

Refining the site conceptual model at a former uranium mill site in Riverton, Wyoming, USA

William L. Dam¹ · Sam Campbell² · Raymond H. Johnson² · Brian B. Looney³ · Miles E. Denham³ · Carol A. Eddy-Dilek³ · Steven J. Babits⁴

Received: 20 February 2015 / Accepted: 20 June 2015
© The Author(s) 2015. This article is published with open access at Springerlink.com

Abstract Milling activities at a former uranium mill site near Riverton, Wyoming, USA, contaminated the shallow groundwater beneath and downgradient of the site. Although the mill operated for <6 years (1958–1963), its impact remains an environmental liability. Groundwater modeling predicted that natural flushing would achieve compliance with applicable groundwater protection standards by the year 2098. A decade of groundwater monitoring indicated that contaminant concentrations were declining steadily, which confirmed the conceptual site model (CSM). However, local flooding in 2010 mobilized contaminants that migrated downgradient from the Riverton site and resulted in a dramatic increase in groundwater contaminant concentrations. This observation indicated that the original CSM was inadequate to explain site conditions and needed to be refined. In response to the new observations after the flood, a collaborative investigation to better understand site conditions and processes commenced. This investigation included installing 103 boreholes to collect soil and groundwater samples, sampling and analysis of evaporite minerals along the bank of the

Little Wind River, an analysis of evapotranspiration in the shallow aquifer, and sampling naturally organic-rich sediments near groundwater discharge areas. The enhanced characterization revealed that the existing CSM did not account for high uranium concentrations in groundwater remaining on the former mill site and groundwater plume stagnation near the Little Wind River. Observations from the flood and subsequent investigations indicate that additional characterization is still needed to continue refining the CSM and determine the viability of the natural flushing compliance strategy. Additional sampling, analysis, and testing of soil and groundwater are necessary to investigate secondary contaminant sources, mobilization of contaminants during floods, geochemical processes, contaminant plume stagnation, distribution of evaporite minerals and organic-rich sediments, and mechanisms and rates of contaminant transfer from soil to groundwater. Future data collection will be used to continually revise the CSM and evaluate the compliance strategy at the site.

Keywords Conceptual site models · Uranium · Unsaturated zone · Groundwater contamination · River flooding · Evaporite mineral deposits

✉ William L. Dam
William.dam@lm.doe.gov

¹ US Department of Energy Office of Legacy Management, 2597 Legacy Way, Grand Junction, CO 81503, USA

² Stoller Newport News Nuclear, Inc., a Wholly Owned Subsidiary of Huntington Ingalls Industries, Inc., 2597 Legacy Way, Grand Junction, CO 81503, USA

³ Savannah River National Laboratory, US Department of Energy Office of Environmental Management, Center for Sustainable Groundwater and Soil Solutions, Aiken, SC 29808, USA

⁴ Shoshone and Arapaho Tribes, 57 Deer Valley Drive, Lander, WY 82520, USA

Introduction

The former uranium mill site (Riverton site) is located 3.9 km southwest of the town of Riverton, Wyoming, USA, on the Wind River Indian Reservation (Fig. 1). The mill operated from 1958 to 1963 and processed a total of 816,470 tonnes of uranium ore that was mined in the Gas Hills mining district in Wyoming (Merritt 1971). In the uranium milling process, ore was crushed and ground, and water was added to create a slurry. Mill tailings that remained after

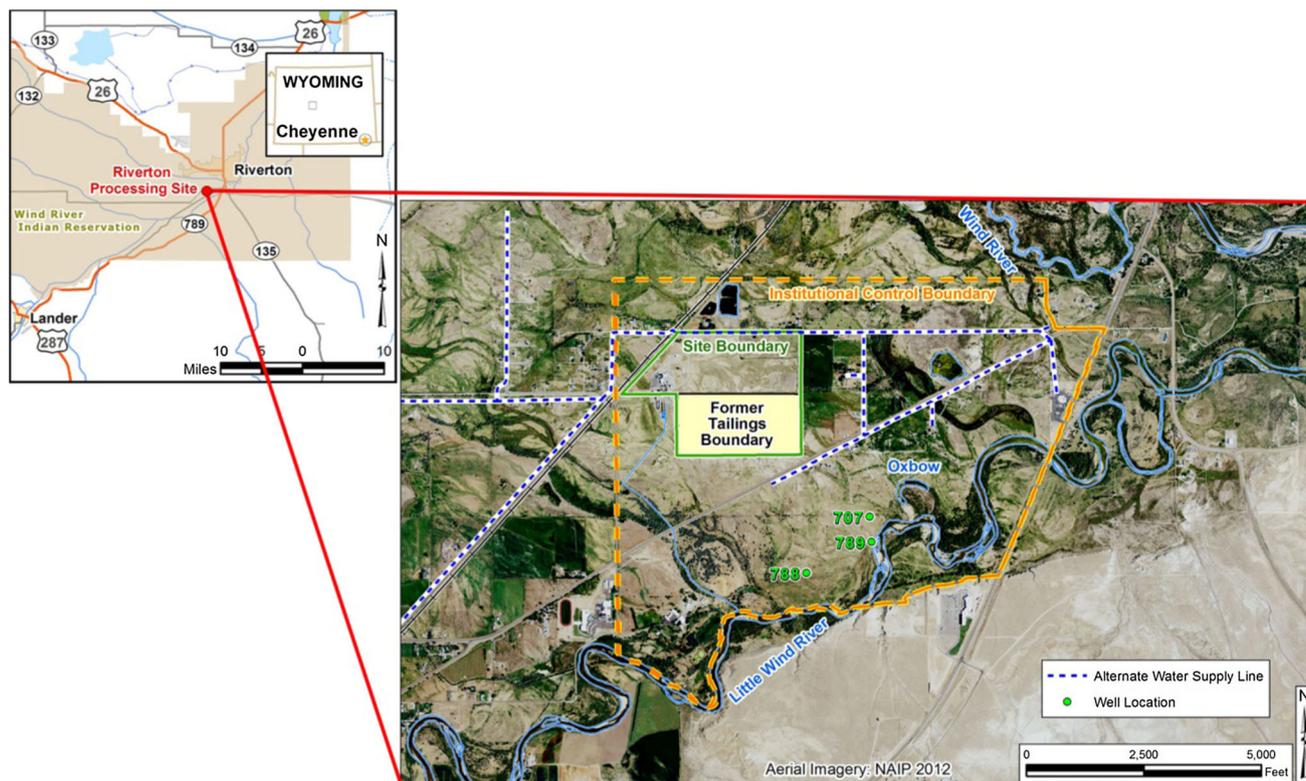


Fig. 1 Former uranium mill site is located southwest of the town of Riverton in central Wyoming on the Wind River Indian Reservation. The Little Wind River, Oxbow Lake, and wells 707, 788, and 789 are frequently discussed in the text. The institutional control boundary

restricts public access to potentially contaminated land and water, and the alternate water supply line provides potable water to the community

extraction of uranium consisted of waste solutions and sand solids, which were conveyed by slurry to a 29-hectare unlined tailings impoundment. The tailings slurry contained high concentrations of calcium, sodium, magnesium, sulfate, chloride, iron, and manganese in addition to trace elements found in the ore, including molybdenum, radium, thorium, vanadium, and residual uranium. The tailings slurry was the primary source that contaminated the shallow groundwater beneath and downgradient of the site (White et al. 1984; Narasimhan et al. 1986; DOE 1998b).

Hydrogeologic setting

The Riverton site lies in the Wind River Basin at an elevation of 1506 m above mean sea level and 80 km east of the Wind River Mountains, which reach elevations exceeding 3960 m. The site is located on an alluvial terrace between the Wind River 1220 m north of the site and the Little Wind River 915 m to the southeast.

Figure 2 illustrates groundwater occurs in three aquifers beneath the site: (1) a shallow, unconfined aquifer, (2) a middle, semiconfined aquifer, and (3) a deeper, confined aquifer (DOE 1998b). The shallow aquifer consists of

approximately 4.6–6 m of unconsolidated alluvial material composed predominantly of sand and gravel, with lesser amounts of clay-sized to cobble-sized particles. The semiconfined and confined aquifers comprise the upper units of the Eocene Wind River Formation, which is over 150 m thick in the vicinity of the site. A discontinuous shale confining layer 2–3 m thick underlies the surficial aquifer, and the semiconfined aquifer ranges from 5 to 9 m in thickness beneath the shale layer. A shale aquitard 3–8 m thick separates the semiconfined and confined aquifers. The confined sandstone aquifer underlies the shale aquitard and is at least 15 m thick in the site area. The confined aquifer is uncontaminated and is the primary drinking water aquifer in the region. Groundwater contaminated with uranium and molybdenum is present in the shallow aquifer, but these milling-related constituents are not detected in the semiconfined aquifer.

Original conceptual site model

The original conceptual site model (CSM) developed from site characterization work in the 1990s determined that once the tailings source was removed, major groundwater

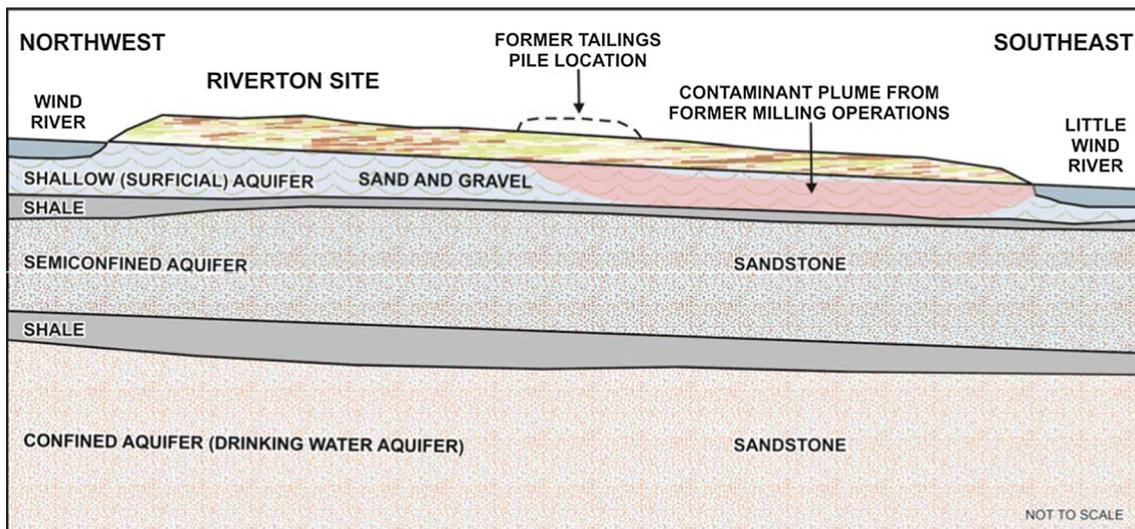


Fig. 2 Groundwater occurs in three aquifers beneath the site. Depth to groundwater in the shallow aquifer is generally <3 m below ground surface. The local topography and the two rivers that bound the site control the groundwater flow direction, which is generally southeast

processes of advection, dispersion, and sorption would dominate contaminant migration. The original CSM coupled with numerical modeling formed the basis for the natural flushing compliance strategy that was approved by the US Nuclear Regulatory Commission (NRC) in 1998 (DOE 1998a). Numerical modeling projected that natural flushing (contaminant movement and removal via groundwater flow) would reduce concentrations to levels below US Environmental Protection Agency (EPA) maximum concentration limits (MCLs) within the 100-year regulatory time frame (DOE 1998b).

Sandia National Laboratories simulated contaminant movement with time in the shallow aquifer using the computer code Groundwater Analysis and Network Design Tool (GANDT) (Knowlton et al. 1997; DOE 1998b). The GANDT code accounted for the uncertainty in groundwater flow and transport through the use of Monte Carlo simulation techniques, honoring the concentration data as well as allowing for spatial variability using geostatistical methods with a single sorption partitioning coefficient (K_d) approach. The Riverton GANDT model predicted that concentrations of uranium and molybdenum in the shallow aquifer would decline to levels below MCLs within approximately 100 years from 1997.

The natural flushing compliance strategy is one of the options allowed in Title 40 *Code of Federal Regulations* Part 192 Subpart B. Provisions in 40 CFR 192 allow for the use of institutional controls in place of active remediation at sites where natural flushing will achieve compliance with groundwater MCLs within 100 years. Institutional controls at the Riverton site consist of four components: an alternate drinking water supply system,

restrictions on new wells and land use, fencing and signs around the oxbow lake adjacent to the Little Wind River, and a deed restriction on privately owned property at the site. The US Department of Energy (DOE) contributed funds to constructing an alternate water supply system in 1998 that supplies drinking water to residents within the institutional control boundary. Water for the alternate water supply system comes from wells completed in the confined aquifer 6 km west of the Riverton site. A perpetual deed restriction is in place for the former mill site property that restricts land development and prohibits well drilling.

EPA requires that the effectiveness of the 100-year natural flushing strategy can be verified and maintained. Metzler (2002) described the compliance strategy used by DOE and cited Riverton as a case study:

This strategy can be effective if 1) the source can be completely decoupled from the groundwater; 2) advective, dispersive, and geochemical processes will be active enough to reduce or dilute contaminant particles within the allowed time frame; 3) the groundwater resource is neither currently nor projected to be a public drinking water supply; 4) monitoring and enforcement of an effective institutional control will be in place for the necessary time period; 5) adequate site characterization, uncertainty analysis, and numerical flow-and-transport modeling have been completed and approved by NRC.

Molybdenum and uranium were selected as indicator contaminants for compliance monitoring (DOE 1998a; Marutzky et al. 1999; DOE 2002), as they form significant

aqueous plumes in the shallow aquifer in the vicinity of the site. The MCL for Mo is 0.10 mg L^{-1} . The MCL for $^{234}\text{U} + ^{238}\text{U}$ is 30 pCi L^{-1} ; assuming secular equilibrium of uranium isotopes, the activity concentration converts to 0.044 mg L^{-1} . This paper focuses on uranium as an indicator contaminant because (1) it is widespread throughout the surficial aquifer; (2) its concentration exceeds the standard in numerous wells in the monitoring network; (3) current concentrations are up to 2–3 orders of magnitude above the standard and background, respectively; and (4) it was one of the constituents whose transport was modeled in previous investigations. Jove Colon et al. (2001) measured the plume length from the site to the Little Wind River as 1.7 km.

Prior to 2010, natural flushing appeared to be progressing based on comparison with the Riverton GANDT modeling predictions, trend analysis, and curve matching/interpolation techniques applied to temporal plots of concentrations at individual locations. These analyses supported a CSM of gradually declining contaminant concentrations after surface remediation of source material on the former mill site.

A flood of new information

A decade of groundwater monitoring indicated that contaminant concentrations were declining at a steady rate and were projected to be below MCLs by the year 2098 (DOE 2009). However, regional rainfall and rapid snowmelt in June 2010 created record flooding, calculated to be a 75-year event (DOE 2013), in the Little Wind River at the site. Overbank flow was observed within a large area downgradient of the former mill site, and floodwaters inundated several wells. The overbank flow, possibly combined with a higher water table, mobilized contaminants held in normally unsaturated materials above the alluvial water table as well as contaminants within the aquifer. Immediately after the flood receded, DOE measured significant increases in contaminant concentrations in monitoring wells where the flooding occurred. For example, uranium concentration in well 0707 (Fig. 1) increased from 0.84 (pre-flood) to 2.70 mg L^{-1} (post-flood) (Fig. 3).

Figure 4 compares the predicted decline in uranium concentrations from GANDT modeling with water quality data collected from well 707. In some wells, natural flushing appears to be on track, except during flood events. Other wells indicate significantly higher concentrations in the shallow aquifer than predicted, with smaller effects from flooding. Overall, groundwater monitoring data from the Riverton site and other remediated uranium-ore-processing sites suggest that natural flushing is occurring at a

slower rate than these numerical models have predicted (Shafer et al. 2014).

The observations made in 2010 revealed that the existing CSM and numerical modeling did not incorporate several important processes occurring at the Riverton site. Consequently, the CSM needs to be revised, and the natural flushing strategy needs to be reevaluated. Observations from the 2010 flood created a renewed interest in understanding site conditions and processes. As part of the renewed interest, the Wind River Tribes retained the US Geological Survey to independently evaluate historical data related to site hydrology and groundwater quality (Ranalli and Naftz 2014) with support provided through EPA.

A collaborative response: post-flood investigation and evaluation

Because of the increased uranium concentrations in groundwater after the 2010 flood, additional investigations focused on evaluating the solid-phase uranium inventory at the site. This information will be used in conjunction with additional groundwater chemistry data to better understand uranium fate and transport mechanisms, with the key being storage of uranium with later release into the groundwater. In 2012, DOE began collaborative efforts with the Wind River Tribes, Savannah River National Laboratory, and the SLAC National Accelerator Laboratory. The enhanced characterization program for the Riverton site included additional groundwater monitoring, field investigation using a Geoprobe[®] drilling rig, evaporite mineral sampling, an evaluation of evapotranspiration, and sampling of organic-rich sediments.

Groundwater monitoring program

A long-term surveillance and monitoring program for the site has included routine collection of groundwater and surface water samples since 1987. DOE analyzed samples for a full suite of major, minor, and trace elements until about 1996, then focused on analysis of the four contaminants of concern (Mn, Mo, SO_4 , and U) along with field geochemical parameters. Recently, to address multiple stakeholder expectations, the DOE monitoring program has progressed beyond simply analyzing samples for the four main contaminants twice per year and comparing concentrations to regulatory limits. In 2012, major cations and anions were added to the analyte list to assess variability of groundwater quality across the site, to assess interaction between aquifers, and to use in geochemical modeling. These data are necessary to fully evaluate uranium fate and

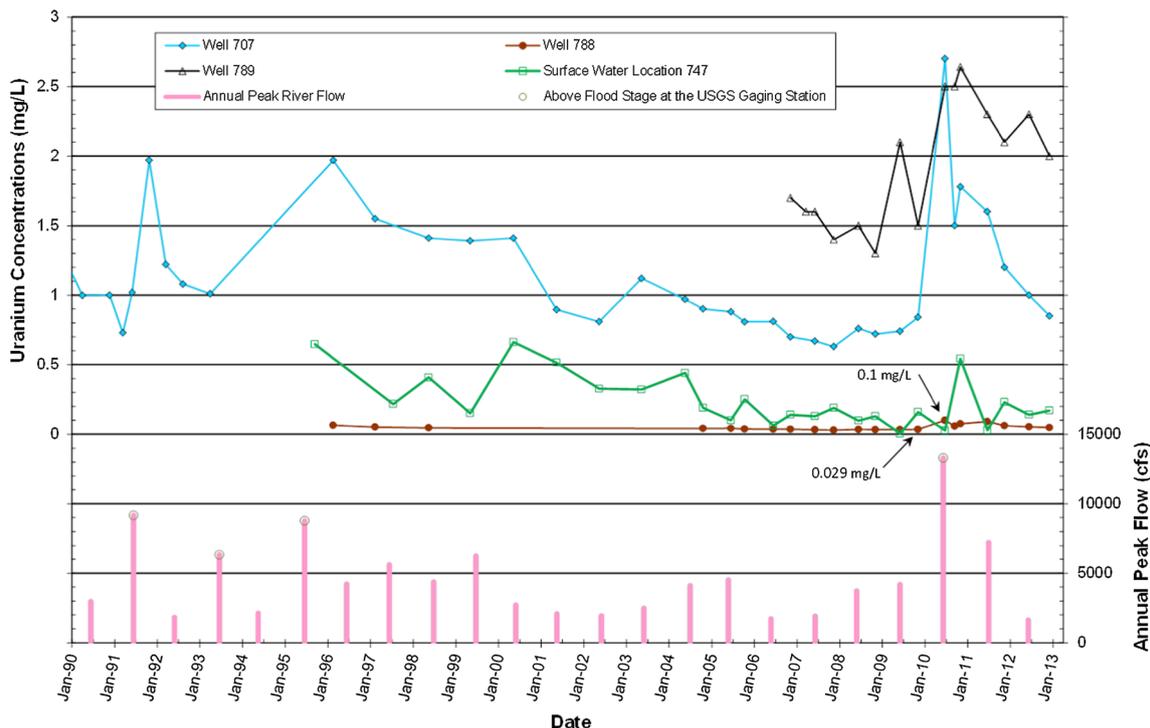
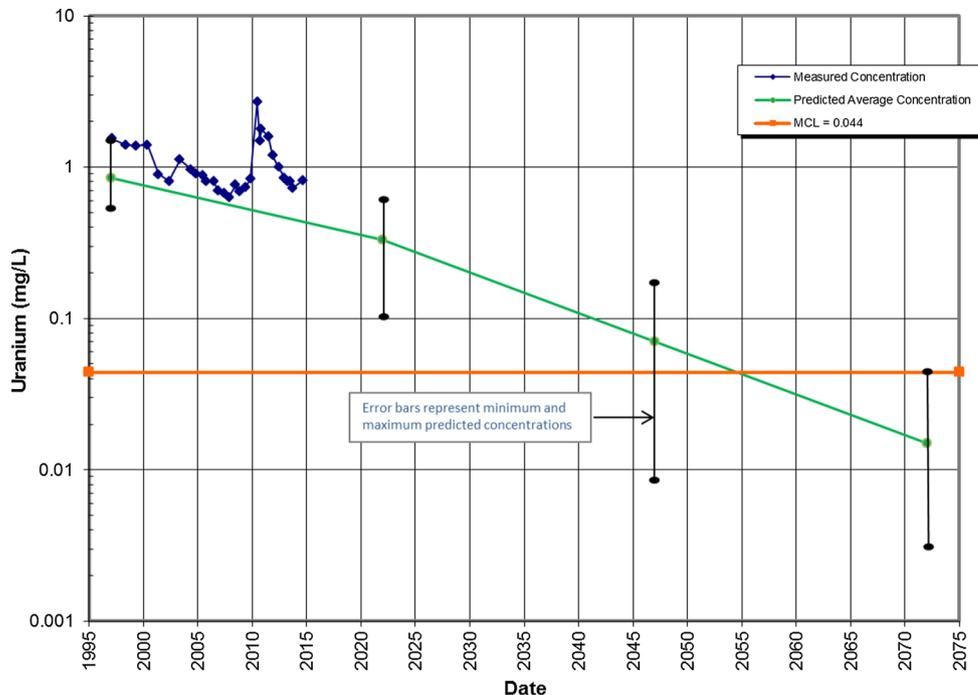


Fig. 3 Uranium concentrations in wells between 1990 and 2013 compared with annual peak flow of the Little Wind River relative to flood stage

Fig. 4 GANDT model uranium predictions from 1998 for well 707 compared with measured concentrations



transport and the potential for geochemical changes that influence rock/water interactions and subsequent uranium mobility. The previous Riverton GANDT model did not consider changes in site conditions, such as the flood in 2010, which could also change groundwater geochemistry and uranium mobility.

Geoprobe® investigation

The purpose of the 2012 field investigation was to obtain additional solid-phase and groundwater data to further characterize the shallow aquifer (DOE 2012; Dam et al. 2013). Specific objectives of the investigation were to:

- Provide enhanced definition of contaminant plumes, including the location of the centroid of each plume and the extent of groundwater contamination for each contaminant of concern.
- Describe the distribution of contaminants in detail for input into an updated groundwater contaminant transport model.
- Provide a detailed and updated baseline of groundwater contamination for tracking plume configuration, movement, and size over time. This baseline will be used to assess the progress of natural flushing if this study is repeated in the future.
- Provide information on soil characteristics, including the leachability of uranium.
- Estimate the mass of uranium remaining or being deposited in the unsaturated zone of the shallow aquifer, which can be used to develop appropriate contaminant source terms in future contaminant transport modeling.

Methods

DOE collected soil and groundwater samples during the 2012 characterization study using a Geoprobe® (Model 7720DT) that employed direct-push technology. Routine groundwater sampling from the long-term monitoring network was supplemented with groundwater samples from 103 borehole locations and soil samples from 34 borehole locations from upgradient of the site to the Little Wind River. Geoprobe® rods were driven to 1.5 m below ground surface at each soil sampling location (approximately 30 cm or more above the regional water table), and two bulk soil samples (0–0.76 and 0.76–1.5 m) were collected for a total of 65 samples (three samples in the lower soil interval were not recovered).

During groundwater sampling, Geoprobe® rods were driven to 3.7 m below ground surface or until rod refusal, and a peristaltic pump was used to purge three rod volumes (approximately 8 L of water) through the rod. The 8 L volume was assumed to be sufficient to obtain a representative sample of groundwater. The 3.7 m depth was chosen to approximate the average midpoint of the screened interval for the monitoring wells in the shallow aquifer that constitute the long-term monitoring network.

Soil samples were analyzed using three different laboratory tests: batch, kinetic, and column tests (DOE 2013). Dried samples were screened through a 2-mm sieve. The <2 mm fraction varied from 20.95 to 99.98 % of the sample. Artificial site water containing a composition similar to that of the Little Wind River was prepared in the laboratory and used as the primary leaching solution for the kinetic, batch, and column tests (DOE 2013). Batch tests

were conducted to determine leachable uranium, column tests to measure changes in uranium concentration over time, and kinetic tests to determine the agitation time required for uranium to reach a steady-state concentration in the batch tests. Results were obtained for uranium concentrations in the water phase and the solid phase.

Results for soil analyses

Soils typically consisted of a dry, pale-yellowish, wind-blown, silt loess in the top 61–91 cm with some near-surface roots, and sand and gravels below the silt. No white evaporite minerals or organic-rich reducing-zone minerals were visually observed in the shallow soil cores.

Bulk soil analyses using X-ray diffraction (XRD) indicated that samples contained mostly quartz and feldspar; some calcite was present in most samples, and one sample had a trace of gypsum. Clay content was low and consisted mostly of smectite with lesser proportions of illite and kaolinite. Cation exchange capacities ranged from 2 to 23 meq/100 g.

Concentrations of uranium in the <2 mm fraction of sediments removed by a 48 h agitation with artificial site water were variable, ranging from 0.04 to 4.8 mg kg⁻¹ with a median of 0.96 mg kg⁻¹. In nearly all paired samples, the upper (shallower) sample had a higher concentration of removable uranium than the lower (deeper) sample. Median uranium values for the upper and lower samples were 2.10 and 0.34 mg kg⁻¹, respectively. In general, the solid-phase uranium removed with the batch tests did not provide a clear correlation with underlying uranium concentrations in the groundwater. The column tests did provide evidence for the possibility of uranium release from the unsaturated zone when contacted with river water. However, the uranium concentrations released during the column tests are difficult to compare directly with the 2010 flood event in terms of kinetics and total uranium mass. Additional discrete soil samples below 1.5 m are needed to fully investigate potential sources of uranium in the unsaturated zone, mechanisms controlling uranium mobility, and potential impact to groundwater.

Results for groundwater analyses

Figure 5 depicts the dissolved uranium plume in the shallow aquifer from groundwater samples collected in August 2012 with a Geoprobe® at a depth of 3.7 m below ground surface. The portion of the uranium plume where concentrations exceed the MCL is beneath and downgradient of the former tailings site; the highest concentrations (>2 mg L⁻¹) are in boreholes adjacent to the Little Wind River. The high concentrations near the river, confirmed by the Geoprobe® results, indicate that the groundwater plume

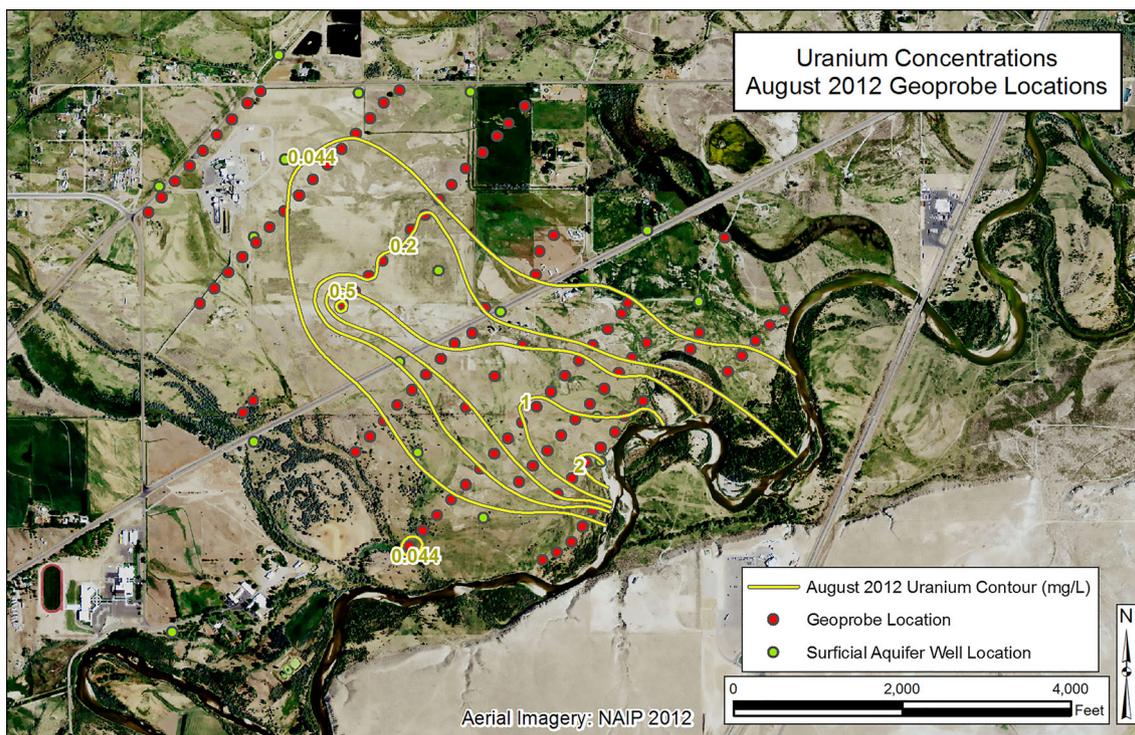


Fig. 5 Dissolved uranium concentrations in the surficial aquifer collected from 103 Geoprobe[®] boreholes in August 2012. The extent of the plume where concentrations exceed the MCL is downgradient

has stagnated over time, which is not consistent with the existing CSM and numerical modeling. Geoprobe[®] results indicate that contaminant plumes are oriented within the existing monitoring well network. However, the Geoprobe[®] results provide a much higher definition of uranium concentrations and detailed groundwater geochemistry within the contaminant plume area. In addition, results show that high uranium concentrations ($>1 \text{ mg L}^{-1}$) remain in the groundwater beneath the former mill site, which was not considered in the existing CSM and numerical modeling. This high-definition groundwater data will be valuable information to compare with future solid-phase data.

General water chemistry varies spatially within the aquifer; upgradient locations have no dominant cation type and are distributed between bicarbonate and sulfate types of water for anions. Locations within the uranium plume tend to also have no dominant cation type and are a sulfate type of water for anions.

Evaporite minerals contain uranium

An efflorescent and solid mineral deposit occurs along the embankment above where the groundwater discharges at the Little Wind River. Samples were collected in December 2013 and May 2014 to determine uranium

of the site. The highest concentrations exceed 2 mg L^{-1} in boreholes adjacent to the Little Wind River

concentrations stored in the solid phase. A grab sample of the efflorescence where the groundwater plume discharged was collected in December 2013 from the escarpment (Looney et al. 2014) and analyzed using two techniques: (1) X-ray fluorescence (XRF) to determine the elemental composition and (2) XRD to determine the primary minerals present.

Uranium values for the laboratory XRF and the portable XRF were 64 and 73 mg kg^{-1} , respectively. Looney et al. (2014) provides the complete set of elemental results.

XRD characterization was performed using a Rigaku Miniflex for bulk soil samples and Bruker D8 Advanced for the evaporite sample. The primary minerals identified in the evaporite sample from the bank of the Little Wind River include halite (NaCl), quartz (SiO_2), blödite [$\text{Na}_2\text{Mg}(\text{SO}_4)_2 \cdot 4\text{H}_2\text{O}$], and various hydrated forms of minerals thenardite (Na_2SO_4) to mirabilite ($\text{Na}_2\text{SO}_4 \cdot 10\text{H}_2\text{O}$).

The combined XRD–XRF calculation indicated the dominant mineral in the evaporite collected from the escarpment at Riverton was blödite (approximately 66–76 % of the sample by weight). The identified minerals closely match the thermodynamic predictions from The Geochemist’s Workbench[®] software for cases where site groundwater is evaporated to dryness. The correspondence of predicted and measured mineralogy suggests the possibility of mineral zonation within the Riverton site

subsurface, in which other evaporite mineral assemblages (e.g., with calcite and gypsum) that precipitate with less evaporation may be present below the surface [as demonstrated in Carlisle (1978)]. Preliminary thermodynamic calculations indicate soddyite $[(\text{UO}_2)_2(\text{SiO}_4)\cdot 2\text{H}_2\text{O}]$ becomes saturated during the evaporation process.

In May 2014, DOE and representatives from the Wind River Tribes collected 32 evaporite mineral samples along the bank of the Little Wind River prior to high river stage. Figure 6 shows the evaporite deposit along the riverbank. Uranium concentrations in the soil samples across 32 locations ranged from a background value of 1.4 mg kg^{-1} to a maximum of 66 mg kg^{-1} (DOE 2014).

Evaporite data do indicate a possible mechanism for short-term uranium storage at the surface with potential for longer-term storage if these evaporites occur at depth away from the river bank. In general, evaporite minerals with higher uranium concentrations correlate with potential uranium plume discharge locations. Understanding the ultimate influence of these evaporites on uranium concentrations in the groundwater will require additional data.

Evaluation of evapotranspiration

The water table is shallow at the Riverton site. The shallow aquifer is relatively thin, and the amounts of water discharging to the Little Wind River or to the unsaturated zone and atmosphere (evapotranspiration and seeps) can control contaminant distribution in soil above the water table. Water that moves upward by evapotranspiration may result in the deposition of dissolved minerals and contaminants in the unsaturated zone and near seeps. Because of this, evapotranspiration at the Riverton site was evaluated in more detail as a possible factor in influencing contaminant distribution in the unsaturated zone.



Fig. 6 Photograph of evaporite mineral deposit adjacent to riverbank, Little Wind River. Sample location MD-12 shown

An informal survey of the vegetation on the land overlying the plume indicated that the flora are typical of regional Wyoming arid to semiarid conditions, including sagebrush, bunchgrasses, and other sagebrush shrub-steppe flora. The landscape vegetation also included a few trees such as native cottonwood and willow and imported Russian olive. Flora present in the landscape comprises phreatophytes that directly extract shallow groundwater.

The phreatophytes cause evapotranspiration to vary throughout the year in response to seasonal climate and plant growth factors. The diurnal variation, or oscillation, in piezometric elevation in well 707 was determined from hourly transducer data (Fig. 7).

These diurnal piezometric elevation changes are reflected in temperature and precipitation records during the time period used for Fig. 7. Daily temperature fluctuations and a cold rain event on 7/29/2014 are reflected by a damped diurnal change in hydraulic head during 7/30/2014. The diurnal changes in Fig. 7 do not reflect any barometric pressure changes and are thus most likely due to daily changes in evapotranspiration. Evapotranspiration could potentially deposit source material in the unsaturated zone and result in an increase in the amount of residual contamination and secondary source material available for future mobilization.

Organic-rich sediments contain uranium

In September 2014, organic-rich sediments were sampled in the bank of the Little Wind River and in an oxbow lake formed in a former meander of the river. Hand auger samples indicated the presence of organic carbon layers beneath sand bar deposits that have sequestered uranium with concentrations up to 75 mg kg^{-1} measured in the carbon-rich sediments. Along a groundwater flow path, the sequestration of uranium on organic-rich sediments may reduce the amount of uranium deposited on surficial evaporite deposits. Detailed biogeochemical analyses of evaporites and organic-rich sediments that affect contaminant mobility are needed following methods described by Campbell et al. (2012).

Additional data need to refine the conceptual model

The discovery of uranium contained in evaporite deposits and organic-rich sediments indicates that additional sources may affect rates of natural groundwater flushing to the river. A revised conceptual model and any future transport modeling will need to account for geochemical reactions between the groundwater and the solid-phase materials. These materials may be present directly along the

Fig. 7 Hydrograph from well 707 depicting diurnal piezometric surface variations likely due to effects of evapotranspiration

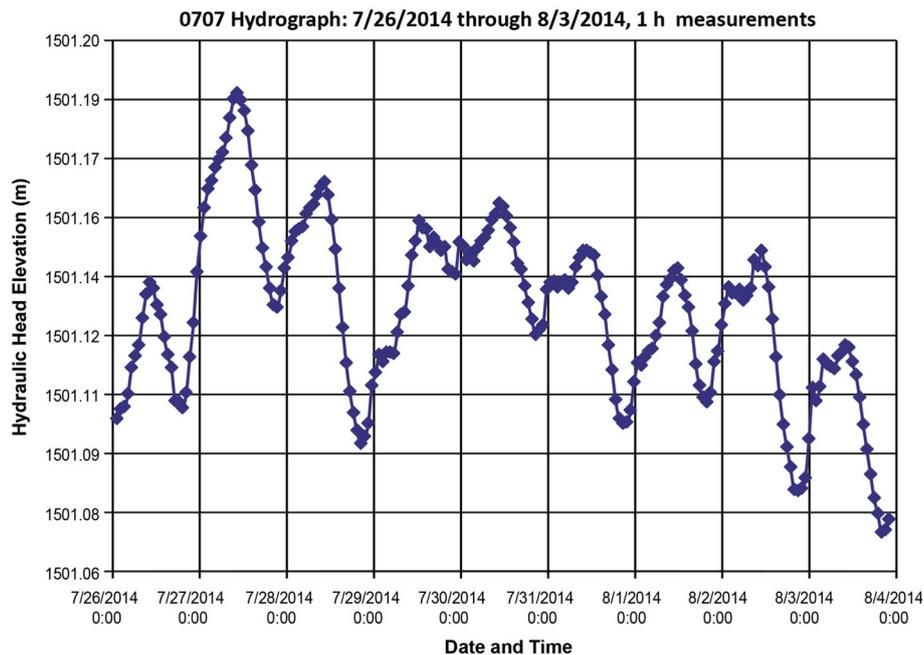


Table 1 Summary of new activities to refine the CSM

Original CSM deficiency	Refined CSM need	New activities
Plume source area: elevated contaminant concentrations in groundwater still remain at the former mill site (source area)	Enhanced delineation of groundwater plumes and soils in the source area	Install additional monitoring wells; collect additional groundwater and soil samples
Stagnation of groundwater plumes: high concentrations in the vicinity of the Little Wind River as a result of groundwater flow conditions	Groundwater flow direction and groundwater gradient near the river	Collect discrete and continuous groundwater-level data; install stilling wells, measure river elevations; model groundwater flow
Stagnation of groundwater plumes: high concentrations in the vicinity of the Little Wind River as a result of geochemical influences	Better definition of geochemical influences on plume stagnation near the Little Wind River	Install and sample well points adjacent to the river; collect soil samples from borings to characterize organic-rich sediments; perform column tests and geochemical modeling
Secondary contaminant distribution: spikes in concentrations were measured after flood events	Contaminant distribution and concentrations in soil and aquifer materials	Collect samples from borings to characterize organic-rich sediments and evaporite layers; perform laboratory testing and analyses
K _d approach to contaminant transport did not account for additional geochemical processes, including contaminant concentration increases after a flood event	Characterization of the solid phase to better understand the geochemical processes that control contaminant transport	Collect soil samples from borings; perform laboratory testing and analysis of soil samples; perform geochemical and reactive transport modeling
Surface water infiltration and the effect on groundwater flow and contaminant plume configurations	Account for all surface water infiltration	Measure flows in ditches, canals, and fields; measure groundwater levels continuously; survey Wind River elevations north of the site; use USGS Wind River gaging station data; model groundwater flow

groundwater flow path, or they could be close enough to influence uranium concentrations in the groundwater due to seasonal variations. Table 1 shows the comparison of the CSM deficiency with new activities proposed to refine the CSM.

The table provides details on proposed solid-phase and groundwater collection methods and analyses that will then

be used to update the CSM. Near-term specific actions include (DOE 2015):

- Additional groundwater and soil investigations using the Geoprobe[®] and backhoe trenching.
- Additional groundwater and soil investigations using sonic drilling and coring technology, including installation of multilevel sampling wells.

- Geochemical modeling to determine geochemical processes controlling contaminant transport and mass transfer rates.
- Stilling well on the Little Wind River to determine interaction between the surficial aquifer and the river.
- Temporary well points along the Little Wind River to determine whether there is geochemical evidence that groundwater discharges to the Little Wind River and why contaminant plumes have stagnated in the area by the river.

Conclusions

EPA regulations in 40 CFR 192 require that, for natural flushing to be a viable compliance strategy, contaminant concentrations must decrease to levels below MCLs within 100 years from the time the strategy is adopted. A decade of groundwater monitoring indicated that contaminant concentrations were declining at a steady rate and would be below MCLs by the year 2098. In June 2010, significant increases in contaminant concentrations in groundwater were measured in several wells coincident with dilute flood water, suggesting that additional contaminant sources existed in the unsaturated and saturated zones.

The observations made in 2010 revealed that the existing CSM and numerical modeling did not account for increases in contaminant concentrations observed in the shallow groundwater, and the CSM needed to be revised. To develop a more complete understanding of the underlying processes that affect contaminant presence at the site, DOE began a collaborative investigation with the Wind River Tribes, Savannah River National Laboratory, and the SLAC National Accelerator Laboratory. The enhanced characterization involved additional groundwater monitoring, field investigation using a Geoprobe[®], evaporite mineral sampling, an evaluation of evapotranspiration, and sampling of organic-rich sediments. The enhanced characterization revealed additional deficiencies with the existing CSM, which did not account for high uranium concentrations in groundwater remaining on the former mill site and groundwater plume stagnation near the Little Wind River.

Beyond the initial collaborative effort of enhanced characterization, additional efforts have been identified to continue refining the CSM and determining the viability of the natural flushing compliance strategy. These efforts involve additional sampling, analysis, and testing of soil and groundwater to investigate numerous aspects of the CSM, including secondary contaminant sources, mobilization of contaminants during floods, geochemical processes, contaminant plume stagnation, distribution of

evaporite minerals and organic-rich sediments, and mechanisms and rates of contaminant transfer from soil to groundwater. Future data collection will be used to continually revise the CSM and to support the natural flushing compliance strategy or to evaluate alternative compliance strategies.

Acknowledgments This study was funded by the US Department of Energy Office of Legacy Management. The authors wish to thank the people living on the Wind River Indian Reservation for active participation and seeking to differentiate between actual and perceived environmental risks. Kent Bostick provided many helpful technical review comments.

Open Access This article is distributed under the terms of the Creative Commons Attribution 4.0 International License (<http://creativecommons.org/licenses/by/4.0/>), which permits unrestricted use, distribution, and reproduction in any medium, provided you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons license, and indicate if changes were made.

References

- Campbell KM, Kukkadapu RK, Qafoku NP, Peacock AD, Leshner E, Williams KH, Bargar JR, Wilkins MJ, Figueroa L, Ranville J, Davis JA, Long PE (2012) Geochemical, mineralogical and microbiological characteristics of sediment from a naturally reduced zone in a uranium-contaminated aquifer. *Appl Geochem* 27:1499–1511
- Carlisle D (1978) The distribution of calcretes and gypcretes in southwestern United States and their uranium favorability: based on a study of deposits in Western Australia and Southwest Africa (Namibia). Report No. GJBX-29/78. U.S. Department of Energy
- Dam WL, Gil A, Campbell S (2013) After the flood: a new approach to the reevaluation of contaminant distributions and attenuation for the surficial aquifer at the Riverton, Wyoming, Uranium Mill Tailings Remedial Action Site. Waste Management conference. Phoenix, Arizona
- DOE (1998a) Final ground water compliance action plan for the Riverton, Wyoming, Title I UMTRA Project Site, attached to letter to the US Nuclear Regulatory Commission from the US Department of Energy, Grand Junction, Colorado
- DOE (1998b) Final Site Observational Work Plan for the UMTRA Project Site at Riverton, Wyoming, Report No. U0013801. US Department of Energy, Grand Junction
- DOE (2002) UMTRA Ground Water Project Management Action Process (MAP) Document, Report No. GJO-2001-216-TAR. US Department of Energy, Grand Junction
- DOE (2009) Verification Monitoring Report, Riverton, Wyoming, Report No. S05094. US Department of Energy, Grand Junction
- DOE (2012) Work Plan for the Enhanced Characterization of the Surficial Aquifer, Riverton, Wyoming Processing Site, Report No. LMS/RVT/S08542. US Department of Energy, Grand Junction
- DOE (2013) 2012 Enhanced Characterization and Monitoring Report, Riverton, Wyoming, Report No. LMS/RVT/S09799. US Department of Energy, Grand Junction
- DOE (2014) Evaluation of Mineral Deposits Along the Little Wind River, Riverton, Wyoming, Report No. LMS/RVT/S12020. US Department of Energy, Grand Junction

- DOE (2015) 2015 Work Plan for Advanced Site Investigation of the Riverton, Wyoming, Processing Site, Report No. LMS/RVT/S12697. US Department of Energy, Grand Junction
- Jove Colon CF, Brady PV, Siegel MD, and Lindgren ER (2001) Historical case analysis of uranium plume attenuation. NUREG/CR-6705. U.S. Nuclear Regulatory Commission, Office of Nuclear Regulatory Research, Rockville
- Knowlton RG Jr, Peterson DM, Zhang H (1997) Analysis of natural attenuation as the preferred ground water alternative at the DOE UMTRA site near Riverton. Sandia National Laboratories, WY
- Looney BB, Denham ME, Eddy-Dilek CA (2014) Independent technical evaluation and recommendations for contaminated groundwater at the Department of Energy Office of Legacy Management Riverton Processing Site. Report No. STI-2014-00163. Savannah River National Laboratory
- Marutzky S, Metzler DR, Bowen R (1999) Performance measurements for natural flushing (attenuation) of contaminated ground water in the UMTRA Ground Water project: Waste Management conference. Phoenix, Arizona
- Merritt RC (1971) The extractive metallurgy of uranium. Colorado School of Mines Research Institute, Johnson Publishing Co, Golden
- Metzler DR (2002) Exploring the potential for natural attenuation to ground water cleanup goals at select former uranium mill tailings sites in the western United States. In: Merkel BJ, Planer-Friedrich B, Wolkersdorfer C (eds) Uranium in the environment, proceedings of the international conference uranium mining and hydrogeology III and the international mine water association symposium. Freiberg, Germany, pp 631–644
- Narasimhan TN, White AF, Tokunaga T (1986) Groundwater contamination from an inactive uranium mill tailings pile: 2. Application of a dynamic mixing model. *Water Resour Res* 22(13):1820–1834
- Ranalli AJ, Naftz DL (2014) Assessment of the quality of groundwater and the Little Wind River in the area of a former uranium processing facility on the Wind River Reservation, Wyoming, 1987 through 2010. Scientific Investigations Report No. 2013-5218. U.S. Geological Survey
- Shafer D, Bush R, Dam WL, Pauling T (2014) The future is now: experience with remediating and managing groundwater contamination at uranium mill tailing sites. Waste Management conference. Phoenix Arizona
- White AF, Delany JM, Narasimhan TN, Smith A (1984) Groundwater contamination from an inactive mill tailings pile: 1. Application of a chemical mixing model. *Water Resour Res* 20(11):1743–1752