80246-1530

Donald Metzler
U.S. Department of Energy
Grand Junction Project office
Grand Junction, Colorado

The City of Rifle, has caused this instrument to be executed this 16th day of October, 2002.

The City of Rifle

By: Keith Lambert
Title: Keith Lambert, Mayor, City of Rifle, Colorado

STATE OF Colorado)
) ss:
COUNTY OF Garfield)

The foregoing instrument was acknowledged before me this 16 day of October, 2002 by Mayor Keith Lambert on behalf of The City of Rifle

Ellen J. Gaugler
Notary Public
4841 154 Road
Address
Glenwood Springs, CO 81601

My commission expires: 11/8/2004

Accepted by the Colorado Department of Public Health and Environment this 29th day of October, 2002.

By: Douglas Benevento

Title: Acting Executive Director

STATE OF Colorado)
) ss:
COUNTY OF Denver)

The foregoing instrument was acknowledged before me this 29th day of October, 2002 by Douglas H Benevento on behalf of the Colorado Department of Public Health and Environment.

Maria S. Zepeda-Sanchez
Notary Public
5863 Magnolia St
Address
Commerce City, CO 80022

My commission expires: 4/14/03

SCHEDULE A
Legal Description

The land referred to in this Commitment is situated in the County of Garfield, state of Colorado and described as follows:

Beginning at a point on the south right of way line of U.S. Highway 6 & 24, said point more particularly described as being South 0°18' West 1415 feet, more or less, from the northeast corner of the NW1/4 of the NW1/4 of Section 15, Township 6 South, Range 93 West, 6th P.M. and running then South 0°18' West 36.5 feet to the North right of way line of the D&RGW Railroad, thence South 76°36' West 1891.8 feet along said right of way, thence continuing along said right of way line the following courses and distances: South 79°2' West, 194.9 feet; South 85°35' West 194.1 feet; North 87°20' West 193.9 feet; North 80°23' West 194.0 feet; North 79°32' West 26.7 feet; thence North 74.5 feet to the South right of way line of the U.S. Highway 6 & 24, and a point on a 673 foot radius curve to the left, thence North-easterly along said curve an arc distance of 453.5 feet (chord bears North 69°26'30" East 445 feet); thence North 50°07' East 655.7 feet to a point on a 472.98 foot radius curve to the right, thence Northeasterly along said curve an arc distance of 223.16 feet (chord bears North 63°38' east 221.1 feet); thence North 80°51'30" East 293.9 feet; thence South79°33' East 157.7 feet to a point on a 2825 foot radius curve to the right, thence Southeasterly along said curve an arc distance of 460.21 feet (chord bears South 74°53' East 459.7 feet); thence South 70°13' East 306.5 feet to a point on a 1081.8 foot radius curve to the left, thence Easterly along said curve an arc distance of 348.81 feet (chord bears South 79°24' East 347.2 feet) to the POINT OF BEGINNING.

EXCEPTING therefrom those portions of the above described property conveyed to the Denver and Rio Grande Western Railroad Company in deed recorded May 8, 1978 in book 509 at age 551 and that part conveyed to the City of Rifle in deed recorded January 18, 1971 in Book 416 at Page 257.

CITY OF RIFLE, COLORADO
ORDINANCE NO. 9
SERIES OF 2008

AN ORDINANCE OF THE CITY OF RIFLE, COLORADO, CREATING THE UMTRA OVERLAY ZONE DISTRICT AND INCLUDING WITHIN THE DISTRICT THE CITY'S EAST AND WEST UMTRA SITES.

WHEREAS, the City of Rifle is the owner of an approximately 21.76 acre parcel of land known as the East UMTRA Site and an approximately 142 acre parcel of land known as the West UMTRA Site, both of which parcels were acquired from the Colorado Department of Public Health and Environment ("CDPHE) following successful remediation of the sites in partnership with the U.S. Department of Energy under the Uranium Mill Tailings Radiation Control Act ("UMTRA"); and

WHEREAS, pursuant to Rifle Municipal Code ("RMC") Section 16-6-140, the Planning Commission initiated an application to create an UMTRA Overlay Zone District for the purpose of establishing procedures and restrictions governing development of East and West UMTRA Sites, which are both zoned Public Zone District; and

WHEREAS, on April 29,2008, the City of Rifle Planning Commission considered the zoning overlay application and found that creation of the UMTRA Overlay Zone District was appropriate given development constraints on the UMTRA parcels created by the presence of residual contaminants from former uranium mining operations and deed restrictions placed on the parcels by CDPHE's conveyance of the sites to the City; and

WHEREAS, the Planning Commission recommended adoption of regulations governing the UMTRA Overlay Zone District by the creation of a new Section 16-3-540 of the Rifle Municipal Code ("RMC") and further recommended the City's East and West UMTRA Sites be included within the new overlay zone district ; and

WHEREAS, the City Council reviewed the zoning application at its May 21,2008 and June 4,2008 meetings and concurred with the Planning Commission's findings; and

WHEREAS, the City of Rifle Planning Commission and the Rifle City Council have held duly-noticed public hearings as required by the Rifle Municipal Code, and now wish to create the UMTRA Overlay Zone District as a new overlay zone district within the City and to include the East and West UMTRA Sites within said UMTRA Overlay Zone District.

NOW, THEREFORE, THE COUNCIL OF THE CITY OF RIFLE, COLORADO, ORDAINS THAT:

Section 1. The aforementioned recitals are hereby fully incorporated herein.

Section 2. A new Section 16-3-540 of the Rifle Municipal Code, entitled "UMTRA Overlay Zone District," is hereby adopted to read as follows.

Section 16-3-540. UMTRA Overlay Zone District.

(a) Description. The intent of the UMTRA overlay zoning district is to set forth the procedures and restrictions governing development on the City-owned East and West UMTRA sites. Due to the presence of residual contaminants on the two UMTRA sites, the City must obtain prior written consent before conducting any operations on either site that will disturb the soil, wetlands or groundwater. Special handling of both soil and groundwater will be required, and the City shall adopt a Materials Handling Plan that details how human health and the environment will be protected during any activities on the sites.

(b) Uses. The uses permitted on sites within the UMTRA Overlay Zone District will be that of the underlying zone district.

(c) Restrictions on use of UMTRA sites. The City must comply with the following applicable provisions of UMTRCA, 42 U.S.C. Sec. 7901, et. seq., as amended:

(1) Ground water from the site shall not be used for any purpose, nor shall anyone construct wells or any means of exposing ground water to the surface unless prior written approval for such use is given by the Colorado Department of Public Health and Environment ("CDPHE) and the U.S. Department of Energy ("DOE).

(2) The land shall not be sold or transferred to anyone other than a governmental entity within the state.

(3) Any sale or transfer of the property described in this deed shall have prior written approval from the CDPHE and the DOE; and that any deed or other document created for such sale or transfer and *any* subsequent sale or transfer will include information stating that the property was once used as a uranium milling site and all other information regarding the extent of residual radioactive materials removed from the property as required by Section 104(d) of the Uranium Mill Tailings Radiation Control Act, 42 U.S.C. Sec. 7014(d), and as set forth in the Annotation attached hereto.

(4) Construction and/or excavation or soil removal of any kind shall not occur on the property without permission from the CDPHE and DOE unless prior written approval of construction plans (e.g., facilities type and location), is given by the CDPHE and DOE.

(5) Any habitable structures constructed on the property shall employ a radon ventilation system or other radon mitigation measures.

(6) Use of the UMTRA sites shall not adversely impact groundwater quality, nor interfere in any way, with groundwater remediation under UMTRCA Sec. 104(e)(1)(c), 42 U.S.C. Sec. 7914 (e)(1)(C).

(d) Procedure. The following are the City's Standard Operating Procedures for conducting activities within the UMTRA Overlay Zone District:

(1) The City of Rifle shall install and maintain a sign at the entrance of both UMTRA sites stating "Any excavation of material or exposure of groundwater on this Property must be approved by the City of Rifle, Colorado Department of Public Health and Environment and U.S. Department of Energy."

(2) When a use is proposed for an UMTRA site, City staff will review the project with the Planning Director. The Planning Director will review the GIS maps and identify the special procedures that must be followed. Staff shall also hold preliminary discussions with DOE and CDPHE to identify any preliminary issues about the use of the property for the proposed project and further define the project for City Council approval of contracts for design and plan preparation.

(3) Staff shall hire consulting engineers or work with the developer's engineers to refine design development project and to identify and obtain other permits or approvals necessary for the project (e.g. USACE permitting, storm water permits, site plan application, etc.).

(4) Staff shall develop a letter of request including a project description (detailing building footprints, location, depth of bury, radon mitigation system design), applicable maps and drawings, and for approval of defined project by CDPHE and DOE. The City Attorney shall review the letter to ensure compliance with deed restrictions and environmental covenants prior to submission to DOE and CDPHE.

(5) Upon written approval by both DOE and CDPHE and approval of the Site Plan by the Planning Department, the City Council shall authorize issuance of a Notice to Proceed with construction and the execution of construction contract. The project will then be eligible for issuance of a building permit.

(6) Appropriate training shall be provided to ensure that all project personnel are aware of the contaminants on site, restrictive covenants, and the requirements of the

Materials Handling Plan. The City shall periodically inspect the site to confirm compliance with all Code requirements.

(7) Upon completion of the project, the developer shall submit a Completion Report to CDPHE containing a construction summary and identifying any deviations from the original proposal. The Completion Report shall also document compliance with the Materials Handling Plan and detail the final disposal and disposition of any uranium mill tailings encountered on the site.

(8) The City Manager shall annually inform all City department heads of these Standard Operating Procedures, deed restrictions, and environmental covenants affecting the UMTRA sites.

Section 3. The City's East and West UMTRA Sites are hereby included within the UMTRA Overlay Zone District established at Section 16-3-540 of the Rifle Municipal Code. The underlying Public Zone District ("PZ") designation for the parcels shall remain in full force and effect.

Section 4. Within thirty (30) days after the effective date of this Ordinance, the City Clerk shall incorporate the terms of this Ordinance into the Geographical Information System described in RMC $16-3-20 shall cause a printed copy of the amendment to the City Zone District Map to be made, which shall be dated and signed by the Mayor and attested to by the City Clerk, and which shall bear the seal of the City. The amended map shall include the number of this Ordinance. The signed original printed copy of the Zoning Map shall be filed with the City Clerk. The Clerk shall also record a certified copy of this Ordinance with the Garfield County Clerk and Recorder. The City staff is further directed to comply with all provisions of the Rifle Land Use Regulations, RMC §16-1-10 *et seq.*, to implement the provisions of this Ordinance.

INTRODUCED on May 21, 2008, read by title, passed on first reading, and ordered published as required by the Charter.

INTRODUCED a second time at a regular meeting of the Council of the City of Rifle, Colorado, held on June 4,2008, passed without amendment, approved, and ordered published in full as required by the Charter.

DATED this 9 day of June ,2008.

CITY OF RIFLE, COLORADO

By Keith J. Lambert
Mayor

ATTEST:

Wanda Nelson
City Clerk

CITY OF RIFLE SEAL GARFIELD COUNTY, COLORADO

Attachment 1

Review of the Natural Flushing Groundwater Remedy at the Old Rifle Legacy Management Site, Rifle, Colorado

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LMS/RFO/S07263

Review of the Natural Flushing Groundwater Remedy at the Old Rifle Legacy Management Site, Rifle, Colorado

July 2011

U.S. DEPARTMENT OF ENERGY | Legacy Management

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LMS/RFO/S07263

Review of the Natural Flushing Groundwater Remedy at the Old Rifle Legacy Management Site, Rifle, Colorado

July 2011

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Contents

Figures

Tables

Abbreviations

1-D	one-dimensional
2-D	two-dimensional
3-D	three-dimensional
ACL	alternate concentration limit
ALARA	as low as reasonably achievable
COC	contaminant of concern
DO	dissolved oxygen
DOC	dissolved organic carbon
DOE	U.S. Department of Energy
EM	Office of Environmental Management
EPA	U.S. Environmental Protection Agency
ERSP	Environmental Remediation Sciences Program
FE(II)	ferrous iron
Fe(III)	ferric iron
ft	feet
ft^3/day	cubic feet per day
GCAP	Groundwater Compliance Action Plan
gpm	gallons per minute
IFRC	Integrated Field Research Challenge
LM	Office of Legacy Management
MCL	maximum concentration limit
µg/L	micrograms per liter
µS/cm	microsiemens per centimeter
mg/L	milligrams per liter
mL/g	milliliters per gram
mV	millivolts
NABIR	Natural and Accelerated Bioremediation Research
NH_4	ammonium
NRC	U.S. Nuclear Regulatory Commission
ORP	oxidation-reduction potential
PEIS	Programmatic Environmental Impact Statement
redox	oxidation-reduction

SC	Office of Science
SOWP	Site Observational Work Plan
TEAP	terminal electron acceptor process
TI	technical impracticability
USGS	U.S. Geological Survey
U(VI)	hexavalent uranium
U(IV)	tetravalent uranium
U-234	uranium-234
U-238	uranium-238
UAR	uranium activity ratio
UMTRA	Uranium Mill Tailings Remedial Action (Project)
UMTRCA	Uranium Mill Tailings Radiation Control Act

Executive Summary

A review of environmental information collected at the Old Rifle, Colorado, Legacy Management Site indicates that the natural attenuation of uranium contamination in the alluvial aquifer at the site is not progressing as quickly as numerical modeling projected. This discrepancy calls into question the validity of the selected compliance strategy of natural flushing. Groundwater uranium concentration data collected at the site since 1996, when the surface cleanup was completed, through 2010 show that, in recent years, uranium levels have tended to either remain relatively constant or gradually increase.

Numerous published and unpublished sources of information have been examined to determine why uranium concentrations in the aquifer are not attenuating. Initially, data and modeling analyses presented in the Site Observational Work Plan (DOE 1999) were reviewed. This review was followed by assessments of recent hydraulic and water chemistry data collected at numerous on-site locations used to monitor both groundwater and surface water. The assessment resulted in an updated understanding of local groundwater flow processes, water sources recharging the alluvial aquifer, and background biogeochemical processes in the subsurface.

To a large extent, this investigation has relied on data collected by scientists participating in research at the site under a U.S. Department of Energy (DOE) initiative called the Rifle Integrated Field Research Challenge (Rifle IFRC). Several reports and papers prepared by IFRC researchers were examined to identify phenomena that can impact natural flushing processes. Enhanced bioremediation experiments, as well as other studies performed by the IFRC team, provide valuable insight into various flow, transport, and biogeochemical processes that potentially have a bearing on the fate of dissolved uranium in alluvial groundwater.

Collectively, the data, reports, and papers reviewed in this study reveal that processes affecting the fate and transport of uranium in the site's groundwater system are more complex than assumed. Significant physical and biogeochemical heterogeneity and temporally variable flow and transport processes characterize the subsurface. Complex phenomena that potentially contribute to persistently elevated uranium concentrations in Old Rifle site alluvium include the slow diffusion of uranium from low-permeability sediments, the occasional mobilization of uranium in the vadose zone, and the natural inflow of uranium in recharge sources north of the site. Such complexities not only limit the degree to which existing technologies can be used to fully characterize local subsurface media but also severely hamper modeling of contaminant transport in the alluvial aquifer on a site-wide scale. Consequently, natural flushing of uranium contamination cannot be reliably forecast at this time. While it is not possible to definitively state that natural flushing cannot achieve the uranium standard in the permitted timeframe, current trends strongly suggest that this is the case.

This report recommends ways to monitor the groundwater system in coming years and discusses prospects for future predictive modeling. A review of the site's regulatory status indicates that a decision framework specifically developed for the Uranium Mill Tailings Remedial Action (UMTRA) Project provides for several compliance strategies that are alternatives to natural flushing.

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1.0 Introduction

This report presents findings from a review of available environmental information on the Old Rifle, Colorado, Legacy Management Site (Old Rifle site; the site) near Rifle, Colorado. The site was previously managed under the former Uranium Mill Tailings Remedial Action (UMTRA) Project administered by the U.S. Department of Energy (DOE). The Site Observational Work Plan (SOWP; DOE 1999) for the Old Rifle site was finalized in 1999, and the Groundwater Compliance Action Plan (GCAP; DOE 2000), which established the groundwater remedy for the site, was completed in 2000. The recommended compliance strategy for uranium was "natural flushing" of the site's alluvial aquifer. Natural flushing is a form of monitored natural attenuation. It depends on a combination of aquifer discharge to the nearby Colorado River and ambient geochemical processes to reduce contaminant concentrations in the groundwater. A numerical model prepared in support of the SOWP had indicated that natural flushing over a 10-year period would meet the applicable groundwater standard for uranium, which is the primary contaminant of concern (COC). The U.S. Nuclear Regulatory Commission (NRC), the regulatory authority for UMTRA sites, approved the GCAP in early 2002, setting in motion a process under which the performance of the remedy could be evaluated.

Groundwater monitoring has continued at the Old Rifle site during the 9 years since NRC approved the GCAP. The first year of post-GCAP monitoring was conducted by the DOE Office of Environmental Management (EM). In early 2003, the DOE Office of Legacy Management (LM) took over administration of the site and has overseen the groundwater monitoring since that time. Semiannual monitoring data collected by both EM and LM suggest that dissolved uranium levels in the alluvial groundwater are not attenuating.

In addition to monitoring efforts by EM and LM, the DOE Office of Science (SC) has sponsored research at the site since the early 2000s; the research largely focuses on the use of enhanced bioremediation technology to decrease dissolved uranium levels in the alluvial groundwater. In 2006, SC established the former milling property as one of three Integrated Field Research Challenge (IFRC) sites in the United States; work began under the Rifle IFRC in 2007. The DOE research has been managed through multiple SC programs, including the Natural and Accelerated Bioremediation Research Program, the Environmental Remediation Sciences Program, and, most recently, Subsurface Biogeochemical Research. SC-sponsored activities have shown success at immobilizing uranium within individual test areas of about 0.1 acre or less through manipulation of groundwater oxidation-reduction (redox) chemistry, but recent IFRC reports corroborate multiple years of uranium concentration data, collected by DOE, that indicate little, if any, progress in the sitewide attenuation of uranium contamination. Analyses presented in this report provide some insight into the reasons for the lack of remediation progress.

The groundwater system at the Old Rifle site is complex. The system is characterized by substantial heterogeneity of the aquifer sediments and significant flow and transport transients, both of which contribute to variable biogeochemical processes that strongly influence dissolved uranium levels. Complex phenomena that appear to contribute to persistently elevated uranium concentrations in Old Rifle alluvium include the slow diffusion of uranium from low-permeability sediments, the occasional mobilization of uranium in the vadose zone, and the natural inflow of uranium in recharge sources north of the site.

Subsurface system complexities limit the degree to which existing technologies can be used to fully characterize groundwater flow and transport processes at the Old Rifle site. Similarly, it is currently difficult, if not impossible, to accurately simulate the transport of uranium in local groundwater on a sitewide scale. As a consequence, natural flushing of uranium contamination from site groundwater cannot be reliably forecast. Despite such obstacles, this report examines the prospects for predictive simulation of contaminant fate at the site, using different modeling alternatives that range from simple to very complex. Regardless of the type of site-scale model that might be used for predictive purposes, the information presented in this study strongly suggests that continued natural flushing processes over the next 100 years will not produce a groundwater system that meets the applicable uranium standard.

This report recommends ways to monitor the groundwater system in coming years, with the intent of better discerning the progress of natural flushing. An assessment of the site's current regulatory status is also provided.

2.0 Objectives and Scope

This study has four objectives:

- Develop an updated conceptual model of groundwater flow and associated contaminant transport in the alluvial aquifer at the Old Rifle site;
- On the basis of the updated conceptual model and field information collected at the site since publication of the GCAP in 2000, develop potential explanations for the apparent lack of progress of natural flushing at the site through 2010;
- Assess the prospects for reliable predictive modeling of the natural flushing remedy; and
- Recommend a path forward regarding environmental monitoring at the site.

Several investigative activities have been carried out to meet these objectives, beginning with a review of the SOWP and GCAP. Hydraulic data collected at numerous groundwater monitoring locations have been analyzed to assess groundwater flow patterns and sources of water to the alluvial aquifer. Chemical data from LM monitoring wells and surface water sampling locations have been evaluated to identify significant temporal trends in concentration or other indicators of subsurface chemical processes.

To a large extent, this investigation has relied on IFRC data as well as reports and papers prepared by IFRC investigators to identify possible reasons why natural flushing is not progressing as predicted. Biostimulation experiments and other studies performed by the IFRC team at several different locations have demonstrated that microbially mediated chemical reactions in groundwater leading to immobilization of uranium can be enhanced by the injection of organic carbon nutrients. The experiments have provided valuable insight into various flow and biogeochemical processes that influence the fate of dissolved uranium in alluvial groundwater. Where relevant to the natural flushing remedy, those processes are discussed in this report.

Though several COCs were identified at the Old Rifle site (see Section 3.3.1), this study focuses almost exclusively on the fate of uranium in the subsurface. This contaminant is the most abundant in the alluvial aquifer and has been considered the contaminant most likely to flush naturally from the aquifer because of its relatively high mobility in the aqueous phase, in comparison to the transport characteristics of other COCs.

3.0 Site Description and Background Information

The Old Rifle site is a former ore-processing facility located in Garfield County, Colorado, approximately 0.3 mile east of the city of Rifle, Colorado. The site is situated on a relatively low-lying alluvial terrace created by a floodplain meander of the Colorado River (Figure 1). The terrace is bounded on its south side by a steep slope that abruptly descends to the river and on the north by U.S. Highway 6.

3.1 Site History

The Old Rifle processing plant was constructed in 1924 for the production of vanadium. The plant closed in 1932 due to a shortage of vanadium ore, but ore processing resumed in 1942 in response to an increased demand for vanadium during World War II. The mill continued to operate until 1946, when it was modified to include the recovery of uranium as well as vanadium. Ore processing continued until 1958, when the plant was replaced with a new mill located approximately 3 miles west of the Old Rifle site.

Buildings used in the ore-processing operations were in the east half and midsection of the site (Figure 1), in areas lying on both sides of an unlined ditch (on-site ditch) that traverses the site in a north-south direction. Vanadium and uranium ores were stockpiled in the east end of the site, and the tailings produced by the milling were placed across a large area that covered most of the site's west half (Figure 1). During milling years, ponds designed to contain mill-process waters were often constructed over large portions of the former mill tailings area.

A relatively flat tailings pile that existed at the site at the end of the ore-processing years was stabilized in 1967 in accordance with State of Colorado regulations. The facility became an UMTRA Project site in 1978 with passage of the Uranium Mill Tailings Radiation Control Act (UMTRCA). Approximately 13 acres of tailings remained at the site when UMTRCA was enacted, but no structures remained. Surface remediation of the Old Rife site began in spring 1992 and was completed in October 1996. Tailings and contaminated sub-tailings soils were removed from the site and relocated to a disposal site approximately 6 miles to the north-northwest. Fine-grained soils from off site were imported and used as fill to replace contaminated sediments that had been relocated. The fine-grained replacement fill was applied across most of the site and today commonly comprises the uppermost 5 to 10 feet (ft) of local surficial material.

Criteria used to determine the depth to which sub-tailings soils and other contaminated soils were excavated and transported off site were based on standards for soil concentrations of radium-226. Because the radium-226 criteria did not reflect the depth distribution of other mill-related contaminants that migrated into the subsurface, several inorganic contaminants remained in sub-fill sediments at many locales.

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Figure 1. Site Features—Old Rifle, Colorado, Processing Site

3.2 Hydrogeology

Groundwater flow at the Old Rifle site occurs primarily within a surficial aquifer composed of Holocene-age alluvium that was deposited by the ancestral Colorado River. The alluvium consists mostly of sandy gravels and gravelly sands interspersed with silts and clays. Sediments described as clayey gravels, silty gravels, and sandy silts are also reported in logs for boreholes drilled into the aquifer. The fine-grained fill that was used to replace contaminated alluvium that was excavated is typically described as silty sand and silt that also contains fine-grained sands, subrounded gravels, clays, and roots. The alluvial aquifer is underlain by the Tertiary Wasatch Formation, an erosion-resistant geologic unit consisting mostly of variegated claystone, siltstone, and sandstone. Depth to the top of the Wasatch from land surface (i.e., from the top of the fill where present) typically varies between 20 and 30 ft.

The alluvial aquifer extends northward to just south of Highway 6, where resistant sedimentary rocks of the Wasatch Formation ascend steeply 40 to 60 ft. Much of the Wasatch face near the aquifer's north boundary is covered with alluvium and colluvium that has descended from elevated areas north of Highway 6. The Colorado River forms the south boundary of the aquifer, and the aquifer's east and west ends are located in areas where the outcropping Wasatch Formation abuts the river (Figure 1), effectively pinching the alluvium out. The areal extent of the alluvial aquifer takes up most of the area contained within the site's property boundary (Figure 1).

The low-permeability Wasatch Formation is thousands of feet thick beneath the site and generally acts as a strong aquitard, such that very little, if any, water appears to be exchanged between unweathered Wasatch sediments and the overlying alluvium. Descriptions in the SOWP (DOE 199) of the geologic logs for three wells drilled more than 30 ft into the Wasatch Formation at the site indicate that the uppermost 8 to 13 ft of the formation tends to be weathered and is in hydraulic communication with the overlying alluvial aquifer. Signs of weathering and fracturing are visually observed in the uppermost portion of the Wasatch in elevated outcrops of the formation just north of Highway 6.

Under base-flow conditions on the Colorado River, the bottom 10 or 15 ft of the alluvial sediments are typically saturated. Groundwater levels in the alluvial aquifer can increase by as much as 5 to 6 ft during late spring and early summer, when surface water discharge and river stage increase substantially due to snowmelt runoff from mountainous terrain in the region. As a consequence, piezometric levels in the aquifer may at times rise above the base of the surficial fill in some locations.

Analyses of aquifer test data collected in support of the SOWP (DOE 1999) resulted in estimates of hydraulic conductivity for the alluvial aquifer that varied from 100 to 125 ft/day. Values used in various studies to represent the alluvium's porosity have ranged between 0.25 and 0.35 (25 to 35 percent). The geometric mean of hydraulic conductivities estimated from slug tests in upper, weathered portions of the underlying Wasatch Formation was 0.017 ft/day (DOE 1999), a value that is more than 3 orders of magnitude less than the hydraulic conductivities ascribed to the alluvial aquifer. An investigation of co-located hydraulic heads in the alluvium and Wasatch Formation at multiple well nests across the site under non-pumping conditions revealed little or no driving force for vertical groundwater migration from one hydrogeologic unit to the other.

Past assessments of the alluvial groundwater flow system during periods of both low runoff and high runoff for the river indicate that groundwater flow in the aquifer is predominantly toward the south-southwest and southwest, although groundwater in the eastern half of the site tends to flow more directly to the west during high-river stage (DOE 1999). Virtually all of the groundwater in the aquifer discharges to the Colorado River. On the basis of previously prepared maps of the aquifer's potentiometric surface, calculated horizontal hydraulic gradients across the site vary from 0.003 to 0.006 ft/ft.

The predominant flow direction of south-southwest to southwest in the alluvial aquifer implies that much or most of the site groundwater derives from water sources north of Highway 6. These sources consist of subsurface inflow from older Quaternary alluvium north of the highway, much of which appears to migrate downward into weathered and fractured portions of the underlying Wasatch before migrating horizontally beneath the highway and recharging the alluvial aquifer. However, some of the inflowing water in the older alluvium apparently fails to migrate downward into Wasatch Formation sediment prior to reaching the site, which results in groundwater seeps on the north side of the highway. One of the seeps is located west of Ash Avenue (Figure 1), which intersects Highway 6 from the northwest. Areal recharge through sediments in higher elevation areas north of the site, either from natural infiltration of precipitation or anthropogenic water sources, is likely to be the origin of water in this seep. The seep water flows into an unlined ditch that parallels the highway on its north side, which in turn conveys water eastward to a culvert under Ash Avenue and then to a culvert under Highway 6, which feeds water to the on-site ditch (Figure 1).

Multiple seeps are present on the north side of Highway 6 in an area of thick vegetation located just east of Ash Avenue (Figure 1). The groundwater discharged there also flows into an unlined ditch that parallels the highway and feeds the on-site ditch via the culvert beneath the highway. The source, or sources, of the groundwater feeding these latter seeps is unknown. As in the case of the seep located west of Ash Avenue, some of this water may derive from natural or anthropogenic recharge in areas lying farther to the north. Alternatively, it is possible that some or all of the surface seepage here can be attributed to infiltration and downward percolation of surface water in two detention lagoons located on a mesa directly north of the site's east end (Figure 1). The City of Rifle periodically disposes of treated Colorado River water via pipelines to the lagoons, where it tends to pond, evaporate and support in-lagoon vegetation. Because the delivery rate of city water to the lagoons can at times be hundreds of gallons per minute (gpm), the potential also exists for some infiltrated water from this source to migrate downward and outward in multiple directions, including to the seep area east of Ash Avenue. Similarly, some of the lagoon water might migrate more directly to the south-southwest and directly recharge the easternmost third of the alluvial aquifer.

The conceptual model of groundwater flow developed for the SOWP (DOE 1999) attributed additional aquifer inflows to surface water seepage losses along the unlined on-site ditch (Figure 1). Areal recharge from precipitation on the site and possible upflow from the underlying Wasatch Formation were considered relatively minor contributors to alluvial aquifer groundwater. The SOWP conceptual model did not directly address potential inflows of river water to the aquifer; boundary conditions used to represent the river in the numerical groundwater flow model developed for the site indirectly accounted for this possibility.

3.3 Water Chemistry

3.3.1 Contaminants

The SOWP identified arsenic, selenium, uranium, and vanadium as COCs in alluvial groundwater at the Old Rifle site, and uranium is the most abundant and widely spread contaminant. Mill-related processes contributed many other inorganic constituents to the groundwater system, some of which continue to impact subsurface geochemical processes, but the aqueous concentrations of these additional constituents in the alluvial aquifer are not considered threats to human health or the environment.

Much of the groundwater contamination currently detected in the aquifer likely resulted from rainfall and melting snow that leached uranium and vanadium ores stored on the east end of the site and from leaching of tailings deposited on the ground surface in the west half of the site. Downward-seeping water from the various mill-water ponds that were occasionally used in the former mill tailings area (Figure 1) also probably contributed tailings-derived aquifer contamination, as did the leaching of contaminants present in the former mill buildings area.

Several types of chemicals used to process the ores undoubtedly added to the inorganic constituent mass that remains in the site's subsurface today. The impacts of most of these chemicals and related chemical residues were likely to have been observed in the former mill tailings area. Though the exact quantities of chemicals used in the milling process are unknown, dissolved inorganic constituents that probably exhibited increased concentrations due to their use included ammonia, bicarbonate, carbonate, chloride, sodium, and sulfate (DOE 1999, Merritt 1971).

To assess the potential for a continued source of groundwater contamination in the subsurface, samples from soils directly beneath the former tailings and ore stockpile areas were collected in the late 1990s (DOE 1999) and analyzed for arsenic, molybdenum, selenium, uranium, and vanadium. The soil testing revealed that concentrations of arsenic, uranium, and vanadium were generally higher than those for molybdenum and selenium, and selenium concentrations were nondetectable. The highest uranium and vanadium concentrations were mostly detected in a sample collected beneath the former ore storage area. Of interest was the fact that uranium concentrations in soil samples collected from two off-site points in a river floodplain about 0.8 mile east-northeast of the site were generally of the same magnitude as concentrations in samples collected beneath the former tailings area.

Site characterization in support of the SOWP also included the collection of surface water samples from a variety of locations. Analyses of several samples collected from seeps north of the highway, the unlined ditch north of the highway into which the seeps fed, and the on-site ditch indicated that uranium in these surface waters ranged from 0.02 to 0.055 milligram per liter (mg/L). Given that all of these waters were considered representative of major recharge sources for the alluvial aquifer (Section 3.2), the reported uranium concentration range indicated that site groundwater could naturally contain uranium at levels approaching 0.03 to 0.05 mg/L. Thus, the background concentration of uranium at the site had the potential to exceed the 0.044 mg/L UMTRA standard for uranium.

Considerable attention was given in the SOWP to the estimation of a representative sediment-water distribution coefficient, or K_d, for each COC in the site's alluvial groundwater. A reliable estimate of K_d was considered critical for assessing the subsurface migration because it reflected the degree to which a contaminant would sorb to aquifer sediments along its transport path, with increasing K_d values signifying greater sorption. Correspondingly, the K_d value adopted for a COC controlled the rate at which its advective transport (due to average linear groundwater velocity) and, therefore, flushing, would be retarded (Freeze and Cherry 1979).

Laboratory batch tests conducted in accordance with a 1987 American Society for Testing and Materials standard was applied to sediment samples from a floodplain location upriver of the site to estimate K_d values for all COCs. The test method generated multiple K_ds for uranium, ranging from 0.2 to 0.9 milliliters per gram (mL/g). These values were considered too large for the alluvial aquifer because a large fraction of the sediments in the test samples consisted of coarse-grained sands and gravels, which were expected to contribute little to uranium sorption in the subsurface. Subsequent adjustment of the original K_d values to reflect the large percentage of coarse materials resulted in a set of final estimated K_ds ranging from 0.2 to 0.3 mL/g, which suggested that uranium in the alluvial aquifer would be relatively mobile and its advective transport only mildly retarded.

3.3.2 Historical Distribution of Uranium in the Alluvial Aquifer

Aqueous constituent concentrations measured at several alluvial wells in 1998 during preparation of the SOWP showed that the largest amount of dissolved uranium mass at the time was present in groundwater underlying the former tailings area. As illustrated in a map of contoured uranium concentrations from a sampling event in May 1998 (Figure 2), uranium concentrations approaching 0.3 mg/L were detected in the west half of the site, and concentrations of about half this value were detected in groundwater on the site's east end. Measured uranium concentrations were noticeably lower in the site's midsection, such as in the vicinity of the on-site ditch. Here, the uranium levels here exceeded the UMTRA groundwater standard of 0.044 mg/L for uranium, which is based on assumed secular equilibrium between isotopes of uranium-234 (U-234) and uranium-238 (U-238). The lowest uranium concentrations were observed at wells located along the aquifer's northwest border.

The areal distribution of aqueous-phase uranium shown in Figure 2 suggests that in 1998, 40 years after cessation of Old Rifle milling operations, a majority of the uranium remaining in groundwater could be attributed to leaching of tailings that had previously covered much of the site's west half. A smaller but nevertheless significant mass of uranium detected in groundwater in the east third of the site was likely caused by leaching of ore that was historically stored there. The presence of uranium concentrations in the central part of the site that were noticeably lower than concentrations observed to the west and east suggested that historical leaching of surface contamination in this area was possibly less than in other site locales. It is also possible that the relatively low uranium levels in the site's midsection were attributable to dilution by fresh surface water seeping into the subsurface from the on-site ditch.

The uranium concentrations posted in Figure 2 for alluvial aquifer wells in May 1998 represent a snapshot in time, and aqueous uranium concentrations measured at some of these same wells in November 1998 were noticeably different from those shown in the figure. This observation illustrates how uranium concentrations can change between sampling events. Despite such temporal variability, the general pattern of uranium distribution shown in Figure 2, with the highest uranium levels beneath the east and west portions of the site and lower concentrations in between, is consistently maintained.

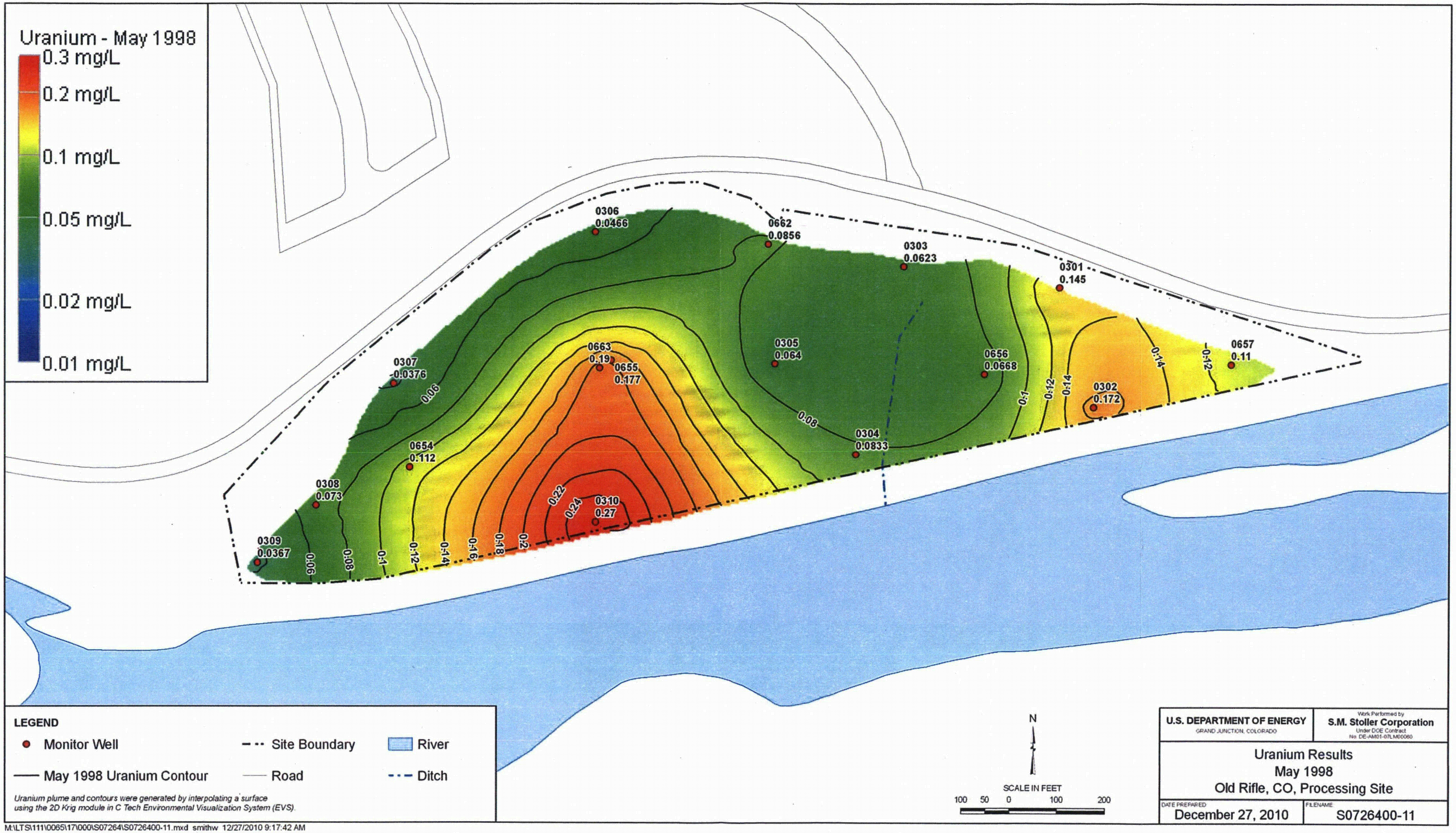

Figure 2. Uranium Concentrations in the Alluvial Aquifer in May 1998

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3.3.3 Ambient Groundwater Chemistry

The general chemistry of water in the site's subsurface strongly affects the fate of uranium remaining in groundwater as a legacy of historical milling operations. Pertinent chemical characteristics of groundwater in the alluvial aquifer, derived primarily from the SOWP (DOE 1999), are summarized in this section.

The specific conductance of alluvial aquifer groundwater varies from about 1,800 to 5,000 microsiemens per centimeter (µS/cm), which is reflective of total dissolved solids concentrations of approximately 1,500 to 4,500 mg/L. Alkalinity concentrations typically fall in the range of 300 to 600 mg/L as calcium carbonate and are indicative of relatively high dissolved bicarbonate concentrations. Dissolved nitrate levels are low; most reported concentrations for this constituent are less than 2 mg/L. Sulfate concentrations, which commonly vary between 500 and 2,000 mg/L, are elevated ostensibly as a result of past milling activity at the site. The pH of the groundwater is circumneutral to slightly basic (6.8 to 8.5).

The redox state of the alluvial groundwater is manifested in a variety of chemical indicators. Dissolved oxygen (DO) concentrations in most horizons within the saturated zone are typically less than 0.3 mg/L (DOE 1999), which signifies anoxic conditions. However, DO levels measured in the shallowest parts of the saturated zone may have values as large as 2 to 2.5 mg/L, and DO concentrations show a tendency to increase during periods of higher groundwater elevation (Yabusaki et al. 2007) in late spring and early summer. Dissolved iron concentrations tend to be relatively high, ranging from 0.003 mg/L to as high as 3 mg/L and averaging near 0.5 mg/L. Similarly, aqueous manganese concentrations are somewhat elevated, and concentrations as high as 2 mg/L are common. The oxidation-reduction potential (ORP) of the groundwater ranges from –250 millivolts (mV) to about 100 mV (DOE 1999). Overall, these characteristics are representative of a slightly reducing chemical environment. Such a redox state suggests that uranium has the potential to naturally occur in a precipitated solid state at some locations within the subsurface.

The low DO and nitrate concentrations in site groundwater provide a subsurface environment that is conducive to the immobilization of uranium using techniques that manipulate redox chemistry. Specifically, biogeochemical reactions that depend on the presence of these two constituents (i.e., aerobic respiration and denitrification) tend to consume only minor amounts of the organic carbon injected by IFRC personnel during biostimulation experiments (see Section 4.1.1), which makes more organic carbon available for reactions that cause uranium to precipitate out of solution.

3.4 DOE Modeling

A groundwater flow and transport model was developed for the SOWP (DOE 1999) to assess the effectiveness of natural flushing as a groundwater remedy. Groundwater flow was numerically represented using the U.S. Geological Survey (USGS) code MODFLOW (McDonald and Harbaugh 1988), and contaminant transport was modeled with the USGS simulator MT3D (Zheng 1990). Flow and transport in the aquifer were assumed to occur solely within a two-dimensional (2-D) horizontal plane.

3.4.1 Groundwater Flow Model

Recharge sources included in the model were represented using prescribed flows in several parts of the flow domain, including at seep locations close to Highway 6 and along the ditch paralleling the highway on its north side. Prescribed flow conditions were also applied along the length of the on-site ditch to account for recharge from this surface water source. A minor amount of recharge from areal infiltration of precipitation on the site was also taken into account. The southern aquifer boundary coincided with the north bank of the Colorado River, which was simulated using prescribed values of hydraulic head.

A trial-and-error approach was applied to calibrate a steady-state version of the flow model, using a set of groundwater elevations collected from site wells during a monitoring event in 1998 as calibration targets. A uniform hydraulic conductivity of 110 ft/day was employed in the final calibrated model, and prescribed flow boundary conditions were adjusted to achieve an acceptable match between computed groundwater elevations and the head calibration targets. A water budget reported for the steady-state flow model (DOE 1999) indicated that water inflow sources north of Highway 6 contribute 6,113 cubic feet per day (ft^3/day), or 31.8 gpm, of recharge to the alluvial aquifer. Inflow to the aquifer from seepage losses along the on-site ditch amounted to 2,484 ft^3/day (12.9 gpm) in the model, and the assumed average recharge rate from areal infiltration of precipitation was limited to 18 ft^3/day (0.09 gpm). All water losses from the aquifer in the steady-state model occurred as discharge to the river.

3.4.2 Transport Model

MT3D simulations of uranium transport accounted for advection and dispersion (Freeze and Cherry 1979) within the aquifer as well as retarded uranium migration due to constituent sorption on aquifer sediments. Contaminant sorption was modeled as a linear equilibrium process using a uniform and constant value of the soil-water partition coefficient, or K_d, considered representative of uranium in the alluvial aquifer. Several different values of longitudinal and transverse horizontal dispersivity were tested in the model before adopting a final set of values for these parameters to be used in predictive simulations.

A probabilistic, or stochastic, modeling approach was taken to predict how natural flushing of uranium would progress at the site. One hundred Monte Carlo simulations, each with a different combination of randomly generated values of stochastic parameters, were conducted to generate a suite of numerical results from which the predicted flushing time for uranium could be ascertained. Stochastic (uncertain) parameters in the Monte Carlo simulations included aquifer hydraulic conductivity, longitudinal and transverse horizontal dispersivities, and the uranium K_d, the last of which was allowed to range between 0.0 and 0.2 mL/g. Aquifer porosity was maintained at a uniform value of 0.25 (25 percent), and the concentration of uranium in recharge waters from north of Highway 6 and on-site ditch seepage was assumed to be 0.038 mg/L in all model runs. The uranium concentrations shown in Figure 2 for conditions in May 1998 were used to develop a spatially distributed set of starting concentrations in each simulation.

Each of the 100 Monte Carlo simulations accounted for 100 years of uranium transport. All of the stochastic model runs predicted that ambient background flow and transport conditions would cause uranium to effectively flush from the alluvial aquifer within 10 simulation years. The largest predicted uranium levels in all model runs after 10 years of flushing were only slightly higher than the 0.038 mg/L concentration assigned to the major recharge sources in the model.

3.5 DOE Compliance Strategy Selection

Based on the information discussed above and the conceptual model developed in the SOWP, DOE was required to select a compliance strategy for site groundwater. Because the modeling showed that natural flushing would achieve the groundwater standard for uranium in a timeframe less than 100 years, DOE selected natural flushing (similar to monitored natural attenuation) as the groundwater compliance strategy for the Old Rifle site (see Section 10.1.3 for further discussion). As noted previously, NRC concurred on this compliance strategy, as described in the GCAP (DOE 2000), in 2002. As part of the compliance strategy, annual monitoring has been required to support the natural flushing evaluation. In addition to monitoring, research at the Old Rifle site has been ongoing to study uranium attenuation mechanisms. Section 4.0 summarizes the activities associated with and results from that research.

4.0 IFRC Studies

Consistent with DOE's goal of uranium attenuation in groundwater, studies by SC researchers at the Old Rifle site began in the early 2000s and have continued through the first half of 2011 (Long 2011). As described in Section 1.0, many of these investigations have been conducted as part of the Rifle IFRC, which began in 2007. The earliest research work comprised experiments aimed at reducing aqueous-phase uranium concentrations in portions of the site's alluvial aquifer comprising less than 0.1 acre. Specifically, uranium was immobilized through subsurface application of an organic carbon amendment that stimulates microbially mediated precipitation of uranium as a solid. As discussed in the following sections, field-scale tests of this form of biostimulation, using acetate as an amendment, have confirmed that this type of stimulation does, for some time, locally reduce dissolved uranium concentrations. Since the earliest experiments and continuing to the present, efforts have been made to more thoroughly understand the geochemistry and microbiology associated with biostimulation. In more recent years, Rifle IFRC researchers have also strived to better describe ambient, background phenomena in the alluvial aquifer, focusing on more detailed characterization of hydrological, contaminant-transport, geochemical, and microbiological processes in areas separate from those subjected to biostimulation. In addition, experiments have been conducted that promote flushing of uranium by enhancing levels of naturally occurring constituents, such as bicarbonate ions, in groundwater. These stimulations induce mobilization of uranium adsorbed to sedimentary materials that constitute the alluvium.

A key goal of the IFRC initiative has been to develop quantitative models that simulate the various flow, transport, geochemical, and microbial processes that occur in the alluvial aquifer, under both biostimulated and ambient background conditions. The models have proved particularly beneficial, not only for synthesizing the numerous physicochemical phenomena that impact the fate of uranium in the aquifer, but also for projecting the results of future experiments.

It should be mentioned that one IFRC task parallels efforts by LM to better understand reasons for the persistence of relatively high uranium concentrations in the alluvial aquifer at the Old Rifle site. This work tacitly acknowledges that natural flushing processes have not been successful in the manner that DOE originally anticipated and provides reinforcement for many of the analyses and findings presented in this report. The specific research activities that IFRC personnel carried out to identify and better understand processes contributing to uranium persistence in groundwater are not addressed in this present study. Nonetheless, readers should be aware that findings developed thus far under the IFRC effort generally comport with reasons presented in this report (see Section 7.0) for recalcitrant uranium in Old Rifle groundwater.

The SC investigations have been concentrated in rectangular areas on the west half of the site. Figure 3 shows the locations of the study areas, along with the adopted names and applicable dates (in parentheses) for several explicit experiments that have been or are being performed at the plots. More than one experiment is typically performed within a study area. The first three enhanced biostimulation tests were performed in the area identified as the location of "2002, 2004, and 2005 experimental plots." Because the Old Rifle site was not designated an IFRC location until 2006, these earliest biostimulation investigations are also referred to as pre-IFRC experiments. New, detailed biostimulation experiments have since been conducted at Plots A and C; investigations at Plots B and D (Figure 3) have primarily focused on the characterization of natural background processes in the alluvial aquifer.

Subsequent parts of this section describe the general groundwater chemistry associated with the biostimulation experiments (Section 4.1.1), the monitoring networks and techniques used to conduct and evaluate the experiments (Section 4.1.2), relevant findings from the biostimulation experiments (Section 4.1.3), the presence of chemically reduced zones in the alluvial aquifer under natural background conditions (Section 4.2), studies designed to characterize processes affecting uranium mobility in groundwater (Section 4.3), and models of some of the IFRC experiments (Section 4.4).

4.1 Biostimulation Experiments

4.1.1 Biogeochemical Reactions

The primary goal of each biostimulation experiment at the Old Rifle site is to use biological processes to promote chemically reducing conditions in uranium-contaminated parts of the alluvial aquifer. Specifically, the aim is to enhance biologically mediated iron reduction, a redox reaction wherein subsurface microorganisms metabolize organic carbon and in the process transfer electrons from a donor chemical (electron donor) to solid-phase ferric iron Fe(III) (Anderson et al. 2003). The IFRC experiments use acetate as the electron donor, and Fe(III) is provided by iron oxyhydroxide and phyllosilicate minerals in the alluvial aquifer matrix. Microbially mediated iron reduction is also referred to as a terminal electron acceptor process (TEAP) in that it facilitates the transfer of electrons to the oxidant Fe(III); in the process of accepting electrons, solid Fe(III) is converted into dissolved ferrous iron Fe(II). Though a generic group of microbes referred to as iron reducers are generally responsible for mediating iron reduction in the environment, *Geobacter* species have been specifically identified as the microorganisms primarily responsible for iron reduction in Old Rifle alluvium (Anderson et al. 2003).

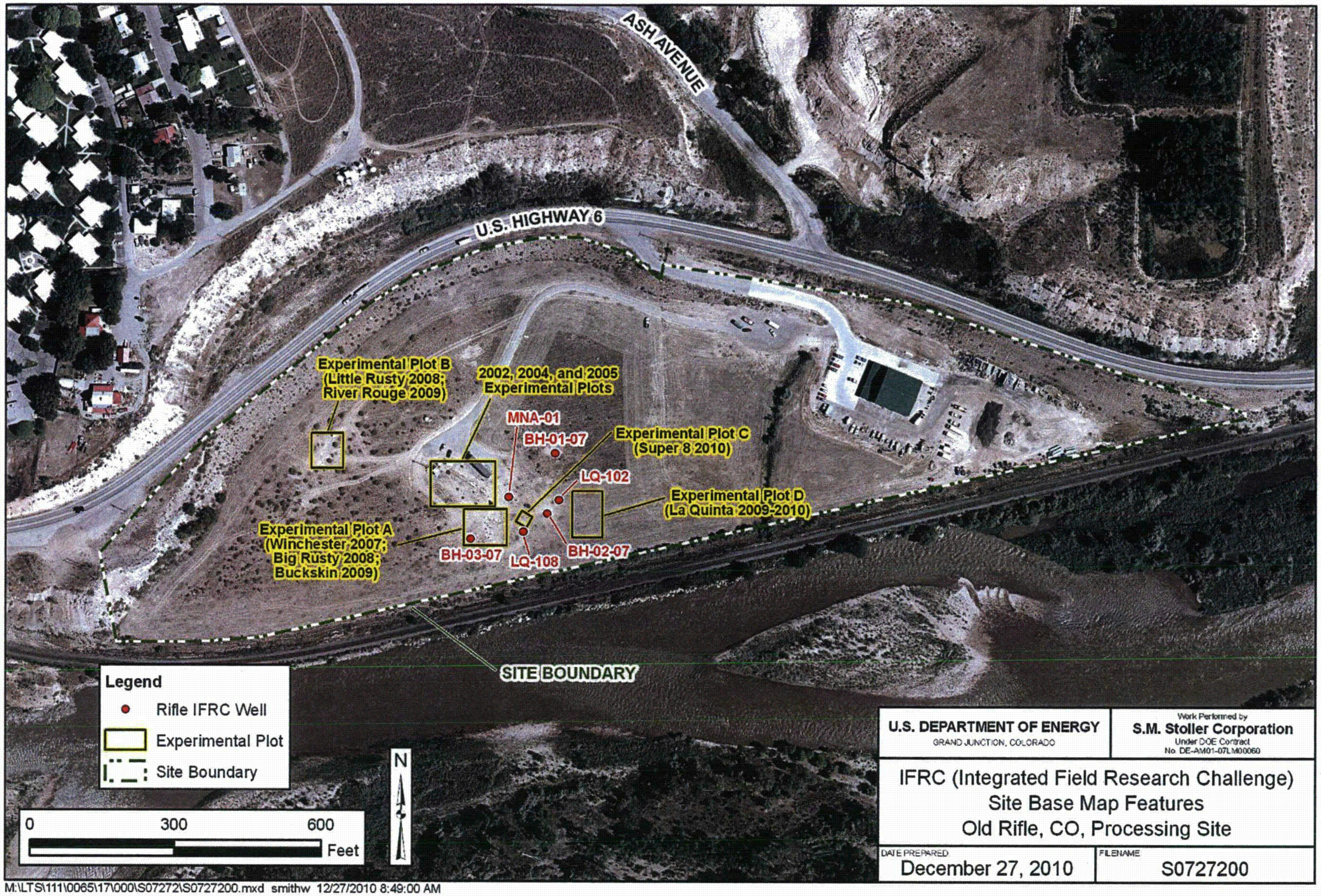

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Figure 3. IFRC Experimental Plots at the Old Rifle Site

Iron-reducing microbes are also capable of facilitating uranium reduction (Anderson et al. 2003), a TEAP in which electrons from an organic carbon source (e.g., acetate) are transferred to dissolved hexavalent uranium U(VI), resulting in the production of tetravalent uranium U(IV). Dissolved U(VI) may be present as a free uranyl ion (UO_2^{2+}), but is more commonly present in aqueous-phase chemical complexes (Sections 4.1.3 and 6.1.2). Minerals containing U(IV) generated by the U(VI) reduction have low solubility and precipitate out of solution. It has traditionally been assumed that the U(IV) generated through biostimulation automatically occurs in the subsurface as uraninite $UO_{2(s)}$. However, work over the past 3 years at the Rifle IFRC and other locations has shown that the biogenic U(IV) is initially present in solid forms different from uraninite. Continued research dealing with this phenomenon has shown that these early forms of U(IV) have the potential to eventually transform into uraninite (Section 4.1.3).

Biostimulated iron reduction decreases U(VI) concentrations in areas of the alluvial aquifer downgradient of an organic carbon application as long as a supply of the electron acceptor Fe(III) is available. However, after about a month of acetate injection, iron reduction tends to be overtaken by biologically mediated sulfate reduction (Long 2011), the next thermodynamically favored TEAP, in which dissolved sulfate becomes the electron acceptor. It has long been known that some sulfate-reducing microbes (sulfate reducers) are also capable of reducing U(VI) depending on local subsurface conditions and the electron donor material driving the sulfate reduction. However, IFRC researchers have shown that the sulfate reducers stimulated by acetate amendments at the Rifle site do not contribute to U(VI) reduction, thus indicating that biologically driven precipitation of uranium during site biostimulation tests is solely attributable to the activity of iron-reducing bacterial species (Long 2011). After sulfate reduction becomes the dominant TEAP in a biostimulation test, iron-reducing bacteria continue to reduce uranium in the presence of Fe(III), but the rate at which U(IV) is generated by iron reducers is noticeably less than occurred when microbial iron reduction predominated. Recent biostimulation experiments conducted by IFRC personnel have been aimed at identifying means of enhancing and sustaining microbially mediated iron reduction with the intent of maximizing uranium immobilization.

4.1.2 Test Plots and Monitoring

Each biostimulation test is performed using an array of wells laid out in a rectangular pattern. Injection wells near the upgradient end of the well array are used to deliver acetate amendment to the aquifer, and multiple rows of wells oriented perpendicular to the ambient groundwater flow direction (Figure 4) are used to monitor the downgradient effects of the experiment on dissolved concentrations of numerous constituents, including acetate, U(VI), and Fe(II). "Background" wells located upgradient of the injection wells are used to characterize the chemistry of ambient water feeding into the test plot.

The sizes of the biostimulation injection and monitoring plots vary among tests, depending on the objectives of the experiment being conducted. However, in general, the dimensions of a rectangular test area typically fall in a range that facilitates experimental control. As shown in the schematic in Figure 4, the widths of the test areas tend to range between 25 and 50 ft, and the plot lengths, extending from the background wells to the farthest downgradient monitor wells, are typically 50 to 70 ft. Hence, the area included in the test monitoring is less than 0.1 acre. Figure 5 presents an areal view of the well layout used in the first biostimulation test, which began in spring 2002 within the "2002, 2003, and 2005 experimental plot" areas (Figure 3). As indicated in the figure, three rows of five monitor wells were used for this test, and the distances from the injection array to monitoring rows were 12, 24, and 48 ft, respectively. The average distance between wells in each monitoring row was about 9 ft, and the row of injection wells was about 48 ft long.

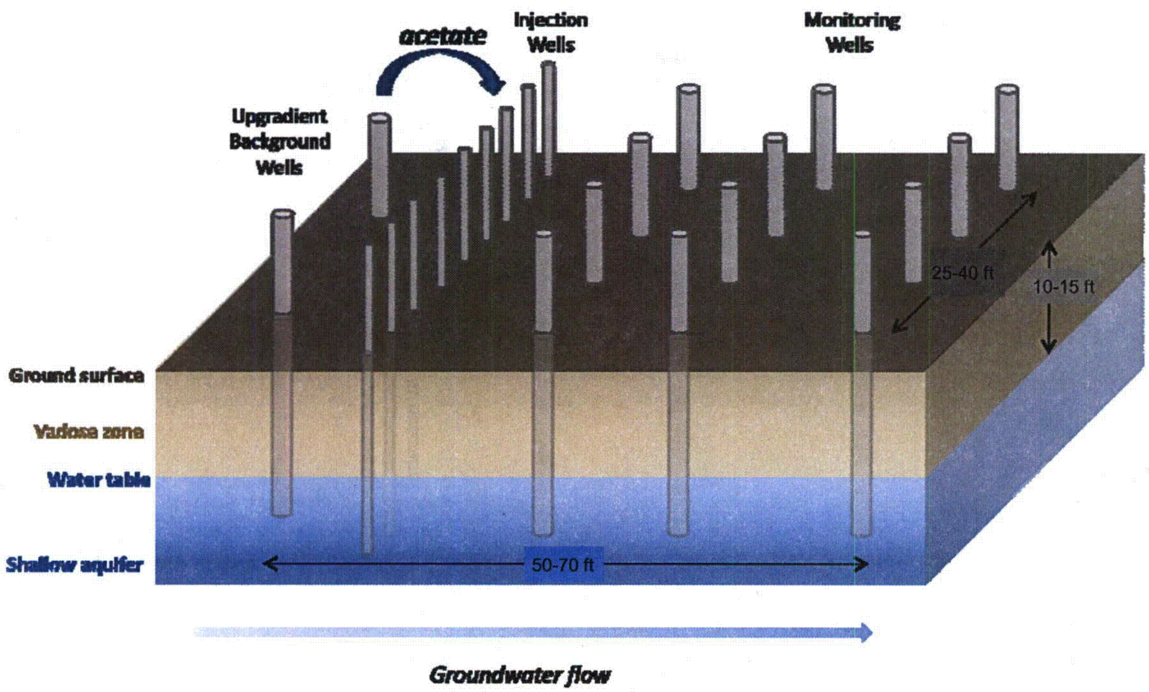

Figure 4. Typical Configuration of Wells in a Biostimulation Test

It is common for multiple biostimulation events to be conducted at a given test plot. Specific reasons for carrying out successive tests vary, though in most cases the motivation is to change test variables (e.g., acetate concentrations, amendment application duration) and study the concomitant impacts on biologically mediated iron, uranium, and sulfate reduction. A second experiment was conducted in summer 2003 at the field plot shown in Figure 5, the location for the first biostimulation test that began in spring 2002. During the 2003 experiment, injected acetate concentrations were 3 times those used in the 2002 test.

Occasionally, multilevel sampling wells are installed within the biostimulation test array for the purpose of discerning and analyzing vertical flow and transport processes. Drill cores of alluvial aquifer sediment are also sometimes collected and chemically analyzed to better understand the solid-phase chemistry associated with iron, uranium, and sulfate bioreduction.

4.1.3 Relevant Findings

Throughout the various biostimulation tests conducted to date, researchers have identified chemical complexes of uranium, calcium, and carbonate (Ca-UO_2-CO_3 ternary complexes) as the primary U(VI) species in groundwater. This finding is expected, given the relatively large concentrations of alkalinity (300 to 600 mg/L as calcium carbonate) in subsurface water at the site (Section 3.3.3). Though the ternary complexes are relatively mobile in groundwater, the biostimulation tests have demonstrated that the application of acetate amendment does

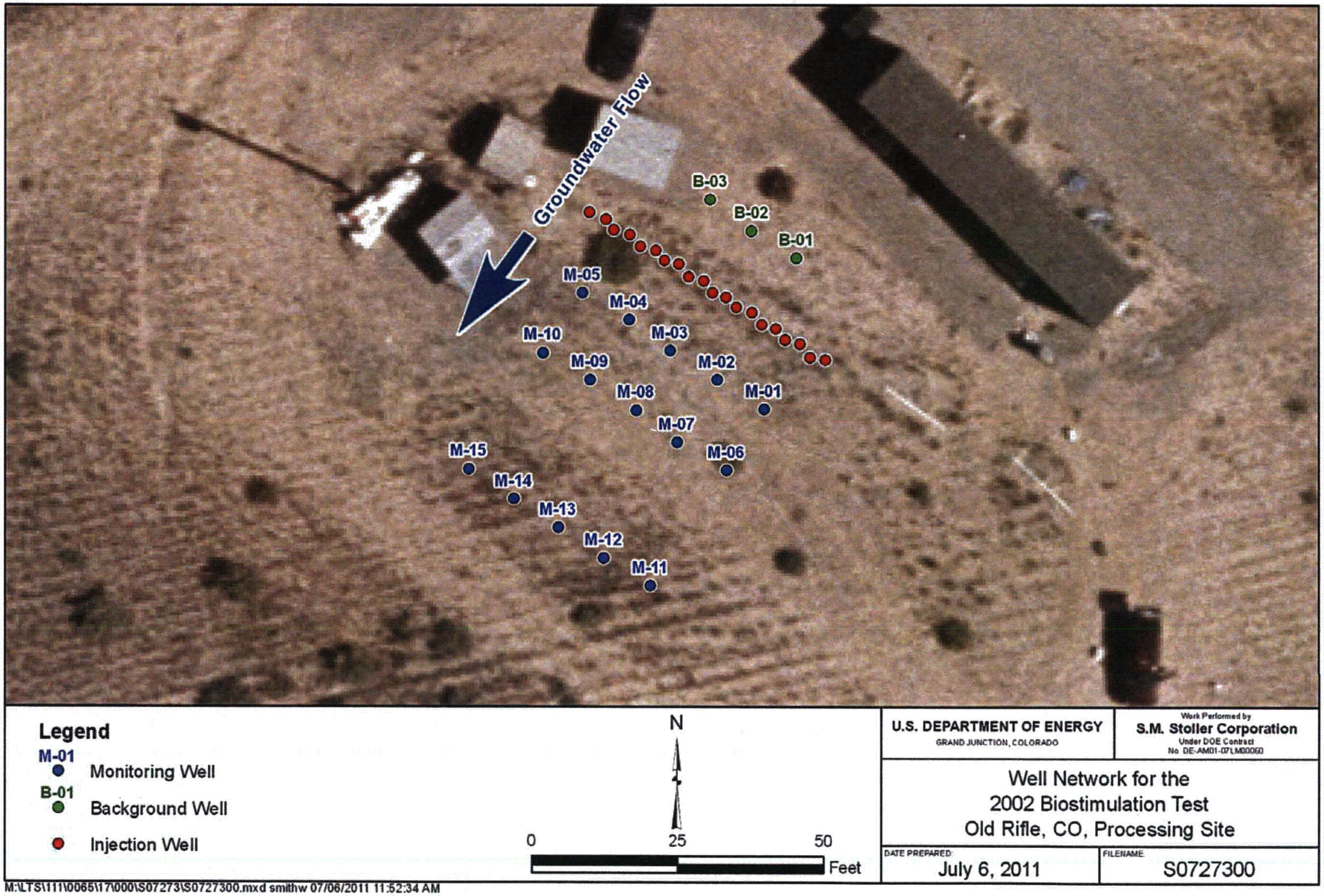

Figure 5. Layout of Wells in the 2002 Biostimulation Experiment

successfully lead to the creation of solid U(IV) species, and that dissolved uranium concentrations in the resulting chemically reduced zones can be decreased to less than the UMTRA groundwater standard of 0.044 mg/L.

One of the observed effects of biologically induced sulfate reduction results in the generation of dissolved sulfide. IFRC experiments have shown that much of the biogenic sulfide combines with the dissolved Fe(II) produced by iron reduction to form iron sulfide precipitates. The presence of these precipitates has been confirmed through the analysis of drill cores collected upon the completion of some of the biostimulation tests. An interesting finding stemming from the study of dissolved sulfide generated by the biostimulation tests is that the sulfide has a tendency to react with dissolved U(VI) and, in the process, abiotically reduce the U(VI) to solid-phase U(IV) (Long 2011). One of the products of this chemical reaction is elemental sulfur, which also appears as a solid on aquifer materials. This finding is considered important because it demonstrates that, under sulfate-reducing conditions, abiotic chemical reactions are an important contributor to the removal of U(VI) from solution, and should be considered in addition to bioreduction processes when attempting to ascertain the effects of biologically reduced conditions on the fate of uranium.

Biostimulation applications are ultimately judged for their ability to immobilize uranium over long-term periods. Invariably, at least some biogenic U(IV) is re-oxidized to aqueous U(VI) as upgradient groundwater flows into the area impacted by the biostimulation. Relatively high alkalinity concentrations in the background groundwater enhances the redissolution of U(IV), as do occasional natural influxes of DO. As discussed subsequently in Section 4.3, a recent biostimulation experiment conducted in Experimental Plot C has shown that methods designed to mobilize uranium in the subsurface may actually help lengthen the period over which U(VI) concentrations remain depressed due to biostimulation.

As mentioned in Section 4.1.1, the solid-phase U(IV) generated by biostimulation initially occurs in forms different from uraninite. Specifically, the biogenic U(IV) is present in the form of solid-phase monomeric complexes that tend to be associated with solid-phase iron and sulfur in the subsurface (Long 2010). In late 2010, an experiment designed to observe the evolutionary behavior of biogeneic U(IV) encased in wells at the Buckskin experimental site (Plot A in Figure 3) showed that, with about a year of aging, monomeric U(IV) did transform into uraninite. This finding encouraged IFRC researchers because uraninite is considered less likely than monomeric U(IV) to be re-oxidized by inflowing water containing relatively high alkalinity.

This, in turn, implies that reduced uranium produced by biostimulation may be slow to reoxidize and re-dissolve in site groundwater, and therefore, could help maintain concentrations of U(VI) below the UMTRA groundwater standard (0.044 mg/L).

4.2 Naturally Reduced Zones

IFRC work in recent years inadvertently led to the discovery of multiple zones in the subsurface that are naturally reducing (e.g., Long 2010). The presence of the naturally reduced zones was not entirely unexpected, given that previous site characterization efforts have occasionally revealed alluvium dominated by fine-grained sediments and containing organic debris, the combination of which has the potential to induce natural biodegradation and consumption of the thermodynamically favorable electron acceptors (e.g., DO, nitrate, iron, sulfate). The identification of such zones, combined with a general interest of uranium on a sitewide scale, eventually led to a new IFRC experimental task (LaQuinta) and a rectangular study area (Plot D in Figure 3) that focused on characterizing the origin of, composition of, and processes occurring within the naturally reduced areas. This research is of great interest because it is believed that the reduced zones not only have the capacity to be subsurface sinks for uranium but also can act as long-term sources of uranium in groundwater.

Investigations of the sediments in the naturally reduced zones indicate that they are dominated by fine-grained materials such as clays and silts that are typically dark gray to black in color. Examination of solid-phase components of the reduced zones shows a significant presence of sulfide minerals, including pyrite. U(IV) is present in the reduced sediments, and analyses of the pyrite (Qafoku et al. 2009) show the presence of both solid-phase U(VI) and U(IV). Relatively high levels of total organic carbon provide evidence of a biological origin for the reduced zones, as do the presence of microbial communities dominated by iron reducers, sulfate reducers and bacteria that facilitate fermentation.

IFRC research conducted thus far on naturally reduced zones at Old Rifle has not shed light on the relative abundance of these features in the alluvial subsurface. However, it has been shown that surface geophysical characterization methods based on electrical resistivity potentially provide a non-invasive means for identifying the locations of buried chemically reduced zones. Further understanding of their overall abundance and the nature of the physicochemical phenomena occurring within them may prove to be important in future years even if the zones comprise only a few percent of the alluvial aquifer. Their potential to act as long-term sources of aqueous-phase U(VI) could detrimentally impact the success of any applied remediation strategy.

4.3 Uranium Mobility

A thorough understanding of processes that influence the mobility of U(VI) in the site's alluvial aquifer is considered critical by IFRC researchers, not only for assessing the efficacy of efforts to effect sustainable immobilization of uranium through biostimulation, but also to ascertain the influence of engineered uranium mobilization techniques on the long-term fate of uranium. Accordingly, several IFRC experiments, in both the laboratory and the field, have been conducted to study in detail uranium mobility under various subsurface conditions.

Consistent with the effort to improve knowledge of uranium mobility, a key IFRC objective has been to improve both the conceptualization and quantification of U(VI) sorption processes under ambient conditions (Long 2011). A test aimed at pursuing this objective was performed at the Little Rusty site (in Experimental Plot B) in fall 2008. The purpose of the test was to accelerate desorption of U(VI) from alluvial sediments by injecting sodium bicarbonate (Long 2009) upgradient of an array of monitor wells used to monitor both sorption and desorption in the subsurface. Using the results of laboratory-batch reaction tests performed earlier (Hyun et al. 2009) on sediments from the Little Rusty area, the bicarbonate was expected to combine with dissolved calcium and sorbed U(VI) to form aqueous Ca-UO_2-CO_3 ternary complexes that are relatively mobile, with the net result being increased concentrations of U(VI) in impacted areas and the creation of additional sorption sites for upstream influent U(VI). The Little Rusty test was distinct in the sense that it was designed to assess sorption/desorption processes in an ambient, non-biostimulated environment.

A Rifle IFRC quarterly report (Long 2009) indicates that a sorption model based on the Hyun et al. (2009) application of surface complexation theory to the above-mentioned batch reaction tests provided a useful tool for simulating uranium and desorption processes at Little Rusty. The quarterly report also mentions that tracer breakthrough data at a downstream multi-level monitor well showed the presence of considerable aquifer heterogeneity, with groundwater at depth (25 ft) in the aquifer migrating much faster than water in shallower portions of the aquifer. Results from the Little Rusty test have not yet been formally reported. Eventual publication of the test results and analysis are expected to show that sorption and desorption of U(VI) are complex processes that vary spatially and temporally, and that are heavily influenced by water pH and aqueous concentrations of calcium, bicarbonate, and U(VI).

The Super 8 experiment, initiated in 2010 in Plot C, provides a more recent test of methods used to enhance uranium mobility by injecting sodium bicarbonate into the alluvial aquifer. Though one of the objectives of the test was to replicate and extend the test conducted at Little Rusty, Super 8 was also designed to study uranium mobility under conditions in which acetate was injected into the aquifer (Long 2011). Thus the Super 8 experiment differed from the Little Rusty test in the sense that uranium mobility could be studied under the iron-reducing conditions created by aquifer amendment with organic carbon.

The Super 8 experiment was designed such that half of the experimental plot accounted for the effects of bicarbonate-induced desorption followed by acetate biostimulation some distance downgradient, and the other half functioned as a control affected only by acetate amendment. In this way, the design enabled a direct comparison of uranium reduction rates under typical and amended bicarbonate concentrations. Test results showed that U(VI) concentrations in the zone affected only by sodium bicarbonate injections were about 2 to 3 times the concentration of U(VI) entering the experimental plot in inflowing groundwater from the north. Data collected from the test also indicated that the rate of uranium reduction occurring in the bicarbonate-amended half of the test was virtually indistinguishable from the rate in the control half that was subjected to biostimulation only (Long 2011). A key interpretation stemming from the latter observation is that, as U(VI) is bioreduced and precipitated from groundwater, the enhanced levels of $Ca\text{-}UO_2\text{-}CO_3$ ternary complexes generated by bicarbonate amendment do not retard bioreduction. The decreased U(VI) concentrations occurring in areas subjected to combined bicarbonate enhancement and bioreduction also stand the chance of persisting longer than those achieved solely through biostimulation.

Recent IFRC experiments shed light on how and at what rate biogenic U(IV) will be re-oxidized and, as a consequence, mobilized in the form of U(VI) complexes in groundwater. These tests, which involved the installation of pure, laboratory-generated biogenic uraninite in wells at Buckskin test site, showed that release of U(IV) under site-specific field conditions was 50 to 100 times slower than was indicated by laboratory flow-through reactor experiments under oxic conditions (Long 2010). A subsequent modeling analysis of the conditions under which these experiments were conducted suggested that the slow oxidation in the field was mostly due to a diffusion barrier created by the sample cells in which the biogenic uraninite was placed. Because natural sediments are expected to create much larger diffusion barriers than those attributed to the sample cells, a logical conclusion derived from the in-well tests of U(IV) release is that oxidation of reduced uranium in alluvial sediments under background conditions is inherently slow (Long 2011).

4.4 IFRC Models

Much of the mathematical modeling performed in support of IFRC research has focused on simulation of numerous chemical reactions that occur in groundwater in response to subsurface injections of acetate. The objective of the reactive transport simulations has been to provide reasonable matches to the observed results of biostimulation tests and, as a consequence, identify which reactions and transport processes exert significant influence on the fate of uranium in site groundwater. Most of the IFRC modeling efforts have also accounted for relatively complex sorption processes that differ considerably from the manner in which sorption of uranium to alluvial sediments was handled in the model developed for the SOWP (Section 3.4.2). As discussed in the following section, one of the IFRC modeling investigations concentrated solely on uranium sorption processes that occur naturally in the alluvial aquifer without influences from biostimulation activities.

4.4.1 Surface Complexation Modeling

The use of a spatially uniform and temporally constant sorption distribution coefficient (K_d) to model sediment-water partitioning of a constituent dissolved in groundwater has several shortcomings. Not only does the "constant K_d" approach fail to take into account the availability and mineral composition of the sediment surfaces upon which the sorption takes place, but it also neglects the effects that variable water chemistry can have on the distribution of the constituent between water and sediment phases. When the impacts of these factors are taken into consideration, researchers tend to find that the K_d for a specific chemical can vary greatly in both space and time. Accordingly, models that allow for a spatially and temporally varying K_d dependent on ambient aquifer conditions are likely to provide more realistic appraisals of groundwater remedies.

To overcome the limitations of uranium transport models that adopt a constant K_d, models based on surface complexation theory (e.g., Davis et al. 2004) have been developed. A considerable amount of aquifer sediment characterization is necessary for the development of surface complexation models capable of accurately simulating sorption processes at specific field sites, but the efforts put into such characterization can prove worthwhile if they are appropriately applied in model simulations that account for spatially and temporally variable sorption as affected by aquifer geochemistry.

Hyuan et al. (2009) developed a site-specific surface complexation model, using data from batch reaction tests on a sediment sample collected from a floodplain location about a mile upriver of the Old Rifle site and on a composite sediment sample collected from two locations at the Little Rusty site (at Plot B in Figure 3). The sample from the upriver location was considered representative of non-contaminated, background conditions in floodplain materials deposited by the Colorado River, whereas the Little Rusty composite sample was potentially impacted by Old Rifle mill activity. The purpose of this model development, based on laboratory analysis of soil samples, was to provide a surface complexation simulator that could be applied to follow-up experiments involving field-scale reactive transport under ambient chemically oxidizing conditions. Subsequent to the Hyun (2009) study, surface complexation modeling was applied to the 2008 Little Rusty field investigation addressing accelerated uranium desorption of sediments at the Little Rusty site (Section 4.3).

Though the results of the Little Rusty field study have yet to be formally reported, modeling by Hyun et al. (2009) of the laboratory-derived results indicated that partitioning of U(VI) between groundwater and sedimentary materials in the alluvial aquifer was strongly affected by water pH and U(VI), calcium, and bicarbonate concentrations. The effective K_ds for U(VI) determined for the sampled sediments varied from about 0.5 to 20 mL/g (Hyun et al. 2009) for a range of geochemical conditions considered representative of the alluvial aquifer. These K_d values, by themselves, indicate that uranium transport in the alluvial aquifer is considerably more retarded than was assumed for uranium in the DOE modeling. They also suggest that the solid-phase uranium available in the alluvial aquifer as a contaminant source is much larger than was assumed for the DOE modeling. As mentioned in Section 3.4.2, the maximum value of K_d used in the SOWP modeling of uranium flushing was 0.2 mL/g, which suggests minimal retardation.

4.4.2 Reactive Transport Modeling

This section describes four separate reactive transport models that have been developed to support IFRC quantitative assessments of enhanced uranium bioreduction processes at the site test plots. All four models have been shown to perform reasonably well in matching the concentrations of dissolved species observed during biostimulation tests. All account for the transport and fate of multiple components in the subsurface and are based on chemical reactions that influence aqueous U(VI) concentrations as well as solid-phase concentrations of both U(IV) and U(VI). The complexity of the models has increased with each successive modeling project in an effort to more fully understand the numerous factors that influence the fate of uranium.

Yabusaki et al. (2007) were the first to simulate the effects of a biostimulation experiment at the site. Their model accounted for one-dimensional (1-D) flow and transport during the first enhanced bioremediation test that began in spring 2002 at the test plot shown in Figure 5, within the rectangular zone defining the boundary of the 2002, 2004, and 2005 experimental plots (Figure 3). Because test results from the acetate injections were collected at an array of wells over the test area, average constituent concentrations along each row of wells oriented perpendicular to the ambient flow direction downgradient from the injection gallery were used to calibrate the 1-D reactive transport model. The model simulated both the effects of an initial acetate-injection phase lasting about 4 months in 2002, and the effects of the follow-up injection phase beginning in spring 2003. The flow model was constructed to maintain a uniform and steady Darcy velocity of 0.25 ft/day throughout the test plot during both amendment-injection phases.

The Yabusaki et al. (2007) transport model was developed using the simulator HYDROGEOCHEM (Yeh et al. 2004, Fang et al. 2006). No attempt was made in the model to simulate sorption of U(VI) on aquifer sediments because the retardation of uranium advection due to such processes was considered relatively minor. Three TEAPs driven by microbial consumption of acetate—iron reduction, uranium reduction, and sulfate reduction—were accounted for using dual Monod rate law algorithms incorporated into the model code. The model accounted for several aqueous- and solid-phase species, including dissolved acetate, Fe(II), Fe(III), U(VI), U(IV), and sulfate, as well as two microbial populations (iron reducers and sulfate reducers). Despite the fact that their model was limited to 1-D transport, Yabusaki et al. (2007) managed to approximately match measured concentrations of dissolved constituents at most test gallery wells over time, indicating that key processes were mostly accounted for in the simulations. The relatively simple reactive transport model used in this case identified several steps that could be taken with future models to improve simulations of bioreduction phenomena.

As follow-up to the Yabusaki et al. (2007) modeling, Fang et al. (2009) performed more detailed simulations of the 2002/2003 experiments at the test plot shown in Figure 5 using a version of HYDROGEOCHEM that handled many more reactions and constituents than were incorporated into the earlier model. Four different TEAPs associated with two different microbial populations (iron reducers and sulfate reducers) were included in the updated model; two of the reactions accounted for uranium and sulfate reduction, and the other two represented reduction of Fe(III) in phyllosilicates and iron oxides, respectively. As in the Yabusaki et al. (2007) model, acetate consumption was simulated using a dual Monod kinetics formulation. An extensive reaction network was incorporated into the Fang et al. (2009) model, which included abiotic chemistry as described by more than 30 equilibrium reactions and 6 kinetic reactions. Sorption and desorption processes were simulated using a surface complexation model that accounted for several aqueous and solid species in the subsurface.

Fang et al. (2009) initially simulated the geochemical conditions observed during the 2002 biostimulation experiment included in the Yabusaki et al (2007) analysis. As with the earlier model, the new flow and transport model was 1-D, and the simulated Darcy velocity field was treated as steady and uniform. In addition to acetate, dissolved concentrations of 10 primary species were simulated, including those for uranyl, calcium, iron, carbonate, and sulfate ions. After using the 2002 experimental data to develop a set of calibrated parameters for the new model, the calibrated reaction simulator was then applied to the 2003 experimental results and subsequently to an entirely new biostimulation test (Winchester) in 2007 within Experimental Plot A (Figure 3). This latter modeling application performed well in capturing the observed dynamics in pH and concentrations of U(VI), Fe(II), sulfate, and acetate. The 1-D simulations performed by Fang (2009) of the 2002, 2003 and 2007 experiments highlighted the importance of integrating abiotic chemical reactions with biologically mediated processes to achieve a more thorough quantitative description of the many processes affecting enhanced bioremediation of subsurface uranium.

A reactive transport modeling investigation by Li et al. (2009) focused on potential aquifer porosity reduction resulting from mineral precipitation and biomass accumulation induced by biostimulation experiments at the Old Rifle site. Like the Fang et al. (2009) study, this modeling effort accounted for multiple biogeochemical reactions associated with consumption of acetate as well as several abiotic reactions taking place in the subsurface. Kinetic biogeochemical reactions were handled using dual Monod reaction rate laws, and surface complexation modeling was employed to simulate sorption effects. The modeling was conducted using the code CrunchFlow (Steefel 2007).

The CrunchFlow simulator was initially applied to simulate the results of laboratory column-based biostimulation experiments using sediments collected from the site. Upon developing a calibrated set of model parameters from analysis of the column tests, the model was subsequently used to simulate the geochemical processes induced by the 2002/2003 field tests. As in the case of the Yabusaki et al. (2007) and Fang et al. (2009) efforts, the model simulated flow and transport processes within a 1-D domain. With the model taking account of biomass produced during both microbially driven iron and sulfate reduction as well as solid mass generation in the form of mineral precipitates, Li et al. (2009) projected that these mass forms could take up as much as 1.5 percent of available pore space in a zone located a short distance downgradient of the tests' acetate injection gallery. This amount of pore clogging was not considered to be problematic in relatively coarse-grained sediments consisting of relatively clean sands or gravels, but it was thought to have significant effects on flow and uranium transport in finer-grained media.

A follow-up modeling investigation by Li et al. (2010) was significant because it represented the first formal effort to simulate 2-D horizontal (depth-averaged) flow and fate and transport associated with an IFRC enhanced bioremediation test. An underlying objective of this new study was to further assess the possible effects of mineral precipitation and biomass accumulation on aquifer porosity. As with the foregoing Li et al. (2009) study, multiple biogeochemical reactions and abiotic chemical reactions, as well as sorption in accordance with surface complexation theory, were included in the 2-D simulations. The 2002/2003 experiments were again the subject of the modeling investigation, and the simulator applied was CrunchFlow. Unlike earlier modeling studies, the flow domain was treated as being heterogeneous rather than homogeneous; thus, simulated flow fields were no longer uniform in space, and local Darcy and average linear velocities were spatially variable. The 2-D hydraulic conductivity field used in the simulations was derived using the code TOUGH2 (Pruess et al. 1999) and associated automated inverse techniques as applied to bromide tracer data collected from the well array for the 2002/2003 experiments.

The Li et al. (2010) modeling indicated that aquifer heterogeneity could significantly influence pore-clogging phenomena in the Old Rifle site alluvial aquifer. Modeling results suggested that accumulated biomass and mineral precipitation associated with stimulated iron and sulfate reduction processes could occupy more than 5 percent of the subsurface pore volume in certain areas downgradient of the acetate injection.

5.0 More Recent Alluvial Aquifer Conditions

LM contractor personnel have been collecting and analyzing groundwater monitoring data on a semiannual basis primarily to assess the progress of natural flushing. These assessments indicate that subsurface flow patterns at the site and the distribution of uranium contamination have changed very little since 1998, when groundwater conditions were documented in support of the SOWP (DOE 1999). Sections 5.1 through 5.3 describe the general findings regarding groundwater flow and uranium contamination at the site in recent years.

5.1 Groundwater Flow

Groundwater elevation data collected at 10 on-site monitoring wells in April 2007 were used to prepare a potentiometric surface map for the alluvial aquifer. An aerial photograph of the surface (Figure 6) indicates that groundwater movement continues to be dominated by flow toward the southwest and south-southwest, in the direction of the Colorado River, with slight variations from this pattern occurring in a few distinct locales. In the north-central portion of the site, a short distance south of Highway 6, plotted groundwater level contours (Figure 6) suggest that the local flow direction is more directly toward the south. This conceptualization supports the hypothesis that subsurface inflows from north of the highway represent a major source of groundwater recharge to the alluvial aquifer. Water level contours near the eastern end of the site exhibit a northwest–southeast orientation that is almost perpendicular to the river, suggesting that groundwater flow here is more parallel to the river than elsewhere in the aquifer. In general, these groundwater flow patterns comport with those that were adopted in the conceptual model developed for the SOWP.

The potentiometric surface presented in Figure 6 indicates that horizontal hydraulic gradients at the site range between 0.003 and 0.006 ft/ft. Assuming that hydraulic conductivities of the alluvial aquifer sediments average 125 ft/day and that aquifer porosity is 30 percent, the hydraulic gradients mentioned translate into average linear groundwater velocities ranging between 0.8 and 2.5 ft/day.

5.2 Spatial Distribution of Uranium

An updated uranium plume map, similar to the one in Figure 2 for the alluvial aquifer in May 1998, has been prepared using uranium concentrations measured at site wells in April 2007. Though the number of monitoring locations used to prepare this figure is substantially fewer than the number of permanent and temporary wells that were available in 1998, the distribution of uranium concentrations in 2007 (Figure 7) appear to be similar to the distribution observed during preparation of the SOWP. By and large, the 2007 plume map supports the observation that dissolved uranium concentrations have not decreased in response to 9 years of through-flow by waters that enter the site north of Highway 6 and eventually discharge to the river. Similarly, the highest uranium levels in the late 2000s continue to be observed beneath the former tailings area west of the on-site ditch. Lesser amounts of apparent uranium contamination are detected east of the ditch (Figure 7), in an area that was likely impacted by leachates from the former ore stockpile area in the eastern half of the former mill buildings area.

A single uranium concentration of 0.062 mg/L in well 0304, about 50 ft west of the on-site ditch (Figure 7), supports the SOWP conceptual and numerical models, which assumed that recharge to the alluvial aquifer from the ditch helped dilute contaminant concentrations both under and on either side of the ditch. If seepage water from the ditch containing relatively low levels of uranium remains a significant source of alluvial groundwater today, local groundwater mounding caused by the recharge provides a reasonable explanation for the two areas of higher uranium concentrations on the east and west halves of the site.

5.3 Uranium Concentration Histories

The apparent lack of natural flushing progress to date is also seen in updated temporal plots of uranium concentration at multiple on-site wells. Figure 8, which presents the uranium concentration histories for six widely spaced wells using semiannual monitoring data through 2010, shows that on-site uranium concentrations have tended to remain elevated since 1998. Though concentrations have fluctuated considerably between consecutive sampling events at well 0310, the uranium levels reported for the remaining locations have either remained fairly constant for 12 years or have gradually increased in the past 5 years (well 0656). Given that there are no obvious downward trends in uranium concentration at these locations, it is safe to conclude that ambient groundwater flows through the alluvial aquifer system have not induced the natural flushing results predicted by the SOWP modeling.

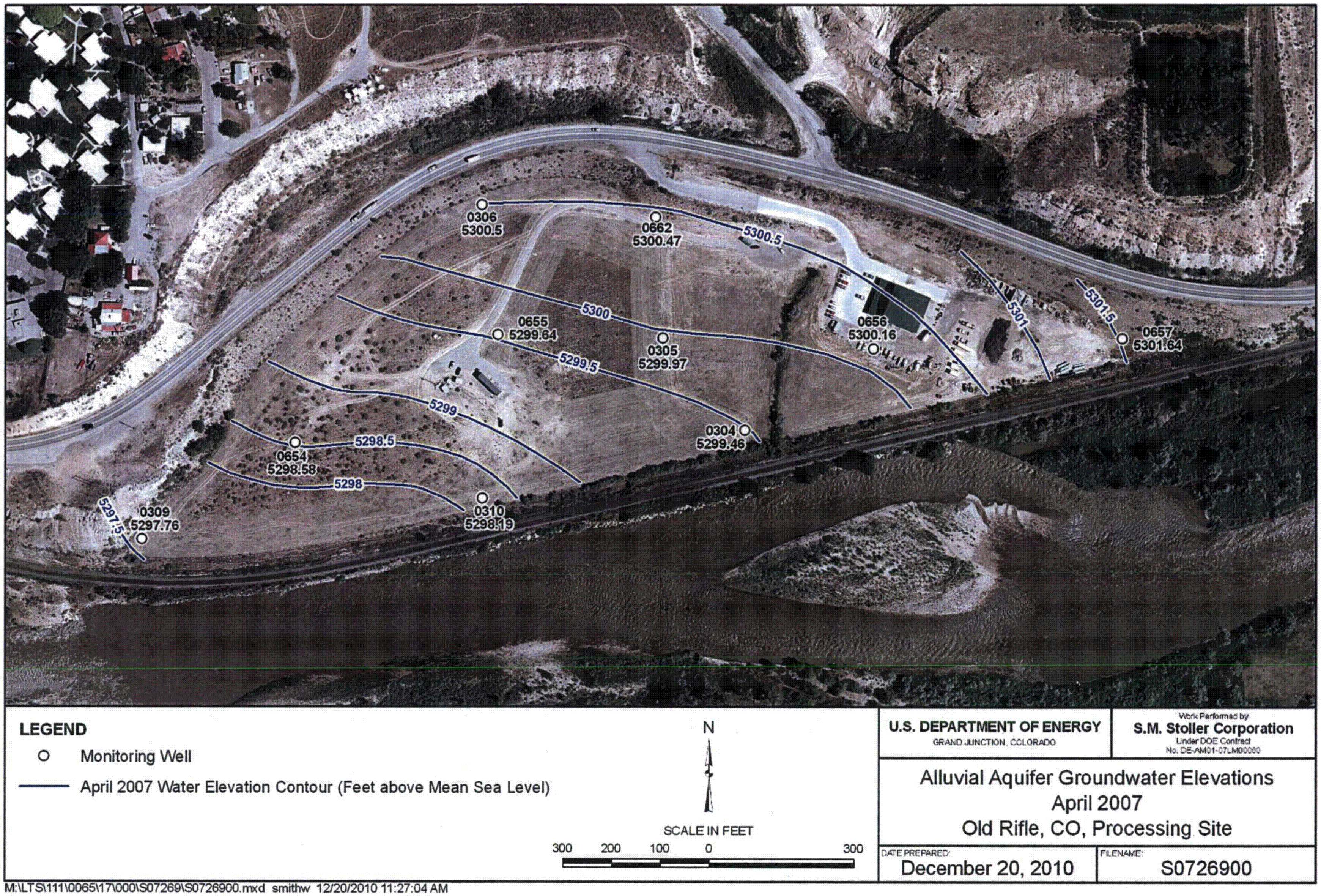

Figure 6. Potentiometric Surface for the Alluvial Aquifer in April 2007

6.0 Updated Conceptual Model

6.1 Subsurface System Complexity

6.1.1 Physical Heterogeneities Affecting Groundwater Flow and Transport

Much of the complexity associated with the Old Rifle groundwater system exists in the form of aquifer heterogeneity. Well logs for the numerous DOE and IFRC wells that have been drilled in the alluvial aquifer at the site indicate that the composition of alluvial sediments ranges from coarse sands and gravels to silts and clays. It is common for a single log to show distinct layers of fine-grained materials interspersed with larger sand and gravel horizons. Though the IFRC work has not focused on the physical characterization of aquifer sediments, descriptions of sediment test plot areas as well as the results of modeling efforts by IFRC researchers have provided valuable additional evidence of substantial aquifer heterogeneity.

Little characterization work has been done to contrast the hydraulic characteristics of the sands and gravels with those of the silts and clays, but the hydraulic conductivities of the coarser-grained materials are likely as much as 3 or 4 orders of magnitude larger than the conductivities of the fine-grained sediments. Moreover, even when an alluvial material at one location appears to be virtually identical to material at a different location (e.g., both are coarse-grained sand), it is possible that the hydraulic conductivities of the materials could differ by a factor of two or more. Such spatial variations in hydraulic conductivity can lead to local groundwater flow directions that diverge significantly from the overall, background flow orientation, which in turn signifies more tortuous flow paths than are generally assumed for the alluvial aquifer system.

The physical heterogeneity of Old Rifle alluvial sediments probably contributes to slow removal of subsurface uranium on a sitewide scale largely because of the disparate groundwater velocities occurring in coarser, high-permeability sediments versus the velocities in finer-grained, low-permeability materials. The more permeable sediments that are connected form preferential pathways (mobile domain) in which contaminant migration is relatively rapid, and the low-permeability zones (immobile domain) slowly feed contaminants into those pathways (Zheng and Gorelick 2003, Bianchi et al. 2010). In some cases, the flow velocity in the less-permeable sediments may be so small that contaminant transport out of them is effectively governed by molecular diffusion rather than the process of advection. Such rate-limited mass transfer, which is capable of taking place even in small areas with dimensions of a few tenths of a foot or less, can cause long-lasting persistence, or tailing, of uranium concentrations at the site's monitoring wells.

As discussed in Section 3.4, the numerical model prepared for the SOWP was based on 2-D horizontal flow, in which the hydraulic conductivity assigned to each location was considered a vertically averaged value of local material layers. Overall, this approach appeared to adequately represent general flow directions over distances of hundreds of feet, but the 2-D model obviously did not capture more localized vertical flow components. Without more detailed studies of local groundwater movement, the potential for three-dimensional (3-D) flow to strongly influence transport of contaminants cannot be discounted.

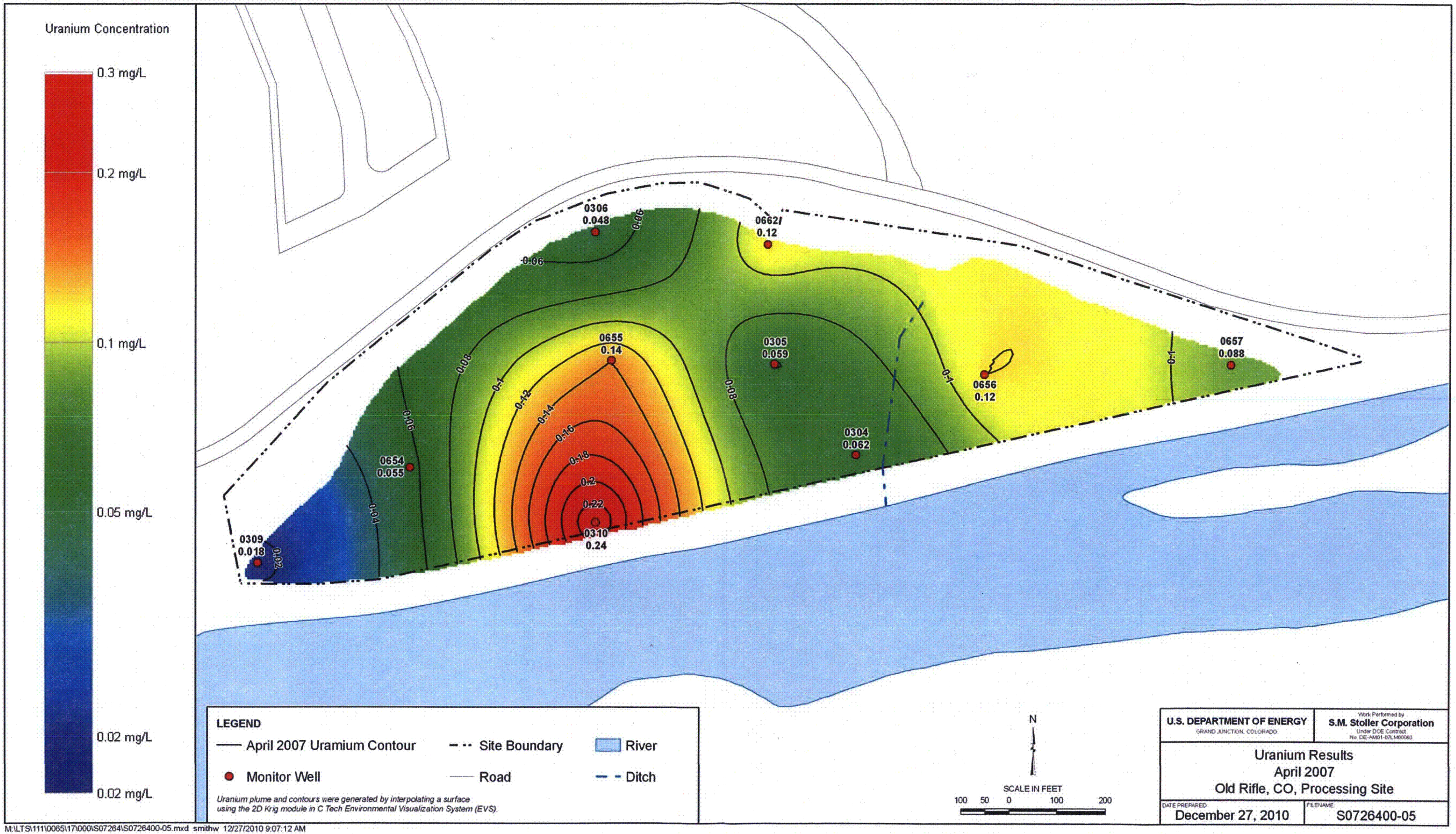

Figure 7. Uranium Concentration in the Alluvial Aquifer in April 2007

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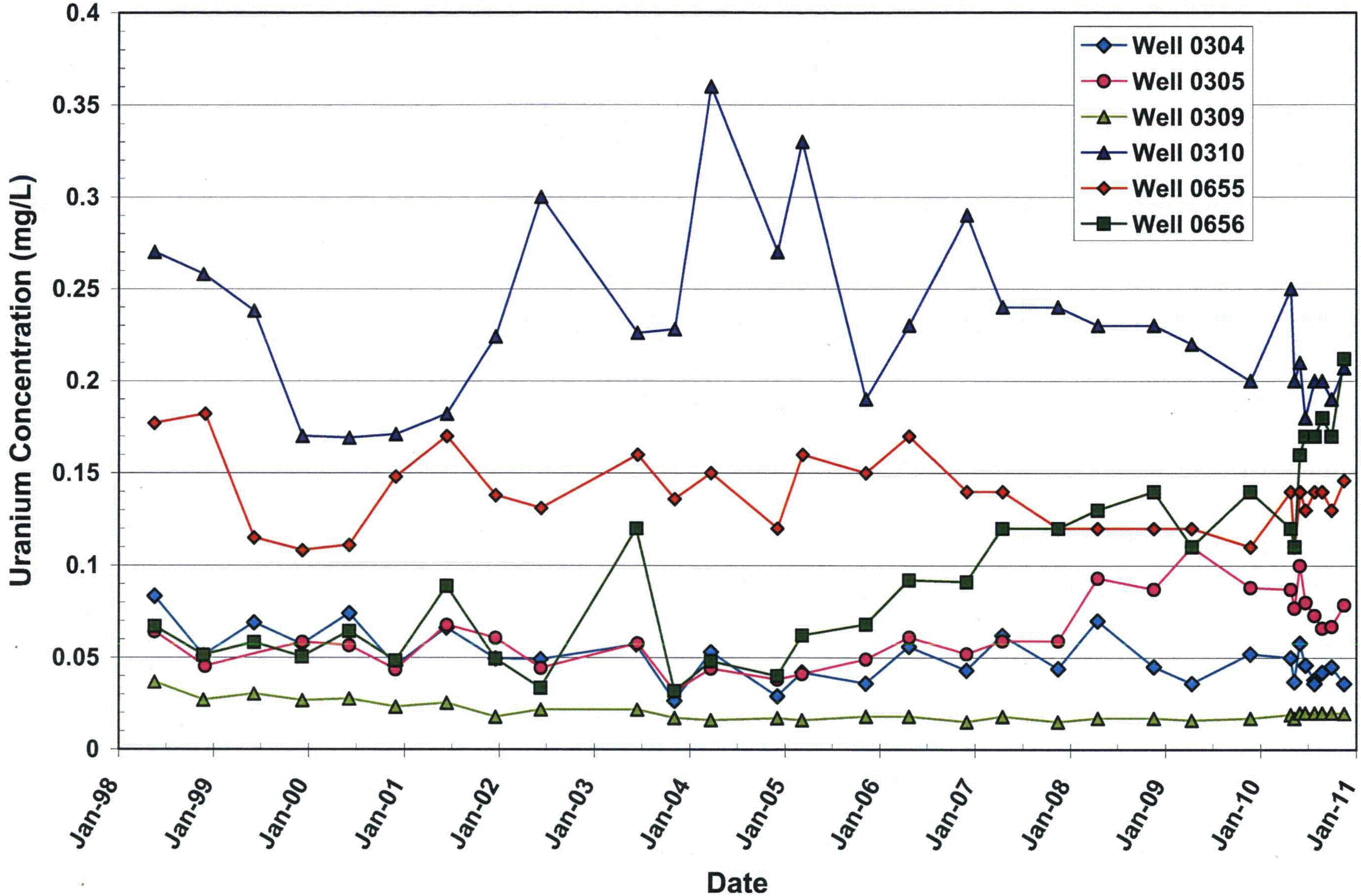

Figure 8. Uranium Concentration Histories at Several On-Site Wells

Logs prepared for the numerous boreholes drilled on the Old Rifle site indicate that the interface between the alluvial aquifer and the underlying Wasatch Formation is irregular, with depressions up to 3 ft deep occurring in the Wasatch surface. At one of the IFRC experimental plots, the logs from monitoring wells show a localized depression with dimensions of 5 to 10 ft wide and several tens of feet long. It is unclear whether the Wasatch surface depressions comprise portions of more extensive paleochannels that traverse the floodplain area, and whether these features significantly influence transport of contaminants in the alluvial aquifer. At a minimum, the irregular surface of this bedrock formation adds to the complexity of the alluvial groundwater flow system at the site.

6.1.2 Biogeochemical Heterogeneity

The IFRC work has provided considerable evidence that, in addition to being physically heterogeneous and complex, the alluvial aquifer is also chemically heterogeneous (Vrionis et al. 2005, Li et al. 2010). Moreover, on the basis of reported water chemistry results from DOE and IFRC wells and biogeochemical analyses of sediment cores, the heterogeneity appears in both aqueous and solid phases within the shallow subsurface. Aqueous-phase variability is seen in different forms of dissolved U(VI) or heterogeneous distributions of electron acceptors, such as sulfate. An example of solid-phase chemical variability is spatially changing mineral types within the alluvial sediments.

Mobile U(VI) in groundwater at the Old Rifle site has the potential to migrate in multiple chemical forms. Though it can migrate as the free uranyl ion at low pH, it tends to form complexes with anions in the aqueous phase. Carbonate, sulfate, phosphate, fluoride, chloride, and dissolved organic carbon are all potential ligands for the uranyl ion at circumneutral and alkaline pH values; however, most of the U(VI) in the alluvial aquifer appears to be transported as $Ca\text{-}UO_2\text{-}CO_3$ ternary complexes (Section 4.1.3) due to the relatively high alkalinity present at the site (Section 3.3.3). Nevertheless, the possibility that multiple U(VI) complexes could exist in the subsurface adds to the complexity of uranium transport and natural flushing processes.

The rate of flushing at the site under natural conditions is heavily influenced by uranium sorption onto and desorption from the sediments in the alluvial aquifer. As discussed in Section 4.4, IFRC modeling analyses have clearly demonstrated that the uniform K_d approach applied in the DOE modeling for the SOWP does not capture the complex nature of sorption under actual field conditions. In particular, the IFRC work confirms that the K_d for uranium will vary both spatially and temporally depending on sediment type and a variety of chemical indicators, such as pH and dissolved U(VI), bicarbonate, and calcium concentrations. Assessment of natural flushing processes should take into consideration the results of the laboratory tests on alluvial sediment samples (Hyun et al. 2009), which indicated that the K_d for uranium at the site was capable of varying by more than an order of magnitude under a range of chemical conditions representative of the site groundwater system.

The naturally reduced zones discovered in the alluvial aquifer further highlight the effects that sediment heterogeneity can have on in situ biogeochemical processes. The reduced zones are typically found in fine-grained, lower-permeability materials, suggesting that the types of sediments with the highest concentrations of U(IV) are also likely to be dominated by slow diffusive transport of U(VI). Thus, even if the naturally reduced zones only compose a relatively small percentage of the aquifer, they can be expected to strongly influence long-term rates of U(IV) mobilization for the site as a whole.

Another factor possibly leading to variable bioreduction of U(VI) on a sitewide scale is the spatial variability of nutrients required for microbial growth. Nitrogen and phosphate are essential nutrients that typically play significant roles in microbial metabolism. Dissolved ammonium (NH_4) has been shown to be an important source of nutrient nitrogen for biologically driven iron reduction by *Geobacter* species (Mouser et al. 2009). However, its concentration in site alluvial groundwater can vary with location by orders of magnitude, which implies that its availability to support biologically mediated iron and uranium reduction can vary significantly in space as well. The reasons for the wide variation in NH_4 levels at the site are unclear, but evidence suggests that they may be related to natural variations in organic matter and organic carbon content in the aquifer sediments (Mouser et al. 2009). Alternatively, the possibility exists that concentration variations reflect differential mass loading of milling-related ammonium to the subsurface.

An IFRC study conducted by N'Guessan et al. (2008) of the biostimulation experiment begun in 2002 provided further evidence of natural bioreduction of U(VI) in the alluvial aquifer in areas that apparently do not contain the fine-grained sediments typically associated with naturally reduced zones. The study pointed out that, at a single time prior to injection of acetate, the concentration of U(VI) in a background well upgradient of the injection gallery was noticeably higher than the U(VI) concentration at a well about 24 ft downgradient of the injection gallery. This pre-test finding implied that natural attenuation of uranium via ambient biological processes was occurring near the upgradient edge of the experimental plot, but no attempt was made to quantify the apparent attenuation rate. The findings of N'Guessan et al. (2008) also had bearing on the many issues that should be taken into account when characterizing the mechanisms that affect natural flushing. In particular, the researchers discovered that removal of U(VI) unexpectedly continued for about 1.5 years after cessation of biostimulation injections, and that the apparent lack of uranium mobilization with reintroduction of oxidizing water could be largely attributed to U(VI) sorption onto the sediment microbial community. Thus, analysis of this experiment revealed alternative means by which U(VI) could be immobilized that had not been considered in previous experiments focused on biologically driven production of U(IV) or sorption of U(VI) to sediments themselves.

Section 6.4 presents a more detailed discussion of the relevant biogeochemical phenomena in the alluvial aquifer, as elucidated in IFRC reports and papers.

6.1.3 System Transients

Temporal variability of subsurface flow and transport processes adds to the complexity of the groundwater system at the Old Rifle site. For example, seasonal highs in water levels induced by high runoff in the Colorado River during April through June make it possible for groundwater to entrain constituents from sediments that normally reside in the vadose zone during other months. Though difficult to identify on the basis of semiannual monitoring, minor to moderate changes in groundwater flow direction probably occur during the high-runoff months and not at other times. It is also probable that the infiltration and subsequent downward seepage of rainfall or melted snow on the site will periodically add recharge to the groundwater system. Despite the fact that several feet of fine-grained materials were used to replace contaminated sediments excavated during surface remediation of the site, the heterogeneity of the replacement materials and desiccation cracks within them make it possible for such recharge to occur in at least some locales. Because this latter type of seepage into the aquifer consists of oxic water, the recharge from it has the capacity to not only impact local flow direction for a time but also to noticeably change water chemistry in at least the shallowest portions of the saturated zone.

Collection of analyte concentration data during some of the enhanced bioremediation experiments conducted by IFRC personnel has revealed a form of short-term chemical variability in the alluvial aquifer. In particular, it has been shown that U(VI) concentrations at some upgradient wells in the experimental plots can double or decrease by half over the course of about a year. Note that the upgradient wells are located in areas with some of the largest on-site total uranium concentrations, and they are unaffected by the injection of organic carbon sources at hydraulically downgradient wells. Consequently, the variations in concentration reflect natural, ambient conditions, the cause of which is unknown. This observation emphasizes that uranium concentration contour maps, such as those presented in Figure 2 and Figure 7, should be viewed only as snapshots, despite the fact that uranium concentrations have not changed drastically since the late 1990s.

6.2 Sources of Alluvial Groundwater

Hydrologic processes that contribute water to the alluvial aquifer strongly affect the distribution of dissolved uranium in the aquifer at any given time. This section reviews the four sources of alluvial groundwater that were mentioned in the SOWP (DOE 1999) and provides an updated perspective on their impact on the fate of uranium.

6.2.1 Subsurface Inflow

Recently prepared maps of the potentiometric surface in the alluvial aquifer (Figure 6) support the original conceptual model of the site, which assumed that the primary source of groundwater in the aquifer is subsurface inflow from north of Highway 6. It is unclear whether the inflowing water occurs along the entire length of the highway in the vicinity of the site, but the existence of surface seeps just north of the highway on both sides of Ash Road (Figure 1) indicates that groundwater is entering the site's alluvial aquifer at multiple locations. These seeps appear to occur in areas where the presence of relatively impermeable Wasatch Formation prevents water in the basal portion of the older alluvium from discharging directly to the site's alluvial aquifer. At other locations north of the highway, it is possible that the upper portion of the Wasatch Formation is fractured, rendering it more permeable and capable of transmitting water from the overlying alluvium directly to the alluvial aquifer south of the highway.

The seep lying west of Ash Road was recently added to the list of monitoring locations for the site (location 0395). Though the flow emanating from this area has not been quantified, analytical results for the limited number of samples collected there help shed light on the possible effects of inflowing water from north of Highway 6 on the uranium chemistry of the alluvial aquifer. The water chemistry of the seep at 0395 is also of interest because it might be used to identify the recharge mechanism for the locally inflowing water. The recharge is likely to take place at least thousands of feet north of the seep, but, as mentioned in Section 3.2, it is unknown whether the recharge occurs naturally or is of anthropogenic origin. Subsequent sections of this report address this issue.

Without key water chemistry data from multiple portions of the long (~300 ft) seep area east of Ash Avenue, the recharge source, or sources, for the seep water remains uncertain. The possibility that some of this seep water stems from recharge in the city detention basins suggests that knowledge of the basin water's chemical signature would assist in tracking its migration within the alluvial aquifer. In addition, further investigation of groundwater levels and water chemistry in a series of on-site wells in the alluvial aquifer immediately south of the highway would help to identify general locations of inflow associated with the seeps and quantify the inflow rates.

6.2.2 Recharge from the On-Site Ditch

The updated conceptual model also assumes that some of the surface water flowing in the on-site ditch seeps into the subsurface and recharges the alluvial aquifer. Because little to no hydraulic data exist for alluvial groundwater under and near the ditch, the evidence for this form of recharge is mostly in the form of relatively low contaminant concentrations at a few monitoring wells located on either side of the ditch. Accordingly, the quantity of recharge from this apparent source remains unknown. Previous stream gaging measurements on the ditch at the outlet of the culvert under Highway 6 and a short distance upstream of the river on two separate occasions helped illustrate the variability associated with ditch loss measurements. In September 1998, the gaged flow at the culvert outlet was 86 gpm, and the downstream flow measurement was about 60 gpm, indicating that the ditch was losing approximately 26 gpm to a combination of downward seepage and evapotranspiration between Highway 6 and the river. Subsequent stream gaging in February 1999, when evapotranspiration would have been insignificant, showed flows of about 40 and 32 gpm at the upstream and downstream locations, respectively, for a loss of approximately 8 gpm. These two loss values represented about 30 percent and 20 percent, respectively, of the flow in the ditch at its upstream gaging location just south of Highway 6. Because the stream gaging results using flow meters can often be in error by 10 percent or more, these previously computed ditch losses should be considered rough estimates. More reliable estimates of ditch losses might be made using alternative forms of flow measurement in the ditch (e.g., Parshall flumes) in combination with the installation and monitoring of wells located adjacent to the ditch at several points along its length.

6.2.3 Inflow of River Water

During the past few years, considerable interest has been given to the interactions between water stage in the Colorado River and groundwater levels in the alluvial aquifer. This interest was recently demonstrated in an IFRC quarterly report published in July 2010 (Long 2010) that examined ways in which groundwater levels in key on-site wells could be predicted using Colorado River stage data from a USGS gaging station located greater than 25 miles upstream of the Old Rifle site. The report formally discussed river-aquifer interaction phenomena that have long been known about the site, namely, that a local increase in river stage during the high-runoff months of April through June produces corresponding and relatively rapid increases of up to 5 or 6 ft in on-site groundwater levels at key wells used to monitor the uranium plume.

Correspondingly, subsequent decreases in river flow and stage in the following months of August and September cause equally responsive drops in on-site water levels. The IFRC report (Long 2010) identifies this correlation between river stage and local groundwater elevation as being important for better understanding of groundwater flow patterns on a sitewide scale and any corresponding changes in biogeochemical conditions, but the report does not identify how flow and biogeochemical responses to river flow variations might be manifested.

Though the IFRC quarterly report (Long 2010) did not address the effect of river changes on on-site groundwater flow patterns, IFRC personnel have previously suggested that a temporary reversal of flow direction occurs in the alluvial aquifer during initial periods of increased river flow in late spring, and a significant effect of this phenomenon is loss of river water to the aquifer and subsequent groundwater flow from near the riverbank toward the north. As yet, a detailed investigation of the hypothesized flow change has not been conducted, but inspection of river stage data from the upriver gaging station suggests that the flow reversals are difficult to sustain and that seasonal incursions of river water into the aquifer are minimal. This is because river flows, and correspondingly, river stages, tend to increase gradually over the month- to two-month-long rising limb of the spring runoff. As a consequence, groundwater elevations throughout the alluvial aquifer are expected to respond relatively quickly and proportionally to the increase in river stage, thereby maintaining a net discharge to the river from the site as a whole.

Assuming that a net discharge of groundwater from the alluvial aquifer to the river predominates throughout each year, it is helpful to assess whether the river is capable of contributing minor amounts of surface water to near-river portions of the aquifer even during average-runoff periods on the river. Such contributions to the groundwater system could be occurring in hyporheic flow paths (e.g., Winter et al. 2002), which are created naturally by surface water entering the aquifer at specific locations and eventually returning to the river at other locations farther downstream. Hyporheic zone processes at the site are significant because mixing of local groundwater with the river-derived water, which tends to be saturated with dissolved oxygen, can influence biogeochemical processes in the near-river subsurface.

The existing monitoring well network at the site is insufficient for identifying hyporheic zone flow processes, if any are actually present. However, the potential existence of on-site hyporheic flow paths can be speculated upon using visual observations of pool and riffle sequences in the river reach abutting the site. In accordance with flow patterns typically observed in floodplain groundwater systems (e.g., Winter et al. 2002), it can be assumed that river water seeps into the subsurface near the downstream end of a river pool preceding (upstream of) a riffle and then discharges back to the river near the downstream end of the riffle. Such patterns are governed by basic hydraulic principles, which state that water flows from a point of higher water elevation to another of lower elevation, and the potential for flow between them increases in proportion to the difference in water level.

Three separate hyporheic flow paths associated with distinct pond and riffle sequences are postulated from the above-mentioned approach. As shown in Figure 9, inflow to the groundwater system from the easternmost hyporheic path (Path 1) appears to result from ponding (Pond 1) created by thick vegetation locally obstructing river flow. In contrast, ponding at the upstream end of Path 2 (Pond 2) is attributed to superelevation of the river surface where river water flows directly into the riverbank at the end of a local river bend. Similarly, the ponding that appears to take place at the upstream end of Path 3 is attributed to west-northwestward-flowing river water that intercepts and mildly obstructs surface water near the tail of Riffle 2.

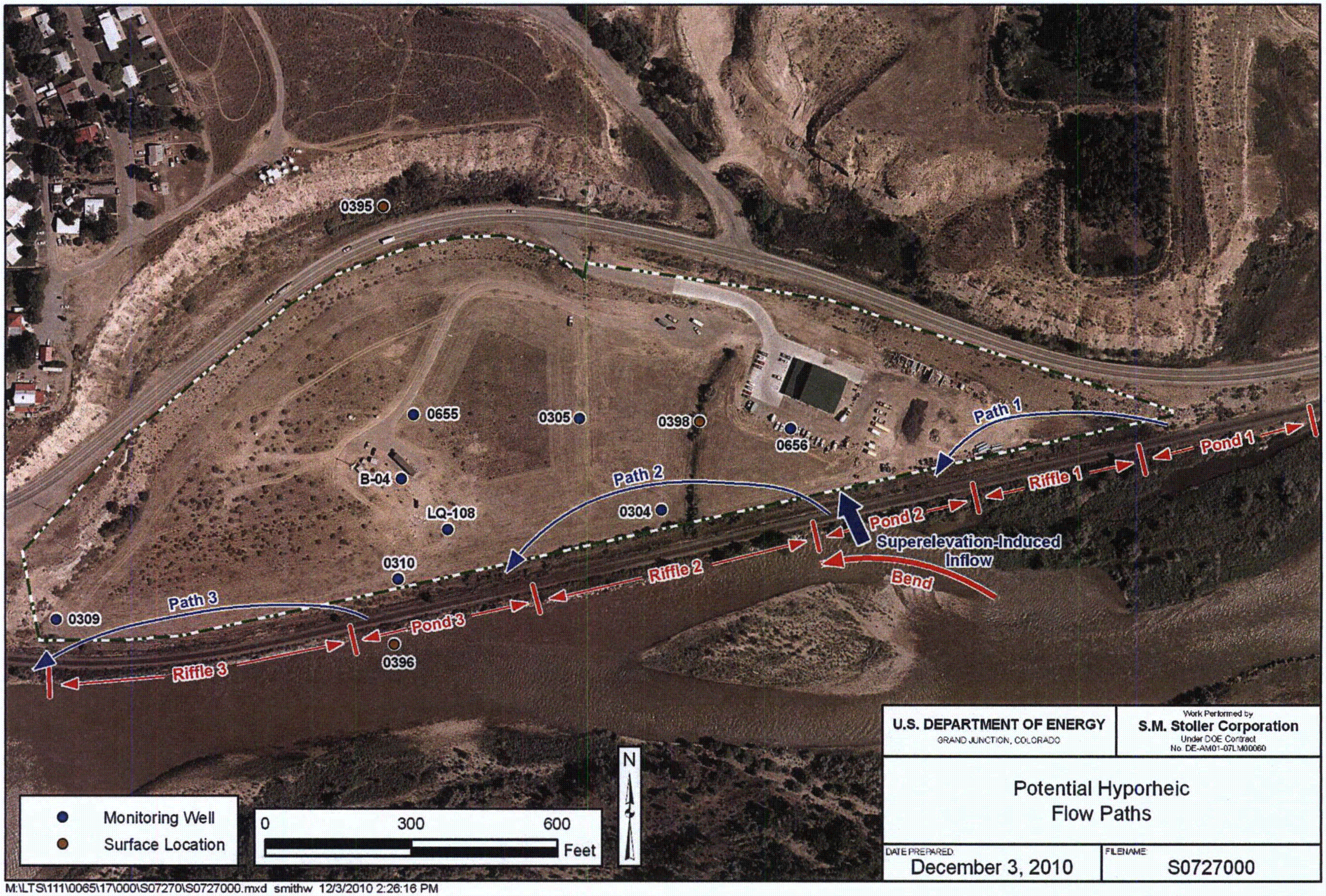

Figure 9. Potential Hyporheic Flow Paths at the Old Rifle Site

Of the three postulated hyporheic paths, Path 1 is considered the most likely to exist. This contention is based partly on the estimated drop in river surface elevation along Riffle 1, which, based solely on rough observations in the field, is significantly larger than drops along Riffles 2 and 3. In addition, the groundwater elevation contours in the vicinity of Riffle 1 (Figure 6) tend to be oriented perpendicular to the river, which suggests that groundwater in this area tends to flow toward the west, or more parallel to the river rather than toward it. In contrast, measured water elevations in the vicinity of and just north of postulated Paths 2 and 3 indicate that groundwater flow there is oriented toward the south-southwest (Figure 4), or more perpendicular to the river.

6.2.4 Episodic Recharge from Infiltration of Precipitation

Because most of the site was covered with fine-grained, low-permeability fill after the removal of radioactively contaminated sediments during surface remediation, the low rate of areal recharge adopted in the SOWP model (0.07 inch per year) was probably appropriate for the purpose of developing a long-term, sitewide water budget. However, the effects of recharge from precipitation on groundwater flow and transport in the alluvial aquifer are probably different from what was assumed during the DOE modeling. Specifically, recharge from rainfall and snowmelt probably varies spatially across the site rather than being distributed uniformly (see Section 6.1.3). Moreover, the recharge from precipitation is also temporally variable because it takes place mostly during or shortly after on-site rainfall and snow events. The combination of both types of variability suggests that precipitation recharge will exhibit relatively acute influences on groundwater in the alluvial aquifer. Assuming that the magnitudes of localized sporadic recharge processes are small due to limited infiltration into fine-grained surface sediments, the overall effects on groundwater flow direction and rate will be minor. However, the possibility exists that the oxic water occasionally contributed to the aquifer by infiltrated precipitation can mobilize uranium in both the vadose and saturated zones.

Evidence for possible episodic recharge and contribution of oxic water to the saturated zone was observed during the 2002/2003 IFRC biostimulation experiments (Yabusaki et al. 2005). Specifically, DO concentrations at three of the test plots' background wells noticeably increased between April and June 2003, and the spikes in DO correlated with a local groundwater elevation increase of more than 4.5 ft. Though an IFRC report (Long 2009) suggested that seasonal DO increases are caused by scavenging of oxygen entrapped in the lower part of the vadose zone by a rising water table, the possibility exists that spatially variable episodic recharge can also contribute DO to the saturated zone. More detailed studies of vadose zone flow and transport processes above areas that exhibit periodic DO spikes would help identify their causes. Because the background wells that show the DO increases in spring 2003 are located more than 300 ft north of the river, inflow of oxic river water to the aquifer and its subsequent migration toward the wells over a limited period of about 3 to 4 months is not considered a feasible explanation.

6.3 Distinguishing Natural Background Uranium from Mill-Related Uranium Contamination

Given that the conceptual model developed for the SOWP (DOE 1999) and this updated conceptual model single out natural waters north of Highway 6 as the primary source of alluvial groundwater at the site, it stands to reason that significant portions of the alluvial aquifer contain natural uranium rather than mill-related contamination. To better understand where the natural recharge waters might be dominant on site, efforts were made in 2010 to identify chemical means of distinguishing natural background uranium from mill-related contamination. As part of these efforts, additional uranium concentration data were collected that shed further light on the background concentration of this constituent at the site.

6.3.1 Uranium Isotope Ratios

One of the tools used to help identify sources of dissolved uranium at the site involved the examination of uranium isotope distributions in water samples collected at several monitoring locations. Specifically, the ratio of the activity concentrations for U-234 and U-238 was calculated under the hypothesis that mill-related contamination would have a U-234/U-238 value, or uranium activity ratio (UAR), that was noticeably different from that of naturally derived uranium. The logic applied was based on similar work by Zielinski et al. (1997), who showed that the UAR in contaminated groundwater samples collected at a former uranium mill site near Cañon City, Colorado, exhibited ratios generally reflective of secular equilibrium ($UAR \cong 1$), while those of natural waters had ratios greater than 1.3. The Cañon City study built upon previous work by Cowart and Osmond (1977) that suggests natural waters tend to show an excess of U-234 activity in comparison to that of U-238 at the mineral/water interface during prolonged mild leaching of subsurface uranium-bearing rock by groundwater. This excess comprises a form of isotopic fractionation related to alpha recoil displacement (Cowart and Osmond 1977) of the U-234 atom from its U-238 parent, with the net effect of enhanced leachability of U-234. In contrast, high-grade uranium ores with more recent histories of open-system alteration appear to be mixtures of materials with both $UAR<1$ and $UAR>1$, which, when leached over periods of just a few decades or more, yield waters with a UAR of 1.0 ± 0.1 (Zielinski et al. 1997).

Tests of the UAR hypothesis at the Old Rifle site were conducted using samples collected at both groundwater and surface water monitoring locations on and near the site in April and June 2010. Table 1 and Table 2 list the resulting uranium mass and activity concentrations along with related isotopic UARs from the April and June sampling events, respectively, and a source designation (mill-related versus natural) is assigned to each listed monitoring location. Figure 10 and Figure 11 present corresponding aerial photographs of the uranium analytical results.

Results from the April 2010 monitoring generally comport with the findings of Zielinski et al. (1997) in that groundwater monitoring locations believed to exist within or on the edge of mill-contaminated areas (0304, 0305, 0310, 0310, 0655, 0656, B-04, LQ-108) show UARs between 1.0 and 1.1, whereas all other groundwater and surface water monitoring locations exhibit ratios of 1.4 or more. The UAR of 1.42 at the single monitoring location on the Colorado River (0396) is expected because U-234/U-238 ratios in stream and river waters typically show U-234 enrichment (Zielinski et al. 1997). Likewise, the UAR of 1.62 for the surface water sample collected from the on-site ditch (0398) is not surprising, since the ditch is fed by a natural drainage system upstream of Highway 6.

Table 1. Uranium Concentrations and Isotope Activity Ratios in April 2010

Location	On Site/ Off Site	Medium (SW/GW)[a]	Uranium Mass Concentration (µg/L)[b]	U-234 Activity Concentration (pCi/L)[c]	U-238 Activity Concentration (pCi/L)[c]	Uranium Activity Ratio (UAR)	Presumed Source (Natural/ Mill-Related)
0304	On	GW	50	17	16.4	1.04	Mill-Related
0305	On	GW	87	30.7	28.3	1.08	Mill-Related
0309	On	GW	19	10.5	5.71	1.84	Natural
0310	On	GW	250	68.9	64.5	1.07	Mill-Related
0395	Off	SW	25	13.1	8.29	1.58	Natural
0396	Off	SW	1.4	1.06	0.748	1.42	Natural
0398	On	SW	16	7.39	4.55	1.62	Natural
0655	On	GW	140	47.2	44.4	1.06	Mill-Related
0656	On	GW	120	47.7	43.8	1.09	Mill-Related
B-04	On	GW	170	61.4	59.7	1.03	Mill-Related
LQ-108	On	GW	240	90.7	84.9	1.07	Mill-Related

[a] GW = groundwater, SW = surface water
[b] µg/L = micrograms per liter
[c] pCi/L = picocuries per liter

Table 2. Uranium Concentrations and Isotope Activity Ratios in June 2010

Location	On Site/ Off Site	Medium (SW/GW)[a]	Uranium (U) Mass Concentration (µg/L)[b]	U-234 Activity Concentration (pCi/L)[c]	U-238 Activity Concentration (pCi/L)[c]	Uranium Activity Ratio (UAR)	Preliminary Assessment (Natural/ Mill-Related)
0304	On	GW	46	19.1	13.9	1.37	?
0305	On	GW	80	33.3	28.8	1.16	Mill-Related
0309	On	GW	20	12.3	7.28	1.69	Natural
0310	On	GW	180	73.2	67.4	1.09	Mill-Related
0395	Off	SW	28	14.7	8.88	1.66	Natural
0396	Off	SW	1	0.416	0.466	0.89	?
0398	On	SW	14	6.83	4.7	1.45	Natural
0655	On	GW	130	52.6	47.2	1.11	Mill-Related
0656	On	GW	170	59.9	55.3	1.08	Mill-Related
B-04	On	GW	210	81.4	75.3	1.08	Mill-Related
LQ-107	On	GW	150	53.5	49.9	1.07	Mill-Related
LQ-108	On	GW	130	49.4	47.3	1.04	Mill-Related

[a] GW = groundwater, SW = surface water
[b] µg/L = micrograms per liter
[c] pCi/L = picocuries per liter

April 2010 results for the remaining surface water sample, collected at the seep north of Highway 6 (0395), are significant because the reported uranium mass concentration here is relatively high (25 micrograms per liter [µg/L]), yet the corresponding UAR is reflective of natural water (1.58). These values tend to confirm SOWP findings that natural sources of alluvial aquifer groundwater located north of the highway can contribute dissolved uranium to the aquifer at levels that are more than half the UMTRA maximum concentration limit (MCL) of 44 µg/L for this constituent.

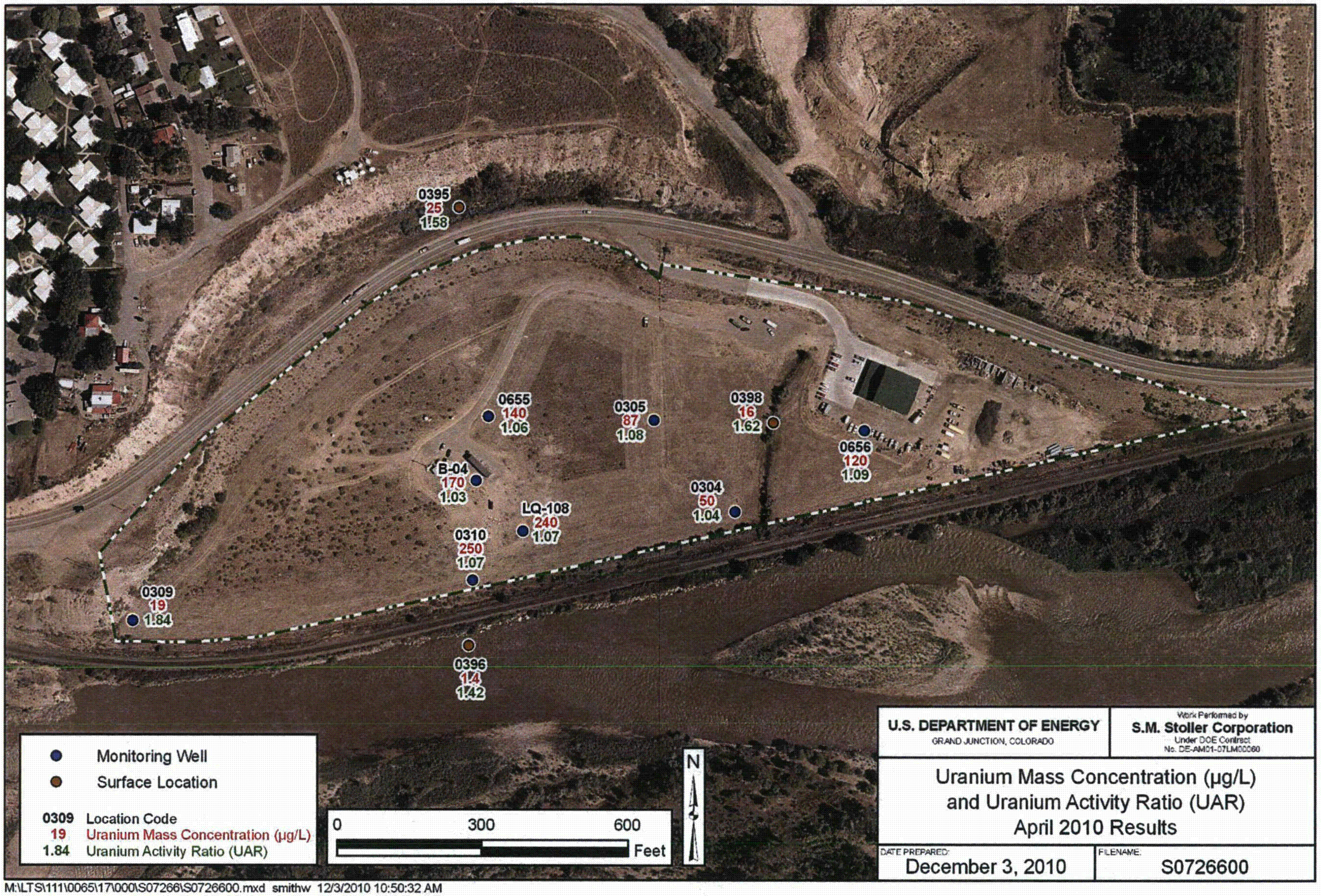

Figure 10. Uranium Concentrations and Uranium Activity Ratios at Selected Monitoring Locations in April 2010

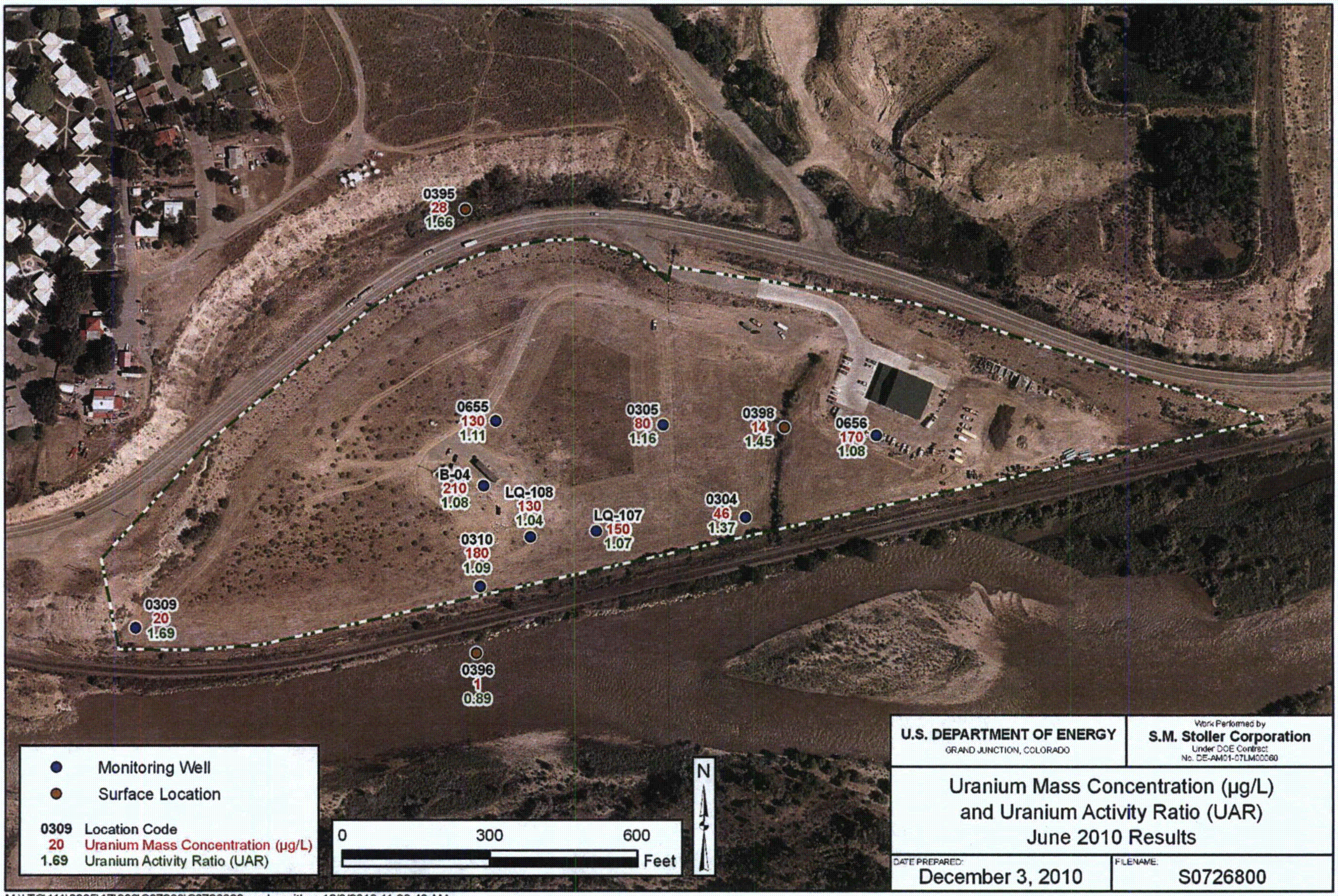

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Figure 11. Uranium Concentrations and Uranium Activity Ratios at Selected Monitoring Locations in June 2010

The calculated UAR of 1.84 during April 2010 for location 0309 in the westernmost corner of the site suggests that uranium in groundwater in the vicinity of this well is naturally occurring rather than legacy contamination from mill operations. This observation, when combined with groundwater flow directions inferred from the site's potentiometric surface (Figure 6) and the fact that the April uranium mass concentration of 19 µg/L at well 0309 is similar in magnitude to the concentration of 25 µg/L at seep 0395, suggests that groundwater in the aquifer's east corner may originate as natural water north of the highway rather than leached tailings water.

An additional monitoring location, well LQ-107, was included in the uranium analyses performed on June 2010 samples (Table 2 and Figure 8). By and large, the uranium concentrations and UARs from the June monitoring event were similar to those reported for the April event. However, uranium data at two locations made it difficult to ascertain whether the samples were reflective of a natural or mill-related uranium source. The calculated UAR of 1.37 at well 0304 was not representative of mill-related uranium despite the fact that the analyses for this location in April 2010 were indicative of uranium contamination. One potential explanation for the higher UAR at well 0304 in June was increased recharge from the on-site ditch, which is about 50 ft west of the well. If flows in the ditch were high due to spring runoff, it is possible that ditch water with a UAR reflective of natural water seeped downward into the subsurface and mixed with local groundwater, thereby producing a UAR reflective of isotope disequilibrium.

A UAR of 0.89 at river sampling location 0396 was considered anomalous because the river is always expected to be representative of natural waters. This discrepancy was attributed to analytical error caused by the very low mass and activity concentrations reported here for uranium in June 2010.

6.3.2 Additional Chemical Indicators

Water samples collected by the LM contractor during 2010 were submitted for tritium analyses with the intended purpose of helping to distinguish natural uranium from mill-related uranium contamination. Given that groundwater discharging at seeps immediately north of Highway 6 originated as natural recharge farther to the north, the potential existed for seep waters to have tritium concentrations reflective of atmospheric conditions prior to above-ground testing of nuclear explosive devices in the 1950s and 1960s. If this were the case, the seep tritium levels were expected to be less than 3 picocuries per liter (pCi/L), whereas the tritium concentrations in all other waters affected by the atmospheric testing were expected to range from 15 to 30 pCi/L. Accordingly, the possibility existed that naturally occurring groundwater in the alluvial aquifer just south of Highway 6 would also exhibit a low-tritium signature, which could in turn indicate the co-presence of naturally occurring uranium.

Though the tritium analyses were subject to considerable uncertainty, all of the reported concentrations, including those for water samples collected at the seeps, fell in the range of 15 to 30 pCi/L. This result indicated that tritium could not be used to help distinguish areas of naturally derived uranium contamination from those affected by mill-related contamination.

Since summer 2010, IFRC personnel have also been attempting to identify explicit chemical fingerprints for different sources of alluvial aquifer groundwater. These efforts have focused on analysis of the stable isotopes oxygen-18 and deuterium. The oxygen-18 and deuterium data collected so far are considered preliminary but will be included in future studies aimed at distinguishing natural waters from mill-derived contamination.

6.4 Biogeochemistry

6.4.1 Background Microbial Processes

Both the site characterization information collected during preparation of the SOWP (DOE 1999) and additional data and investigations conducted in recent years, particularly in association with IFRC projects, suggest that microbial processes affecting alluvial groundwater chemistry are common under ambient background conditions at the Old Rifle site. For example, low nitrate concentrations collected in support of the SOWP and IFRC work indicate that any nitrate fed to the aquifer is likely to be quickly consumed by microbially mediated denitrification. Similarly, relatively high concentrations of dissolved iron (Fe[II]) in groundwater indicate that background iron reduction driven by microbial processes is likely. In addition, very low levels of DO (<0.3 mg/L) combined with relatively low values of oxidation-reduction potential signify the presence of conditions that are somewhat chemically reducing, which could be the result of biologically mediated redox reactions. These lines of evidence by themselves do not indicate that sulfate reduction is occurring throughout the alluvial aquifer, but conditions amenable to pervasive iron reduction do appear likely.

The discovery of naturally reduced sediment zones (e.g., Long 2008) in the subsurface has shown that some portions of the aquifer are more reducing than others, and the presence in these zones of other chemical data indicative of biologically mediated iron as well as sulfate reduction implies that background microbial metabolism in these isolated zones can also influence ambient groundwater chemistry. Whether the naturally reduced zones represent sinks or sources for dissolved uranium, or both, remains to be determined. The N'Guessan (2008) study that presents evidence possibly indicative of natural bioreduction of uranium upgradient of IFRC experimental plots also supports the presence of background microbial processes.

If biological activity in the form of microbial iron reduction is pervasive in the alluvial aquifer, a natural source of electron donor chemicals is needed. IFRC studies have suggested that much of donor source is ultimately attributable to solid organic matter co-existing with the alluvial sediments that compose the aquifer. To help assess how these and other potential organic carbon sources are manifested in local water chemistry, recently measured concentrations of dissolved organic carbon (DOC) at several monitoring locations were examined.

Figure 12 and Figure 13 are aerial photographs showing measured DOC levels on and near the site in April 2010 and June 2010, respectively. Both figures indicate that wells screened in the alluvial aquifer maintain DOC concentrations ranging between about 2 and 5 mg/L, and a similar concentration range is observed at surface water monitoring locations that include the seep north of Highway 6 (0395), the on-site ditch (0398), and the Colorado River (0396). Though it is unclear what percentage of the DOC is labile and, therefore, available for biologically mediated chemical reactions in the subsurface, the reported concentrations by themselves do suggest that ambient background microbial processes are likely.

To date, thorough analyses of the dissolved chemicals contributing to DOC in local water have not been performed. Assuming that at least a portion of the DOC consists of dissolved acetate that originated from the dissolution of solid organic matter in alluvial sediments, it is likely that the acetate was produced through a series of natural fermentation reactions occurring in the subsurface (e.g., Bartlett et al. 2010) rather than directly resulting from the leaching of buried organic solids.

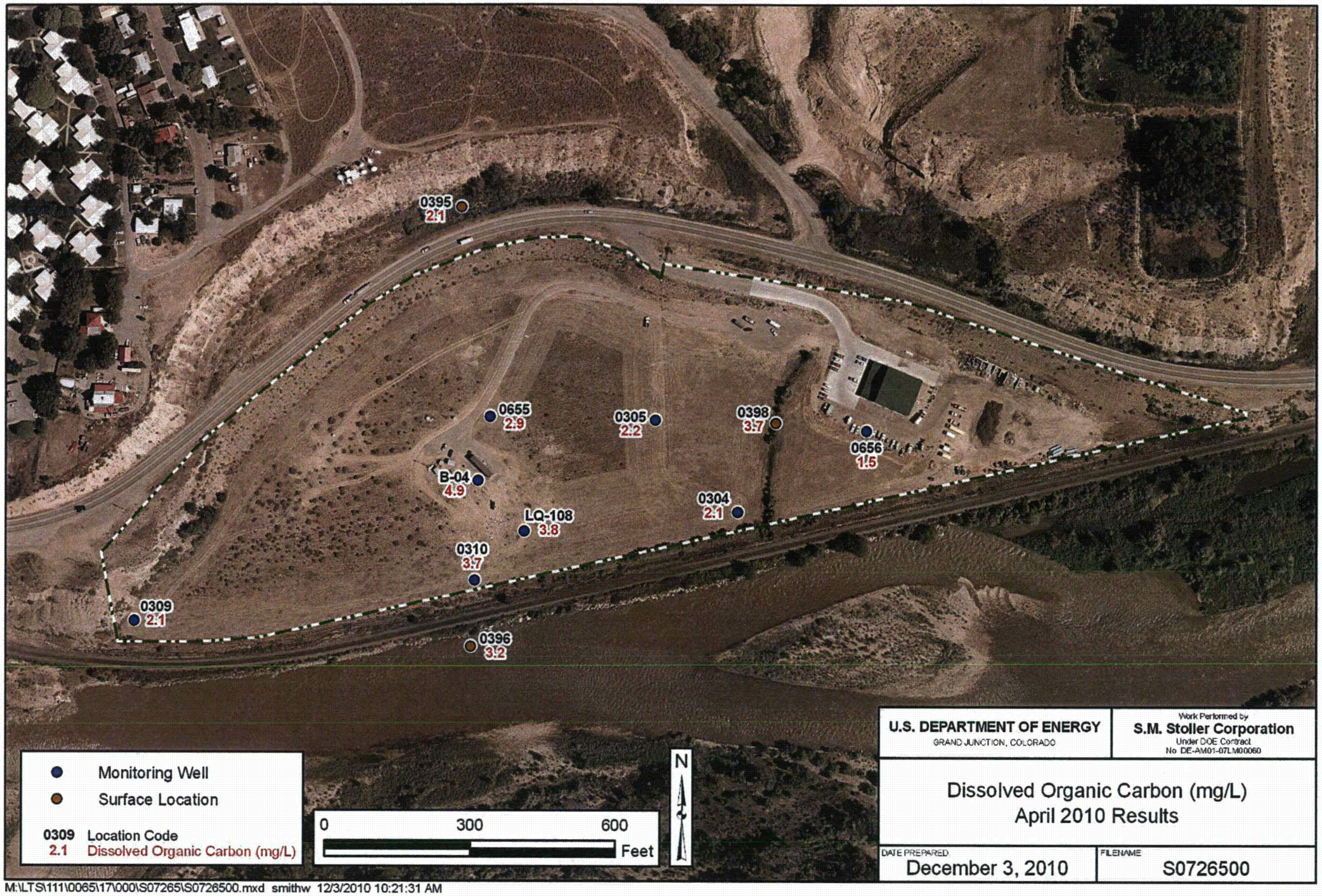

Figure 12. Dissolved Organic Carbon Concentrations at Selected Monitoring Locations in April 2010

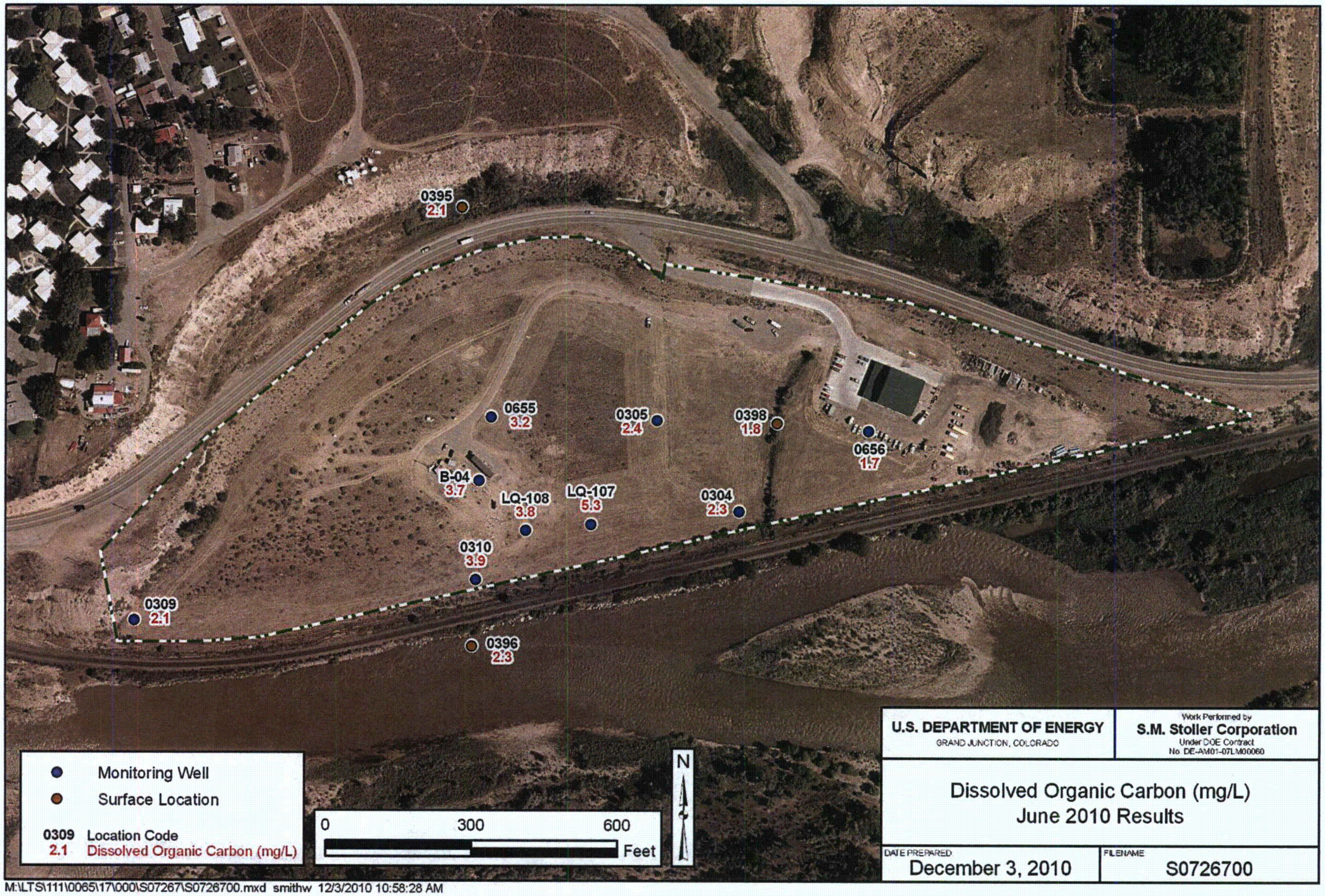

Figure 13. Dissolved Organic Carbon Concentrations at Selected Monitoring Locations in June 2010

The DOC concentration of 2.1 mg/L reported for both April and June 2010 (Figure 12 and Figure 13) at the seep above Highway 6 (location 0395) is of interest because it suggests that recharge to the alluvial aquifer due to subsurface inflow from off-site water sources is an additional source of organic carbon that sustains on-site microbial processes. Similarly, the two DOC concentrations in surface water from the on-site ditch (3.7 and 1.8 mg/L) are significant because recharge due to seepage losses from the ditch could influence microbial activity locally in the subsurface.

6.4.2 Oxidation and Dissolution of Uranium

As previously discussed, research into the speciation and stability of the reduced uranium produced during biostimulation experiments at the IFRC plots revealed that the solid-phase uranium created consists of "monomeric U(IV)" rather than uraninite (Long 2010). This finding has bearing on the persistence of uranium in the subsurface at the Old Rifle site, because the rate at which the monomeric form reoxidizes and subsequently dissolves in groundwater as a U(VI) species is expected to be greater than the equivalent rate associated with uraninite. The variation in rates is attributed in part to abundant cation impurities in the natural uraninite. Results from some of the most recent IFRC testing—which show that, with aging, monomeric U(IV) eventually transforms into uraninite (Long 2011)—suggest that biogenic U(IV), whether created naturally due to background iron reduction or via biostimulation, will tend to mobilize in groundwater relatively slowly. Regardless of the form of U(IV) present in the alluvial aquifer, oxidation of the reduced uranium and its eventual dissolution as a U(VI) species increases with the presence of increased DO and alkalinity concentrations.

An investigation by Qafoku et al. (2009) of the chemistry of naturally reduced sediments at the site reported that at least a portion of the U(IV) and some U(VI) in the reduced zones was incorporated into solid-phase iron sulfides, including pyrite. Moreover, some of the pyrite exhibited framboidal structure. Qafoku et al. (2009) indicated that the interaction of aqueous U(VI) with the framboidal pyrite was complex, with possible augmentation of uranium in the pyrite resulting from the interaction. Alternatively, the research also indicated that the pyrites incorporated into the naturally reduced zones at the site were capable of acting as long-term sources of aqueous U(VI) in groundwater.

The recent experiments on uranium redissolution involving the installation of pure, laboratory-generated uraninite in wells at the Buckskin site (see Section 4.3) also suggest that release of biogenic U(IV) under Old Rifle field conditions is very slow. Though much of the slow release observed in these experiments was attributed to diffusion from the sample cells containing the uraninite (Long 2010), the much larger diffusion barrier associated with lower-permeability alluvial sediments is expected to greatly limit the oxidation of U(IV) under background conditions. Though these findings pertain solely to reduced uranium, they are also relevant to the mobilization of U(VI) in low-permeability sediments.

7.0 Potential Causes of Persistently High Uranium Concentrations

An evaluation of the updated conceptual model suggests that three potential phenomena are contributors to the high uranium concentrations currently observed in Old Rifle site groundwater. These phenomena, summarized below in Sections 7.1 through 7.3, comport with explanations by IFRC researchers (Long 2011) for the persistence of elevated uranium concentrations in Old

Rifle groundwater. It is important to note that none of the potential causes of persistently high concentrations of dissolved uranium has yet been identified as a dominant explanation for the limited progress of natural flushing to date.

7.1 Slow Diffusion of Uranium from Low-Permeability Zones

As discussed in Section 6.1.1, preferential flow processes in heterogeneous porous media are characterized by the slow release of dissolved constituents from the lower-permeability portions (immobile domain) of an aquifer to the more conductive portions (mobile domain), which produces long-term tailing of constituent concentrations in monitoring wells screened in the preferential flow paths. In effect, water molecules in the low-permeability zones move so slowly that the effective mechanism for transporting U(VI) to the mobile domain is molecular diffusion in response to concentration gradients. The visually observed heterogeneity of alluvial aquifer sediments suggests that the aquifer is capable of sustaining preferential flow effects, and the lack of declining uranium levels at key monitoring wells since 1998 (Figure 8) possibly indicates diffusion-limited transport and concentration tailing.

By itself, the concept of dual-domain porous media (Flach et al. 2004) provides what is fundamentally a physical explanation for slow attenuation of uranium contamination at the site. However, as the updated conceptual model indicates, several chemical processes could also contribute to the release of uranium from low-permeability zones.

7.2 Mobilization of Vadose Zone Uranium

Surface remediation at the site using only radium-226 concentrations as cleanup criteria made it possible for several mill-derived inorganic constituents to remain undetected in the vadose zone below the former tailings pile and the ore-storage area. Indeed, the leaching tests conducted on soil samples from beneath the former tailings and ore piles (Section 3.3) suggested that uranium could remain in the vadose zone. Accordingly, occasional mobilization of uranium that remains in the vadose zone today should be considered a potential long-term contributor to saturated zone uranium. The fact that alluvial groundwater levels increase up to 6 ft during high-river-runoff months implies that a rising water table could periodically leach uranium from the vadose zone. Similarly, it is also possible that downward seeping moisture from episodic precipitation events could leach uranium from the vadose zone.

The exact mechanisms through which uranium is mobilized in the vadose zone remain uncertain. A more thorough study of vadose zone processes represents the most reliable means to identify and characterize this potential source of saturated-zone contamination.

7.3 Uranium in Subsurface Inflow

Data presented in this study and collected over the past several years clearly demonstrate that recharge sources to the alluvial aquifer from multiple areas north of Highway 6 contribute a portion of the on-site dissolved uranium seen today. The uranium concentrations measured for this investigation at the seep discharging just north of Highway 6 and west of Ash Road (0395) (Section 6.3.1) imply that a background concentration of 25 to 30 µg/L would be representative of subsurface inflows from north of the site. However, historical data collected from various off-site sampling locations indicate that uranium levels in potential aquifer recharge sources north of the highway are temporally and spatially variable and may at times reach concentrations as high as 55 µg/L. Additional investigation of the chemistry of water seeps north of the highway as well as in alluvial groundwater just south of the highway would assist in better defining such variability. It can be concluded that the highest uranium concentrations observed in on-site wells (0.1–0.25 µg/L) are not due solely to background uranium contributions from north of Highway 6.

8.0 Prospects for Predictive Modeling

With a new understanding of the complexity of subsurface flow and biogeochemical processes in Old Rifle groundwater, the prospects for developing numerical models capable of successfully predicting the future progress of sitewide natural flushing can be discussed. The types of models included in this assessment range from the relatively simple one applied in the SOWP to the much more detailed simulators developed by IFRC researchers in recent years.

The predictive success of any model applied to the site will greatly hinge on the model's ability to match uranium concentration histories at numerous monitoring wells throughout the site. At a minimum, this will mean that the model is capable of capturing any long-term concentration trends, if present, at key wells. If the temporal plots of uranium concentration presented in Section 5.2 for six on-site wells (Figure 8) are used as a guide, the likelihood is small that any model developed at this time would project successful flushing of uranium in the alluvial aquifer within the next 100 years. For example, if the model originally employed by DOE to assess natural flushing were reapplied to the site with the intent of roughly duplicating the concentration histories shown in Figure 10, either the assumed uranium source mass or the uniform K_d employed in the model, or both, would probably be many times higher than values originally adopted for these model features, and predicted flushing time would extend well beyond 100 years.

To address the possibility that slow diffusion of uranium from low-permeability zones in the alluvial aquifer is a major cause of slower contaminant release (Section 6.1.1), a dual-domain simulator might be applied. This type of model has been successfully employed in a variety of studies (e.g., Flach et al. 2004, Zheng et al. 2010) in an effort to capture concentration tailing phenomena and is conceptually logical because it directly accounts for contaminant mass exchange between the mobile and immobile domains. Yet the key parameters used to simulate the mass exchange are effectively nothing more than model-fitting parameters, because they have no true physical basis. Though a dual-domain simulator could be developed to approximate the uranium concentration histories shown in Figure 8, it also would probably predict a natural flushing scenario extending beyond 100 years.

Regardless of the type of model used, a reliable estimate of the total current uranium inventory in the alluvial aquifer is crucial for accurately predicting future flushing. Strictly speaking, this means that all uranium that has the potential to eventually migrate in groundwater to the river would have to be accounted for, including the uranium mass sequestered in low-permeability sediments, sorbed to aquifer sediments, and existing in vadose zone sediment possibly subject to periodic leaching. Because most currently available site characterization techniques still rely heavily on the drilling of boreholes and collecting samples for analysis, accomplishing this task in the next few years would be extremely difficult and very expensive.

The multicomponent reactive transport models developed by IFRC researchers during the past several years have demonstrated that it is possible to produce fairly reliable simulators of many of the complicated flow, sorption, and biogeochemical processes occurring in site alluvium in response to biostimulation experiments. It is currently possible to apply numerical simulators that collectively account for several tens of chemical constituents, both equilibrium and kinetic reactions between the constituents, mineral precipitation, microbial population dynamics, and sorption and desorption processes for key analytes via surface complexation modeling. As the research models have grown increasingly complex with each successive application, IFRC personnel have added greatly to a knowledge base that will be crucial to understanding the eventual fate of uranium on a sitewide basis. However, the inputs to these complex models have also risen proportionately, and many of them vary both spatially and temporally. Thus, it is unclear how the numerous parameters used in these advanced models could be ascertained for the entire alluvial aquifer if they were needed for predicting the site-scale fate of uranium. The use of IFRC models to project future concentrations of dissolved uranium at the site would probably be most beneficial if applied to active remediation schemes such as those based on biostimulation or enhanced mobilization, rather that natural processes.

The proceedings from a recent DOE workshop (DOE 2010) hosted by the Office of Biological and Environmental Research under SC provides some insight into how future predictive models might be developed to better predict the fate of contaminants like uranium on a site-wide scale. The approaches discussed involve the use of principles and methods integral to a research field called complex systems science. The science, as applied to the subsurface, acknowledges that the holistic behavior of a groundwater system includes features at higher spatial scales that cannot be readily derived from the sum of features observed at smaller scales. Key to this is the concept of emergent behavior, which comprises system features that do not cleanly derive from examining all individual components of subsurface processes but are discerned at a greater scale due to the multiple interactions between those components. The goals of this approach are to identify macroscopic laws for the larger-scale system and develop a predictive model that comports with such laws. The type of simulator resulting from the approach can be referred to as more of a phenomenological model, in lieu of a fully mechanistic one, because it derives from examination of the interaction of multiple processes on larger-scale behavior rather than being built from the bottom through a simple additive combination of many small-scale processes.

It is difficult, if not impossible, to foresee what form of model will, or can, be developed to reliably predict the fate of uranium in the Old Rifle site alluvial aquifer. So far, the methods used to develop IFRC models of ever-increasing complexity appear to be following a more-traditional "bottom-up" approach rather than attempting to identify larger-scale emergent behaviors. The hope is that findings from the numerous plot-scale biostimulation experiments and other IFRC research will eventually be translated into a model or models capable of accurately simulating groundwater remediation effects for the site as a whole.

9.0 Recommendations for Monitoring

This section provides several recommendations for groundwater monitoring that will assist in developing an improved understanding of local subsurface flow and transport processes, particularly if natural flushing remains a component of the groundwater remedy at the site.

Suggestions include installing new wells and adding some existing IFRC wells to the current LM monitoring network. Note that some or all of the recommended monitoring steps may not be relevant if a new compliance strategy were adopted that is less dependent on continued groundwater monitoring.

Though the following discussion focuses solely on the use of wells to monitor groundwater, it is important to mention that site characterization activities that extend beyond simple monitoring might be considered in the future, particularly if they can contribute to a clearer understanding of processes affecting uranium contamination in the alluvial aquifer. Though the types of characterization that would assist this purpose depend somewhat on the compliance strategy that is taken at the site, examples include the drilling and sampling of wells that intersect groundwater in Wasatch Formation sediments underlying Highway 6 and improved measurements of flows in upstream and downstream portions the on-site ditch.

9.1 New Well Installation

This report has highlighted the likelihood that portions of the alluvial aquifer underlying the site contain uranium that has a natural origin, specifically as a result of subsurface inflows to the aquifer from areas north of Highway 6. Though the nature of the uranium in these inflows has not been fully characterized, existing chemical analyses indicate that U(VI) concentrations in the inflowing water are as high as 25 to 30 µg/L, but concentrations could be higher in some areas and at certain times. Additional chemical characterization efforts focused on the analysis of uranium isotopes, and analyses of isotopes of oxygen and hydrogen (deuterium) are expected to help distinguish natural U(VI) influxes from mill-related uranium contamination. To avoid the unnecessary remediation of natural uranium, five to six new wells are proposed for installation in areas where groundwater is potentially dominated by the natural inflows. Decisions regarding specific well locations would be made by taking into account site-specific criteria, but most of the wells would likely be evenly spaced along a narrow band of alluvium just south of the highway, and one additional well would be placed near the aquifer's west boundary in the vicinity of IFRC Experimental Plot B. After initial water testing aimed at discerning the source of uranium at these locations, monitoring would be focused on identifying temporal variations in concentrations of naturally derived uranium from north of the highway.

New well installations are also recommended at multiple locations located within 50 ft of and on either side of the on-site ditch. It is expected that these wells would not only help quantify recharge created by ditch water losses along its length, but also help to ascertain whether such recharge is flushing any local residual uranium contamination from the former mill. The data collected at these monitoring sites could prove valuable if they identify a swath of aquifer that is responding positively to the influx of uncontaminated surface water.

Natural flushing at the site could be tracked more comprehensively using additional monitoring wells installed east of the on-site ditch, particularly in the vicinity of the former ore storage area. Currently, monitoring of uranium concentrations east of the ditch is limited to a single well (0656), which is insufficient for delineating uranium levels in areas closer to the Colorado River and the east end the site.

9.2 IFRC Wells

Monitoring of several of the background wells employed during the various IFRC experiments would improve delineation of subsurface uranium contamination in several locales west of the on-site ditch. Existing candidate wells that should be considered for this purpose include the multiple background wells previously installed at the IFRC plot used for the 2002, 2004, and 2005 experiments and those within Plots A, B, C, and D.

A strong possibility exists for a 5-year extension of current SC-funded research at the Old Rifle site. If this occurs, researchers plan to investigate hydrological and biogeochemical processes occurring for the site as a whole. LM will coordinate with these efforts to maximize accrued research and applied science benefits. The extended research effort will involve the installation of additional wells that serve the needs of both LM and SC.

10.0 Regulatory Analysis

10.1 Regulatory Assessment

Standards for the cleanup of residual radioactive materials from inactive uranium-ore processing sites were published by the U.S. Environmental Protection Agency (EPA) in 40 CFR 192. Standards for the cleanup of land and buildings were put in place well before those for groundwater were finalized. As a result, the UMTRA surface program was nearly completed by the time the groundwater regulations were finalized in January 1995. DOE's final Programmatic Environmental Impact Statement (PEIS) (DOE 1996) for the groundwater program was issued in October 1996 and provided the framework for selecting groundwater compliance strategies. DOE's authorization to conduct further surface cleanups expired in 1998.

Cleanup standards for the surface program were based on meeting numerical criteria for radium-226 in uranium mill tailings and tailings-contaminated soils. Background and planning documents published by EPA and DOE in support of the UMTRA groundwater standards and groundwater program are premised on the assumption that cleanup under the surface program was adequate in achieving source removal for groundwater contamination, even though the groundwater standards address constituents other than radium.

Surface cleanup at the Old Rifle site was completed in October 1996, and fieldwork to characterize post-surface-remediation conditions and to support selection of a groundwater compliance strategy was conducted in 1998. The site conceptual model, fate and transport model, and preliminary compliance strategy options presented in the SOWP (DOE 1999) led to the selection of natural flushing as the compliance strategy, which was finalized with NRC concurrence in the GCAP in 2002.

10.1.1 40 CFR 192 Groundwater Standards

EPA established several standards that can apply to groundwater at Title 1 UMTRCA sites. These include (1) background levels, (2) maximum concentration limits (MCLs), (3) alternate concentration limits (ACLs), and (4) supplemental standards. Several criteria are provided in 40 CFR 192.11(e) whereby supplemental standards could apply. These criteria are:

(1) The concentration of total dissolved solids is in excess of 10,000 mg/L (not milling-related); or

(2) Widespread, ambient contamination not due to activities involving residual radioactive materials from a designated processing site exists that cannot be cleaned up using treatment methods reasonably employed in public water systems; or

(3) The quantity of water reasonably available for sustained continuous use is less than 150 gallons per day.

The regulations also provide for an "extended period" of remediation of up to 100 years at Title I sites where groundwater cleanup may be "reasonably accomplished in full or in part through natural flushing." Institutional controls are specified as a critical component of a natural flushing remedy, to ensure protectiveness during the extended remediation period.

10.1.2 DOE's Programmatic Environmental Impact Statement

DOE's PEIS (DOE 1996) provides the decision framework for selecting a groundwater remediation strategy at a given site. This "decision tree" was accepted by NRC and incorporated into their standard review plan for Title I sites with contaminated groundwater (NRC 2000). Figure 14 is a reproduction of the decision tree flow chart. According to the PEIS, three basic compliance strategies may be applied at a site: (1) no remediation, (2) natural flushing, or (3) active remediation. In addition, a combination of natural flushing and active remediation is a further option. According to the decision tree, the preferred compliance strategies are no remediation, followed by natural flushing, followed by active remediation (with or without natural flushing) in order to achieve one of the standards.

10.1.3 Rationale for Compliance Strategy Selection

Compliance strategies have been selected and proposed for all Title I sites, though not all have received regulatory approval from NRC. The compliance strategy selection process, as has been conducted to date, is discussed here and is relevant to reevaluating the compliance strategy for the Old Rifle site.

The compliance strategy selection process at Title I sites first involves a determination of the applicability of supplemental standards based on the criteria for classifying groundwater as "limited use." For sites with limited-use groundwater, it is assumed that any beneficial groundwater uses would not require improvements in water quality, and no remediation is required. For sites with groundwater that is not considered to be limited use, the selection of an appropriate compliance strategy requires the identification of appropriate groundwater standards (e.g., MCLs, ACLs) and a means for achieving those standards (e.g., passive versus active remediation).

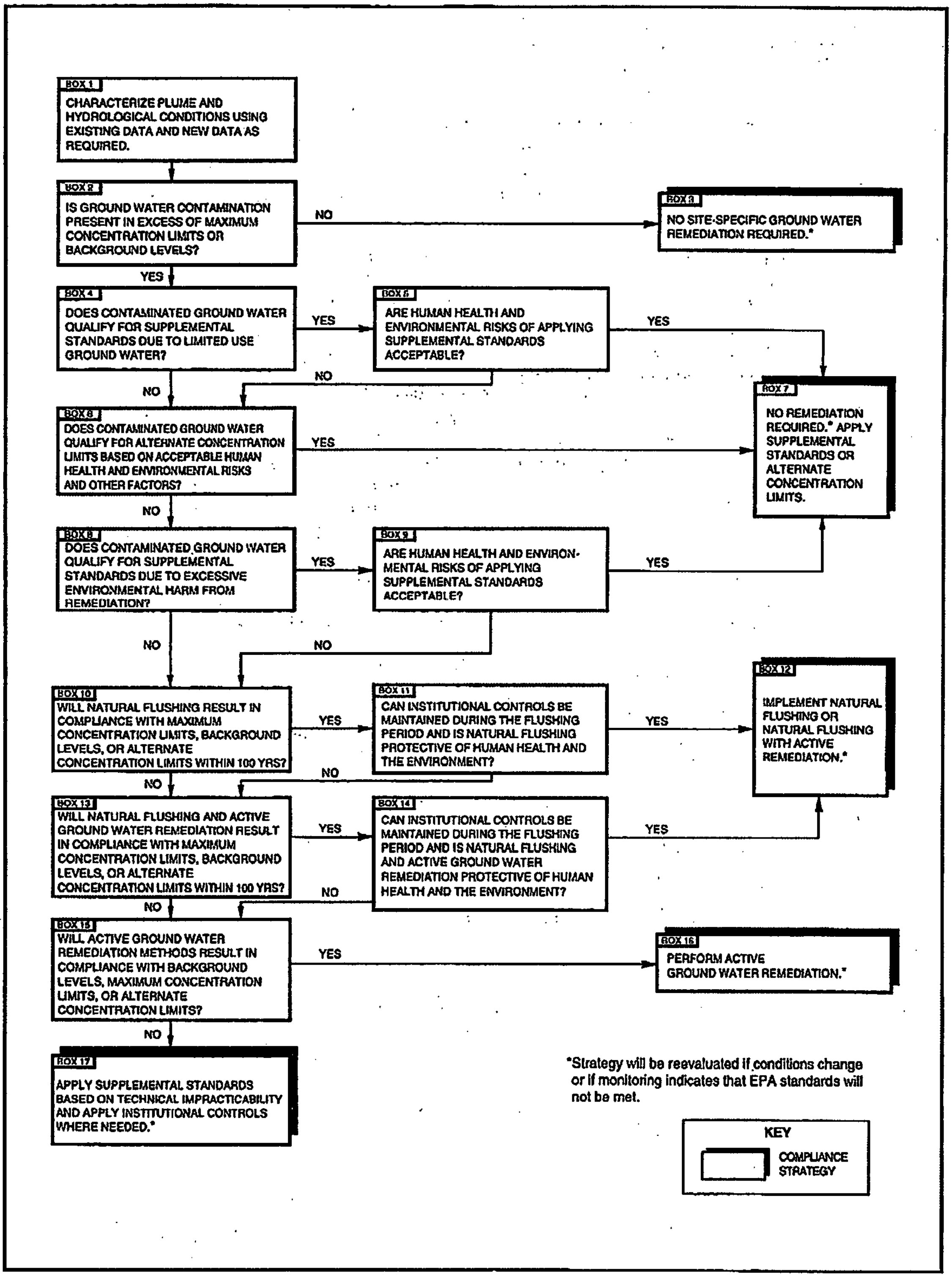

Figure 14. Ground Water Compliance Strategy Decision Process (from DOE 1996)

Two major assumptions have guided DOE's compliance strategy selection process at Title I sites, including the Old Rifle site. The first is that the most stringent standards should be met if possible. This meant that MCLs or background concentrations were assumed to be the default standards. The second assumption is that passive remediation (i.e., natural flushing) is preferable to conducting active remediation. Therefore, if modeling predicted that MCLs or background levels could be met in groundwater within the 100-year timeframe permitted for natural flushing, this was the preferred compliance strategy. Other options were considered only if it was determined that natural flushing was unlikely to achieve MCLs or background levels. At Title I sites where it was determined that natural flushing could not achieve MCLs or background levels, the selected compliance strategies usually involved either (1) active remediation to continue to try to meet MCLs, or (2) no remediation, with the application of less stringent cleanup standards (usually ACLs). At one site, the proposed strategy was to continue to employ natural flushing, but to establish less stringent cleanup goals (e.g., ACLs) that would be met at some future time. At some sites, multiple compliance strategies were selected to address different constituents.

Note that the flow chart in Figure 14 is not strictly consistent with the rationale presented above. Box 6 in the flow chart appears to provide for the use of ACLs before necessitating an evaluation of either natural flushing or active remediation. This implies that if ACLs can be demonstrated to be protective, no remediation is required, and neither passive nor active remediation need be considered. The text in the PEIS confirms that DOE anticipated applying ACLs in lieu of performing remediation, so long as institutional controls (ICs) were applied as needed and the remedy could be demonstrated to be protective. It is potentially significant that NRC accepted this decision-making logic and placed this figure in its standard review plan published as NUREG-1724 (NRC 2000).

According to Figure 1, the compliance strategy of "last resort" is the application of supplemental standards on the basis of technical impracticability (TI; Box 17). This compliance strategy would be appropriate where no method of remediation—passive or active—is likely to achieve applicable cleanup standards. Institutional controls are employed to prevent unacceptable exposures. This alternative has not been selected for any Title I site to date, primarily because NRC has been reluctant to approve this approach without extensive evidence to demonstrate that active remediation would not be effective. This is consistent with the fact that the TI compliance strategy is not actually referred to as a "no remediation" strategy, as is the case with limited-use groundwater. However, data compiled on the application of TI to CERCLA groundwater cleanups has shown that most of the approved TI waivers for those sites were "front-end" decisions made because of the documented complexity of the sites—not based on failed attempts at active remediation (USAEC 2004). The study recommends an earlier consideration of TI for all sites that have complex contaminant and hydrogeologic characteristics.

Because of the separation of the UMTRA surface and groundwater cleanup programs, the "no remediation" compliance strategy is misleading for most Title I sites, particularly those where tailings were removed and disposed of at an off-site location. At these sites, source removal was performed, which significantly reduced the contaminants in groundwater and stabilized groundwater plumes. The justification for any groundwater compliance strategy should "take credit" for the source removal remedy component. However, surface remediation was focused only on meeting cleanup standards for radium-226 in soil. Soil sampling conducted as part of the groundwater cleanup program suggests that other constituents in soil that were not addressed during surface cleanup may remain at levels that could have a continuing impact on groundwater quality. As presented in the natural flushing evaluation report (DOE 2011), residual uranium in soil at the Old Rifle site may serve as a long-term source of groundwater contamination.

10.2 Protectiveness of Human Health and the Environment

The ultimate goal in the selection of any groundwater compliance strategy is the protection of human health and the environment. This requires an evaluation of contamination present, potential pathways for exposure, and potential receptors. Contaminated groundwater at the Old Rifle site is laterally and vertically isolated from any other aquifer by the presence of bedrock that bounds the alluvial aquifer on its north side and underlies it as well. As a consequence, the contaminated groundwater discharges from the site to the Colorado River. However, river flows, even at low stages, are so high that discharged groundwater quickly mixes with river water; river water quality adjacent to the site is indistinguishable from background river concentrations. Therefore, there are no unacceptable risks to potential receptors in the river.

Institutional controls in the form of a quitclaim deed have been placed on the Old Rifle site to prevent the use of groundwater. Therefore, there are no complete exposure pathways to contaminated groundwater and no unacceptable risks associated with use of the site.

10.3 Reconsideration of the Old Rifle Compliance Strategy

Because technical information presented in this report strongly suggests that natural flushing processes will not successfully remove uranium from the alluvial aquifer within a reasonable timeframe, an alternative compliance strategy at the site should be considered. The process for selecting a revised strategy, based on the decision framework discussed above and illustrated in Figure 14, is quite detailed and beyond the scope of this study. If and when the strategy is reconsidered, it is recommended that several possible options be examined, each with its distinct benefits and drawbacks.

11.0 Conclusions

Several conclusions are drawn from the information and analyses presented in this report:

- Contrary to modeling predictions presented in the SOWP, uranium concentrations in groundwater at the Old Rifle site have not attenuated during the past 10 years in response to ambient natural flushing processes. Uranium levels at most on-site wells have remained relatively constant over that time or have gradually increased in recent years.
- Alluvial aquifer zones with the greatest uranium contamination in groundwater are located beneath the former mill tailings area on the west half of the site (0.1–0.3 mg/L), and beneath the former ore stockpile area on the site's east end (0.1–0.15 mg/L). Groundwater with lower uranium concentrations is found in between these two zones, including in the vicinity of the on-site ditch, which may lose surface water to the subsurface and dilute local aquifer sections impacted by former mill processes.

- Biostimulation experiments and other studies conducted by IFRC personnel at the site since 2002 show that flow, geochemical, and biological processes in the site's subsurface are complex, and especially more complex than was assumed during preparation of the SOWP.
- The numerous site complexities revealed through recent IFRC research efforts indicate that accurate modeling of subsurface flow and biogeochemical phenomena at the site is very challenging, particularly given that required model inputs increase with each new effort to simulate the impacts of IFRC biostimulation experiments.
- Recent IFRC modeling of the partitioning of uranium between groundwater and sediments indicates that the sorption distribution coefficient (K_d) for uranium in the site's alluvial aquifer can vary from 0.5 to 20 mL/g, suggesting that uranium transport in the aquifer can be moderately to heavily retarded. The uranium transport modeling used in the SOWP to evaluate natural flushing was probably overly optimistic because the maximum uranium K_d employed in the simulations was 0.2 mL/g, which suggested minimal retardation. Use of such a low K_d in the SOWP model meant that the total mass of uranium in the alluvial aquifer system was underestimated.
- An updated site conceptual model presented in this report indicates that groundwater flow and concomitant uranium transport is strongly affected by physical and biogeochemical heterogeneities in the subsurface, groundwater system transients, recharge due to seepage losses from an on-site ditch, and recharge attributed to subsurface inflows from areas north of the site.
- Though seasonal increases in river stage on the nearby Colorado River can increase site groundwater levels by as much as 5 to 6 ft each year, inflows of river water to the alluvial aquifer during spring runoff months (April–June) are thought to be minimal. This is because river flows tend to increase gradually over the month- to 2-month-long rising limb of the spring runoff, and groundwater elevations throughout the alluvial aquifer are expected to respond relatively quickly and proportionally to the increase in river stage, thereby maintaining a net discharge to the river.
- An assessment of potential hyporheic flow processes at the site suggests that near-river portions of the aquifer might be influenced by river losses at a few locations, but areas farther from the river are probably not impacted by river water.
- Concentration data collected in 2010 showed that uranium isotopes can potentially be used to distinguish site-related uranium contamination from ambient uranium occurring in recharge from subsurface inflows north of the site as well as from seepage losses along the on-site ditch. The usefulness of additional chemical indicators for distinguishing mill-related contamination from naturally occurring uranium in groundwater has yet to be determined.
- Water chemistry data from several groundwater and surface water monitoring locations on and near the site indicate that ambient concentrations of DOC (~2–5 mg/L) are sufficiently high to support multiple background biogeochemical reactions in the subsurface.
- Potential causes of persistently high uranium concentrations in parts of the alluvial aquifer include slow diffusion of uranium from low-permeability sediments, occasional mobilization of uranium in the vadose zone, and natural inflow of uranium in recharge sources north of the site. Chemically reduced zones that are naturally occurring represent possible long-term sources of uranium contamination.

- Groundwater system complexities limit the capacity of existing numerical models to simulate uranium transport in the alluvial aquifer on a sitewide scale; as a consequence, natural flushing of uranium contamination cannot be reliably forecast or controlled. Any model developed at this time to match uranium concentration histories at multiple on-site wells would likely predict that the time needed to complete natural flushing of mill-related uranium contamination from the alluvial aquifer would exceed 100 years.
- It is not possible at this time to definitively state that natural flushing cannot achieve the uranium standard within the next 100 years, but uranium concentration histories at several on-site wells and phenomena contributing to flow and transport complexities suggest that this is the case.
- Several new wells are recommended for installation at the Old Rifle site to enhance the monitoring network currently used to track uranium contamination in groundwater. Five to six of the new wells would be located along a narrow band of alluvium just south of Highway 6 for the purpose of detecting naturally inflowing groundwater underneath the highway, and others would be located close to the on-site ditch and in the east third of the site.
- The decision logic specifically developed for the UMTRA Project will be followed if the decision is made to consider alternative compliance strategies. Reconsideration of the compliance strategy would likely involve assessment of several different options, each with its distinct benefits and drawbacks.

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