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U.S. Nuclear Regulatory Commission
ATTN: Dr. Hans Arlt
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Mail Stop 8F 5
Rockville, MD 20555

Subject: Intermediate Milestone 20.15265.21.021.160, Analysis of Mill Tailings Cover Performance

Dear Dr. Arlt:

This letter acknowledges completion of deliverable 20.15265.21.021.160 by the Center for Nuclear Waste Regulatory Analyses (CNWRA®) for Task Order 21, Engineered Cover Support for Decommissioning and Uranium Recovery. It was transmitted to the U.S. Nuclear Regulatory Commission (NRC) using the NRC/CNWRA shared computer drive. A Portable Document Format (pdf) file of the report was placed in the Task Order 21 folder. If NRC wants a hard copy of the 200-plus page report, we will transmit one.

The final report for Task Order 21, Analysis of Mill Tailings Cover Performance, describes (i) development of databases for radon emission fluxes and groundwater geochemical observations at 11 UMTRCA Title II sites, (ii) site-specific analyses of cover performance with respect to radon emissions and groundwater releases, (iii) analyses of methodology for estimating inflow through covers, and (iv) recommended approaches for monitoring cover inflow at existing and potential future mill tailings sites.

If you have any questions concerning this deliverable, please do not hesitate to contact S. Stothoff at (210) 522-6828 or me at (210) 522-6418.

Sincerely,

Robert Lenhard, Ph.D.
Program Manager
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ANALYSIS OF MILL TAILINGS COVER PERFORMANCE

Prepared for

U.S. Nuclear Regulatory Commission
Contract NRC–41–09–011

Prepared by

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San Antonio, Texas

August 2012

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EXECUTIVE SUMMARY

The objective of the 2-year Cover Performance at Uranium Mill Tailings Title II Sites project, using observations from mill tailings sites with existing covers, is to identify methodology that may enhance or supplement current methods for monitoring and evaluating cover performance at present and potential future mill tailings sites. Data from mill tailings sites typically were collected for two purposes: (i) demonstrate that the radon barrier adequately limits radon gas emissions and (ii) demonstrate that any seepage of tailings fluids either does not adversely impact groundwater quality and groundwater protection, or demonstrate that a groundwater corrective action is adequately remediating the site. The current project seeks to examine the radon flux data to identify potential additional information about radon fluxes, and use the groundwater quality data to identify information specific to the tailings covers. Although current sites were analyzed to accomplish this objective, site analysis *per se* is not the primary focus of the project.

During this project, the Center for Nuclear Waste Regulatory Analyses (CNWRA®) staff approached the objective with four subtasks:

- Subtask 1. CNWRA staff reviewed documents provided by the U.S. Nuclear Regulatory Commission (NRC) on background information and engineered cover performance of 11 sites to acquire specific knowledge and understanding of the site disposal cells, the engineered cover designs, and the radon and groundwater monitoring programs

- Subtask 2. CNWRA staff, with NRC assistance, obtained radon and groundwater monitoring data on the 11 sites that NRC identified and compiled an electronic database of these data

- Subtask 3. CNWRA staff evaluated site-specific engineered cover performance by analyzing the radon and groundwater monitoring data compiled in the database

- Subtask 4. CNWRA staff prepared an evaluation report of cover performance at uranium mill tailings sites (this report), including recommendations for future radon and groundwater monitoring programs and for data analyses at each site or group of sites

As a final subtask to complete the project, CNWRA staff will provide NRC with the database and associated documentation and training to operate and maintain the database.

Subtasks 1 and 2 were performed during fiscal year 2011, with Subtask 2 completed early in fiscal year 2012. This report discusses Subtasks 3 and 4, which have been the primary focus in fiscal year 2012.

The first year of the project focused on Subtasks 1 and 2, by (i) gathering information about the sites, (ii) evaluating site characteristics at a high level in a uniform manner, and (iii) compiling the databases. The intention during the first year was to develop the information base for subsequent analyses. Each of the NRC project officers for the individual sites compiled appropriate references, supplemented by searches of the publicly available documents in the NRC Agencywide Documents Access and Management System (ADAMS) database. These compilations were aimed at identifying data and at identifying site descriptions and analyses relevant to cover performance. Several hundred of the most pertinent documents were obtained during this process. Supplementing this effort, licensees and U.S. Department of

Energy (DOE) Legacy Management staff provided electronic versions of geochemical and well data for some of the sites, which otherwise were only available in the ADAMS system as scanned reports.

By the end of the first two subtasks, CNWRA staff had developed summary reports for each of the sites and provided the reports to NRC staff. These reports are several pages long, and consider cover performance as described by the publicly available literature. CNWRA staff had also compiled two Microsoft® (MS) Access® electronic databases. At the end of Subtask 2, the resulting databases included more than 1,900 radon flux observations from 9 sites and more than 800,000 geochemical observations from 11 sites.

Radon analyses were limited to the Grants site in New Mexico, because the Grants site is the only site with multiple surveys. The data suggest that large-scale spatial patterns of radon flux are persistent from year to year, but with substantial year-to-year variability at each nominal location. Presumably the radon sampling canisters are not precisely placed at precisely the same location each year, and the variability implies that there may be significant local variability in flux. The data also suggest that there may be a systematic influence, much smaller than spatial variability, due to rainfall or seasonal changes in soil characteristics, with dry (summer) conditions reducing fluxes relative to wet (autumn) conditions. These analyses suggest that accounting for spatial variability is the most important aspect of estimating total emissions across the cover. The current number of samples provides a reasonably reproducible mean and median flux estimate from year to year at the Grants site.

The project focused much more on cover performance with respect to releases to groundwater, commensurate with the amount and variety of available data. Based on the types of data that were available, staff developed a working concept that it might be fruitful to consider groundwater releases by performing statistical analyses on the time series of selected geochemical constituents from selected locations. To apply this approach, selecting the wells for analysis only requires appropriate maps and figures from the literature. The initial working concept helped guide the design of the geochemical database, which accordingly focused on developing time series of geochemical data with little emphasis on either precise geolocation or water level information.

An initial ranking of the qualitative likelihood of developing performance estimates for each site was developed to focus the studies. The Sequoyah site in Oklahoma was immediately dismissed from further consideration because it does not have a tailings impoundment, thus it has no cover. Among the other 10 sites, the Highland (Wyoming), Church Rock (New Mexico), and Split Rock (Wyoming) sites were thought to be most amenable to analysis, because each site had numerous monitoring wells, reasonably extensive geochemical information, and reasonably simple hydrologic regimes. The Grants site features an extensive database, but cover performance with respect to meteoric inflow was not analyzed because (i) it features a complex hydrologic regime and (ii) the one impoundment with a final cover is largely overlain by active evaporation ponds. The remaining sites were thought to be less promising for analysis because they had relatively few wells or relatively limited geochemical data.

Staff used a worksheet provided by NRC staff to guide analyses, ultimately considering 6 of the 9 sites. The worksheet requested information on available data, conceptual models, and geochemical analyses. Working through the worksheet questions proved very helpful in understanding the constraints that the available data placed on the analyses. The original worksheet and site analyses are provided as appendices.

As the available data became better understood, the initial concept of using geochemical analyses to assess cover inflow appeared less promising. Staff formalized potential approaches to evaluating cover performance using the kind of information available at the sites (i.e., water levels, temperatures, and geochemical data), first at a high (strategic) level, then at a more specific (tactical) level. Staff identified three potentially useful strategies for identifying inflow through the cover: (i) observing a unique cover signature, (ii) observing a water or temperature signal consistent with inflow, and (iii) observing a geochemical signal consistent with inflow through the cover. Staff then identified three tactics as potentially most effective for identifying inflow at the analyzed sites: (i) tracer applications to the cover, (ii) analysis of water level fluctuations within the tailings, and (iii) water balance calculations. Analyses suggested cover inflow geochemical signals may require unrealistically accurate and detailed geochemical sampling to be used for inflow calculations even within tailings, implying that existing geochemical observations outside an impoundment are unlikely to be of use for identifying a natural cover inflow signature distinct from tailings drainage.

Staff applied three tactics to the 10 sites. The tactics consider (i) water level and geochemical signals measured in the tailings fluids, (ii) return of water levels to pre-operation conditions, and (iii) control volume calculations to provide estimates of cover inflow. The first tactic could not be applied at any site, because no site was identified with publicly available observations suitable for examining signals in tailings fluids, although some of the sites may have observations that are not publicly available. The second tactic could be reasonably applied only at the Church Rock site. The third tactic could be applied at most sites, at least to provide rough bounding estimates combining cover inflow, tailings drainage, and natural recharge outside the impoundment area. The third tactic identified several sites with insufficient information to perform bounding calculations, and identified three sites where seepage mixes with such large natural fluxes passing by the impoundment that even numerous monitoring wells would not be likely to detect a cover inflow signal.

A recommendation was spurred by the difficulty in extracting the available data for analysis. The recommendation suggests that NRC may wish to consider requiring electronic submittal of any data provided in tables or figures as a routine accompaniment to requests for licensing actions. Any data presented in tables or figures used to support a licensing request are already in electronic form, thus supplying any tabular or graphical data in electronic form is straightforward. For example, such data would include geolocated geochemical data, water levels, and geologic unit characteristics. This recommendation would permit improved regulatory decisions at the end of the facility life cycle, but would require careful thought as to how the submitted data would be managed.

The study suggests that existing water level and geochemical data streams collected at the existing mill tailings sites, while useful for characterizing performance of the impoundment system, usually cannot be expected to distinguish cover inflow from other fluxes in the system, such as tailings drainage and natural recharge outside the impoundments. Water balance approaches (control volume approaches or numerical simulations) using measurements outside the tailings can provide bounding estimates for cover inflow, but only when other fluxes are small or a persistent recharge mound exists that is too large to be maintained by tailings drainage. The study identified two practical data streams that offer possibilities for quantifying subsystem performance with respect to inflow through tailings covers: (i) unique tracers directly applied to the cover and (ii) water level measurements within coarse tailings.

Staff recognizes that monitoring cover performance would be more straightforward in future impoundments that are constructed with relatively impermeable liners and a drainage system to promote tailings dewatering, because any water produced from the drainage system after the tailings have finished dewatering must stem from cover inflow. However, extremely watertight impoundments run the risk that the drainage system fails at some future point, which would ultimately increase the water level to near the ground surface and potentially induce surface seeps of concentrated tailings fluids. A potential backup strategy would be to include an overflow drainage layer immediately below the cover, allowing relatively dilute inflow waters to drain prior to substantially contacting the tailings.

The analyses show that characterizing site heterogeneity in detail may be an important consideration in future sites if performance depends on low-permeability units. Further, pre-operation water level data becomes valuable for assessing the extent of restoration and placing compliance and exposure monitoring wells as the restoration phase nears completion.

Finally, staff recognizes that channels and low spots foster focused infiltration. Typical design strategies for surface water conveyance facilities consider water conveyance and bed erosion under maximum conditions, but do not necessarily consider infiltration or bed erosion under the riprap layer. It is recommended that future work considers potential tradeoffs between surface water routing, erosion, and infiltration.

ACKNOWLEDGMENTS

This report was prepared to document work performed by the Center for Nuclear Waste Regulatory Analyses (CNWRA®) for the U.S. Nuclear Regulatory Commission (NRC) under Contract No. NRC–41–09–011. The activities reported here were performed on behalf of the NRC Office of Federal and State Materials and Environmental Management Programs, Division of Waste Management and Environmental Protection. This report is an independent product of CNWRA and does not necessarily reflect the view or regulatory position of NRC.

The authors wish to thank G. Walter and G. Wittmeyer for constructive discussions regarding methods for evaluating cover performance. The authors thank R. Lenhard for his editorial review, G. Walter for his technical review, G. Wittmeyer for his programmatic review, and L. Selvey and A. Ramos for secretarial support.

QUALITY OF DATA, ANALYSES, AND CODE DEVELOPMENT DATA

DATA: CNWRA did not generate data for this report. Sources of other data should be consulted for determining the level of quality of those data.

ANALYSES AND CODES: Staff used commercial off-the-shelf software including (i) Mathworks Matlab® Version 7.11.0.584 (The MathWorks, Inc., 2010), (ii) Microsoft® Office Excel® 2007 (12.0.6661.5000) SP3 (Microsoft Corporation, 2007a), and (iii) Microsoft Office Access 2007 (12.0.6606.1000) SP3 (Microsoft Corporation, 2007b) for analysis. Staff used Adobe Illustrator® CS4 Version 14.0.0 (Adobe Systems, Inc., 2008) to prepare figures. All commercial off-the-shelf software packages used in this report are controlled under Technical Operating Procedure 18.

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1 INTRODUCTION AND BACKGROUND

The over-arching objective of the 2-year Cover Performance at Uranium Mill Tailings Title II Sites project is to, using observations from mill tailings sites with existing covers, identify methodology that may enhance or supplement current methods for monitoring and evaluating cover performance at present and potential future mill tailings sites. Data from mill tailings sites typically were collected for two purposes: (i) analyses of cover performance with respect to radon gas emissions and (ii) analyses of tailings fluids impacting groundwater quality and groundwater protection. The current project seeks to examine the radon flux data to identify potential additional information about radon fluxes, and repurpose the groundwater quality data to identify information specific to the tailings covers. Although current sites were analyzed to accomplish this objective, site analysis *per se* is not the primary focus of the project.

During this project, the Center for Nuclear Waste Regulatory Analyses (CNWRA) staff approached the objective under four subtasks:

- Subtask 1. CNWRA staff reviewed the documents provided by the U.S. Nuclear Regulatory Commission (NRC) on background information and engineered cover performance of 11 sites to acquire specific knowledge and understanding of the site disposal cells, the engineered cover designs, and the radon and groundwater monitoring programs

- Subtask 2. CNWRA staff, with NRC assistance, obtained radon and groundwater monitoring data on the 11 sites that NRC identified and compiled an electronic database of these data

- Subtask 3. CNWRA staff evaluated site-specific engineered cover performance by analyzing the radon and groundwater monitoring data compiled in the database

- Subtask 4. CNWRA staff prepared an evaluation report of cover performance at uranium mill tailings sites (this report), including recommendations for future radon and groundwater monitoring programs and for data analyses at each site or group of sites

As a final subtask to complete the project, CNWRA staff will provide NRC with the database and associated documentation and training to operate and maintain the database.

Subtasks 1 and 2 were performed during fiscal year 2011, with Subtask 2 completed early in fiscal year 2012. This report discusses subtasks 3 and 4, which have been the primary focus in fiscal year 2012.

A substantial component of the project required exploring the available data to understand the opportunities and limitations of the data for understanding cover performance. Staff focused on strategies and tactics for evaluating cover performance, as opposed to performing actual evaluations. Analyses of cover performances described in this report are at the most abstracted level consistent with understanding a methodology, and are intended only for illustration.

The first year of the project focused on gathering information about the sites, evaluating site characteristics at a high level in a uniform manner, and compiling the database. The intention during the first year was to develop the information base for subsequent analyses. Each of the NRC project officers for the individual sites compiled appropriate references, supplemented by searches of the publicly available documents in the NRC Agencywide Documents Access and Management System (ADAMS) database. These compilations were aimed at identifying data and at identifying site descriptions and analyses relevant to cover performance. Several hundred of the most pertinent documents were obtained during this process. Supplementing this effort, licensees and U.S. Department of Energy (DOE) Legacy Management staff provided electronic versions of geochemical and well data for some of the sites, which otherwise was only available in the ADAMS system as scanned reports.

At the end of the initial information-gathering phase, CNWRA staff developed summary reports for each of the sites and provided the reports to NRC staff. These reports are several pages long, and consider cover performance as described by the literature. In compiling the reports, particular focus was placed on describing aspects of the tailings impoundments and tailings covers, and developing initial insights into impoundment performance with respect to radon emissions and releases to groundwater.

In parallel with this information gathering, the available radon flux and geochemical observations for each site were compiled into Microsoft® (MS) Access® electronic databases. At the end of the formal data compilation task, Subtask 2, the resulting databases included more than 1,900 radon flux observations from 9 sites and more than 800,000 geochemical observations from 11 sites. The radon flux database is orders of magnitude smaller than the geochemical database because radon flux sampling considers one constituent and is generally performed only once (after the cover is in place), whereas geochemical sampling occurs repeatedly over time and numerous geochemical constituents are measured in each sample. Additional geochemical observations for several sites, provided in electronic form, became available too late in the project for use in analyses. Section 3 summarizes the structure of these databases. At the end of the project, the databases, fuller documentation, and training will be provided to NRC staff.

Once initial information gathering and formal data compilation were complete (Subtasks 1 and 2), the project focus turned to using the available information to assess cover performance with respect to radon emissions and releases to groundwater. The approach for evaluating cover performance was not precisely defined in the initial project stages, because any approach necessarily depends on the available information. The two aspects of cover performance were considered separately.

Analysis of performance with respect to radon emissions was necessarily limited because of the available data set. Only the Grants site offers a multiyear time series of radon flux observations, thus analysis focused on the Grants site. The data suggest that large-scale spatial patterns of radon flux are persistent from year to year. Substantial year-to-year variability exists at each location; presumably the canisters are not precisely placed at the same location each year, implying that there is significant local variability in flux. The data suggest that there may be a systematic influence, much smaller than spatial variability, due to rainfall or seasonal changes in soil characteristics, with dry (summer) conditions reducing fluxes relative to wet (autumn) conditions. These analyses are described in Section 4.

The project focused to a much greater extent on cover performance with respect to releases to groundwater, commensurate with the amount and variety of available data. Based on the types of data that were available, staff started with the concept that it might be fruitful to consider groundwater releases by performing statistical analyses on the time series of selected geochemical constituents from selected locations. To apply this approach, selecting the wells for analysis only requires appropriate maps and figures from the literature. The initial working concept helped guide the design of the geochemical database, which accordingly focused on developing time series of geochemical data with little emphasis on either precise geolocation or water level information.

As requested by NRC staff, CNWRA developed an initial ranking of the qualitative likelihood of developing performance estimates for each site. A high-level description of the sites is provided in Appendix A, developed prior to commencing analyses. Key site aspects are also summarized in Section 2. Appendix A focuses on identifying aspects of the sites influencing hydrologic analyses, and provides a site layout figure for reference. For completeness, the site descriptions in Appendix A also summarize analyses of the respective site.

The Sequoyah site was immediately dismissed from further consideration because it does not have a tailings impoundment, thus it has no cover. Among the other 10 sites, the Highland, Church Rock, and Split Rock sites were thought to be most amenable to analysis, because each site had numerous monitoring wells, reasonably extensive geochemical information, and reasonably simple hydrologic regimes. The Grants site features an extensive database, but cover performance with respect to meteoric inflow was not analyzed because (i) it features a complex hydrologic regime and (ii) the one impoundment with a final cover is largely overlain by active evaporation ponds. The remaining sites were thought to be less promising for analysis because they had relatively few wells or relatively limited geochemical data.

NRC staff provided additional guidance to help focus the cover performance analyses. A worksheet with a series of questions related to particular aspects of cover performance with respect to groundwater release was provided to CNWRA staff. Appendix B contains this worksheet. Staff used the worksheet questions, slightly rephrased, as a framework for examining the data typically provided at mill tailings sites. In some cases, sufficient data were available to develop considerable insight into site conditions, independent of prior assessments. In others, very little publicly available data were available to develop independent evaluations. Staff used the questions to consider (i) how relevant available data are for evaluating cover performance, (ii) what additional data would be useful, and (iii) how the information might be more usefully presented for subsequent analyses. These insights inform discussions in Sections 5–8.

Appendices C–H capture the worksheet evaluations in the order that they were developed. CNWRA provided the worksheet evaluations to NRC staff as they were developed, and the worksheets inspired many useful and informative discussions. The appendices reproduce these worksheets in the original format provided to NRC staff, not including clarifications suggested by the NRC staff during their review and subsequent discussions, to document how staff understanding of the issues related to cover performance evolved over time. NRC clarifications and insights are folded into the discussions in the main body of the report.

Staff performed the first two site evaluations for the Highland and Church Rock sites (Appendices C and D) as the databases were being completed. Both sites feature (i) relatively extensive available documentation; (ii) relatively complete well, water level, and geochemical data provided by the licensee in Excel spreadsheets; and (iii) only moderately complex hydrological conditions. The first two aspects of the site represent particularly favorable conditions for evaluating cover performance, and the initial concept of considering the time series of geochemical observations to assess cover performance appeared particularly promising for these sites relative to other sites.

For these first two sites, staff developed independent assessments of the site conditions based to the extent possible solely on the available data. The assessments largely relied on independent graphical and relational representations to develop insights, such as time histories, contour plots, Stiff and Piper diagrams, and two- and three-dimensional animated movies. The assessments stopped short of developing numerical models, which represents a substantial effort outside the project scope.

These two sites were very useful for developing insight into processes and observations that might be expected at mill tailings sites. The Highland site features several potential seepage pathways; multiple permeable units; water level, temperature, and geochemical observations; significant information regarding geologic conditions; and a series of prior analyses considering seepage, groundwater flow, and geochemical evolution. The Church Rock site featured a similar degree of information and similar degree of site complexity.

As it turned out, addressing the straightforward worksheet questions required a surprisingly substantial effort for these two sites. Developing insight from a set of observations is necessarily an involved process, but even a short negative answer to a question required substantial work to provide a basis for the answer. For example, the straightforward answer that some piece of information is not available requires verifying that the information is not contained in any of the thousands of pages gathered for the particular site.

After performing the first two site evaluations, staff came to the tentative conclusion that the geochemical observations were not likely to provide significant insight into cover performance for these relatively promising sites. At these sites, large volumes of tailings seepage drained to groundwater in the environment outside of the tailings during the operational period (i.e., prior to cover emplacement), and expected inflows through the cover would be only a small fraction of the operational losses. Staff tentatively concluded that this prior influence would largely mask any cover signature, without a firm technical basis quantifying the conclusion.

The final NRC worksheet question, requesting a conclusion on the extent that the cover performance could be evaluated for the site, was difficult to answer definitively without further analysis.

Given the experiences with detailed and high-level site analysis, staff next considered project objectives at a high level of abstraction, as described in Section 5. Section 5 describes strategies, or overall approaches, for evaluating cover performance given the kinds of data gathered at a mill tailings site. Staff considered the data collected at the Highland and Church Rock sites as representative of typical mill tailings sites. Section 5 identifies three general strategies for identifying inflow through the cover: (i) observing a unique cover signature, (ii) observing a water or temperature signal consistent with inflow, and (iii) observing a geochemical signal consistent with inflow through the cover.

With strategies for evaluating cover performance identified, staff used the worksheet questions to consider the Split Rock site (Appendix E). Staff early identified this site as one of the three most promising sites for evaluating cover performance, because of numerous wells, extensive geochemical sampling, and uncomplicated hydrologic conditions. The Split Rock site proved less useful than anticipated, despite relatively simple hydrologic conditions, because wells adjacent to the impoundments were removed during reclamation. Long-term monitoring relies on wells that are distal from the impoundments, providing less direct information on cover characteristics. The Split Rock analysis reinforced the tentative staff conclusion that the geochemical observations typically found at a mill tailings site, which are intended for monitoring the extent that impoundment seepage has influenced the groundwater, do not provide much insight into the extent that the emplaced cover influences seepage because the releases largely occurred during and shortly after the operational period prior to cover emplacement. The final NRC worksheet question, requesting a conclusion regarding the extent that the cover performance could be evaluated for the site, again proved difficult to answer definitively.

Staff next considered tactics for implementing the cover performance evaluation strategies given constraints found at the mill tailings sites. Section 6 enumerates tactics for estimating cover performance directly from data (i.e., without using numerical simulations), and indicates what site conditions might be appropriate or inappropriate for each tactic. Section 6 suggests that the most effective tactics for addressing cover performance will rely on observation within the tailings, particularly water levels in the coarser tailings. Section 6 identifies three tactics as most effective for identifying inflow: (i) tracer applications to the cover, (ii) analysis of water level fluctuations within the tailings, and (iii) water balance calculations.

Section 6 considers when tactics are applicable, suggesting that an inflow signal stemming from natural sources is strongly attenuated as it exits the impoundment. Section 6 illustrates that geochemical signals diluting existing concentrations are much less distinctly identified than signals causing increased concentrations. This feature implies cover inflow signals may require unrealistically accurate and detailed sampling to be used for inflow calculations even within tailings, and further implies that existing geochemical observations outside an impoundment are unlikely to be of use for identifying a cover inflow signature.

Section 7 applies three tactics to the 10 sites, addressing the final NRC worksheet question for all sites. The tactics consider (i) water level and geochemical signals measured in the tailings fluids, (ii) return of water levels to pre-operation conditions, and (iii) control volume calculations to provide estimates of cover inflow. The first tactic could not be applied at any site, because no site was identified with publicly available observations suitable for examining signals in tailings fluids, although some of the sites may have observations that are not publicly available. The second tactic could be reasonably applied only at the Church Rock site. The third tactic could be applied at most sites, at least for rough bounding estimates combining cover inflow, tailings drainage, and natural recharge outside the impoundment area. The third tactic identified several sites with insufficient information to perform bounding calculations, and identified three sites where seepage mixes with such large natural fluxes passing by the impoundment that even numerous monitoring wells would not be likely to detect a cover inflow signal.

Concurrent with considering tactical approaches to evaluating cover performance, staff considered the worksheet questions for three sites: Ambrosia Lake West, Bear Creek, and Shirley Basin North (Appendices F–H). These sites were considered in less detail than the first three sites, because relatively less information is publicly available for these sites. The three Gas Hills sites were considered poorly suited to analysis with the publicly available information; no worksheet was completed for these three sites given the project resources and the perceived likelihood that worksheet questions would not provide additional insights. For similar reasons, no worksheet was completed for the Sequoyah or Grants sites.

Section 8 collects the insights gained during the project and recommendations for potential future sites. Section 8 offers suggestions for potential changes in the type and extent of data collected from licensees, and the ways that the data are collected, that may also be applicable for other facilities that provide NRC with geochemical data. Section 8 concludes that the available radon flux data suggest that the current methods for collecting radon flux provide fairly close bounds on radon flux emissions during the first years after the cover has been emplaced. Section 8 also concludes that data streams currently provided by licensees bound cover inflow at some study sites, but not all sites provide sufficient information to perform bounding analyses and some site conditions are poorly suited for performing informative bounding analyses. Section 8 identifies two tactics based on monitoring well measurements inside the tailings that promise to provide information useful for directly quantifying cover inflow across the set of sites and at potential future sites.

2 KEY SITE CHARACTERISTICS

There are 11 U.S. Nuclear Regulatory Commission (NRC)-regulated sites classified as Title II sites under the Uranium Mill Tailings Radiation Control Act (UMTRCA) Act of 1978, as amended. Seven sites are located in Wyoming:

- Site 2, Bear Creek (Anadarko)
- Site 4, Gas Hills East (UMETCO)
- Site 5, Gas Hills North/Lucky Mc (Pathfinder)
- Site 6, Gas Hills West (ANC)
- Site 8, Highland (ExxonMobil)
- Site 10, Shirley Basin North (Pathfinder)
- Site 11, Split Rock (Western Nuclear)

Three sites are located in New Mexico:

- Site 1, Ambrosia Lake West (Rio Algom)
- Site 3, Church Rock (UNC)
- Site 7, Grants (Homestake)

One site is located in Oklahoma: Site 9, Sequoyah (Sequoyah Fuels).

Two mill tailings sites managed by the U.S. Department of Energy (DOE) Office of Legacy Management are near NRC-regulated Title II sites and have similar names. These sites are mentioned to avoid confusion, but the project did not analyze these sites. The Title I Ambrosia Lake site is located approximately 2.2 km (1.4 mi) ENE of the Ambrosia Lake West site, and the Title II Shirley Basin South site is approximately 4.5 km (2.8 mi) SSW of the Shirley Basin North site. Seepage from the Ambrosia Lake site mingles with seepage from the Ambrosia Lake West site, as mentioned in Appendix F.

The Wyoming and New Mexico sites have existing interim or final tailings covers, and these 10 sites are considered further in this report. The Sequoyah site is in the process of constructing a lined cell and no cover exists at this time, thus Sequoyah (Site 9) is not analyzed further in this report. However, the Sequoyah site is much more humid than the other sites, implying that inflow for a given hypothetical cover would be expected to be substantially larger at Sequoyah than at the other sites.

Appendix A summarizes aspects of the individual sites that influence cover performance. Appendices C–H describe Sites 1, 2, 3, 8, 10, and 11 in greater detail. Note that worksheets were not developed for Sites 4–6, thus Appendix A considers aspects of cover performance in somewhat greater detail for these three sites. Tables 2-1 and 2-2 summarize site characteristics relevant to cover performance.

The 10 selected sites share certain common factors. All of the sites are located in a semiarid climate, with mean annual precipitation (MAP) between 23 to 30 cm/yr [9 and 12 in/yr] and mean annual potential evapotranspiration (PET) between 90 to 130 cm/yr [36 and 50 in/yr] {only the Shirley Basin North site has PET less than 114 cm [45 in/yr]}. With these climatic conditions, a substantial unsaturated zone existed at each site under natural conditions. The geologic setting for each site includes a combination of alluvium and sedimentary bedrock units (the Split Rock site, the only site directly underlain by igneous rock, includes granite underlying the sedimentary unit). Most sites dam a natural draw, wash, or other ephemeral drainage to provide a local depression for the tailings impoundments and other ponds. Most impoundments and ponds at the sites were placed directly on alluvium or bedrock without a liner. A clay liner was used for the tailings impoundments at Gas Hills East, a compacted soil liner was used at the Bear Creek site, and two of the ponds at the Ambrosia Lake West site were lined. The impoundment system at Gas Hills North/Lucky Mc was constructed on low-permeability shale.

All of the sites have experienced releases or seepage. Without corrective measures, contaminant plumes within alluvium tend to move down the bedrock surface, and within sandstone units the plumes tend to move in the bedding dip direction. During operations, seepage formed recharge mounds in some locations (e.g., Church Rock, Highland), thereby inducing radial flow under an impoundment. After operations ceased, decay of the recharge mound induced decay of radial flow. In some cases, seepage from evaporation or solution ponds has also produced a contaminant plume. Several sites (Bear Creek, Church Rock, Gas Hills East, Grants, Highland, and Split Rock) developed multiple plumes, usually in different units and moving in different directions.

Seepage from several of the sites is or has been influenced by perturbations to the hydrologic system from onsite or offsite mining activities, such as (i) mine dewatering (Ambrosia Lake West, Church Rock, Gas Hills North/Lucky Mc, and Highland), (ii) permanent modification of the hydrologic system (Highland), or (iii) in situ recovery pumping (Highland). A groundwater corrective action program (CAP) or earlier remediation equivalent has been applied at each site to limit seepage or reduce the extent of contamination; some programs have been terminated and some continue at present. One site (Ambrosia Lake West) is influenced by a contaminant plume from an offsite facility.

The amount of observational data describing the sites varies widely, as does the style of reporting. Provided data are available (i) electronically, (ii) in tables, (iii) as laboratory sample sheets, or (iv) graphically. The number of monitoring wells ranges over two orders of magnitude, from 5 (Gas Hills North/Lucky Mc) to 530 (Grants). License conditions do not require water table elevations, and at some sites water table elevations are not provided or are only provided graphically. The reported geochemical constituents vary widely from site to site, ranging from just the particular constituents required by licensing through a comprehensive suite of geochemical observations. License conditions do not explicitly require provision of borehole locations and screened intervals; for some sites, borehole information was not provided or is not available in ADAMS.

One round of radon emission testing is required upon completion of the final tailings cover. Radon emissions have been annually sampled since 2003 at the Grants site, which is near several housing communities. The Grants site is the only site with multiple rounds of radon emission sampling, and is the only site monitoring atmospheric radon.

Table 2-1. Status of Site Reclamation, Cover Emplacement, and Radon Emission Surveys.

Title II Site Designation	Tailing Pond or Cell		RECLAMATION and COVER STATUS: Operation Dates	Decommission & Reclamation Dates	Cover Construction Dates	Final Cover	Partial or Interim	None	Radon Barrier	Underlying Material	Drained?	Notes	RADON FLUX SURVEY STATUS: Performed	Dates	Notes
1 - Ambrosia Lake West (Rio Algom), NM	Pond	1	1958-1985	1989-	mid-1990's	Y			Y	alluvium	?	Used for solid tailings	N	N/A	No Rn flux survey
	Pond	2					P		Y	alluvium	?	Used for solid tailings	N	N/A	Rn flux survey conducted on yearly basis (?, results not available)
	Pond	3			Inc.		P		N	alluvium	?	Decant and seepage collection pond. Rock cover over wind-blown and clean soil	N	N/A	No Rn flux survey
	Pond	4						N		alluvium	?	Evaporation pond (Liquids from 1 and 2). Needs soil and rock covers	N	N/A	No Rn flux survey
	Pond	5						N		alluvium	?	Evaporation pond (Liquids from 1 and 2). Needs soil and rock covers	N	N/A	No Rn flux survey
	Pond	6						N		alluvium	?	Evaporation pond (Liquids from 1 and 2). Needs soil and rock covers	N	N/A	No Rn flux survey
	Pond	7					P		N	alluvium, SS	?	Evaporation pond (Liquids from 1 and 2). Soil cover only, need rock cover	N	N/A	No Rn flux survey
	Pond	8					P		N	alluvium, SS	?	Evaporation pond (Liquids from 1 and 2). Soil cover only, need rock cover	N	N/A	No Rn flux survey
	Pond	9				?	?	?		alluvium	?	Evaporation pond (Liquids from 1 and 2) Little info. available	N	N/A	No Rn flux survey
	Pond	10			mid-1990's	Y			N	alluvium	?	Evaporation pond (Liquids from 1 and 2). Materials moved to pond 2. Only backfilled	N	N/A	No Rn flux survey
	Ponds	11 to 19						N			?	Evaporation ponds located in Section 4. (Received liquids from a nearby Rio Algom's mill). Sediments moved to pond 2	N	N/A	No Rn flux survey
2 - Bear Creek (Anadarko), WY	Tailings Impoundment	1	1977-1986	1987-2000	1997-1998	Y			Y	compacted soil, thin alluvium, SS	Y?		Y	1997-1998	Survey done in 2 separate events, 1 year apart

Table 2-1. Status of Site Reclamation, Cover Emplacement, and Radon Emission Surveys

Title II Site Designation	Tailing Pond or Cell		RECLAMATION and COVER STATUS										RADON FLUX SURVEY STATUS		
			Operation Dates	Decommission & Reclamation Dates	Cover Construction Dates	Final Cover	Partial or Interim	None	Radon Barrier	Underlying Material	Drained?	Notes	Performed	Dates	Notes
3 - Church Rock (UNC), NM	Cell	South	1977-1982	1987-1996	1996		P		Y	alluvium, SS	Y?	Two 17-acres total lined evaporation ponds within that cell to receive final cover by 2014	Y	1996	Reports do not specify on which cells the sampling points were located
	Cell	Central			1996	Y			Y	alluvium, SS	Y?		Y	1996	
	Cell	North			1996	Y			Y	alluvium, SS	Y?		Y	1996	
4 - Gas Hills East (Umetco), WY	Gas Hills Pond 2	GHP-2	1954-1984	1987-2006	2006	Y			Y		Y?	Was a lined evaporation pond	Y	2006	Sampling points locations mapped for each pond area
	Above Grade Tailings Impoundment	AGTI			2002	Y			Y	clay liner	N?	Overall site reclamation completed in 2006	Y	2000	
	Heap Leach Area				2002	Y			Y	clay liner	N?	Overall site reclamation completed in 2006	Y	1999	
	C-18 pit				2006	Y			N		N?	Former pit mine backfilled with soil only	Y	2006	
	A-9 Repository				2006	Y			Y	clay liner	N?	Former pit mine, was lined	Y	2003	
5 - Gas Hills North/Lucky Mc (Pathfinder), WY	Tailing Pond	1	1958-1988	1993-2004	2004	Y			Y	shale	N?	Tailings disposal	Y	1998-2002	Reports and data do not indicate at which ponds the sampling points were located
	Tailing Pond	2				Y			Y	shale	N?		Y		
	Tailing Pond	2A				Y			Y	shale	N?		Y		
	Waste water pond	3				Y			Y	shale	N?	Wastewater disposal	Y		
	Waste water pond	3A				Y			Y	shale	N?		Y		
	Wastewater and Evaporation Pond	4			2005	Y			Y	shale	N?	Next to TP4. Received groundwater. Completed in 2005	Y	2004-2005	
6 - Gas Hills West (ANC), WY	Tailing Pond	1	1960-1982	1988-1997	1997		I		N	silty sands	N?	Allowing for settlement before contructing a final cover	N	N/A	No Rn flux survey, final cover not constructed
	Tailing Pond	2			1997	Y			Y	silty sands, clay	N?	No construction report available	Y	1997	

Table 2-1 Status of Site Reclamation, Cover Emplacement, and Radon Emission Surveys (continued)

Title II Site Designation	Tailing Pond or Cell		RECLAMATION and COVER STATUS: Operation Dates	Decommission & Reclamation Dates	Cover Construction Dates	Final Cover	Partial or Interim	None	Radon Barrier	Underlying Material	Drained?	Notes	RADON FLUX SURVEY STATUS: Performed	Dates	Notes
7 - Grants (Homestake), NM	Tailing Pile	LTP	1958-1990	1993-2017 (?)	1994-1995		I		P	alluvium	N	Several lined evaporations ponds on and near the 2 piles. Final cover of the 2 piles expected by 2017 while groundwater CAP is active	Y	1995, 2003+	Annual surveys starting in 2003 as part of a request for license amendment extension
	Tailing Pile	STP			1994-1995		I			alluvium	<4 ft est		Y		
8 - Highland (Exxon), WY	Tailings Impoundment (or basin)		1970-1984	1984	2000-2001	Y			Y	shale, SS	Y	Single solid tailings impoundment	Y	2002	
9 - Sequoyah (Sequoyah Fuels), OK	Disposal Cell		1970-1993	1993-	Inc.			N				Phase I of the disposal cell construction started in 2009. Completion expected in 2012	N	N/A	No Rn flux survey
10 - Shirley Basin North (Pathfinder), WY	Pond	3	1971-1992	1992-	N/A			N				Active wastewater pond for disposal of 11e.(2) byproduct material from off-site sources	N	N/A	No Rn flux survey
	Pond	4			2008	Y			Y	claystone, sandy clay	N	Solid tailings impoundment	Y	2006	Sampling points locations mapped for each pond area
	Pond	5			2008-2009	Y			Y	claystone, sandy clay	N	Solid tailings impoundment. Cover completed in 2009 for two related evaporation ponds near Pond 5	Y	2006	
11 - Split Rock (Western Nuclear), WY	Old tailings area		1957-1981	1998	1998	Y			Y	sand, SS	N	Solid tailings impoundments	Y	1998	
	Alternate tailings area					Y			Y	sand, SS	Y		Y	1998	
	New tailings area					Y			Y	sand, SS	Y		Y	1998	
	Evaporation Pond	1		2006	2007	Y			Y	sand, SS		Lined pond for groundwater CAP (Cover for minimizing water infiltration, not for radon emission)	N	N/A	Rn flux survey not needed
	Evaporation Pond	2				Y			Y	sand, SS		Lined pond for groundwater CAP (Cover for minimizing water infiltration, not for radon emission)	N	N/A	Rn flux survey not needed
					Totals →	25 40	8	6	25				24		

Table 2-2. Site Groundwater Impacts

Title II Site Designation	Aquifer(s)	Depth to Aquifer (ft)	Precipitation (in/yr)	Temperature (F)	Potential ET (in/yr)	Plume(s) of Impacted Groundwater	GW CAP*	GW Standards **	Notes
1 - Ambrosia Lake West (Rio Algom), NM	Alluvium Dakota TRA TRB	150 (est.)	11.1	48.7	50 (est.)	1. Alluvial aquifer 2. TRB	Y	ACLs since 2006	
2 - Bear Creek (Anadarko), WY	Upper alluvial Clay/siltstone	50 (?)	12.5	44.6	45 (est.)	1. Lang Draw 2. North flow path	Y	ACLs in 1997	Deemed impractical to remediate
3 - Church Rock (UNC), NM	SW Alluvial Zone 1 (Upper Gallup Lower Sandstone) Zone 3 (Upper Gallup Upper Sandstone)	60 (est.)	13.7	48.6	50 (est.)	1. SW Alluvium 2. Zone 1 3. Zone 3	Y end by 2013	MCLs	An EPA NPL since 1983
4 - Gas Hills East (Umetco), WY	2 permeable units of the Wind River Formation	100-150	10.1	42.1	46 (lake)	1. W flow regime, plume extends to the NW 2. SW flow regime, plume extends to the S	1983-2002	N	
5 - Gas Hills North/Lucky Mc (Pathfinder), WY	Lucky MC aquifer (only about 45 ft thick at the site); combines Fraser Draw alluvial aquifer (up to 65 ft thick) and the Wind River Formation aquifer (up to 800 ft thick)	100-150 (est.)	9.5	43.3	46 (lake)	1. N of pond 4 discharging toward Reid Draw 2. NE and E of ponds discharging to Fraser Draw	1980-2002	ACLs in 2002	Major P&T and reinjection system, with 28 pumping wells and 17 injection wells. Cleanup goals were not achieved and modeling suggested they were not practical to achieve
6 - Gas Hills West (ANC), WY	Alluvial Underlying weathered bedrock	100-150 (est.)	9.6	43.2	46 (lake)	1: Gas Hills Draw area	Y	Back-ground	
7 - Grants (Homestake), NM	Alluvial Chinle Formation San Andres	25-50 (est.)	11.0	50.2	50 (est.)	1. Shallow aquifer (since 1975) 2. Chinle aquifer	1977-	ACLs	Also an EPA NPL site. Major ongoing P&T and reinjection remediation system. CAP revision for 2011
8 - Highland (Exxon), WY	Alluvial Tailings Dam Sandstone Ore Sand	110 (est.)	9.1	43.0	45 (pan)	1. Radial plume in TDSS, SE alluvium, Ore Sand	1984-	ACLs	
9 - Sequoyah (Sequoyah Fuels), OK	Alluvial aquifer	100 (est.)	46.3	61.2	48 (est.)	1. Alluvial aquifer	Y	MCLs	Spills and leaks from past operations, remediated via recovery trenches
10 - Shirley Basin North (Pathfinder), WY	Alluvial aquifer White River (confined)	60 (est.)	12.7	38.8	47 (est.)	1. Alluvial aquifer, E of pond 5	1984-2005	ACLs since 2005	Unconfined portion of alluvial aquifer discharges to Spring Creek
11 - Split Rock (Western Nuclear), WY	Sweetwater River alluvial aquifer Split Rock aquifer	5-50	10.9	41.4	36	1. NW valley 2. SW valley	1990-2006	ACLs 2005-06, revi-sed in 2010	Groundwater was extracted from the NW and SW valleys into the 2 lined ponds

* : Groundwater Corrective Action Program
** : Groundwater Standards applicable to individual site (ACLs, Background, MCLs or N/A)

3 DESIGN AND CONTENT OF THE TITLE II SITE DATABASES

The water quality and radon flux data sources are a mix of electronic spreadsheets, scanned or electronic documents, and paper documents. The quantity and breadth of data differs widely across the set of eleven sites. In some cases, long and detailed water quality histories are available as electronic spreadsheet files, provided by the licensee in more detail than required by the terms of the license. In other cases, the available data are limited to scanned Portable Document Format (pdf) files, publicly available in ADAMS, containing semiannual or annual reports limited to precisely the constituents spelled out by the terms of the license. Document quality ranged from barely legible to immaculate, largely dependent on the age of the document.

In order to effectively work with this disparate set of data, two Microsoft® (MS) Access® databases were developed in the first year of the project, one containing the available groundwater quality observations and one containing radon flux observations. More than 814,000 groundwater quality observations are included in the groundwater database, with the total for each site ranging from 408 to 511,000 observations. The radon database consists of 1,910 flux observations from nine sites. Much of the database was compiled by transforming electronic files into the appropriate format, but some of the scanned images were of such poor quality that manual retyping was required to populate the database.

Following Access principles, both databases consist of several linked tables. The groundwater database is necessarily more detailed than the radon database because more types of information are included in the database. The two databases are described briefly in the following sections.

3.1 Database Design Approach and Limitations

At the outset of the project, the databases were intended to be used to supply data primarily for analyzing time series of geochemical observations at selected wells. The particular wells were not defined *a priori*; rather, they were to be selected from graphs and figures during the second year of the project. With this goal, database design focused on populating the geochemical database with ready extraction of data for particular sites or wells. Provision was made to identify wells according to geologic unit as well.

Once the data were assembled into the database and particular sites began to be examined, two limitations to the database format became evident. Because the wells of interest were to be selected using publicly available documents, and the analyses were anticipated to primarily rely on geochemical time series, water level data were not considered and no effort was made to describe well characteristics in detail. In hindsight, water levels and geospatial information are important, even vital, for many types of analysis. With water levels and geospatial coordinates, it is possible to construct figures identifying how flow changes over time. Without this information, analyses rely on interpretations in publicly available documents. Several analyses in this report use water level and geospatial information that is not included in the electronic database. It may be desirable to add this information into the database in future work.

3.2 Radon Database

The radon database consists of three tables:

- tblSites: a table listing features of the 11 sites
- tblRepositories: a table listing the covered impoundments found at the sites
- tblResults: a table listing flux observations

The three tables are linked, assuring that each flux observation is linked to a valid cover and each cover is linked to a valid site.

The table describing each flux observation contains one row for each observation. Each row contains a column for several key pieces of information, such as the repository, location within the repository, relevant dates, licensee identification numbers, calculated fluxes, detection limits, and the ADAMS accession number for the document containing the flux information.

The database does not contain the coordinates for the flux measurements. Measurement coordinates are typically not contained in the publicly available documents, although sometimes figures are provided graphically displaying the measurement locations.

3.3 Geochemical Database

The geochemical database consists of six tables:

- tblSites: a table listing features of the 11 sites
- tblZones: a table listing zones (formations) found at the sites
- tblLocations: a table listing sample locations (wells, streams, and lakes)
- tblAnalytes: a table describing each type of observation found at any site
- tblUnits: a table listing units (e.g., mg/L)
- tblResults: a table listing geochemical observations

As with the radon database, the geochemical database links information between tables and ensures that links between tables are valid. And as with the radon database, the tblResults table lists one geochemical observation per row. Unlike the radon observations, a complete sample contains several geochemical observations; therefore, dozens of rows may be necessary in the geochemical database to completely describe a single water sample.

The tblAnalytes table keeps track of the different kinds of observations, the tblUnits table enforces unit consistency among observations, and the tblLocations table describes measurement points. These tables are tacitly included in the radon database as part of the tblResults table: only one type of observation is included in the database, all observations have the same units, and each observation occurs at a unique location. Separate tables are important for ensuring relational consistency in the geochemistry database but would be redundant for the radon database.

The tblZones table is roughly analogous to the radon tblRepositories table, except that geologic formations are described rather than particular impoundment covers.

3.4 Extracting Information From a Database

MS Access provides a number of options for interactively exploring data. These options readily permit screening the database based on one or several database components, and interactive exploration may be the most effective means for extracting limited data.

Powerful extraction capability is available for larger data exports as well. MS Access uses a query function to extract information from the database, and readily stores the query in a MS Excel® file. The query function is a powerful and flexible means for formatting data, even linked across several tables. In general, a user will create a special query to extract data in a desired format, perhaps for a specific site, formation, or chemical. The results of the query look and act like one of the data tables, thus query results can be interactively explored just like data tables.

Several example queries are provided with the databases. Extracting the query to an Excel file requires two separate steps: first running the query to create the results table, then exporting the query results to the Excel file.

4 RADON SURVEYS

Licensees are required to perform a radon flux survey upon completion of a tailings cover. The radon survey typically considers at least 100 locations distributed across the tailings cover. Sampling at each location is performed by placing a canister containing activated carbon on the ground surface for at least 24 hours, removing the canister, and counting emissions using gamma-ray spectroscopy. A formula [U.S. Environmental Protection Agency (EPA) Method 115] accounts for the decay of radon over time, background radon, and detector efficiency to estimate radon flux at the canister location. Radon flux through the tailings cover is estimated using an area-weighted average flux across all of the canisters.

The set of calculated radon fluxes for nine sites were compiled into an MS Access database. Individual sites include 37 (Bear Creek) to 757 (Grants) flux values. No radon measurements were identified in the publicly available ADAMS documents for the Ambrosia Lake West site. The Sequoyah site has no tailings cover and therefore has no radon measurements.

At most of the sites, a one-time radon survey was performed. At the Grants site, radon surveys are performed approximately annually on both tailings piles, and semiannual averages of atmospheric radon are monitored at eight locations in and near the site. Because of the additional information available from the time series at the Grants site, the project focused on examining the radon flux values from the Grants site.

4.1 Grants Tailings Radon Flux Database Manipulations

The radon flux survey at Grants is performed approximately annually, with sampling dates between June and October. Each survey is performed at specific locations, described with identifiers called waypoints, and one or more canisters are placed at each waypoint. Waypoints appear to be at relatively unchanged locations from year to year, as best as can be seen from the figures. Canisters are “randomly” assigned to waypoints each year. Typically, the tables report flux by canister (not waypoint). There is generally enough information provided to link waypoints with canisters, in the form of handwritten or typed tables and sketches. The initial document included columns for both waypoints and canisters, but most years the canister identification was not recorded in the database.

The initial report supplies coordinates for 49 locations in a table. Other pages in the table are missing from the scanned document and may have been incorrectly scanned. The annual reports provide a sketch with waypoint locations; some years both waypoint and canister numbers are plotted, some years just waypoints. In 2003–2007, the sketch only generally indicated a background image. In 2008, the locations were superimposed on a fuzzy satellite image, and in 2009 the locations were superimposed on a clearer but muted satellite image. Figure 4-1 shows the image for 2009.

Canister coordinates are necessary for plotting the canister locations on the tailings cover, which is useful for examining spatial patterns and flux persistence. Representative coordinates were estimated by digitizing the set of maps. To digitize representative coordinates for the waypoints, each sketch was extracted and superimposed on a Google Earth image that includes four benchmarks with known latitude and longitude. Each sketch was scaled and shifted so that the waypoint pattern generally lined up. It appears that the same locations may have been used from year to year except that some edge locations in the large tailings pile were adjusted.

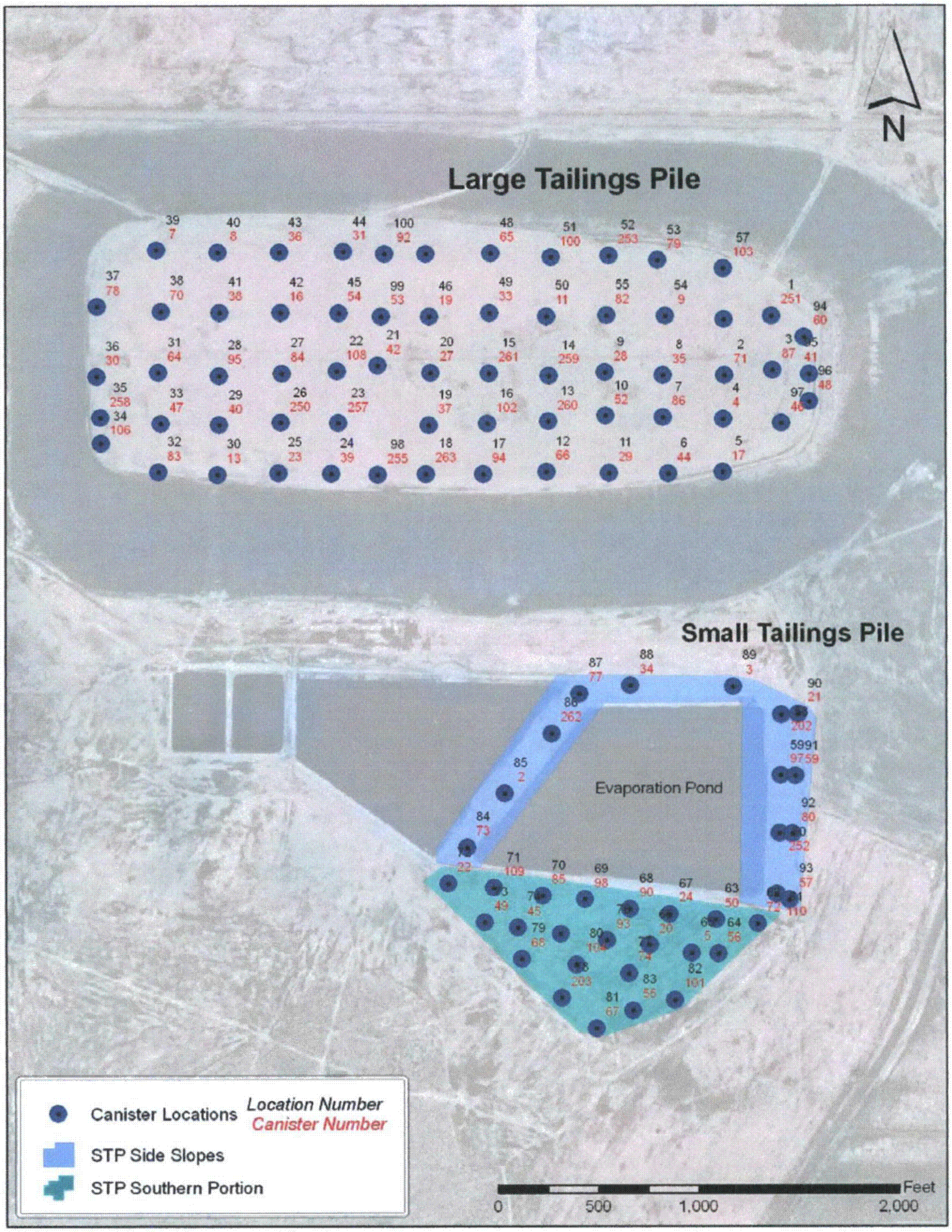

Figure 4-1. Locations of Radon Sampling Points (Homestake, 2010, Appendix F, Figure 2-1)

Cross checks of the sketches reveal

- Locations for 2003 and 2004 match precisely
- The numbering scheme changed in 2005 and remained generally consistent afterwards
- Locations for 2004 and 2005 largely match, with several edge locations moved
- Locations for 2005, 2006 and 2007 match
- Locations for 2007 and 2008 generally match
  - 2007 location 31 was moved
  - 2008 locations 98, 99, 100 new
- Locations for 2008 and 2009 match

The values of the fluxes contained in the database were double-checked by independently extracting the data from the Portable Document Format (pdf) reports and correlating them with the database values. The data sheets were cut and pasted from an optical-character-recognition-filtered version of the pdf table for all years except 2008 (which has a poor image quality). The process revealed 4 flux typos in the database and a typo in the original data report. The process also revealed inconsistencies between reported location and canister numbers. Figure 4-2 shows the reported values for each location, superimposed on cumulative precipitation for each water year.

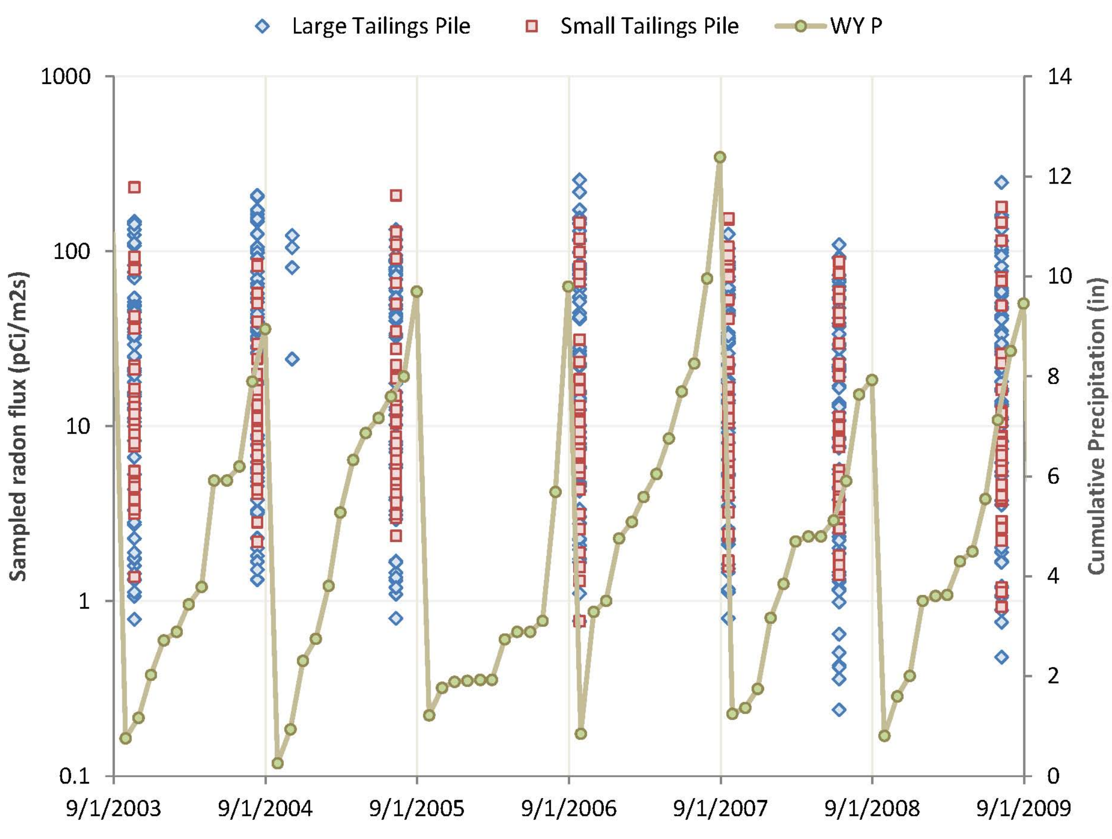

Figure 4-2. Reported Radon Fluxes Superimposed on Cumulative Water Year Precipitation

Both field duplicates and lab replicates are reported. Field duplicates are locations with two canisters emplaced next to each other. Laboratory duplicates represent independent emission counts using the same container. In 2003 and 2004, two field replicates were reported with different location numbers and different canister numbers; one of the two canisters is used to represent the location flux. In later years, field replicates are reported with the same location number but different canister numbers. Laboratory duplicates are reported using a separate subscript attached to the canister number. In some years, the first (more accurate) reading is tabulated; in other years, the average of the two readings is reported.

In order to resolve some typographic inconsistencies in the reported values, calculation checks were made using the supplied data sheets. The detailed appendix tables provide all information required to calculate the fluxes using the cited formula except for the canister area, which appears in the denominator of the formula. In 2003, comparing the reported values with a newly calculated value uniformly provides an implied canister diameter of 25 cm [10 in]. This canister diameter is consistent with an undated powerpoint presentation by Kenneth Baker and Alan Cox reporting radon flux estimates from evaporation pond 1, and is consistent with the cited EPA protocol. An email[1] confirms that the canister diameter is 25 cm [10 in] and the same canisters have been used since 2003.

Based on the calculation check:

- The same check on the implied canister area gives a variety of canister diameters ranging from 15 to 25 cm [6 to 10 in] (apparently sampled from a uniform random distribution) in all later years. Because the same canisters are used from year to year, there may be an ongoing systemic calculation or reporting error. Using the 25 cm [10 in] diameter consistently reduces calculated fluxes compared to the tabulated fluxes; average reported values are larger than the newly calculated values by 54, 54, 39, 27, and 51 percent in 2004, 2005, 2006, 2007, and 2009, respectively.

- Canister 16 (2003) appears to have a typo for reported flux in the Appendix table.

- In 2003, the background counts in the first 12 rows (canisters 34 through 40) have a negative background count (using the absolute value reduces calculated flux). It is not clear what would cause this. Calculated values drop by 25 percent using the absolute value instead.

Although the calculation check revealed inconsistencies, smaller fluxes are calculated using the corrected information. Accordingly, the inconsistencies do not appear to pose a public health issue.

4.2 Grants Tailings Cover Flux Calculations

Staff considered two questions using the Grants time series: (i) Is there some obvious correlation between antecedent rainfall and calculated radon flux? (ii) Do the spatial patterns vary over time?

[1]Cox, A. "Canister Diameter Information." E-mail (October 21) to K. Baker, U.S. Nuclear Regulatory Commission. Grants, New Meaxico: Homestake Mining Company of California. 2011.

Figure 4-2 illustrates the time series of reported tailings cover fluxes superimposed on the cumulative monthly precipitation at the nearby Grants airport COOP weather station. The observations suggest year-to-year variability is small relative to the variability among the observations within a year. Figure 4-2 hints that slightly larger fluxes may be associated with wet periods and slightly smaller fluxes may be associated with dry periods.

The sampling strategy maintained some of the canisters in the same location year after year, but other canister locations shifted over time. In light of the large variability in fluxes among the set of canisters, only the canisters in Figure 4-2 with approximately the same location in all seven sampling years are considered further. The publicly available documents were not clear whether the same physical locations were sampled each time, but presumably the sample locations plotted at similar locations in the figures are closely adjacent. By restricting the set of canisters in this way, both local sampling (placement) variability and systematic changes by year can be examined.

Each large circle in Figure 4-3 represents the radon flux for one canister location, averaged over the seven replicates. The locations are sorted by the mean flux across the seven samples. The jagged line left of the circles represents the log-average radon flux for each canister. The jagged line deviates further from the circles as the variability from year to year increases.

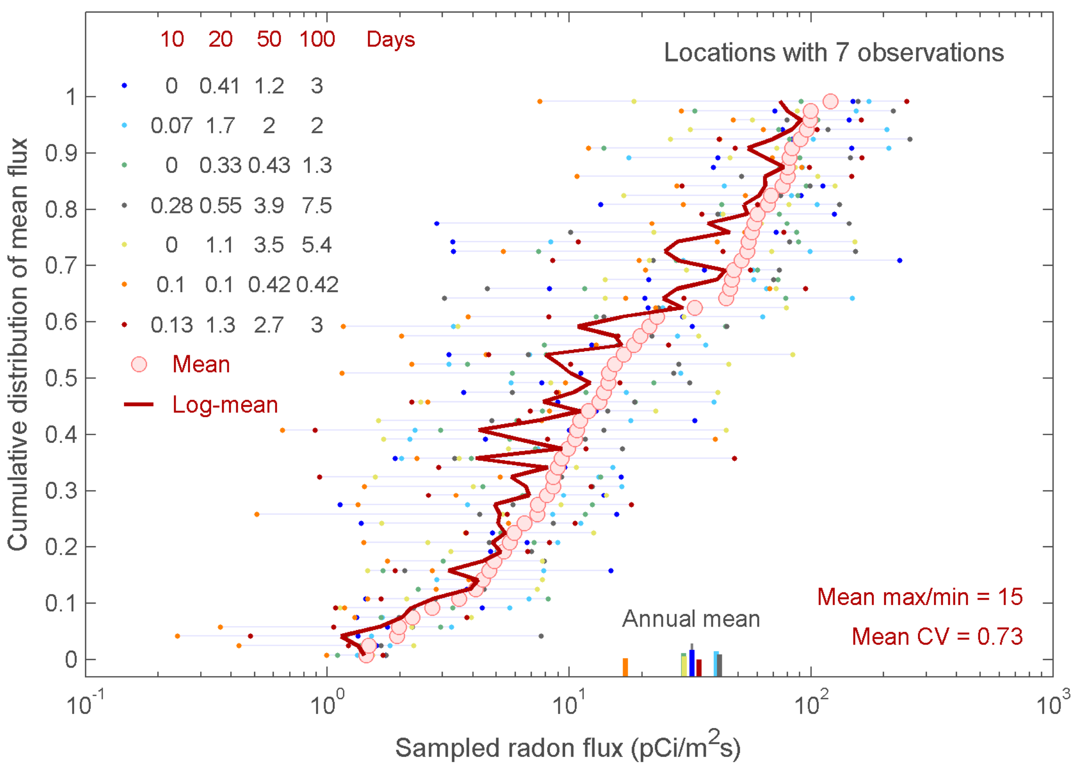

Figure 4-3. Reported Radon Fluxes at All Locations With Seven Replicates. Tabulated Values Are Precipitation in Inches for the Preceding Days at the Grants Airport COOP Station. Rows Correspond to Years From 2003 to 2009. The Annual Mean Is the Average Over All Canisters for Each Year.

The small colored symbols represent flux values from each year. The upper left corner tabulates the average precipitation at the COOP station at the Grants airport in the 10, 20, 50, and 100 days prior to sampling, with the rows representing years 2003 through 2009 in sequence. None of the sampled days experienced precipitation in the prior 3 days, and only 1 sampled day experienced precipitation in the prior 5 days. Sampling typically occurred in late summer or early fall, when local thunderstorms are common. The precipitation totals at the tailings likely differed somewhat from the COOP values, but general trends are likely similar because the airport is only 9 km [6 mi] from the large tailings pile.

There is considerable scatter in measured radon flux from year to year at each location, with the largest flux at a location 15 times larger than the smallest flux on average. The average coefficient of variation is 0.73, also indicating considerable variability. Even with this variability, the spatial patterns of sampled flux are relatively persistent from year to year; high-flux areas tend to be high-flux locations every year, and low-flux areas tend to remain low-flux areas every year.

The average flux across all canisters varies from year to year, with the largest average flux 2.4 times larger than the smallest average flux. This variability is much smaller than the year-to-year variability at each location. Although this may simply be an artifact of variability, there appears to be a small but systematic effect that stems from preceding rainfall. The mean flux for each year falls into one of three clusters: low, medium and high. The low cluster has one value (2008), the high cluster has two values (2004 and 2006), and the other four years fall in the medium cluster. The 2008 sampling followed an extended dry period, and the 2006 sampling followed a particularly wet period. Larger fluxes appear to be associated with larger precipitation in the previous 20 to 50 days, which is long compared to the radon half-life of 3 days.

The logarithm of flux arguably represents flux variability better than untransformed flux. Using the logarithm of flux to estimate central tendencies from year to year yielded an essentially identical clustering (the same clusters were identified, with similar separations, but the order of years in the middle cluster changed).

A systematic increase in flux with larger preceding rainfall is counter intuitive, because the gas-phase diffusion coefficient within a porous medium should decrease as the moisture content increases. Radon releases are generally thought to occur in the form of gas-phase diffusion, augmented by barometric pumping. Increased releases may have several explanations:

- Sampling may be systematically influenced by a very dry soil. Perhaps the contact between the canister and the soil deteriorates with dry soil, or wind through the soil may provide an advective gas pathway that bypasses the canister.

- A rainfall event induces advective transport for gas that more than counterbalances the decrease in porous medium diffusion. In the days after a substantial event, an advancing wetting front may pressurize the tailings and force radon-laced air through the cover. This would be most expected in the few days following an event, but cannot be tested with this dataset because sampling took place at least 5 days after precipitation in almost every instance. It seems odd that a wetting front would still be influencing gas pressures weeks after significant precipitation in this hot climate, as implied by the dataset.

- A rainfall event increases the cover's bulk diffusion coefficient. Even though the vapor-phase effective diffusion coefficient for a porous medium decreases when the moisture content increases and blocks air passages, perhaps the drying process forms discrete features such as desiccation cracks that increase the bulk diffusion coefficient. Such features may develop during the drying process then heal as the grains further dry, lose cohesion, and collapse into the feature.

- A rainfall event indirectly stimulates biological activity that increases the vapor pressure within the cover, again inducing advective transport to relieve the excess pressure.

- Moisture changes at the top of the tailings may have influenced radon gas production. Dry conditions inhibit production of the radon gas phase in a porous medium, because emitted particles preferentially embed in the solid media unless captured by a water film. Sun and Furbish (1995, Figure 7) provide numerical results suggesting that gas-phase emissions decrease roughly linearly with moisture content below a threshold on the order of 30 to 40 percent of saturation.

- Seasonal changes in texture may increase the diffusion coefficient. These changes may be confounded with precipitation in the limited record.

- Operations at the site may have influenced the cover or tailings. Regrading or other surface operations could influence cover properties. Injection and extraction from the tailings is ongoing as part of the reclamation; the low fluxes in 2008 may have stemmed from some unusual reclamation condition.

As a practical matter, the observed systematic changes in flux associated with precipitation are small relative to the spatial variability across the site, and the temporal variability at each location. None of the estimated fluxes across the set of canisters for a single year varied from the average across all seven years by as much as a factor of two. The results suggest that flux tests obtained during an extended dry period may under-represent the average flux under more typical years, but this effect is likely to be of practical significance only when an estimated flux is within a factor of two of a regulatory limit.

Further field testing of this effect would need to consider the large temporal variability exhibited at each location. Presumably much of the variability arises because the canisters are in slightly different locations each year. As a practical matter, a large number of canisters are required to sense the relatively small systematic changes in flux. Further, precisely locating the canisters in each replicate would provide information regarding local spatial variability. If the canisters are precisely located and the variability is greatly reduced, the implication is that significant local spatial variability exists. If the variability persists, the implication is that significant temporal variability exists at a given location, presumably due to either meteorological factors or due to processes within the cover.

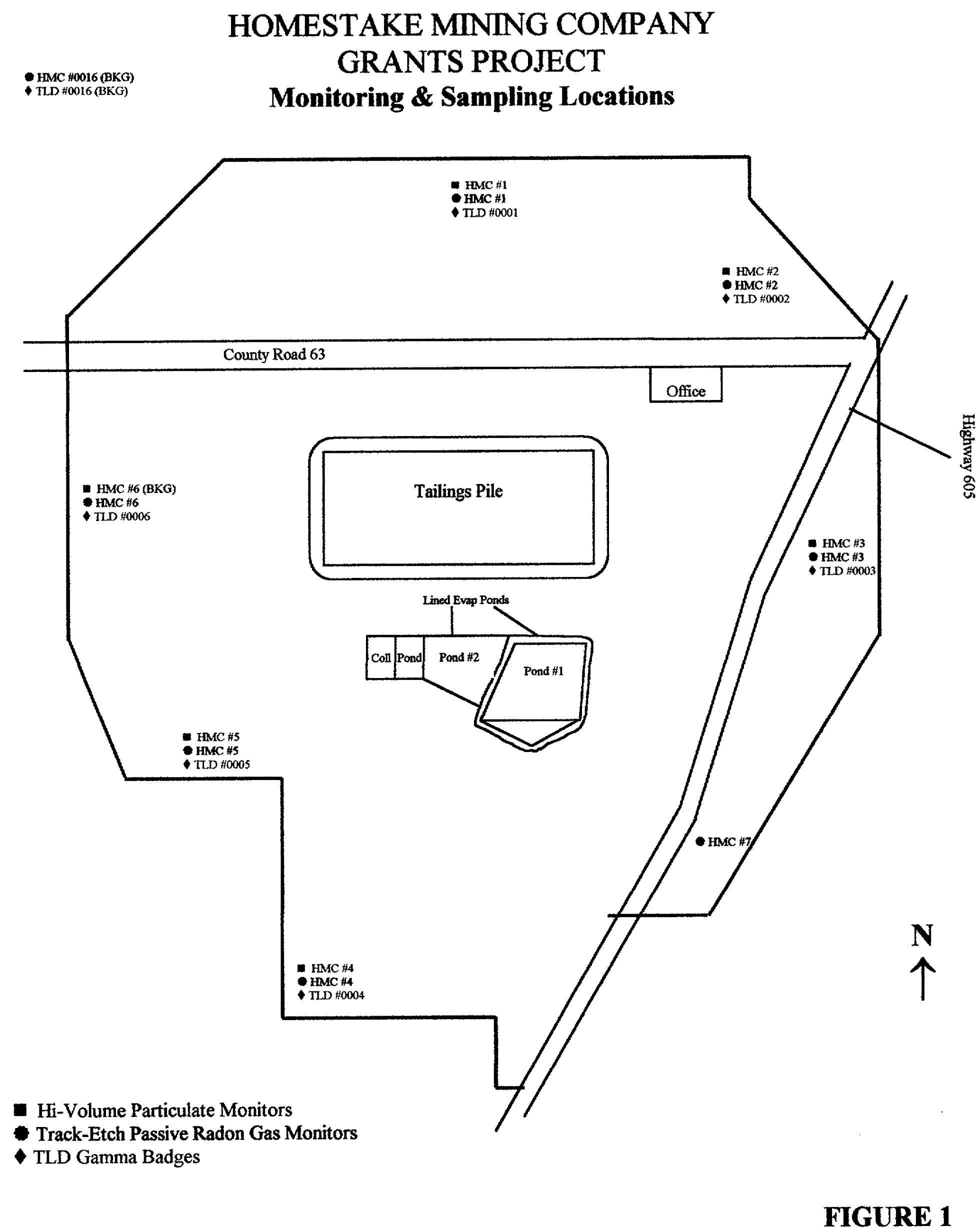

Figure 4-4. Air Sampling Locations (From Homestake, 2001, Figure 1). Prevailing Winds are NW, W, or SE According to Season.

4.3 Grants Atmospheric Radon Sampling

Eight locations for atmospheric radon sampling are maintained at the Grants site (Figure 4-4). The background station is HM-16, located offsite to the northwest. Seven closer sites (HM-1 through HM-7) surround the tailings piles. Sampling is conducted on a semiannual basis, and consists of placing alpha-particle sensors at selected locations to accumulate imprint tracks over six months. The imprint tracks are counted in the lab after removal from the field. Reported values are shown in Figure 4-5.

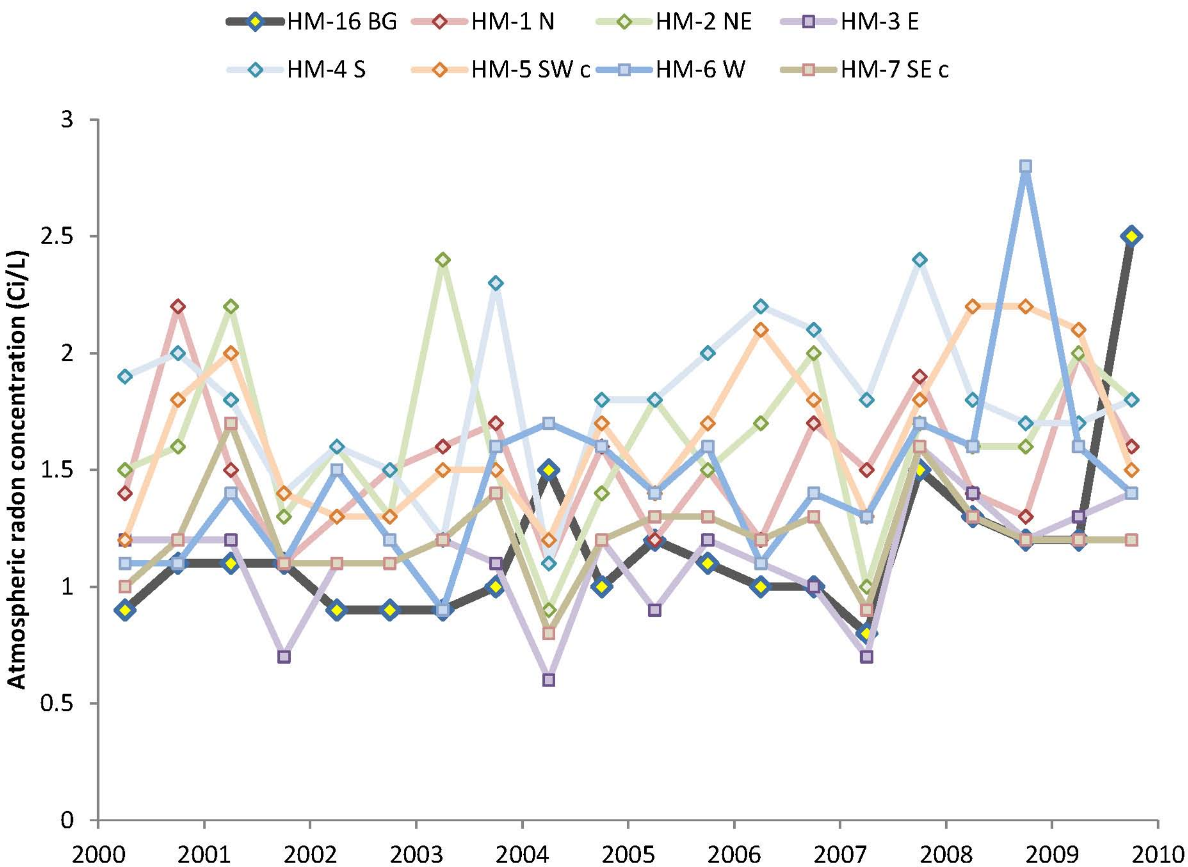

Figure 4-5. Semiannual Average Atmospheric Concentrations. Directions Relative to the Tailings Are Indicated by the Letters Following the Site Number.

Prevailing wind direction at Grants Airport {9 km [6 mi] SSW of the site} is NW from September through March, W from April to June, and SE in July and August. The airport is within a constricted valley oriented generally NW to SE. The site is in a more open portion of the valley, and perhaps prevailing winds deflect to a more N-S axis based on the general valley topography. The background reading is among the lowest values 18 of the 20 reported periods.

The E and SE locations consistently have nearly background values. The S, SW, and NE locations consistently have relatively high concentrations. These trends are interesting because the lower concentrations are generally downwind and the higher concentrations are generally upwind. Two large center-pivot irrigation fields lie 3 km [2 mi] W and 4 km [3 mi] SW of the large tailings pile. Perhaps there may be some irrigation effect that releases radon.

Concentrations tend to be slightly larger in the second semiannual period, ranging from −6 to 15 percent larger. The average second-period concentration is 8 percent larger than the average first-period concentration. These trends may not be meaningful with the large scatter from period to period, but are loosely in accord with the tendency for larger estimated fluxes in samples obtained later in the year noted for the canister sampling.

Some of the periods exhibit increases or decreases in most or all of the sampling locations, implying that there may be some systematic influence on observations, but usually at least one location varies separately from the group. Scatterplots (not shown) of semiannual average precipitation and semiannual average concentration did not suggest any noticeable correlation between measured rainfall and concentration. There may be a slight systematic increasing trend in average atmospheric radon concentration over the sampling period; a linear trendline fit to the average concentration across all sites increased from 1.28 to 1.6 pCi/L over the 10-year period. Systematic measurement effects would be one explanation for synchronous changes at all locations, but the different locations did not always track synchronously.

4.4 Summary of Radon Sampling

Radon flux sampling, typically a single round, is required after cover completion to assure that radon fluxes are with regulatory limits. All available flux samples were compiled into an MS Access database.

The Grants site provides a unique opportunity to examine multiple radon flux measurements, because a similar sampling program has been repeated every year starting in 2003. Sixty locations were sampled 7 years in a row, using the same protocols for placing the canisters, although the physical placement likely varied somewhat from year to year. Temporal variability at each sampled location is quite large, but both spatial patterns and the average over all the locations are consistent from year to year.

Despite the large variability at each location, the large number of replicates allows systematic trends to be considered. The one year that sampling occurred after an extended dry period exhibited distinctly lower average fluxes, and the highest fluxes occurred in an extended wet period. These effects are small relative to the temporal and spatial variability, and may be coincidental. Intuition suggests that wetter intervals would reduce the diffusion coefficient in the cover, thus reducing radon emissions, and the apparent opposite behavior is puzzling. Possible explanations are that (i) sampling may be affected by the antecedent moisture, (ii) the additional moisture may promote gas-phase advection from the tailings, (iii) wetting and drying may temporarily increase the bulk diffusivity even though the porous medium matrix has a smaller diffusivity, or (iv) seasonal changes may be confounding the apparent precipitation effects.

The sampled semiannual averages of atmospheric radon at the Grants site provides a loose indication that seasonal effects may slightly alter fluxes, but any correlation between precipitation and atmospheric concentration is not readily apparent in scatterplots.

5 STRATEGIES FOR TESTING COVER PERFORMANCE WITH RESPECT TO GROUNDWATER RELEASES

5.1 Overview and Background

Regulations for managing uranium and thorium byproduct materials are specified in 10 CFR Part 40, Appendix A, which requires that hazardous constituents entering the ground water from a licensed site must not exceed the specified concentration limits in the uppermost aquifer beyond the point of compliance during the compliance period. The objective in selecting points of compliance is to provide the earliest practicable warning that the impoundment is releasing hazardous constituents to the ground water. Points of compliance must be selected to provide prompt indication of groundwater contamination on the hydraulically downgradient edge of the disposal area, i.e., the area containing byproduct materials. 10 CFR Part 40, Appendix A defines a point of compliance as a site-specific location in the uppermost aquifer where the groundwater protection standard must be met. 10 CFR Part 40, Appendix A defines the uppermost aquifer as the geologic formation nearest the natural ground surface that is an aquifer, as well as any lower aquifers that are hydraulically interconnected with this aquifer within the facility's property boundary.

As described in 10 CFR Part 40, Appendix A, concentrations of hazardous constituents (as observed at compliance points) determine impoundment performance. Performance is defined using the metric that observed concentrations are less than the concentration limits specified by the license. Compliance points are typically located inside the borders of the long-term surveillance boundary, so natural attenuation may reduce concentrations as affected waters move from the impoundment to the compliance point. Additional point of compliance monitoring wells may be needed to provide a greater degree of certainty that the attenuative capacity of the aquifer is performing as expected. Supplemental information regarding subsurface conditions is often developed during groundwater corrective action programs, including (i) aquifer testing; (ii) geologic interpretations; (iii) corrective pumping, injection, and monitoring at numerous wells and along selected streams; and (iv) numerical modeling. Often the additional wells are decommissioned as corrective action goals are met.

The metric for impoundment performance, based on concentrations of hazardous constituents, implies that impoundment performance is determined by contaminant transport. Reducing concentrations of a constituent after some transport distance from the impoundment can be accomplished by (i) reducing impoundment leach rates, (ii) reducing the dissolved constituent mass during transport by sorption or precipitation, (iii) mixing with dilute waters, or (iv) sufficiently slow transport rates that radioactive decay is significant. Of these factors, the tailings cover only influences the impoundment leach rates, by eliminating or reducing infiltration through the cover.

The tailings cover is an earthen cover or approved alternative that 10 CFR Part 40, Appendix A only explicitly calls upon to reduce radon emissions to the atmosphere. The thickness of fine material (soil) that is sufficient to reduce radon fluxes may also provide substantial near-surface storage capacity for infiltrating wetting pulses, permitting later consumption by evapotranspiration and thereby reducing net infiltration and associated water fluxes through the tailings to the environment. Net infiltration is likely to be no more than a few percent of precipitation with vegetated deep natural soils under the climatic conditions at the 10 sites considered here, although focused recharge may occur along channels at a higher rate.

Because the 10 Title II sites generally do not have liners or other seepage-prevention measures under the tailings, the cover's role in reducing net infiltration is the key process that minimizes leaching from the sites once the large volume of initial tailings fluid is removed, assuming that the tailings impoundment is above the water table and no lateral inflow occurs. Because leaching releases hazardous constituents to the groundwater, eliminating infiltration through the cover eliminates long-term leaching and thereby strongly influences overall impoundment performance, again assuming that lateral inflow below the cover is negligible.

The geochemical behavior of the hazardous constituents directly influences impoundment performance when leaching does occur. Some leachate constituents are conservative, not precipitating or sorbing under normal conditions, and these constituents move most rapidly through the environment. Because chloride is a conservative constituent, chloride is often used as an indicator that leaching is occurring or has occurred. On the other hand, some leachate constituents are sorbing or precipitate, and this behavior may be strongly influenced by pH (e.g., uranium) or geochemical constituents supplied by the environment (e.g., sulfate concentrations may be influenced by equilibrating with gypsum in the soil). Accordingly, impoundment performance also depends on the particular constituent and conditions within the tailings and surrounding environment.

5.2 Potential Strategies for Assessing Cover Performance

The leaching rate from an impoundment is the only aspect of impoundment performance with respect to groundwater protection that the tailings cover influences, so that the protective role of the cover is to limit net infiltration sufficiently that environmental processes are able to maintain concentrations at the compliance point below the corresponding criteria. Accordingly, the focus in considering potential methods for assessing cover performance is on detecting fluids that have passed through the cover and contacted tailings prior to leaching. In other words, the scientific problem is to quantify the net infiltration through the cover. Three general approaches were identified: (i) observe a signature unique to the cover in the environment, (ii) observe a hydraulic or thermal signature in the environment linked to net infiltration through the cover, and (iii) observe a water quality signature in the environment consistent with inflow through the cover.

Methods based on water balances, energy balances, or constituent mass balances have been used to assess water fluxes. These methods use observations of water levels, temperature, and concentration, which have different representative averaging volumes. Water levels represent the largest averaging area, because pressure is highly diffusive, and concentrations represent the smallest averaging volume, because advection drives mass transport. For this reason, water balance measurements are more likely to represent bulk behavior of an impoundment and geochemical measurements are more likely to represent individual flow pathways through an impoundment. For this reason, it is important to have a good representation of the flow paths in order to appropriately interpret geochemical measurements.

5.2.1 Observation of a Unique Cover Signature

The first general approach for estimating net infiltration links unique aspects of the cover to downstream observations. The expected outcome of a successful cover is that there is little or no net infiltration, in which case waters infiltrating during an infiltration event would likely take an extended duration to progress through the unsaturated cover, unsaturated tailings, and environmental media to reach an observation point. In principle, a perfectly performing cover is positively identified when (i) there is a signature imparted to leaching waters by the cover, unique with respect to the tailings fluid and environment; (ii) all possible pathways are sampled with no evidence of the unique signature; and (iii) sufficient time has passed for infiltrating waters to reach the observation point. One way that all pathways might be sampled would be if all pathways discharge to a surface water body such as a stream or lake, although the concentrations would be reduced upon discharge and other sources may influence concentrations in the surface water. In practice, monitoring occurs primarily in wells at these sites, so only a limited number of pathways are sampled and failure to observe the cover signature would only provide partial confirmation of performance. Nevertheless, a single observation of the unique signature at any sampling point implies that the cover does not eliminate net infiltration, and might serve as a measure spurring further investigation.

Unfortunately, the potential that a cover at one of the 10 sites provides a unique geochemical signature is extremely small. The earthen material is typically derived from local materials, thus do not offer a distinct geochemical signature. At some sites, erosion protection is afforded by rock fragments obtained offsite, but the water contact time is so short for these sites that any chemical signature transferred from the rocks must be extremely dilute.

The best prospect for a unique signal might be to apply a readily detectable tracer to the cover, perhaps as part of the reclamation process. Herbicides applied for weed or brush control might provide an inadvertent tracer, but vegetation control is not likely to be desirable at the 10 sites. Or and Dinwiddie (2007) identify several conservative tracers that might be useful in this context, such as stable isotopes, ethanol, benzoate, and fluorobenzoates. Bromide and iodide can also be used as tracers.

5.2.2 Observation of a Hydraulic or Thermal Event or Feature

The second general approach for estimating water flow through the cover seeks to identify some change in mass or energy indicating that water is moving vertically through the impoundment. Water moving in the subsurface leaves a hydraulic or thermal signature in several ways: (i) maintenance of a recharge mound, (ii) fluctuations in water levels, (iii) correspondence between saturation and flux, (iv) deviations from a purely conductive temperature profile, and (v) fluctuations in temperatures not accounted for by annual cycles. A water balance calculation may also identify a flux imbalance indicating that flux is passing through or exiting the impoundment.

Presence of a water table mound under a tailings impoundment is an unambiguous indicator that water has passed through the impoundment, often from tailings drainage prior to cover emplacement. When the hydraulic conductivity and aquifer thickness are both known, an analytic or numerical model can be used to estimate the flow required to support the mound. This method requires that the mound is sufficiently large to measure (recharge fluxes are large relative to the aquifer transmissivity) and sufficient numbers of wells are present to determine the shape of the mound. Recharge mounds formed prior to placing the cover complicate this type of analysis while the mound formed during operations is dissipating. Dipping topography or bedrock units tend to displace a mound downdip.

Episodic water table fluctuations beneath the impoundment may indicate episodic recharge. Other processes also can induce fluctuations, such as intermittent pumping, streamflow, or barometric fluctuations. Further, unambiguously linking a water table fluctuation to flow through an impoundment (as opposed to recharge outside the impoundment) may require spatial and temporal resolutions that are not supported by quarterly to annual sampling.

Water potentials and saturations can provide an indication of groundwater fluxes within unsaturated media, such as the tailings within the impoundment. Under gravity-dominated flow, the unsaturated hydraulic conductivity of the media adjusts to carry the flow, which in turn influences the pressure and saturation of the media. Unsaturated water pressure and unsaturated hydraulic conductivity are linked by retention properties, which can be measured for the tailings. This technique may not be suitable for long-term monitoring, because of the difficulty in maintaining and calibrating the equipment.

Thermal techniques can be used to estimate water fluxes. There is a natural thermal gradient delivering heat from the earth's core to the atmosphere, largely through conduction. Conductive heat transfer typically is evidenced by a piecewise-linear temperature profile; units with different thermal conductivities have different temperature gradients for the same heat flux. Moving water deflects the temperature profile, and the amount of deflection can be used to estimate water fluxes. Thermal techniques have an advantage over geochemical techniques insofar as the averaging volume for thermal techniques is larger. However, Stothoff (2009, Section 5) considered the influence of vertical subsurface flow on thermal signals, and the results suggest that pathways hundreds of meters in length may be required to identify a flow signal distinct from uncertainty in thermal conductivity profiles under the flow conditions nominally expected for the 10 sites. The method requires high-quality estimates of thermal conductivity profiles and relatively numerous temperature measurement points.

Episodic temperature fluctuations may indicate recharge events. Aliasing effects may occur with the typical quarterly to annual sampling protocols, because natural sinusoidal annual and diurnal cycles penetrate to depth as well as any recharging waters. Within a profile, particularly at bedding changes, local temperature fluctuations may occur that indicate lateral movement of water along the bedding plane. Vertical air or water movement within a well or the zone disturbed by drilling also can cause a temperature fluctuation that mimics lateral flow.

Water balance calculations provide an additional method for estimating water fluxes when all but one of the components of the water balance can be quantified. The most common approach uses a numerical simulator, which in principle can describe a site in detail. Such approaches are often used during corrective action programs. Control volume approaches, which balance fluxes across the boundary of a control volume with changes in storage within the volume, provide integrated estimates that may require less detail.

5.2.3 Observation of a Water Quality Event or Feature

The third general approach for estimating water flow through the cover uses the geochemical signature of observed waters in the environment to infer flow rates through the impoundment.

Geochemical methods generally consider starting concentrations and ending concentrations to infer balances. For example, the chloride mass balance method is a common method for estimating recharge based on observations in an aquifer. This method uses a chloride balance to infer the corresponding water balance. Observations of chloride concentrations in precipitation and within the aquifer imply the degree of evaporative concentration that has occurred; applying the evaporative concentration to the precipitation provides a straightforward method for estimating recharge. In applying the method, however, it is important to account for all sources and sinks in both the water and chloride balance equations. Geochemical methods may be applied using numerical models or control volume methods, typically in conjunction with water balance methods, but the necessary level of detail may be much larger to account for heterogeneity.

In principle, a geochemical method might be applied with respect to meteoric inputs or with respect to the tailings. The simplest application for a geochemical method occurs for steady flow of a conservative species, because storage effects are not important. The method is applied to jointly consider water constituent balances by comparing two incoming streams, each with a water flux and constituent concentration, with a downstream mixture of the two streams, again with a water flux and constituent concentration. One component can be determined if all other components are known. For example, water flux through the tailings can be identified once the tailings have drained if the upstream and downstream concentrations in the environment, environmental water fluxes, and concentrations in the tailings are all relatively well characterized. In relatively simple cases, the balance calculation can be performed by hand. The method relies on distinct differences between the two incoming streams, so that the signature passing through the tailings impoundment is different from the environmental stream. The method becomes much less tractable for identifying cover inflow if a third stream must be considered, such as a combination of cover inflow, transient tailings drainage, and environmental fluxes, because an additional concentration and flux must be estimated.

Two factors may complicate the method when considering meteoric inputs of conservative species. One factor occurs when the conservative species is predominately of meteoric origin, because the tailings waters and surrounding environment would then be likely to have similar concentrations. The second factor occurs when the tailings themselves contain the constituent, which would mask the meteoric input.

Conceptually the same approach can be applied when considering inputs from the tailings, and a much wider range of constituents is potentially available. For example, uranium, chloride, sulfate, magnesium, and pH have been considered to represent the tailings fluids leaching from impoundments during operations. In this case, however, it may be difficult to quantify the concentrations that result from waters passing through the tailings. Further, many of the tailings constituents, such as uranium, may react, sorb, or precipitate, perhaps to differing extents depending on environmental conditions. These attenuation processes make it difficult to apply the balance approach, and often nonlinear geochemical models are applied for such constituents. When the plume is being flushed with upgradient waters, in principle a transient mixing analysis can be performed to evaluate the dilution of the plume.

Three effects that confound the use of the tailings as a source for the 10 sites are a result of the large releases that occurred during the operations period prior to placing the cover. One confounding effect is that the geochemical characteristics of leachage before and after the cover emplacement may not change, so that it may be extremely difficult to distinguish between leaching that occurred before and after the cover was emplaced. This is particularly true when a plume is solely derived from leachate.

A second confounding effect occurs when some of the prior release is stored within the aquifer within small pores, sorbed to the matrix, or precipitated. The stored constituents slowly release as more dilute waters pass through the system, providing a delayed source term to consider in analyses. This delayed source term is not present during the initial development of a plume.

The third confounding effect is that each site has undergone groundwater remediation programs because of these releases, substantially influencing groundwater flow paths. Application of geochemical mixing methods is substantially more complicated in transient flow regimes relative to steady conditions, invariably requiring the use of computer models.

Fluctuations in water quality, similar to fluctuations in water level or temperature, may provide an indication of a recharge event. Interpretation of the timing and source for a water quality fluctuation may differ from a hydraulic or thermal fluctuation, because pressure and temperature pulses propagate with a different velocity than water quality pulses. For related reasons, interpretations of water quality observations are more strongly dependent on understanding flow paths than interpretations of hydraulic and thermal observations.

At higher concentrations, sometimes geophysical techniques can identify locations where plumes have formed, supplementing a well-based monitoring system. Once detected, the progress of the plume provides an indication of the mass leaving the impoundment and flow directions.

5.3 Summary

Tailings covers are placed on top of uranium mill tailings to provide a protective barrier reducing radon gas migration and a physical barrier eliminating access to the mill tailings for an extended period of time. These primary objectives do not directly influence groundwater protection, but a tailings cover may control or reduce inflow into the tailings, thus limiting the amount of water that may leach into the groundwater. In many cover designs, a thick zone of low-permeability material reduces radon gas migration, which is also compatible with limiting groundwater influx.

Three general strategies for identifying inflow through the cover were identified: (i) observing a unique cover signature, (ii) observing a water or temperature signal consistent with inflow, and (iii) observing a geochemical signal consistent with inflow. A unique cover signal might be observed if the cover itself provides a unique signature, which appears unlikely for the 10 sites considered, or if some tracer (such as an herbicide or an inert conservative chemical) is applied to the cover. A water or temperature signal consistent with inflow might be identified in a number of ways. Water table fluctuations may provide the most direct evidence that water inflow has occurred, whereas numerical or control volume methods may provide indirect estimates of water inflow. A geochemical signal consistent with inflow is more difficult to identify, because a number of confounding characteristics of the tailings sites limit the usefulness of geochemical methods. A conservative species such as chloride will likely provide the most useful geochemical signal for identifying inflow.

6 TACTICS FOR DETECTING AND QUANTIFYING INFLOW THROUGH GENERIC TAILINGS COVERS

Section 5 provides an overview of strategies that might be used to identify inflow through a tailings cover. This section expands the discussion to consider strengths and weakness of specific methods that might be applicable for a generic tailings cover. Section 7 applies selected methods to the 10 specific sites of interest.

The focus in this section is on identifying particularly promising and unpromising methods and sampling locations among the variety of possible approaches for quantifying inflow through a cover, and evaluating why the approaches may be promising or unpromising. The generic site of interest lies above the water table in a semiarid environment, experienced seepage during the operations and reclamation period, and may continue to experience seepage for some duration after reclamation. These conditions are typical of the 10 sites analyzed in Section 7. The same concerns would also apply for wetter locations, although inflows are likely to be a substantially larger fraction of annual precipitation in more humid climates and it is more likely that a water table might encroach on the tailings.

Certain characteristics vary across the 10 sites. Tailings covers may use different earth materials for the radon barrier and other components of the cover, and may use vegetation or rock as an erosion control strategy. Most impoundments are unlined, but some were above a high-permeability substrate, some above a low-permeability substrate, and some featured a mix of substrate permeabilities. Some impoundments were designed to limit seepage and others facilitated water balances by promoting seepage.

Each of the 10 sites features multiple monitoring wells outside of the impoundments, and some sites monitored or performed corrective actions within the tailings as well. This section particularly considers the likely differences in quality for cover inflow estimates using monitoring within the tailings compared to monitoring outside the tailings.

One notable difference between the 10 sites and any potential new site is the degree that seepage influenced groundwater quality. Seepage prior to cover emplacement has strongly influenced site conditions at the 10 sites, but seepage should not be a factor at a new site constructed with an intact low-permeability lining. Uranium mill tailings impoundments received very large quantities of water during the operations period, typically operating for years with inflow rates substantially larger than annual precipitation. Some of this large volume of water evaporated, with the remainder either seeping from the impoundments or remaining within the tailings. At infiltration rates typical of natural systems, a few percent of precipitation at the sites considered, it would take decades to centuries to achieve the same total influx through a cover. Because expected influx represents a small perturbation to the conditions existing before cover emplacement, detecting an infiltration signal is likely to require care and quantifying the signal will be difficult. Effective strategies must minimize potential confounding signals to provide the smallest degree of ambiguity in interpreting small perturbations. Methods that may be appropriate at a new site, with no environmental contamination, may not be appropriate once the environment is disturbed. The focus of this section is to assess methods that may work even under pre-existing seepage.

Section 6.1 describes relevant site characteristics, Section 6.2 describes methods using hydraulic observations, and Section 6.3 describes methods using geochemical observations.

6.1 General Site Characteristics

The collection of sites provides a representative sample of different geometric design strategies for constructing tailings impoundments. The sites use three design strategies: (i) take advantage of a natural channel by placing one or more dams along the axis of the channel to form impoundments, (ii) place a dam at the base of a side slope, and (iii) place an impoundment atop a relatively horizontal landscape. The tailings impoundments can be large; a single impoundment at Site 1 (Ambrosia Lake West) contains 27 million tonnes [30 million ton] of mill tailings and covers 105 ha [260 ac]. Total basin area ranges from 40 ha [101 ac] at Site 2 (Bear Creek) to 136 ha [335 ac] at Site 4 (Gas Hills East).

From the perspective of containment, the geologic setting is important with respect to the permeability and continuity of the unit(s) under the impoundment. Two endpoint situations occur: (i) inherently leaky underlying units (i.e., all units contacting the tailings have large saturated hydraulic conductivity relative to an inflow pulse), and (ii) inherently containing underlying units (i.e., all units contacting the tailings have small saturated hydraulic conductivity relative to long-term-average inflow). An example of the inherently leaky condition occurs when the topmost unit is permeable, such as sandstone or unconsolidated sediments, and extensive, forming a pathway for release. Occasionally different permeable units contact or underlie different areas of an impoundment, perhaps with different directions of dip (e.g., Church Rock, where flow is in the channel flow direction in the alluvial aquifer and flow is in the dip direction in the bedrock aquifers). An example of the inherently containing condition occurs when a low permeability layer, such as siltstone, is at or near the ground surface everywhere near the tailings and the impoundment dam keys into the low permeability layer.

Unit permeability is classified as high or low, for the purposes of evaluating cover performance, relative to potential large inflow pulses. If the underlying unit has sufficiently low permeability to temporarily perch water given an infiltration pulse in a wet season, then cover performance can be readily assessed by considering whether perched water exists above bedrock and if water levels respond to a wet season. If the underlying unit is inherently leaky, then this relatively simple and direct option can be applied above a laterally extensive zone of low permeability slimes within the tailings or above a low permeability unit below the tailings. A change in water level after a large infiltration event, combined with appropriate estimates of areal average specific yield, provides a quantitative estimate for change in water content and therefore net infiltration. Note that the tailings are highly unlikely to be homogeneous. Low-permeability portions of a tailings impoundment (e.g., slimes) (i) remain essentially saturated, (ii) do not provide pathways for infiltration pulses to propagate within the tailings, and (iii) have small specific yield relative to high-permeability zones.

From the available documentation, at most sites it is difficult to identify whether the tailings have completed draining. None of the sites currently report water levels within a tailings impoundment, therefore it is not possible to directly identify whether a tailings impoundment is currently retaining water. Water levels are monitored in the alluvium underlying the Large Tailings Pile at the Grants site, providing a somewhat indirect indication of tailings water levels. At some sites, available documentation describes the tailings as either drained (corresponding to a leaky impoundment) or slowly draining (corresponding to a contained impoundment), typically without describing the basis for the assessment. Some of the sites estimate water levels or future declines in seepage rates over time as a basis for design.

6.2 Infiltration Detection Strategies Using Hydraulic Signals

6.2.1 Hydraulic responses to infiltration water in tailings

Water infiltrates into a porous medium like a cover under two general conditions: (i) as distributed infiltration, where overland flow is minimal and (ii) as focused infiltration, where overland flow locally focuses water. Focused recharge is more likely to generate deep wetting pulses driven by gravity drainage that can escape the evapotranspiration zone, but these focused wetting pulses may bypass most of the tailings. Most or all of the cover area at each site is rather flat and has minimal grade, thus the potential for long overland flow paths is relatively small and focused infiltration would be limited to local depressions, presumably with small catchments. Some of the sites feature drainage channels within or adjacent to the tailings, which provide a potential for focused recharge during and shortly after storms. Channel designs at the sites tend to focus on erosion control rather than minimizing seepage losses; however, the total quantity of focused recharge in these channels is limited by the ephemeral duration of flow in the channel.

Once water penetrates the cover, the cover designs tend to hold wetting pulses near the surface because of the soil moisture storage offered by an intact radon barrier and associated porous layers. Evapotranspiration reclaims some fraction of the wetting pulse, but evapotranspiration is highly seasonal. In Wyoming, pan evaporation measurements at 15 sites range from 89 to 140 cm/yr [35 to 55 in/yr], but 85 percent of annual pan evaporation occurs from May through September and average daily pan evaporation peaks at approximately 3 cm [1 in] per 3 days in July. In New Mexico, pan evapotranspiration ranges from 107 to 287 cm/yr [42 to 113 in/yr] at 39 sites, averaging 3 cm [1 in] per 4.5 days annually and peaking at 3 cm [1 in] per 2.4 days in July. Accordingly, holding the wetting pulse near the surface can rapidly deplete the stored water during the summer months, so snowmelt and early spring and late fall precipitation typically provide the greatest potential for infiltration.

In natural western systems, recharge events do not occur every year, because recharge events typically require favorable conditions that may only occur in wet years. Accordingly, a recharge event may create a response several times larger than suggested by long-term average recharge. In more humid environments, recharge events would be expected to be a larger fraction of precipitation and occur more frequently.

The impoundment design and tailings characteristics may also amplify a signal because of lateral movement above low-permeability features. The pre-impoundment natural system at the sites constructed on hillsides and in drainages exhibited a surface slope of 1 to 6 percent, approximately estimated using Google Earth. When only the downhill portion of the tailings impoundment is saturated, lateral downhill flow may amplify the signal at the downgradient end if there is a liner or low-permeability bedrock under the tailings. In dammed drainages, an additional degree of focusing from the drainage sides to the original channel may also occur, further amplifying water table responses. The correspondence between water level rise and infiltration volume would depend on the water table elevation in this situation, because changes in stored water volume would affect both wetted area and water table elevation. It may be difficult to observe this type of amplification, however, because the response time for lateral flow may be orders of magnitude slower than the response time for vertical flow. An unconfined water table within a tailings impoundment would respond slowly, and pressure pulses would propagate slowly in typical tailings impoundments featuring shallow gradients and long horizontal distances.

Differential sediment distribution during tailings emplacement is likely to make portions of the tailings (e.g., the slimes) effectively impermeable on the time scales of a recharge pulse, thus all of the water infiltrating over the low-permeability tailings may funnel into the coarser tailings near emplacement spigots. Conservation of mass requires that a given pulse volume will produce a larger rise if the funnel area is smaller. Some of the sites describe studies of the initial ground surface, but this information is only available for a few sites and only in the form of cross sections and contour plots.

6.2.2 Estimating Flow Through Covers After Dewatering Ceases Using Tailings Water Levels

Saturated conditions are much easier to sample than unsaturated conditions, because water freely enters a well, so sampling equipment for saturated conditions tends to be more accurate, more robust, less expensive, and require less training than equipment for unsaturated conditions. Accordingly, if at all feasible sampling from a saturated zone is preferable to sampling from an unsaturated zone.

Two types of locations may feature a perched zone within tailings. The base of the tailings is likely to have at least a transient perched zone if the impoundment is lined or the underlying unit has a smaller saturated hydraulic conductivity than the mean annual infiltration through the cover. Even if the base unit for the tailings has higher permeability, a declining water table is present during the drainage process. A perched zone may also form above an extensive area of low-permeability slimes, regardless of the tailings base unit.

Documentation for several of the sites reports estimates of long-term recharge through the cover consistent with natural conditions. Under the semiarid western climatic conditions typical of these sites, natural vegetated systems tend to have small rates of net infiltration, generally no more than a few percent of annual precipitation. Total recharge predominately occurs in upland areas with shallow soil and in stream channels. Based on the Parameter-Regression Independent Slopes Model (PRISM) gridded representation of the 1971 through 2000 climate normals (PRISM Climate Group, 2008), mean annual precipitation ranges from 28 to 36 cm/yr [11 to 14 in/yr] at the New Mexico sites and 23 to 33 cm/yr [9 to 13 in/yr] at the Wyoming sites. A recharge event that is 3 percent of annual precipitation would range from 0.7 to 1 cm [0.27 to 0.41 in] of recharge at these sites; with a porosity of 0.1, such an event would induce a water table rise of 8 to 10 cm [3 to 4 in], which is very small relative to annual water table changes observed during operations and remediation periods.

Under western climatic conditions, it is more typical that recharge is dominated by events occurring in wet years, thus significant events not occur every year but are larger than average in the years when they do occur. Accordingly, a 0.3 m [1 ft] rise during a wet year at a typical site, roughly 4 times the expected average recharge, may simply reflect expected cover performance during a wet year. At such sites, it is essential to average recharge estimates over a number of wet and dry years to calculate a representative long-term average.

Some sites use riprap or rock fragments instead of vegetation for erosion control. This practice may alter cover performance depending on how the fragments are placed with respect to the fine materials. Natural systems with desert pavement tend to inhibit infiltration and promote runoff, which would be likely to improve performance. On the other hand, a layer of coarse rock resting on the surface may act as mulch, inhibiting evapotranspiration and promoting infiltration. Rock mulches are used to promote recharge in dryland agriculture. Under extreme conditions, a rock mulch may permit more than 50 percent of precipitation to become net infiltration, although such high rates may not persist on a cover if vegetation is able to establish and take advantage of the moist conditions. Site-specific conditions would determine if and how a rock cover would influence infiltration.

Covers exhibiting net infiltration that is more than 10 percent of annual precipitation are unexpected for natural conditions at the western sites, especially the New Mexico sites, although may occur locally. Assuming that net infiltration through a cover is 10 percent of annual precipitation, the water table rise for a 4-year event would be on the order of 1 to 2 m [3 to 5 ft] with the same assumptions regarding the tailings. Accordingly, a water table rise of a few feet during a wet year is a signal that the cover may be performing poorly and should be analyzed further with site-specific data. A change in water level of a few feet should be readily observable with monitoring wells in a tailings impoundment.

Although the Sequoyah, Oklahoma, site was not considered in detail, it should be noted that the mean annual precipitation is approximately 117 cm [46 inches]. If an impoundment was located at this site, the expected water table responses would be much larger than at the other sites because of the wetter conditions. The increased precipitation directly increases recharge. Further, the fraction of precipitation becoming recharge tends to increase with increasing precipitation. However, interannual variability in precipitation would tend to be relatively small at the Sequoyah site, thus interannual variability in recharge would be expected to be smaller at the Sequoyah site than at the other sites.

The speed at which a rise occurs depends on how the pressure pulse propagates to the water table. Unless highly preferential flow pathways are present through the tailings, waters passing through the cover may take multiple events to reach the water table. In relatively uniform media, waters are displaced downward in a roughly piston-like fashion. As a rule of thumb, the velocity that a wetting pulse propagates above the water table is

$$v = \frac{q_w - q_d}{(\theta_w - \theta_d)\varepsilon} \quad (6\text{-}1)$$

where v is wetting-front (or pressure-pulse) velocity, q_w is the infiltration flux plus background flux, q_d is the background flux, θ_w is the saturation behind the wetting front, θ_d is the saturation ahead of the wetting front, and ε is porosity. The wetting front velocity always propagates faster than the fluid velocity in unsaturated media, and this effect is stronger in relatively permeable media where only a small difference between saturations is necessary to transmit the pulse.

A water balance of a perched zone can be used to estimate recharge flux between two observations. The water balance is in the form

$$\frac{1}{\Delta T}[\Delta V - A(q_i - q_o)] = 0 \quad (6\text{-}2)$$

where ΔT is the time interval, ΔV is the change in storage, A is the area of the perched zone, q_i is distributed inflow to the perched zone, and q_o is distributed outflow from the perched zone. When the water table covers the entire area, change in storage corresponds to change in water table elevation; otherwise, a change in storage also includes a change in wetted area. Rearranging,

$$\frac{\Delta V - Aq_o}{A\Delta T} = q_i \tag{6-3}$$

If recharge events are infrequent, average distributed outflow is estimated during periods when inflow is negligible using the left-hand side of this equation and setting q_i to zero.

A water table rise resulting from a recharge event would be superimposed on long-term declines stemming from seepage (and dewatering pumping during the restoration period), thus the effects of seepage must be removed prior to interpreting changes in water table elevation from recharge. Water levels must be measured frequently enough to identify a water table change stemming from a recharge event as separate from the long-term signal. As a rule of thumb, it would take at least three or four water level observations while the water table is rising from a recharge event to easily distinguish the event from background trends. This rate of change is likely to be site-specific, depending on material properties and tailings thickness. The rule of thumb may imply more frequent sampling than quarterly to annual monitoring.

When flow in the tailings responds to flow through the cover as piston-like displacement, dilute precipitation waters may take many recharge events to reach the water table. Accordingly, waters seeping from the tailings may not substantially change in composition until the initial tailings waters have seeped and enough recharge events have occurred to flush the unsaturated pore volume in the tailings. Tailings impoundments may be several tens of feet thick, compared to a typical recharge height on the order of 0.07 m [0.25 ft] thick, thus many years of precipitation may be required to significantly dilute the geochemical signature within the tailings.

6.2.3 Estimating Flow Through Covers During a Dewatering Program Using Tailings Water Levels

At some sites, pumping from the tailings occurred for several years after cover emplacement (e.g., at the Shirley Basin North site). Estimating cover performance can be greatly complicated by pumping, and in general would likely require a numerical model with detailed pumping and geophysical data (e.g., hydraulic conductivity distributions) to compensate for water table perturbations from pumping wells.

Groundwater monitoring reports typically provide average annual pumping rates without breaking down the pumping at finer intervals or describing the accuracy of the technique used to measure pumping. If pumping rates are comparable to or larger than expected recharge events, using water level measurements to detect the amount of water entering the tailings from a recharge event during such programs requires both that pumping rates and operations schedules are carefully and accurately monitored and that these data are reported in detail. For example, a 2.5 cm [1 in] recharge event over 117 ha [290 ac] totals 29 ML [8 Mgal] (i.e., approximately 3 years worth of recharge at 3 percent of annual precipitation over the two tailings impoundments at the Shirley Basin North site). Pumping at 57 L/min [15 gpm] would remove this amount of water in 1 year. For comparison, tailings dewatering at the Shirley Basin North site during 2001 averaged 197 L/min [52.1 gpm] using 48 wells (Hydro-Engineering, 2002, Section 8), and the tailings water levels declined by 0.9 to 1.8 m [3 to 6 ft] in Pond 5 and 0.6 to 1 m [2 to 4 ft] in Pond 4. This site is subject to freezing, and pumping rates are smaller in the winter by some unspecified amount. The consequence of shutting off all of the pumps for three months, one potential operational strategy, would provide an average water level signal analogous to a hypothetical 3-year recharge event at this site. Without detailed pumping histories, normal operating procedures may erroneously imply that the cover is performing poorly or may mask the occurrence of a recharge event.

The rate of sampling required to robustly estimate cover performance during dewatering activities may be difficult to justify at a mine site. Risks associated with a poor cover are smallest immediately after emplacement, because the initial performance of a cover is likely to be initially very good and cover degradation (e.g., formation of macropores) is likely to be a slow process. Once pumping within the tailings no longer occurs at a site, removing a substantial confounding flux, the process for identifying recharge events using water levels becomes much simpler and more robust.

6.2.4 Estimating Flow Through Covers in Tight Impoundments Using External Water Levels

The use of water levels outside the tailings impoundment to estimate recharge adds complicating factors to the analysis in the same way that dewatering pumping adds complicating factors to analyses considering tailings water levels, except that variation in water levels in the natural system stem from causes that cannot be as well characterized as pumping rates.

A tight impoundment is an impoundment with a perennial water table that has a relatively low-permeability basal unit restricting seepage. The restriction to seepage damps the infiltration signal outside the impoundment. In this case, seepage fluxes are proportional to the head difference across the resistive layer. For example, the head difference exceeded approximately 12 m [40 ft] for Pond 5 at the Shirley Basin North site and the Main Impoundment at the Split Rock site, based on the last monitoring report with reported tailings water levels (tailings water levels are no longer monitored at these sites). An increase of 0.3 m [1 ft] in water level (the hypothetical four-year recharge event) would change the seepage flux by 2.5 percent at these sites. Further, the natural system would also be subject to the same climatic signal as the tailings cover. Accordingly, essentially all of a transient recharge signal observed in the natural-system water levels at these sites would be expected to stem from recharge in the natural system, not infiltration though the tailings cover.

For comparison, under the optimistic assumptions that (i) porosity is uniform from the tailings through the restrictive layer, (ii) the recharge event delivers pure water to the perched tailings water, and (iii) full mixing occurs throughout the tailings and restrictive layer, the geochemical characteristic of tailings seepage would also be diluted by 2.5 percent. In actuality, mixing would be minimized because the less dense recharge-event waters would tend to float atop the tailings waters and only mix through diffusion, thus it may require drainage of most of the initial tailings waters before a dilute signal reaches the external environment.

Some of the sites may have a relatively conductive pathway to the underlying aquifer, so that the tailings water has already drained. For example, this may be the case for the Old and Alternate Impoundments at the Split Rock site, based on descriptions that characterize these impoundments as fully drained. Presumably all of the sites will ultimately reach a fully drained stage. If not, the tailings water table would tend to rise until close enough to the ground surface that evapotranspiration or lateral seepage can balance recharge.

Note that it would be difficult to engineer a resistive layer that maintains a perennial perched water table supplied by recharge and drained only by seepage, because this configuration can only be maintained when the average basal hydraulic conductivity is equal to the average recharge rate. Sites with sloping bases (e.g., a dammed drainage channel) are more likely to have a perennial water table when the bottom is leaky, because the drainage rate is proportional to the wetted area and the wetted area modulate seepage by expanding and contracting. When the resistive layer closely balances the recharge, one signal would be that the water table experiences relatively wide fluctuations from year to year and decade to decade.

In extremely tight impoundments, maximum seepage rates are less than average inflow rates through the cover. This situation would ultimately result in a shallow water table in the impoundment. This situation may be undesirable, because a shallow water table produces a risk that tailings water reaches the surface in extremely wet years.

6.2.5 Estimating Flow Through Covers in Leaky Impoundments Using External Water Levels

When the base of a tailings impoundment is sufficiently leaky that no water table exists and infiltrating pulses are not retained within the tailings, the underlying aquifer serves as an analog to the perched zone within the tailings. Analyzing the aquifer system to identify cover performance requires accounting for additional factors, including lateral inflows and water table fluctuations because of recharge in the natural system. There are often historic or ongoing external influences on hydrologic conditions, such as injection, dewatering, and discharges from ongoing mining activities or groundwater corrective actions. Sometimes the hydrologic regime has been permanently altered during groundwater corrective action programs, for example by constructing trenches (e.g., Ambrosia Lake West), rerouting stream channels (e.g., Ambrosia Lake West), or leaving open pits as permanent water bodies (e.g., Highlands). Accounting for such additional factors would is likely to require numerical modeling in all but the most idealized situations.

Water table responses in an unconfined aquifer under an impoundment are likely to be small relative to responses in a perched zone within the tailings. Recharged water will influence a larger horizontal area than the impoundment footprint if the aquifer is laterally extensive, thus mass conservation requires that the maximum vertical response must be smaller. Unlike a perched zone in an impoundment, recharged waters are likely to continue downdip rather than be constrained by a low-permeability dam that allows waters to collect. A highly transmissive aquifer may efficiently transmit recharging waters, thus exhibit little response even under a poor cover. The amount of muting is site specific, depending on the aquifer transmissivity and areal extent.

When no recharge zone exists near the impoundment (e.g., the impoundment covers a hillslope and crest, or is in an alluvial flat far from a sideslope or channel), there may be little recharge signal from the natural system. In this case, an analysis would parallel an analysis for a perched zone.

The natural recharge signal may be larger than the cover recharge if there is an extensive upslope or lateral catchment, and the natural system signal must be removed from the water level observations in order to estimate cover recharge. Separating water table fluctuations resulting from recharge through a cover from water table fluctuations resulting from natural recharge may prove to be extremely challenging in such cases. The climatic signal is the same for the two recharge sources, thus the two signals will be strongly correlated in time. Unlike pumping signals, which in principle can be carefully monitored and numerically subtracted from the signal, the natural system signal must be determined in the field. A natural recharge signal may peak before or after a cover recharge signal, so that an extensive network of monitoring wells with frequent and precise data acquisition may capture subtle shifts in the water table gradient that identify the direction of a recharge source. The data requirements in this situation are site specific, but are likely to be much more stringent than needed for analyzing perched zones in the impoundment.

Another approach is restricted to arid environments. A formation underlying the impoundment may have been dry prior to operations but have developed a perched water table during operations and as the impoundment drained. The rate that the perched water body recedes depends on the seepage rate from the impoundment. After the tailings have drained, the seepage rate is equal to inflow to the impoundment, therefore the rate at which the water table responds provides information on the inflow rate. This approach is indirect, so estimates of inflow rates are likely to be rather uncertain. The hydraulic properties governing water table response are typically uncertain, and the water balance in the perched water may also be affected by natural recharge that has a similar magnitude as the inflow to the impoundment.

6.3 Infiltration Detection Strategies Using Geochemical Signals

Geochemical signals provide an alternative to hydraulic signals for estimating inflow through a tailings cover. Compared to hydraulic signals, geochemical signals tend to reflect much smaller averaging volumes but longer averaging durations. Accordingly, assurance that the cover is not allowing substantial inflow may require many more sampling locations for geochemical methods than for hydraulic methods, perhaps with a relatively longer duration between samples.

6.3.1 Geochemical Considerations

6.3.1.1 Signal Detection

In many environmental scenarios using geochemical methods, the problem focuses on measuring relatively small volumetric releases of contaminants into a relatively dilute environment. Current highly accurate sampling methods can detect even greatly diluted levels of a contaminant. When the contaminant is above the detection limit, a small absolute change in concentration can provide a strong signal in a dilute environment by inducing a large relative change in concentration.

Geochemical signals provided by inflow represent dilution of existing concentrated waters. Detecting the signal from a small amount of dilution in strongly concentrated water is inherently more difficult than detecting the signal from a small amount of contamination in very dilute water.

An example illustrates the difference between detecting enrichment and dilution. Consider mixing 1 mL [0.034 fl oz] of influx fluid with 100 mL [3.4 fl oz] of original fluid that has a concentration three orders of magnitude lower (seepage entering an aquifer) or higher (rainwater entering tailings) than the influx. These two cases represent equal signals (three orders of magnitude relative difference) before mixing. When the influx mixes with a very dilute original fluid (seepage), the concentration of the mixture is 11 times larger than the concentration of the original fluid. When the original fluid is very concentrated (tailings dilution), the concentration of the mixture is 1 percent smaller than the concentration of the original fluid. If the measurement technique is sensitive enough to distinguish the most dilute concentration, adding a small amount of influx to the dilute fluid provides a large and unambiguous signal. Adding the same influx to the concentrated fluid changes the concentration in the second decimal place, requiring two measurements with no error at the resolution that laboratories typically report chemical analyses.

In this example, the signal is three orders of magnitude larger when enriching the dilute solution than when diluting the concentrated solution.

6.3.1.2 Potential Inflow Tracers

This simple example suggests that quantifying inflow is likely to be much more feasible using a unique tracer associated with or applied to the cover than using dilution of tailings waters. The tracer might be (i) some geochemical signature of the cover itself, (ii) an unintended tracer such as a herbicide, or (iii) an intentionally applied tracer. A tracer applied to the cover could be tracked using wells inside and outside a tailings impoundment, because influx through the cover would have a different signal than recharge outside the impoundment. Tracer arrival may be substantially delayed and diluted in the wells outside the impoundment, making the signal harder to interpret. No such tracer or surrogate has been identified for any of the sites.

Anthropogenic atmospheric tracers used for groundwater dating may provide a measurable signal that differentiates precipitation from tailings fluids. A number of anthropogenic tracers, such as tritium, chlorofluorocarbons, and sulfur hexafluoride, have been used to distinguish recent recharge from old groundwater. When the tailings waters are derived from pumping aquifers that are isolated from the surface, prior to milling the waters are depleted in anthropogenic tracers. Depending on the milling process, amount of precipitation added prior to cover emplacement, and degree of atmospheric exchange, the tailings waters may remain depleted relative to present precipitation. On the other hand, some anthropogenic tracers have been declining over time, thus the tailings may be enriched relative to present precipitation. This method would only be applicable to wells screened within the tailings, because the same signal applies to recharge inside and outside the impoundment. No information on anthropogenic tracers was identified in any of the site documents reviewed.

As alluded to in Section 4.3.1.1, the lack of a chemical constituent also provides information. For example, an anti-plume may form when dilute waters remain distinct from more concentrated waters. Precipitation is dilute relative to the tailings waters with respect to the measured geochemical constituents at the sites, so there is potential for an anti-plume to develop. However, precipitation waters exchange with subsurface pore waters during travel, so that the waters reaching the water table may have substantially altered concentrations.

6.3.1.3 Detection of Tracers

Geochemical signals are most precisely detected using laboratory analysis of water samples, which allows the concentration of many chemical species to be simultaneously measured. In this approach, the representative volume being sampled is many orders of magnitude smaller than a tailings impoundment. Geochemical methods requiring sampling are difficult to use for unsaturated conditions, because it is extremely difficult to repeatedly obtain representative samples from an unsaturated porous medium. It is more practical to consider geochemical sampling within a saturated zone.

The concentration of some species (e.g., Cl) linearly influences the electrical properties of the fluid, allowing a less precise identification of the chemical composition but at a much larger scale than a single water sample. Geophysical techniques measure changes in resistivity at a much larger scale than an individual water sample, thus may provide a means for estimating large-scale changes. Geophysical measurements can be performed both from the surface and from boreholes. Geophysical methods rely on acquisition of many measurements to identify spatial patterns. Geophysical methods typically require supplemental observations, such as water levels, to constrain factors other than geochemical composition that influence resistivity.

6.3.1.4 Detection of Dilution

The mixing example in Section 6.3.1.1 suggests that environmental processes affecting the concentration of seepage outside a tailings impoundment (e.g., mixing, diffusion), which influence released concentrations by orders of magnitude along a plume, is likely to strongly mask any dilution resulting from influx through a cover. The large set of geochemical observations collected at the various sites describe conditions resulting from seepage volumes that are generally comparable to decades or centuries of expected natural recharge, and influx waters are likely almost wholly contained if the impoundment has not fully drained. For these reasons, it is not feasible to unambiguously identify influx through the covers based on the existing geochemical observations within seepage plumes.

The environment within the impoundment is more controlled than the external environment, and under certain conditions it may be feasible to use geochemical methods on tailings waters to quantify influx through a cover. In particular, geochemical methods are best suited to situations where influxes remain distinct from existing tailings waters, perhaps by forming a layer on top of existing waters. It may be feasible when (i) the influx composition significantly differs from the tailings fluid, (ii) the influx minimally mixes with the tailings fluid, (iii) a time series of samples are obtained, and (iv) each sample is obtained using identical strict measurement protocols. Baseline sampling when the cover is emplaced would aid in identifying any existing signature from recharge prior to cover emplacement, which should have a very similar composition to inflow after cover emplacement.

The utility of a particular species to examine inflows depends on the extent that the tailings remain a continuing source of the species. If it requires many pore volumes flushing through the tailings before a particular species is depleted, successive recharge events (representing a small fraction of a pore volume) will have essentially identical concentrations. Species not sorbing to the tailings, such as chloride, deplete more rapidly than sorbing species.

The utility of a particular species also depends on how conservative the species is under changing oxidation states. The oxidation state may evolve over time in impoundments that are relatively isolated from the environment. Species that strongly alter their equilibrium concentration with changes in oxidation state are poorly suited for use in examining small changes in concentration from inflows.

Based on these considerations, chloride may be the most widely applicable geochemical constituent to use for estimating inflows using dilution methods.

6.3.2 Geochemical Methodology

A mixing model can be used to quantify inflows when the inflow and initial fluids are either well mixed or strongly stratified. In the simplest form of a mixing model,

$$C_m V_m = C_i V_i + C_o V_o - C_e V_e \tag{6-4}$$

where C is concentration, V is volume, and subscripts i, o, e, and m denote influx, original, efflux, and mixture. In a well-mixed scenario, the efflux concentration is the same as the original concentration ($C_e = C_o$). This mixing model is used to estimate a fluid influx volume given known chemical concentrations and known water volumes. For a fixed measurement volume, such as the top meter of the water table

$$V_m = V_o \text{ and } V_i = V_e \tag{6-5}$$

leading to

$$(C_m - C_o)V_m = (C_i - C_e)V_i \tag{6-6}$$

An example illustrates how the mixing model might be applied to estimate the magnitude of a recharge event in a tailings impoundment. Under optimal conditions a recharge event through the cover would tend to produce a layer of relatively dilute waters on top of relatively concentrated existing tailings waters. Assume that the recharged layer is 0.5 m [1.6 ft] thick with a concentration of 1 mg/L [1 ppm] and the existing waters have concentration of 10 mg/L [10 ppm] (an extremely large difference). Further assume that two zones are considered by packing off the top 1 m and 5 m [3 and 16 ft], respectively. Three samples are drawn from the zone, two local samples from the top (C_i) and bottom (C_e), and one from the entire zone (C_m). The measured average concentrations in the first and second zones are 5.5 and 9.1 mg/L [5.5 and 9.1 ppm], respectively. Note that it is not clear exactly how to obtain a single sample that represents an entire zone; it might be necessary to sample at multiple locations.

Now assume that another recharge event added 0.1 m [0.3 ft] to the dilute layer. The same sampling strategies are used. The measured concentrations for the two zones are 4.6 and 8.92 mg/L [4.6 and 8.92 ppm], respectively. These concentrations are very similar to the original concentrations, illustrating the need for measurement precision. The 0.1-m [0.3 ft] thickness is calculated consistently using either the 1- or 5-m [3- or 16-ft] zone samples. However, if the calculation for the 5-m zone is performed using the average concentration from the 1-m [3-ft] zone, the calculated influx is 3 m [16 ft].

This example illustrates that the mixing method requires stringent measurement protocols and measurement accuracy as well as a significant difference between the influx and existing waters. The mixing method is likely to be poorly suited to estimating the magnitude of individual recharge events within a tailings impoundment given that the influx concentrations are typically unknown and may be strongly modified by the tailings before reaching the water table.

When the influx and original fluids have distinct properties and remain stratified, a geochemical signature may allow the thickness of the topmost layer to be explicitly tracked. In this case, the sampling strategy will require multiple physical samples from the water column to identify the geochemical layering. If the stratified fluids have different electrochemical properties, profiling (e.g., sampling resistivity, pH, EH) within the borehole may be useful for identifying layering.

6.3.3 Seepage Rates Using the Geochemical Observation Database

The discussion in Sections 4.3.1 and 4.3.2 suggests that three categories of geochemical signals might be used for identifying or quantifying inflow through a cover: (i) increases in tracer concentrations associated only with inflow through the cover, (ii) increases in tracer concentrations associated with recharge in general, and (iii) dilution of tailings waters associated with inflow and recharge (dilution tracers). Only the first of these three categories might have an unambiguous inflow signal potentially feasible to observe outside of the impoundment. Potential tracer candidates in the first two categories were identified in general terms, but none of the potential tracer candidates are contained in the geochemical database.

The geochemical database does contain several potential dilution tracer candidates at several sites, most notably chloride. Befitting the intent of the observations, which was to monitor groundwater conditions resulting from seepage, the existing geochemical database exclusively contains measurements from wells and surface water bodies outside any impoundment (some sites did monitor geochemistry within the tailings, but the data are not available). However, locations outside the tailings are typically poorly suited for detecting a dilution-tracer inflow signature.

Given that the geochemical database derives from measurements intended to detect seepage and is not suited for detecting dilution plumes, is there any information about the cover that might be gleaned from the existing geochemical database?

6.3.3.1 Seepage and Geochemical Signals

The seepage rate does provide some information regarding inflow. At some point in time, a hydraulic equilibrium state evolves so that average seepage is equal to average inflow. Once this condition is reached, combining the geochemical signatures of background groundwater and seepage fluids with a mixing model and observations outside the impoundment can be used to infer inflow. However, it is important to understand the hydraulic system before a mixing model can be appropriately applied.

When the bottom of the impoundment is sufficiently leaky, the impoundment will completely drain. If the impoundment is sufficiently impermeable (a “bathtub”), the impoundment water table will rise close to the surface and the water table will equilibrate through evaporation or development of springs (and induce surface water flow). Between these extremes, water table levels may be ephemeral or may be controlled by horizontal seepage or expansion and shrinking on a sloping bottom.

All of the impoundments were emplaced above an unsaturated zone, implying that the equilibrium condition should also have an unsaturated zone under the impoundment. In most cases, the dominant seepage pathway is vertical. At Bear Creek and Gas Hills North/Lucky Mc, lateral seepage may be the dominant pathway.

Seepage is controlled by Darcy's law, and can be written

$$Q = -AK\nabla h \tag{6-7}$$

where Q is total volumetric flow, A is cross-sectional area, K is hydraulic conductivity, and h is head.

When the dominant seepage pathway is vertical, the unsaturated zone will form during drainage or once the draining finishes, depending on the hydraulic conductivity of the tailings and underlying materials. Once the tailings waters become perched, the seepage rate is proportional to the saturated thickness above the restricting (least permeable) layer, thus the seepage rate will decrease as the water table drops. The seepage rate will continue decreasing until it reaches the inflow rate.

When the dominant seepage pathway is lateral, the seepage rate is proportional to the hydraulic conductivity and saturated thickness of the lateral release layer. Again the seepage rate will decrease as the water table drops until it reaches the inflow rate.

This behavior of seepage decreasing to an asymptotic rate balancing inflow will result in distinct geochemical signatures in the environment under certain conditions. Seepage from the tailings impoundments usually mixes with dilute waters flowing under the impoundments. Assuming the seepage concentration is relatively steady, at least for conservative constituents, a hydraulic signal with large initial flows that decline over time to a much smaller steady rate will result in a chemical signature of high initial concentrations where the seepage meets the underflow. As long as the seepage rates can maintain a groundwater mound, the concentrations at the center of the mound should remain relatively steady with radial growth of a plume.

Once seepage rates no longer support a mound, underflow can begin diluting the seepage and, where the mound previously existed, concentrations decline over time until hydraulic equilibrium is established. From this time on, concentrations under the impoundment very gradually decline as inflow through the cover depletes the store within the tailings.

Concentrations under the impoundment are expected to fluctuate once the groundwater mound decays. These concentration fluctuations stem from fluctuations in seepage and underflow rates. Before the long-term hydraulic equilibrium develops, underflow rates will fluctuate in response to natural recharge events even though seepage rates remain fairly steady. After the long-term hydraulic condition develops, inflow events will create transient seepage rates that may spike concentrations. Concentration fluctuations will be small when the underflow is small.

Two limiting cases illustrate how the seepage plume may evolve over time: (i) very slow drainage (background fluxes are large) or (ii) very rapid drainage (background fluxes are small). In the slow drainage case, the seepage fluxes will evolve into a quasi-steady elongated plume. In a homogeneous medium, this plume would have concentrations monotonically decreasing with distance from the impoundment and with distance from the plume axis. Once the plume reaches a quasi-steady state, concentrations will drop uniformly as the seepage flux declines.

In the rapid drainage case, the sudden flush of seepage induces a hydraulic mound with high concentrations. As seepage drops to the long-term inflow rate, the mound declines and the released seepage waters move downgradient. Because the rate that mass enters the groundwater is much smaller than early seepage, this scenario results in a contaminated zone moving with the background flow. For some time in a homogeneous medium, concentrations would monotonically decline away from the center of the moving contaminated zone, not from the impoundment seepage point. Once enough time has passed, continued steady influx will allow the plume to evolve into a quasi-steady state.

6.3.3.2 Inflow and Geochemical Signals

The transport equation for a conservative species can be written as

$$R\frac{\partial c}{\partial t} = -v\nabla c + \nabla(\boldsymbol{D}\cdot\nabla c) + c_i Q_i \qquad (6\text{-}8)$$

where R is a retardation coefficient, c is concentration, v is velocity, $\boldsymbol{D}$ is a dispersion tensor, $c_i Q_i$ represents the seepage mass influx, and t is time. In principle, the seepage mass influx can be identified knowing the distribution of the input parameters, seepage concentration, and shape of the plume from observations.

Several analytic solutions have been developed for the transport equation. The analytic solutions require that velocity and dispersion remain constant over time. Typically the analytic solution requires that velocity is uniform spatially. When the analytic solutions can be applied, they are readily evaluated. In practice, using an analytic method might be applicable once the flow fields are close to equilibrium after the drainage pulse has decayed. Solving the transport equation usually requires numerical modeling when considering an actual site.

The two limiting cases illustrate that a more-or-less quasi-steady plume will ultimately develop regardless of how quickly an impoundment drains. Clearly the plume will exhibit fluctuations because of episodic recharge and inflow events perturbing the system, but these may be minor relative to the overall configuration. The key difference between the two limiting cases is that under slow drainage a quasi-steady plume develops while the tailings are draining, but under rapid drainage the quasi-steady plume only develops after drainage is complete.

Once a quasi-steady plume develops, estimates of inflow through the cover can be estimated from the velocity field and concentration field on planes perpendicular to flow upstream and downstream of the impoundment in the environment. The restriction is that the concentration of the tailings water is known and longitudinal dispersive transport is small (i.e., the longitudinal concentration gradient is small). This method applies continuity of mass

$$\int_{A_i} c_i q_i dA = \int_{A_{e1}} c_e q_e dA - \int_{A_{e0}} c_e q_e dA \qquad (6\text{-}9)$$

where c is concentration, q is volumetric water flux, and A is area. Subscripts i and e represent impoundment and environment, respectively. A_i represents the impoundment area; A_{e0} and A_{e1} represent the area of the upstream and downstream planes, respectively. Preferably the impoundment concentration would be measured within the tailings at representative locations. Assuming that the concentration at the base of the tailings is fairly uniform, total inflow is the total mass flux passing across the plane divided by the tailings concentration. In practice, directly measuring the mass flux passing the plane would require a dense set of observations to delineate the volumetric water flux and plume concentration fields. An analytic or numerical model might be used to estimate how these fields are spatially distributed given limited observations.

Without additional information regarding water levels within the impoundment, it may be difficult to identify when drainage is complete and the plume concentrations reflect inflow instead of drainage. The rapid drainage case provides additional transient information because the initial blob of high concentrations can be tracked as it moves downgradient, providing clues regarding whether drainage has completed and the groundwater velocity field. The slow drainage case does not provide these clues.

6.4 Summary

A variety of methods for estimating inflow through a cover can be devised using water level and geochemical observations.

The most direct monitoring method uses water level observations from within the tailings, using fluctuations in the water level to infer inflow events. This method requires that a water table exists, thus may not be appropriate after the tailings drain unless the impoundment can support an ephemeral perched zone.

A second monitoring method uses a unique conservative tracer applied to the cover. Observing the tracer in the tailings fluids or the environment unambiguously indicates that inflow has occurred. This method can use observations within the impoundment or in the environment, but observations from within the impoundment are more suitable for quantitative analysis.

It is likely to be very difficult to quantify inflow by identifying waters with an inflow signature unless the inflow is enriched relative to the tailings. Using dilution of preexisting waters to quantify inflow is likely to require unrealistically precise measurements.

Observations external to the impoundment are unlikely to provide direct estimates of inflow to the cover until the transient response to tailings drainage has largely passed, at least near the impoundment. Seepage from the impoundment is likely to be dominated by drainage rather than inflow for years to decades, masking any estimates of inflow. Once the system approaches equilibrium, mass balance approaches may allow estimates using observations from the environment near the impoundment. In order to estimate parameters, however, it is likely to be very important to consider the transient behavior of the system starting as early as possible.

7 SITE-SPECIFIC GROUNDWATER PERFORMANCE TESTING

The methods discussed in Section 6 provide a means of estimating the performance of a tailings cover. In this section, selected methods are assessed with respect to the 10 sites with tailings covers.

In reviewing the publicly available reports for each of the sites, no document was identified for any of the sites that explicitly measured fluxes through the covers.

Some of the 10 sites of interest included emplaced or natural features that tend to reduce losses of the tailings fluids to the environment during operations (e.g., clay liners, low-permeability underlying units), and others used losses to the environment as part of the operations strategy. Each of the sites experienced sufficiently large fluid losses that a strategy of recapturing fluids lost to the environment became part of the operating or reclamation program. Further, residual tailings drainage has occurred at some locations after cover emplacement. Because these fluids lost to the environment during operations mask any later fluid movement through a cover, assessments of cover performance are inherently more uncertain at the 10 sites than at sites designed to limit losses to the environment.

7.1 Observations Within the Tailings

7.1.1 Water Levels

The most direct method for estimating inflow through a cover identified in Section 6 considers fluctuations in the water levels within an impoundment. This method requires estimates of tailings porosity, impoundment geometry, a sequence of measured water levels within the impoundment, and detailed dewatering and injection pumping rates.

Impoundment monitoring wells were not identified in examined documents describing Ambrosia Lake West, Gas Hills East, Gas Hills West, Highland, or Split Rock.

Monitoring wells were located in impoundments at Bear Creek, Church Rock, Gas Hills North/Lucky Mc, Grants, and Shirley Basin North. None of the examined documents described water levels within the impoundments at Bear Creek, and the monitoring wells identified in a map (Anadarko, 1996) may have been completed in the underlying bedrock. Only snapshots of tailings Church Rock water level data during the operations period were identified. Pathfinder (2000) reports 71 tailings wells for the Gas Hills North/Lucky Mc site but did not report water levels. The Grants site has numerous tailings wells, but these wells are associated with an active injection/extraction program intended to flush out contaminants and the influences of an inflow event are likely to be small relative to the corrective action program. Grants tailings wells report water levels for the underlying alluvium. The Shirley Basin North site maintained an active tailings monitoring system, and recorded water levels in the tailings, but the water levels are not tabulated and are only available as poorly legible undated values reported in contour plots in the subset of the annual monitoring reports that are publicly available.

It appears that the Grants site is the only remaining site with active tailings monitoring wells. Each of the other sites with tailings monitoring wells decommissioned the wells prior to the stability period.

Based on these considerations, there is insufficient publicly available information to apply this method at any of the sites. The licensees at several of the sites may have gathered sufficient data to have performed estimates using this method during corrective actions, although analyses using this data would need to account for pumping and injection wells.

7.1.2 Geochemical Signatures Specific to the Cover or Inflow

Geochemical samples of tailings fluids provide unambiguous evidence of inflow through the cover if the cover has some geochemical signature that is not otherwise found in the tailings fluids. The covers are typically constructed using site materials or relatively inert rocks, and no geochemical signal specific to a cover was identified in the documentation examined that might provide an indication of cover inflow at any of the sites.

A signal might have occurred if an herbicide had been applied, but no documentation of such an event was identified for any site.

Future investigations might consider applying a targeted tracer during or after construction, which would provide a direct means for estimating inflow. Future investigations might also consider the potential for an atmospheric signal to contrast with the tailings waters, such as might occur if the tailings water source and milling process was isolated from atmospheric inputs.

7.1.3 Geochemical Dilution

Section 6 identifies another way for estimating inflow through a cover, using a time series of geochemical observations within the tailings fluids in a mass balance model. Inflow of dilute waters into a concentrated solution decreases the concentration of a conservative chemical species, such as chloride.

Most of the tracked species at the sites are not conservative, because their solubility and sorption characteristics depend on the oxidation state and thus will naturally evolve over time due to microbial action and atmospheric exchange.

As described in Section 6, even under optimal conditions care would be necessary to quantify inflow using chloride concentrations, because it would be necessary to track the vertical concentration profile over time. Dilution calculations require greater analytic accuracy than tracer calculations to achieve a given precision for an inflow estimate. Further, the mass balance approach applied to the tailings waters is sensitive to the concentration of inflowing waters that reach the water table within the impoundment, which is likely to be substantially influenced by exchange with concentrated trapped fluids in the unsaturated zone between the cover and tailings water table. It is not clear how the contributions from trapped fluids would be quantifiable.

Because of these considerations, observations of geochemical dilution are likely to be more qualitative than quantitative estimates of inflow. A long time series of increasingly dilute chloride concentrations reproducibly obtained from the top of the tailings water table would be an indication that inflow is occurring, but it is likely that quantitative estimates would require substantial dilution. If substantial dilution were observed, it would be a reason to consider further investigation.

7.2 Return to Pre-Operation Conditions

As described in Section 6, water level observations could provide information regarding the performance of a tailings cover with respect to net infiltration through the cover. Some of the 10 sites of interest included features that tend to reduce losses of the tailings fluids to the environment during operations (e.g., clay liners, low-permeability underlying units), and others used losses to the environment as part of the operations strategy. Each of the sites experienced sufficiently large fluid losses that a strategy of recapturing fluids lost to the environment became part of the operating or reclamation program.

Cover inflow is most readily identified once the perturbations to the environment stemming from tailings drainage have decayed, so that any signals in the environment that are related to an impoundment are a result of inflow and not drainage. Accordingly, it is important to identify whether the drainage signal has decayed. The drainage signal unambiguously has finished decaying once the water table in the environment has recovered to levels consistent with minimal seepage from the impoundment. If a water table persists at levels consistent with ongoing drainage, it implies that either drainage has not completed or there may be significant cover inflow. Therefore, comparing ongoing water levels with pre-operation water levels is a useful first step in assessing whether seepage has ceased.

Although not measured at any site, pre-operation natural recharge at each of the 10 sites would typically be a few percent of annual precipitation. Natural recharge is likely largest in channels, and is likely to be smallest in deep soil away from channels. Outcrop areas are thought to recharge bedrock at some of the sites (e.g., Ambrosia Lake West, Highlands). If a cover experiences inflow similar to recharge in deep alluvium, as might be expected, placing a tailings impoundment and cover would result in either minimal change or a reduction in recharge once the tailings have drained. In this case, ultimately water tables should decline to pre-operation levels or lower.

In order to compare water tables, pre-operation and current levels are required. The comparison is direct if the site is expected to return to pre-operation levels. If some feature at the site has changed (e.g., an interceptor trench has been installed), an indirect comparison would require estimating the equivalent water levels that would have occurred with the changed feature. Typically an indirect comparison would require numerical modeling.

It is not possible to directly compare pre-operation and current water levels at any site because no precise observation of a pre-operation water table elevation was found in any of the documents examined.

A less precise comparison is possible at the Ambrosia Lake West and Church Rock sites, both with tailings impoundments predominantly sited on alluvium. The available information indicates that the alluvium was unsaturated at these sites prior to mining. Therefore, an ultimate return to unsaturated conditions in the alluvium would be expected at these sites.

The Church Rock alluvium has not completely desaturated, but water levels have been continually dropping in all alluvium wells for more than 20 years (aside from minor responses to changing corrective action pumping). Any cover inflow is clearly insufficient to maintain water levels at this site (although corrective action pumping also has influenced the rate of decline), and it appears that the alluvium will desaturate in the future. At the Church Rock site, the rate of decline evident in the available observations may permit approximate alluvium water balance calculations providing information on the impoundments, because the decline is generally due to vertical losses into the bedrock predominantly supplied by storage and inflow from the tailings impoundments. Cover inflow at this site is the difference between the rate that the alluvium is draining into the underlying bedrock and the capability for the bedrock to accept waters draining from the alluvium. Given hydraulic property measurements for the bedrock and pumping rates, it would be possible to construct a groundwater model to estimate combined cover inflow, tailings drainage, and natural recharge; however, the available documents may not provide sufficient information for firm estimates.

Water levels in most Ambrosia Lake West alluvium wells are decreasing (some are relatively steady or even increasing) since the discharge of mine dewatering waters ended in 2006. This behavior is a signature of laterally redistributing waters, perhaps draining into a permeable bedrock zone, reacting to the stoppage of mine discharge. Although generally declining water tables exist at this site, monitored alluvium wells may provide little information on cover performance (unlike the Church Rock site) because the interceptor trench hydraulically isolates the impoundments from the monitored alluvium. Note that the trench may provide a recharge source to the bedrock aquifer that was not previously present.

At the Highland site, pre-operation water level information is available from one or two wells, but this does not locate the pre-operation water table elevation because the location of the wells is not provided in the available reports and there may have existed a significant hydraulic gradient across the site. Further, the Highland Pit Lake has permanently lowered the water table at the Highland site, so it would be necessary to model the long-term water level to make a comparison with observed levels.

At the seven other sites, the long-term hydrologic balance with a cover behaving like deep alluvium should return water tables to levels similar to the pre-operation conditions, but no estimate of the pre-operation water table was found in the publicly available documents.

7.3 Site-Specific Control Volume Estimates

The control volume approach calculates cover inflow by (i) defining a control volume around part of the environment surrounding the impoundment, (ii) estimating changes in storage and fluxes through all control volume sides that are not contacting the impoundment, and (iii) calculating outflow from the impoundment as the residual after accounting for all other fluxes. The outflow boundaries for the impoundment form part of the control volume boundary. The control volume method can be applied both for water volumes and for constituent species, such as chloride mass. The control volume approach is particularly useful for relatively simple geometries; for more complex conditions, it is generally necessary to use numerical methods to estimate fluxes. Formally applying the control volume approach is useful for identifying all of the data streams necessary for estimating fluxes based on field observations, and for identifying situations where uncertainties may overwhelm the contributions from impoundment outflow.

In selecting control volume boundaries, it is useful to align boundaries along surfaces expected to experience negligible fluxes across the boundary. For example, the base of a low-permeability unit is a reasonable boundary in the saturated zone. Control volume boundaries perpendicular to and parallel to flow paths are also useful for calculating fluxes and assigning no-flow boundaries, respectively. Note that a flow path represents a no-advective-transfer boundary in calculating constitutive mass balances, but diffusive or dispersive mass transfer may occur perpendicular to flow paths close to a plume.

The control volume approach is mathematically stated as

$$\frac{\Delta S}{\Delta t} + \sum Q_i - \sum Q_o = Q_t \qquad (7\text{-}1)$$

where S is mass stored in the control volume, Q is total flux across a control volume surface, and subscripts i, o, and t represent inflow, outflow, and outflow from the impoundment, respectively. Note that a positive Q_t represents total outflow from the impoundment so that the opposite of Q_t represents input to the control volume. Also note that the outflow from the impoundment represents the total of tailings drainage and cover inflow.

In this approach, a robust estimate for Q_t requires that either (i) both inflows and changes in storage are small relative to outflows or (ii) inflows and outflows are both small relative to change in storage. Further, a robust estimate for cover inflow requires that tailings drainage is small relative to cover inflow (i.e., the tailings have essentially finished draining). When these conditions are not met, estimates of Q_t are calculated by taking the difference between large numbers. It may be necessary for extremely detailed site investigations to reduce uncertainties in the flux estimates sufficiently to provide meaningful estimates of Q_t.

The method may provide useful bounding estimates for Q_t even when other inflows are difficult to quantify. For example, under steady conditions total outflow divided by the area of the cover provides a bounding estimate for cover inflow. If this bounding estimate is sufficiently small, it indicates that the cover is not experiencing substantial inflow without precisely quantifying the actual inflow. On the other hand, if the bounding estimate is large, it indicates that further investigation may be warranted to more precisely quantify the various inflow sources.

The following examples represent first-order applications of the approach, using available information publicly available in ADAMS. At many of the sites, the licensee collected detailed site characterization information, usually for numerical modeling purposes. Refined estimates would be possible in most cases if the more-detailed information were available. In particular, no geologic framework model for the various units is publicly available, and hydraulic conductivity measurements are only very approximately described in the public information.

7.3.1 Site 1—Ambrosia Lake West

The two tailings impoundments at Ambrosia Lake West were formed by constructing embankments of coarse tailings across a shallow ephemeral draw. The impoundments were constructed on alluvium and outcrops of the Tres Hermanos B (Trb) unit. No information was identified regarding the presence or absence of a water table within the tailings. No information as identified regarding the primary seepage pathways, although the impoundment was designed to allow flow to escape through the embankment. Appendix A provides a location figure and additional site background for Site 1, and Appendix F contains the site evaluation worksheet for the site.

A representative control volume for this site can be constructed in several ways.

The base of the Trb would make a convenient bottom boundary. The base of the Tres Hermanos A (Tra) unit may be appropriate as well, because faults roughly perpendicular to flow connect the two units and no estimates of flow down the faults were identified. The low-permeability Mancos shale forming the base of both units likely restricts vertical flow away from faults.

The hydraulic barrier of the interceptor trench forms a clear eastern downstream boundary for part of the control volume. This is a well-defined outflow boundary for the alluvium under the tailings impoundments. Elsewhere, the alluvium may gain some water laterally if runoff from the outcrops seeps into the base of the side slopes and may lose water to the bedrock within the control volume. Flow into the interceptor trench would provide an upper-bound estimate for outflow from the impoundments through the alluvium. No estimates of flow into the interceptor trench were identified. No monitoring wells are screened into the alluvium upgradient of the interceptor trench. Accordingly, no flow estimates are possible for tailings outflow into the interceptor trench.

Flow paths in the Trb and Tra west of the interceptor trench are poorly determined from the available data, because few wells are screened in the relevant units. Three Tra wells and four Trb wells are currently monitored; several additional wells were last monitored in 2005. The set of Trb observations imply that flow is radial outward from somewhere near the northern end of the tailings, presumably the now covered make-up reservoir adjacent to the milling facilities. The Tra observations are too sparse to determine if flow in the Tra is also radial. Regional gradients for both units are to the northeast; the radial pattern would be superimposed on the regional trends. The northern end of the impoundments would represent an outflow boundary. There appears to be a strong downward gradient north of the tailings impoundments, with a water level difference of approximately 46 m [150 ft]; the available data suggests this difference is a local extreme, but implies that there may be relatively little within-fault transfer from the Trb to the Tra.

The upstream boundary could be selected as a vertical plane or as the lateral extent of updip area for the unit. At this site, there are no wells south and west of the impoundments for estimating fluxes across a vertical plane. Approximate estimates for lateral flow across the plane could be constructed by considering recharge in the bedrock outcrop area plus seepage from unlined upstream Ponds 7 and 8, but again no observations are available to constrain the estimates.

Based on the available information, an approximate outflow estimate can be constructed for the Trb unit using the regional Trb gradient of 0.02 reported by Rio Algom Mining, LLC (2010), an estimated transmissivity of 0.4 m^2/d [4.7 ft^2/d] (AVM, 2000; Maxim, 2000), and a cross-section width of 1,829 m [6,000 ft], yielding estimates of approximately 57,000 m^3/yr [2×10^6 ft^3/yr] passing out of the tailings impoundment width in the Trb. If this is applied over an area of 140 ha [350 acre], roughly the tailings cover area, Trb outflow corresponds to 0.41 cm/yr [0.16 in/yr], roughly 1.6 percent of mean annual precipitation.

Rio Algom Mining, LLC (2010) estimates a regional gradient of 0.009 for the Tra. No transmissivity estimate for the Tra was identified, but AVM (2000, Section 2.3.1) characterizes flow in the Tra as much less than flow in the Trb.

No estimate of outflow can be made for the alluvium, because no information on hydraulic gradient or saturated thickness is available for the alluvium upstream of the interceptor trench. If the tailings have desaturated, vertical unsaturated flow to the Trb would be the expected primary release pathway; otherwise, seepage towards the interceptor trench might be the primary release pathway.

At this site, there is insufficient information to estimate even a bounding estimate for outflows from the tailings impoundments because the alluvium pathway cannot be quantified. Given the lack of data, indications that the Trb outflow is substantially larger than expected natural recharge might be a reason for further investigation; otherwise, no conclusion on cover performance can be drawn.

As it turns out, the Trb outflow estimates are approximately the order of magnitude that might be expected for natural recharge through the cover, so no conclusion can be drawn for this site.

7.3.2 Site 2—Bear Creek

The tailings impoundment at Bear Creek was lined with compacted soil above shallow alluvium, claystone outcrops, and the K and N sands of the upper Wasatch Formation. A dam placed across the ephemeral north-draining Lang Draw, and keyed into the claystone below the N sand unit of the Wasatch formation, formed the tailings impoundment. The primary seepage pathway is lateral flow under the northeast end of the embankment within a highly weathered sandstone lens associated with the N sand. This seepage is isolated from the Lang Draw alluvium by an unsaturated rise in the N sand. Seepage through the embankment may also drain directly to Land Draw. Appendix A provides a location figure and additional site background for Site 2, and Appendix G contains a site evaluation worksheet for the site.

The Bear Creek site uses a design approach meant to restrict seepage losses, unlike the Ambrosia Lake West site where losses were an intended part of the design. Unexpected higher-permeability features at the site allowed lateral flow from the side of the impoundments that bypassed the ephemeral channel.

A simple control volume approach applies at the site. The base of the lowest aquifer contacting the impoundments forms the bottom surface. The local hydrobasin boundaries form most of the perimeter of the control volume. An outflow boundary is constructed perpendicular to the primary seepage pathway. Estimates of the outflow in the primary seepage pathway provide a first approximation for inflow through the cover.

Tetra Tech GEO (2011) describes the Bear Creek N sand as formed of small channel sands and overbank sands, dipping to the east-northeast (roughly perpendicular to the original channel). The extent of the N sand could not be identified from the available documentation. At the embankment, the N sand is on the order of 5 to 9-m [15 to 30-ft] thick, with the base roughly at the original channel and eroded away on the west side of the drainage (Anadarko, 2011, Figure 4). In this configuration, seepage exiting the embankment within the N sand can wrap around the embankment keyed into the underlying unit and drain to Lang Draw parallel to the embankment. More distally, the N sand crops out in the unnamed draw and above the Lang Draw channel, thus seepage may only supply Lang Draw near the embankment. The pathway is confined when the tailings water table is more than 20 ft above the original ground surface at the embankment, and unconfined otherwise. Anadarko (2011, Figure 3) suggests that desaturation started prior to 1995. Hydraulic gradients in the vicinity of the seepage pathway appear to be roughly 0.003 to 0.006 in 1996 and 2011, respectively, based on Tetra Tech GEO (2011, Figures 7 and 8). Neither the cross-sectional outflow area nor the hydraulic conductivity were identified. These parameters were measured or estimated in order for Tetra Tech GEO (2011) to perform numerical modeling, but the data were not found in publicly available documents.

Tetra Tech GEO (2011) does provide an estimated groundwater velocity of 20 m/yr [65 ft/yr] for the northern Bear Creek pathway, which roughly corresponds to the primary seepage pathway. This can be converted to a groundwater flux by multiplying by porosity, which was not found in publicly available documents. Assuming a porosity of 0.3, a saturated thickness of 6 m [20 ft], a flow width of 305 m [1,000 ft], and a cover area of 41 ha [100 ac], the calculated flux applied over the cover area is roughly 2.8 cm/yr [1.1 in/yr] or 9 percent of mean annual precipitation. This recharge fraction is somewhat larger than expected for natural recharge. Some of the parameters may provide upper bound flow estimates, and the calculation neglects inflow entering the control volume, which may account for some of the outflow.

7.3.3 Site 3—Church Rock

The Church Rock impoundments were constructed by placing embankments at the base of a slope immediately adjacent to the Pipeline Arroyo channel. The arroyo experienced ephemeral flows during the pre-operation period. Mine dewatering discharge into the arroyo was sufficient to induce perennial flow; with the end of operations, the arroyo has returned to ephemeral flow.

The impoundments are partially constructed above alluvium and partially directly on several sandstone bedrock units (the Z3 and Z1 units of the upper Gallup sandstone). Borrow pits used as evaporation and holding ponds for tailings liquids were also constructed partly on alluvium and partly on bedrock, and seepage from these borrow pits is thought to have entered the alluvium and bedrock units. The combination of impoundment seepage and channel losses created a water table in the previously unsaturated alluvium and bedrock units. Appendix A provides a location figure and additional site background for Site 3, and Appendix D contains a detailed site evaluation worksheet for the site.

At this site, seepage exited vertically from the impoundments and entered the underlying unit. Some seepage within the alluvium redistributed laterally down the dip of the top of bedrock, to the southwest under the South, Central, and parts of the North cells and to the northeast under part of the North cell. Water entering the bedrock units, either directly from the impoundments or after draining through the alluvium, generally moved to the northeast down the bedding dip.

The base of the Z1 (lower) unit is a reasonable bottom boundary for a Church Rock control volume, because flow seeping below the Z1 unit is likely negligible. Lateral horizontal boundaries aligned with the arroyo likely would experience small influxes or effluxes because flows are likely parallel to the arroyo axis.

Two control planes perpendicular to the arroyo axis, bracketing the impoundments, complete the control volume. Aligning one control plane with the downstream end of the Z1 unit eliminates the possibility of inflows across this plane for the Z1 and Z3 units.

Chester Engineers (2010, Table 5) estimates groundwater velocities downstream of the South Cell of approximately 14 to 18 m/yr [45 to 59 ft/yr] for wells 805 and 624. With an estimated median porosity of 0.31, downgradient Darcy fluxes are approximately 4 to 5 m/yr [14 to 18 ft/yr]. The saturated cross section at well EPA 28 is approximately triangular, with a maximum thickness of about 8 m [25 ft] and width of 305 m [1,000 ft], yielding an estimated cross-section area of approximately 1,161 m^2 [12,500 ft^2] and outflow of approximately 4,955 to 6,371 m^3/yr [175,000 to 225,000 ft^3/yr]. This outflow corresponds to 1.0 to 1.4 cm/yr [0.44 to 0.56 in/yr] normalized over the 45 ha [110 ac] combined cell area, or 3 to 4 percent of PRISM 1971 to 2000 precipitation normals at the site.

Some of the alluvium outflow stems from change in alluvium storage. The alluvium water table dropped 0.6 m [2 ft] from 2005 to 2010, or approximately 8.8 ML/yr [3.1×10^5 ft^3/yr] based on an approximate water table area estimated from saturated contours presented by Chester Engineers (2010, Figure 3B). When normalized over the 110-acre cell area, the water table volume change corresponds to 2.0 cm/yr [0.8 in/yr] or 5.7 percent of PRISM precipitation normals.

Only extremely approximate outflow flux estimates can be made using the available information. Wells in the Z1 unit are located downdip of the Borrow Pit 1 contaminant source, so some of the flow passing under the impoundments is not monitored. Wells in the Z3 unit are located downdip of the Borrow Pit 2 contaminant source, which is off the axis of flow passing under the impoundments. The cross-sectional area of flow is difficult to estimate without observations. Further, no data were found with respect to hydraulic conductivity or porosity in either the Z1 or Z3 units. Layer thickness is approximately 23 m [75 ft] for both the Z1 and Z3 units, based on cross sections (Canonie Environmental, 1987, Figure 3).

Chester Engineers (2010) estimates a groundwater velocity on the order of 12.2 m/yr [40 ft/yr in] the Z1 unit during October 2007. Flow lines bounding the tailings impoundments are separated by approximately 610 m [2,000 ft], implying a cross-sectional area of 13,936 m^2 [150,000 ft^2] perpendicular to the groundwater flow direction. Assuming that the porosity is 0.15, outflow in the Z1 unit is approximately 25 ML/yr [9×10^5 ft^3/yr], roughly 5.8 cm/yr [2.3 in/yr] averaged over the impoundment area.

No velocity estimate for the Z3 unit was found in available information, but the saturated thickness adjacent to the impoundments is on the order of 10 ft and the hydraulic gradient is approximately 1.5 times larger than the gradient in the Z1 unit. Assuming that the hydraulic properties are the same in both units, outflow in the Z3 would be approximately 1.14 cm/yr [0.45 in/yr] averaged over the cover area, roughly comparable to outflow in the alluvium.

Based on these approximate estimates, estimated outflow is on the order of 8.1 cm/yr [3.2 in/yr], of which 2.0 cm/yr [0.8 in/yr] is supplied from lost storage as the alluvium water table drops. Based on this estimate, combined cover inflow, tailings drainage, and natural recharge entering the control volume is approximately 6.1 cm/yr [2.4 in/yr], or approximately 18 percent of the PRISM precipitation normal from 1971 to 2000. This is substantially larger than would be expected for natural recharge.

7.3.4 Site 4—Gas Hills East

Two impoundments were constructed at the Gas Hills East site, the Above Grade Tailings Impoundment (AGTI) and the A-9 Repository. The two impoundments are located on the north and south faces of an east-west trending ridge. Eight of the 13 monitoring wells at the site are screened in the Lower Wind River formation, almost all downgradient from the AGTI. The other 5 wells are screened in the Upper Wind River downgradient from the A-9 Repository. The Upper and Lower Wind River formations are separated by a mudstone layer that crops out north of the AGTI and dips to the south-southwest (Umetco, 2001, Appendix C). Appendix A provides a location figure and additional site background for Site 4.

Umetco (2001, Figure 1.17) provides a north-south cross section through the AGTI and A-9 Repository. Umetco (2001, Table 2.7) provides estimated hydraulic property values for many of the wells near the impoundments.

Umetco (2001, Appendix C) models the Upper Wind River with hydraulic conductivities between 0.06 and 0.6 m/d [0.2 and 2 ft/d], with the largest values in a band approximately the width of the A-9 Repository extending to the southwest from the vicinity of the A-9 Repository. Saturated thickness of the Upper Wind River ranges from 0 to 30 m [0 to 100 ft]. Umetco (2001, Appendix C) models the Lower Wind River with hydraulic conductivities between 0.08 and 0.4 m/d [0.27 and 1.4 ft/d], with the largest values extending to the west from the vicinity of the northern portion of the AGTI. Saturated thickness of the Lower Wind River ranges from 0 to 30 m [0 to 100 ft].

Umetco (2001, Appendix C, Figure C-17) describes the flow patterns based on monitoring well water levels. East of the impoundments, the regional flow direction is generally to the west in both the Upper and Lower Wind River units. The Upper Wind River is perched north of the A-9 and the flow direction bends to the southwest near the A-9. The Lower Wind River is unconfined north of the A-9, confined at and to the south of the A-9, and continues to the west through the site.

The operational period for the AGTI resulted in a recharge mound in the Upper Wind River under the AGTI that dropped by approximately 40 m [120 ft] from 1979 to 1996 (Umetco, 2001, Figure 1.17), inducing perched radial flow in the Upper Wind River. No publicly available document was identified that describes the flow patterns during the operational pattern in detail. Presumably the mudstone layer dipping to the south diverted most of the water under the A-9 Repository, and the plume in the Southwestern Flow Regime may largely be AGTI seepage augmented by A-9 seepage.

The Western Flow Regime plume appears to be relatively narrow compared to the AGTI, and the presence of a plume despite a low-permeability mudstone layer seems odd. No description of the source plume was found in publicly available documents. The plume may represent westerly or northwesterly flow during the active period that was able to bypass the mudstone layer. Detailed information on the mudstone topography was not found, so bypassing pathways can only be speculative. The cover abuts East Canyon Creek on the east flank of the AGTI, immediately upgradient of where the plume exists on the west side of the AGTI. Under this scenario, movement of the plume upgradient with respect to the regional flow gradient ceased once the recharge mound decayed sufficiently, so that this pathway may no longer connect AGTI seepage with the Western Flow Regime plume.

Using data provided by Umetco (2001, Appendix C), the hydraulic gradient in the Western Flow Regime is approximately 0.025 and transmissivity values near the AGTI are within an order of magnitude of 10 m^2/d [100 ft^2/d]. Assuming that the length of the AGTI is 1,000 m [3000 ft] in the direction of flow, the flow in the Western Flow Regime corresponds to a recharge of approximately 90 mm/yr [3.5 in/yr] along the length of the AGTI. This flux is sufficiently large and uncertain that it is unlikely that a recharge signal from the AGTI could be unambiguously determined using a control volume approach applied to the Western Flow Regime data, even assuming the pathway for AGTI seepage entering the Western Flow Regime waters could be identified.

The Southwestern Flow Regime had a gradient of approximately 0.1 during September, 2010. Given a saturated thickness of approximately 10 m [30 ft] and hydraulic conductivity of 0.3 to 0.6 m/d [1 to 2 ft/d], the transmissivity is approximately 3 to 6 m^2/d [30 to 60 ft^2/d]. Assuming a representative length for the AGTI along the dip direction of 600 m [2,000 ft], this flux corresponds to recharge of 180 to 360 mm/yr [7 to 14 ft/yr]. Again the flow through the system is so large that inflow through the cover is not likely to be measurable using the control volume approach with the Southwestern Flow Regime data.

7.3.5 Site 5—Gas Hills North/Lucky Mc

The series of tailings impoundments at Gas Hills North/Lucky Mc were formed by constructing a series of embankments down north-draining Reid Wash. The impoundments were constructed between bedrock highs of low-permeability Cody Shale, which serves as an aquitard. The primary seepage pathway is lateral flow within a sand lens that cuts through the eastern bedrock high from the vicinity of the tailings impoundment to the alluvium in adjacent Fraser Draw. Drainage down Reid Wash is thought to be minor because the lowest embankment is keyed into the Cody Shale. Appendix A provides a location figure and additional site background for Site 5.

Like the Bear Creek site, the Gas Hills North/Lucky Mc site uses a design approach meant to restrict seepage losses, where losses were an intended part of the design. In both sites, unexpected higher-permeability features at the site allowed lateral flow from the side of the impoundments that bypassed the ephemeral channel.

The same control volume approach applies at both sites. The base of the lowest aquifer contacting the impoundments forms the bottom surface. The local hydrobasin boundaries form most of the perimeter of the control volume. An outflow boundary is constructed perpendicular to the primary seepage pathway. Estimates of the outflow in the primary seepage pathway provide a first approximation for inflow through the cover.

At the Gas Hills North/Lucky Mc site, the primary seepage pathway is called the Lucky Mc aquifer, connecting Reid Draw and Fraser Draw in two zones near Tailings Impoundments 1 and 2, even though the steep natural gradient implies flow down Reid Draw. The impoundment dams largely block the natural flow. Estimated hydraulic conductivity for the channel area ranges from 0.03 to 8 m/d [0.1 to 25 ft/d], averaging 3 m/d [10 ft/d] (Pathfinder, 2000). Water levels are monitored at the outflow of the channel as it discharges to the Fraser Draw alluvium, but not upstream at the tailings, so a gradient cannot be calculated with present-day observations. Accordingly, no pathway flow estimates can be performed using just present-day data.

Historical observations allow a rough estimate of flow in the channel area. Pathfinder (2000, Section 1.3.3.2) estimates a hydraulic gradient of 0.003 m/m [0.01 ft/ft] in the channel and a cross-sectional area of 1,269 m^2 [13,660 ft^2] (this area decreases as the water table drops). Pathfinder (2000) does not explicitly discuss how the gradient was estimated, but observation wells were located in the tailings and the upstream side of the channel. With these parameters, the calculated flux applied over the cover area is roughly 1.5 cm/yr [0.6 in/yr]. Pathfinder (2000, Figure 1.3-1) suggests that the 20-year average precipitation was 16 cm/yr [6.2 in/yr] at the site, implying that losses through the channel were approximately 10 percent of mean annual precipitation. This recharge fraction is somewhat larger than expected for natural recharge. The PRISM 1971 to 2000 precipitation norm for this site is 25 cm/yr [10 in/yr], implying that losses through the channel were approximately 6.3 percent of mean annual precipitation. Like the Bear Creek site, some of the parameters may provide upper bound flow estimates, and the calculation neglects lateral inflow entering the control volume, which may account for some of the outflow. Pathfinder (2000) refers to estimates of the relevant parameters based on site data, but these values could not be determined in detail from the reviewed documents.

Water levels in TI-12 dropped approximately 2.5 m [8 ft] from 2000 to 2010. Assuming that the present gradient is similar, Pathfinder (2000, Figure 1.3-4) suggests this drop has desaturated the portion of the channel near Tailings Impoundment 1 and has reduced the cross-sectional area in the portion of the channel near Tailings Impoundment 2 by roughly 40 percent over this period.

7.3.6 Site 6—Gas Hills West

Two impoundments were constructed at the Gas Hills West site. A final cover has not been constructed for the smaller impoundment, Tailings Pond #1, so no calculations were performed for Tailings Pond #1. Sixteen of the 19 monitoring locations at the site are linked to Tailings Pond #1. Tailings Pond #2 has been fully reclaimed, but little information is available for estimating fluxes. No geologic cross sections or other data sources suitable for calculating cross-sectional flow areas were identified. The only identified hydraulic conductivity value (SMI, 1996, Section 2.4.1) is a regional hydraulic conductivity value provided as background information. Appendix A provides a location figure and additional site background for Site 6.

The available information is inadequate for estimating seepage fluxes from Tailings Pond #2.

7.3.7 Site 7—Grants

Two impoundments were constructed at the Grants site, both directly emplaced on alluvium. This site is densely monitored, and continues to undergo a complex groundwater corrective action program including active injection and extraction within the tailings proper. Although this site has numerous wells inside the tailings, which is favorable for evaluating cover performance, the corrective action process is so intensive that numerical methods would be the only option for examining the site with any possibility of identifying unusual fluctuations. Appendix A provides a location figure and additional site background for Site 7, and Section 4 describes cover performance with respect to radon emissions.

MFG (2006) describe hydraulic properties, which can be used to estimate control volume properties. The maximum separation between two flow paths that contact the large tailings impoundment is approximately 1,219 m [4,000 ft]. The impoundment is located over a paleochannel, with the saturated thickness of the alluvium ranging from 5 to 18 m [15 to 60 ft]. The saturated cross-sectional area is approximately 1,394 m^2 [150,000 ft^2], and the hydraulic conductivity is between 6 to 15 m/day [20 and 50 ft/day] under the large tailings impoundment. The large-scale hydraulic gradient, excluding the local groundwater corrective action perturbations, is on the order of 0.0037. Assuming a hydraulic conductivity of 3,000 m/yr [10^4 ft/yr], through-flow under the large impoundment is approximately 160 ML/yr [5.6×10^6 ft^3/yr]. Averaged over the impoundment area of 420 ha [170 ac], through-flow would correspond to approximately 23 cm/yr [9 in/yr], which is almost 90 percent of annual precipitation.

This site is poorly suited for evaluating cover performance using observations exterior to the tailings, even with no ongoing corrective program. Natural recharge is typically no more than a few percent of annual precipitation in this climate, thus cover inflow similar to natural recharge would augment through flow by a few percent. Such a small perturbation would require extremely precise measurements to quantify.

7.3.8 Site 8—Highland

The tailings impoundment at the Highland site was constructed by placing an embankment across an ephemeral draw, keyed into a low-permeability unit, like the Bear Creek and Gas Hills North/Lucky Mc sites. Like the other sites, the predominant pathway for seepage losses from the Highland impoundment was through a permeable sandstone unit [the Tailings Dam Sandstone (TDSS]. Like the Church Rock and Grants sites and unlike the Bear Creek and Gas Hills North/Lucky Mc sites, the bedding dip and channel gradient are in opposite directions. In this case, the top of the permeable unit subcrops the impoundment along a long exposure, rather than the side being exposed. This configuration favors vertical losses into the TDSS, then radial seepage superimposed upon downdip flow. Appendix A provides a location figure and additional site background for Site 8, and Appendix C contains a detailed site evaluation worksheet for the site.

At the Highland site, the permeable unit crops out adjacent to the embankment and subcrops in a regolith-filled channel. During the pre-operation period, the TDSS was probably desaturated near the impoundment location aside from any recharge waters from the updip exposure. During the operations period, the substantial recharge mound provided sufficient head for seeping fluids to move updip to the outcrop and subcrop zones, bypass the low-permeability unit under the TDSS, and enter other units. With the decay of the mound, the TDSS has largely or completely desaturated updip of the impoundment. The Highland Pit Lake created during mining operations has permanently lowered the water table in units below the TDSS, and may have influenced the TDSS some distance downdip.

The control volume for this site is reasonably constrained to include only the TDSS, because this is the primary seepage unit. The bottom of a control volume for this site is reasonably located at the base of the TDSS. The updip boundary, presumably an inflow boundary with small inflow under current conditions, reasonably lies where the TDSS crops out or subcrops.

The outflow boundaries are more difficult to identify and quantify, because seepage entering the TDSS may be fanning out in response to the Pit Lake to the west, the downdip direction to the northwest, and a small channel to the north. The water table gradient was 0.0055 in November, 2010, immediately downdip of the TDSS subcrop zone within the impoundment, calculated with TDSS wells 120, 175, and 178. The gradient is diverted slightly towards the Pit Lake relative to the dip direction, but the magnitude is generally representative of other potential well combinations. Upgradient wells 178 and 120 have a saturated thickness of approximately 2 and 6 m [6 and 20 ft], respectively, based on digitized TDSS basal contours (ECMC, 1998, Figure 1.5).

A flux cross-sectional area of 2,600 m^2 [28,000 ft^2] was estimated using 430 m [1,400 ft] to represent the width of the impoundment and 4 m [13 ft] to represent the saturated thickness. Carovillano (1998) modeled the TDSS as having a horizontal hydraulic conductivity of 0.015 cm/s [42 ft/d]. With these ballpark values, the outflow flux from the control volume, normalized by the 81 ha [200 ac] cover area, is 5 cm/yr [2 in/yr]. This corresponds to 24 percent of the PRISM 1971 to 2000 precipitation normals at this location.

Some of this volume may be due to loss of storage. Water levels at the three wells increased by 0.2 m [0.5 ft], decreased by 0.3 m [1.05 ft], and decreased by 0.4 m [1.4 ft] over the previous 5 years. Water levels for the 3 wells fluctuated by 0.5 to 1.3 m [1.7 to 4.2 ft] (19 to 27 percent of their saturated thickness) in the last 5 years, not necessarily synchronously, suggesting that the water level change may not be systematic. The average rate of change for the three wells is 0.04 m/yr [0.13 ft/yr] decline. Assuming that porosity is 0.15, the volume released from storage over the area of the cover is equivalent to 0.58 cm/yr [0.23 in/yr], small compared to the calculated outflow.

The bounding estimate suggests that (i) the combination of cover inflow and tailings drainage is a significant fraction of precipitation or (ii) inflow from upgradient recharge is significantly larger than originally anticipated.

7.3.9 Site 10—Shirley Basin North

The Shirley Basin North site includes two tailings impoundments formed by placing embankments across Mine Creek, a tributary to perennial Spring Creek. The lower embankment parallels Spring Creek at a distance of 305 to 396 m [1,000 to 1,300 ft]. Appendix A provides a location figure and additional site background for Site 10, and Appendix H contains a site evaluation worksheet for the site.

The hydraulic boundary at the stream provides the opportunity for a different measurement approach at the Shirley Basin North site, taking advantage of streamflow measurements. The control volume approach takes advantage of a well-defined outflow boundary and a limited catchment area.

Spring Creek is the primary discharge point for the surficial aquifer passing under the impoundments. Pathfinder (2001, Section 1.2.4) describes base flow measurements of Spring Creek and tributaries in 1982 and 1999, including flow in Mine Creek. Measured Mine Creek flows were 19 L/min [4.9 gpm] in 1982 (a dry year) and 110 L/min [30 gpm] in 1999 (a wet year). Gains to Spring Creek attributed to groundwater discharge to Mine Creek and Spring Creek from the tailings side of the creek were approximately 91 L/min [24 gpm] in 1982. In 1999, gains in the impacted reach were between 140 and 260 L/min [38 and 68 gpm]. These estimates represent gains in streamflow on the order of 10 percent over the reach, and reported optimal flow measurement accuracy is 3 percent. If all of these gains were normalized by the 117 ha [293 ac] cover area, the equivalent flux from the impoundments would range from 4 to 11 cm/yr [1.6 to 4.5 in/yr], or 12 to 35 percent of the PRISM 1971 to 2000 precipitation normal for this site. Pathfinder (2001) attributes some of this flow to recharge to the surficial aquifer upstream of the impoundments, with the flow passing under the impoundments. Note that a groundwater corrective action program was in place during 1999, which included injection wells along the embankment intended to form a groundwater ridge in order to control releases.

Information regarding surficial aquifer topography and hydraulic conductivity was provided, but figures containing the information are poorly legible or missing from the publicly available version in ADAMS. Were this information available, it would be possible to estimate groundwater discharge to Spring Creek using the line of monitoring wells and water levels in Spring Creek to estimate gradients. The Mine Creek contribution could not be estimated without further information.

7.3.10 Site 11—Split Rock

The Split Rock site features two sets of impoundments constructed above a sequence of unconsolidated deposits, the Split Rock Formation, and granite bedrock. The Split Rock Formation primarily consists of sandstones and conglomerates with silty sands. This site is unusual, in the sense all other sites consist solely of sedimentary units. The Old and Alternate impoundments are located in the southwest valley and the Main impoundment is located in the northwest valley. The top of the granite bedrock is V-shaped for both valleys. The valleys are separated by a buried granite ridge, and all of the impoundments are located adjacent to the ridge adjacent to a granite sideslope and near the highest elevation of the sandstone. The two valleys are thought to have drained independently prior to tailings emplacement, but the recharge mound formed by tailings seepage raised the water table sufficiently to allow some flow from the northwest valley to the southwest valley. Appendix A provides a location figure and additional site background for Site 11, and Appendix E contains a detailed site evaluation worksheet for the site.

The hydrologic conditions at this site are relatively simple compared to other sites because of the straightforward geometry and lack of surface water features. The control volume approach is suited for performing a water balance on the closed basins because all outflows are essentially one-dimensional in the Split Rock Formation through the valley mouths. The control volume could consist of the entire basin or just the Split Rock Formation; if just the Split Rock Formation, run-on inflow from the exposed granitic bedrock must be considered.

Outflow from a valley can be estimated across a plane perpendicular the mouth of the valley. This outflow represents the combination of tailings impoundment seepage, drainage from water table decline, and natural recharge. No monitoring wells are located in or near the impoundments, thus it is not possible to develop a more refined estimate near the impoundments.

Cross sections H-I and J-K (SMI, 1999, Figures 18 and 22) suggest triangular cross-sectional areas of 0.058 and 0.045 km^2 [6.2×10^5 and 4.8×10^5 ft^2] for the mouths of the northwest and southwest valleys, respectively.

Four wells are available to calculate outflows, and for all four water levels in 2004 and 2010 are similar suggesting an approximate steady state has been achieved. Using the average water levels over 2006 through 2010, two wells (Well-4R and Well-5) along the northwest valley axis provide an outward gradient of 0.0039 in the northwest valley. Two wells (Well-1 and WN-21) along the southwest valley axis provide an inward gradient of 0.00031 in the southwest valley (water levels in the closer well are 0.2 m [0.5 ft] lower than the outer well). The conceptual model for this site suggests that inward flow is unexpected in the southwest valley. The measuring points for the wells may be inconsistently surveyed. On the other hand, the water levels are in the southwest valley wells are approximately 3 m [10 ft] higher than the northwest valley water levels, so the upper southwest valley may be draining to the northwest valley. For the purposes of the calculation, it is assumed that the southwest valley is an inflow boundary and the northwest valley is an outflow boundary. The southwest valley inflow is approximately 6 percent of the northwest valley outflow.

SMI (1999, section 2.2.3) describe regional values of hydraulic conductivity ranging from 0.2 to 1.6 m/d [0.5 to 5.4 ft/d]. The SMI (1999) appendix containing site measurements is not publicly available in ADAMS. MFG (2003, Figure 4.6-1) displays calibrated hydraulic conductivity values in the southwest valley, implying that the calibrated values for the cross section may be between 3 to 24 m/d [10 and 80 ft/d]. If hydraulic conductivity is assumed to be 3 m/d [10 ft/d] in both valleys (the low end of the site-measured values), the combined northwest and southwest valley outflow flux is 33 cm/yr [13 in/yr] averaged over a cover area of 73 ha [180 ac]. This is 120 percent of the PRISM 1971 to 2000 precipitation normal at this location. A larger value for hydraulic conductivity would increase the calculated outflow proportionately; site-specific information missing from the publicly available version of SMI (1999) may be very useful for constraining the calculated flows.

MFG (2003, Figure 4.3-1) tabulates recharge estimates for the granite outcrops surrounding the valleys. MFG (2003) assumes that 15.4 cm/yr [6.07 in/yr] runs off the granite and recharges at the base of the hillslope, although it is not clear how the estimate was verified with site observations. The combined outcrop area contributing to the two valleys totals 144 ha [356 acres], double the cover area. Scaling this flux to the cover area corresponds to 30 cm/yr [12 in/yr]. MFG (2003) and SMI (1999) assume that direct recharge into the valley floor occurs at 1.5 cm/yr [0.6 in/yr]. These combined recharges would essentially balance outflow with the lowest estimated hydraulic conductivity.

The available information suggests that large fluxes are passing through the system, much larger than the inflow that would be expected from even a poorly performing cover. Although the calculations are necessarily very approximate given the available data, they suggest that it is unlikely that measurements using existing wells will be sufficiently precise to permit estimating cover influxes. If wells adjacent to the impoundments existed, it might be possible to better constrain fluxes across a control volume.

7.3.11 Implications of Site Analyses

All of the analyzed sites include unconsolidated units (i.e., alluvium, regolith, or eolian deposits) and at least one seepage pathway within a permeable sandstone unit. The permeable sandstone unit formed the primary seepage pathway in several of the sites.

Most of the impoundments were constructed by placing an embankment across an ephemeral draw. Every such impoundment included a seepage pathway releasing to a permeable sandstone unit, even at the two sites (Bear Creek and Gas Hills North/Lucky Mc) that initially were thought to have a low-permeability rock underlying the impoundments. These sites are typically constructed on units formed in a fluvial depositional environment, which is inherently heterogeneous because of later paleochannel erosion. If the containment strategy for a future impoundment relies on a low-permeability unit to retain water in the impoundment, it would be wise to ensure that no such lens exists around the perimeter of the impoundment. A lens may only contact a fraction of the impoundment base.

Most of the sites included at least one alluvium pathway and one sandstone pathway. During the operational period, a recharge mound typically formed and often created radial flow from the impoundment. As the mound decayed, the alluvium pathway typically drained down the top of bedrock and the bedrock units typically drained approximately in the down-dip direction. At different sites, these pathways were in the same direction, opposite directions, or perpendicular to one another. Surface water bodies locally influence these patterns. Monitoring wells placed in the consistent drainage patterns at any future sites are most likely to observe seepage.

7.4 Summary and Conclusions

Several general techniques for testing cover performance with respect to inflow were evaluated against available site data in this section. These techniques consider (i) signals measured in the tailings fluids, (ii) return to pre-operation conditions, and (iii) control volume calculations to provide bounding estimates of cover inflow. The control volume calculations are a simple form of a numerical model.

Transient measurements of water levels from wells screened within coarse portions of the tailings are likely to identify inflow through the cover. A rise in the water level is an unambiguous signal that an inflow event has occurred. Even when the water level is continually falling, a perturbation in the rate may also signal an inflow event. Several of the sites monitored wells sampling the tailings during operations or groundwater corrective action programs. After examining the available information from the sites, it is clear that there is insufficient publicly available information to detect an inflow event from water level observations in the tailings at any of the sites. The licensees at several of the sites may have gathered sufficient data to have performed estimates using this method during corrective actions, although analyses using this data would need to account for pumping and injection wells.

No geochemical signature was identified specific to a cover or surface application at any site that would provide an indication of inflow. Future investigations might apply a tracer to the surface or during cover construction to provide an unambiguous inflow indicator.

Under favorable conditions, dilution of a conservative species, such as chloride, in tailings waters may provide an indication of inflow. There is no publicly available data set for any of the sites that would permit testing this method.

A simple reality check considers whether the site conditions are returning to the pre-operation conditions, or to an equivalent state if the mining activities have permanently affected the hydrologic conditions at the site. The method could not be applied directly, because no precise pre-operation water level measurement was found in publicly available information for any site. Three sites did have some initial information. A reasonable comparison could be made at the Church Rock site, because the available information identified the alluvium aquifer as initially desaturated and the water levels are currently monitored. Even though similar information was available at the Ambrosia Lake West site, it is not possible to make a comparison because no information is available regarding current conditions near the impoundment. The Highland site has reported early water levels, but the location and unit of the water levels are unknown and the site hydrology has been permanently modified.

The control volume method uses approximate estimates of inflows, outflows, and changes in storage to estimate inflows from the impoundments. In some cases, sufficient information is available to perform an upper-bound calculation for cover inflow or identify whether site measurements would not be expected to constrain seepage estimates. Performing a control volume calculation is particularly useful for quickly identifying data gaps and potential pitfalls in numerical modeling. Note that an inability to estimate seepage does not necessarily imply that the site is experiencing significant seepage.

The calculations for Ambrosia Lake West were indeterminate because requisite data have not been collected. Similarly, requisite data have not been collected to characterize the Gas Hills West site.

At Bear Creek and Gas Hills North/Lucky Mc, the approximate calculations suggest that the total of cover inflow, tailings seepage, and any other inflows not accounted for would correspond to cover inflow that is somewhat larger than might be expected for natural recharge. At Church Rock, the calculations suggest impoundment seepage may be several times expected natural recharge. At Highland, the calculations suggest that either seepage is larger than expected or recharge inflow from updip outcrops is larger than expected.

The Shirley Basin North site is the only site that allows quantification of total outflow by measuring changes in streamflow. This may not be suited for routine measurements, but presumably would be valuable for calibrating discharge estimates based on water levels measured in the stream and groundwater. Unfortunately, the only available streamflow observations are prior to the end of the corrective action program. Some of the key information at Shirley Basin North for developing flux estimates from groundwater is poorly legible or missing from publicly available documents.

Using the control volume approach at the Grants site strongly suggests that the Grants site has such large flows passing under the impoundment that it would not be suitable for applying a control volume approach (or a numerical model) to estimate cover inflow. The Split Rock site initially appeared particularly promising for a control volume approach, but the natural control volume of the closed hydrologic basin appears to experience such large natural fluxes that expected tailings seepage could not be discerned. The Gas Hills East site also appears to have sufficiently large natural fluxes that tailings seepage is unlikely to be measurable with a control volume approach.

8 SUMMARY AND RECOMMENDATIONS

8.1 Project Summary

The two-year project had two main objectives: (i) seek clues regarding the performance of mill tailings covers at 11 sites and (ii) provide recommendations for improved methods for examining cover performance at existing and potential future sites.

The 11 NRC-regulated sites of interest are classified as Title II sites under the UMTRCA Act of 1978, as amended. A wealth of data has been provided to the NRC across these sites, in some cases representing decades of measurements. One data stream, radon flux emissions, directly measures cover performance, although typically at a single snapshot in time. Another data stream, geochemical measurements, measures overall impoundment performance (thus only indirectly measures cover performance), but the data stream represents numerous measurements over time.

The first year of the project was devoted to (i) collecting publicly available data from all of the sites, (ii) building a database of all radon flux and geochemical measurements, and (iii) developing a high-level understanding of the site characteristics pertaining to the covers. These tasks drew to a close in early FY2012. This effort produced two MS Access databases and 11 site summary reports. The radon flux database includes more than 1,900 radon flux observations from 9 sites, and the geochemistry database includes more than 800,000 geochemical observations from all 11 sites. Additional geochemical observations were obtained late in the project for several sites, too late for site analyses, but the observations will be added to the geochemistry database prior to the end of the project.

The second year of the project has been devoted to exploring limitations and potentials in the databases with respect to evaluating cover performance at 10 sites. The eleventh site, the Sequoyah site in Oklahoma, was not considered because there are no mill tailings on the site. Cover performance with respect to radon flux was considered independently from cover performance with respect to inflow of meteoric water into the tailings impoundments.

8.1.1 Cover Performance With Respect to Radon Flux

The Grants site proved to provide useful additional data regarding radon fluxes, because 60 locations at this site were sampled in seven consecutive years. As discussed in Section 3, these measurements indicate that radon flux emissions are likely to be quite spatially heterogeneous at a local scale (on average varying by a factor of 15), but large-scale patterns appear to be persistent across a site over time (mean values vary by almost a factor of 100). The measured mean fluxes for each year only differ by a factor of 2.4, small relative to other sources of variability. The small range in measured mean flux implies that each observed mean flux was within a factor of two of the average, implying that systematic effects may be of regulatory significance if a measured mean radon flux at a site was within a factor of two of the regulatory limit.

This observed range in mean fluxes may be an artifact of variability or changes in site operations. However, the available data hint that antecedent moisture conditions or seasonal changes in properties may systematically influence the mean flux. If so, it implies that extended dry conditions may reduce radon gas emissions relative to the average and particularly wet conditions may increase radon gas emissions relative to the average. Possible explanations include temporary increases in bulk diffusivity due to wetting and drying cycles or systematic decline in radon gas production under dry conditions.

8.1.2 Cover Performance With Respect to Infiltration

At the project outset, staff anticipated that time-series analyses of geochemical observations would be a useful method for estimating cover performance, using data from wells selected from graphs and figures in site documents provided by the licensees. Staff used this conceptual framework to construct the geochemical database described in Section 3. Guided by an NRC-provided worksheet (Appendix B), staff performed a series of site-specific analyses to explore the utility of the databases for examining meteoric inflow through covers (Appendices C–H). As the analyses proceeded, it became clear that seepage from the impoundments during operations prior to cover emplacement at the sites substantially influences site conditions. At these sites, antecedent seepage is so large compared to expected cover inflows that the initial analysis approach does not appear feasible.

Sections 5 and 6 examine the theoretical potential for measuring cover inflows using the types of data that are routinely collected from at least one of the sites. Section 5 describes three general strategies for identifying inflow: (i) tracing geochemical signatures unique to the cover, (ii) using hydraulic or thermal signals, and (iii) using geochemical signatures in seepage water. Section 6 examines specific tactics for applying the strategies. These theoretical analyses suggest that

- Tracers applied to the cover would provide unambiguous indications of inflow

- Meteoric tracers indicating cover inflow may exist, but it would be extremely difficult to quantify infiltration with such signals

- Water level fluctuations within the tailings would provide the most directly quantifiable potential inflow signal

- Distinguishing cover inflow from natural recharge would be difficult or impossible using water level fluctuations outside the tailings

- Water balance studies provide a potential bounding estimate of inflow

- Thermal signals are unlikely to provide quantifiable information regarding inflow

- Dilution of tailings fluids is expected to be the dominant geochemical signal from meteoric inflow, but deriving a signal from decreasing concentrations requires much greater measurement precision than deriving a signal from increasing concentrations

- Meteoric dilution of tailings waters may occur, but dilution is unlikely to provide quantifiable information on cover inflow inside the tailings and will almost certainly prove useless outside the tailings

Section 7 describes site analyses using selected tactics. Based on these analyses

- No publicly available meteoric, applied, or cover-specific tracer data were identified for any site

- Some sites measured water levels within the tailings during operations or corrective action programs, but none of these data are publicly available and no site currently monitors within the tailings

- Enough information is available to estimate pre-operation water levels at Church Rock, Ambrosia Lake West, and Highland, which can provide a crude check that inflows are not substantially influencing site water levels. At the Church Rock site, water levels are returning to the pre-operation condition. No information is available at Ambrosia Lake West on current water levels in or under the tailings, thus it is not possible to identify whether the site is returning to pre-operation conditions. The presence of the Ambrosia Lake West interceptor trench represents a changed hydrologic condition that influences the flow fields during the seepage period, although once the seepage period ceases (if it hasn't already ceased) the interceptor trench may not significantly influence the hydrologic state at the site. A different long-term hydrologic condition may occur at Highland, because of the Pit Lake. However, even if the Pit Lake did not influence the site hydrology, the pre-operation data are not sufficiently precisely located to constrain pre-existing water levels.

- Enough publicly available information is available to perform a first-order control volume water balance estimate at most of the sites, allowing bounding estimates for cover inflow. This approach is the only identified method that uses existing data to provide quantitative estimates. The method uses water level data, which is included in the geochemical database for some sites. The method also uses formation topography and hydraulic conductivities, which are external to the Access databases.

- The control volume approach provides the tightest bounds on cover inflow when natural recharge and natural-system fluxes are small, and do not constrain estimates on cover inflow when natural recharge and natural-system fluxes are large or have uncertainties larger than the cover inflow. Numerical water balance simulations are a more detailed way of developing the same type of estimates. Because the two approaches are fundamentally similar, an important implication is that numerical models are most likely to constrain inflow estimates when control volume approaches provide tight bounds and are unlikely to constrain inflows when control volume approaches provide loose bounds.

8.2 Cover Performance at Existing Sites

The most direct means of estimating cover performance with respect to meteoric inflow would be available at a site featuring an impermeable liner or underlying low-permeability bed combined with an internal drainage system. Once the tailings completed the dewatering process, any inflow eventually converts into directly measurable discharge, providing a direct inflow measurement. This necessarily requires that a drainage system exists, which is impractical to install at existing sites.

Tailings water level observations provide the most direct means for estimating cover inflow at sites without internal drains, like the Title II in closure sites of interest. Water balance methods such as the control volume approach provide a less direct method that also can provide flux estimates. Tracers applied to the cover provide another indirect method that can indicate that inflow has occurred. These three approaches are the most promising approaches for estimating cover performance at the existing sites. No other method was identified that provides a practical method for estimating inflow at any of the sites.

Tailings water level observations are most appropriate for tight impoundments (i.e., relatively slow leakage rates). The method is appropriate prior to completion of tailings drainage and, given a sufficiently tight impoundment, after completion of drainage. The method requires that the drainage rate from the impoundment is sufficiently slow that a wetting pulse induces a measurable change in water level. As a rule of thumb, a large wetting pulse should take at least a few months to drain (presuming automated frequent water level measurements) for the method to be applicable. The method is probably not practical if the impoundment hydraulic conductivity is larger than approximately 1 mm/day [14 in/yr].

Water balance methods are most appropriate for impoundments that provide a large seepage signal relative to the environment. Leaky impoundments with little environmental flow are suited for this method. Typically this method would be most appropriate for hillslope impoundments with relatively little upstream catchment.

Tracer methods provide the fallback methodology when the water-level and water-balance methods are not tractable. The tracer approach usefully indicates that inflow occurs, but is less useful for quantifying inflow. The tracer approach is appropriate for leaky impoundments with significant environmental influences, which cannot be considered with the other methods. The tracer method can supplement the water balance approach by confirming that an observed response is because of inflow rather than environmental fluxes. Tracers may also help identify which portion of a cover is poorly performing, if different tracers are applied to different portions of the cover.

Based on analyses presented in Section 7 and the appendices, specific recommendations for estimating cover performance at each of the individual sites include

- Site 1—Ambrosia Lake West (Rio Algom), New Mexico. There is little publicly available information to identify whether the impoundments are tight or leaky, or even if the tailings have finished dewatering. This site is likely dominated by roughly unidirectional downhill flow to the east, perhaps in both the alluvium and uppermost bedrock, and probably has little flow from the catchment above the impoundments. Given the straightforward hydraulic configuration and paucity of site information, a reasonable approach for estimating cover performance would include (i) several water level wells in coarse tailings within the tailings impoundments to estimate water level changes, (ii) several pairs of water level wells bracketing the downstream dam to estimate fluxes across and under the dam, and (iii) monitoring of seepage into the interceptor trench. Tracers would be very useful to distinguish between seepage and flows associated with the Arroyo del Puerto.

- Site 2—Bear Creek (Anadarko), Wyoming. The publicly available information suggests that the impoundment is fairly tight, based on the low-permeability underlying units and discussions describing slow tailings dewatering. This impoundment appears to have a single exit on the north flank of the impoundment, which appears likely to remain active unless the tailings are completely desaturated. The water-level approach is likely to work for this site. Given the straightforward hydraulic configuration, a reasonable approach for estimating cover performance would include (i) several water level wells in coarse tailings within the tailings impoundments to estimate water level changes (especially near the dam) and (ii) several additional water level wells near the exit point to estimate hydraulic fluxes. The combination of the two methods would provide good redundancy at relatively little additional effort.

- Site 3—Church Rock (UNC), New Mexico. The publicly available information suggests that the impoundments are at least moderately leaky, depending on the permeability of the underlying clay-rich alluvium. Seepage from the impoundments is likely to be predominantly vertical. Tracers provide the most likely means to provide an indication that cover inflow is occurring, but a lengthy monitoring period may be necessary before a breakthrough would occur given the fairly thick vadose zone and small influxes. Tracer methods may fail in the long run as the alluvium continues to desaturate. If the underlying alluvium is sufficiently clay rich, water level monitoring with frequent measurements within the tailings may reveal cover inflow. If the underlying alluvium is sufficiently permeable, water level monitoring in bedrock depressions may reveal cover inflow in the future, although responses to an inflow event will likely be spread over a long time because of travel through the unsaturated zone. Monitoring water levels in a bedrock depression may be the most feasible monitoring technique until the depressions desaturate.

- Site 4—Gas Hills East (Umetco), Wyoming. The publicly available information suggests that the AGTI impoundment is likely to be leaky, based on estimates of hydraulic conductivities, with most or all AGTI seepage passing under the A-9 Repository to reach the Southwestern Flow Regime and some unknown amount (possibly none) reaching the Western Flow Regime. Large flows are passing through the system in both regimes. Under these circumstances, the tracer method is preferred for identifying inflow through the AGTI cover. The base of the A-9 Repository is clay-lined, thus the water-level method may work if the sides are not too leaky. Otherwise the tracer method would be favored for the A-9 Repository. The two impoundment covers should have different tracers applied because seepage waters are likely to mix.

- Site 5—Gas Hills North/Lucky Mc (Pathfinder), Wyoming. The impoundments are located above low-permeability units, suggesting that the impoundments are tight except for release pathways on the east flank of the impoundments. Accordingly, the water-level approach in the impoundments is favorable at this site. As a confirmation, it is desirable to consider flows through the release pathways, as recommended for Bear Creek. The release pathways may no longer be active if high water levels are required to activate them. If the release pathways are likely to be active, then it would be appropriate to monitor the pathways with new water-level wells to estimate hydraulic fluxes. If the release pathways are nominally inactive, then tracer testing monitored in Fraser Draw would be recommended to confirm that the pathways are indeed inactive.

- Site 6—Gas Hills West (ANC), Wyoming. This site has two unlined impoundments placed atop bedrock consisting of sandstones, claystones, and conglomerate. One impoundment has a final cover and one has an interim cover. SMI (1996) describes (i) bedrock hydraulic conductivity (presumably horizontal conductivity) as 0.8 to 7 mm/d

(1 to 8 ft/yr), (ii) water levels below the tailings as 12 to 15 m [40 to 50 ft] below original ground surface, and (iii) horizontal hydraulic gradients as 1 percent near the tailings. The hydraulic conductivity range implies that the impoundments are too leaky for the water level approach. The hydraulic conductivity values, combined with the horizontal gradient and assuming that the saturated thickness is several meters thick, imply that the environmental underflows may be significantly larger than the expected cover inflow and therefore the water balance method may not be favored. Under these conditions, tracer methods would be favored. However, vertical conductivity is often smaller than horizontal conductivity by one to two orders of magnitude in sedimentary units. If so, the water level approach would be favored using boreholes in the tailings. Also, the actual saturated thickness is not available, and a water balance approach may be applicable with a thin saturated zone. If so, a water balance could be constructed using fluxes calculated using several pairs of monitoring wells upgradient and downgradient of the impoundments.

- Site 7—Grants (Homestake), New Mexico. This site has two unlined impoundments placed atop alluvium, a classic scenario for a leaky impoundment. Seepage is likely to be vertical through the unsaturated zone to the water table. In this case, significant underflow exists below the impoundments. Accordingly, tracer methods would provide the most feasible indicator of cover performance.

- Site 8—Highland (Exxon), Wyoming. This site features a single unlined impoundment formed by damming an ephemeral channel. During operations, large volumes of seepage escaped vertically into the permeable TDSS bedrock unit exposed within part of the impoundment and thereafter radially within the unit. The impoundment as a whole is leaky, although portions of the impoundment where the TDSS does not subcrop may not be leaky. The radial flow regime within the TDSS appears to be returning to a predominantly downdip regime, potentially spreading because of the Highland Pit Lake and ephemeral channels passing east of the impoundment. Some water may be passing under the impoundment because of recharge updip of the impoundment. These factors create significant uncertainty regarding future flow paths and water level responses. Accordingly, tracer methods would be useful at this site. It may also be feasible to use the water level method within the tailings, and it may be feasible to use a water balance approach within the TDSS surrounding the impoundment. However, it is likely that a relatively larger density of wells would be necessary at this site than at others because of the flow-path uncertainties.

- Site 9—Sequoyah (Sequoyah Fuels), Oklahoma. This site has no tailings impoundment.

- Site 10—Shirley Basin North (Pathfinder), Wyoming. This site features two unlined impoundments formed by damming Mine Creek, an ephemeral channel. A clay unit separates the tailings from the surficial aquifer. The primary seepage exit from the impoundments appears to be associated with permeable units along the initial channel. Water levels downgradient from the impoundments are strongly controlled by a perennial stream roughly paralleling the embankment. The impoundments appear to be relatively tight, thus the water level method is favored at this site. Given the straightforward hydraulic configuration, a reasonable approach for estimating cover performance would include (i) several water level wells in coarse tailings within the tailings impoundments to estimate water level changes (especially near the dam) and (ii) several additional water level wells near the Mine Creek exit point to estimate hydraulic fluxes. The combination of the two methods would provide good redundancy at relatively little additional effort.

- Site 11—Split Rock (Western Nuclear), Wyoming. This site features several unlined impoundments above eolian sand and sandstone, which would typically imply a leaky impoundment. The smaller impoundments are described as drained, but further tailings dewatering is expected in the Main Impoundment. Very substantial recharge in the valleys outside the impoundments is associated with runoff from the surrounding granite ridges, so that substantial flow may occur under the impoundments. Water level or water balance approaches may be feasible if suitable wells are placed in and near the impoundments, but tracer methods are likely to be more robust given the substantial valley recharge.

Each of the sites where the water level or water balance methods are used would likely require a certain amount of testing to determine parameters such as porosity and hydraulic conductivity. These parameters have been investigated at some sites, but the information is typically not publicly available.

8.3 Recommendations and Considerations for Future Sites

8.3.1 Electronic Submittal of Data Supporting Requests for Licensing Actions

During the project, staff analyzed data provided to NRC from a variety of sources, with the sources typically related to licensing actions. In some cases, electronic datasets were provided that are far more complete than required by license conditions. Some project analyses were akin to analyses that might be performed to make regulatory decisions on groundwater protection. Directly manipulating available data supported publicly available analyses at times, and at times suggested potential alternative conceptual models. Lack of relevant publicly available data hampered performing simple site analyses at each of the 10 analyzed sites, even at sites where the licensee collected and referred to relevant data. The lack of data from early and middle phases of site operations was notable, which is particularly relevant for determining whether the site was returning to its initial state after restoration was complete. This experience led staff to consider implications in the context of licensing actions.

In order to effectively perform licensing actions such as selecting points of compliance, it is generally necessary to consider and interpret the available site data, and it is often desirable to confirm licensee assertions regarding site conditions. NRC staff routinely rely on licensee documents to provide both the data required for licensing actions and any contextual information necessary to interpret the required data, but the project analyses indicate that a more informed and precise analysis can be performed when the data are available to manipulate. It is common for licensees to internally maintain such data in electronic formats, such as Excel spreadsheets. Any data presented in tables or figures used to support a licensing request is already in electronic form, thus supplying any tabular or graphical data in electronic form is not onerous to the licensee.

The site analyses suggest that a licensing action related to placing a point of compliance or determining an alternate concentration limit would need to consider the movement of water and water quality constituents across the site. In turn, the relevant data include

- The time history of geolocated water levels across the site
- The time history of geolocated water quality observations
- Geologic unit characteristics (e.g., thickness, dip, faults, hydraulic conductivity, sorption characteristics)
- Stresses and confounding data (e.g., pumping rates)

Geolocating an observation requires that the three-dimensional position of the sample is provided, for example by providing the well location, screening data, and host formation. Geologic unit characteristics are typically determined from borehole logs, outcrop observations, pumping tests, and other relevant tests performed on geolocated core samples. Geolocation data are straightforward to collect as site data are collected, but may be difficult after the fact.

Key issues from a regulatory perspective include

- Ensuring that key licensee assertions are supported by data
- Ensuring that regulatory decisions are able to consider relevant observations
- Ensuring that regulatory decisions at the end of the facility life cycle can consider appropriate data from other phases of the life cycle
- Appropriately managing the data

Based on these considerations, staff recommends that NRC require that requests for a licensing action are routinely accompanied by electronic versions of any data that the licensee uses to support the request. The guiding principle is that the electronic data should be sufficiently complete to permit staff to independently reproduce tables and figures, and to verify data that support conclusions. With this policy, the licensee (or sequence of licensees) maintains a database that will support end-of-facility regulatory actions, perhaps decades after site initiation, and at each regulatory step NRC considers a suitably up-to-date and complete database, provided by the licensee.

The guiding principle would require that geochemical data necessary for a regulatory conclusion are provided electronically (e.g., semiannual water quality report data). The clear implication is that geolocation data must be provided if data are plotted on a site map, water level data must be provided if water levels are plotted, geologic data must be provided if geologic cross sections or topographic maps are provided, hydraulic conductivity estimates must be provided if discussed in the document, and so on. By logical extension, the time history of observations is necessary to support conclusions, implying that semiannual reports include the prior time history of observations. Such historical information is routinely provided by some licensees and is not onerous with current technology.

Providing acceptable (but not required) templates for anticipated data streams would likely be useful for the licensees.

A similar policy would likely be useful for other facilities providing NRC with required geochemical data, such as *in-situ* recovery facilities, decommissioning sites, and geologic repositories.

8.3.2 Considerations Regarding Current Radon Flux Methodology

The time series of Grants radon flux measurements suggests that radon flux emissions are likely to be quite spatially heterogeneous at a local scale, but large-scale patterns appear to be persistent across a site over time. The available data hint that antecedent moisture conditions or seasonal changes may systematically influence flux measurements, but this influence appears small relative to other sources of variability. Winter and spring may exhibit wetter conditions, which may systematically influence radon emissions. No data were available to consider the extent that summer and fall measurements are representative of winter and spring emissions, but the available data do not suggest that a strong affect might be expected.

The large variability in radon flux measurements in the Grants database, both locally and across the site, suggests that addressing spatial variability is the most important aspect of estimating total emissions across the cover. The Grants database suggests that the current number of samples provide a reasonably reproducible mean and median flux estimate from year to year, despite local variability.

8.3.3 Considerations Regarding Measuring or Bounding Cover Inflow

Several lines of analysis suggest that existing water level and geochemical data streams collected at the mill tailings sites, while useful with respect to characterizing performance of the impoundment system, usually cannot be expected to distinguish cover inflow from other fluxes in the system, such as tailings drainage and natural recharge outside the impoundments.

Water balance approaches (control volume approaches or numerical simulations) using measurements outside the tailings can provide bounding estimates for cover inflow, but when other fluxes are large or uncertain calculated bounds do not substantially constrain inflow estimates. Water balance approaches may provide tight bounds on inflow under two related situations:

- Natural-system fluxes are small relative to expected cover inflow and tailings drainage has neared completion

- A distinct and persistent recharge mound exists under the impoundment and tailings drainage is too small to maintain the mound

Monitoring wells placed close to the impoundment are likely to provide tighter balance estimates than wells placed far from the impoundment. At the studied sites, most wells are decommissioned after restoration is complete and remaining long-term monitoring wells are generally located distally from the impoundments (e.g., near the long-term care boundaries). By implication, water balance methods for studying cover performance after restoration would require that more wells are monitored than the current practice.

The study identified two practical data streams that offer possibilities for quantifying subsystem performance with respect to inflow through tailings covers: (i) unique tracers directly applied to the cover and (ii) water level measurements within the tailings. These approaches would apply to present and potential future sites. Both approaches require a time series of observations from downhill zones of coarse tailings, which could be obtained from monitoring wells using present technology.

Documentation for some sites discusses the difficulty of maintaining wells within the tailings because of the harsh chemical conditions. If wells cannot be reliably maintained within the tailings because of maintenance issues, then long-term tracer tests may be the best approach for positively identifying that inflow through the cover has occurred.

8.3.4 Considerations Regarding Potential Future Impoundments

Monitoring cover performance may be relatively straightforward in future impoundments.

Potential future impoundments may be constructed with relatively impermeable liners and a drainage system to promote tailings dewatering. Assuming that no leaks occur, any water produced from the drainage system after the tailings have finished dewatering must stem from cover inflow. Drainage flux provides a direct measure of cover inflow. A rise in water level readings within the tailings would provide an independent means for estimating inflow through the cover, as well as indicating the extent of tailings dewatering.

Assessments of potential future impoundments are advised to consider methods for controlling and monitoring water levels within the tailings many decades after closure.

Each of the sites considered in this project exhibited substantial seepage out of the impoundment, intentionally or accidentally. Potential future impoundments may be constructed using liners, intended to prevent loss of fluids from within the impoundment except for controlled releases through drains. If the impoundments remain watertight but the drainage system fails, cover performance with respect to inflow may be important for long-term performance after site restoration. Continually adding water to an impoundment without losses will ultimately increase the water level to near the ground surface, potentially inducing surface seeps of concentrated tailings fluids.

Because of the potentially deleterious consequences of the bathtub effect, provisions for controlling and monitoring water levels for long durations after closure may be important for future impoundments. One strategy that might prove workable as a fail-safe should a drainage system fail would be to include an overflow drainage layer immediately below the cover, allowing relatively dilute inflow waters to drain prior to substantially contacting the tailings.

Assessments of potential future impoundments are advised to consider site heterogeneity, especially if reliance is placed on low-permeability units.

Two of the sites considered in this project were located on low-permeability units, favorable for retaining fluids within the impoundment, yet both leaked through a permeable lens. Mill tailings sites are typically located in sedimentary rock formed in fluvial environments, which is likely to have created substantial spatial variability. A permeable lens, fault, or ephemeral channel may provide the dominant transport pathway even if it has a small cross section.

Pre-operations flow and tracer data are valuable.

Pre-operations water level data become valuable as the restoration phase nears completion, especially when the site has been disturbed but has not experienced measurable seepage. A point of compliance or point of exposure well is most useful when it is directly in the path that any release would follow. Presuming that impoundments are well constructed, water levels across the site should return to the initial water levels as operational disturbances decay.

Observed seepage plumes indicate that flow pathways exist at the studied sites. Because of heterogeneities, the flow pathways may not be completely obvious from water levels alone. It may be a wise precaution to perform tracer injection studies in the pre-operations period to characterize potential release pathways, thereby allowing better placement of compliance and exposure monitoring wells.

Channels and low spots foster focused infiltration.

Several of the tailings covers feature channels or swales to route rainfall away from the cover. Flow focusing makes such features the most likely sources of focused infiltration through the cover. Such channels are often armored with riprap, which is likely to further promote infiltration because evaporation is dramatically reduced under rock mulch. The design of such channels represents a tradeoff between rapid and slow conveyance of water offsite. Rapid conveyance reduces infiltration by reducing the water contact time, but may foster erosion of the soil cover under the riprap. Slow conveyance increases infiltration by increasing the water contact time, but protects against erosion.

Some sites do not include channels or swales. These sites may also produce runoff without planned conveyance structures, which may create erosion features. Low spots in the cover topography may also foster ponding, particularly likely if tailings settlement modifies topographic gradients. Ponded areas provide a greater potential for cover inflow.

Typical design strategies for surface water conveyance facilities consider water conveyance and bed erosion under maximum conditions, but do not necessarily consider infiltration or bed erosion under the riprap layer. It is recommended that future work considers the tradeoffs between surface water routing, erosion, and infiltration.

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APPENDIX A

SUMMARY DESCRIPTION OF EACH SITE

A SUMMARY DESCRIPTION OF EACH SITE

Appendix A provides a summary description for each of the sites, focused on identifying aspects of the site relevant to hydraulic and geochemical analysis of cover performance in order to guide further analyses. Initial summary descriptions were developed while the electronic databases were approaching completion, and contain less detail than the fact sheets developed in the initial stages of the project.

Each section also includes a short summary of the subsequently developed site analyses. The summary of analyses was developed at the end of the project to provide insight into the extent that the provided information proved useful.

SITE 1—AMBROSIA LAKE WEST (RIO ALGOM), NEW MEXICO

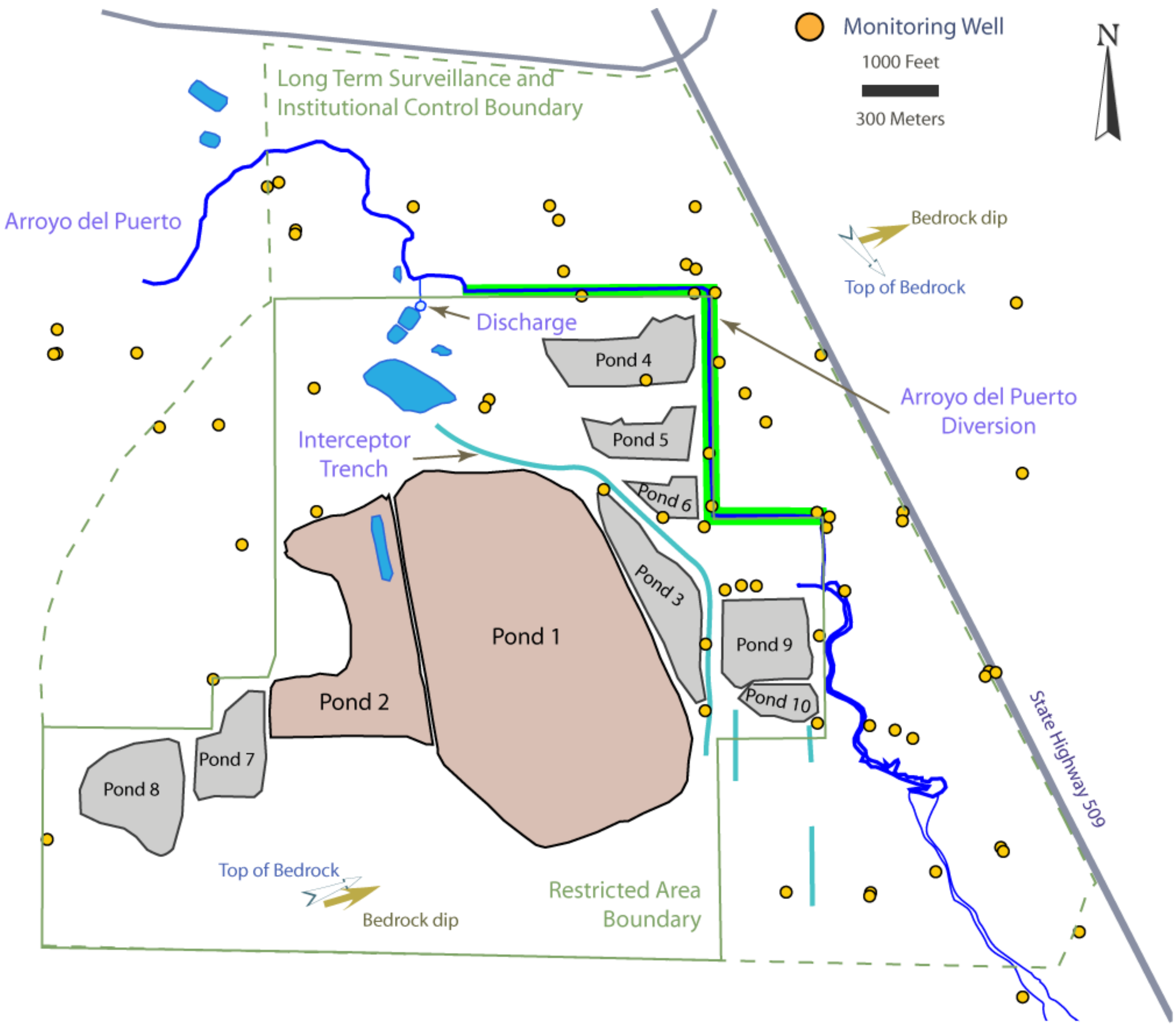

Figure A–1. Site Features at Ambrosia Lake West (Rio Algom), New Mexico

Initial Summary Description

Maxim (2001) describes the geology and hydrology of the site and impoundments in detail. U.S. Nuclear Regulatory Commission (NRC) (2007) provides background information. Tailings basin operations initiated in 1958 and terminated in 1983 at this site. Two tailings impoundments were emplaced at the mouth of a shallow ephemeral drainage emptying to the northeast into the Arroyo del Puerto. The lower impoundment, Tailing Impoundment 1, covers 105 ha [260 ac] and contains 27 Tg [30 million ton] of tailings. Immediately above TI-1, Tailing Impoundment 2 covers 36 ha [90 ac] and contains 2.7 Tg [3 million ton] of tailings. Six unlined ponds were located at the base of the TI-1 dam and two lined ponds were located above TI-2.

Over time, the ponds have been reclaimed with evaporation residues consolidated into TI-1 and TI-2.

The natural channel of the ephemeral Arroyo del Puerto roughly parallels the TI-1 dam; a diversion channel was created further from the dam in 1976.

The tailings impoundments are located on weathered Mancos Formation sandstone (saprolite) or the alluvium (clay to clayey sand) formed from and overlying the Mancos. Two unlined ponds lie on bedrock, the remainder lie on the alluvium. The Tres Hermanos B (Trb), Tres Hermanos A (Tra), and Dakota Sandstone units (all sandstone) underlie the Mancos in descending order. The bedding dip is to the north-northeast, as is the topographic downslope. Underground mines are located downdip. Mine dewatering caused a cone of depression that influenced bedrock water levels near the impoundments. Mine water was discharged into the Arroyo del Puerto upslope of the diversion channel, recharging the aquifer system and potentially cycling back to the mines through the bedrock.

Prior to mining, the alluvium was unsaturated. Most seepage from the tailings impoundments migrates downslope in the saprolite and alluvium, but some migrates more deeply in the Trb and lower units. A 1,890-m [6,200-ft] interceptor trench was excavated to bedrock, up to 11-m [35-ft] deep, generally parallel to the TI-1 dam in 1984, to capture seepage water from the tailings impoundments. The trench has reversed the natural gradient, capturing seepage from the six adjacent ponds prior to reclamation and later flushing the locations using water lost from the Arroyo del Puerto diversion channel. In the late 1990s, the potential for cycling tailings seepage waters through the mine dewatering system and thereby resulting in discharge to the Arroyo del Puerto caused some NRC concern, but the licensee demonstrated that seepage waters would form a negligibly small fraction of the total dewatering flow.

The Access database contains geochemistry records from 6 Dakota Formation wells, 3 Tra wells, 5 Trb wells, and 39 alluvium wells. The semiannual groundwater reports tabulate depth to water, but I have not located well coordinates or measuring point elevations.

Discussion of Analyses

Initial examination of the sites ranked the Ambrosia Lake West site as among the less likely to be amenable to analysis, in part because of the large number of ponds that were expected to complicate the hydraulic behavior at the site. Later examination indicated that the site hydrologic conditions were also strongly impacted by mine dewatering discharge and reclamation activities such as installation of the interceptor trench.

Appendix F contains the worksheet developed for this site, which describes the site in more detail. This worksheet was developed after project staff digested insights from the three most promising sites. Worksheet preparation uncovered a small amount of additional tabulated data not included in the original database preparation. Most site documents predate the NRC Agencywide Documents Access and Management System (ADAMS) system and are not publicly available, hampering site interpretation.

Sections 7 and 8 contain further site analyses. These analyses confirmed that the site was not amenable to analysis with the publicly available information, largely because the monitoring wells are located to track conditions away from the impoundments that are strongly influenced by sources external to the tailings impoundments.

SITE 2—BEAR CREEK (ANADARKO), WYOMING

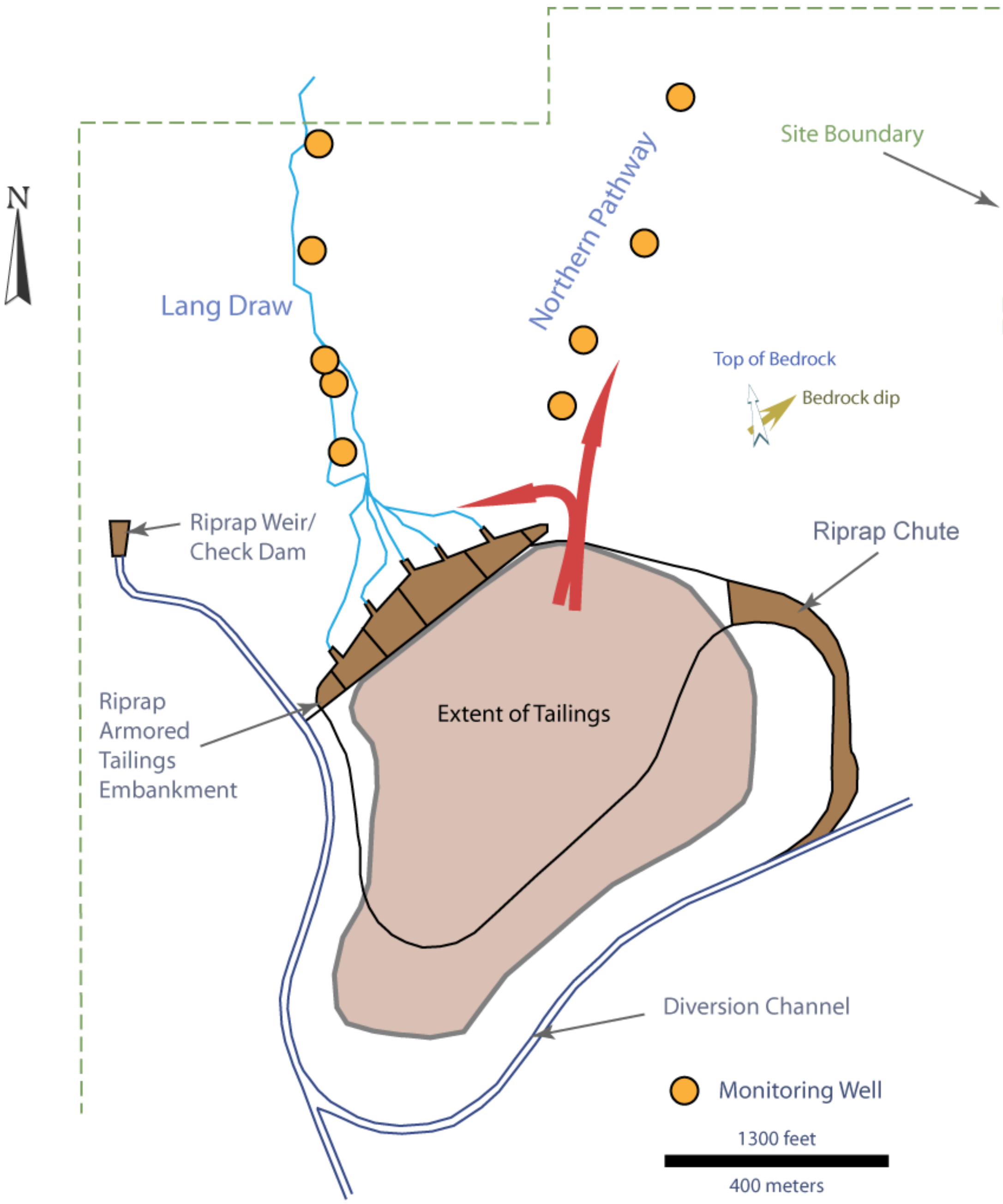

Figure A–2. Site Features at Bear Creek (Anadarko), Wyoming

Initial Summary Description

Anadarko (2011) summarizes the history of the site. Milling operations initiated in 1977 and terminated in 1986 at this site.

A single tailings impoundment was constructed in Lang Draw, lined with compacted soil above a low-permeability unit consisting of interbedded claystone and siltstone. The N Sand sandstone layer under the confining unit drains into alluvium downslope of the tailings dam. The tailings dam was keyed into claystone and siltstone below the N Sand. The basin covers 41 ha [101 ac] and contains 4.3 Tg [4.7 million ton] of tailings. An interim cover was constructed in 1988 and the tailings area reclamation was completed in 1999.

Seepage was first observed in 1978 and a pumpback system was initiated in 1979. Two plumes draining to the north were observed, corresponding to Lang Draw and the adjacent drainage. Groundwater corrective action was completed in 1996, having recovered an estimated 1.14 GL [301 Mgal] of seepage waters. Modeling using a one-dimensional code suggested that an acid front would expand in the decades after pumping stopped. Observations over 2000 to 2011 in the monitoring network included higher concentrations than expected, attributed to the model not accounting for lateral dilution induced by pumping during the pumping phase. This dilution ceased as water level gradients recovered.

The Access database includes data for 9 wells, 5 aligned with the assumed axis of the Lang Draw plume and 4 aligned with the assumed axis of the Northern Pathway plume.

Discussion of Analyses

Initial examination of the sites ranked the Bear Creek site as among the less likely to be amenable to analysis, largely because the available monitoring wells were located along the axis of the plumes, limiting the ability to examine the flow fields.

Appendix G contains the worksheet developed for this site, which describes the site in more detail. This worksheet was developed after project staff digested insights from the three most promising sites. Most site documents predate the NRC ADAMS system and are not publicly available, hampering site interpretation.

Sections 7 and 8 contain further site analyses. These analyses suggest that the site hydrologic conditions are relatively uncomplicated and do not suggest that the existing monitoring wells are unreasonably placed for their intended purpose. This interpretation is tentative given that most site information is not publicly available.

SITE 3—CHURCH ROCK (UNC), NEW MEXICO

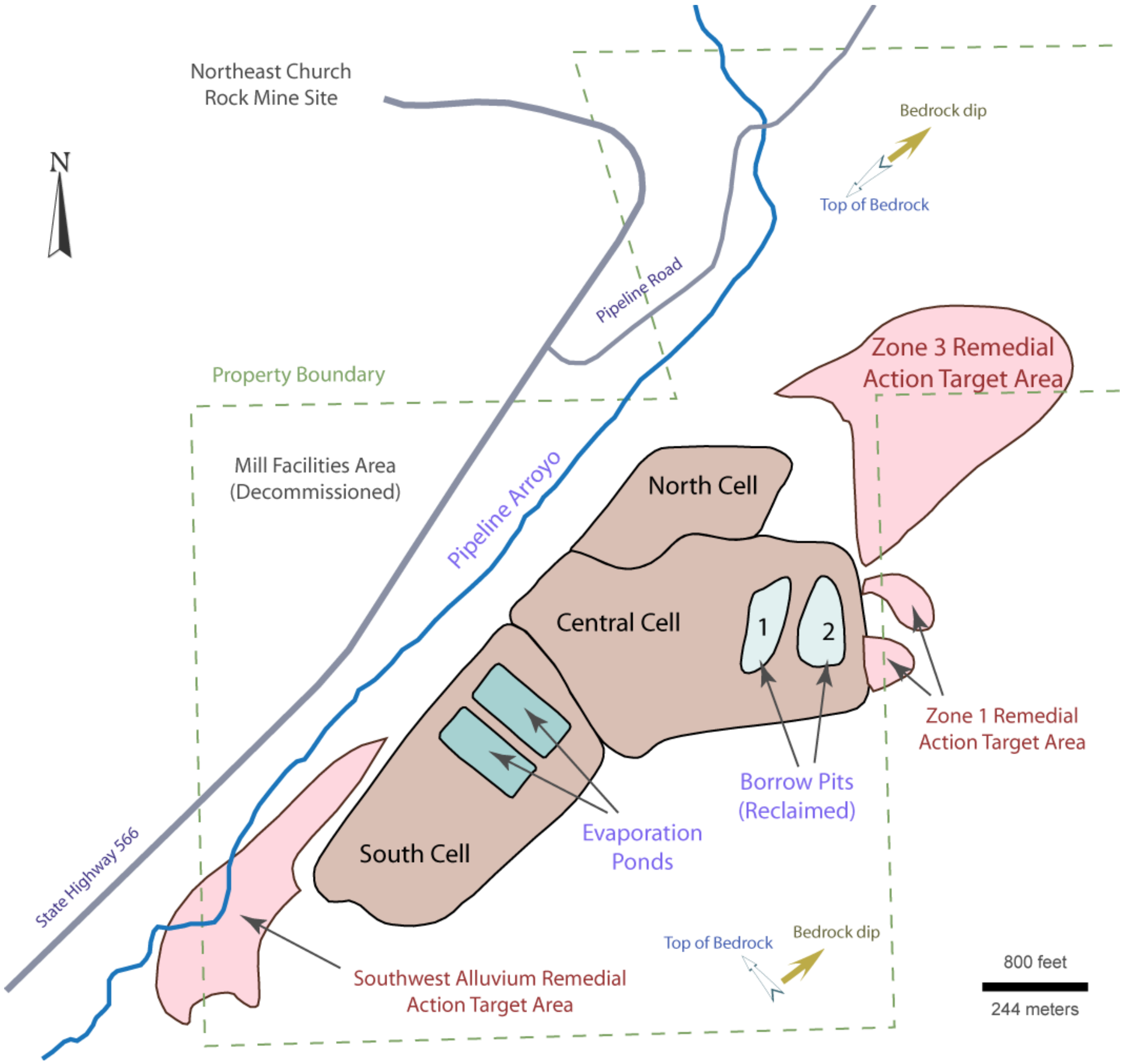

Figure A–3. Site Features at Church Rock (UNC), New Mexico

Initial Summary Description

Milling operations initiated in 1977 and terminated in 1982 at this site. Three tailings basins, the South, Central, and North cells, were placed along the flank of an ephemeral arroyo where a lateral drainage joined the main channel. These cells received tailings from 1977 through 1982; two borrow pits also were active during part of this period. Two lined evaporation cells are located on top of the tailings impoundments to receive waters pumped during groundwater corrective action activities. Radon and erosion barriers were completed by 1996 except for the evaporation cells. The combined tailings basins cover 110 acres and contain 3.1 Tg [3.4 million ton] of tailings.

The arroyo drains to the southwest. Portions of the cells contact two sandstone units dipping to the northeast, the Zone 1 (or Z1) and Zone 3 (or Z3) units, which are separated by a confining unit, and portions of the cells are underlain by alluvium. The borrow pits also partially contacted bedrock, contributing to seepage into the bedrock units. Discharge from dewatering two mines was released to the arroyo from 1967 through 1985, at an estimated average rate of 17 m^3/min [5.3 Mgpd]. Cessation of operations has resulted in substantial drops in water levels.

Interpretation of the Church Rock site data is complex because of (i) direct commingling of mine discharge with tailings seepage under the basins, (ii) opposite flow directions in alluvium and bedrock, and (iii) large pre-existing major-ion stores within the alluvium (e.g., gypsum). These factors make it difficult to interpret what fraction of the observed plumes results from seepage instead of mine discharge.

The Access database includes data for 23 wells in the southwest alluvial aquifer, 13 wells in Zone 1, and 35 wells in Zone 3. Electronic licensee-provided data includes water levels, major ions, minor ions, U, Ra-226, Ra-228, Th-230, Pb-210, and gross alpha. Licensee electronically provided coordinates and screening data for boreholes.

Discussion of analyses

Initial examination of the sites ranked the Church Rock site as among the most likely to be amenable to analysis, because of the relatively large number of monitoring wells and wide variety of geochemical analytes.

Appendix D contains the worksheet developed for this site, which describes the site in detail. This worksheet was the second worksheet developed, during the project stage where staff was initially exploring what types of analyses might be possible given the collected data. This site was useful for developing initial concepts for analysis strategies. Specific suggestions for further analyses are offered at the end of the worksheet. Staff used these suggestions as a motivation for developing the more general analyses of strategic and tactical approaches to evaluating cover performance.

Sections 7 and 8 contain further site analyses. These analyses suggest that the site hydrologic conditions are still recovering from the disturbances during the mining and operational period. The analyses do not identify a cover inflow signature and suggest that even a poorly performing cover may be difficult to identify at this site because the arid climate and large hydraulic conductivities in the system will tend to maintain unsaturated conditions even with cover inflow.

SITE 4—GAS HILLS EAST (UMETCO), WYOMING

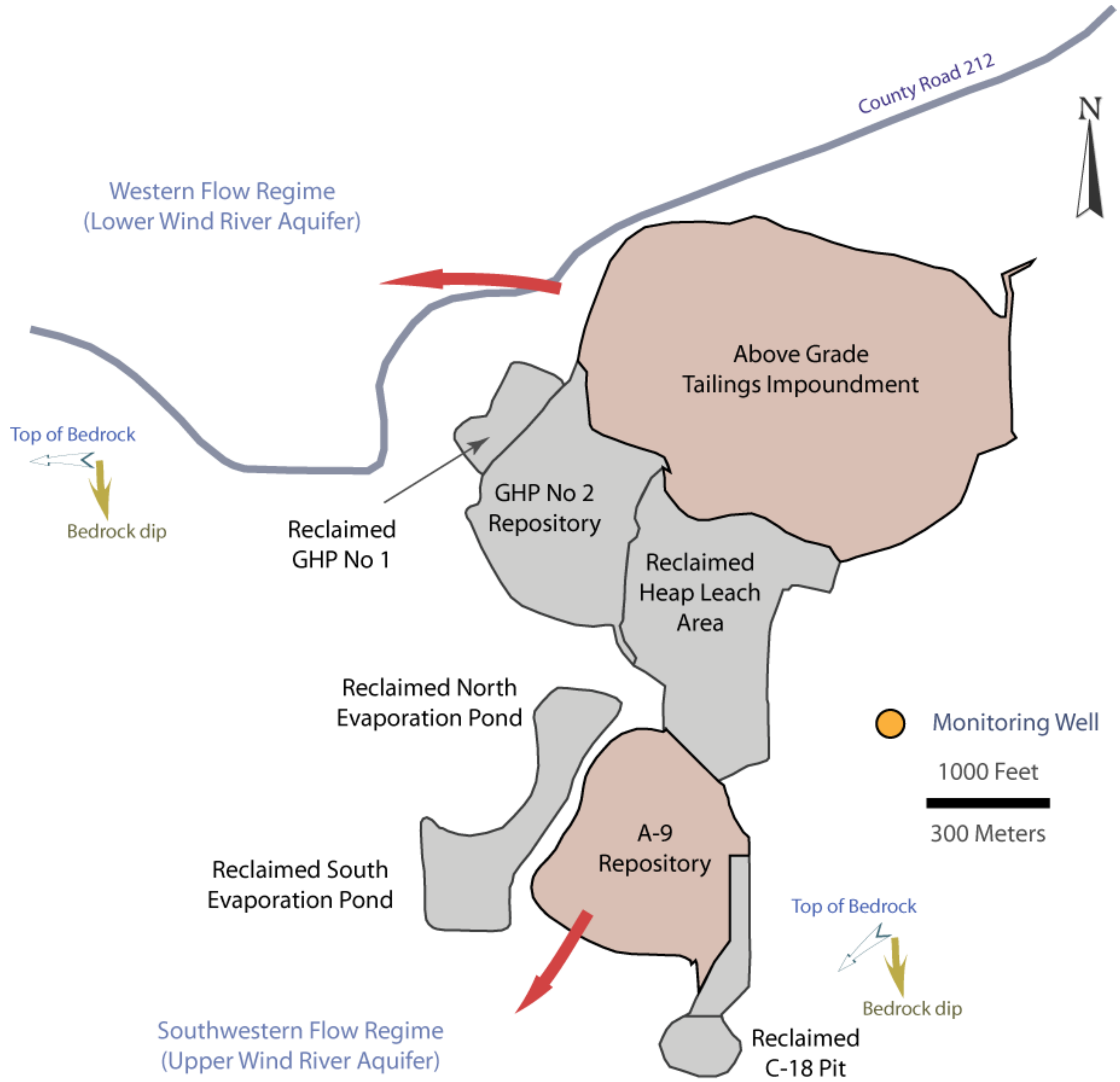

Figure A–4. Site Features at Gas Hills East (UMETCO), Wyoming

Initial Summary Description

Milling operations initiated in 1959 and terminated in 1984 at this site. Two tailings basins, the Above Grade Tailings Impoundment (AGTI) and A-9 Repository, are respectively located on the north and south sides of a ridge. The ephemeral East and West Canyon Creek drainages drain the north and south faces of the ridge to the west. Gas Hills Pond 2 (GHP2) and the Heap Leach Repository, both located intermediate between the tailings basins, contained byproduct but have been remediated. The A-9 Repository was constructed with a 1-m [3-ft] compacted clay liner. The GHP2 was constructed with a combination of clay and geomembrane layers that were largely removed during remediation. The U.S. Department of Energy (DOE) (2009) describes the site characteristics. Total basin area is 136 ha [335 ac]. The AGTI impoundment contains 5.8 Tg [6.4 million ton] of tailings; the A–9 repository contains 1.5 Tg [1.6 million ton] of tailings processed at the Gas Hills East mill and 1.6 Tg [1.8 million ton] from the Riverton Uranium Mill Tailings Radiation Control Act (UMTRCA) Title I site.

Two sandstone units are found at the site, the Upper and Lower Wind River aquifers, dipping to the south(?) and separated by a possibly discontinuous mudstone unit. The entire site is underlain by the Lower Wind River, unconfined under the AGTI and confined under the A–9, with flow generally to the west. The Upper Wind River is only found in the south of the site, with flow to the south-southwest. Seepage from the AGTI occurs into the Lower Wind River and seepage from the A–9 occurs into the Upper Wind River.

The electronic database includes data for 3 wells in the southwest regime and 3 wells in the western regime, taken from annual reports. Umetco Minerals Corporation (Umetco) annually provided data in tabular form for Point of Compliance wells (e.g., Umetco, 2010). The database includes chloride, sulfate, uranium, several radionuclides, and minor ions. Umetco also provided chemical constituents at a total of 11 monitoring wells, and water levels at 13 wells, in the form of graphs and figures; not all are included in the electronic database.

Discussion of analyses

Initial examination of the sites ranked the Gas Hills East site as among the least likely to have data suitable for examining cover performance because of the few wells available for analysis, lack of tabulated water levels, and restricted geochemical dataset. Project resources focused on sites more likely to develop insights, and no worksheet was developed for this site. To replace the worksheet, salient aspects of the covers with respect to potential performance are discussed here.

Umetco (2001) reports model-estimated seepage rates from the AGTI of 380 L/min [100 gpm] in 1979, decreasing to 75 to 110 L/min [20 to 30 gpm] in 2001 and less than 4 L/min [1 gpm] by 2010 to 2020. Model-estimated seepage from the A-9 Repository in 1998 was estimated at 12 L/min [3.3 gpm]. A large mound existed under the AGTI in 1979, extending

Umetco (2007), reporting reclamation construction activities at the Gas Hills East site, provides a description of the impoundments and cover characteristics. As completed, the tailings covers typically include 0.45 m [1.5 ft] of radon barrier, 1.4 m [4.5 ft] of frost protection, and 0.15 to 0.3 m [0.5 to 1 ft] of riprap. The radon barrier consists of variably silty shale soils. The frost protection layer is generally clayey to silty sand. The riprap erosion control layer replaced the initial vegetated layer. Umetco used quartzite riprap, with median particle diameter of 1.3 to 7.6 cm [0.5 to 3 in] over most of the cover area. Cover slopes are generally shallower than 10:1 for the AGTI and 30:1 for the A-9 repository.

From the perspective of cover inflow, the riprap layer likely acts as a rock mulch that promotes net infiltration. Evaporation may largely overcome the mulch effect if the thick frost protection layer provides sufficient near-surface moisture storage.

Given the very sparse site database, little cover performance analysis was possible even though more publicly available site characterization information (e.g., hydraulic conductivity data, cross sections, annual pumping rates) is available at this site than most of the other sites. Additional analysis is performed in Section 7 and 8. The analyses suggest that site data are unlikely to provide information on cover performance because of the large fluxes passing through the system.

Too late to be considered for analysis, the DOE Legacy Management program provided electronic databases with water level and geochemical observations from the operations and restoration period for 56 wells. These databases include geochemical observations as early as 1983 and water level observations as early as 1980. The database includes 13 wells with water level data as late as 2010 and 11 wells with geochemical data for several species as late as 2009. The geochemical species considered in the database remains restricted. Not all of the wells used for the corrective action program are included in the database, based on tables provided by Umetco (2001), and it does not appear that tailings wells are included in the database.

SITE 5—GAS HILLS NORTH/LUCKY MC (PATHFINDER), WYOMING

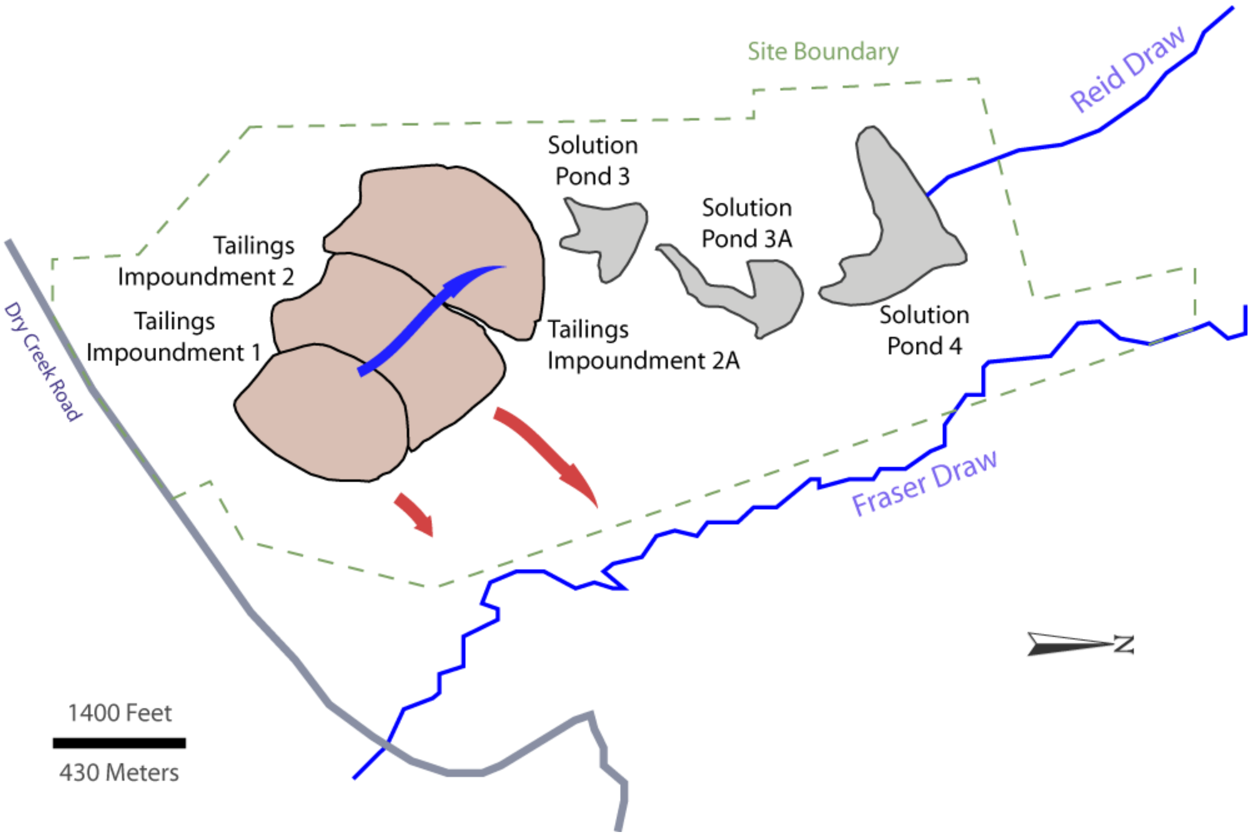

Figure A–5. Site Features at Gas Hills North/Lucky Mc (Pathfinder), Wyoming

Initial Summary Description

Milling operations initiated in 1958 and terminated in 1988 at this site. A stepped series of three tailings impoundments and three solution ponds were emplaced along the axis of Reid Wash directly on bedrock, a low-permeability shale. The tailings impoundments have a combined area of 89 ha [220 ac] and contain 10.6 Tg [11.7 million ton] of tailings. The lowermost dam was keyed into the shale, which is thought to have minimized seepage down the draw. Tailings solution releases routinely occurred down Reid Wash from 1958 to 1960 prior to construction of Tailings Impoundment 2, and an intentional release occurred in 1963 during an unusually wet year. Seepage from Tailings Impoundments 1 and 2 also moved into permeable lenses in the east flank of Reid Wash, allowing seepage to enter the shallow alluvial aquifer in adjacent Fraser Wash. Fraser Wash also received mine drainage at an average rate of 3 m^3/min [0.94 Mgpd] from 1974 through 1981. The uppermost bedrock aquifer is a sandstone unit, the upper Wind River.

Groundwater corrective action activities began in 1980 from collection wells in the plume, augmented in 1988 with additional pumping wells and two horizontal collection drains and in 1989 with injection wells. Tailings dewatering initiated in 1989 and expanded in 1992. The corrective action program terminated in 2002. DOE has transmitted a long-term surveillance plan (DOE, 2011) to NRC in preparation for accepting responsibility as the long-term custodian of the site.

The electronic database includes data for 4 wells in Fraser Wash and one upslope of the tailings basins in Reid Wash. The database includes several major ions, several radionuclides, minor ions, water levels, pH, conductivity, and total dissolved solids.

Discussion of Analyses

Initial examination of the sites ranked the Gas Hills North/Lucky Mc site as among the least likely to have data suitable for examining cover performance because of the few wells available for analysis and restricted geochemical dataset. Project resources focused on sites more likely to develop insights, and no worksheet was developed for this site. To replace the worksheet, salient aspects of the covers with respect to potential performance are discussed here.

Pathfinder Mines Corporation (Pathfinder) (2005) describe the completion of reclamation, including aspects of cover design. The cover consisted of a clay radon barrier, 0.9 m (3 ft) thick for Tailing Impoundments 1 and 2 and 0.6 m [2 ft] thick for Tailing Impoundment 2A. The radon barrier was covered by either a minimum of 20 cm [8 in] of topsoil or crushed limestone riprap with a median diameter between 2.5 and 5.5 cm [1 and 2.2 in]. Because of the relatively steep slope down Reid Wash, the cover over the tailings impoundments and solution ponds was constructed in 35 sub-basins to minimize erosion. The design diverts runoff to the flanks of Reid Wash using channels with riprap armor.

Erosion and radon emission control appears to have been the primary cover design constraints at this site. In areas covered by riprap, the riprap may act like a rock mulch that promotes net infiltration by reducing evaporation. An intact low-permeability clay radon barrier would limit inflow through the cover, but the lack of a thick soil layer above the radon barrier makes the radon barrier into a point of potential failure. The riprap-filled channels in the cover may promote focused inflow into the tailings.

Sections 7 and 8 contain site analyses. Given the sparseness of the dataset, relatively little could be concluded about cover performance. Too late to be considered in the analysis, the DOE Legacy Management program provided electronic databases with water level and geochemical observations from the operations and restoration period for more than 160 wells. These databases include geochemical observations as early as 1979 and water level observations as early as 1980, including both tailings wells and external wells. Observations in this database from late in the corrective action program would be able to refine the cover performance analysis in Section 7, but the database provides no new information after the end of the corrective action program.

SITE 6—GAS HILLS WEST (ANC), WYOMING

Figure A–6. Site Features at Gas Hills West (ANC), Wyoming

Initial Summary Description

Milling operations initiated in 1960 and terminated in 1982 at this site. Wyoming Department of Environmental Quality is administering reclamation because ANC became insolvent in 1994.

Two tailings basins exist, of 40 [Tailing Pond 1 (TP1)] and 80 [Tailing Pond 2 (TP2)] acres, respectively. The interim covers were emplaced in 1988 (TP1) and 1990 (TP2), and the TP2 final cover was emplaced by 1997. The TP1 final cover has not been emplaced. The basins are placed directly on the fine-grained upper Wind River formation, were formed by damming adjacent drainage channels (FAP Draw and Willow Springs Draw), and are separated by a drainage swale. A total of 21 wells are included in the electronic database, almost all associated with TP1.

I have not found information in ADAMS discussing seepage, groundwater modeling, or groundwater corrective action plans at this site. Annual reports typically consist largely of sample analysis sheets for the monitored locations with little discussion. Water level data is not routinely provided.

Discussion of Analyses

Initial examination of the sites ranked the Gas Hills West site as among the least likely to have data suitable for examining cover performance, especially considering that almost all monitoring is associated with the impoundment lacking a final cover. Project resources focused on sites more likely to develop insights, and no worksheet was developed for this site. Because no worksheet was developed, salient aspects of the covers are discussed here with respect to potential performance.

SITE 7—GRANTS (HOMESTAKE), NEW MEXICO

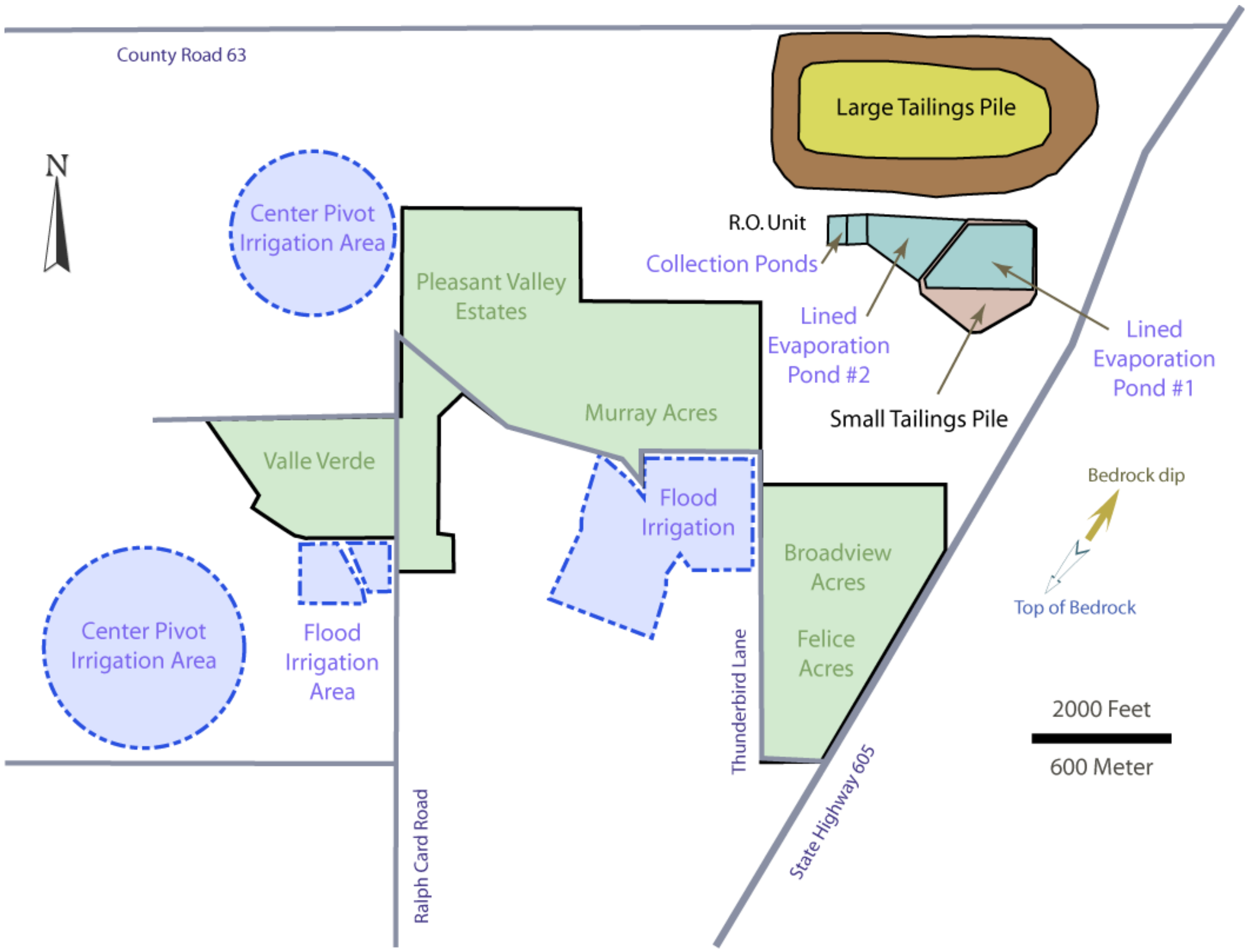

Figure A–7. Site Features at Grants (Homestake), New Mexico

Initial Summary Description

Milling operations initiated in 1958 and terminated in 1990 at this site. Two tailings basins exist at the Grants site, both placed on alluvium underlain by sandstone aquifers (the upper, middle, and lower Chinle, and the San Andres). The large tailings basin covers 69 ha [170 ac] and contains 19 million tonnes [21 million ton] of tailings; the small basin covers 16 ha [40 ac] and contains 1.1 million tonnes [1.2 million ton]. Neither tailings basin directly contacts bedrock. The Grants site is the only site with significant nearby population. The alluvium aquifer and bedrock aquifers formerly provided drinking water to nearby residents, but seepage has impacted the water supply and the residents now use externally provided water supplies. Pumping to reclaim seepage from the tailings started in 1975 and there is an ongoing groundwater corrective action program, including both extraction and injection wells to adjust the natural gradients.

The unperturbed flow system in the alluvial aquifer is down the topographic gradient towards the exposed population (to the southwest). The unperturbed flow system in the bedrock is downdip (to the north). Two large north-south faults with increased permeability complicate the flow system.

The Grants site features annual radon sampling on at ~100 locations. Grants is the only site with multiple radon samples. This is the only site at which a time-series analysis of radon flux is possible.

Discussion of Analyses

The relatively extensive radon emission sampling at the Grants site permitted a time-series analysis of radon emissions, described in Section 4.

There is extensive documentation regarding groundwater conditions at this site, and the electronic database includes 590 wells. Despite the large amount of available data, cover performance analysis using groundwater historical observations is not appropriate for this site because (i) the large tailings pile does not have a final cover and (ii) the small tailings pile (which does have a final cover) has a large active evaporation pond on most of the cover. These conditions make the site unrepresentative for analysis. Accordingly, no worksheet was compiled for this site and there is little analysis of the site in Sections 7 and 8.

SITE 8—HIGHLAND (EXXONMOBIL), WYOMING

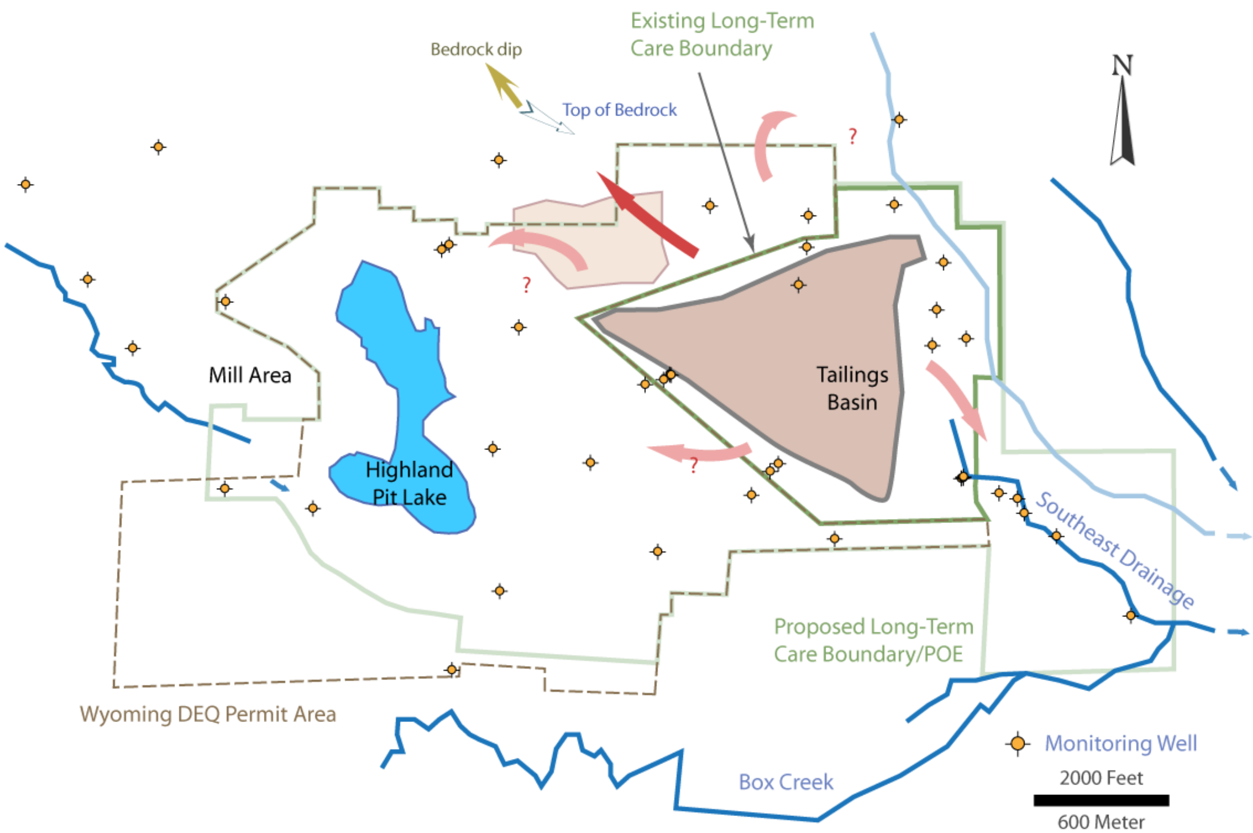

Figure A–8. Site Features at Highland (ExxonMobil), Wyoming

Initial Summary Description

Milling operations initiated in 1972 and terminated in 1984 at this site. One tailings basin exists, covering 81 ha [200 ac] and containing 9.5 million tonnes [10.5 million ton] of tailings. Several sandstone units contain tailings seepage. At first glance, the seepage directions would appear to drain into the hydrologic sink represented by Pit Lake. However, seepage directions are also affected by dip direction and drainages east of the tailings basin. Nearby *in-situ* recovery operations may influence water movement, and appear to track the dewatering and Pit Lake recovery.

There is extensive documentation. The electronic database includes 52 wells, pit lake sampling, and Box Creek sampling.

Discussion of Analyses

Initial examination of the sites ranked the Highland site as among the most likely to be amenable to analysis, because of the relatively large number of monitoring wells, wide variety of geochemical analytes, and long publicly available history of investigations. The initial thought was that the hydrologic conditions were likely to be uncomplicated, given the hydraulic presence of the Pit Lake.

Appendix C contains the worksheet developed for this site, which describes the site in detail. This worksheet was the first worksheet developed, during the project stage where staff was initially exploring what types of analyses might be possible given the collected data and developing analysis tools. Development of the worksheet provided the first indication that geochemical methods would not be useful for evaluating cover performance even though they are useful for identifying seepage. This site was useful for developing initial concepts of analysis strategies, in particular the potential for applied tracers to provide useful information. The site data also illustrate the potential and drawbacks associated with temperature proxies for inflow. Staff used these concepts as a motivation for developing the more general analyses of strategic and tactical approaches to evaluating cover performance.

Sections 7 and 8 contain further site analyses. These analyses suggest that the site hydrologic conditions are still recovering from the disturbances during the mining and operational period. The analyses do not identify a cover inflow signature, but suggest that the downdip flow below the basin (combining inflow, updip recharge, and tailings drainage) is approximately 25 percent of precipitation over the basin. The initial impression of the site as having relatively uncomplicated hydrologic conditions was true during the operations period and is likely to be true in the future, but the two hydrologic conditions are very different and the remnants of the large initial disturbance make it difficult to track how flow conditions have evolved. Interestingly, the initial concept identified two likely flow pathways, towards Pit Lake and down the Southeast Drainage, and subsequent analysis suggests that flow paths likely move downdip at present and may bypass the initially identified pathways.

SITE 9—SEQUOYAH (SEQUOYAH FUELS), OKLAHOMA

Initial Summary Description

The Sequoyah Fuels site was a processing site and does not have a tailings impoundment. A lined basin is being designed to decommission the site. Lacking a tailings impoundment, no analysis of a tailings cover is possible at this site.

SITE 10–SHIRLEY BASIN NORTH (PATHFINDER), WYOMING

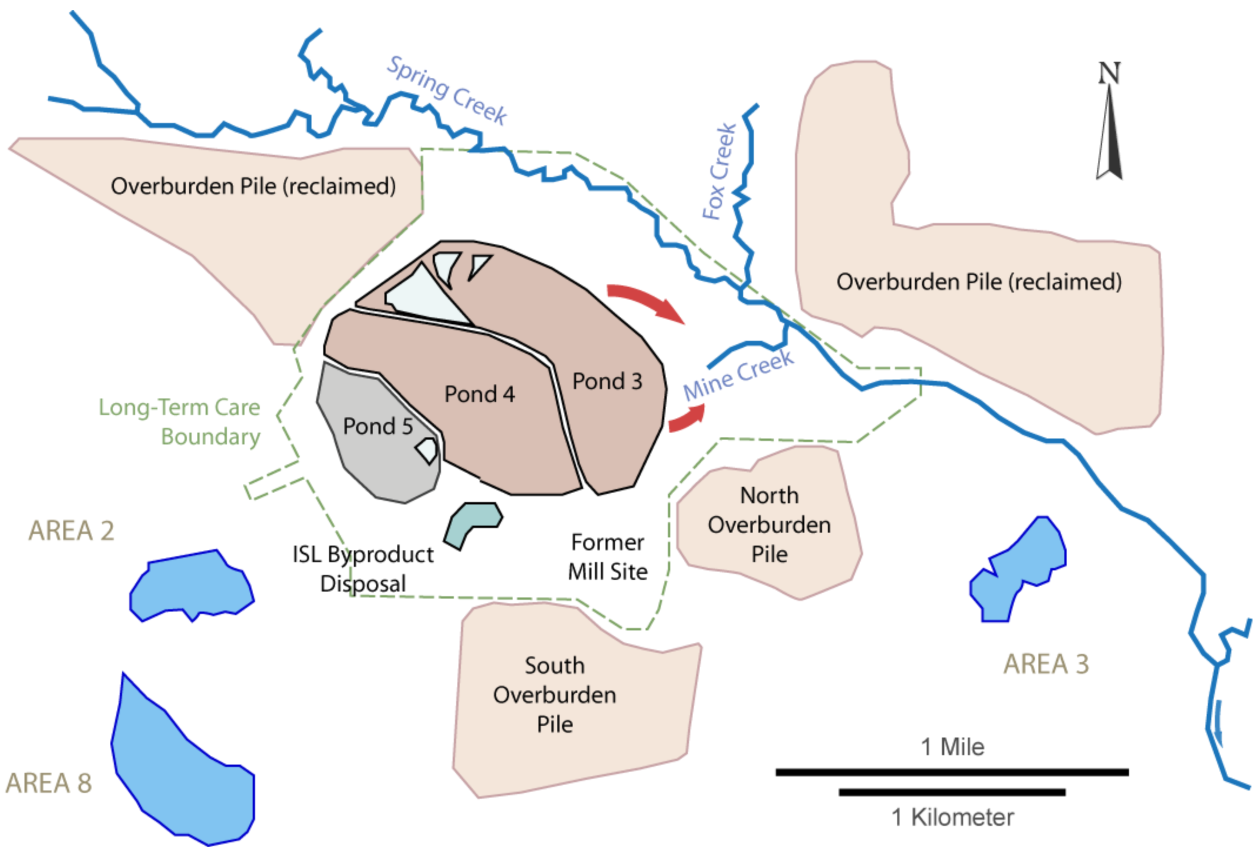

Figure A–9. Site Features at Shirley Basin North (Pathfinder), Wyoming

Initial Summary Description

Milling operations initiated in 1971 and terminated in 1992 at this site. The site has 4 units of interest, a surficial aquifer and the Lower Wind River, Main Wind River, and White River sandstone aquifers. The surficial aquifer discharges to Spring Creek, which parallels the downhill tailings dam at a distance of approximately 0.4 km [0.2 m]. The lower aquifers are hydraulically separated from the surficial aquifer by siltstone and claystone. Two tailings basins exist, in combination covering 119 ha [293 ac] and containing 7.8 million tonnes [8.6 million ton] of tailings. The basins are emplaced on the surficial aquifer and separated only by a dam. Three additional ponds are uphill, including one used to contain tailings solution. The basins and solution pond were emplaced along a hillslope draining to the surficial aquifer. Uranium mining occurred in the Lower and Main Wind River units. The site has had an active pumping/recharge program to control tailings basin seepage released into the surficial aquifer. Seepage is thought to have almost ceased by 2005.

A total of 14 wells are included in the electronic database, with observations from 1979 through 2010. Well locations and depths are tabulated on available Portable Document Format (pdf) documents, with the screened unit identified, but I have not identified screened intervals.

Chemistry data appears reasonably complete with respect to sampling major ions, radionuclides, and minor ions. Many of the wells have a short sampling history. There are numerous wells at the site that are not included in the database; for example, the 2004 annual report states that 36 wells were pumped during 2003 and the 2000 application for alternative concentration limits states that 65 wells are in place on the tailings.

The 2005 TER refers to models but it is not clear what kind of modeling was done. I have not found any documentation of groundwater flow or transport modeling.

Discussion of Analyses

Initial examination of the sites ranked the Shirley Basin North site as moderately amenable to analysis. This ranking was based on the moderate number of available monitoring wells, each with fairly complete geochemical data but many with a relatively short history.

Appendix H contains the worksheet developed for this site, which describes the site in more detail. This worksheet was developed after project staff digested insights from the three most promising sites. Many site documents predate the NRC ADAMS system and are not publicly available, hampering site interpretation.

During the worksheet preparation, staff found an extensive set of tabulated geochemical data from the operational and reclamation periods in site documents. These data were not initially included in the database. Site personnel provided the geochemical database in electronic format, but too late to use for site analyses. Unfortunately the database does not include water level data.

Sections 7 and 8 contain further site analyses. These analyses suggest that the site hydrologic conditions are relatively uncomplicated. Streamflow studies at the site provide a means for bounding cover inflow that is not available at any of the other sites.

SITE 11—SPLIT ROCK (WESTERN NUCLEAR), WYOMING

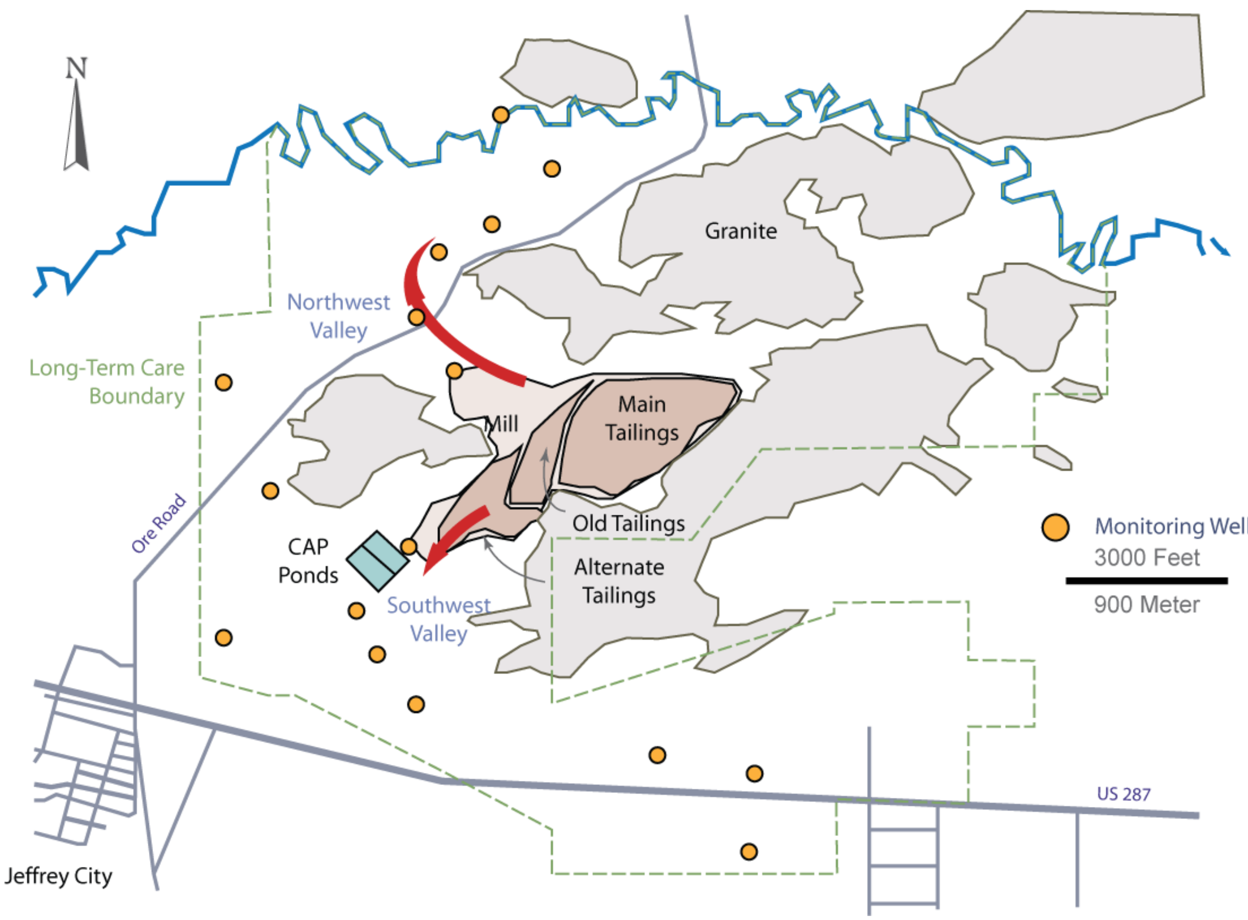

Figure A–10. Site Features at Split Rock (Western Nuclear), Wyoming

Initial Summary Description

Milling operations initiated in 1958 and terminated in 1981 at this site. Split Rock has 3 units of interest: (i) an eolian aquifer, (ii) a floodplain aquifer, and (iii) underlying granite. The site is unique in the sense that it is the only site with granite bedrock. The database includes typical well characteristics such as depth, screened interval, etc., but does not identify which unit that the well is screened into (presumably no wells are screened in the granite). I found a table that describes units for many wells—I don't know if all wells are included. The top of granite appears to be variable, based on cross sections.

Three tailings basins (Old, Alternate, Main) were emplaced on the surficial material in a natural basin formed between two granite ridges. Two seepage plumes were created, one moving down the main axis between the ridges (SW Valley, primarily from the smaller Alternate and Old basins) and one moving perpendicular to the axis through a gap in the north ridge (NW Valley, exclusively from the Main basin). The basins are adjoining, covering 73 ha [180 ac] and containing 7 million tonnes [7.7 million ton] of tailings.

There is a 1999 document produced by Shepherd Miller, Inc. (SMI) that does a groundwater assessment, including flow and transport modeling. Most of the data collection occurred immediately prior to the modeling, presumably to support the modeling. The most recent modeling document (an update to the model in 2003) points back to the 1999 document as containing the detailed information. I found the main document and Appendix I, but was unable to find Appendices A–H (which apparently contain the detailed information) on ADAMS. I was unable to locate water level data.

A total of 386 wells are included in the electronic database, many located offsite. Many of the wells (particularly offsite wells) were sampled for a limited duration in the 1970s, 1980s, or 1990s to establish background groundwater characteristics for modeling. The ongoing monitoring sites appear to all be at compliance points, which are somewhat distal from the tailings. Estimates of cover performance would be easier with a variety of close and far wells.

Discussion of Analyses

Initial examination of the sites ranked the Split Rock site as among the most likely to be amenable to analysis, because of the relatively large number of monitoring wells, wide variety of geochemical analytes, and relatively uncomplicated site conditions.

Appendix E contains the worksheet developed for this site, which describes the site in detail. This worksheet was the third worksheet developed, during the project stage where staff had digested the first two worksheets but were still exploring what types of analyses might be possible given the collected data. The site proved less amenable to analysis than initially anticipated, because documents with information on some relevant site characteristics are not publicly available and no monitoring wells are proximal to the impoundment basins after reclamation.

Sections 7 and 8 contain further site analyses. These analyses bear out the initial assessment that the hydrologic conditions are uncomplicated, but suggest that cover performance is likely to be difficult to assess at this site because any recharge from the impoundments is small compared to recharge caused by runoff from the surrounding granite ridges.

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APPENDIX B

U.S. NUCLEAR REGULATORY COMMISSION SITE EVALUATION QUESTIONNAIRE

B U.S. NUCLEAR REGULATORY COMMISSION SITE EVALUATION QUESTIONNAIRE

(1) Describe available information and insights on the hydrogeology (units, potentiometric surfaces, specific discharges, etc.) in the near vicinity of the covered tailings area from the time period immediately prior to cover construction until the present.

(2) Describe information and insights on natural (rainfall events) and artificial (watering or injection) recharge since cover construction.

(3) Describe information on the transient drainage expected to occur after cover placement. Some sites may have estimated the volume of water remaining, estimated drainage rate over time, and the duration of the expected drainage.

(4) Describe information of wells/boreholes that have been collecting hydro-chemical data since any time period immediately prior to cover construction until the present and identify hydrogeological unit origin of samples.

(5) Using the information from (1)–(4), try to construct a hydrological conceptual model of the unsaturated and saturated zone in the near vicinity of the tailings since the cover construction.

(6) Determine which wells/boreholes are downgradient of recharge from the covered tailings area. Assign an approximate degree of certainty to this determination, or tailings recharge influence, for each well (or well cluster): high, medium, or low.

(7) Identify key chemical species or indicators in the tailings pore water to eliminate non-key chemical species from being evaluated in the background groundwater quality or even the plumes. Some of the sites could be influenced by outside factors such as ore bodies in close proximity to the site that had a different mineralogical makeup than the ore body from which the tailings were derived, e.g. if the tailings pore water has a very low historic selenium content then eliminate it from the data represented in background or in the plume.

(8) Identify certain key chemical species or indicators for each site to discern temporal and spatial trends in groundwater quality (e.g., pH, chloride, sulfate, ionic strength). (What effluents are in the plume? What constituents are in the background water?)

(9) Create trilinear-shaped diagrams or stiff diagrams for the tailings pore water and for the background groundwater.

(10) Using the hydrological conceptual model of the site, for each identified well located in the tailings plume, determine if data from the well show any indication of the covers existence.

(11) Considering the quantity and quality of the data from each well, what time-series trends and statistical analyses of these data are available, if any?

(12) The final Center for Nuclear Waste Regulatory Analyses draft of Appendix F for NUREG–1569 titled, Guidance for Using Statistical Methods to Evaluate Water Quality discusses Trend Estimation in Section F2.4. Is this applicable to any of the Title II in-closure data?

(13) Document results of Steps (1)–(12), if applicable. Document conclusions; either:

(i) Document why data from wells and other information will not allow any determination to be made cover performance. What would be needed/required to evaluate cover performance in the future?

(ii) Document why data from wells and other information will allow a partial or thorough evaluation to be made on cover performance. What can be stated on the cover's ability to influence the rate of contaminated seepage from the tailings into the groundwater?

APPENDIX C

SITE EVALUATION FOR SITE 8, HIGHLAND (EXXONMOBIL), WYOMING

SITE EVALUATION FOR SITE 8, HIGHLAND (EXXONMOBIL), WYOMING

C1 INFORMATION AVAILABILITY FOR GEOLOGIC STRUCTURE AND PROPERTIES

ExxonMobil possesses a digital geologic structure model for the site (not currently in hand). A general picture of the geologic structure can be gained from a number of cross sections, elevation maps, and measurements that are available from reports (e.g., ExxonMobil ExxonMobil, 2011; ARCADIS, 2008; Tetra Tech, 2007a; WWL, 1988; EPRC, 1982; Dames & Moore, 1980).

ExxonMobil (2011, Appendix A) summarizes 12 documents produced from 1973 through 2007 that examine hydrologic modeling or contaminant transport at the Highland site. These documents and references therein describe hydraulic and geochemical properties. Subsequent sections discuss some of the information in selected documents from this collection.

C2 INFORMATION AVAILABILITY FOR NATURAL AND ARTIFICIAL RECHARGE

One way that a cover may provide protection is by preventing water from contacting the tailings and subsequently draining into the environment. Accordingly, the net flux through the cover provides a metric for evaluating cover performance. For the purposes of evaluating cover performance, recharge occurring over the tailings is of primary interest. Focused recharge may be of greater concern than diffuse recharge, because focused recharge is more likely to escape the evapotranspiration trap and penetrate to depth in semiarid environments. Recharge over more distal portions of the cover or even outside the cover may also be of concern because of the geometric configuration of the bedrock; if subsurface flow occurs down the pre-existing bedrock surface beneath the cover, it may contact the tailings and then focus into the smaller contact area where the Tailings Dam Sandstone (TDSS) subcrops under the tailings basin.

Direct measurements of recharge through the cover are not presented or mentioned in any of the documentation that I reviewed, and there are no reported wells within the tailings basin. Accordingly, there is no direct basis for estimating recharge through the cover at this site. Observations of seepage waters in wells outside the tailings basin may provide indirect indicators of recharge.

Often recharge is quantified in terms of a percentage of precipitation. There is no onsite meteorological station. Three National Weather Service stations, 32–64 km [20–40 mi] from the Highlands site, provide climatic information. The observations from these stations have similar annual averages and seasonal variation for both precipitation and temperature, and are each at similar elevations to the site, thus this set should be representative of site climatic conditions. Mean annual precipitation over 1971 to 2000 is between 31 and 34 cm/yr [12.2 and 13.4 in/yr] for the three stations. These stations have daily observations since the 1940s and 1950s to the present (except the closest station, Glenrock, stopped recording in 2008). These observations would likely be suitable for comparing with subsurface water level and geochemical observations to assess potential recharge events, although observations at each of the available wells (all exterior to the tailings cover) may reflect recharge sources other than the tailings.

Two types of models considered recharge, site-scale models and two-dimensional cross-section models. Site-scale modeling exercises typically applied areally uniform seepage conditions across the site (sometimes singling out the basin area and the pit) with little discussion of the estimate basis.

Total tailings cover area is 69 ha [170 ac], larger than the final tailings basin area of 39 ha [95 ac]. WWL (1984) developed an estimate of 13 L/m [3.5 gpm] as expected long-term seepage, using an infiltration rate of 1.0 cm/yr [0.4 in/yr] applied to the basin area and apparently using an area of 26 ha [65 ac] to estimate 13 L/m [3.5 gpm]. The 0.4 in/yr infiltration rate implies a recharge fraction of approximately 3 percent, and is based on regional recharge estimates (Dames & Moore, 1980). Carovillano (1998, section 5.3.2) defined regional recharge as 1.3 cm/yr [0.5 in/yr], except that she assigned the two cells within the tailings basin rates from 12 to 61 cm/yr [4.7 to 24 in/yr] depending on well discharge (no further description is provided). Tetra Tech, Inc. (2007a) groundwater modeling used a calibrated rate of 19 L/m [5 gpm], which closely corresponds to 1.0 cm/yr [0.4 in/yr] over the final tailings basin area of 39 ha [95 ac].

None of the studies assessed uncertainty with respect to the range of recharge rates that might occur under nominal conditions. The Maxey-Eakin approach suggests that a central tendency for recharge (at a regional scale) would be approximately 5 percent of precipitation, which is approximately 1.7 cm/yr [0.65 in/yr], but a deep vegetated cover is likely to exhibit less recharge than upland areas. Based on experience at Yucca Mountain, I would estimate that the uncertainty on recharge is likely more than a factor of 2 and less than an order of magnitude.

Local features may provide a source of focused net infiltration. For example, several man-made reservoirs (dammed drainages, stock ponds) were constructed for water supply and storage during mining operations (Dames & Moore, 1978), including Buck, Doe, and Fawn Reservoirs immediately to the north of the tailings basin. I have not located recharge estimates for any of these reservoirs. The reservoirs were filled in and a diversion channel was constructed during 1988 and 1989 (Shepherd Miller, 2002, Section 4.1). The diversion channel drains 76 ha [188 ac] north of the tailings cover into the southeast drainage (WWL, 1984). The two low-flow drainage channels draining the tailings cover into the diversion channel were constructed in 1990 and 2001 (Shepherd Miller, 2002). The low-flow drainage channels were paved with rock mulch (Shepherd Miller, 2002, Section 8.4), therefore may be sufficiently permeable to create localized infiltration into the tailings. Neither the diversion channel nor the low-flow channels are represented as distinct features in any groundwater model.

C3 INFORMATION AVAILABILITY ON TRANSIENT DRAINAGE AFTER EMPLACEMENT

Seepage from the tailings basin has been a concern since early in the milling period. Several estimates of the time history for seepage are available, discussed in the next section. Seepage from the basin predominantly occurred in the form of recharge to the TDSS unit, some of which discharged to the southeast drainage, although some seepage likely passed through the retaining dam. The unit confining the TDSS has a low permeability, thus likely experienced less seepage. Discharge from the tailings basin to the southeast drainage has also been referred to as seepage, although it was only part of the total flow lost from the basin. In the following, tailings basin seepage is assumed to refer to recharge to the TDSS.

Prior to construction of the tailings basin, seepage was anticipated to occur at initial rates of 300 L/m [80 gpm] into the TDSS and 75 L/m [20 gpm] through the dam, decreasing 1 to 2 orders of magnitude within 2.25 years as the low-permeability tailings sealed off the TDSS [U.S. Atomic Energy Commission (AEC) 1973). Dames & Moore (1978) estimated that total tailings pond seepage was 1,140 L/m [300 gpm] in 1977, of which 380 L/m [100 gpm] was entering the pit during operation, compared to 3,800 L/m [1,000 gpm] pumped by all dewatering wells, underground mines, and surface mines combined. Dames & Moore (1978) estimated that the total seepage would increase to 1,300 L/m [350 gpm] in 1985.

EPRC (1982) modeled seepage and migration of seepage using 3 vertical cross sections and an areal model, using an unnamed variably saturated finite difference code. EPRC (1982) estimated a fluctuating seepage rate, increasing to 380 L/m [100 gpm] in 1974, dropping to 190 L/m [50 gpm] in 1975, gradually increasing to a peak of 760 L/m [200 gpm] in 1983, and ceasing in 1991. The fluctuations reflect changes in tailings thickness, pond size, and ultimate removal of water because of evaporation and drainage.

WWL (1989, Section 1.2.3) describes a seepage pumpback system in the southeast drainage, installed in 1975 to control visible seeps from the TDSS into the southeast drainage. Discharge into the sump system ceased in July, 1987 (WWL, 1989, Section 1.2.3).

The latest groundwater model (Tetra Tech, 2007a, Sections 2.1.3 and 3.4.4) used estimates of seepage from the tailings basin that decayed from 680 L/m [180 gpm] in 1984 (at cessation of dewatering) to a long-term rate of 13 L/m [3.5 gpm] achieved in 1992. Tetra Tech, Inc. (2007a) based the duration of transient drainage on flow histories calculated using an unnamed variably saturated finite-difference model applied to three representative 2D cross sections (EPRC, 1982, Chapter 6).

C4 INFORMATION AVAILABILITY ON HYDROCHEMICAL OBSERVATIONS

The site has an electronic database of water levels (starting in 1981) and an electronic database of fairly extensive geochemical sampling (starting in 1986) in 52 wells. WWL (1988) describes additional information, typically as plots, on older observations (including chemistry and water level in the tailings basin, seep sumps in the southeast drainage, and older boreholes) from 27 locations in the context of assessing tailings basin seepage. These plots appear to include data from initial observation through 1988. WWL (1988, section 2) transferred these early observations from an electronic database maintained by Exxon Coal and Minerals Company into a Lotus 1-2-3 database; I did not find documentation that indicates either database was provided to NRC.

WWL (1989, Appendix E) tabulates water quality (but not water level) information from 1972 to 1982 obtained from two TDSS wells (009 or TDM-A and 010 or TDM-B), located immediately west of wells 179 and 176 north of the tailings basin, both decommissioned in 1982. The earliest observations occurred prior to mining. WWL (1989, Appendix D) tabulates water quality information from the pit lake from 1982 through 1985 that is not included in the electronic database. EPRC (1982, Figures 64–71) list calcium, chloride, magnesium, and pH measurements from October 1981. Dames & Moore (1978) tabulates static water level and geochemistry from piezometer tests (at unknown locations), and operating water levels and geochemistry from dewatering wells north and west of the pit lake and tailings basin.

Dames & Moore (1980, Plate 6) contours static water levels under pre-operation conditions from earlier reports, including a reading of 1,564 m [5,130 ft] from an unlabeled well (possibly a subsequently decommissioned dewatering well) between the tailings basin and backfilled pit 1 in the vicinity of TDSS well 178. For comparison, water level observations in TDSS well 178 ranged from 1,558 to 1,1559 m [5,113 to 5,116 ft] since 2000; water levels since 2006 in the 50SS at this location are likely between 5072 (MFG-1) and 1,564 m [5.100 ft] (well 114). Dames & Moore (1980, p. 8) notes that early USGS topographic maps indicate that the North Fork Box Creek is a perennial stream.

Site-scale hydrologic models [e.g., Tetra Tech, Inc., 2007a; ECMC, 1998; EPRC, 1982) include associated documentation of conceptual models and applied stresses (pumping, recharge, seepage). Site-scale geochemical models (e.g., Tetra Tech, Inc., 2007b; EPRC, 1983, 1982) include discussions of conceptual models and transport parameters.

C5 SUMMARY OF CONCEPTUAL MODEL FOR WATER FLOW NEAR THE TAILINGS COVER

The following conceptual model for flow near the tailings cover is a synthesis of the available hydrologic and geochemical data in the electronic database, the series of reports provided by ExxonMobil from 1973 through 2011, and geologic information provided as maps, cross sections, and borehole logs. The following is generally similar to the conceptual model presented by ExxonMobil (2011, Section 1.3), although differs in certain details as described at the end of this section.

TDSS and 50SS outcrops in and near the southeast drainage likely served as a minor recharge source during the pre-operation period; the basin site itself may have been a focused recharge zone because of the ephemeral channel incised into the TDSS outcrop. Flow recharged at outcrops in these units likely passed through the basin area moving downdip to the northwest as gravity-driven flow, based on recent water level gradients in both the TDSS and 50SS. AEC (1973) describes the TDSS as variably saturated and the 50SS as wholly unsaturated, but does not provide the borehole locations that the assessment is based on. Subsurface contacts between these units and the unconfined aquifer in the southeast drainage alluvium may have also provided some local recharge or discharge and an opportunity for water to transfer from overlying units to lower units, analogous to a permeable fault cutting through a series of layers.

Insufficient information exists to directly determine water fluxes in units below the 50SS, because a minimum of 3 wells are needed to determine a gradient and only one well is screened into each of the lower units. However, some inferences can be drawn. North Fork Box Creek represented a groundwater discharge point during the pre-operation period, evidenced by the AEC (1973) description of ephemeral springs in Box Creek. Dames & Moore (1980, p. 8) notes that U.S. Geological Survey topographic maps indicate that the North Fork Box Creek was a perennial stream. The discharge was likely from the 40SS and 30SS units underlying the 50SS, to be consistent with the reported dry 50SS (this discharge was from offsite sources, likely to the west). Flow from the bedrock units likely discharged into the base of the Box Creek and southeast drainage alluvium, even without visible springs. If water levels in the alluvium were sufficiently high water levels in the 50SS may have equilibrated with the 30SS and 40SS at the alluvium contact. In this conceptualization of the flow patterns, the small amount of water in the TDSS near the tailings basin was disconnected from the lower units and moved in a roughly opposite direction.

During operations, the tailings basin received large quantities of water from pit sumps and dewatering wells. A substantial fraction of this water drained into the TDSS at the estimated peak rate of 680 L/m [180 gpm] (Tetra Tech, Inc., 2007a), corresponding to 43 cm/yr [17 in/yr] applied over a 81 ha [200-ac] basin site. For comparison, annual precipitation is approximately 33 cm/yr [13 in/yr] and regional estimates of recharge are1.0 to 1.3 cm/yr [0.4 to 0.5 in/yr]. This applied water fully saturated the TDSS near the tailings basin and formed a substantial groundwater mound {well 114 has dropped 27 m [90 ft] since 1981 and well 117 has dropped 18 m [60 ft]}. The Tailings Dam Shale (TDSH) formed an effective barrier to flow between the TDSS and 50SS, for example downdip of the tailings basin a head difference of as much as 30 m [100 ft] existed in 1981 (between TDSS well 120 and adjacent 50SS well 129). At the same time, dewatering formed a depression in the pit area, drawing water radially into the depression. The large mound forced essentially radial flow in the TDSS, resulting in substantial seepage to the south and east of the dam and substantial flow into the pits to the west.

Seepage was observed in the southeast drainage. Site-scale hydrologic modeling by Tetra Tech, Inc. (2007a) and Carovillano (1998), which was intended to examine pit lake dynamics, does not represent the southeast drainage alluvium. ExxonMobil (2011) estimates groundwater fluxes within the southeast drainage, but does not appear to characterize potential interactions between the alluvium and the Ore Sand (OS). Particle-tracking methods on cross sections (EPRC, 1982) suggested that seepage moved vertically through the TDSH as the pathway for seepage reaching the 50SS, with little remaining transfer to lower units. However, the large head gradient across the TDSH coupled with a relatively small head change within the 50SS during active discharge to the tailings basin appears to be consistent with low flow across the TDSH. The long-term lack of hydraulic response to pit water levels exhibited by TDSS wells west of the pit lake provides additional indication that the TDSH is likely an effective barrier to vertical flow. WWL (1988, section 3.2.3) suggested chloride concentrations in seeps 012, 013, and 014, and 50SS wells 111 and 148, are consistent with the southeast drainage alluvium forming the pathway for movement of seepage into the 50SS. The water level history in 50SS well 129 provides a hydraulic indicator that the 50SS and alluvium are in direct communication, changing from (i) slowly increasing from 1981 to 1988, (ii) jumping 4 m [13 ft] between October 25, 1987 and February 25, 1988, and (iii) thereafter maintaining a declining pattern in sync with the other 50SS wells. This history may be result of the shutdown of the southeast drainage seep sump system in July 1987, approximately 1,219 m [4,000 ft] away from Well 129. All 50SS wells show a consistent water table gradient down to the northwest, suggesting inflow from the alluvium. An obvious implication of this pathway is that TDSS flow seeping into the southeast drainage may also have formed a source of water that migrated into the underlying 40SS and 30SS units where the alluvium aquifer contacted these units further down the drainage.

Dewatering and concomitant discharge to the tailings basin ceased after the operations period, so that the pit lake depression substantially recovered and the TDSS mound declined (see TDSS figures). Both of these recoveries initially involved decay of their respective predominantly radial flow fields. Estimated seepage from the tailings basin is approximately 1.5 to 1.7 orders of magnitude smaller than the peak seepage during operations. Because the tailings basin is a much smaller seepage source, supplied only by recharge through the cover, residual drainage, and perhaps ephemeral streamflow in the local watershed, the flow system in the TDSS under the tailings basin has returned to flowing predominantly downdip. Assuming that recharge through the tailings cover occurs, three flow pathways from tailings seepage would potentially develop (i) minor northerly flow draining into the two alluvium channels east of the dam and returning south within the alluvium aquifers, (ii) westerly to northwesterly flow captured by the steep gradient at the edge of the TDSS and draining to the pit lake, and (iii) intermediate flow generally northwesterly downdip between these two sinks. The northerly pathway to the southeast drainage and the westerly pathway to the pit area may provide a long-term source of tailings seepage to the ore-body units. Until the TDSS becomes substantially unsaturated under the tailings basin, some flow will likely be maintained west and east from the tailings basin, supported by pressure gradients maintained by evapotranspiration at outcrop areas and drainage into the pit backfill. The TDSS has largely dewatered east and south of the tailings basin and adjacent to backfilled Pit 2, but remains fully saturated to the north.

C6 WELLS DOWNGRADIENT OF THE TAILINGS COVER

Subsurface flow patterns near the tailings basin have shifted over time, first adjusting to recharge during the operations period then adjusting to the end of operations. During the operation period, flow from the tailings basin formed a large mound in the TDSS that induced essentially radial flow. The presence of the mound drove tailings water to all of the wells near the tailings basin during operations and during initial decay of the mound. Gradients are returning to the natural state away from the mining operations, indicating that transport from the tailings basin is generally to the northwest (downdip). Absence of the TDSH near the mined pit and in the southeast drainage locally influences water table gradients and flow directions because the missing low-permeability unit increases the potential for hydraulic communication between the TDSS and OS.

In the direction of natural flow, TDSS wells 114, 120, 150 (dry), 151 (dry), 172, 175, 176, 179, and 183 are generally downgradient of the tailings basin (wells 150 and 151 are at the edge of excavated areas). TDSS wells 112, 125, 127 (dry), 181, and 182 are indicator wells on the east of the tailings that received seepage because of mounding but should gradually return to natural conditions. TDSS wells 117 (dry), 177 (dry), and 178 are between the tailings and the pit, and would probably return to natural conditions with low seepage rates and may remain an active flow pathway with high seepage rates. Note that wells on the north side of the tailings (especially 120, 176, 179, 181, and 183) may be subject to recharge from the diversion channel along the north of the tailings cover. Wells 117, 127, 150, 151, and 177 went dry as the seepage mound decayed or TDSS water drained into an excavation.

Wells in other units are less useful for indicating cover performance because the tailings are not in direct contact with the unit, so that the flow pathways from the tailings to the well must be inferred, are likely circuitous, are subject to mixing, and therefore cover performance is more ambiguous.

C7 KEY CHEMICAL SPECIES OR INDICATORS IN THE TAILINGS PORE WATER

Geochemical sampling has been performed since the 1970s at the site, but the electronic database starts in 1986. Reports suggest that earlier data, including tailings water, were compiled in at least two electronic databases that were not provided to the U.S. Nuclear Regulatory Commission (NRC). I did not identify any geochemical samples obtained prior to mining; WWL (1988) describes limited data from the 1970s for 5 wells.

The tailings basin received waters from a variety of sumps and dewatering wells. Some of the water was derived from each of the units at the site, including the TDSS and the ore sandstone units, and some was received as direct precipitation and overland flow. Undoubtedly some of the dewatering flow was derived from basin seepage.

The background major ion chemistry is dominated by Na, Ca, and SO_4. Site studies have used chloride and sulfate to indicate seepage. Magnesium was discussed in early studies as a potential tracer of seepage water, which may be better than sulfate for indicating seepage because seepage would be more distinctly delineated from the background water chemistry.

C8 KEY CHEMICAL SPECIES OR INDICATORS FOR DISCERNING TEMPORAL AND SPATIAL TRENDS IN GROUNDWATER QUALITY

Site studies have used chloride and sulfate as conservative tracers, as well as uranium. Magnesium also has been suggested. Selenium might also be a potential tracer, although featuring restrictive detection limits and large variability in some wells.

C9 CHEMICAL DIAGRAMS OF PORE WATER

Sufficient information exists in the database to construct Stiff and Piper diagrams for 6 major ions (Ca, Mg, Na, Cl, SO_4, and HCO_3) for 1988 through 2004. Data for K and CO_3 are more limited, but where available have small concentrations relative to the other species. The data for HCO_3 are reported in multiple formats over time (as many as 5 formats for one well), and the dominate format appears to have switched in 2004. The Stiff and Piper diagrams suggest that well chemistry is fairly consistent over the last 20 years for most wells. Background chemistry favors Ca, Na, and SO_4, with all constituents elevated near the tailings. Mg was discussed in early studies as a potential tracer of seepage water, and this appears reasonable based on low background values and elevated values near the tailings basin.

Four other species (Ni, Se, U, and Ra) are widely measured above the detection threshold. A few wells near the edge of the tailings basin show elevated Se or Ni.

C10 INDICATIONS OF COVER EXISTENCE BASED ON GEOCHEMICAL OBSERVATIONS

The most direct indicator of cover performance would be a unique geochemical signature associated with the cover but not the tailings or underlying units. Presence and absence of the unique signature would provide an unambiguous geochemical signature for performance. Such a signature has not been identified.

The time history of geochemical signatures can provide indirect indicators of cover performance. An unchanging geochemical history, coupled with minimal lateral flow through the TDSS, would be consistent with stagnant flow and therefore good performance. A declining history would be consistent with mixing with more dilute waters, such as net infiltration through the cover or lateral flow. An increasing history in distal downstream regions would be consistent with plume expansion or movement of the plume.

Seepage losses from the tailings basin to the TDSS occurred at rates that overwhelmed natural recharge, as indicated by the growth of a large mound. Waters that show indications of tailings seepage are gradually dropping in concentration at updip locations and increasing at downdip locations. Reductions in concentration are consistent with greatly reduced seepage and mixing with dilute waters from natural recharge, but it would be difficult at best to quantify seepage because the pore waters in the tailings basin are not being sampled.

C11 DOCUMENTED TIME-SERIES TRENDS AND STATISTICAL ANALYSES

Groundwater flow and geochemistry as impacted by tailings seepage has been considered at the site in three dominant contexts: (i) seepage from the tailings basin during and shortly after the operations period, (ii) the hydrologic and geochemical evolution of the pit lake, and (iii) transport of seepage water within the southeast drainage. In general, these studies provide useful information regarding the tailings basin hydraulic and geochemical evolution, and water level trends in boreholes, but trends and analyses of the groundwater geochemistry near the tailings does not appear to have been documented in a comparable level of detail.

The database of geochemical observations is reasonably extensive for the wells of interest, although geochemical measurements were made prior to 1986 and are not included in the electronic database.

C12 APPLICABILITY OF NUREG–1569, APPENDIX F

Appendix F discusses methods for quantifying trends in a time series of chemical samples in a well field, with potentially noisy observations. Such methods are appropriately applied to the observational data.

However, correctly quantifying a trend is only part of an evaluation. The important question is what the trend means, or what is causing the trend. This question appears to be beyond the scope of the appendix.

C13 APPLICABILITY OF SITE OBSERVATIONS TO EVALUATE COVER PERFORMANCE

The site observations clearly demonstrate that the present-day hydrogeochemical system substantially differs from the system during the active mining period, with water levels and geochemical indicators of seepage gradually dropping towards pre-operation conditions. Changes in concentrations of conservative species generally reflect a mixing process of two different sources of water.

Under perfect cover performance, geochemical trends would reflect previously seeped waters diluted by waters recharged at the outcrop zone and perhaps the alluvial water table in the eastern drainages. The potential for natural recharge to the TDSS is likely largest at the drainage channels north and east of the tailings basin. There are some indications that TDSS wells along the TDSS strike and updip (e.g., 112, 125, 178) are gradually dropping in concentrations while the seepage plume is continuing to spread to the north and west in the TDSS, consistent with previously seeping waters moving downdip and being partially replaced with natural recharge.

Although the observations do indicate a dramatic change in conditions after cover emplacement, the disturbance due to the tailings basin seepage during operations was so large that the recovery observations could be consistent with a nonzero recharge fraction. A water balance model in conjunction with geochemical indicators might provide more robust bounds on the recharge fraction than the geochemical indicators alone. For example, the forty-year period from 1970 through 2010 might be considered using seasonal precipitation signals to estimate flow fields, and the resulting flow fields then used to estimate transport of a conservative species such as chloride. For the final report, it may be useful to demonstrate the approach using a relatively simple model of the TDSS and alluvium near the tailings basin, including the TDSS wells near the basin. This would allow a high-level assessment of the methodology and associated uncertainties.

A defensible assessment at the level that might be required for a regulatory action would require substantially greater effort. A water balance model that describes the potential recharge pathways would require more detailed modeling near the tailings basin than previous site models to represent potentially important interactions between the southeast drainage and bedrock units below the TDSS. It would be difficult to develop a defensible model because of the relatively small set of observations in the TDSS and 50SS available for calibration, complete lack of observations within the tailings basin, and almost complete lack of observations below the 50SS. Given the set of observations, a water-balance model may be more appropriate to assess uncertainty rather than a calibrated model. Such a model might be able to assess the range of site conditions that would produce the observed water levels and chemical signals. The level of effort necessary to perform modeling work that constrains the recharge fraction would be beyond the scope of this project, however, because of the level of detail required, the lack of observations to support the model, and the potentially large number of simulations to account for different hypotheses and uncertainty.

Some of the 50SS boreholes appear to be reflecting a short circuit, in the sense that both temperature and geochemical fluctuations are much larger than the overlying TDSS observations. Typically this behavior would indicate shallow or surface waters draining down the borehole. These boreholes may be unreliable for evaluating performance.

In summary, it would be difficult at best to provide estimates of recharge through the tailings basin cover at the Highland site. The time history of groundwater hydrology and geochemistry is generally consistent with minimal seepage from the tailings basin, as the water levels are declining over time and the geochemical signature is diluting. However, the large fluxes from the basin while it was active induced widespread and large responses in the aquifer. Even if the cover was not performing well with respect to net infiltration, it is expected that the seepage fluxes would be at least one to two orders of magnitude smaller than when the tailings basin was active. Such seepage fluxes may be large enough to be readily identifiable in a pristine aquifer but be masked until the prior disturbance is flushed from the system. With the low natural recharge in this site, it may be several more decades before an unambiguous seepage signal could be resolved.

The most direct method for identifying cover performance is by using a conservative chemical constituent unique to the cover as a tracer. Or and coworkers (Or and Dinwiddie, 2007; Or, et al., 2006) described tracers that could be used for performance confirmation in the vadose zone, identifying H-2, C-13, N-15, O-18, S-34, ethanol, benzoate, and fluorobenzoates as candidate tracers with desirable characteristics. The presence of such a constituent in downgradient wells would provide unambiguous evidence that recharge is occurring through the cover, and the time history of observed concentrations would provide indirect information on travel times. No such constituent has been identified for the cover materials. A tracer could be spread over the surface in the future, but it would likely take many years before it became evident in downstream wells without focused recharge.

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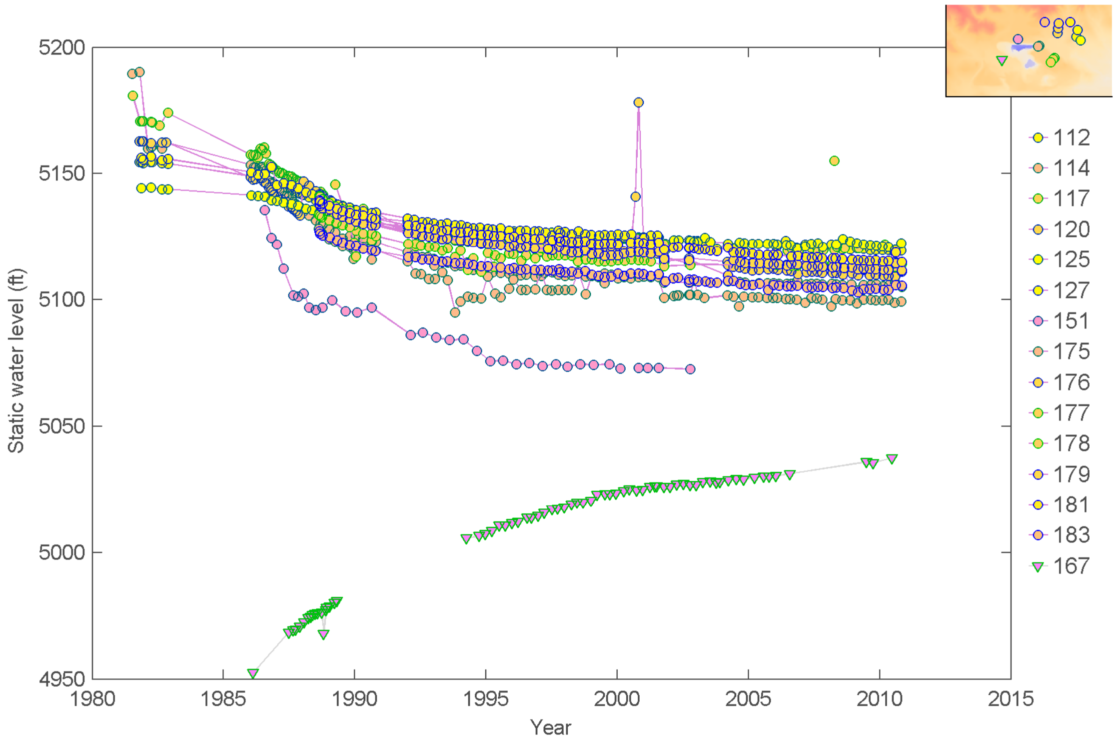

Figure C–1. TDSS Boreholes and Pit Lake Water Levels

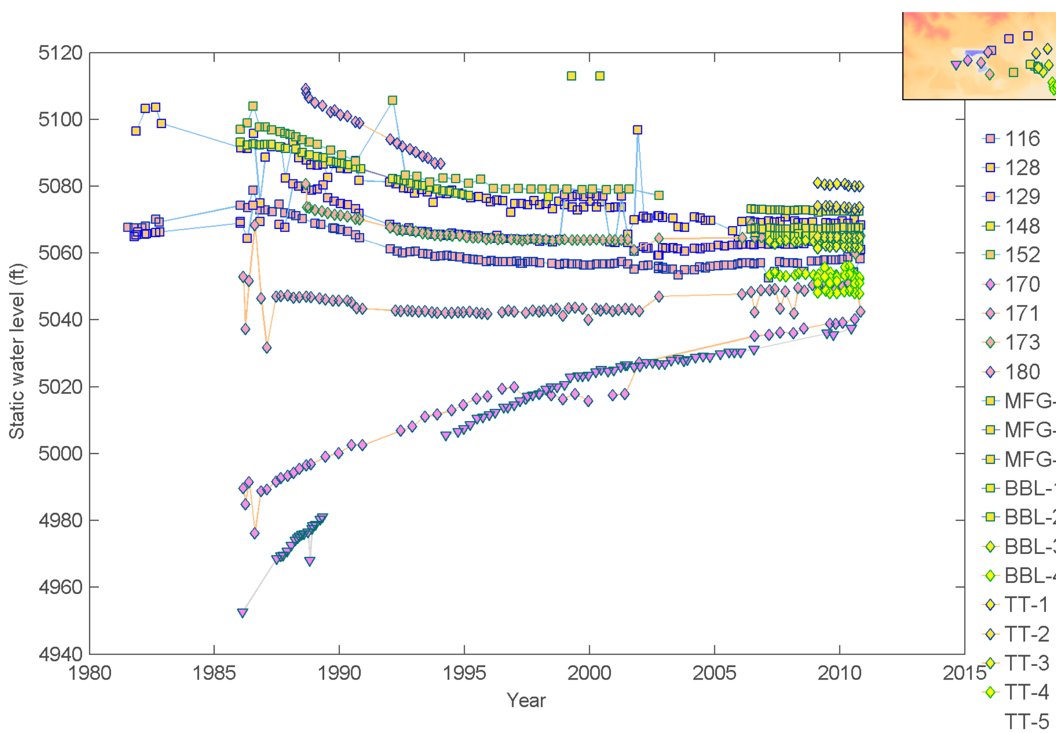

Figure C–2. Alluvium, Backfill, and OS Boreholes, and Pit Lake Water Levels

TDSS water levels

OS, alluvium, backfill water levels

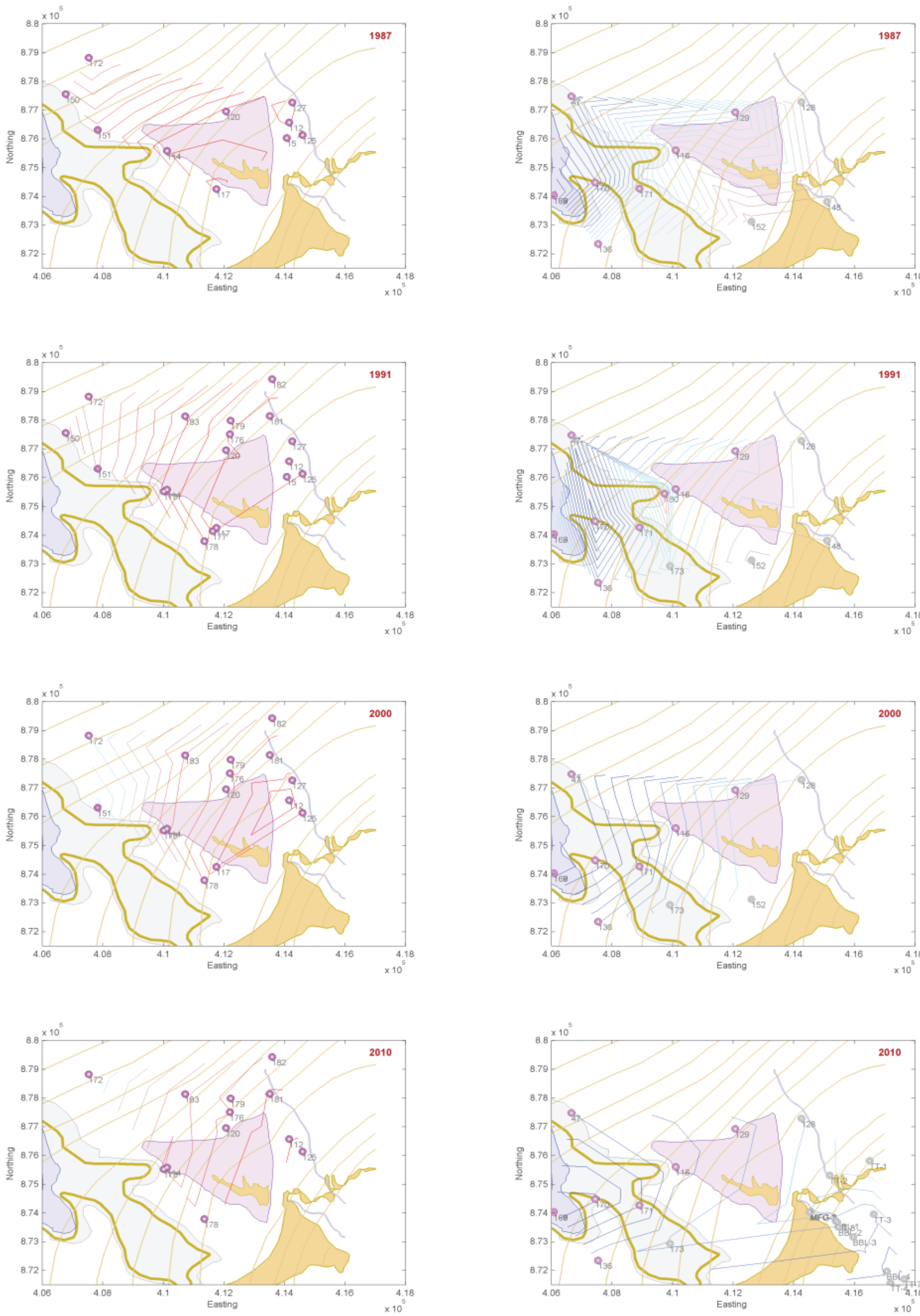

Figure C–3. Snapshots of Water Level Contours in the TDSS and OS

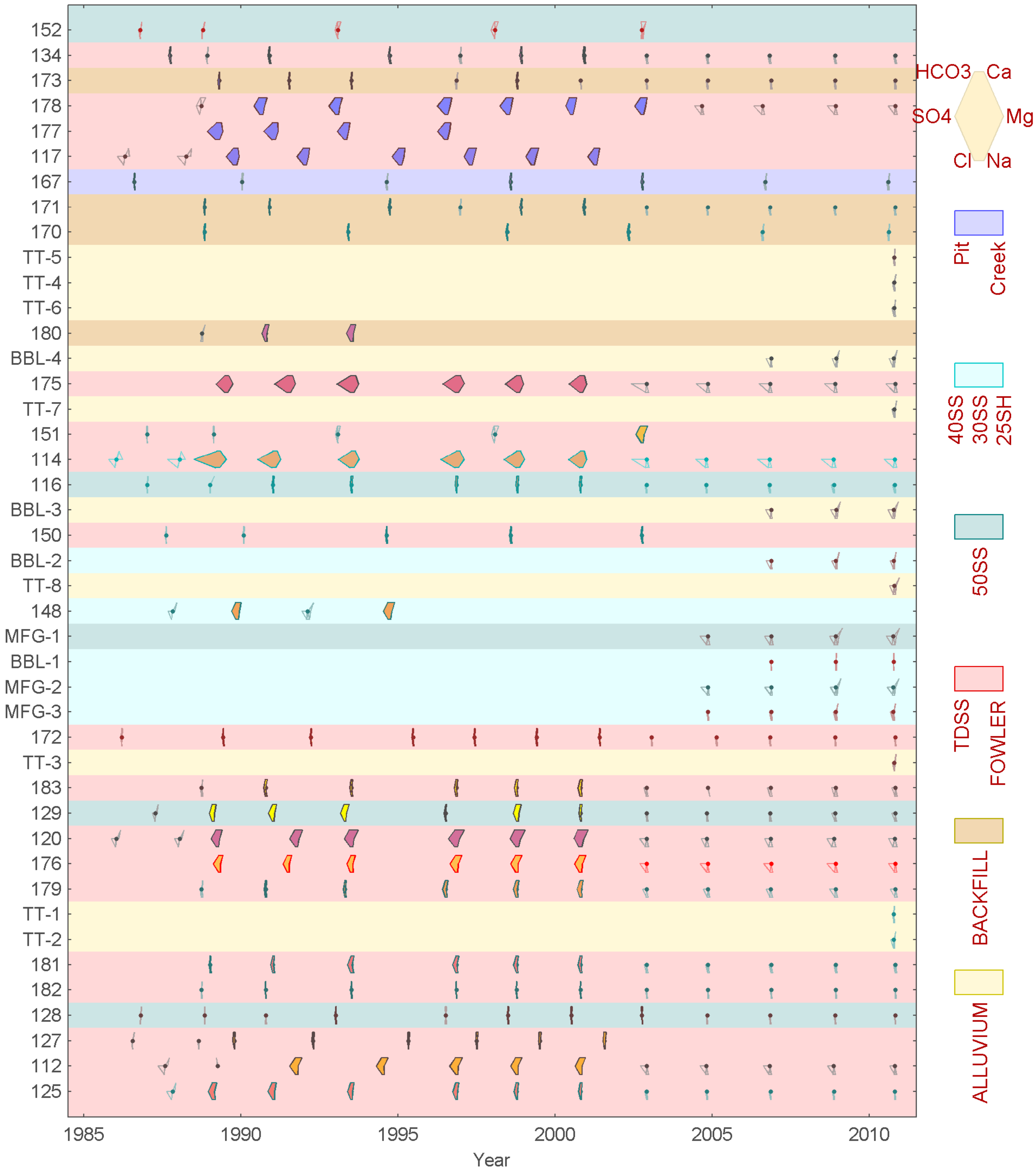

Figure C–4. Stiff Diagram of Major Ions (Every Fourth Reading) in meq/l. Background Color Represents the Unit That the Well Is Completed in. The Same Color Scheme Is Used for the Other Stiff and Piper Diagrams.

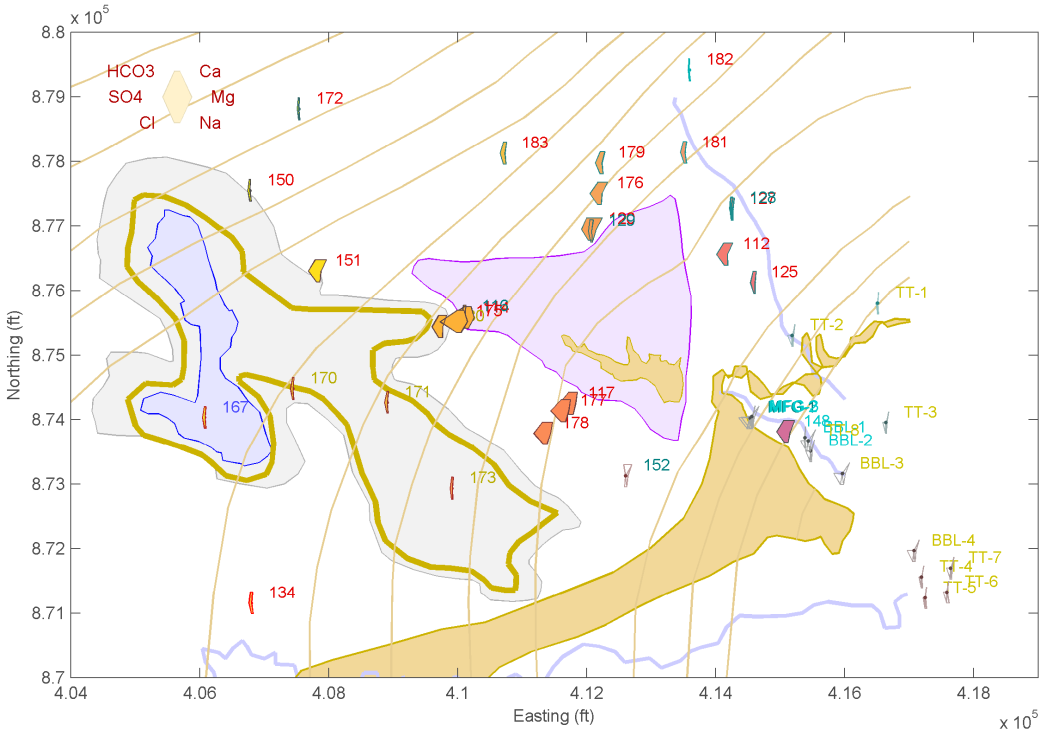

Figure C–5. Stiff Diagram of Major Ion Concentrations (meq/l) at Last Available Reading. Contours Represent the Base of the TDSS (10-ft Interval) and Orange Shaded Areas Are TDSS Outcrop (Digitized From 1998, Figures 1.4 and 1.5). Gray Area Is Extent of Excavation. See Previous Figure for Color Scheme Used for Well Label Color.

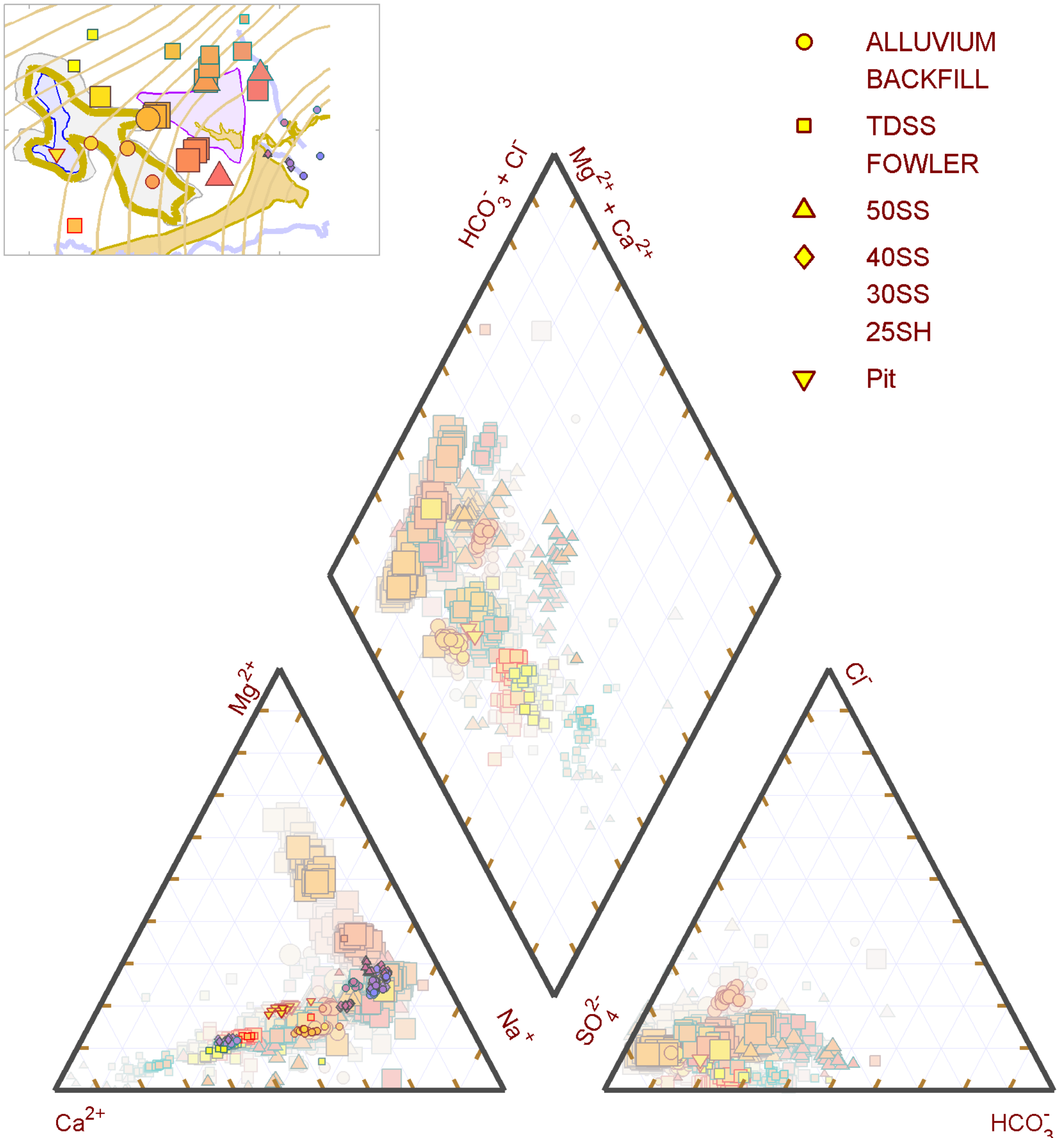

Figure C–6. Piper Diagram of Major Ionic Concentration (meq/l). Symbol Size Is Proportional to the Logarithm of Combined Ionic Concentration. Earlier Readings Are Indicated by Whiting Out the Symbol.

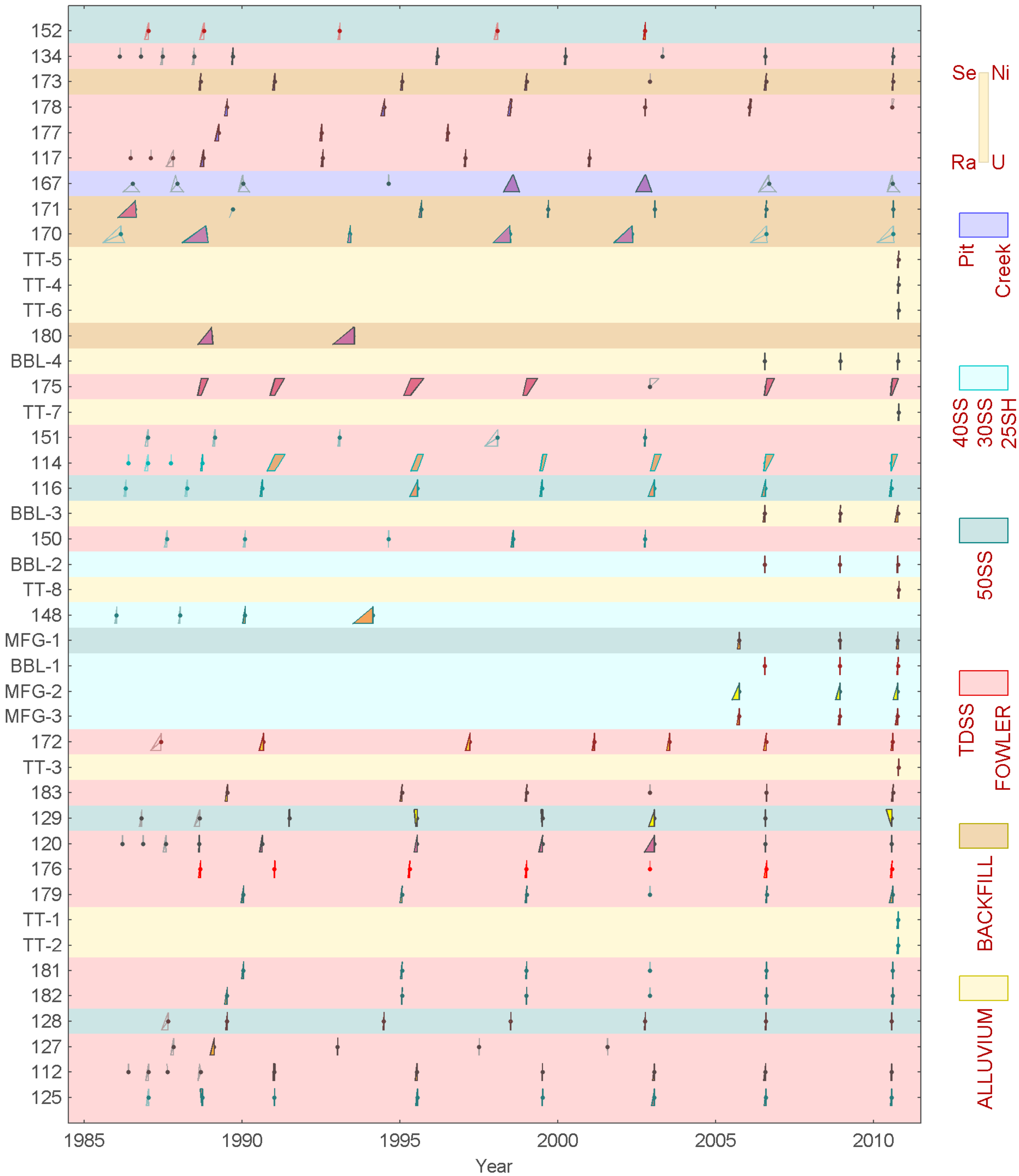

Figure C–7. Selected Elements (Every Fourth Reading) in mmol/l)

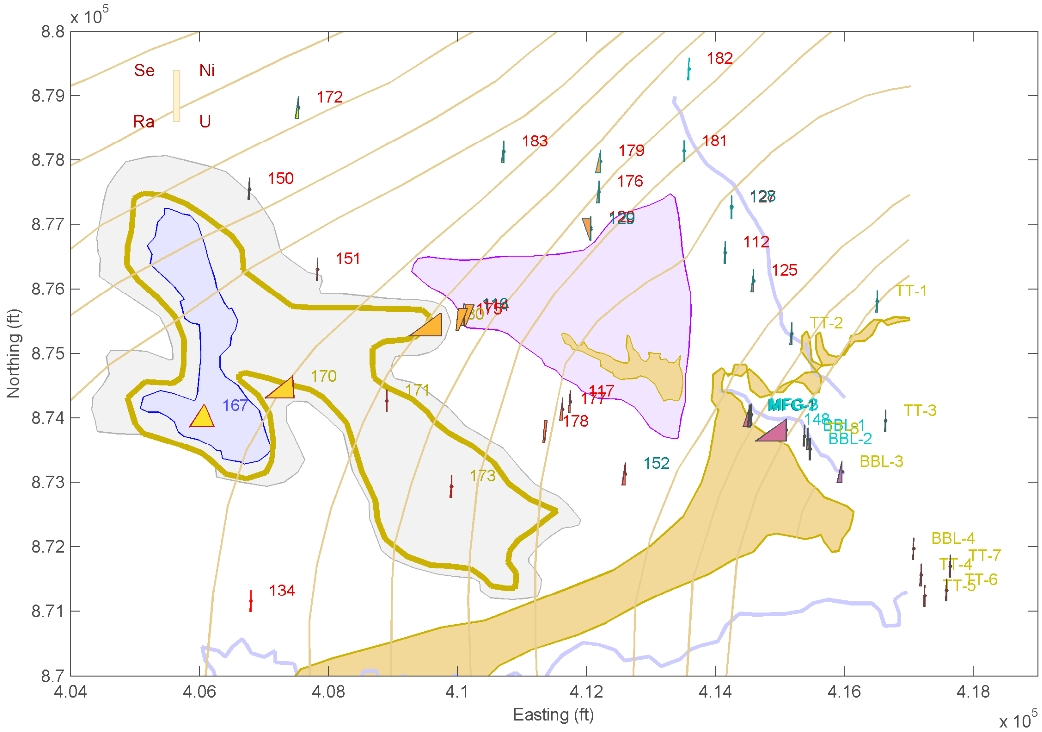

Figure C–8. Concentrations (mmol/l) for Selected Elements. Contours Represent the Base of the TDSS (10-ft Interval) and Orange Shaded Areas Are TDSS Outcrop. Gray Area Is Extent of Excavation.

APPENDIX D

SITE EVALUATION FOR SITE 3, CHURCH ROCK (UNC), NEW MEXICO

SITE EVALUATION FOR SITE 3, CHURCH ROCK (UNC), NEW MEXICO

D1 INFORMATION AVAILABILITY FOR GEOLOGIC STRUCTURE AND PROPERTIES

Raymondi and Conrad (1983) describe the hydrogeology of Pipeline Canyon, which contains the tailings site. Raymondi and Conrad (1983) summarize the geology, well tests, recharge zones, and observations prior to 1983. UNC provided an Excel well database containing summary observations from 441 wells; 432 include well depth and more than 320 include at least some unit elevation data. UNC provided copies of the borehole logs as Portable Document Format (pdf) files for 63 wells, in some cases including static water levels prior to 1988 (the earliest observations in the electronic database).

D2 INFORMATION AVAILABILITY FOR NATURAL AND ARTIFICIAL RECHARGE

Tailings disposal occurred from May 1977 through May 1982. McLin (1982) estimated seepage rates from the central cell of the tailings basin between 77 and 450 m^3/d [1.7×10^4 and 1×10^5 gpd] (during two months in the summer of 1980), and estimated an average seepage of 240 m^3/d [5.3×10^4 gpd] during this period. For comparison, average annual precipitation over the central cell area is approximately 120 m^3/d [2.6×10^4 gpd]. U.S. Environmental Protection Agency (EPA) (2011) reports that an estimated 3.1 GL [8.2×10^8 gal] of acidic mine water and sludge were discharged into the tailings cells over the lifetime of the project, of which 1.3 GL [3.5×10^8 gal] seeped into underlying units or remained in the sludge.

Raymondi and Conrad (1983) mention a limited onsite meteorological station and a long-term record at Gallup, NM, approximately 25 km [16 m] WSW of the site at 240 km [150 m] lower elevation. Raymondi and Conrad (1983) suggest that precipitation may be somewhat larger at the site than at Gallup. Other long-term records are available at Thoreau, NM, 37 km [23 m] SE of the site at 56 km [35 m] higher elevation.

The tailings cells are adjacent to the channel in Pipeline Arroyo for approximately 1.3 km [0.8 mi], thus surface-water flow in the arroyo influences interpretations of tailings seepage. Mine dewatering discharges started in 1967 and ended in 1985, releasing approximately 140 TL [3.7×10^{10} gallon] of mine discharge at a peak rate of 19 m^3/min [5,000 gpm, 7.2 Mgpd] and 5.4 Mg [600 ton] of uranium. The average mine dewatering discharge was 14 m^3/min [5.3 Mgpd], two orders of magnitude larger than the tailings seepage estimated by McLin (1982).

A large transient seepage event occurred in July 1979 after the south tailings pond dam failed, which released 94 Mgal and 16 Gg [18,000 ton] of suspended solids into Pipeline Arroyo and transported tailings up to 129 km [80 mi] downstream (EPA, 2011). The water level in Z1 well 0029 (the top of screen is 3 m [10 ft] below the alluvium contact) rose 2 m [8 ft] from the initial observation in June 1980 until August 1982, declined back to the June 1980 point by July 1989, and declined an additional 3.4 m [11 ft] by October 1993. Well 0029 is located at the southern end of the South Cell.

D3 INFORMATION AVAILABILITY ON TRANSIENT DRAINAGE AFTER EMPLACEMENT

Several reports describe the changes in static water level declining over time. Prior to mining, the southwest alluvium and upper Gallup formation units were unsaturated and water levels rose at least 30 m [100 ft] as a result of mine discharge and seepage during operation of the tailings cells (Canonie Environmental, 1987). Water levels in the alluvium and upper Gallup sandstone units have been gradually dropping since the cessation of mining activities, leaving increasingly large areas of these units desaturated. The maximum Z3 water level in 1987 reported by US Filter Engineering and Construction (2004, Figure 15) is 2,121 m [6,960 ft]. The maximum water level is 6941.3 in any unit reported in the electronic database (which starts in July 1989).

Dwyer (2011) evaluated drainage from the north and central cells after emplacement as part of estimating the potential for settlement to squeeze water from the fine-grained tailings. The study focused on comparing water potential with field capacity using models with and without additional overburden. Dwyer (2011) modeled drainage for representative columns using UNSAT-H, using an average year to estimate potential evapotranspiration and a combination of measured and assumed parameters. Initial conditions are based on literature values from 1991, and no later measurements are mentioned. The simulations suggest that the system is still draining the initial tailings water after 21 years; Dwyer (2011) does not report the calculated infiltration rates.

D4 INFORMATION AVAILABILITY ON HYDROCHEMICAL OBSERVATIONS

The site has an electronic database of water levels and geochemical sampling (starting in 1989). Some additional information on older water level observations is available from well logs as early as 1980 (e.g., well 0029 A). Some geochemical observations prior to 1989 are plotted in reports.

Wells and piezometers that are used solely for monitoring water levels are not included in the electronic database. Water level information for these wells are available in the semiannual reports (and to a lesser extent the annual reports), which are available on Agencywide Documents Access and Management System (ADAMS). No semiannual or annual reports prior to 1999 were found on ADAMS, although the annual report series started in 1989. The earlier reports contain a mix of typed and handwritten water levels. Later reports also report pH and temperature in many of the wells. According to the table of contents, water level data from 1987 and 1988 are contained in the Tailings Reclamation Plan (Canonie Environmental, 1991, Vol. 2) but are not available because the electronic file in ADAMS (ML103230255) is truncated (Tables 6.10 through 6.28 and all 72 figures are missing).

The EPA issued three five-year reviews on the site (including data tables that replicate the electronic database). The 1998 and 2003 reports (EPA, 1998, 2003) are available online but the EPA (2008) report is not available from either the EPA site or ADAMS.

D5 SUMMARY OF CONCEPTUAL MODEL FOR WATER FLOW NEAR THE TAILINGS COVER

Mine dewatering higher in the arroyo provided a steady stream of water in the alluvial channel from 1967 through 1985. Pre-operation, the arroyo was an ephemeral stream and has returned to that condition. Perched waters in the alluvium follow the topographic gradient down the arroyo (to the southwest). The geochemistry of the waters is altered as it equilibrates with the alluvium.

The bedrock units dip 4 to 8 degrees to the north or northwest. Under natural conditions the units are unsaturated, and the underlying unit has a relatively low permeability, thus bedrock flow is expected to the north or northwest.

Tailings disposal occurred from 1977 through 1982, with a north and south pond (in the north and south cells) and a central tailings cell. Borrow pits 1 and 2 were constructed in the eastern portion of the central cell. Borrow Pit 1 was used to dispose of tailings and Borrow Pit 2 was used to retain tailings liquids until it was dewatered in 1989.

The North and South mill ponds were constructed on alluvium between Pipeline Arroyo and higher exposed bedrock to the east, both ponds generally abutting exposed bedrock on their east or south flank (see Figure D–1). Between zero and 30 m [100 ft] of alluvium underlie the tailings cover (see Figure D–2). Near the ponds, the Z1 (lowest) unit of the upper Gallup sandstone underlies the arroyo channel with variable thicknesses of overlying alluvium. The Z3 (uppermost) unit of the upper Gallup sandstone subcrops below both mill ponds, but the Z1 unit only subcrops below the south mill pond. Water seeping from the north pond may have overflowed down the alluvium/bedrock contact and thereby also reached the Z1 unit. Canonie Environmental (1987) identified direct contact of tailings seepage with unit Z3 in the northeast section of the north tailings cell, and with unit Z1 in Borrow Pit No. 2. Canonie Environmental (1988) clarifies that the alluvium contains a large natural buffering capacity lacking in the sandstone units, and noting that the waters discharged from mine dewatering operations were of good quality and low in total dissolved solids until dissolving solutes within the alluvium. Canonie Environmental (1988) claims that tailings seepage could not be distinguished from the mine dewatering waters because of the buffering in the alluvium. Presumably this rationale drove remediation activities to focus on the two zones where tailings water directly contacted the Z1 and Z3 units.

Alluvium-filled paleochannels cut through bedrock at the south end of the South Cell, through the Central Cell, and at the north end of the North Cell. The Z3 unit is missing in these paleochannels, so that the Z1 unit subcrops alluvium in the paleochannels. A bedrock ridge extends towards the arroyo at the southern edge of the central cell, forming a so-called Nick Point in the channel. The Z1 unit is less permeable than the Z3 unit. During the tailings emplacement period, water levels in the alluvium were high enough near the mill ponds that perched water formed atop the Z1 unit along the arroyo channel and in the paleochannels. During tailings emplacement in the central cell, central cell alluvium water levels were elevated sufficiently that essentially all of the Z1 subcrop area in the central cell experienced perched water in the overlying alluvium (draining towards the arroyo along the bedrock topography) based on reported water levels in 1981 at 3 wells (Misra, 1981).

Once waters seeping from the mill ponds entered the aquifers, the flow spread radially near the source and more distally moves in the dip direction. During mine dewatering and active mill ponds, the water levels in the alluvium were high enough to form a continuous flow past the tailings, but the saturated volume in the alluvial aquifer has been greatly reduced as water levels declined. NA Water Systems (2008, Figure 8) suggests that by Octover 2007 perched conditions in the alluvium had shrunk to less than 40 m [131 ft] wide at the Nick Point, in a trough passing under the northwestern flank of the evaporation ponds in the central cell.

Canonie Environmental (1987) describe the tailings area as unsaturated prior to mining based on geotechnical borings completed in 1968 (in the alluvium) and 1976 (in the Z1 unit). Canonie Environmental (1987) describes the water levels as 81 [266 ft] and 30 m [100 ft] above the completion depth in these two boreholes in 1987. The precise location of these boreholes is not legible in the pdf file, but they appear to lie in the south and north cells, respectively.

D6 WELLS DOWNGRADIENT OF THE TAILINGS COVER

Most of the wells in the database are downgradient of a cell. Few wells are available to provide a background observation, aside from several northern wells completed in the alluvium, but it is not clear whether any well would provide representative background premining water quality data given the initial dry state of the aquifers.

D7 KEY CHEMICAL SPECIES OR INDICATORS IN THE TAILINGS PORE WATER

The background major ion chemistry is dominated by Mg, Na, and SO_4. Site studies indicate that calcium and sulfate are strongly buffered by carbonates and gypsum within the alluvium. Aluminum and Mg are discussed as a potential tracer of seepage water. Note that aluminum solubility is strongly dependent on pH, with a minimum solubility in a pH range of 5.5 to 6.0, thus neutralization of waters will also tend to reduce aluminum concentrations.

Earth Tech, Inc. (2000a, Section 2.2.3) identified bicarbonate and chloride as indicators for tailings seepage in the southwest alluvium. Earth Tech, Inc. (2000a) also identified that manganese and chloroform exceed standards in localized areas immediately adjacent to the tailings impoundment. Elevated chloride levels were present in acid seepage, motivating Earth Tech (2000a) to use a chloride level of 150 mg/L [150 ppm] to distinguish between seepage and background concentrations of 60 to 120 mg/L [60 to 120 ppm]. Earth Tech, Inc. (2000a) describes seepage as being neutralized within a few feet of the alluvium/tailings contact, which increases calcium and bicarbonate concentrations, and suggests that bicarbonate concentrations above 1,000 mg/L [1,000 ppm] would indicate seepage relative to background concentrations of 500 to 900 mg/L [500 to 900 ppm]. Earth Tech (2000a) also indicates that a calcium-to-magnesium ratio less than 1.5 is typical of seepage-impacted water.

Earth Tech, Inc. (2000b, section 1.2) identified cobalt, nickel, combined radium-226 and 228, manganese, sulfate, and total dissolved solids as above standards outside property limits in the Z1 unit. Earth Tech (2000b, Section 2.2) used chloride concentrations above 50 mg/L [50 ppm] as an indicator of seepage, noting that other constituent concentrations change with chloride.

Chester Engineers (2011) collect two earlier reports on tailings seepage and groundwater recharge into the Z3 unit, adding updated information. In particular, Chester Engineers (2011) make recharge estimates based on responses of water levels during a month with large precipitation, suggesting that total recharge is small. US Filter Engineering and Construction (2004), one of these two reports, indicates that focused recharge may be occurring in two diversion channels and one of these channels may also provide a source of tailings leachate. US Filter Engineering and Construction (2004) also interpret field indications as indicating that water perched in the tailings above the alluvium. These field indications are water levels in boreholes adjacent to the north pond, drilled in 1979 during active milling, that dropped 6 to 8 m [20 to 25 ft] within 2 hours as the Z3 unit was penetrated.

D8 KEY CHEMICAL SPECIES OR INDICATORS FOR DISCERNING TEMPORAL AND SPATIAL TRENDS IN GROUNDWATER QUALITY

The typical chemical species used for trend analysis include pH, chloride, and sulfate. At this site, manganese, aluminum, and several heavy metals may also be useful for trend analysis in the bedrock units.

D9 CHEMICAL DIAGRAMS OF PORE WATER

Sufficient information exists in the database to construct Stiff and Piper diagrams for 6 major ions (Ca, Mg, Na, Cl, SO_4, and HCO_3) for 1989 through 2010 (see figures). K concentrations are small relative to Na. No data for CO_3 is available. The Stiff and Piper diagrams suggest that well chemistry is fairly consistent over the last 20 years for most wells. Background chemistry favors Mg, Na, and SO_4, with all constituents elevated near the tailings.

Six other species (Al, Co, Ni, Se, U, and Ra) are widely measured above the detection threshold. A few wells near the north cell show greatly elevated levels of some constituents. Earth Tech (2000b) demonstrated that neutralization of the source reduced the concentrations, arguing that solubility is much smaller for such constituents under near-neutral pH levels.

D10 INDICATIONS OF COVER EXISTENCE BASED ON GEOCHEMICAL OBSERVATIONS

Under premining conditions, available information indicates that the alluvium and upper bedrock units were unsaturated. Mine discharge introduced relatively clean water to the alluvium along the channel, inducing perched conditions in the alluvium that were heavily concentrated from equilibration with precipitants in the alluvium. This perched unit also provided a source to the bedrock units. The mill tailings cells provided a later, and much larger, source of water until the tailings operations ceased.

The system has undergone a systematic decrease in water levels in all monitored units since mining and tailings operations have stopped, desaturating in some wells, consistent with return to premining conditions. The geochemistry has also shown indications that source areas are less acid. Such responses are expected because large amounts of additional water are no longer being applied to the alluvial channel and tailings areas.

D11 DOCUMENTED TIME-SERIES TRENDS AND STATISTICAL ANALYSES

The database of geochemical observations is reasonably extensive for the wells of interest, although few geochemical measurements are available prior to 1989 and are not included in the electronic database.

The series of annual groundwater corrective action plan reports include plots with spatial patterns of groundwater levels and groundwater quality with respect to pH and chloride. The series also provides time series graphs for water levels, major ions, and uranium. The text of these reports interprets the trends.

I have not found documented statistical analyses of the geochemical observations.

D12 APPLICABILITY OF NUREG–1569, APPENDIX F

Appendix F discusses methods for quantifying trends in a time series of chemical samples in a well field, with potentially noisy observations. Such methods are appropriately applied to the observational data.

However, correctly quantifying a trend is only part of an evaluation. The important question is what the trend means, or what is causing the trend. This question appears to be beyond the scope of the appendix.

D13 APPLICABILITY OF SITE OBSERVATIONS TO EVALUATE COVER PERFORMANCE

The role of a cover with respect to protecting groundwater consists of reducing vertical fluxes of water from both focused recharge and distributed recharge. Focused recharge may occur in drainage channels during surface water flow. Distributed recharge may occur between drainage channels. In principle, lateral inflow from outside the tailings emplacement zones may allow recharge to contact the tailings if the subsurface topography tends to focus water to the tailings (e.g., as a temporary perched zone with lateral flow).

This site features a large perturbation to the premining conditions from six sources: mine dewatering discharged to the alluvium channel; drainage from the north, central, and south cells; and drainage from borrow Pits 1 and 2. Natural recharge appears insufficient to maintain spatially continuous saturated conditions in any of the units, based on two dry boreholes drilled prior to mining.

Given that (i) a large influx of water occurred during mining and tailings emplacement (larger than natural precipitation); (ii) water is no longer being supplied; and (iii) pumping has removed water from all units and is continuing in the Z3 unit, it is expected that water levels would generally decline over time even with poor cover performance.

Assuming that the cover completely prevents recharge, water levels would continue to decline until the units completely desaturate. The groundwater plume would be expected to spread through diffusion and dispersion, with the center of mass moving downgradient and some mass being removed in recovery wells. A certain amount of drainage from the tailings would have provided a delayed source after cover emplacement. Under these conditions, the groundwater chemistry for many species would tend to remain similar over time, but some constituents would preferentially decrease in concentration as acid conditions gradually neutralize. Although evaporation is known to increase concentrations of conservative species in groundwater, the rate of evaporation should be small for the deep water tables at the site.

In order to quantitatively identify poor cover performance, two general methods apply: (i) identify a geochemical indicator found in the cover but not in the applied liquids or natural system or (ii) identify one or more indicators that distinctively modify the natural evolution of the groundwater system.

The first general method could be satisfied if the interim or final cover material has a distinctly different rock type than the tailings and other units, or if a conservative tracer was applied to the cover as part of emplacement activities. For the central cell, Canonie Environmental (1995) reports that the radon barrier and top soil cover used previously excavated site soil, which presumably has a similar composition as the alluvium under the tailings. A basaltic rock mulch obtained offsite was emplaced with minimum thickness of 8 cm [3 in] for cover erosion protection, and as riprap in drainage channels and drainage swales. Canonie Environmental (1995) reports that the rock mulch was tested with respect to rock quality but does not present a geochemical analysis; it is unlikely that one was performed. A similar procedure was followed for the other cells. Although the basaltic rock is not native to the site, it is highly unlikely that a usable signature would be picked up in monitoring wells even with poor cover performance because the mass transfer from the basalt to the water would be limited: the basalt layer is very thin and the contact of water interacting with the basalt is highly transient. Any analysis would be hampered by the lack of precise geochemical information on the basalt composition.

There is no record that a tracer was applied during cover emplacement, and it is highly unlikely that one was. Note that water was applied as part of the cover construction process; adding a tracer to construction water during cover construction could provide a reasonable method for evaluating cover performance at other sites.

Based on these considerations, the Church Rock site is highly unfavorable for analyzing cover performance using some geochemical aspect of the cover to provide a tracer.

The following scenarios might allow analysis in the second general method when (i) waters moving through the tailings cover and tailings provide a distinctly different geochemical signal than the pre-existing plume, (ii) a well-quantified external source of water is modifying the pre-existing plume, (iii) the plume is evolving more slowly or extending more broadly than expected, (iv) a water balance identifies unusual rates of water level changes, or (v) transient fluctuations can be tied to rainfall events. The first two approaches are generally attacked using mixing analyses, and many geochemical species require specialized geochemical software to consider the implications of geochemical interactions. The third and (to some extent) fourth approaches generally require numerical modeling, which is subject to considerable uncertainty with respect to model input. The fifth approach requires rainfall data, which is only available offsite.

Geochemical methods at this site are hampered by the strong buffering capacity of the alluvium, thus the Z1 and Z3 units are relatively more amenable to analysis. There is considerable uncertainty regarding the composition of potential sources of water, as well as transport rates. Accordingly, geochemical methods (addressing the first three scenarios) are not likely to strongly constrain estimates of recharge through the cover. Some indication of recharge may be provided by considering time series of the ratio of geochemical species.

The rate that water levels change depends on aquifer properties, pumping rates, and recharge rates. The groundwater system is probably dominated by natural downdip drainage and pumping at Church Rock, with recharge through the tailings and natural recharge relatively small components of the water balance. Downdip drainage rates strongly depend on hydraulic conductivity. It is expected that the uncertainty in hydraulic conductivity is sufficiently large that natural recharge would be masked by uncertainty regarding the ongoing drainage of the initial pulse. Chester Engineers (2011) used a one-dimensional analysis to estimate that Z3 downdip drainage is comparable in magnitude to gravity-induced drainage as the water table drops, illustrating an analysis approach.

The time series for water levels and several geochemical constituents exhibit fluctuations that may be related to episodic recharge, and US Filter Engineering and Construction (2004) suggests that focused recharge may occur at drainage ditches. Some analysis of this data may provide hints regarding recharge, but rapid recharge pulses cannot be detected with the quarterly sampling frequency. Further, water levels are not in the electronic database for wells that are not sampled for geochemical data, which would require either obtaining the data electronically from UNC or transferring the data from semiannual reports (not all of which are in ADAMS).

In conclusion, a limited amount of followup analysis of the Church Rock data may be warranted for the final report, using site data as examples of methodology and associated uncertainties. Three analyses may be appropriate: (i) geochemical evolution, in the form of geochemical ratios of conservative species, which may provide indications of mixing; (ii) bounding analyses to examine the minimum detectable recharge rate; and (iii) bounding analyses to examine implications of transient fluctuations in water levels and geochemistry.

D14 REFERENCES

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Figure D–1. 1987 Photo With Geologic Outcrops

FIGURE 8
Estimated thickness of alluvium between tailings and rock on circa 1997 aerial photographic base
(10-foot contour interval; geology after Canonie, May 1987)

Figure D–2. As-Built Topography and Alluvium Thickness Below Tailings

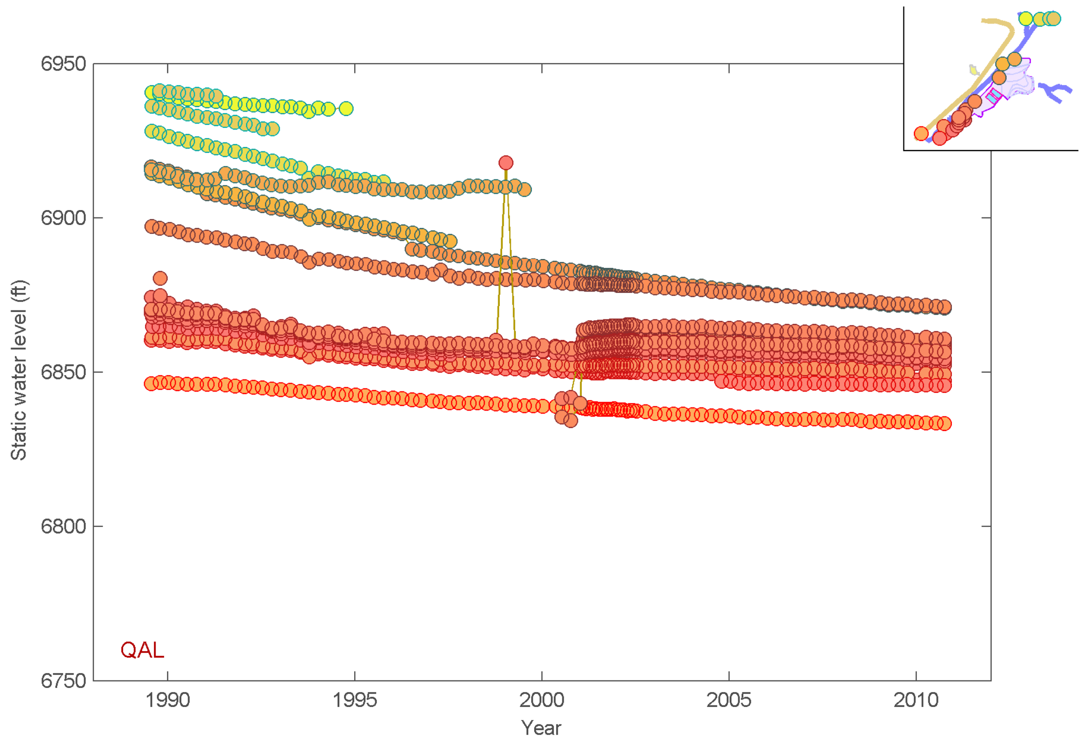
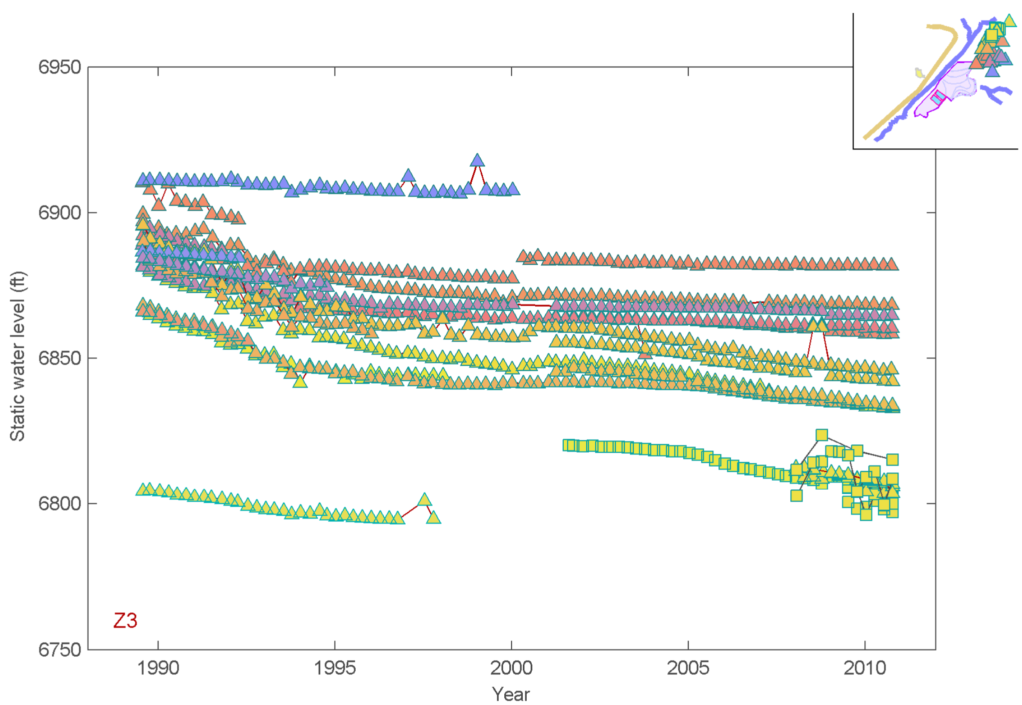


Figure D–3. (a) Alluvium Boreholes



D–3. (b) Upper Gallup Sandstone (Z3)

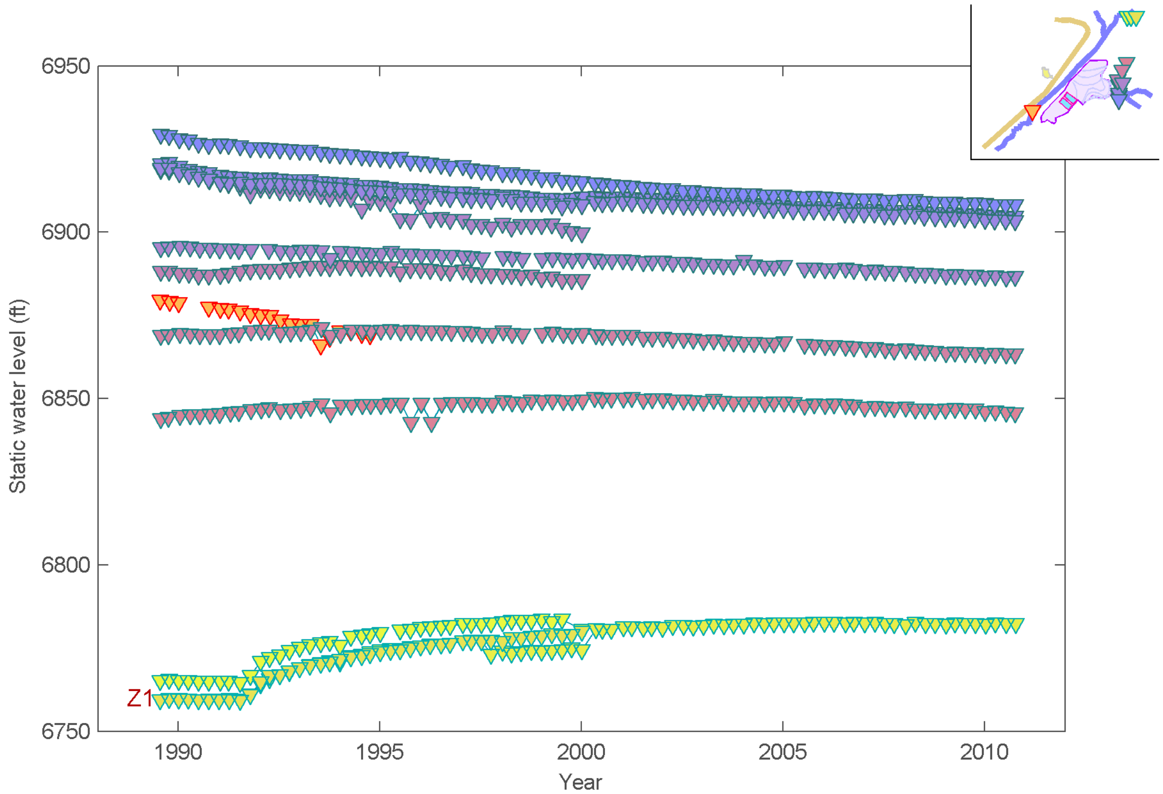


Figure D–3. (c) Lower Gallup Sandstone (Z1)

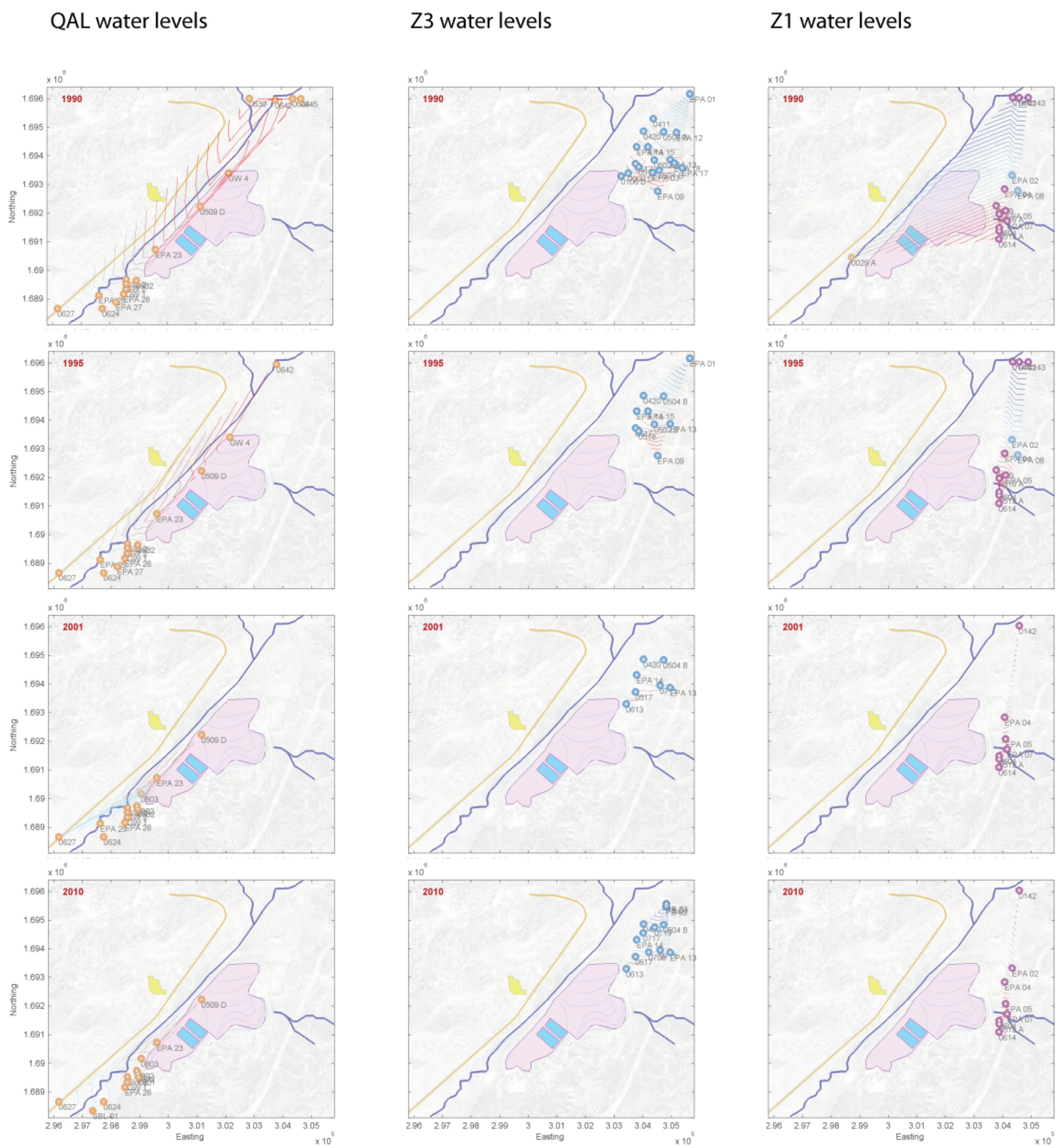


Figure D–4. Five-Foot Contours of Static Water Level in 1990, 1995, 2001, and 2010 (Water-Level Monitoring Wells Without Geochemical Information Not Included in the Database)

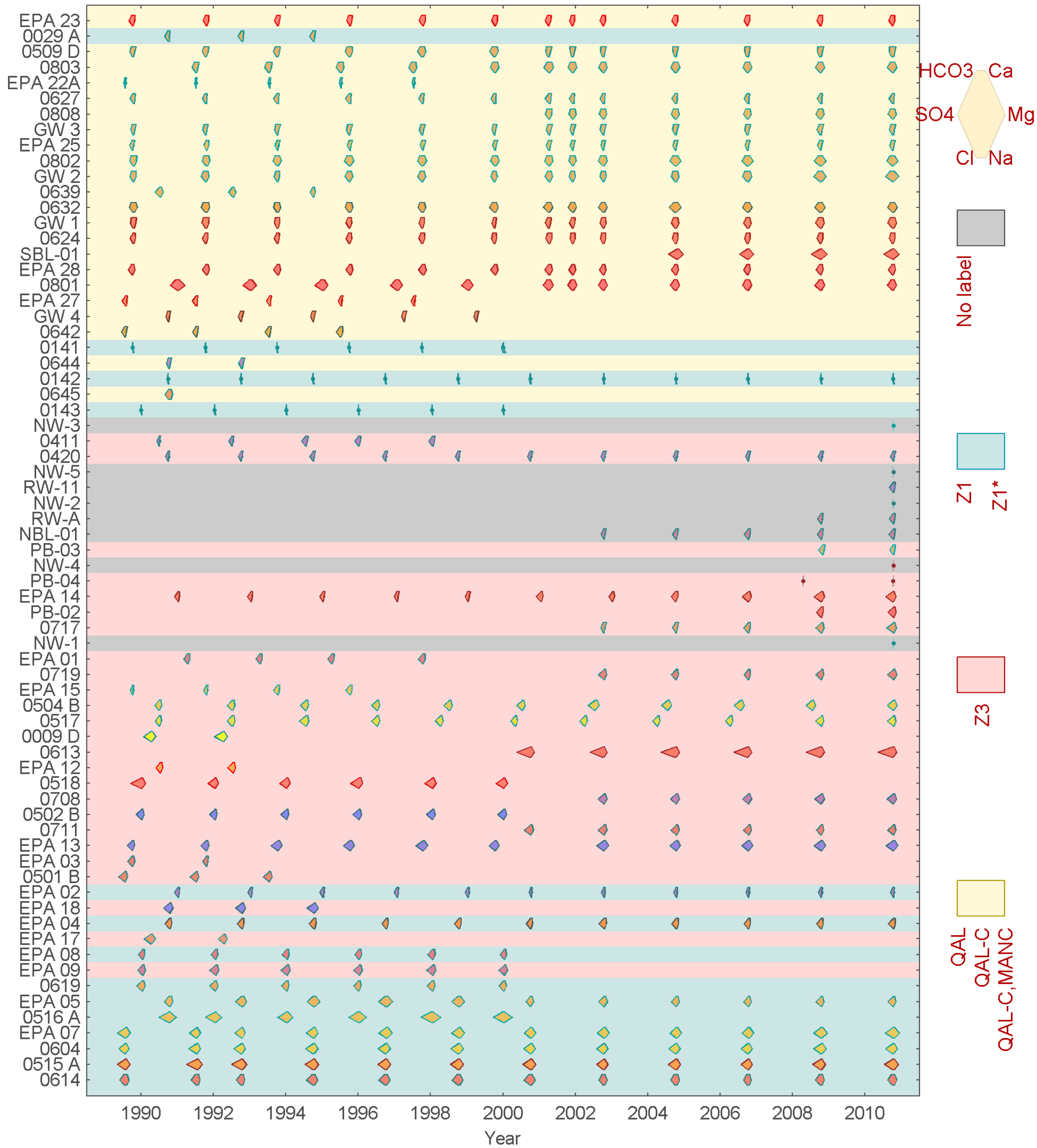


Figure D–5. Time Series of Stiff Diagrams for Major Ions (Every Eighth Reading) in meq/l

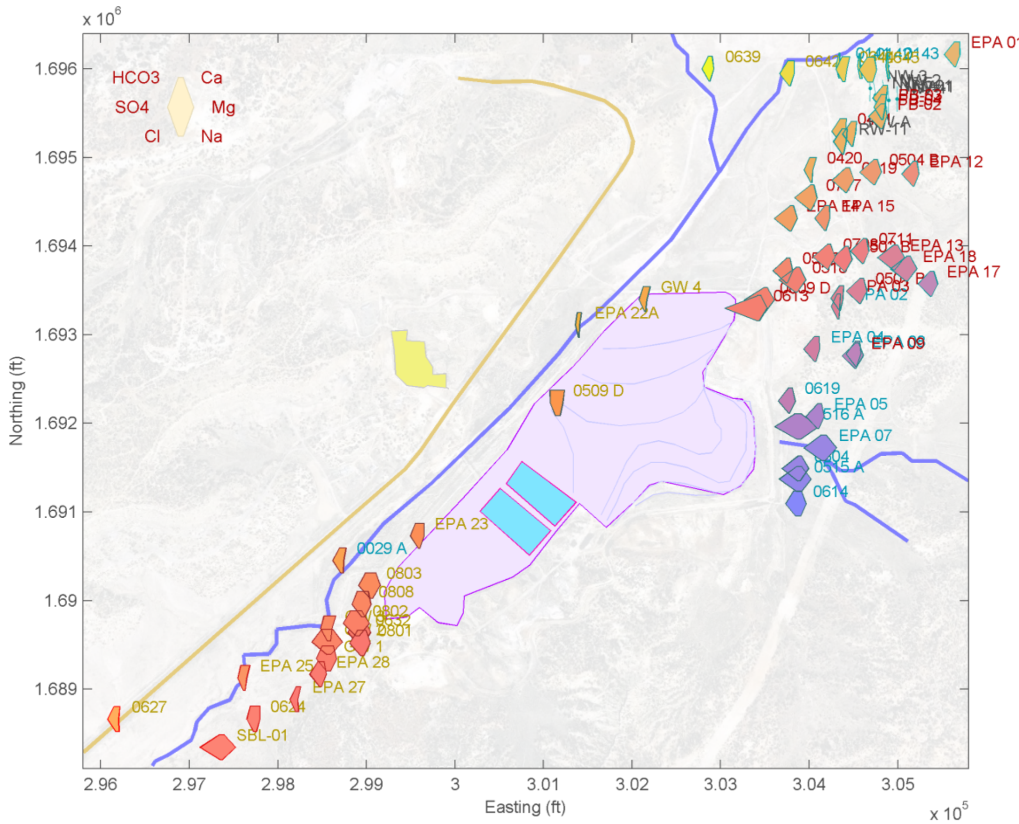


Figure D–6. Stiff Diagram of Major Ion Concentrations (meq/l) at Last Available Reading. Label Color Represents the Completion Unit for Wells: Tan, Red, Blue, and Gray Represent Alluvium, Zone 3 (Upper Gallup Sandstone Unit), Zone 1 (Lower Gallup Sandstone Unit), and Unknown or Mixed. The Tailings Cover Is Indicated by Violet, With Active Evaporation Ponds in Cyan.

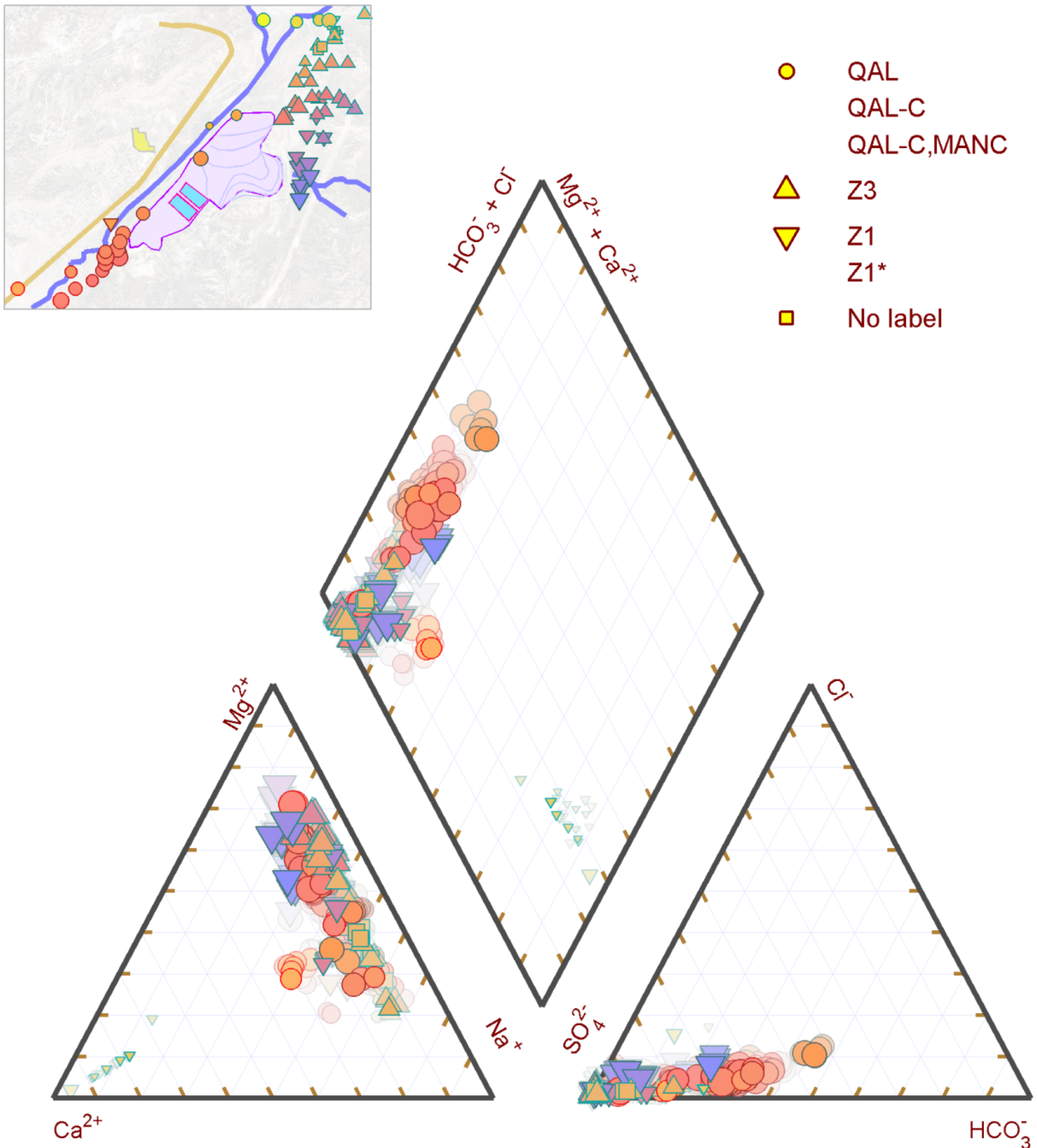


Figure D–7. Piper Diagram of Major Ionic Concentration (meq/l). Symbol Size Is Proportional to the Logarithm of Combined Ionic Concentration. Earlier Readings Are Indicated by Whiting Out the Symbol.

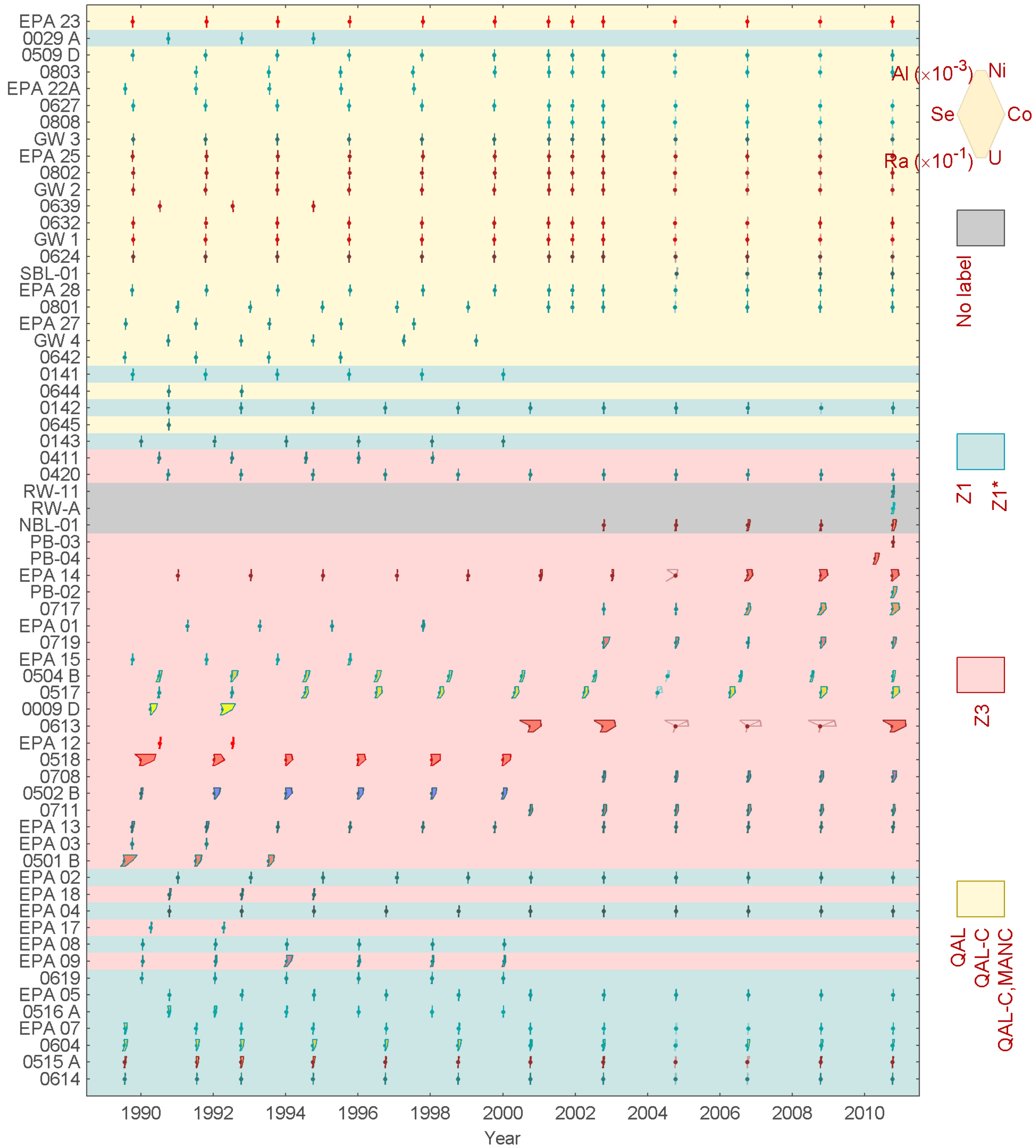


Figure D–8. Selected Elements (Every Eighth Reading) in mmol/l (Al and Ra Are Scaled)

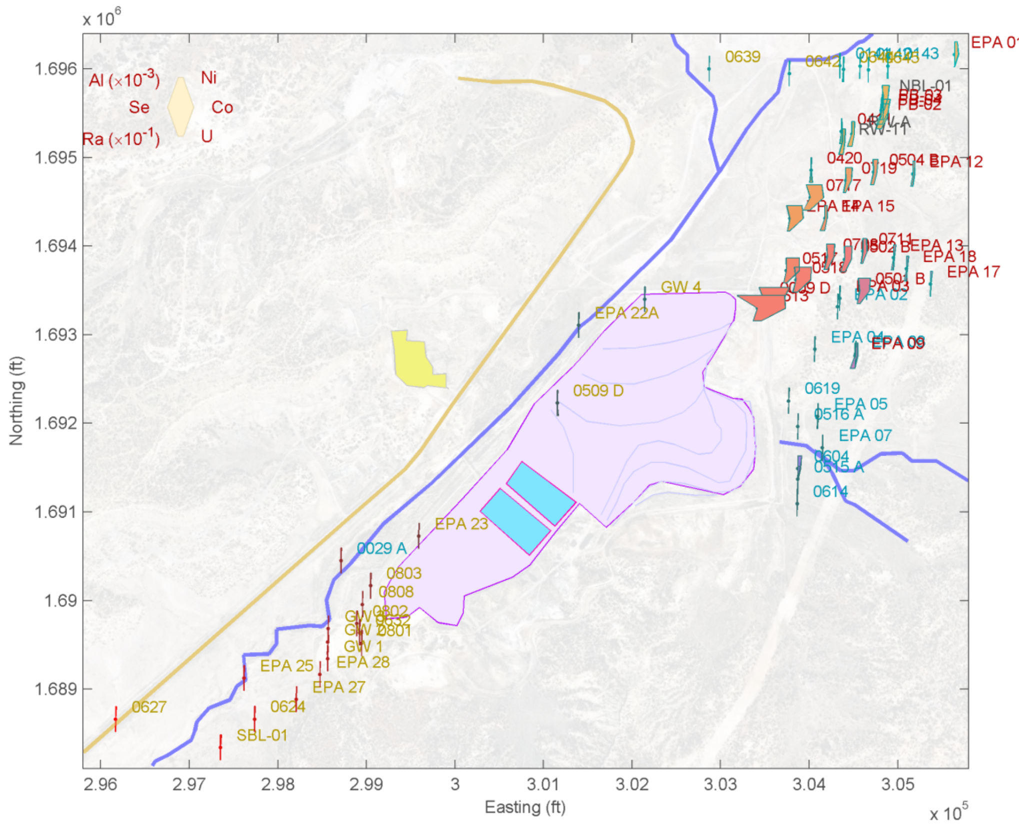


Figure D–9. Concentrations (mmol/l) at Last Observation for Selected Elements (Al and Ra Are Scaled)

APPENDIX E

SITE EVALUATION FOR SITE 11, SPLIT ROCK (WESTERN NUCLEAR), WYOMING

EVALUATION FOR SITE 11, SPLIT ROCK (WESTERN NUCLEAR), WYOMING

E1 INFORMATION AVAILABILITY FOR GEOLOGIC STRUCTURE AND PROPERTIES

SMI (1999a, Section 2.2) provides a high-level description of site characteristics, and points to a detailed discussion of site assessment work and previous work in appendices to the document. Portions of the SMI (1999a) document were not found on Agencywide Documents Access and Management System (ADAMS); these portions include the cited appendices and figures associated with Section 2.2. Some of the figures do provide general indications of site characteristics. Subsequent reports (e.g., MFG, 2003) refer back to the SMI (1999a) appendices.

SMI (1999a, Section 2.2.2) states that Western Nuclear possesses a three-dimensional digital geologic structure model for the site. NRC does not appear to have been provided with the model.

E2 INFORMATION AVAILABILITY FOR NATURAL AND ARTIFICIAL RECHARGE

One way that a cover may provide protection is by preventing water from contacting the tailings and subsequently draining into the environment. Accordingly, the net flux through the cover provides a metric for evaluating cover performance. For the purposes of evaluating cover performance, recharge occurring over the tailings is of primary interest. Focused recharge may be of greater concern than diffuse recharge, because focused recharge is more likely to escape the evapotranspiration trap and penetrate to depth in semiarid environments. Recharge over more distal portions of the cover or even outside the cover may also be of concern because of the geometric configuration of the bedrock; if subsurface flow occurs down the pre-existing bedrock surface beneath the cover, it may contact the tailings.

SMI (1999a, Section 2.2.4.2) describes recharge as occurring from direct precipitation on the valley floors and from run-on from the surrounding granite hillsides, reporting estimates of 1.5 cm [0.6 in/yr] from direct precipitation and 15 cm [6 in/yr] from run-on (although the percentage of valley recharge stemming from the run-on contribution is not reported). SMI (1999a, Section 2.2.5.2) estimates total recent recharge of 95 and 120 L/min [25 and 32 gpm] to the Northwest and Southwest Valleys, respectively. SMI (1999a, 2.2.1.1) reports that mean annual precipitation at the Jeffrey City station was approximately 28 cm [11 in/yr] from 1964 to 1993. Jeffrey City is approximately 3 km from the center of the tailings basins. The estimated recharge in the valley floors is approximately 5.5 percent of annual precipitation. The missing appendices provide the technical bases for the recharge estimates.

SMI (1999a, Section 2.2.5.1) reports that recharge through the compacted clay impoundment covers is estimated to be similar to the valley floor recharge 1.5 cm [0.6 in/yr]. None of the reviewed documents report direct measurements of recharge through the cover, and there are no reported wells within the tailings basin. Accordingly, there is no direct basis for estimating recharge through the cover at this site. Observations of seepage waters in wells outside the tailings basin may provide indirect indicators of recharge.

E3 INFORMATION AVAILABILITY ON TRANSIENT DRAINAGE AFTER EMPLACEMENT

SMI (1999a, Section 2.2.5.1) reports estimates of drainage rates from the impoundments. Disposal of water in the impoundments ceased in 1986. Peak drainage from the Main Impoundment was estimated at 4,540 L/min [1,200 gpm]; drainage was estimated at 3,400 L/min [900 gpm] in 1986, declining to 490 to 570 L/min [130 to 150 gpm] in 1996, and was estimated to decline to 110 L/min [30 gpm] within the following 30 years. SMI (1999a, Section 2.2.5.1) describes the Old Tailings and Alternate Tailings Impoundments as completely drained. This information implies that drainage from the Main Impoundment flowing down the Northwest Valley currently is likely somewhat larger than or comparable to natural recharge in the Northwest Valley, and overflow into the Southwest Valley is likely less than natural recharge in the Southeast Valley.

Figure 1 displays the static water levels in the electronic database. Several dozen water levels in the database were clearly incorrect, with obvious typographic errors (e.g., a missing decimal point, different number in the hundreds or thousands place within a sequence) and were corrected if possible. There may remain incorrect values in the database that were not obvious. In particular, some of the readings during 1995 through 1998 seem to have values that are potentially inconsistent with nearby wells. Some may be due to nearby pumping; others appear to be anomalously higher than neighbors.

E4 INFORMATION AVAILABILITY ON HYDROCHEMICAL OBSERVATIONS

The site has an electronic database of water levels and geochemical sampling. The earliest year with water level data is 1977, and the earliest year with geochemical data is 1975. There are 418 wells reported in either the electronic database or by SMI (1999a, Tables 9 and 11). Many of the wells are located offsite to delineate regional flow and transport pathways. The electronic database does not include the formation that the wells are screened in, although SMI (1999a, Tables 9 and 11) provides this information for 238 wells. Borehole locations are available for 388 wells and elevations of the screened interval in 305 wells.

There are 337 wells with at least one water level observation; 184 have less than 10 observations and 88 have observations for 4 years or longer. A total of 254 wells have at least one geochemical observation; 65 have observations for 4 years or longer.

The electronic database includes 165 geochemical analytes. Most analytes are hydrocarbons that were sampled less than 20 times.

E5 SUMMARY OF CONCEPTUAL MODEL FOR WATER FLOW NEAR THE TAILINGS COVER

SMI (1999a, Section 2.2) describes the site setting and associated site hydrogeologic conceptual model developed by the licensee.

The regional geologic setting consists of a granite bedrock overlain by variable thicknesses of the Split Rock Formation (primarily sandstones and conglomerates with silty sands), with a saturated thickness of 152 to 914 m [500 to 3,000 ft] south of the Sweetwater River and 61 to

183 m [200 to 600 ft] north of the river. Unconsolidated sediment overlying the Split Rock Formation consist of either a wind-blown sand layer 3 to 12 m [10 to 40 ft] thick or a shallow floodplain alluvium aquifer hydraulically linked to the Sweetwater River. The Sweetwater River is the primary discharge point for the regional flow, although it recharges the shallow floodplain alluvial aquifer during high flow conditions.

The site is located in two adjoined valleys within a local granite bedrock rise forming two ridges. Southwest Valley is aligned with the ridges and drains to the southwest, and Northwest Valley drains to the northwest through a break in the northwest ridge. The valleys are partially separated by a local bedrock rise. Within the valleys, the Split Rock Formation (primarily sandstones and conglomerates with silty sands) is up to 46 m [150 ft] thick in the upper valleys and 152 m [500 ft] thick at the valley mouths. A wind-blown sand layer 3 to 12 m [10 to 40 ft] thick overlies the Split Rock Formation, thought to have a minor influence on bulk transport relative to the much thicker Split Rock Formation. North of the outcrop, a shallow and highly permeable floodplain alluvium aquifer 5 to 9-m 15 to 30–ft]- thick is hydraulically linked to the Sweetwater River, with essentially all groundwater within the floodplain alluvium and underlying Split Rock Formation discharging to the Sweetwater River north of the Northwest Valley where the river runs on a local granite bedrock rise.

Three tailings basins (Old, Alternate, Main) were emplaced on the surficial material. Two seepage plumes were created, one moving down the main axis between the ridges (Southwest Valley, primarily from the smaller Alternate and Old basins) and one moving perpendicular to the axis through a gap in the north ridge (Northwest Valley, exclusively from the Main basin). The basins are adjoining, covering 73 ha [180 ac] and containing 7 million tonnes [7.7 million ton] of tailings.

Preceding development, recharge to groundwater occurred from local recharge to the valley floor at an estimated 1.5 cm [0.6 in/yr] average. Runoff at the base of the granite side slopes augmented the valley recharge at a rate of 15 cm [6 in/yr] (SMI, 1999a), but it’s not clear whether this rate represents an average over the entire valley or a local rate at the base of the outcrop. Prior to installation of the tailings basins, groundwater in the upper valley discharged through the Northwest Valley because of the local bedrock rise; the rise in water table from basin seepage allowed some water to discharge down the Southwest Valley.

The regional groundwater gradient is easterly. Seepage from the Main tailings basin primarily moves northwest down the Northwest Valley within the Split Rock Formation and overlying windblown sand layer, then bends to the east following the regional gradient. The shallow portion of the plume enters the floodplain alluvium associated with the Sweetwater River, which passes north of the granite outcrops. Seepage from the Old and Alternate basins, plus a portion of the seepage from the Main basin, moves southeast down the Southeast Valley within the Split Rock Formation and overlying windblown layer, then meets the regional flow dividing around the granite outcrops. SMI (1999a) estimates that approximately 25 percent of the flow diverts to the north, and the remainder moves to the east. MFG (2003, Figure 6.0-6) shows a predicted 1,000-year uranium plume extending approximately 2 miles from the Alternate tailings basin, moving down the Southwest Valley, turning east, and ultimately turning northeast to wrap around the outcrop.

The hydraulic conditions at the site have been perturbed by the tailings basins and subsequent groundwater correction programs. Prior to 1986, extraction wells returned all flow down the Northwest Valley to the tailings impoundment, with peak pumping rates of 5,490 L/min

[1,450 gpm] prior to 1977, reducing to 2,080 L/min [650 gpm] in 1981. From 1983 to 1986, extraction wells returned all flow down the Southwest Valley to the tailings impoundment. No extraction occurred from 1986 through 1989. In 1990, the groundwater extraction resumed at an initial rate of 340 to 470 L/min [90 to 125 gpm] combined for the two valleys. Extraction wells and pumping periods were modified in 1992 and 1995, maintaining the annual target rate, and in 1997 the target pumping rate was reduced to 75 L/min [20 gpm] (approximately half from each valley) because of the reduction in evaporation capacity from reclamation.

E6 WELLS DOWNGRADIENT OF THE TAILINGS COVER

Two sets of wells are downgradient of the tailings, corresponding to the Northwest and Southwest Valley plumes. Many of the wells have a relatively short period of record, making it difficult to use to track changes in plume characteristics. Nineteen wells have observations over 10 years or more. Sampling ceased in most wells after 2005, and only a restricted set of geochemical analytes were obtained after 2005 in the remaining wells.

FigureE–2 displays Stiff diagrams for all wells near and potentially downstream of the tailings with at least one geochemical reading for Northwest Valley, and Figure E–3 shows the corresponding wells for the Southwest Valley.

E7 KEY CHEMICAL SPECIES OR INDICATORS IN THE TAILINGS PORE WATER

The background major ion chemistry is dominated by Ca, Na, and HCO_3, whereas the tailings waters are dominated by Ca and sulfate. Sulfate and magnesium might provide a potential tracer of seepage water. Magnesium may be better than sulfate for indicating seepage because seepage would be more distinctly delineated from the background water chemistry. Chloride is also associated with the tailings pore water, albeit at a smaller concentration.

E8 KEY CHEMICAL SPECIES OR INDICATORS FOR DISCERNING TEMPORAL AND SPATIAL TRENDS IN GROUNDWATER QUALITY

SMI (1999a) modeled uranium and sulfate transport, stating that uranium transport was the most conservative and extensive constituent of concern. MFG (2003) considered uranium transport in the Southwest Valley in greater detail using extended modeling.

Constituents of concern at the site include ammonia, manganese, molybdenum, nitrate, combined radium, and uranium SMI (1999a). Nitrate is formed by breakdown of ammonium, which is produced from ammonia in acidic environments. Relatively large quantities of ammonia were used in the milling process. Several additional species appear to be associated with the tailings seepage, including sulfate, magnesium, ammonium, and chloride. SMI (1999a) includes figures indicating extent of manganese, nitrate plus nitrite, ammonia, and radium; these suggest that nitrate, ammonia, and to a lesser extent manganese are strongly indicative of tailings seepage. The available figures do not provide an easy means of comparing the extensive nitrate plumes with the uranium plumes.

E9 CHEMICAL DIAGRAMS OF PORE WATER

Sufficient information exists in the database to construct Stiff and Piper diagrams for seven major ions (Ca, Mg, Na, Cl, SO_4, K, and HCO_3) for 1981 through 2010. Data for CO_3 are limited. The Stiff and Piper diagrams suggest that well chemistry is fairly consistent over the last 20 years for most wells. Background chemistry favors Ca, Na, and SO_4, with all constituents elevated near the tailings.

Figures E–4 through E–15 plot selected geochemical data extracted from the database. Some figures consider the Northwest and Southwest Valley domains separately. As is obvious in Figures 4 and 5, most of the wells were sampled infrequently.

E10 INDICATIONS OF COVER EXISTENCE BASED ON GEOCHEMICAL OBSERVATIONS

The most direct indicator of cover performance would be a unique geochemical signature associated with the cover but not the tailings or underlying units. Presence and absence of the unique signature would provide an unambiguous geochemical signature for performance. Such a signature has not been identified. The cover material is obtained from local sources, including granite rip-rap (SMI, 1999b).

The time history of geochemical signatures can provide indirect indicators of cover performance. A declining history is consistent with a declining fraction of tailings seepage mixing with sources of dilute waters. On the other hand, the lack of a declining history does not necessarily imply that the cover is not performing well. A declining amount of seepage may not change the geochemical signature if the flow of water from other sources is small (e.g., the waters under the tailings are stagnant), and increasing trends in distal downstream regions may be consistent with natural progression of waters released during the operations period.

Seepage from the tailings basins overwhelmed natural recharge during operation. Some wells near the basins are gradually dropping in concentration for some constituents and others at more distal locations are increasing in concentration. Reductions in concentration are consistent with greatly reduced seepage and mixing with dilute waters from natural recharge. It may be possible to perform a bounding mixing analysis to estimate current seepage with assumptions regarding recharge versus tailings seepage. Such an analysis is hampered by a lack of geochemical data regarding current tailings pore waters. Further, no data on the recharge water geochemistry has been found in the publicly available documentation.

During operation, wells in the mouth of both valleys returned water to the basins, thereby capturing the plumes. Essentially all seepage waters were captured through 1986, followed by a series of pumping cessations and reductions. Because extension of the plumes downstream is an expected consequence of pumping reduction and cessation, observed downstream expansion beyond the deactivated pumping wells does not necessarily imply anything about cover performance.

E11 DOCUMENTED TIME-SERIES TRENDS AND STATISTICAL ANALYSES

The semiannual water quality reports provided by the licensee typically provide plots of pH, uranium, sulfate, and total dissolved solids for each monitored location. The plots do not necessarily provide data from the entire well history.

Each of the plotted values in the semiannual water quality reports appear to be included in the range of years covered by the database of geochemical observations.

SMI (1999a, Section 2.2.6) summarizes statistical analyses to estimate upper prediction limits for background water quality. The basis for the estimates is in an appendix missing from ADAMS.

E12 APPLICABILITY OF NUREG–1569, APPENDIX F

Appendix F discusses methods for quantifying trends in a time series of chemical samples in a well field, with potentially noisy observations. Such methods are appropriately applied to the observational data. However, the available data may not be suitable for estimating cover performance.

E13 APPLICABILITY OF SITE OBSERVATIONS TO EVALUATE COVER PERFORMANCE

In general, site observations could be used to evaluate cover performance by considering hydraulic responses, thermal responses, and geochemical responses. Estimates by SMI (1999a) suggest that residual drainage from the Main Impoundment was 570 L/min [150 gpm] in 1996 and would decline to 110 L/min [30 gpm] by 2026. SMI (1999a) estimated natural recharge in the valleys (excluding the impoundment areas) at 215 L/min [57 gpm] in 1996, and estimated ultimate recharge through the impoundment covers at 19 L/min [5 gpm]. These estimates suggest that residual seepage is currently 5 to 10 times larger than the expected ultimate recharge through the cover, and of comparable magnitude to natural recharge in the valleys. Under these conditions, recharge through the cover must be very distinct from residual seepage to provide a measurable signal.

One hydraulic response consistent with a performing cover is a declining water table mound under the tailings basins. The available data suggest that the water table is gradually declining, although no observations in the impoundment areas are available after 1998.

The site conditions are suitable for estimating flow down the valleys at this site, which provides an indication of recharge that can be compared with the estimated natural recharge. The licensee performed groundwater modeling, but the data and parameters in the model are not in ADAMS. This method might be useful in future decades, once residual seepage becomes negligible.

Hydraulic fluctuations under a tailings basin might occur if flow occurred through the cover and tailings; residual seepage does not provide this signal. At this site, runoff from the relatively impermeable granite bedrock tends to maintain water levels in the valleys, providing a source of recharge water immediately upgradient from the tailings basins that would provide a similar signal. With a suitable monitoring network, this signal could be disaggregated across the large basins, but the available wells measure too infrequently and too far downstream to allow hydraulic interpretations of this nature.

Temperature observations (Figure E–16) are not useful for evaluating cover performance at this site. The site is unsuited for estimating flux using temperature as a means for directly estimating recharge. Sampling is quarterly at best, thus the annual thermal cycle masks any hydraulic fluctuations.

Geochemical signals could provide some indication of cover performance if the cover provided a distinct signal. No such geochemical signals were identified. The dataset does not appear to have many systematic trends visible to the eye, suggesting that the potential for a useful analysis is weak and suggesting that residual seepage is still substantial. Further, all available wells are downstream from the boundary of the tailings basins, making it difficult to estimate flow from the tailings using mixing analyses with a known inflow and outflow. This method would require application of a distinct tracer to the surface of the tailings and monitoring for the tracer.

E14 REFERENCES

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SMI. "Split Rock Tailing Reclamation Construction Completion Report." ML11209C525, ML11215A121, ML11215A122. Fort Collins, Colorado: Shepherd Miller, Inc. April 1999b.

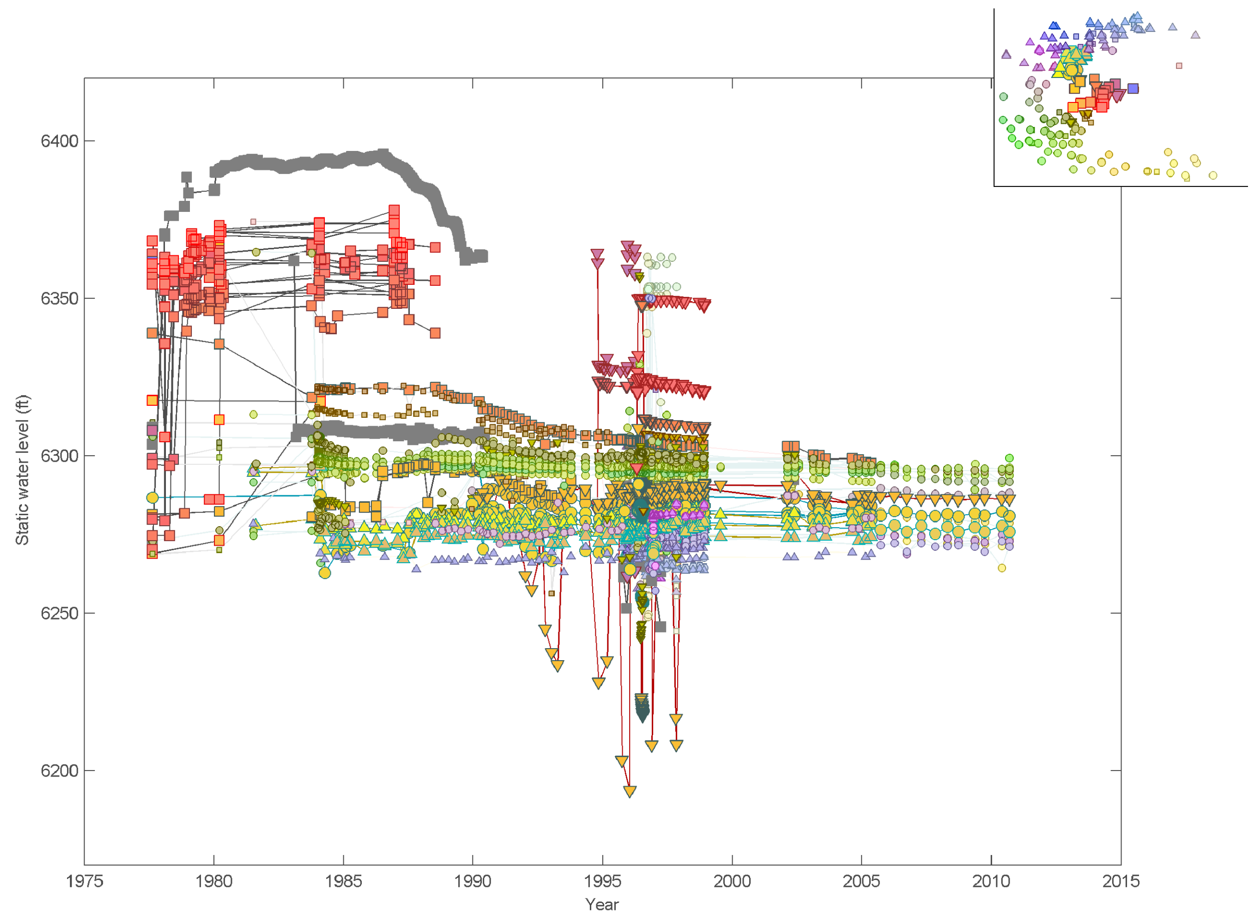

Figure E–1. Static Water Levels in all Wells

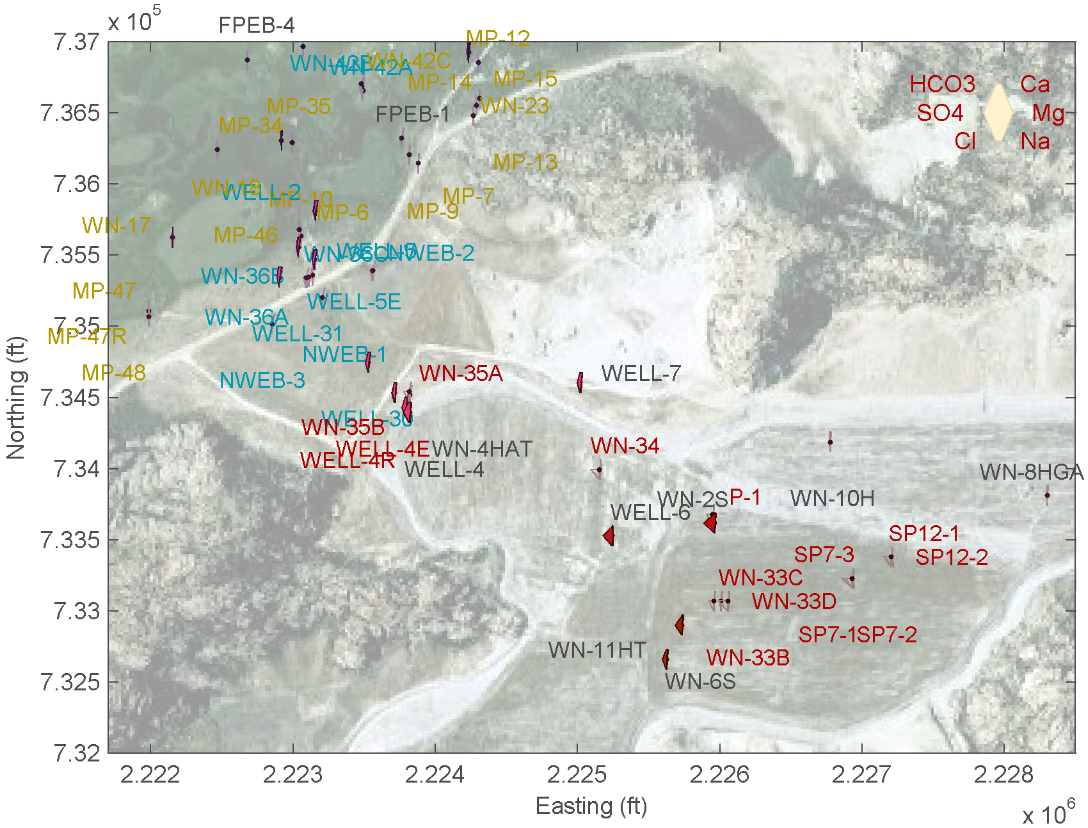

Figure E–2. Stiff Diagram of Major Ions (Last Reading) for the Northwest Valley. Wells Labeled in Red and Gray Are Within the Main Tailings Basin. Wells Labeled in Blue Are in the Split Rock Formation, and Wells Labeled in Orange Are in the Sweetwater River Floodplain Alluvium. Flow Is to the Northwest, Turning to the Northeast Past the Road. The Granite Forms a V-Shaped Valley Filled With the Split Rock Formation, With the Split Rock Formation in Excess of 400 ft Thick on the Axis of the Valley at the Mouth. The Base Image Was Extracted From Google Earth. Coordinates Are Wyoming State Plane, NAD 83.

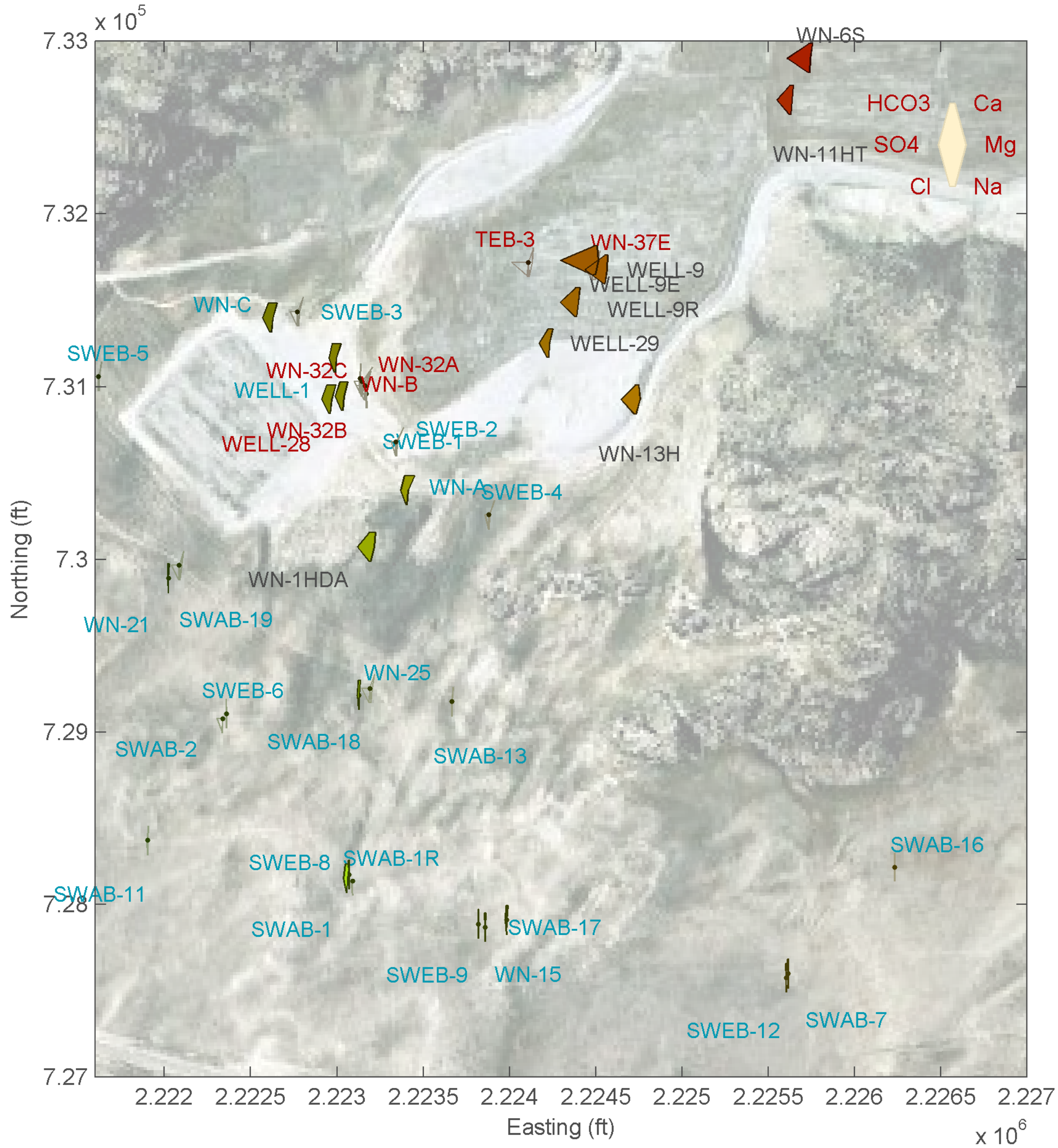

Figure E–3. Stiff Diagram of Major Ions (Last Reading) for the Southwest Valley. Wells Labeled in Red and Gray Are Within the Old and Alternate Tailings Basins. Wells Labeled in Blue Are in the Split Rock Formation. The White Rectangles Are Remediated Evaporation Ponds. Flow Is to the Southwest, Turning to the East Past the Outcrop. A Lesser Amount of Flow Turns West. The Granite Forms a V-Shaped Valley Filled With the Split Rock Formation, With the Split Rock Formation in Excess of 122 m [400 ft] Thick on the Axis of the Valley at the Mouth.

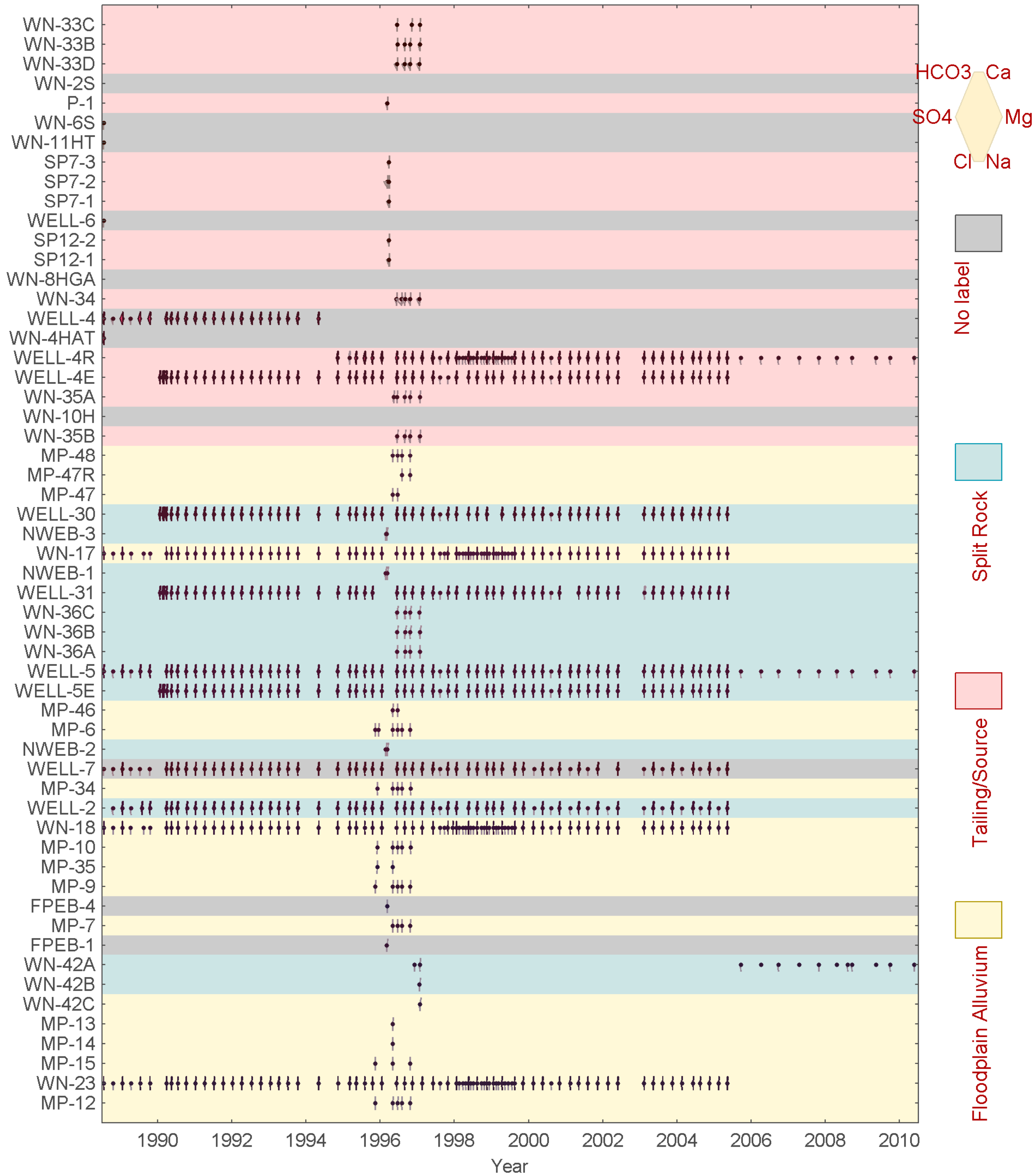

Figure E–4. Stiff Diagram of Major Ions (Every Reading) in meq/l for the Northwest Valley. Background Color Represents the Unit That the Well Is Completed in. The Same Color Scheme Is Used for the Other Stiff and Piper Diagrams.

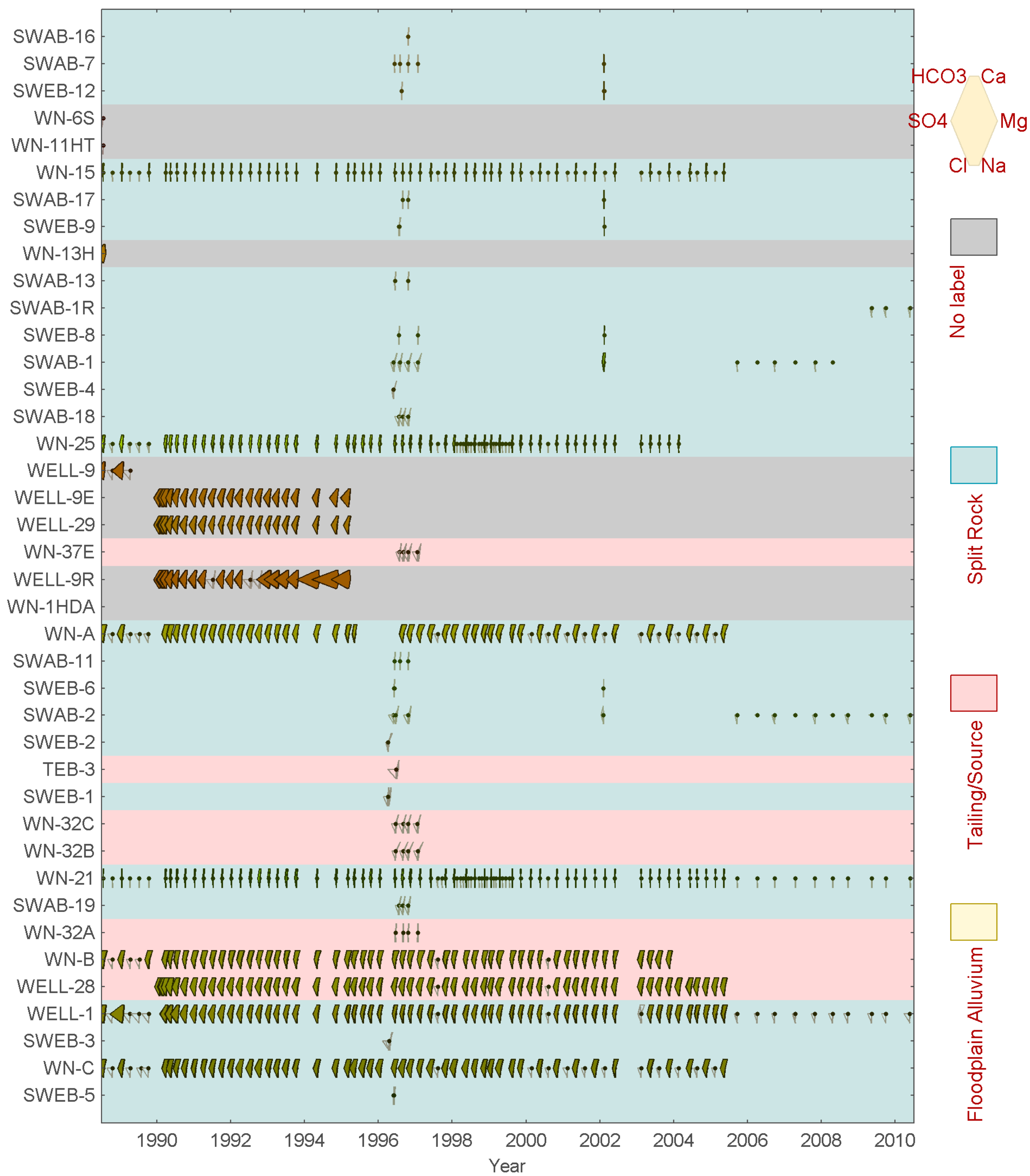

Figure E–5. Stiff Diagram of Major Ions (Every Reading) in meq/l for the Southwest Valley

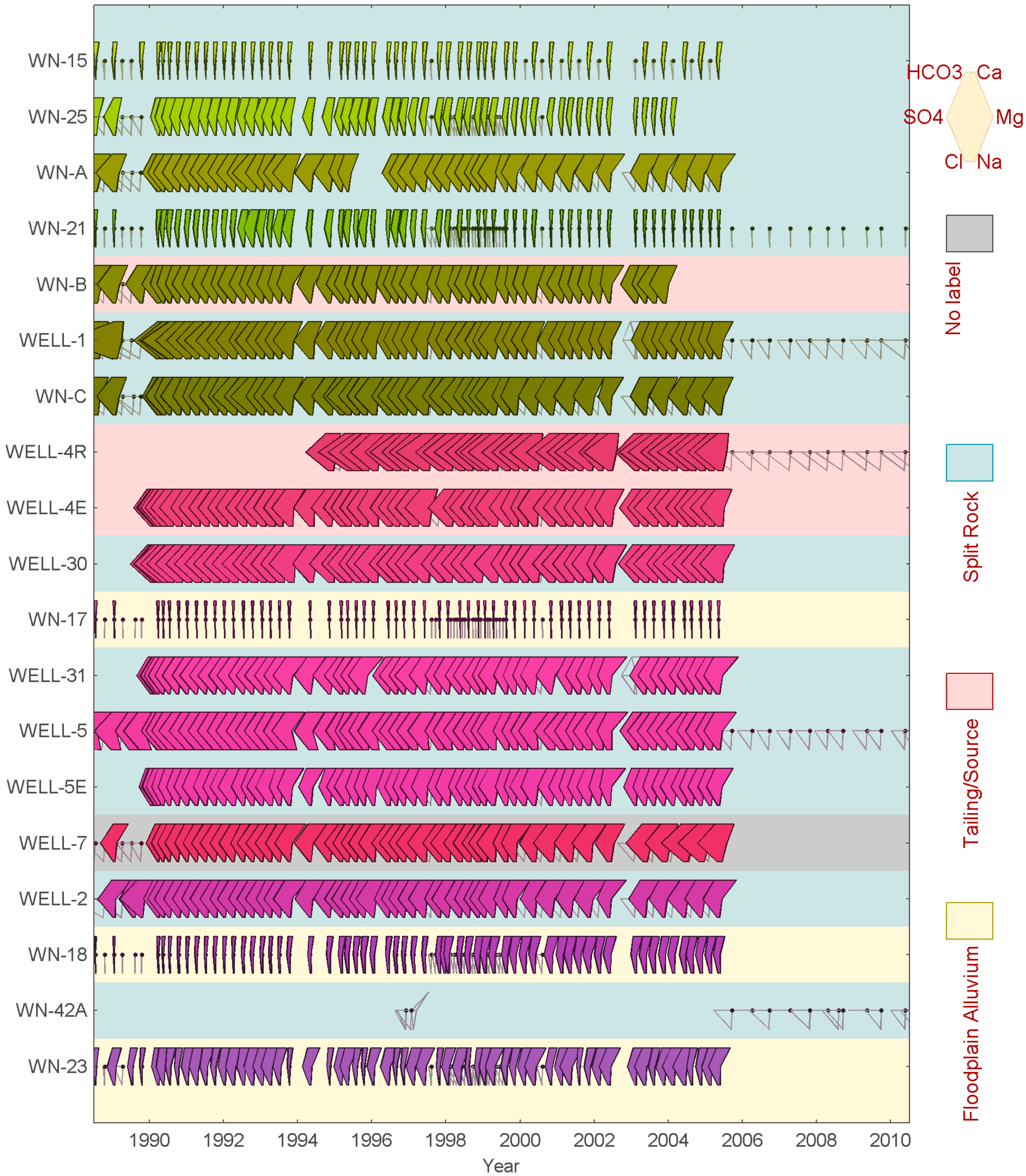

Figure E–6. Stiff Diagram of Major Ions (meq/l) for Wells With a Long Record

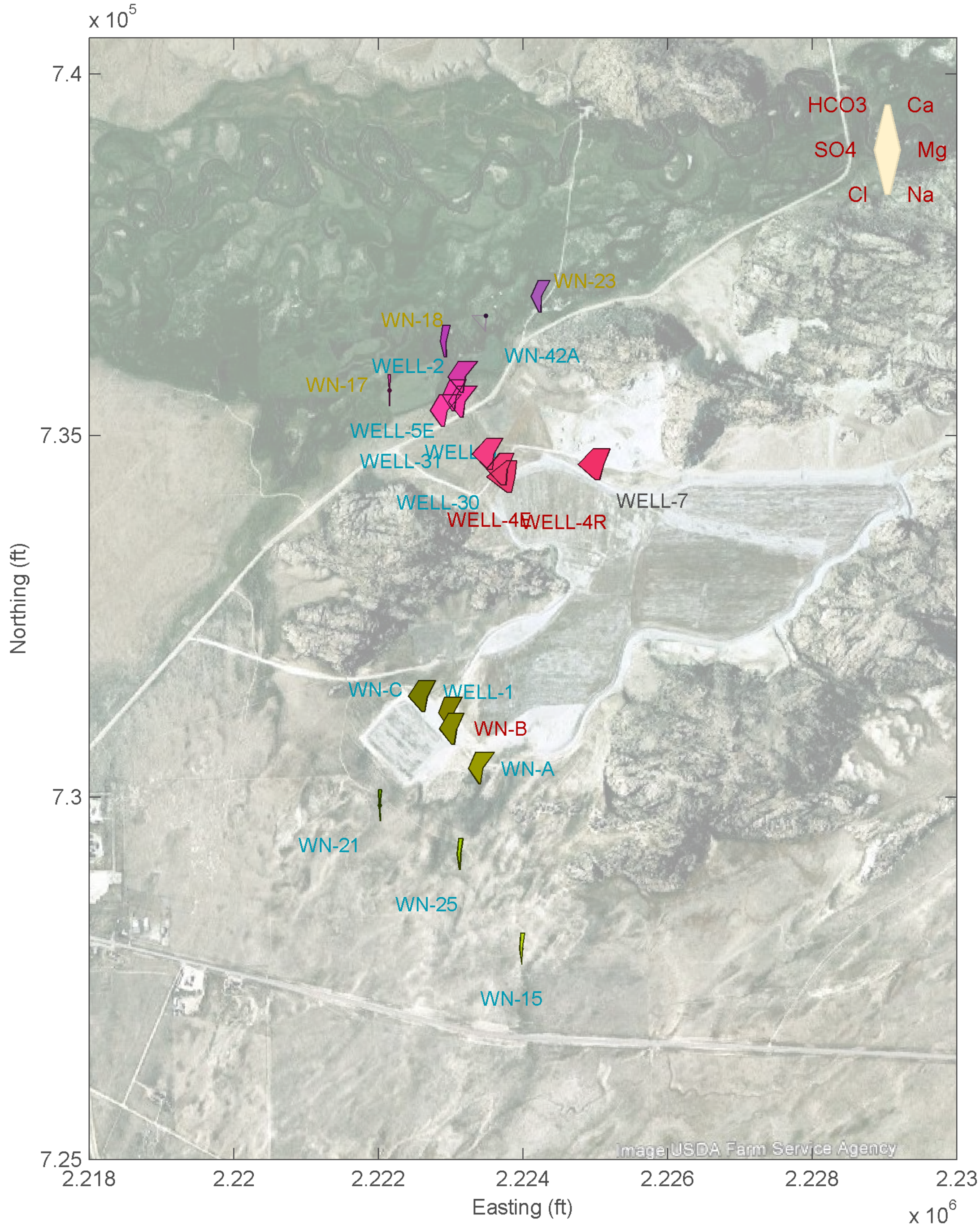

Figure E–7. Stiff Diagram of Major Ion Concentrations (meq/l) at Last Available Reading in Wells With a Long Record. See Previous Figure for Color Scheme Used for Well Label Color.

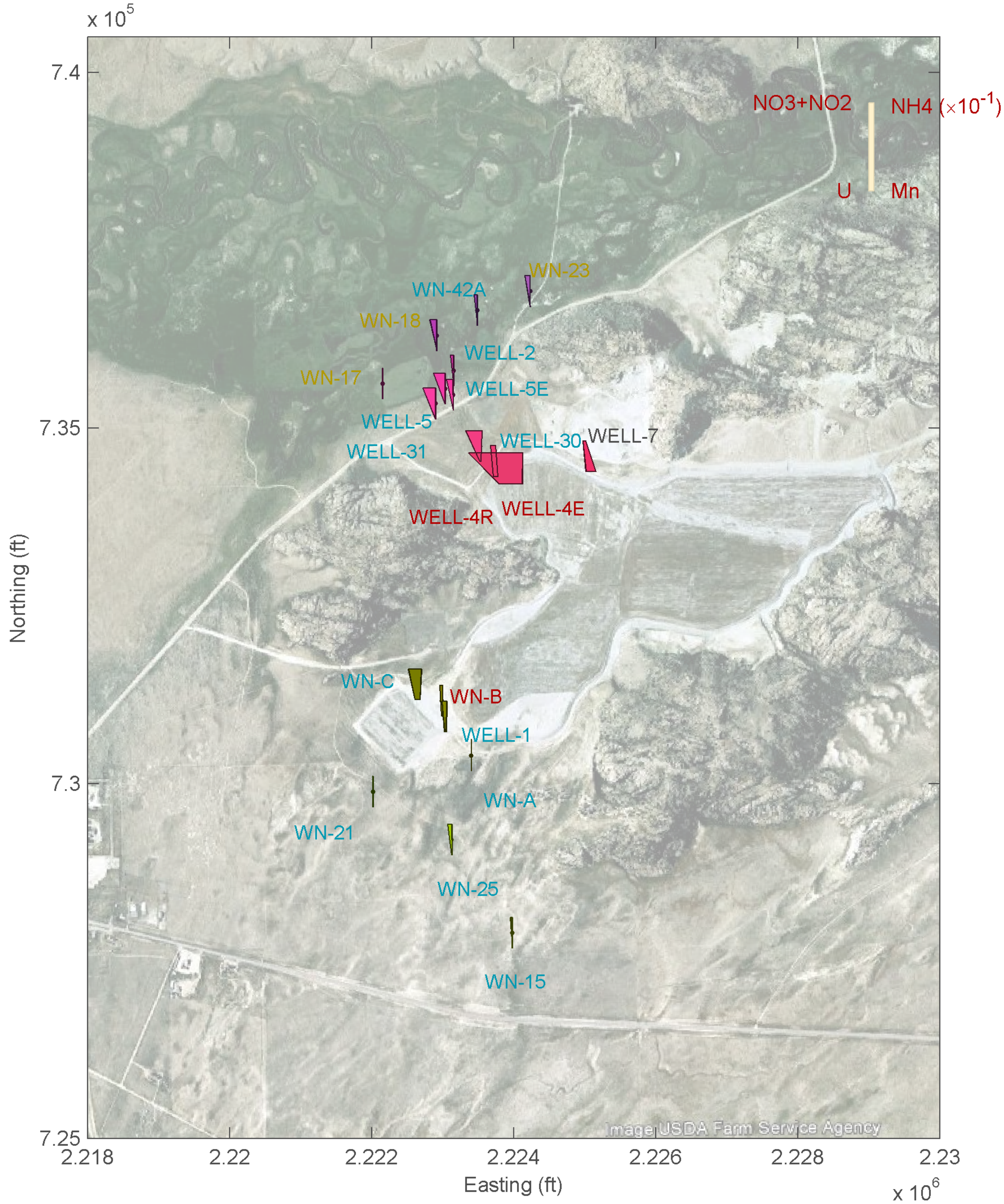

Figure E–8. Stiff Diagram of Potential Tracer Concentrations (mmol/l) at Last Available Reading in Wells With a Long Record

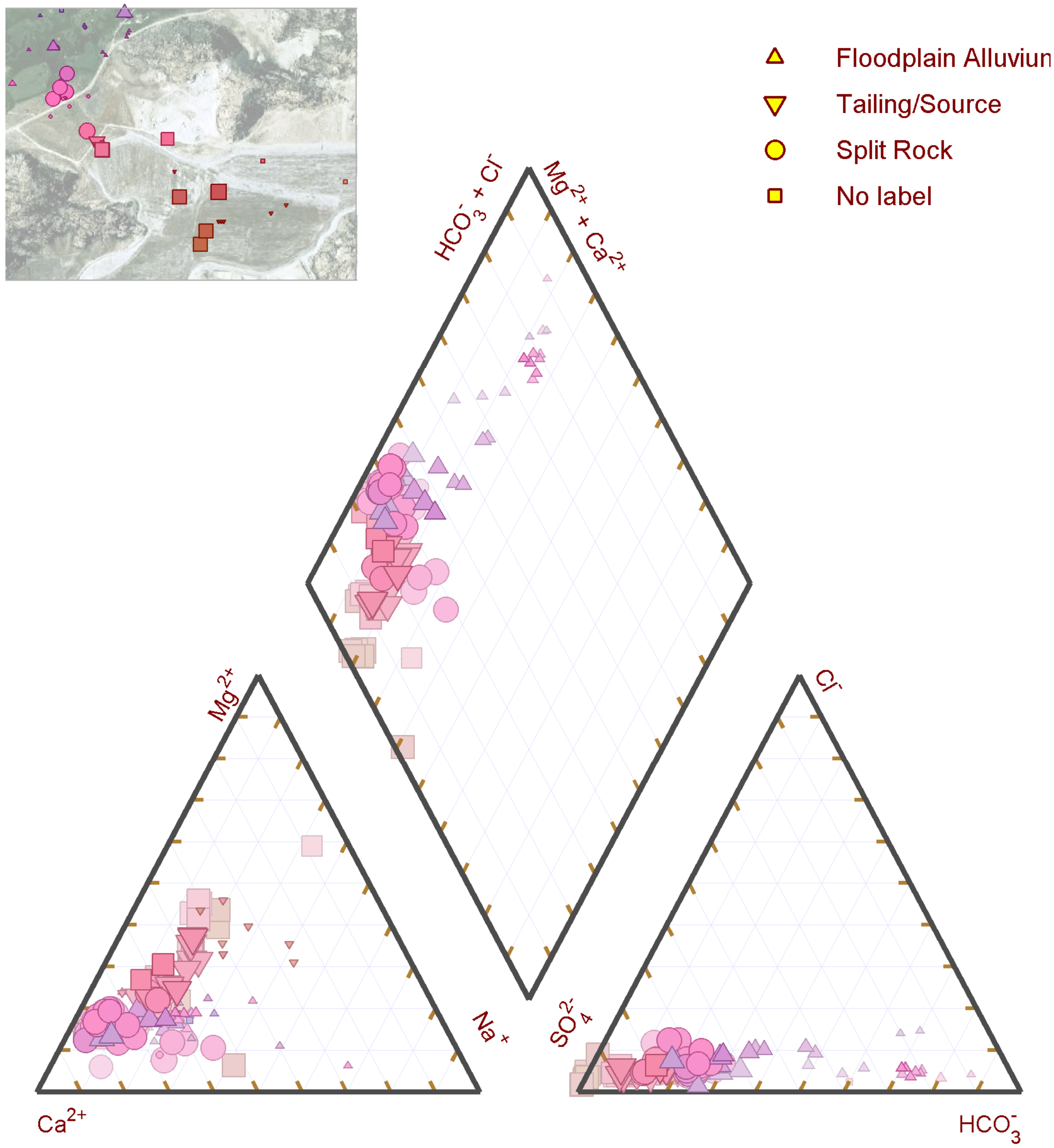

Figure E–9. Piper Diagram of Major Ionic Concentration (meq/l) for the Northwest Valley Wells. Symbol Size Is Proportional to the Logarithm of Combined Ionic Concentration. Earlier Readings Are Indicated by Whiting Out the Symbol.

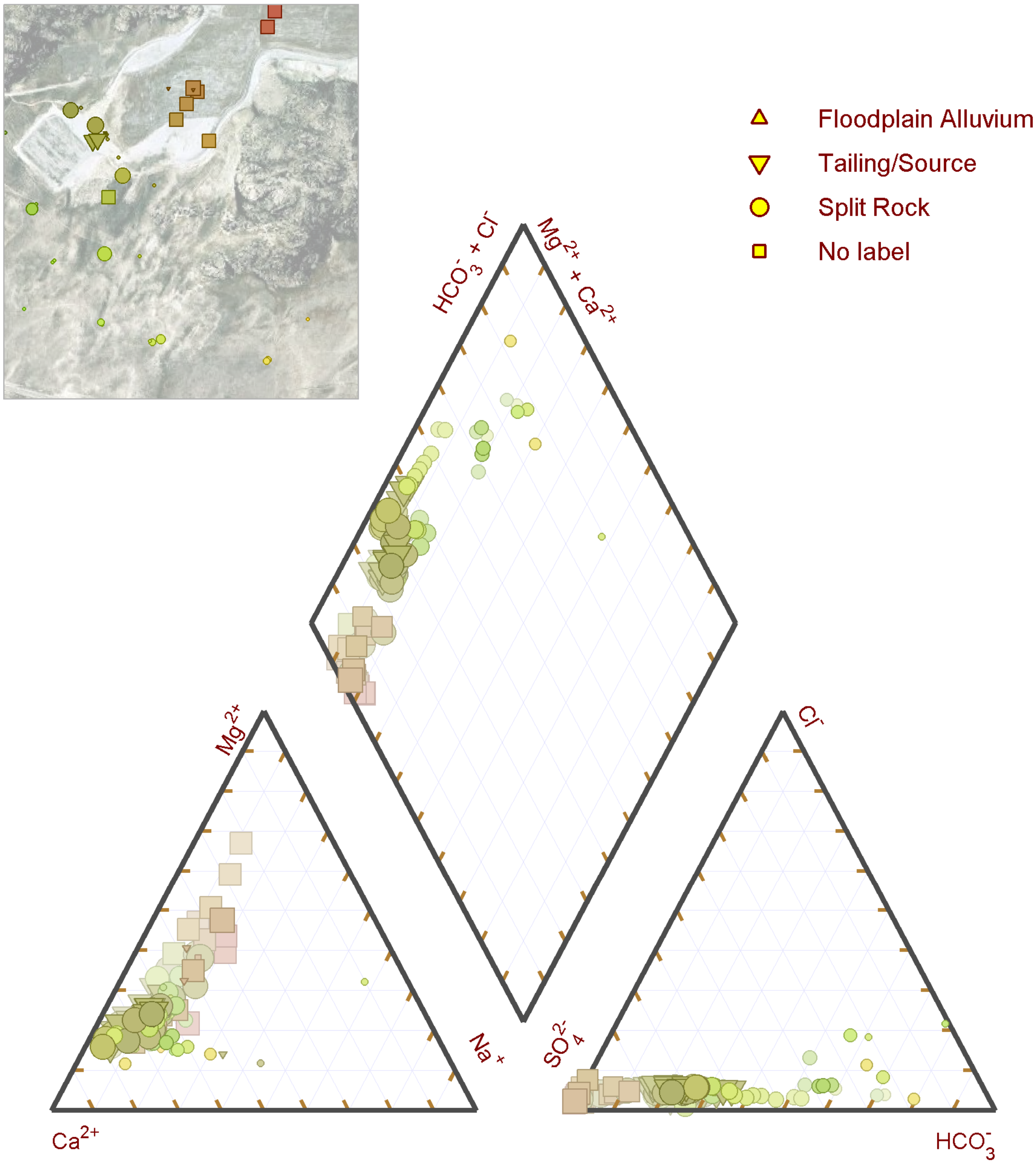

Figure E–10. Piper Diagram of Major Ionic Concentration (meq/l) for the Southwest Valley Wells. Symbol Size Is Proportional to the Logarithm of Combined Ionic Concentration. Earlier Readings Are Indicated by Whiting Out the Symbol.

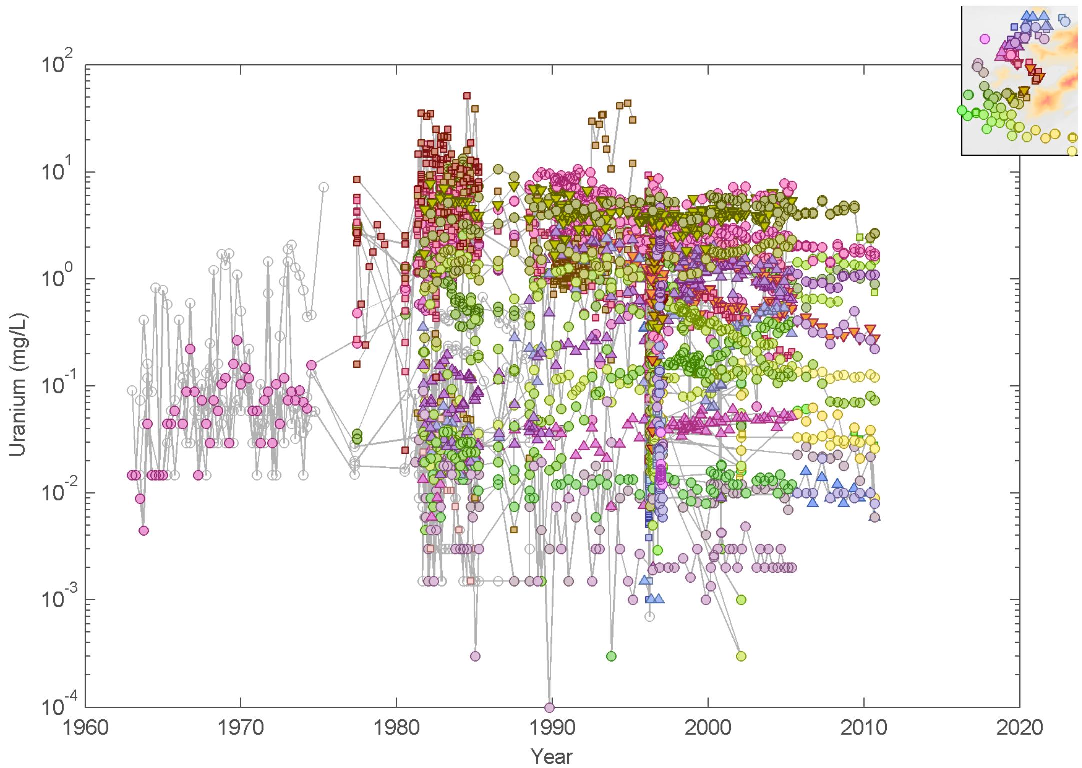

Figure E–11. Uranium Is Gradually Evolving

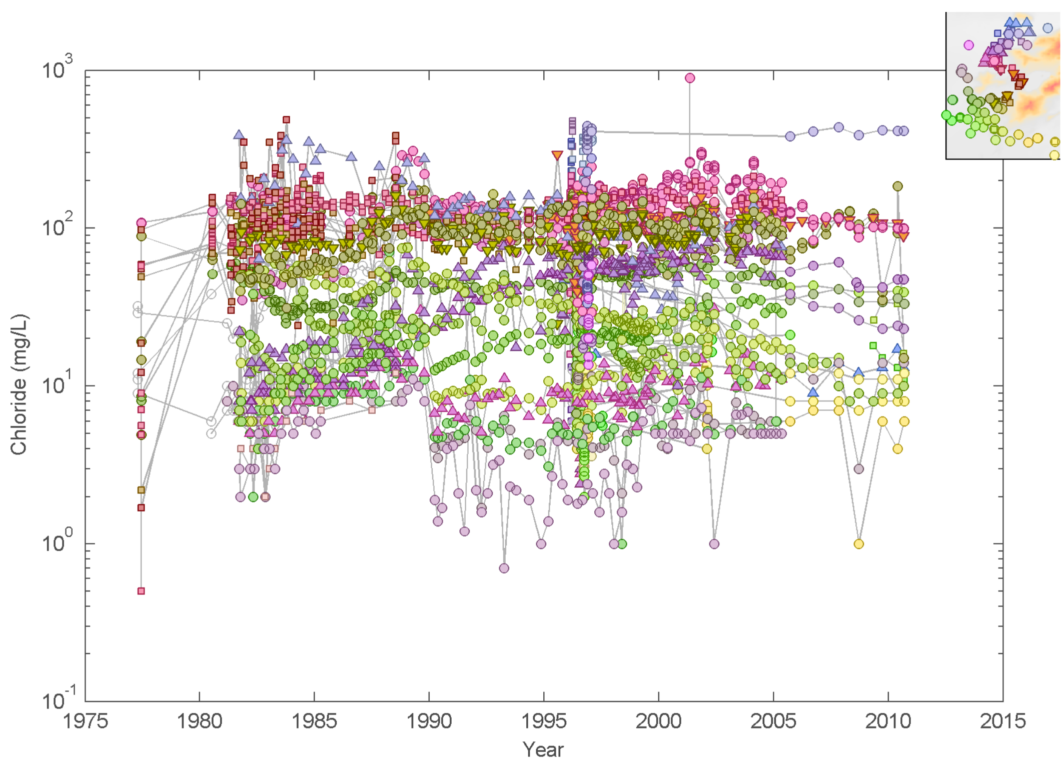

Figure E–12. Chloride Is a Marker of Tailings Seepage That Gradually Evolves

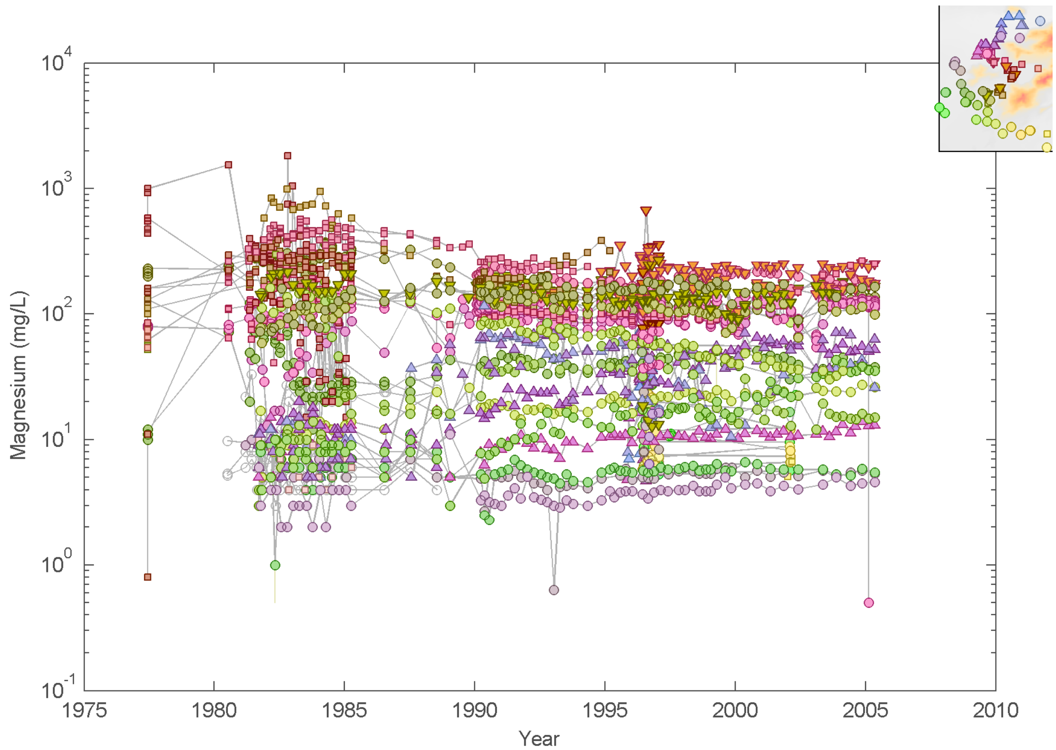

Figure E–13. Magnesium Has an Elevated Signal Near the Tailings

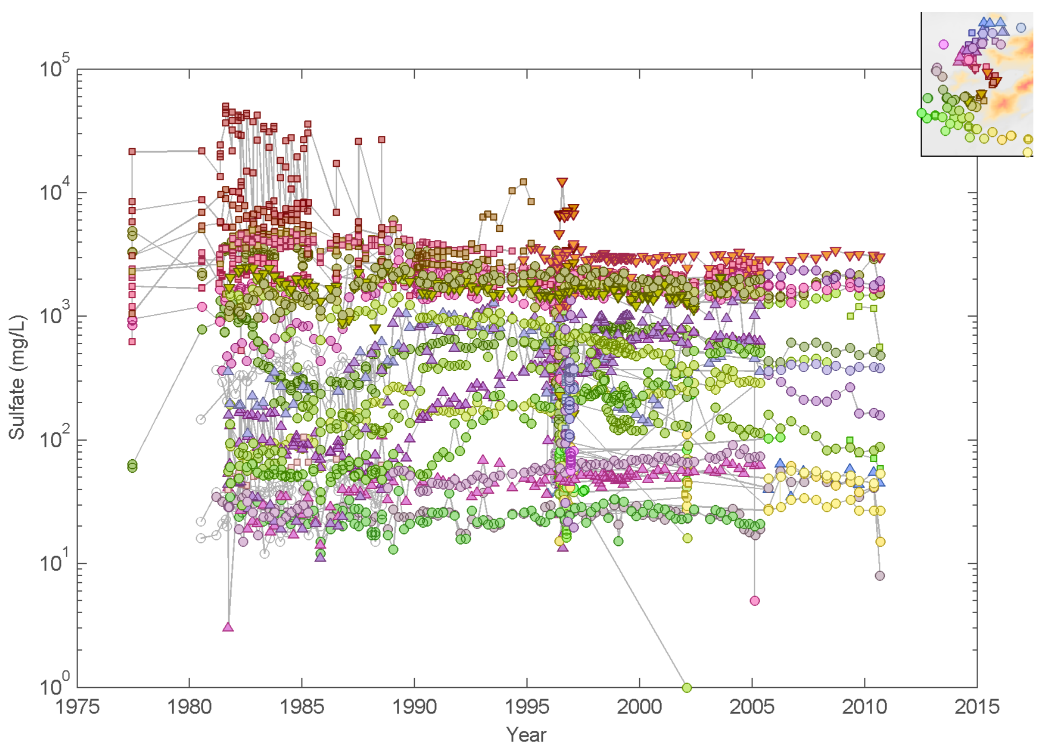

Figure E–14. Sulfate Is Slowly Responding Over Time

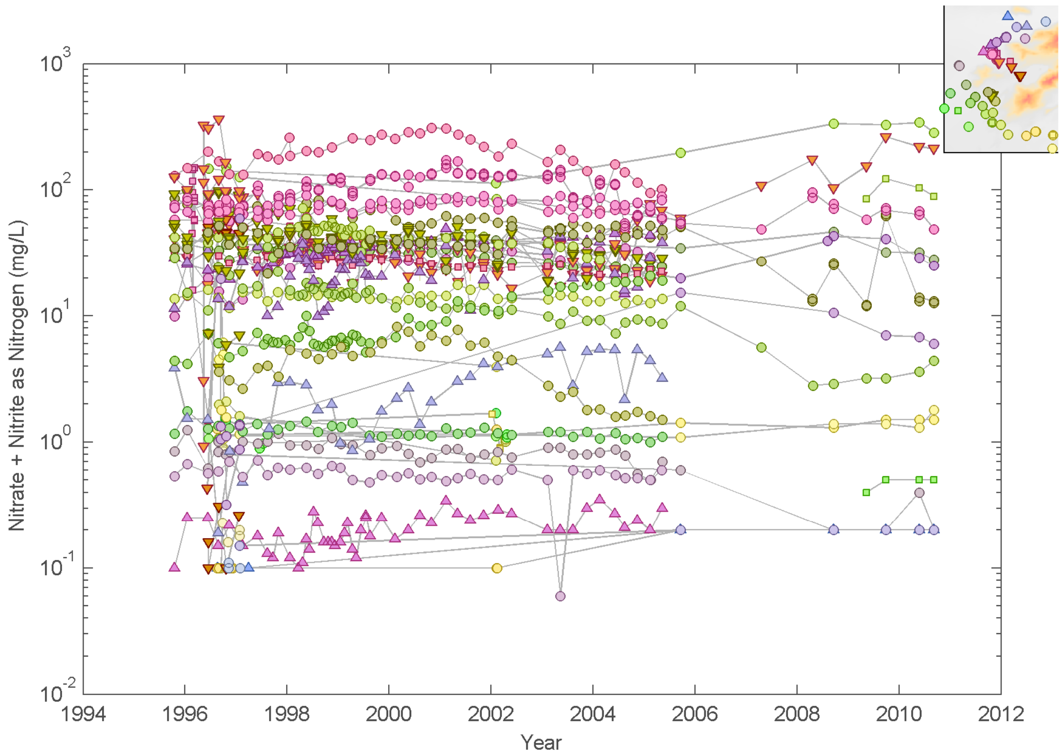

Figure E–15. Nitrate and Nitrite Show Indications of Tailings Seepage

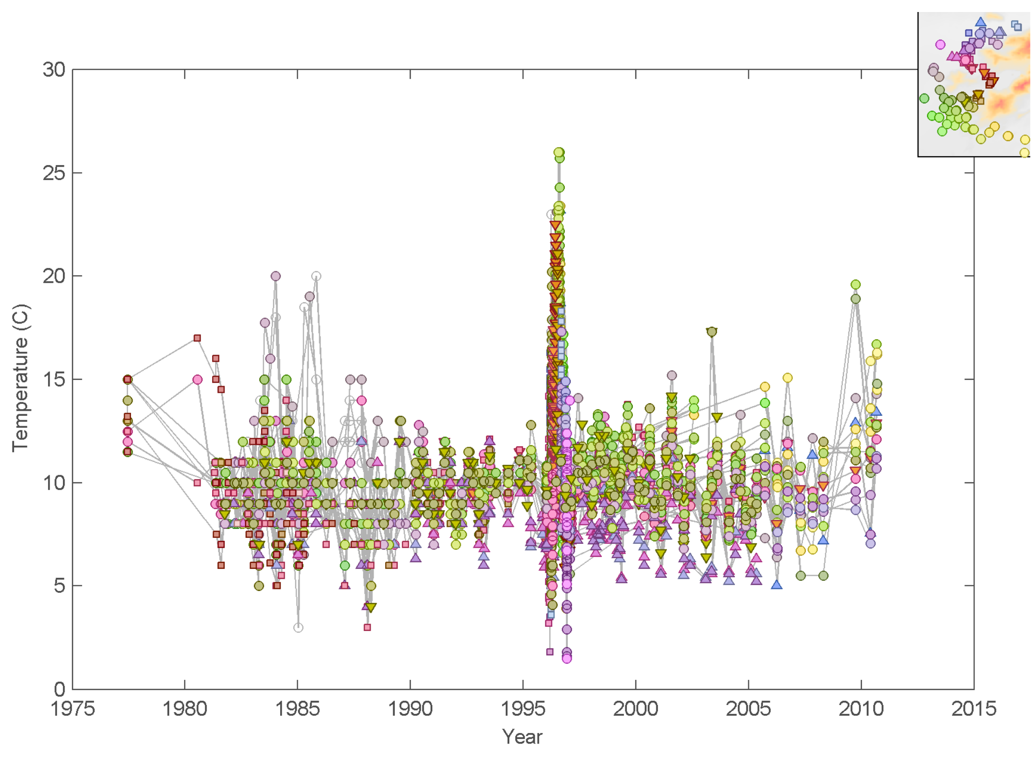

Figure E–16. Temperature Is Too Sparsely Sampled for Use in Estimating Fluxes

APPENDIX F

SITE EVALUATION FOR SITE 1, AMBROSIA LAKE WEST (RIO ALGOM), NEW MEXICO

SITE EVALUATION FOR SITE 1, AMBROSIA LAKE WEST (RIO ALGOM), NEW MEXICO

F1 INFORMATION AVAILABILITY FOR GEOLOGIC STRUCTURE AND PROPERTIES

Bostick (1985) describes the geologic setting, providing representative cross sections indicating layering, faulting, and groundwater levels. AVM Environmental Services, Inc. (AVM) (2000) describes site characteristics in the context of a groundwater corrective action program. Maxim (2001) provides limited hydraulic parameterization.

The geologic setting consists of a series of sedimentary rocks dipping to the northeast. At the site, the layers consist of (in descending order) alluvium, Mancos shale, Tres Hermanos C, B, and A sandstones (Tra, Trb, and Trc, respectively), Dakota sandstone, and the Brushy Basin and Westwater Canyon units of the Morrison Formation (Bostick, 1985). Cross sections indicate that Mancos subunits underlie each of the three Tres Hermanos units. The uppermost units are not present over portions of the site.

F2 INFORMATION AVAILABILITY FOR NATURAL AND ARTIFICIAL RECHARGE

Little information on recharge was identified in the available documents. Bostick (1985) describes recharge as occurring on outcrops, but does not quantify the outcrop recharge and during modeling exercises assumes that the recharge is zero outside of the Arroyo del Puerto. Tetra Tech, Inc. (2010, Section 5.4.1) describes the Arroyo del Puerto as an ephemeral surface water resource only supplying native plants and animals, and not recharging any aquifer. Tetra Tech, Inc. (2010) does not quantify recharge on outcrops, but indicates that upper bedrock units are were historically desaturated prior to mining.

The qualitative description of recharge under natural conditions is generally consistent with current understandings in semiarid climates. Natural recharge under similar conditions is typically a few percent of mean annual precipitation in outcrop areas. Natural recharge in alluvium is typically negligible except for localized recharge, which in turn depends on contributing areas and runoff durations.

F3 INFORMATION AVAILABILITY ON TRANSIENT DRAINAGE AFTER EMPLACEMENT

I was unable to identify water level data from within an impoundment in any available report.

Bostick (1985) describes the tailings embankment as made of coarse tailings, intended to allow “marginal weeping” that was initially captured in Pond 3 and is now captured in a seepage interception trench. Bostick (1985) describes the water balance for operations in general terms. Based on the Bostick (1985) numbers, as much as 6,360 L/min [1,680 gpm] was supplied to the tailings impoundments as slurry. Bostick (1985) reports estimates of losses of up to 2,210 L/min [585 gpm] by evaporation and 770 L/min [203 gpm] by seepage during operations. These estimates included contributions from unlined Ponds 3–8 and lined Ponds 9 and 10, as well as the tailings impoundments in unlined Ponds 1 and 2. Bostick (1985) indicates that discharges to Ponds 4 through 8 were discontinued in 1983 and discharges from Pond 3 discontinued in

1984, and concludes that evaporation and seepage losses had both been reduced from the peak by 1985 because of these actions.

Maxim (2001, Section 1.3.1.1) describes seepage from the tailings as occurring laterally down-dip within the alluvium and shallow saprolite, and captured by an interception trench paralleling the impoundment. Maxim (2001, Section 3.3.1) describes all unlined evaporation ponds at the site as dewatered, with the exception of Tailings Impoundments 1 and 2. For the purposes of numerical modeling, Maxim (2000, Section 5.3.2) estimated the existing tailings water volume and assumed that seepage fluxes would logarithmically decrease over 100 years. Maxim (2001, Section 3.3.1) suggests that enhanced dewatering would require installation of 50 wells within the tailings that are pumped for at least four years, and indicated that the slimes within the impoundments are likely to take a very long time to dewater.

F4 INFORMATION AVAILABILITY ON HYDROCHEMICAL OBSERVATIONS

Geochemical monitoring was required on a semiannual basis, and some of the monitoring reports are publicly available in Agencywide Documents Access and Management System (ADAMS). The available database in ADAMS consists of monitoring reports for 1999 and 2006 through 2010, and includes 47 wells. Tabulated values are reported only for the period of interest, although time series plots present values from the 1970s through the report date. AVM (2000) provides tabulated values from 1977 through 1999 for bedrock wells (not included in the database). Bostick (1985) describes a single sampling round in 1984 at 20 monitoring wells (not included in the developed database). AVM Environmental Services, Inc (AVM) (2000) provides several tables with observations from 1997 through 1999 of “hazardous constituents” (not included in the developed database). Maxim (2001) considered impacts from the nearby U.S. Department of Energy (DOE) Title I Ambrosia Lake impoundment and included an electronic database of well information and water quality data on a floppy diskette that is not available in ADAMS (and therefore not included in the developed database).

No information on well coordinates or screened intervals was identified. Water level data is provided as depth to water without a measurement point elevation, thus water table elevations cannot be determined.

The electronic database includes 12 geochemical analytes, including only chloride and sulfate out of the major ions. Accordingly, Piper and Stiff diagrams are not useful with this database.

F5 SUMMARY OF CONCEPTUAL MODEL FOR WATER FLOW NEAR THE TAILINGS COVER

The geologic setting consists of a series of sandstone aquifers separated by shale units, dipping to the northeast. During operations, tailings were discharged to unlined Ponds 1 and 2. Bostick (1985) describes the Pond 1 embankment, constructed in 1958, as consisting of coarse tailings that were intended to weep, with the weeping fluids captured in Pond 3 and conveyed to Ponds 4 through 10 for evaporation. Bostick (1985) describes Ponds 9 and 10 as plastic lined, with the remainder unlined. Ponds 1, 2 and 7 contact Tres Hermanos units and Pond 8 contacts the Dakota sandstone; the remainder of the ponds are constructed on alluvium. Ponds 3 through 8 were no longer in use by 1985. The hydrologic capture function of Pond 3 replaced by an interceptor trench, constructed into the Trb, that parallels the embankment.

The conceptual model for the hydrologic cycle prior to operations consisted of recharge on updip outcrops recharging the sandstone units and flowing down dip, with minimal recharge from the ephemeral Arroyo del Puerto. The alluvium at the site was initially unsaturated. The site should return to a similar state once operations-induced perturbations to the hydrologic system have dissipated.

The hydrologic behavior of the site was extensively altered during operations and reclamation. Units above the Westwood Canyon Member (i.e., Tra, Trb, Trc, Dakota, and Brushy Basin) were extensively dewatered north of the mill and tailings facility during operations, with the mine dewatering discharged to the Arroyo del Puerto north of the site. The Arroyo del Puerto drains to the south, originally paralleling the tailings embankment between Pond 3 and Ponds 4 through 10. During reclamation, the Arroyo was relocated further from the embankment. These operating conditions lowered the sandstone water tables above the Westwood Canyon Member, and augmented gradients within the sandstone units towards the mine dewatering wells (northerly flow, approximately down dip). At the same time, mine dewatering waters were discharged to the Arroyo del Puerto. Waters seeping from the Arroyo created a perched water table within the alluvium that drained to the south along the Arroyo del Puerto. Some of the alluvium waters passed under Ponds 4 through 10 and were captured in the interceptor trench.

The Ambrosia Lake Uranium Mill Tailings Radiation Control Act Title I disposal site, currently controlled by the DOE Office of Legacy Management, is located approximately 0.9 m [1.6 km] east of the relocated Arroyo channel. Seepage from the tailings basin at the DOE site historically entered the alluvium and drained above the bedrock towards the Arroyo, potentially merging with seepage from the Rio Algom site along the Arroyo. DOE (2010, Figure 3) indicates that seepage from the cell also entered the Trc where it subcrops the alluvium. Any flows continuing above the bedrock within the alluvium would also encounter subcropping Trb before reaching the Arroyo. Presumably, any seepage entering the Trc or Trc flows down-dip, generally to the northeast.

F6 WELLS DOWNGRADIENT OF THE TAILINGS COVER

The interceptor trench is immediately downgradient of the embankment. No wells are located between the embankment and interceptor trench.

F7 KEY CHEMICAL SPECIES OR INDICATORS IN THE TAILINGS PORE WATER

Bostick (1985, Table 2) reports water quality samples for a make-up reservoir and Ponds 1 and 3 (1981) and Pond 9 (1983). Reported Pond 9 concentrations are 14, 28, 1.7, 1.7, and 4.6 times larger than reported Pond 1 concentrations for Cl, Na, K, SO_4, and total dissolved solids, respectively. Reported Pond 1 concentrations are 2.8, 1.7, 4.4, 5.8, and 4.1 times larger than reported Pond 3 concentrations for the same species.

F8 KEY CHEMICAL SPECIES OR INDICATORS FOR DISCERNING TEMPORAL AND SPATIAL TRENDS IN GROUNDWATER QUALITY

Monitored water chemistry values include U-nat, Ra-226+Ra-228, Th-230, Pb-210, Cl, SO_4, NO_3, Ni, and Se. Reported values also include depth to water, electrical conductivity, pH, temperature, and total dissolved solids. The maximum reported Cl concentration in the environment is 3,350 mg/L [3,350 ppm], compared to 2,774 and 990 mg/L [2,774 and 990 ppm] reported in Ponds 1 and 3, respectively. The maximum reported SO_4 concentration in the environment is 9380 mg/L, compared to 37,483 and 6,454 mg/L [37,483 and 6,454 ppm] reported in Ponds 1 and 3, respectively.

F9 CHEMICAL DIAGRAMS OF PORE WATER

Insufficient information exists in the database to construct Stiff or Piper diagrams.

F10 INDICATIONS OF COVER EXISTENCE BASED ON GEOCHEMICAL OBSERVATIONS

The most direct indicator of cover performance would be a unique geochemical signature associated with the cover but not the tailings or underlying units. Presence and absence of the unique signature would provide an unambiguous geochemical signature for performance. Such a signature has not been identified for this site.

A time series of geochemical observations within the tailings might indicate recharge through the cover if the tailings concentrations became more dilute over time. No hydraulic or geochemical observations obtained within the tailings were identified in publicly available documents, except for one geochemical sample of tailings fluids (Bostick, 1985, Table 2).

The zone between the interceptor trench and the tailings impoundments would be well suited for examining seepage from the impoundments because the trench is a hydraulic sink that isolates the impoundments from downstream hydrologic conditions. No monitoring wells are located in this narrow zone. Geochemical observations in the trench and areas further from the impoundment are strongly influenced by groundwater corrective action and mine dewatering, thus are poorly suited to identify inflow through the cover into the impoundment.

F11 DOCUMENTED TIME-SERIES TRENDS AND STATISTICAL ANALYSES

The series of groundwater stability monitoring reports (e.g., Rio Algom Mining, LLC, 2010) graphically describe the time series of monitored constituents at selected wells. Some of these time series start in the 1970s.

F12 APPLICABILITY OF NUREG–1569, APPENDIX F

Appendix F discusses methods for quantifying trends in a time series of chemical samples in a well field, with potentially noisy observations. Such methods are appropriately applied to the observational data. However, the available data are poorly suitable for estimating cover performance.

F13 APPLICABILITY OF SITE OBSERVATIONS TO EVALUATE COVER PERFORMANCE

This site is poorly suited for evaluating cover performance at present. There is no information available regarding the hydraulic or geochemical conditions within the tailings impoundments, aside from one chemical sample in 1981. The interceptor trench captures all seepage from the impoundments within the alluvium, but also collects mine dewatering waters that are discharged to the Arroyo del Puerto and pass under prior unlined ponds. Uncertainties in site hydrological conditions because of groundwater corrective actions and mine dewatering operations are likely to dominate any signal from the cover in the interceptor trench. Because the interceptor trench isolates the impoundments from downstream hydrologic influences, any wells located between the trench and the tailings impoundment would be well positioned to sample seepage protected from interference.

In principle the site may offer potential for examining cover performance once the perturbations from operations and remediation decay. The interceptor trench provides a unique opportunity for ensuring that a substantial fraction of seepage can be directly observed, in opposition to the typical scenario where measurements can only be made at a few scattered monitoring wells. After the alluvium no longer contains a perched zone, any seepage from the tailings impoundment through the alluvium and embankment will be identifiable. The trench would not be expected to capture any losses to the Tres Hermanos units, thus supplemental monitoring within the Tra and Trb would be necessary to examine flows in those units.

F14 REFERENCES

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Bostick, K. "Ground-Water Discharge Plan Analysis for Kerr-McGee Nuclear Corporation Ambrosia Lake Uranium Mill, Quivira Mining Company." ML012180223. Ground Water Section, Ground Water Quality and Hazardous Waste Bureau, New Mexico Environmental Improvement Division. <no location given> February 1985.

DOE. "Groundwater Investigations at the Ambrosia Lake and Bluewater Uranium Mill Tailings Disposal Sites." LMS/AMB/BLU/506533. ML101600455. Grand Junction, Colorado: U.S. Department of Energy Legacy Management. May 2010.

Maxim. "Groundwater Modeling and Feasibility Analysis for the Application of Alternate Concentration Limits, Quivira Mill Site, Ambrosia Lake, New Mexico." Draft. ML003737960. Albuquerque, New Mexico: Maxim Technologies, Inc. May 2001.

Maxim. "Application for Alternate Concentration Limits for the Alluvial Materials, Quivira Mill Facility, Ambrosia Lake, New Mexico." ML011690068. Albuquerque, New Mexico: Maxim Technologies, Inc. May 2000.

Rio Algom Mining, LLC. "Rio Algom LLC Ambrosia Lake Facility Groundwater Stability Monitoring Report 1st Half 2010." ML102170384. Grants, New Mexico: Rio Algom Mining, LLC. July, 2010.

Tetra Tech, Inc. "Reclamation Plan for Disposal of Pond Sediments and Ancillary Materials, Tailings Cell 2 Expansion." Rev. 1. ML071790245. No location given: Tetra Tech, Inc. July 2010.

APPENDIX G

SITE EVALUATION FOR SITE 2, BEAR CREEK (ANADARKO), WYOMING

SITE EVALUATION FOR SITE 2, BEAR CREEK (ANADARKO), WYOMING

Almost all Agencywide Documents Access and Management System (ADAMS) documents related to the Bear Creek site are on microfiche (1687 documents in the public legacy library compared to 55 documents in the public library). The task scope did not include examining microfiche documents. The public library documents describe the site assuming that prior documents are available (e.g., reclamation plans, corrective action plan data, cross sections, well location data), thus only limited analysis of the site is possible under the task scope.

G1 INFORMATION AVAILABILITY FOR GEOLOGIC STRUCTURE AND PROPERTIES

Anadarko Petroleum Corporation (Anadarko) (2011), Tetra Tech GEO (2011), and the U.S. Department of Energy (DOE) (2009) provide high-level descriptions of site characteristics. Selected cross section figures illustrate interpreted layers.

G2 INFORMATION AVAILABILITY FOR NATURAL AND ARTIFICIAL RECHARGE

Very little information on recharge was identified in the available documents. DOE (2009) summarizes the cover design. The cover was designed to isolate the tailings from water from the drainage area above the tailings by diverting flows into a diversion channel. The diversion channel also receives runoff from the vegetated cover. Although not quantified, natural recharge under similar conditions is typically a few percent of mean annual precipitation.

G3 INFORMATION AVAILABILITY ON TRANSIENT DRAINAGE AFTER EMPLACEMENT

Anadarko (2011, Figure 4) illustrates static water levels in the impoundment in 1986 and 1995. Water levels dropped from 10 m [34 ft] above the plotted base of the tailings in 1986 to approximately 2 m [7 ft] above the plotted base of the tailings in 1995. According to the figure, the tailings are in direct hydraulic communication with the N sand, which may provide a pathway for seepage around the dam even though the dam is keyed into the underlying low-permeability claystone. It is likely that the tailings are essentially dewatered by now.

G4 INFORMATION AVAILABILITY ON HYDROCHEMICAL OBSERVATIONS

The site has an electronic database of water levels and geochemical sampling. The portion of the database provided to the U.S. Nuclear Regulatory Commission (NRC) consists of nine wells monitored after the end of the groundwater corrective action program activities. The licensee has a more extensive database describing wells used in the corrective action program, including at least 100 monitoring wells that can be identified in figures. The database provided to the NRC includes well coordinates, depths, and screened formations for the nine wells. The western four wells (Lang Draw) are screened in alluvium, the others (Northern Path) are screened in the uppermost sandstone unit (which is hydraulically connected to the alluvium). Starting in 1998, the database only records water levels in three of the alluvium wells and two of the sandstone wells.

The electronic database includes 12 geochemical analytes, including only chloride and sulfate out of the major ions. Accordingly, Piper and Stiff diagrams are not useful with this database.

G5 SUMMARY OF CONCEPTUAL MODEL FOR WATER FLOW NEAR THE TAILINGS COVER

The geologic setting consists of a series of sandstone aquifers separated by low-permeability siltstone and claystone units. A dam placed across the ephemeral Lang Draw, and keyed into the claystone below the N sand unit of the Wasatch formation, formed the tailings impoundment. The tailings basin was lined with compacted soil above shallow alluvium, claystone outcrops, and the K and N sands of the upper Wasatch Formation. The underlying Ore Sand aquifer is separated from the K and N sands by at least 15 m [50 ft] of claystones and siltstones. The K and N sands are interbedded with claystone, and are locally eroded. The K sand is generally above the tailings. The N sand is 5 to 50 m [5 to 50 ft] thick in the vicinity of the tailings. Tetra Tech GEO (2011) describes the N sand as changing from a small channel sand into several sands splaying into an overbank environment, suggesting that the N sand is locally heterogeneous.

DOE (2009) characterizes the primary seepage pathway as a highly weathered sandstone lens under the northeast end of the embankment, allowing release to the north that diverges into Lang Draw and the Northern Pathway. DOE (2009) interprets two flow paths developing from seepage, forming narrow plumes along Lang Draw and the Northeast Pathway. These pathways are thought to merge approximately 914 m [3,000 ft] downstream.

The available water level contour plots (Tetra Tech GEO, 2011, Figures 6 and 7) indicate a sharp gradient at the northeast side of the impoundment based on a single well (MW-32A). Such gradients typically indicate a resistant unit between two disparate permeable zones, which would suggest that seepage to the northeast is small.

Water level contours from 1986 and 1996 (Tetra Tech GEO, 2011, Figures 6 and 7) and pH observations plotted in 1990 or 1991 (Anadarko, 1996, ML12046A866) are consistent with seepage passing through or under a zone centered near the northeastern end of the embankment. A cross section parallel to the embankment (Anadarko, 2011, Figure 4) suggests that the tailings are emplaced directly on the N sand in the central and northeastern portions of the impoundment, with the N sand providing a continuous pathway bypassing the embankment. If seepage was distributed over this zone, this would imply a seepage plume as much as 213-m [700–ft]-wide (independently estimated using Google Earth) exiting the impoundment to the north.

Neglecting MW-32A observations, the water table contours indicate that the seepage predominantly curved to the west during active seepage and discharged to the Lang Draw alluvium over more than 305 m [1,000 ft], with the northeast edge of the plume perhaps following the Northern Pathway (see FigureG–1, illustrating water levels prior to the groundwater corrective action program). As the tailings water levels subsided, water levels have become less controlled by Lang Draw (see FigureG–2, illustrating water levels in February 2011) so that any remaining seepage is likely moving to the north generally parallel to Lang Draw, discharging over a distance as much as 914 m [3,000 ft].

The water level contours may provide a misleading indication of flow pathways, however. Tetra Tech GEO (2011, Section 2.2.1) indicates that the N sand tends to be unsaturated east of Lang

Draw, which would greatly reduce westerly flow. Unsaturated N sand east of Lang Draw would favor a conceptual model of seepage predominantly flowing along the Northern Pathway and leaking towards Lang Draw at a reduced rate.

G6 WELLS DOWNGRADIENT OF THE TAILINGS COVER

All of the wells in the electronic database are downgradient of the tailings cover. Additional wells were monitored during the corrective action program but are not in the electronic database. Some of the wells were located upgradient of the basin or were screened within the tailings. These observations may be reported in the public legacy library in ADAMS.

G7 KEY CHEMICAL SPECIES OR INDICATORS IN THE TAILINGS PORE WATER

DOE (2009, Table 2-1) collects representative water chemistry values describing background and tailings wells. The table includes U, Ra-226+Ra-228, Th-230, Se, Cl, SO_4, and five metals (no background values are provided for Cl and SO_4). Tailings water concentrations are generally enriched by at least an order of magnitude for these species.

G8 KEY CHEMICAL SPECIES OR INDICATORS FOR DISCERNING TEMPORAL AND SPATIAL TRENDS IN GROUNDWATER QUALITY

The electronic database of water quality samples includes U, Ra-226, Ra-228, Th-230, Se, Cl, SO_4, pH, electrical conductivity, and five metals. Of these, the more illuminating species may be Cl, pH, U, and Ra-226.

Tetra Tech GEO (2011) re-evaluated the transport modeling of metals at the site, indicating that four of the metals and Th-230 are unlikely to be mobile at the expected pH values. Tetra Tech GEO (2011) modeled U, Ra-226+Ra-228, Ni, Cl, SO_4, and pH.

G9 CHEMICAL DIAGRAMS OF PORE WATER

Insufficient information exists in the database to construct Stiff or Piper diagrams.

G10 INDICATIONS OF COVER EXISTENCE BASED ON GEOCHEMICAL OBSERVATIONS

The most direct indicator of cover performance would be a unique geochemical signature associated with the cover but not the tailings or underlying units. Presence and absence of the unique signature would provide an unambiguous geochemical signature for performance. Such a signature has not been identified for this site. The cover material is clay covered with topsoil (DOE, 2009).

A time series of geochemical observations within the tailings might indicate recharge through the cover if the tailings concentrations became more dilute over time. No geochemical observations obtained within the tailings are included in the electronic database.

Geochemical observations outside the impoundment are poorly suited to identify recharge through the cover into the impoundment, because the volume of tailings fluids emplaced during operations is much larger than cumulative recharge through the cover that might be expected under adverse conditions. The effect of recharge would be to dilute the concentrations, which also occurs through processes such as mixing and diffusion. These other pathway-dependent processes are typically associated with substantial uncertainties that are almost certain to dominate the signal that might be identified from recharge through the cover.

G11 DOCUMENTED TIME-SERIES TRENDS AND STATISTICAL ANALYSES

Available reports (Anadarko, 2011; Tetra Tech GEO, 2011; DOE, 2009) graphically describe the time series of selected constituents at selected wells. Tetra Tech GEO (2011) also provides contour plots of water levels and saturated thickness at three selected snapshots in time. It is likely that measurements were obtained at other wells and reported in documents in the public legacy library.

G12 APPLICABILITY OF NUREG–1569, APPENDIX F

Appendix F discusses methods for quantifying trends in a time series of chemical samples in a well field, with potentially noisy observations. Such methods are appropriately applied to the observational data. However, the available data are poorly suitable for estimating cover performance.

G13 APPLICABILITY OF SITE OBSERVATIONS TO EVALUATE COVER PERFORMANCE

In general, site observations could be used to evaluate cover performance by considering hydraulic responses, thermal responses, and geochemical responses. Temperature is not reported at this site, precluding analyses based on thermal responses.

Water levels were monitored within the tailings at several wells. These data are not available, but a long-term decline in water levels within the impoundment prior to cover emplacement is reported. If the sampling program extended after cover emplacement and water levels were sampled sufficiently frequently, episodic rises in the water level associated with precipitation or snowmelt events would provide an indication that the cover admitted recharge. Such data are not included in the available reports.

Site characteristics may allow for directly probing hydraulic responses within the tailings impoundments using new wells, especially on the east side of the impoundment. The low permeability of the underlying claystone would tend to capture infiltration pulses in a perched layer above the claystone. However, such an approach is difficult to implement once the tailings desaturate, and it is likely that the tailings have essentially desaturated by now based on the rate of decline from 1986 to 1996.

At this site, the tailings are relatively isolated from the downstream wells. Transients resulting from infiltration events through the cover are likely to be delayed and have a small amplitude upon reaching the downstream wells because of this isolation, thus would be difficult to separate from recharge events occurring outside the impoundments with a transient response that is not filtered by the intervening flow pathways. Further, measurements have been made annually since 2001, which is insufficiently frequent for identifying potential responses to large precipitation events.

Geochemical signals could provide some indication of cover performance if the cover provided a distinct signal. No such geochemical signals were identified. This method would require application of a distinct tracer to the surface of the tailings and monitoring for the tracer.

Infiltration passing through the cover would dilute the tailings pore waters. Monitoring within the tailings might capture such dilution, but the sampling scheme since cover emplacement has not included sampling in the tailings. Such an approach is difficult to implement once the tailings desaturate, and it is likely that the tailings have essentially desaturated by now based on the rate of decline from 1986 to 1996.

G14 REFERENCES

Anadarko. "Alternate Concentration Limit Proposal for the Ground Water Resources at the Bear Creek Uranium Mill." ML12046A854. Houston, Texas: Anadarko Petroleum Corporation. November 2011.

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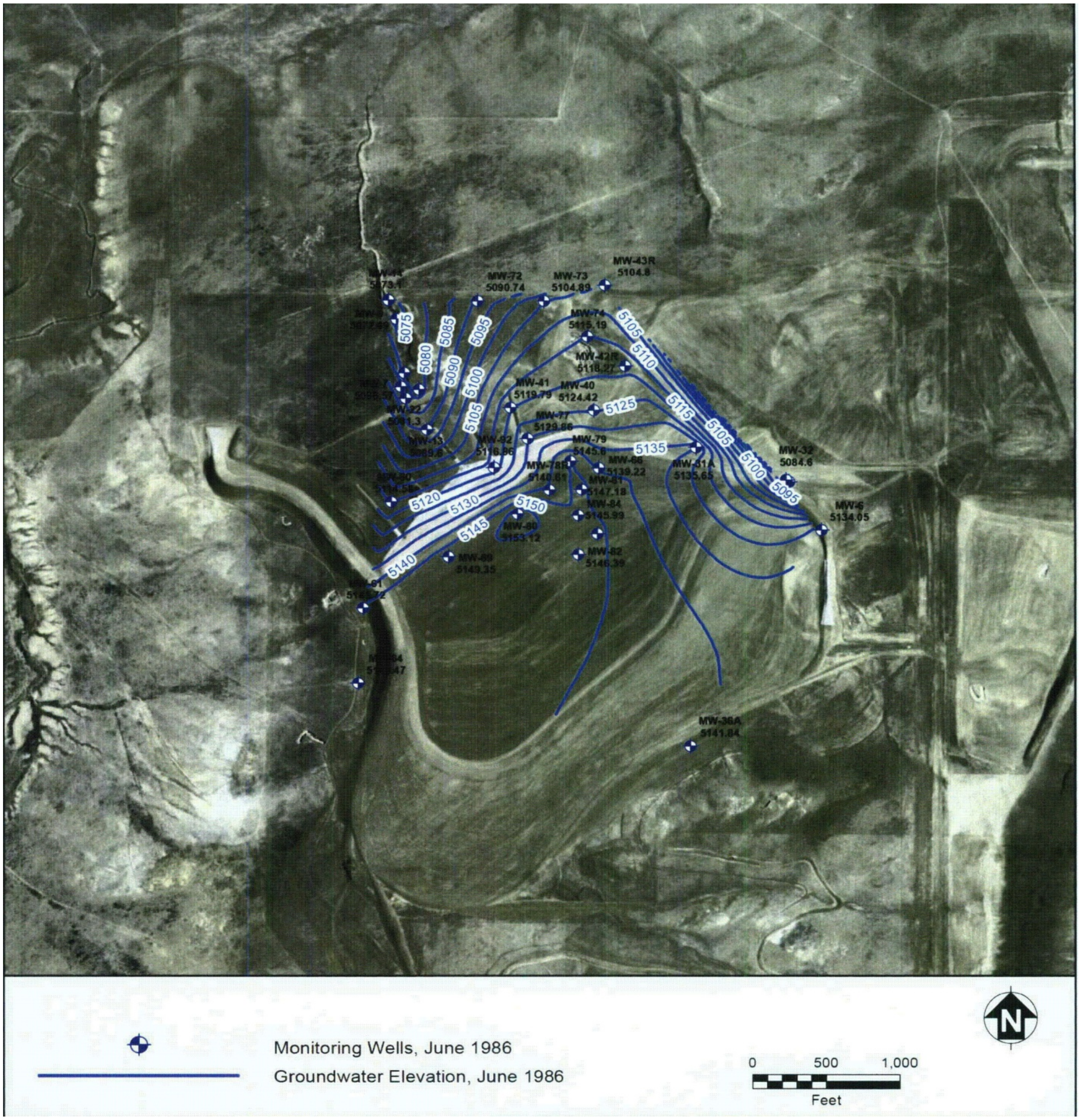

Figure G–1. Static Water Levels Prior to the Groundwater Corrective Action Program. The Steep Contours on the Northeast Edge of the Impoundment May Be an Artifact of MW-32 Being Screened in a Disconnected Unit. Reproduced From Anadarko (2011, Figure 6).

Figure G–2. Present-Day Static Water Levels. These Water Levels Are Consistent With Any Continuing Seepage Discharging Almost Exclusively to Lang Draw. Reproduced From Anadarko (2011, Figure 8).

APPENDIX H

SITE EVALUATION FOR SITE 10, SHIRLEY BASIN NORTH (PATHFINDER), WYOMING

SITE EVALUATION FOR SITE 10, SHIRLEY BASIN NORTH (PATHFINDER), WYOMING

H1 INFORMATION AVAILABILITY FOR GEOLOGIC STRUCTURE AND PROPERTIES

Pathfinder Mines Corporation (Pathfinder) (2001, Section 1.3) provides a high-level description of site characteristics, citing numerous well logs and pumping tests. Figures illustrating interpreted properties are not legible in the electronic file.

Pathfinder (2001) describes modeling work assessing flow and transport. Summary tables describe model inputs based on the geologic structure at a high level. None of the available documents identified either the distributed parameter values or the data that the parameter values were developed from.

H2 INFORMATION AVAILABILITY FOR NATURAL AND ARTIFICIAL RECHARGE

Three pathways for recharge are of general concern for a tailings cover: (i) distributed recharge through the cover, (ii) focused recharge in local areas of the cover, and (iii) recharge upslope of the tailings that subsequently moves laterally down the bedrock and thereby contacts waste.

Total distributed recharge is likely to be much larger than total focused recharge because the cover design limits focusing. Some focused flow may occur because of runoff from the roadways on the cover. The potential contributing area for upslope recharge extends approximately1,219 m [4,000 ft] upslope, based on estimates using Google Earth.

Pathfinder (2001) provides general descriptions of recharge, noting that the piezometric surface in the surficial aquifer is supported by natural recharge and describing Mine Creek (the discharge point for the surficial aquifer) as a perennial stream. Pathfinder (2001, Section 3.1.1) states that recharge in the mid-1990s (prior to cover emplacement) was a substantial fraction of tailings dewatering, in part stemming from leaky evaporation ponds. Pathfinder (2001) also provides a high-level description of the corrective action program, which used a series of injection and extraction wells.

H3 INFORMATION AVAILABILITY ON TRANSIENT DRAINAGE AFTER EMPLACEMENT

Pathfinder (2001) projects seepage rates from the impoundments after emplacement. No estimates of drainage rates were found in available documents subsequent to emplacement.

H4 INFORMATION AVAILABILITY ON HYDROCHEMICAL OBSERVATIONS

The site has an electronic database of water levels and geochemical sampling. The portion of the database provided to the U.S. Nuclear Regulatory Commission (NRC) consists of 18 wells monitored after the end of the groundwater corrective action program activities, and 18 wells with unknown locations apparently from elsewhere on the site. The licensee has a more extensive electronic database describing wells used in the corrective action program (Hydro-Engineering, LLC, 2005, Appendices A through C). These appendices contain an apparently complete history of geochemical observations for all of the wells, but water levels are not tabulated in the appendices. Tables in the corrective action program monitoring reports provide coordinates for at least 212 wells. Figures provided with the corrective action monitoring reports display limited water level data from some of the additional wells. Contours on some figures appear to locally not match the reported values, and may also combine the hydraulically isolated surficial and White River aquifers.

Figure H–1 displays the static water levels for all 18 wells adjacent to the tailings impoundments that are included in the electronic database. These wells are adjacent to the tailings impoundments (14 in the surficial aquifer, 4 in the underlying White River aquifer). Comparison of the surficial aquifer wells with the White River wells suggests that the two units are hydraulically distinct, evidenced by a lack of response in the surficial wells even with drawdowns on the order of 31 m [100 ft] resulting from pumping in the White River wells.

The electronic database includes more than 30 geochemical analytes. Many of the analytes are not included in the electronic database for the surficial aquifer wells, including major ions other than chloride and sulfate. Several of the trace constituents are consistently measured at the detection limit. Accordingly, Piper and Stiff diagrams are not useful except for the White River aquifer, which in turn does not appear to be hydraulically connected to the tailings impoundments and seepage.

Figure H–2 displays the Piper diagram for the White River wells in the electronic database. Figures H–3 through H–6 display selected constituent histories.

H5 SUMMARY OF CONCEPTUAL MODEL FOR WATER FLOW NEAR THE TAILINGS COVER

Pathfinder (2001, Section 1.3) describes the site setting and associated site characteristics developed by the licensee.

The geologic setting consists of a series of sandstone aquifers separated by low-permeability siltstone and claystone units. The Lower and Main Wind River units of the Wind River formation are the ore-bearing formations, overlain by the White River Aquifer and surficial units. Pathfinder (2001) describes the White River Aquifer as geologically part of the Wind River formation but hydrologically distinct. A layer of siltstone and claystone 3 to 18 m [10 to 60 ft] thick separates the White River Aquifer and the surficial aquifer, which consists of eroded and reworked White River material. The backfilled Area 2/8 mine pit immediately west of the tailings area penetrates to the Lower Wind River unit, providing a potential connection between aquifers.

Tailings impoundments Nos. 4 and 5, and Pond 3, were formed by damming Mine Creek, a small drainage tributary to Spring Creek terminating several thousand feet from the tailings area. Pathfinder (2001, Section 1.3.3) describes a relatively continuous clay layer in the tailings area separating the tailings from the surficial aquifer, with the vicinity of the Mine Creek channel providing a relatively permeable pathway.

The available water level and geochemical observations in the electronic database and suggest that piezometric levels at the base of Tailings Impoundment No. 5 (the furthest downslope) are strongly controlled by perennial flow in Spring Creek. Water within the impoundments appears to generally flow to the northeast, down the original Mine Creek channel; downgradient of the dam, flow diverts to the east to follow and discharge to Spring Creek. The lack of response in overlying wells to substantial drawdowns in the underlying Wind River aquifer suggests that the surficial and White River aquifers are poorly connected hydrologically. Monitoring after the cessation of the groundwater corrective action program suggests that the normal groundwater flow direction in the Wind River may be to the north or northeast under the tailings impoundments, but this conclusion may change after Wind River water levels finish recovering from pumping. Chloride, sulfate, and uranium concentrations in Wind River dewatering wells suggest that a plume from the Area 2/8 mine pit is developing in the Wind River aquifer. The hydraulic gradient has historically been downward at the site, thus this plume is unlikely to impact interpretations of tailings seepage.

H6 WELLS DOWNGRADIENT OF THE TAILINGS COVER

The groundwater corrective action program used lines of injection and extraction wells parallel to the No. 5 dam to create a linear groundwater mound blocking migration from the dam to Spring Creek, approximately 305 m [1,000 ft] downslope. Fourteen surficial aquifer wells are monitored in this zone.

H7 KEY CHEMICAL SPECIES OR INDICATORS IN THE TAILINGS PORE WATER

Pathfinder (2001, Table 2.1-1) describes water quality samples obtained from tailings wells in 1993 through 1995 that include U, Ra-226, Se, Cl, and SO_4, pH, total dissolved solids (TDS), electrical conductivity, and 9 other chemical species. Six of the additional species were typically observed at concentrations below the detection limit, except for Fe, Ni, and As.

H8 KEY CHEMICAL SPECIES OR INDICATORS FOR DISCERNING TEMPORAL AND SPATIAL TRENDS IN GROUNDWATER QUALITY

Pathfinder (2001) modeled U, Th-230, Se, Cl, Ra-226 + Ra-228, and TDS transport. These constituents were predicted to increase in concentration at the four reference locations for approximately 10 years after pumping stopped, then gradually decline. The trend of an increase in concentration after stoppage in the model results is consistent with observations, although the observations have not yet reached the 10-year period.

Prior to 2005, observed concentrations of thorium-230 are often at or below the detection limit. There is a transition marked by a lower detection limit apparently stemming from improvement in laboratory methods.

The available monitored constituents appearing potentially useful include U, Ra-226, Se, Cl, and SO_4, with Cl and SO_4 appearing most useful because the signals are larger relative to the detection limit. Two species with detectable signals in tailings (Fe and Ni) are not useful, because Fe was not recorded in the surficial aquifer database and Ni is generally below the detection limit.

H9 CHEMICAL DIAGRAMS OF PORE WATER

Sufficient information exists in the database to construct Stiff and Piper diagrams for seven major ions (Ca, Mg, Na, Cl, SO_4, K, and HCO_3), but only in the White River aquifer. Data for CO_3 are limited.

H10 INDICATIONS OF COVER EXISTENCE BASED ON GEOCHEMICAL OBSERVATIONS

The most direct indicator of cover performance would be a unique geochemical signature associated with the cover but not the tailings or underlying units. Presence and absence of the unique signature would provide an unambiguous geochemical signature for performance. Such a signature has not been identified, and is unlikely because the cover material is sand and clay obtained on-site (Hydro-Engineering, LLC, 1999, Section 10.5.1.2).

The end of the groundwater correction action program pumping in 2005 provides an unusual opportunity for evaluating transient transport, which may provide clues to discharge from the tailings. The corrective action program dropped Cl and SO_4 concentrations by approximately an order of magnitude downgradient from Dam No. 5. The end of the pumping period allowed the concentrations to return to the levels observed prior to pumping with an advancing front. The rate of advance may provide useful information.

Geochemical observations are consistent with hydrologic indications with respect to the isolation of the surficial aquifer and White River aquifer, in the sense that the two aquifers appear to have distinct geochemical characteristics. It appears that the Area 2/8 mine pit are allowing waters from the Wind River ores to migrate into the overlying White River, based on higher U, Cl, and SO_4 concentrations in the upgradient wells adjacent to the pit. The current downward hydraulic gradient suggests that these waters are unlikely to influence the tailings, but the available information is insufficient to determine whether the pre-operation (and likely long-term) gradient was downward.

Wind River waters were used to supply injection wells, so the geochemical signature from the Wind River aquifer may have been partially observed during the corrective action period. Upstream Spring Creek waters may also have been drawn towards the tailings.

H11 DOCUMENTED TIME-SERIES TRENDS AND STATISTICAL ANALYSES

The semiannual water quality reports provided by the licensee typically provide time-series and spatial plots of several constituents for each (post-2005) or selected (during the corrective action period) monitored location. The plots do not necessarily provide data from the entire well history.

H12 APPLICABILITY OF NUREG–1569, APPENDIX F

Appendix F discusses methods for quantifying trends in a time series of chemical samples in a well field, with potentially noisy observations. Such methods are appropriately applied to the observational data. However, the available data may not be suitable for estimating cover performance.

H13 APPLICABILITY OF SITE OBSERVATIONS TO EVALUATE COVER PERFORMANCE

In general, site observations could be used to evaluate cover performance by considering hydraulic responses, thermal responses, and geochemical responses. However, temperature is not reported at this site, precluding analyses based on thermal responses.

This site is favorable for directly probing hydraulic responses within the tailings impoundments, because the low permeability of the underlying bedrock would tend to capture infiltration pulses in a perched layer above the bedrock. Lack of transient fluctuations and a long-term declining water table are two hydraulic responses that would be consistent with a performing cover. No current monitored wells are positioned to directly observe a perched water table in the impoundments. Numerous dewatering wells within the impoundments are positioned appropriately, and had water levels been monitored in these wells following the end of the corrective action program may have provided a good direct indication of cover performance.

Observed hydraulic responses for the wells in the database appear to be highly constrained by the nearby perennial Spring Creek and corrective action injection and pumping. At this site, the low permeability of the underlying bedrock and dams appears to hydrologically isolate the tailings from the downstream wells. Transients resulting from infiltration events are likely to be delayed and have a small amplitude upon reaching the downstream wells because of this isolation, thus would be difficult to separate from recharge events occurring outside the impoundments with a transient response that is not filtered by a low-permeability unit.

Geochemical signals could provide some indication of cover performance if the cover provided a distinct signal. No such geochemical signals were identified. This method would require application of a distinct tracer to the surface of the tailings and monitoring for the tracer.

Dilution of the tailings pore waters with rainwater is expected if the cover did not preclude infiltration. The nature of the corrective action program, combining active injection and extraction and influenced by Spring Creek, makes it difficult to untangle the influence of dilution within the tailings pore waters from dilution from other waters. This approach for estimating infiltration would require good characterization of both the fluxes and the compositions of the injection wells and Spring Creek waters, as well as compositions of the tailings waters. Pathfinder (2001, Table 2.1-1) reports tailings water compositions, but the remaining data does not appear to be easily available.

H14 REFERENCES

Hydro-Engineering, LLC. “Hydrologic Monitoring for Shirley Basin’s Tailings Seepage Control Plan.” ML050730219, ML050730224. Casper, Wyoming: Hydro-Engineering, LLC. February 2005.

Hydro-Engineering, LLC. “Shirley Basin Mine Tailings Reclamation Plan.” Rev. 9/8/1999. ML081570290, ML082100049. Casper, Wyoming: Hydro-Engineering, LLC. September 1999.

Pathfinder. “Application for: Alternate Concentration Limits, Pathfinder Mines Corporation, Shirley Basin Mine.” Rev. 8/28/2001. ML012530116, ML012530146. Shirley Basin, Wyoming: Pathfinder Mines Corporation. August 2001.

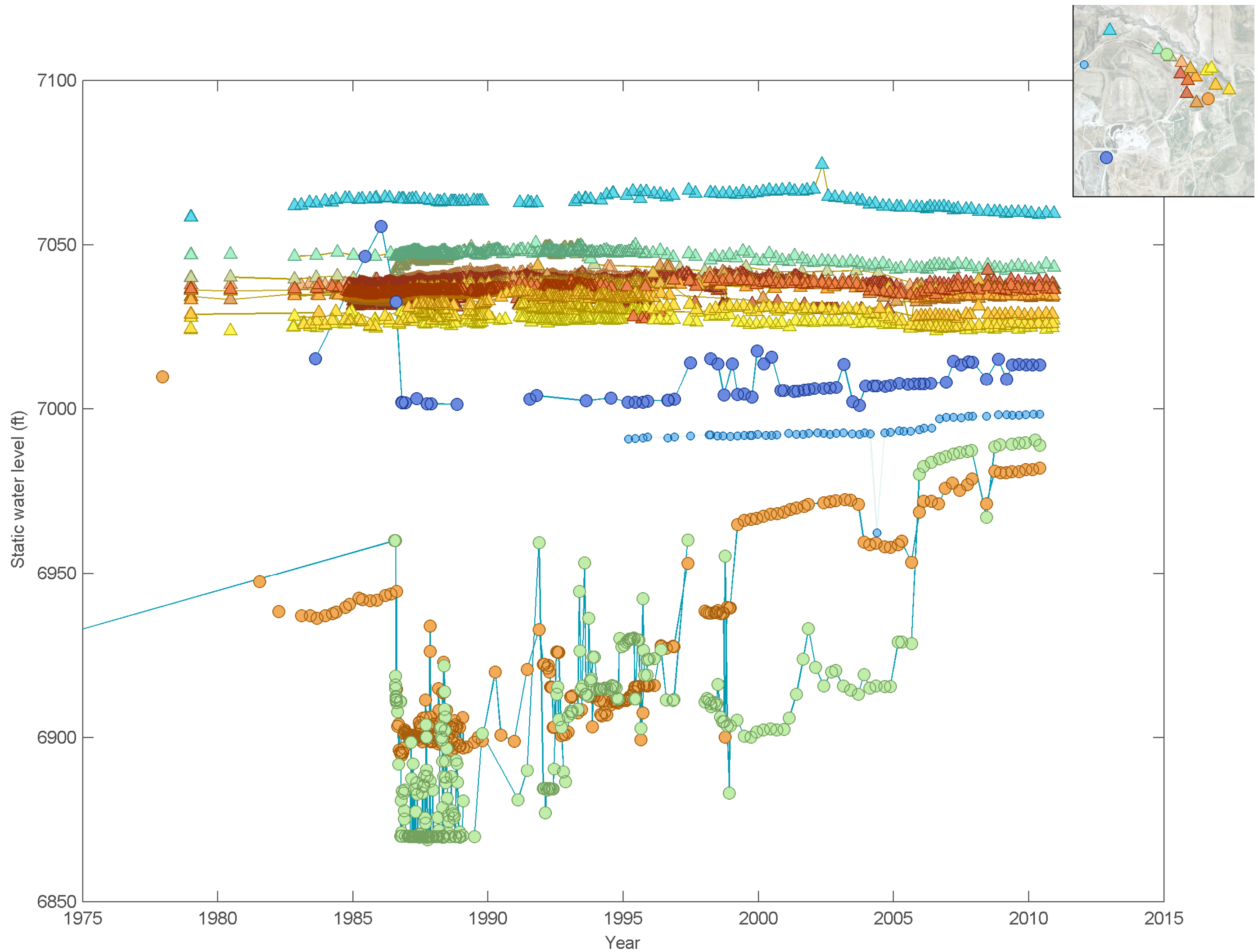

Figure H–1. Static Water Levels in All Wells (Triangles Are Surficial Aquifer Wells, Circles Are White River Wells)

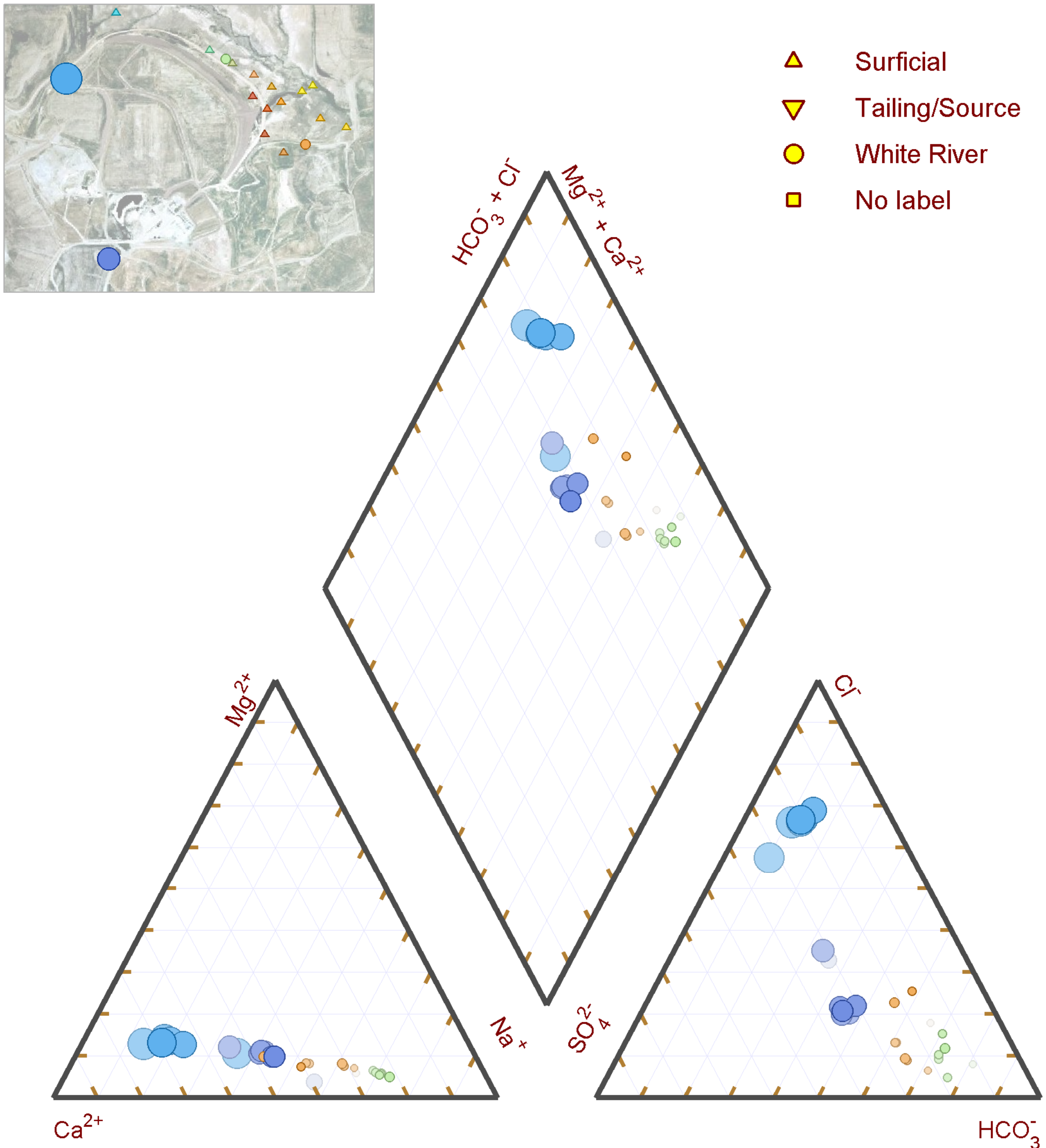

Figure H–2. Piper Diagram of Major Ionic Concentration (Meq/L). White River Wells Have the Necessary Set of Constituents in the Database, But Not the Surficial Aquifer Wells. Symbol Size Is Proportional to the Logarithm of Combined Ionic Concentration. Earlier Readings Are Indicated by Whiting Out the Symbol.

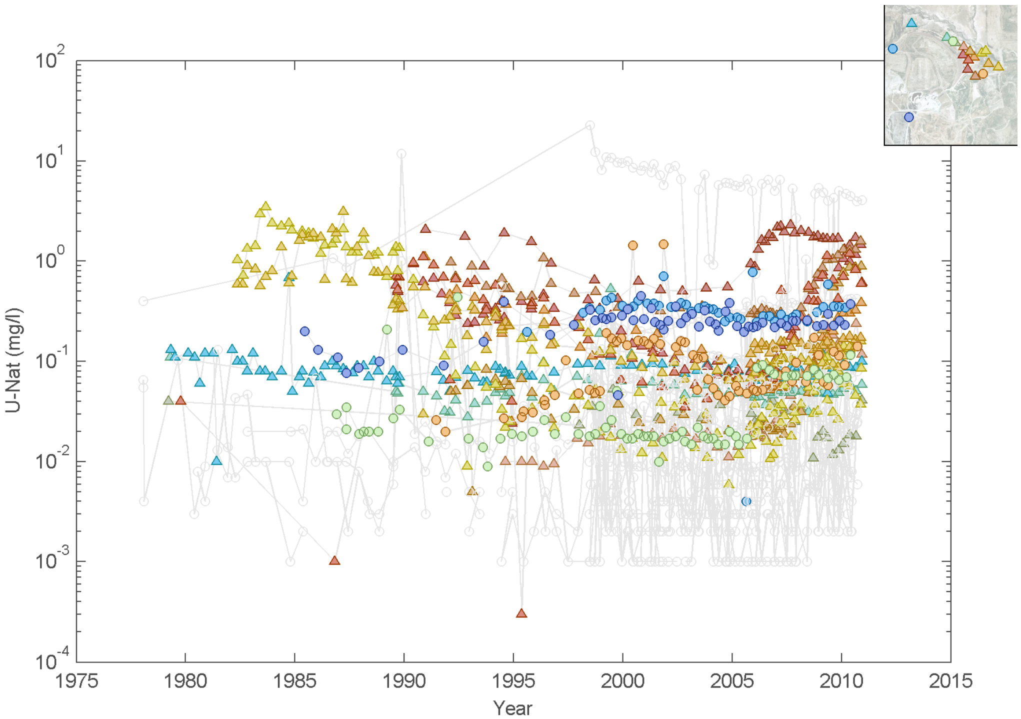

Figure H–3. Uranium Is Gradually Evolving (White Are Mine Locations)

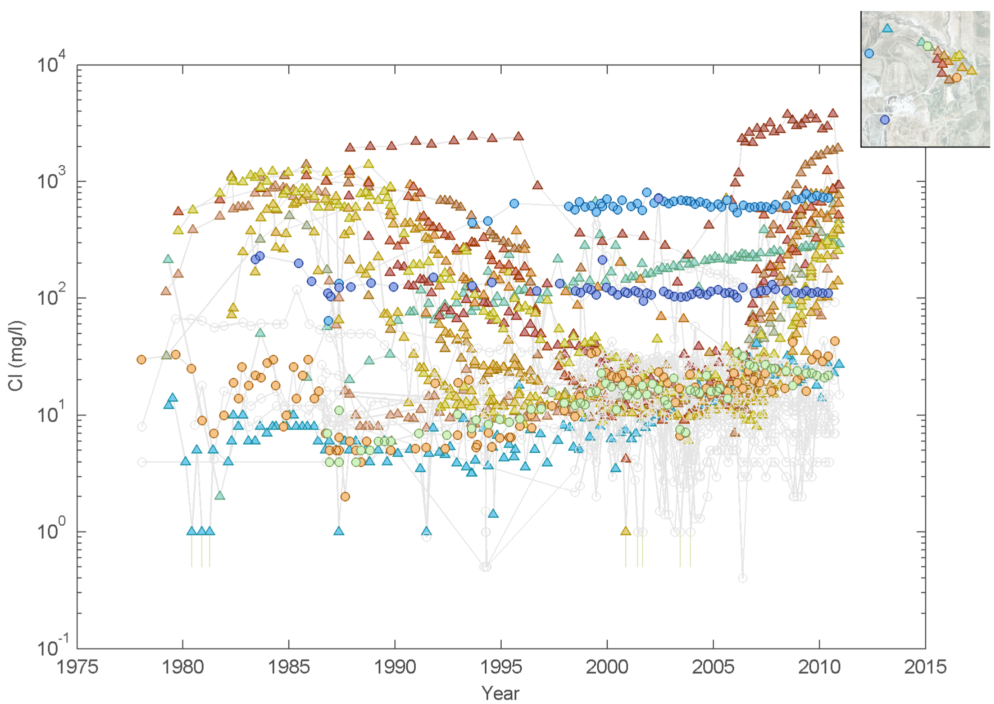

Figure H–4. Chloride Shows a Response to the 1995–2005 Corrective Action

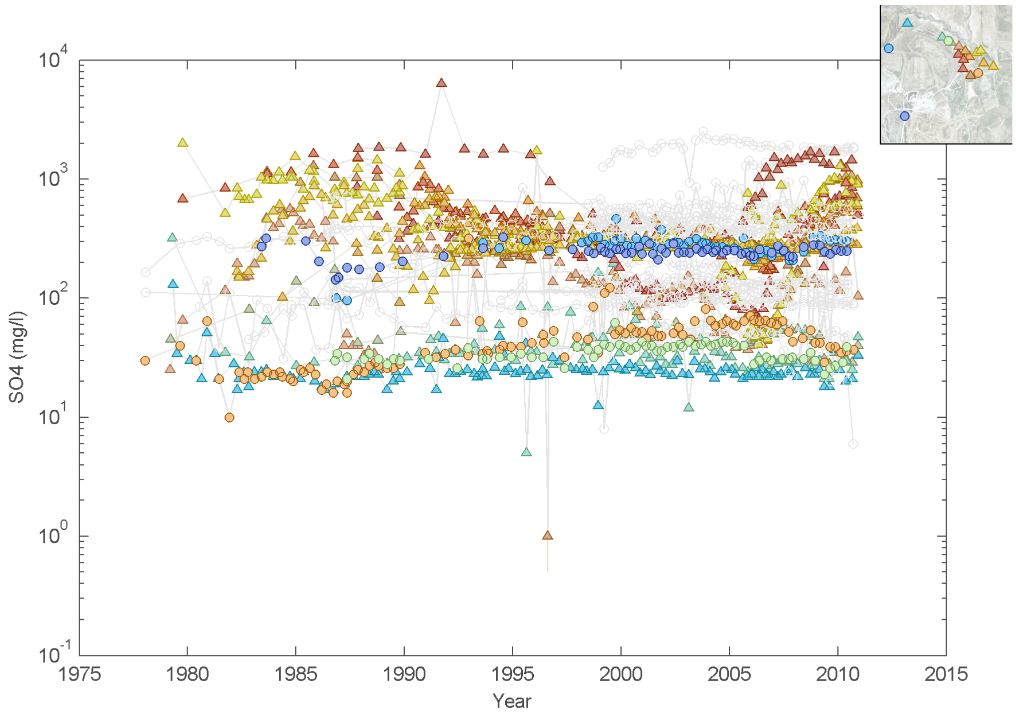

Figure H–5. Sulfate Also Shows Pumping Signal

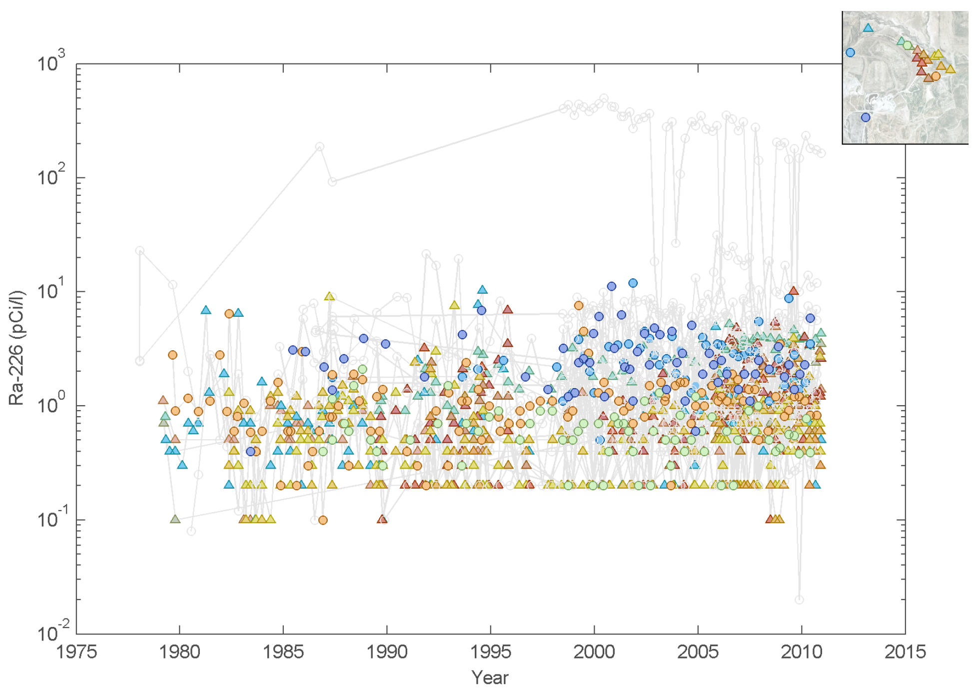

Figure H–6. Radium Has a Generally Higher Concentration in the White River