3.0 Milling History

3.1 General Description

The Bluewater mill began operations in 1953, processing both limestone and sandstone ores using a carbonate leach. In 1955, an acid leach circuit was added to process sandstone ore from the Jackpile mine located on the Laguna Reservation about 50 miles east of the site. Only sandstone ores were processed after mid-1959, and the carbonate circuit was phased out. Although some early limestone tailings were initially deposited in the carbonate tailings pond, beginning in 1956, all the tailings were deposited in the main tailings impoundment. Sandstone ore was crushed and leached with sulfuric acid to extract the uranium oxide.

From 1953 to 1977, uranium was removed from the leached solutions by absorption onto resins in ion-exchange vats; the remaining solution and crushed ore and leachate were transported as a slurry to the tailings ponds. Sodium chloride was used in an elutriation process to remove uranium, except for the time period from December 1955 to August 1957 when a nitrate eluent was used. After January 1977, the mill used the solvent extraction method rather than ion-exchange for removing uranium. Solvent extraction resulted in higher concentrations of total dissolved solids and chloride, and higher pH, in the leachate slurry that was pumped to the main tailings impoundment. In 1980, the mill process was again changed to allow for recycling a portion of the tailings liquor from the evaporation ponds and tailings pond.

3.2 Milling Operations

Milling operations were conducted 24 hours per day, 365 days per year. The initial mill rate of 300 tons per day in 1953 was incrementally increased over time, reaching a nominal rate of 6,000 tons per day by 1977. The milling byproduct materials (tailings) were transported in a slurry to tailings impoundments. The solids content of slurry discharged to the main tailings impoundment varied between 30 and 40 percent, so significant quantities of water were needed to convey the slurry to the impoundment. Water for mill operations was supplied by five groundwater production wells completed in the San Andres aquifer south of the mill. These wells, Anaconda #1 through Anaconda #5 (shown in Figure 1), operated at various durations and rates throughout the years of milling operations.

3.3 Tailings Disposal History

Initial deposition of tailings in the main tailings impoundment began in 1956 in a basalt depression that was located in what is now the middle of the main tailings disposal cell. A limited quantity of carbonate tailings was deposited in this depression, followed thereafter by acidic tailings. After initial depositions began to fill the depression, a series of soil starter dikes were constructed along the north, northeastern, and eastern limits of the tailings to control the surface area of the pond. At this point, the footprint of the tailings pond covered not only basalt surfaces, but also windblown sand deposits and an outcrop of San Andres Limestone.

Tailings were discharged continuously from three movable spigots along the south side of the impoundment. Coarser sands settled near the spigots, mixed fine sand, silt, and clay settled in the middle portion of the impoundment, and silt and clay (referred to as "slimes") settling out in the north end where a tailings pond developed. Figure 5 shows the approximate distribution of these materials.

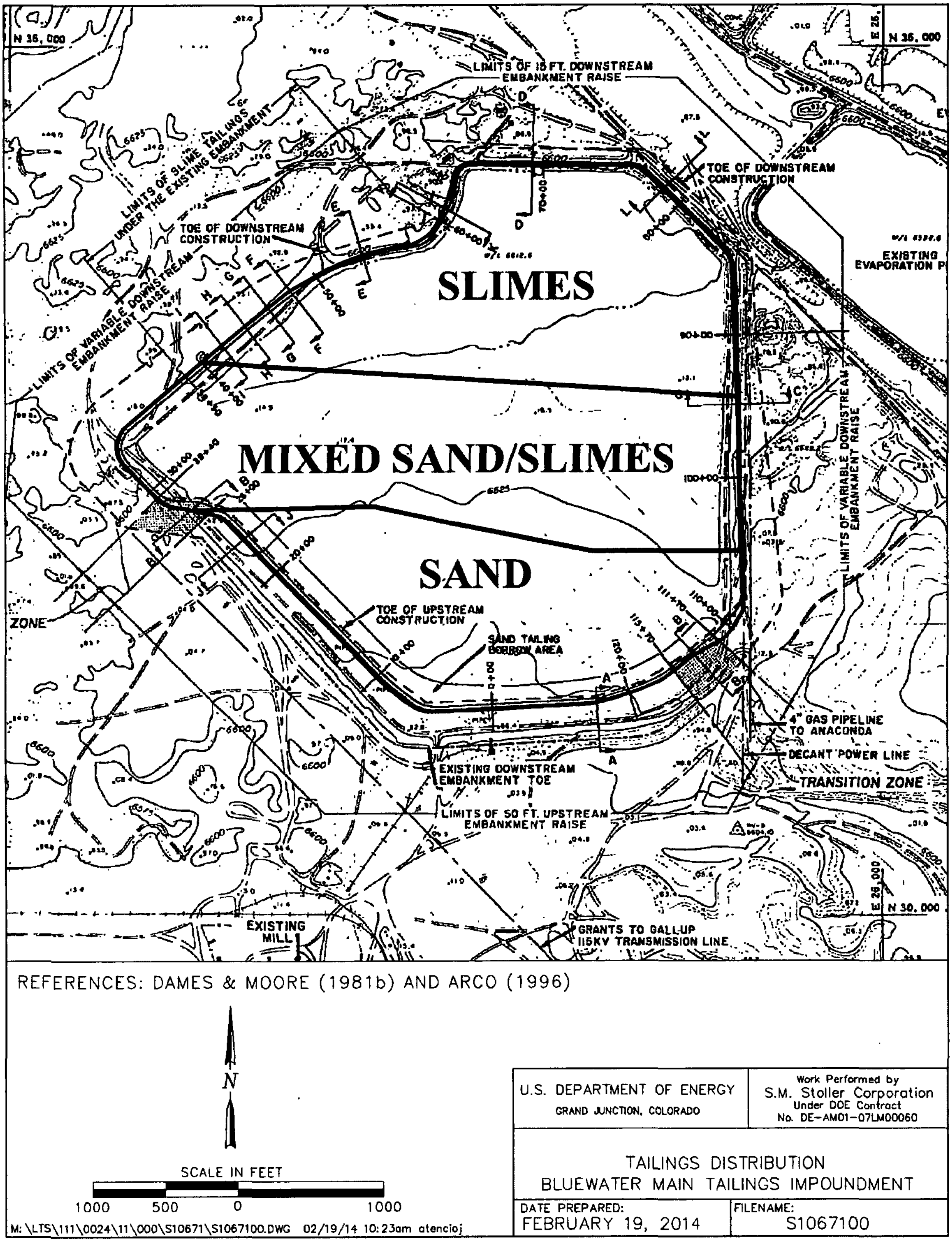

Figure 5. Approximate Distribution of Materials Within the Main Tailings Impoundment

The deposition of slimes toward the north, northwest, and northeast made it necessary to raise the dikes to increase the capacity of the impoundment. A series of crisscrossing, low dikes were pushed up from the tailings, and further deposition occurred in the segmented ponds. During this time, natural soil dikes were compacted on sand tailings at the southeast corner of the impoundment. The main tailings impoundment attained a configuration similar to that of the final impoundment (and disposal cell) except there was no western dike, where the slime tailings were settling directly against higher basalt outcrops.

A western dike was constructed in 1957 over tailings slimes to contain the tailings and effluent. Also at this time, rapid buildup of sand tailings was occurring along the south embankment, and additional dikes were constructed from sand tailings in this area.

In October 1977, tailings impoundment dikes were raised again on the east, west, and north sides to allow for additional ponding of tailings liquor due to a modification in operations. These dikes were constructed from compacted, natural clayey soil. Simultaneously, the sand tailings dikes on the south side were raised. Impoundment dikes continued to be raised to contain the tailings; by 1981, the elevation on the south side was 56 ft higher than the north side because of the buildup of sand tailings in that area.

3.4 Main Tailings Impoundment Seepage

ARCO recognized that substantial quantities of tailings fluids seeped through the bottom of the main tailings impoundment, through the underlying unsaturated materials, and into the alluvial and San Andres aquifers. Anaconda and ARCO hydrology subcontractors made various estimates of seepage losses through the bottom of the main tailings impoundment (Arlin et al. 1978, Dames & Moore 1984a, ARCO 1990, Applied Hydrology Associates Inc. 1995). All agreed that high seepage losses of at least 1,000 gallons per minute (gpm) occurred in the 1950s. To reduce the amount of seepage, Anaconda constructed a deep injection well in 1960.

The injection well, located more than a mile northeast of the tailings impoundment, was completed in the Yeso Formation that underlies the Glorieta Sandstone. Tailings fluid decanted from the pond that persisted at the north (lowest elevation) end of the main tailings impoundment was injected into the well from 1960 through 1977. The injection rate was regulated to ensure only gravity flow within the well (i.e., injection was not under pressure). Approximately 501 million gallons of decanted fluid had been injected by the end of 1965 (West 1972), which is an average rate of approximately 190 gpm. Assuming this rate continued, a total of approximately 1.7 billion gallons of decanted fluids were injected during the operation of the well. In their evaluation of the Bluewater injection process, the U.S. Geological Survey considered it to be the most satisfactory and economically feasible method of effluent disposal (West 1972).

After 1977, tailings fluids were evaporated in lined evaporation ponds constructed north of the impoundment. Use of the evaporation ponds removed approximately 525 million gallons of liquid that otherwise would have infiltrated into the tailings. During the years 1977 through 1982, much of the uranium in the decanted water was recovered by recycling the evaporation pond water through the mill (Applied Hydrology Associates Inc. 1995).

Ore-milling operations and tailings deposition ceased in March 1982. Subsequently, ARCO installed 58 extraction wells in the sand portion of the tailings impoundment. These wells removed approximately 122 million gallons of interstitial fluids from the tailings as part of a program to dewater the impoundment and recover uranium. The extracted fluids were treated at the mill, and most of the barren solution was pumped to the evaporation ponds. The remaining unreported amount of treated water was sprayed on the tailings for dust control during interim tailings impoundment stabilization activities. Pumping from these wells ceased in 1985 when water levels and well yields dropped to levels where pumping was no longer practical (Applied Hydrology Associates Inc. 1995).

Prior to placement of the radon barrier, ARCO installed vertical band drains to wick fluids out of the slimes. The purposes of this procedure were to reduce the quantity of tailings fluids available for seepage and to consolidate the slimes. Tailings were loaded with a consolidation layer of windblown silty and sandy clay materials (the same type of material used to construct the radon barrier) to squeeze fluid out of the slimes and into the drains.

The wicks drew approximately 24 million gallons of tailings fluids to the surface of the impoundment, where the fluids ponded and evaporated. ARCO calculated that up to 16 million gallons of fluids moved into unsaturated materials of the consolidation layer, thus removing a total of approximately 40 million gallons from potential seepage (Applied Hydrology Associates Inc. 1993). Approximately 7.4 million gallons of fluids were estimated to have been forced through the bottom of the impoundment during the consolidation process (derived from Appendix A Table A-1). Monitoring results from wells adjacent to the impoundment, however, did not show any increase in contaminant concentrations in either the alluvial or San Andres aquifers as a result of this activity. The band drains were removed when 90 percent consolidation of the slimes had been attained and flow from the band drains ceased. The final cover materials (radon barrier and rock) were installed at that time.

Estimated seepage rates from the tailings impoundment into underlying materials and aquifers were based on mill water-balance calculations, including fluid discharge to the tailings impoundment, decantation of the ponded fluids to the injection well and later to the evaporation ponds, cell dewatering activities, and tailings fluid reprocessing, and precipitation. However, ARCO did not account for evaporation of the tailings fluid and precipitation runoff that ponded at the north end of the impoundment prior to decantation activities. Evaporation of the ponded fluids following the start of decantation for deep-well injection (and later disposition in the evaporation ponds) was assumed to have been minimal (Dames & Moore 1981a). Figure 6 shows a schematic of the Bluewater mill impoundment water cycle.

Cumulative seepage rates from the main tailings impoundment, based on ARCO's last estimates (Applied Hydrology Associates Inc. 1995), are plotted in Figure 7. ARCO estimated that approximately 2.7 billion gallons of tailings fluid seeped from the main tailings impoundment by the time deep-well injection commenced in 1960. Thereafter, seepage continued at a reduced rate. By the time construction of the disposal cell and placement of the rock cover was completed in 1995, ARCO estimated that approximately 5.7 billion gallons of fluid had seeped through the bottom of the impoundment (Appendix A Table A-1). Although evaporation of tailings pond fluid would have removed some water from the cycle, ARCO's estimate of 5.7 billion gallons of seeped fluid through 1995 is considered to be the best available estimate and is used in this assessment.

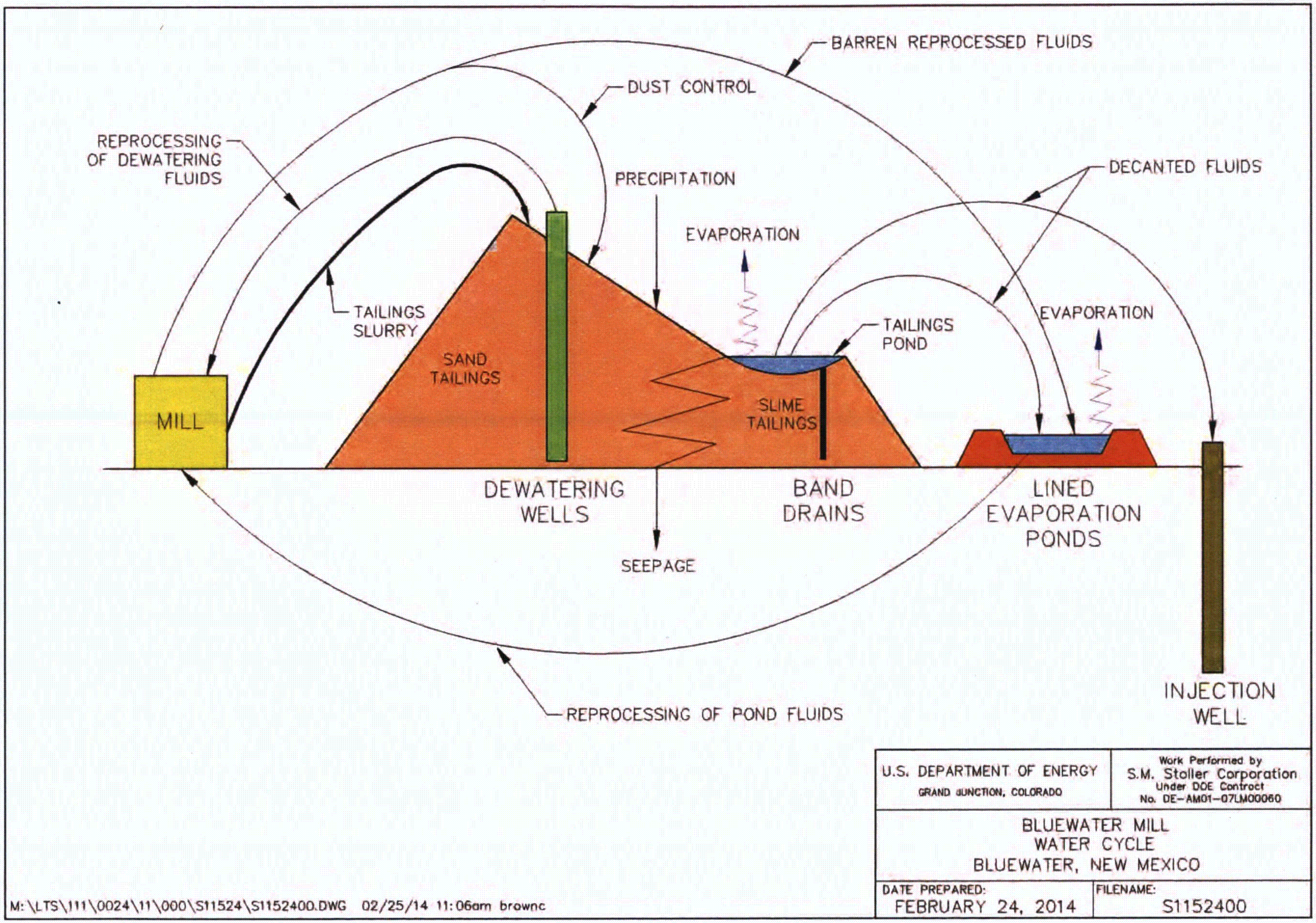

Figure 6. Schematic of the Tailings Impoundment Water Cycle

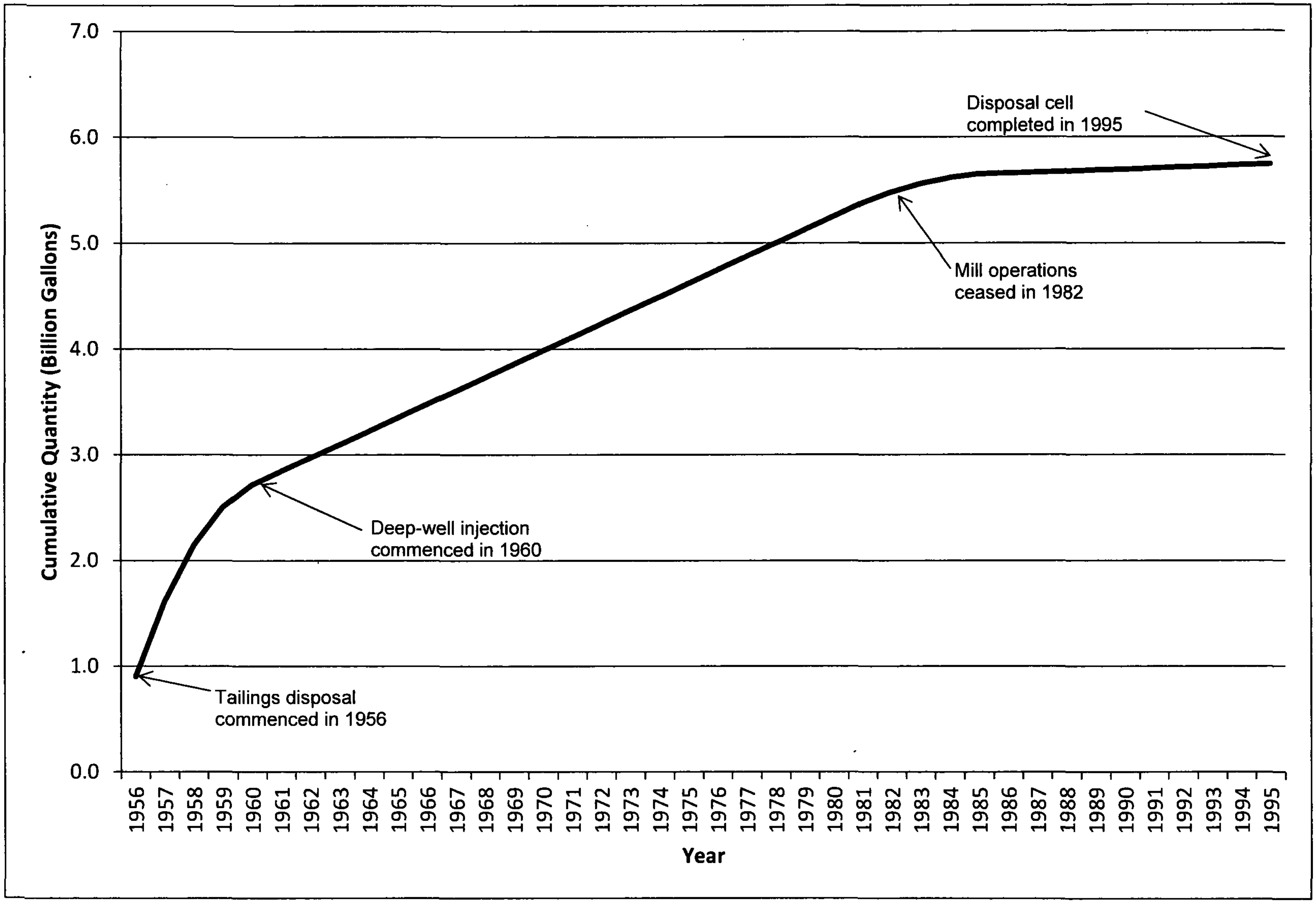

Figure 7. Estimated Cumulative Seepage from the Main Tailings Impoundment Through 1995

4.0 Disposal Cell Cover Characteristics

A liner was not installed prior to tailings placement, and the tailings were encapsulated in place. Therefore, tailings fluids remaining in the main tailings disposal cell, and additional fluids from infiltration of precipitation through the cover, could continue to seep through the bottom of the disposal cell.

A key component of understanding how much fluid could seep out of the disposal cell is evaluating how much precipitation is entering the cell. Therefore, an understanding of how the disposal cell cover was designed and constructed, and how it may change over time, is necessary to characterize the potential hydraulic performance of the cover.

4.1 Cell Cover Design and Construction

The main tailings disposal cell cover, completed in December 1995, was designed primarily to satisfy federal regulations and standards for radon attenuation and erosion protection as promulgated under UMTRCA of 1978. Federal regulations and NRC guidelines require groundwater protection but do not include standards or criteria for cover permeability or percolation. Nor was the potential for plant encroachment, root intrusion, or animal burrowing in the cover evaluated. The assumption, however, was that the engineered cover would prevent infiltration of precipitation into the encapsulated tailings, thus eventually eliminating the disposal cell as a continuing source of contamination (after seepage of residual fluids).

Designers used NRC guidelines and the NRC computer model, RAECOM, to calculate radon barrier thicknesses for different surfaces of the main tailings disposal cell to limit radon flux, as required, to less than the 20 picocuries per square meter per second (pCi/m^2s) standard. The radon barrier, consisting of sandy-clay material from the site, was constructed according to the following thicknesses: 1.0 to 2.2 ft over the slimes tailings, 1.7 to 2.6 ft over the mixed tailings, and 2.3 to 4.2 ft over the sand tailings (ARCO 1996). Prior to placement of the radon barrier, the tailings surface was graded and covered by up to 15 ft of compacted relocated materials derived from natural windblown deposits and evaporation pond dike materials from the site (primarily sandy-clay material similar to the radon barrier material). The greatest thicknesses of relocated materials were placed over the slimes portion of the tailings, most of which were placed for dewatering through the band drains. Some of these materials contained low levels of windblown radioactive contamination.

The radon barrier was compacted to 100 percent of maximum dry density based on Standard Proctor density (ASTM D698). In-place compaction was tested using nuclear gage and sand cone methods. As-built permeability values were not reported. However, a common construction assumption at the time was that laboratory permeability (saturated hydraulic conductivity [*Ks*]) results could be achieved in the field. Designers likely assumed, based on their laboratory results, that by compacting the radon barrier to 100 percent of Standard Proctor density they had achieved an as-built permeability in the range of 1×10^{-7} to 1×10^{-8} centimeters per second (cm/s).

NRC guidelines (NRC 1990) were used to calculate runoff discharge and velocity from the top and side slopes of the cell and the size of basalt rock necessary to control erosion of these slopes.

The NRC procedure is based on calculations of the probable maximum precipitation event and resulting probable maximum flood event.

Cover slopes were designed to shed runoff water primarily to the north. However, the north top slope was designed at a 0.5 percent slope, leaving little latitude for construction irregularities or settlement. The final constructed surface in this area had a 0.45 percent slope (ARCO 1996). The as-built surface topography and cross sections of the main tailings disposal cell are shown in Appendix B Figures B-1 through B-3.

The condition of vegetation along the north toe slope indicates that runoff is not shedding off the north edge of the cover as intended. If the disposal cell were shedding runoff to the north, more abundant plant growth would be present along the flat north toe slope where runoff water would accumulate. However, plant growth along the north toe slope appears to be no greater than in surrounding areas, and moist areas have not been observed in this area.

4.2 Depressions on the Disposal Cell Cover

Depressions have formed on the north end of the disposal cell cover, which is over the portion of the cell containing slimes. These depressions collect runoff water after storm events of sufficient magnitude or intensity (Figure 8). They were first observed by DOE inspectors during the first annual inspection in 1998. Satellite imagery taken in 1997 verifies that they had already started developing before DOE acquired the site. The depressions apparently formed as the slimes continued to consolidate after completion of the cover, which occurred soon after removal of the band drains (see Section 3.4).

Observations of differential settlement and ponding of water have raised concerns about the physical integrity of the disposal cell cover. Specifically, have the depressions degraded the performance of the radon barrier, or have they compromised the stability of the north end of the disposal cell? Field observations of the persistence of ponded water suggest that most of it dissipates by evaporation rather than percolation through the cover. The role of evaporation is addressed further in Section 5.3.2.

4.2.1 Cover Topography

In 2012, DOE conducted a high-resolution topographic survey of the main tailings disposal cell using a light detection and ranging (LiDAR) method to provide a baseline to determine if differential settlement in the depression area is ongoing. No standing water was present on the cover at the time of the survey. The digital LiDAR survey data were used to develop 6-inch contour intervals for the disposal cell surfaces (Figure 9) and to calculate the areas, depths, and volumes of the depressions. It is not known if settlement has stabilized. DOE plans to conduct periodic LiDAR surveys until the data verify that settlement has ceased.

Figure 8. Ponds in Depressions on the Main Tailings Disposal Cell in August 2012, Following a Summer Storm

Based on light-colored evaporite minerals that form as ponded water evaporates from the depressions and corresponding elevations determined by the LiDAR survey, the maximum ponded area has been approximately 15.3 acres. The maximum depth of ponded water has been 2.5 ft in the deepest depression, and the maximum quantity of ponded water has been approximately 4.3 million gallons (Figure 10). This maximum ponded area appears to have occurred during spring 2012 following melting of unusually high snowfall amounts during the previous December. No significant precipitation occurred during the spring, but standing water persisted until mid-June.

4.2.2 Cover Radon Flux

After consultation with NRC, DOE measured radon flux on the uncovered surface of the radon barrier over the area encompassing the depressions (Figure 11). The measurements were taken in early July 2013, after a dry spring and prior to the annual "monsoon" season; no ponded water was present on the cover. The cell cover materials were at their driest condition of the year, which would be when the highest radon emissions would be expected. Moisture attenuates radon, so radon emission would not occur through wet materials or standing water. Figure 12 shows a typical measurement location.

Radon was below the laboratory detection limit of 0.5 pCi/m^{2}s at all of the locations. These results suggest that the deformation of the cover in this area has not opened pathways (i.e., cracks or soil fissures through the radon barrier) for radon emission from the underlying tailings materials. The development of depressions on the cover, therefore, has not had an adverse effect on the performance of the radon barrier. These results may also imply that the permeability of the radon barrier has not been increased by development of the depressions and associated deformation of the surface.

4.2.3 Cover Stability

The depressions and ephemeral ponds that develop within them were evaluated as possible paths of erosion that could destabilize the north portion of the disposal cell. To date, no evidence of erosion has been observed, and the radon flux study confirmed the integrity of the radon barrier.

The cover and side slopes of the disposal cell were designed to shed runoff from the probable maximum precipitation event, primarily over the north side slope. If the depressions developed in a way that provides a preferential flow path for the ponded water, the riprap along the edge of the cover would still protect the cover from erosion. Also, as the depressions fill with water and a large pond develops, the ponded water would greatly dissipate the energy of the runoff from the south portion of the cover, resulting in a lower runoff velocity over the north edge of the cover. Therefore, although the cell cover was designed to shed runoff water, the presence of the depressions and ponds are not expected to compromise the stability of the disposal cell.

4.3 Cell Cover Evolution

Research has shown that surface layers of rock on covers create a favorable habitat for deep-rooted plants in all climates, even in the desert. Depending on climatic conditions and cover design, the rock layer may act as a mulch, effectively reducing soil evaporation (increasing soil water storage) and trapping windblown dust, thereby providing the water and nutrients needed for the germination and establishment of vegetation. Vegetation is establishing on the main tailings cell cover and consists primarily of annual weeds, but populations of perennial grasses, forbs, and deep-rooted woody plants are also establishing. An understanding of the ecology of these plant species provides clues about past and possible future changes in the condition of the disposal cell cover.

Currently, deep-rooted Siberian elm saplings and robust fourwing saltbush shrubs grow on the cell cover, primarily on the south two-thirds of the cover (DOE controls the elm saplings with herbicide to avoid the establishment of mature trees). Their presence suggests that the underlying relocated materials and tailings are moist, particularly in that area. The sparsity of deep-rooted plants on the north portion of the cover may be because the thick layer of compacted relocated materials over the slimes is inhibiting root penetration.

The long-term consequences of changes in the ecology of covers, including the encroachment and establishment of populations of deep-rooted plant species, can be either detrimental or beneficial depending on the cover design and management practices (Link et al. 1994). A key issue is whether deep-rooted plants that establish on the cover will increase or decrease the likelihood of precipitation percolation through the cover and into the tailings. Detrimental effects are related to root growth through covers and into tailings; plants can increase percolation flux

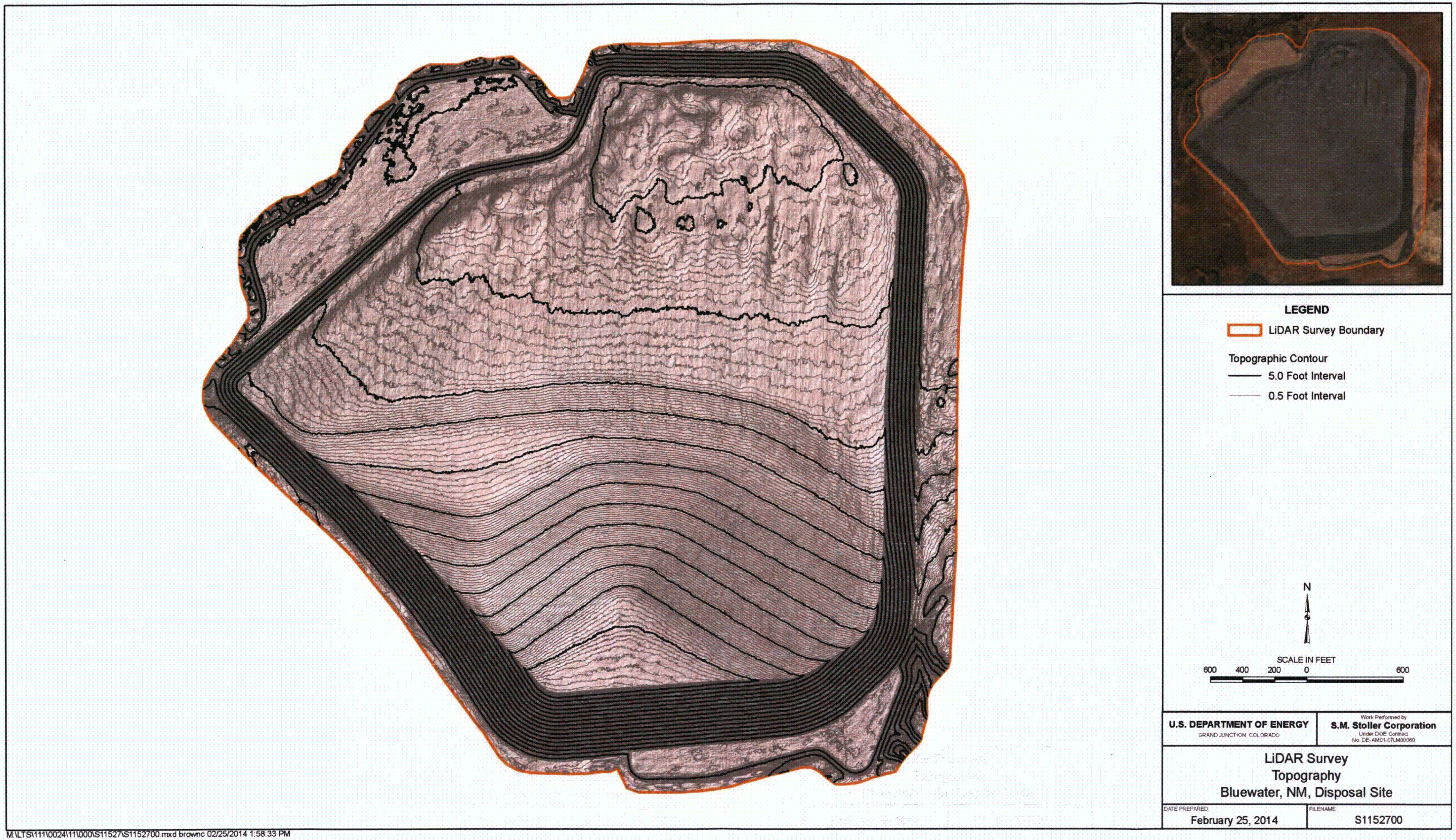

Figure 9. Topographic Map of the Main Tailings Disposal Cell (July 2012 LiDAR Survey Data)

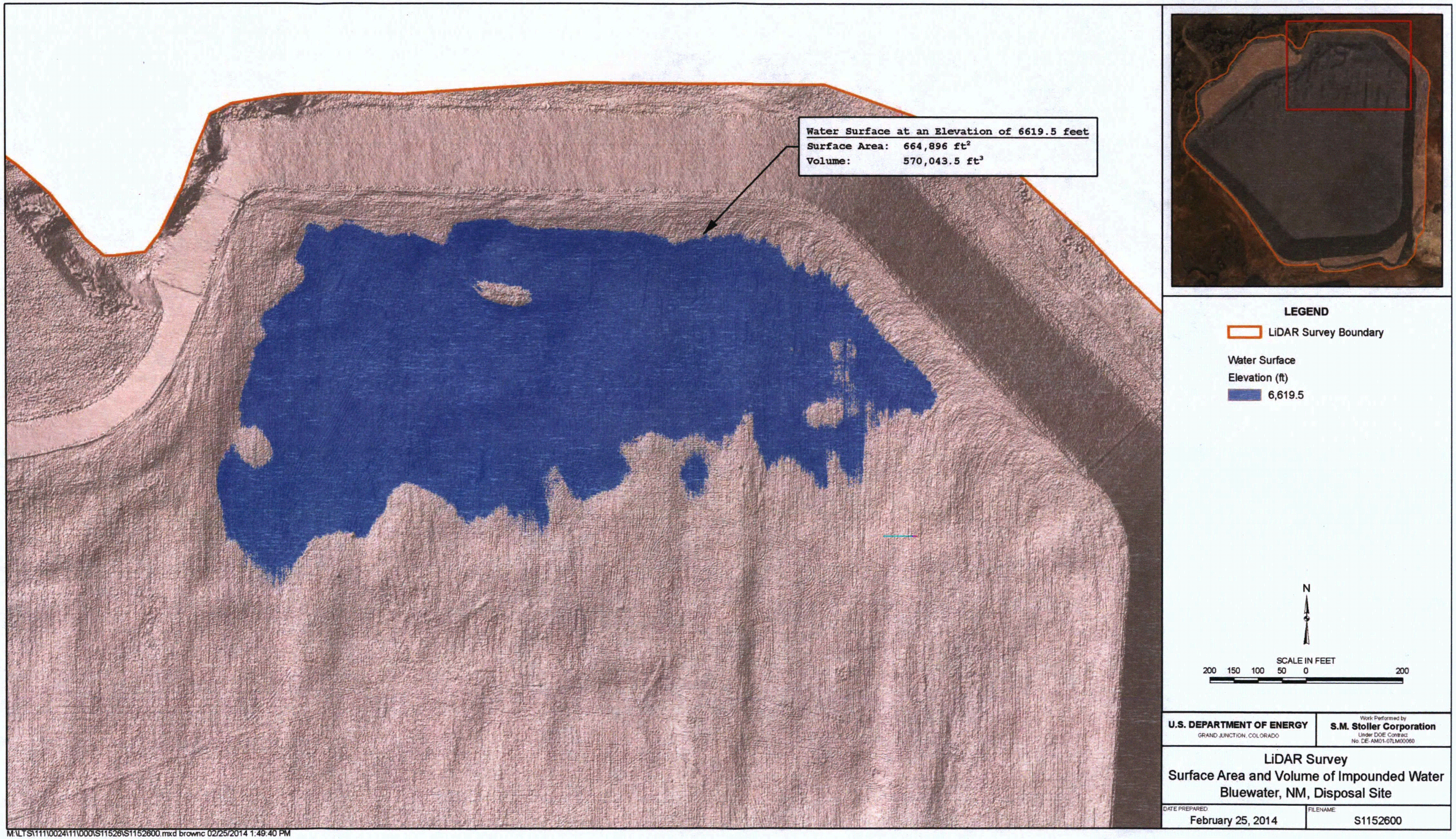

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Figure 10. Projected Maximum Area to Date of Ponded Water on the Main Tailings Disposal Cell (July 2012 LiDAR Survey Data)

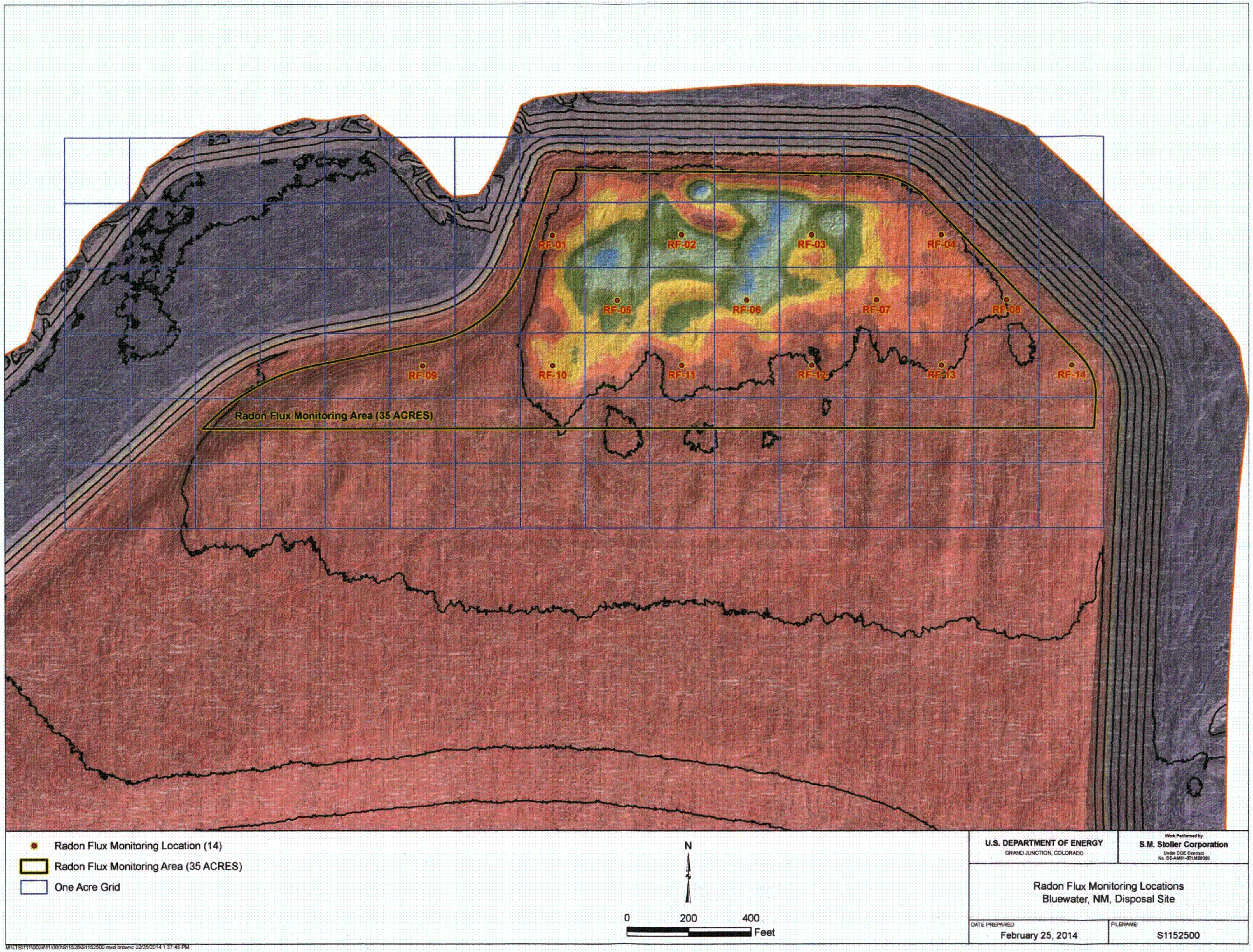

Figure 11. Radon Flux Measurement Locations in the Area of Depressions (July 2013)

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Figure 12. Radon Measurement Location RF-05 in the Area of Cell Cover Depressions

by accelerating soil development, which increases permeability by creating fissures or planes of weakness in the soil structure. Beneficial effects are related to the extraction of soil water by plants (transpiration) and erosion protection; consequently, plant encroachment could actually enhance the performance of the cover. Transpiration can greatly limit percolation if habitat characteristics favor the establishment and resilience of a diverse plant community. A combination of high transpiration rates and erosion protection can be achieved.

Natural soil-forming processes are inevitable and will create fissures in radon barriers, increasing permeability and loosening soil compaction—even in the absence of vegetation. Natural soil-forming processes have likely increased the permeability of the radon barrier by one to several orders of magnitude. Therefore, percolation flux is likely to increase with or without vegetation on the cover.

Ecological succession and soil development processes alter engineered soil covers over relatively short time periods regardless of climate, cover design, or service life. Studies of disposal cell and landfill covers across the country have shown that compacted soil layers (similar to the main tailings radon barrier) often fall short of low-permeability targets, often during or shortly after construction, and sometimes by several orders of magnitude (NRC 2011). For example, if compaction of the radon barrier achieved a permeability of 1×10^{-7} cm/s as designed, the current permeability may be closer to 1×10^{-5} cm/s.

4.4 Cover Hydraulic Performance

The Reclamation Plan (ARCO 1990) did not reference soil physical or hydraulic property criteria for the cover. Apparently there were no criteria for the permeability of the cover or for percolation flux through the cover. However, it did provide results of grain-size analyses and *Ks* tests for samples of materials specified for use in constructing the radon barrier. Test materials were low-plasticity clay and sandy clay. Geometric means of permeability tests were 1.7×10^{-8} cm/s for the clay and 2.4×10^{-7} cm/s for sandy clay, with all samples compacted to the specified 100 percent of Standard Proctor dry density. Although the as-built permeability of the radon barrier was not measured directly, it was likely assumed that the as-built *Ks* was between 1×10^{-7} and 1×10^{-8} cm/s, as noted in Section 4.1.

It would seem likely that percolation into tailings is potentially greatest where water ponds in depressions. However, as noted previously, evaporation appears to be the dominant factor in reducing the pond volumes (rather than percolation through the cover). ARCO also believed evaporation to be the dominant factor, as this was the method used to eliminate ponded fluids during the wicking procedure (Applied Hydrology Associates Inc. 1993). Even if the permeability of the radon barrier is increasing as expected, the permeability of the underlying thick layer of relocated material likely remains close to the presumed original rate of 1×10^{-7} cm/s—those materials would not be impacted by the environmental forces affecting the surface materials.

At the Burrell, Pennsylvania, UMTRCA Title I disposal cell, the mean *Ks* was 3.0×10^{-5} cm/s where Japanese knotweed roots penetrated the radon barrier, compared to 2.9×10^{-7} cm/s at locations with no plants (Waugh et al. 1999). The weighted average *Ks* for the entire cover, calculated using the community leaf area index for Japanese knotweed and the methods of Wells and Norman (1991), was 4.4×10^{-6} cm/s. At the Lakeview, Oregon, Title I Disposal Site, the mean *Ks* for the radon barrier on the cell cover, both with and without sagebrush and bitterbrush roots, was 3.0×10^{-5} cm/s (Waugh et al. 2007). The highest *Ks* values occurred near the top of the radon barrier; the lowest values occurred deeper in the radon barrier. At the Shiprock, New Mexico, Disposal Site, the mean *Ks* in the cell cover radon barrier was 4.4×10^{-5} cm/s (Glenn and Waugh 2001). Results were highly variable and lower where tamarisk and Russian thistle were rooted in the radon barrier. The Shiprock cell radon barrier was nearly saturated at the four locations where measurements were taken. At the Tuba City, Arizona, Title I Disposal Site cell, which is sparsely vegetated, the mean *Ks* of the radon barrier was 8.7×10^{-6} cm/s, and values ranged from a low of 9.8×10^{-9} to a high of 1.18×10^{-4} cm/s.

The radon barrier permeability measurements at the referenced UMTRCA Title I sites suggest that the permeability of the radon barrier at the Bluewater site may be on the order of 1×10^{-5} cm/s. However, because of the area of the cover and expected variability of hydraulic performance of the radon barrier (due to variable thicknesses of the barrier and non-uniformity of plant growth), extensive field permeability tests would be required to determine the actual permeability of the radon barrier of the main tailings disposal cell. Because the performance criterion for radon emission is being met, and because permeability is only one factor affecting the amount of precipitation that percolates through the cover, permeability tests are not considered to be necessary at this time.

5.0 Disposal Cell Seepage

5.1 Conditions for Seepage

ARCO assumed that seepage of fluids remaining within the tailings would continue to occur after closure of the cell but did not predict the rate or quantity of seepage (ARCO 1990). The cover design was intended to control emanation of radon from the encapsulated tailings and shed precipitation runoff without causing erosion of the cover; percolation of precipitation through the cover and into the cell was not a factor in the design requirements.

Seepage from the disposal cell is controlled by a difference in total hydraulic head. Seepage flow occurs from a higher total hydraulic head to a lower total hydraulic head. Total hydraulic head is the sum of hydraulic pressure head and elevation head above a reference datum. Because the elevation of the tailings is greater than the elevation beneath the disposal cell, the total hydraulic head within the final disposal cell is greater than the total hydraulic head underlying the disposal cell. Therefore, fluid seepage from the tailings into the underlying foundation material is expected to persist in both saturated and unsaturated conditions.

The degree of saturation within the disposal cell is a key component in evaluating unsaturated seepage. Actual saturation within the disposal cell is unknown. Cell material saturation was not measured or estimated by ARCO and has not been measured since DOE acquired the site. However, for the purposes of this assessment and based on studies conducted on the Shiprock disposal cell (DOE 2012), it is assumed that the sand tailings are moist but unsaturated. Although ARCO attempted to dewater the sand tailings, pumping likely did not completely drain the tailings, and precipitation would have recharged the tailings to some degree after pumping ceased in 1985.

As found in the Shiprock cell, the slimes in the main tailings disposal cell are assumed to be saturated. Although ARCO's efforts to consolidate the slimes removed a substantial quantity of tailings fluid, clay minerals tend to hold liquid. The overlying silty-clay materials placed to consolidate the slimes are assumed to be unsaturated. However, due to natural soil-forming processes and the heterogeneity of these materials, they could eventually become saturated, allowing precipitation to percolate into the slimes.

5.2 Seepage Rate

The rate of seepage, or tailings fluid flow through the tailings into underlying foundation material, is governed by the hydraulic conductivity of each material within the disposal cell. The main tailings disposal cell can be described as a layer-cake type of arrangement with the cover materials (i.e., the radon barrier and underlying soil placed to attain the final construction grade), which overlie the tailings mass (sands and slimes), which in turn overlie foundation materials (alluvium, basalt, and limestone). Under saturated conditions, when the largest volume of tailings fluid flow would occur, hydraulic conductivity of the overall system is controlled by the lowest hydraulic conductivity of the materials in the layer-cake arrangement.

Table 1 provides estimates for saturated hydraulic conductivities (*Ks*) of materials existing in and under the disposal cell that are used in this analysis. Assuming that tailings fluid seepage is controlled by natural flow, values provided in Table 1 indicate that moisture will percolate through the cover, flow at a slower rate through the tailings, and eventually discharge into the underlying foundation materials (which have the highest *Ks*).

Because of the presence of sand in the slimes-sand portion of the disposal cell, that portion is conservatively assumed to have the same hydraulic conductivity as the sand portion. Therefore, the sand and slimes-sand portions are hereafter included together as "coarse tailings." The slimes portion of the cell is considered to be "fine tailings."

Table 1. Estimated Saturated Hydraulic Conductivities for the Bluewater Disposal Cell

Layer	Vertical *Ks* (cm/s)
Cover	$10^{-5} - 10^{-4}$ [a]
Tailings: Sand[b]	$10^{-6} - 10^{-5}$
Slimes-Sand[b]	$10^{-6} - 10^{-5}$ [c]
Slimes[b]	$10^{-7} - 10^{-6}$
Foundation Materials: Alluvium	$10^{-4} - 10^{-3}$
Basalt	$10^{-2} - 10^{-1}$

Key: cm/s = centimeters per second; *Ks* = saturated hydraulic conductivity
[a] Long-term value after soil development effects have occurred (NRC 2011)
[b] Licensing Documentation, Volume 22, Page 7 (Dames & Moore 1984b)
[c] Conservatively assumed to be controlled by interbedded sand layers

5.3 Seepage Quantity

5.3.1 Water-Balance Equation

For this assessment, the following basic water-balance equation is used to estimate seepage amount after construction of the cover in 1995.

$$I - O = \Delta S, \quad \text{where: } I = \text{inflow}, \; O = \text{outflow}, \; \Delta S = \text{change in storage}$$

5.3.2 Inflow

Inflow quantity to the disposal cell is governed by site-specific climatic parameters, which are unavailable. However, average monthly precipitation quantities are available for the Grants, New Mexico, airport, and average monthly evaporation quantities are available for the region (Table 2). Due to its proximity, it is assumed that these quantities are representative of precipitation and evaporation at the Bluewater site. From the values in Table 2, the Bluewater disposal cell cover receives an annual average of approximately 10.3 inches of precipitation, with an average free-surface evaporation of 45.9 inches per year.

As presented in Table 2, yearly free-surface evaporation rates are about 4.5 times greater than yearly precipitation. Evaporation exceeds precipitation in 9 months of the year. During the wettest months of July through September, evaporation rates range from 3.3 to 4.6 times greater than monthly precipitation. Not all precipitation evaporates, however; the water cycle includes infiltration into the ground (some of which recharges aquifers), uptake by vegetation, and diversion into surface water systems. Also, evaporation is an ongoing phenomenon averaged over time, whereas about half of the annual precipitation at the site occurs from July through September as high-intensity, short-duration convective storms. During such storm events, the rate of precipitation far exceeds the rate of evaporation. Regardless, evaporation in the region and at the site is a significant factor in reducing precipitated moisture.

Table 2. Precipitation and Evaporation in the Region of the Bluewater Site

Parameter	Location	Month[a]												Total
		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	
Precipitation	Grants, NM[b]	0.50	0.43	0.52	0.45	0.51	0.56	1.72	2.01	1.29	1.09	0.55	0.67	**10.3**
Class A Pan Evaporation	Farmington, NM	0.00	0.00	0.00	7.97	10.06	12.00	12.52	10.70	8.15	5.41	0.00	0.00	66.8
	Gallup, NM	0.00	0.00	0.00	6.61	9.31	12.12	10.50	8.70	7.95	5.07	2.20	0.00	62.5
	Laguna, NM	0.00	0.00	0.00	8.47	9.33	11.98	10.76	8.88	6.83	5.00	1.98	0.00	63.2
	Mt. Taylor, NM	0.00	0.00	3.83	8.09	9.07	12.08	9.70	8.80	6.36	4.65	0.00	0.00	62.6
	Average	0.00	0.00	0.96	7.79	9.44	12.05	10.87	9.27	7.32	5.03	1.05	0.00	63.8
Free-Surface Evaporation[c]	Region	0.00	0.00	0.69	5.61	6.80	8.67	7.83	6.67	5.27	3.62	0.75	0.00	**45.9**

[a] Values in inches
[b] Grants airport meteorological data averaged for the period 1953–2012
[c] Average pan evaporation multiplied by an average pan-to-lake coefficient of 0.72

Runoff on the disposal cell cover occurs only during rainfall events of sufficient magnitude and intensity, and after melting of significant snow accumulations. However, there is no evidence that runoff has spilled over the edge of the cell cover. Instead, cell cover runoff accumulates as ponds in depressions that have formed over the slimes area on the north portion of the cover. These ponds persist for long periods of time that correlate to the quantity of accumulated water, indicating that percolation through the cover is minimal at this location. Evaporation, therefore, is the primary cause for loss of ponded water in the depressions.

Shallow- and deep-rooted vegetation is establishing on the disposal cell cover as noted in Section 4.3. It can be assumed, therefore, that some percentage of precipitation percolates through the cover; apparently more over the sand tailings area than the slimes area because that is where deep-rooted vegetation occurs. The vegetation also indicates that evapotranspiration is occurring.

There are no site-specific data to estimate the actual amount of precipitation that percolates through the cover and into the tailings. Studies performed on other covers are not directly applicable to the Bluewater site because of differences in designs, cover materials, and climate. However, percolation rates that have been measured at other capped landfills have ranged up to 18 percent in studies by Albright et al. (2004) and up to 42 percent by Abichou el al. (1998). Rock covers such as on the Bluewater cell may act as mulch and retain moisture, which would tend to decrease evaporation and increase percolation. However, vegetation, which is gradually establishing on the Bluewater cell cover, has been shown to significantly decrease percolation of precipitation (Benson et al. 2011, Waugh et al. 2009). For the purposes of this assessment to estimate a range of potential seepage from the disposal cell after construction, tailings storage and outflow are calculated based on inflow quantities of 50 percent and 25 percent of precipitation.

5.3.3 Change in Storage

Moisture in the tailings is stored in voids within the tailings mass. A saturated volumetric moisture content is defined as the condition in which all void space is occupied by moisture, and 50 percent saturation is when half the void space is occupied by moisture. Porosity is defined as the ratio of void space to the total volume of mass. Therefore, when soil is fully saturated, the volume of moisture is equal to the porosity of the soil mass.

As tailings voids drain from a saturated condition to a lower degree of saturation, negative pore pressures develop within the tailings materials. The relationship between the volumetric moisture content and negative pore pressures is provided on soil moisture characteristic curves. There are no data for moisture-holding properties of the Bluewater tailings, nor detailed gradation data for the tailings. Therefore, tailings characteristics from the Shiprock disposal cell were used to represent Bluewater cell tailings characteristics. Although mined from different geographic locations, the uranium ore processed at both sites was derived from sandstone in the Saltwash Member of the Jurassic Morrison Formation (Merritt 1971).

Estimated soil moisture characteristic curves (negative pressure head [cm] versus volumetric moisture content [θ]) for coarse-grained tailings (sands and slime-sands) and fine-grained tailings (slimes) are presented in Appendix C Figures C-1 and C-2. These curves are derived from hydraulic parameters developed for the Shiprock cell drainage analysis (DOE 2012), which are provided in Table 3. The *Ks* values for the Shiprock cell are consistent with the estimated *Ks* values for the Bluewater cell (Table 1).

Table 3. Unsaturated Tailings Hydraulic Parameters Based on Shiprock, New Mexico, Disposal Cell Data

Material	θ_r	θ_s	α (1/cm)	n	*Ks* (cm/s)
Coarse tailings	0.127	0.470	0.00035	3.923	5.0×10^{-5}
Fine tailings	0.223	0.640	0.00085	3.857	3.1×10^{-6}

Key: α = curve-fitting parameter; n = curve-fitting parameter; *Ks* = saturated hydraulic conductivity;
θ_r = residual volumetric moisture content; θ_s = saturated volumetric moisture content

Appendix C Figures C-3 and C-4 show volumetric moisture content versus log hydraulic conductivity that can be used to relate a moisture content to an unsaturated hydraulic conductivity, or influx value. For example, if the cover functions at a 5×10^{-5} cm/s seepage rate, underlying tailings will also function at a 5×10^{-5} cm/s conductivity.

Table 4 presents volumetric moisture contents related to influx for the range of expected operating values as derived from the figures. The moisture contents are theoretical volumetric contents that can be realized after infinite time for free drainage from the base. The low 1×10^{-7} cm/s influx is provided as the design operating value for radon barrier covers and is used for this assessment. As discussed in NUREG/CR-7028 (NRC 2011), initially low *Ks* values in constructed radon barriers have been shown to increase a few orders of magnitude after being subjected to various climatic forces such as wet-dry cycles, freeze-thaw episodes, and root penetration from plants. Therefore, the maximum cover influx rate is assumed to be 5×10^{-5} cm/s for this assessment.

Table 4. Long-Term Volumetric Moisture Contents at Estimated Influx Rates

Influx Rate	θ (Coarse Tailings)	θ (Fine Tailings)
1×10^{-7} cm/s	0.185	0.385
5×10^{-5} cm/s	0.290	0.640

Key: cm/s = centimeters per second; θ = volumetric moisture content

The volume available to store moisture that will drain from the tailings given an infinite amount of time can be estimated using the information provided in Table 3 and Table 4. The available change in storage value is computed as the difference in porosity (saturated volumetric content from Table 3) and the long-term volumetric moisture content equivalent to the seepage flux (from Table 4). The resulting storage volumes listed in Table 5 represent the theoretical volumetric moisture content in the tailings after infinite time for drainage, assuming free drainage at the base and a consistent upper boundary pressure condition at the surface.

Table 5. Estimated Storage Volumetric Moisture Content

Material	θ_s [a]	ΔS Available [b]	
		1×10^{-7} cm/s influx	5×10^{-5} cm/s influx
Coarse tailings	0.470	0.285	0.180
Fine tailings	0.640	0.255	0.000

Key: cm/s = centimeters per second; θ_s = saturated volumetric moisture content;
ΔS = change in storage
[a] From Table 3
[b] Equals θ_s minus θ from Table 4

According to Table 5, when the cover is operating at 5×10^{-5} cm/s influx, the resulting volumetric moisture content of fine tailings (slimes) equals the saturated volumetric moisture content. In other words, when the cover allows an influx of 5×10^{-5} cm/s, which is equivalent to the saturated hydraulic conductivity of the slimes, the moisture flux that enters the disposal cell will displace existing moisture in the saturated slimes. Therefore, there is no change in storage, and moisture will flow through the slimes at the influx rate.

Based on the estimated annual rainfall of 10.3 inches (26.16 cm) presented in Table 2, inflow would be 13.08 cm if 50 percent of precipitation infiltrated the cover and 6.54 cm if 25 percent infiltrated. The depth of tailings required to store infiltration without outflow is computed by dividing the infiltration amount by ΔS from Table 5. Results are presented Table 6.

Table 6. Required Tailings Depth Needed for Storage of Infiltration

Material	Infiltration Percentage	Infiltration (cm)	1×10^{-7} cm/s Influx		5×10^{-5} cm/s Influx	
			ΔS Available	Depth (cm)	ΔS Available	Depth (cm)
Coarse tailings	50	13.08	0.285	45.89	0.180	72.67
	25	6.54	0.285	22.95	0.180	36.33
Fine tailings	50	13.08	0.255	51.29	0.000	no storage
	25	6.54	0.255	25.65	0.000	no storage

Key: cm = centimeters; cm/s = centimeters per second; ΔS = change in storage

The course tailings (sands and slime-sands) have an average depth of 45 ft (1,372 cm) in the disposal cell. The fine tailings (slimes) have an average depth of 20 ft (610 cm). Therefore, the available storage is greater than the volume of voids that would be filled by precipitation infiltrating the cover. An exception occurs for the fine tailings at an influx rate of 5×10^{-5} cm/s, when no available storage exists in the saturated slimes. Under this condition, outflow equals inflow regardless of the depth of tailings. This creates a steady-state influx/outflow condition when influx equals the saturated hydraulic conductivity of the tailings.

5.3.4 Outflow

When moisture infiltration exceeds available storage, outflow will begin. The rate of discharge will asymptotically approach the cover infiltration rate. Estimates of the volume of moisture that can potentially seep through the base of the disposal cell can be calculated using the storage estimates from the previous section and assumptions taken from the impoundment geometry provided in Figure 5. The approximate areas of the two types of materials covering the bottom of the disposal cell are provided in Table 7.

Table 7. Footprint of Tailings Materials

Material	Percentage of 260-Acre Footprint	Area (ft^2)
Coarse tailings	67	7,588,152
Fine tailings	33	3,737,448

Estimates of stored moisture volumes subject to eventual drainage from the disposal cell (since completion of the cell cover) can be derived from the estimated areas computed in Table 7 and the estimated required storage depths in Table 6. The estimated drainable volumes based on the assumed cover infiltration rates and assumed infiltration percentages of precipitation are provided in Table 8 and Table 9. The estimated drainable volumes, therefore, are a combination of infiltrated precipitation and the unsaturated storage already present in the tailings.

Table 8. Estimated Drainable Volume from the Disposal Cell (Low-Permeability Cover)

Material	Infiltration Percentage	1×10^{-7} cm/s Cover Influx				
		Storage Depth		Area[a]	Drainable Volume	
		(cm)[b]	(ft)	(ft^2)	(ft^3)[c]	(gallons)
Course tailings	50	45.89	1.50	7,588,152	11,382,228	84,342,310
	25	22.95	0.75	7,588,152	5,691,114	42,171,155
Fine tailings	50	51.29	1.68	3,737,448	6,278,912	46,526,738
	25	25.65	0.84	3,737,448	3,139,456	23,263,369

Key: cm = centimeter; cm/s = centimeter per second; ft = feet
[a] From Table 7
[b] From Table 6
[c] Storage depth times area

Assuming the average cover infiltration rate is 1×10^{-7} cm/s and 50 percent of precipitation percolates through the cover (Table 8), then approximately 131 million gallons of tailings fluid would be available for eventual drainage from the coarse and fine tailings storage depths within the disposal cell; more drainable volume would be available if the cover infiltration rate is 5×10^{-5} cm/s. Annual stored volume will decrease as saturation of the tailings increases.

Table 9. Estimated Drainable Volume from the Disposal Cell (High-Permeability Cover)

Material	Infiltration Percentage	5×10^{-5} cm/s Cover Influx				
		Storage Depth		Area[a]	Drainable Volume	
		(cm)[b]	(ft)	(ft^2)	(ft^3)[c]	(gallons)
Course tailings	50	72.67	2.38	7,588,152	18,059,802	133,823,132
	25	36.33	1.19	7,588,152	9,029,901	66,911,566
Fine tailings	50	NS	NS	3,737,448	NC[d]	NC[d]
	25	NS	NS	3,737,448	NC[d]	NC[d]

Key: cm = centimeter; cm/s = centimeter per second; ft = feet; NC = not calculated; NS = no storage
[a] From Table 7
[b] From Table 6
[c] Storage depth times area
[d] Drainage volume will be equal to the cover flux multiplied by the time since cover construction in 1995

Because the hydraulic head will be greater in the tailings than in underlying materials, either saturated or unsaturated drainage will occur. These estimated drainage values are applicable only if the tailings drained below the computed depths provided in Table 6 during and after placement of the final cover. All potential saturation depths are less that the average tailings depth. Since saturated drainage is not expected at this time, drainage will be in an unsaturated condition at very low rates and volumes.

If the tailings become saturated, drainage will occur at the influx rate if the saturated hydraulic conductivity of the tailings is greater than or equal to the influx rate. If the saturated hydraulic conductivity of the tailings is less than the influx rate, the tailings will store much of the moisture until full saturation occurs. Table 10 provides the potential annual seepage that could occur if the tailings become saturated and outflow equals inflow.

Table 10. Potential Annual Outflow if the Tailings Become Saturated

Material	Infiltration Percentage	Infiltration Rate[a]	Area[b]	Outflow Volume		Outflow Rate
		(ft/yr)	(ft^2)	(ft^3)	(gallons)	(gpm)
Coarse Tailings	50	0.430	7,588,152	3,262,906	24,178,134	46.0
	25	0.215	7,588,152	1,631,453	12,089,067	23.0
Fine Tailings	50	0.430	3,737,448	1,607,102	11,908,626	22.7
	25	0.215	3,737,448	803,551	5,954,313	11.3
Total	50	0.430			36,086,760	68.7
	25	0.215			18,043,380	34.3

Key: ft = foot or feet; gpm = gallons per minute; yr = year
[a] Derived from an average annual precipitation rate of 10.3 inches per year
[b] Cell cover area is approximately equal to the tailings footprint (Table 7)

Based on the results of Table 10, the extreme scenario suggests that approximately 36 million gallons of tailings fluid could seep from the disposal cell annually if the tailings become saturated and if 50 percent of precipitation percolates into the tailings. This annual volume equates to approximately 0.6 percent of the total fluids that seeped from the tailings impoundment prior to disposal cell completion. Until the tailings become saturated, the annual seepage rate would be less, and would gradually approach the saturated tailings seepage rate.

The estimated 36-million-gallon annual seepage rate is based on an assumed upper limit of precipitation percolation through the cover and into saturated tailings. As noted in Section 5.3.2, however, studies show that increasing vegetation on the cover reduces percolation of precipitation into the tailings because of evapotranspiration. As vegetation is allowed to establish (or is enhanced to accelerate establishment) on the Bluewater cell cover, the precipitation inflow could reduce to substantially less than 25 percent of annual precipitation. And, it is possible that the tailings would not become saturated and that seepage would remain minimal as unsaturated drainage.

The upper limit seepage rate is equivalent to a rate of approximately 69 gpm (Table 10). This rate is substantially greater than the 1995 seepage rate of approximately 16 gpm estimated by ARCO, prior to closure of the disposal cell (Appendix A Table A-1). If the encapsulated tailings are not saturated, then current actual seepage rates could be closer to ARCO's 1995 estimated rate, or possibly even lower.

Although water levels in both aquifers fluctuated, elevations in 1995, when the cell was closed, were similar to elevations in 1984, near the end of cell dewatering activities (pumping from the sand tailings). However, alluvial aquifer water levels in wells T(M) and X(M), downgradient of the disposal cell, have dropped approximately 13 ft since 1995 (Figure 13). Also, San Andres aquifer levels in wells OBS-3 and S(SG), located adjacent to and downgradient of the disposal cell, have dropped approximately 46 ft since 1995 (Figure 14). These significant drops in water levels can be attributed, at least in part, to a persistent regional drought. However, it seems likely that if seepage is occurring at a rate of 69 gpm, or even 34 gpm (based on a 25 percent precipitation infiltration rate), the declines in water levels would not have been nearly as great near the cell. The declining water levels, therefore, suggest that current seepage from the cell is having a minimal impact on the aquifers.

Continued elevated uranium concentrations in the San Andres POC wells suggest a continuing source of contamination, but the contribution from cell seepage is unknown; however, the greatest contribution is most likely from groundwater flow through the mineralized zone. Groundwater chemistry is being evaluated as part of the groundwater conceptual model to provide a better technical basis for whether there is evidence of continuing seepage.

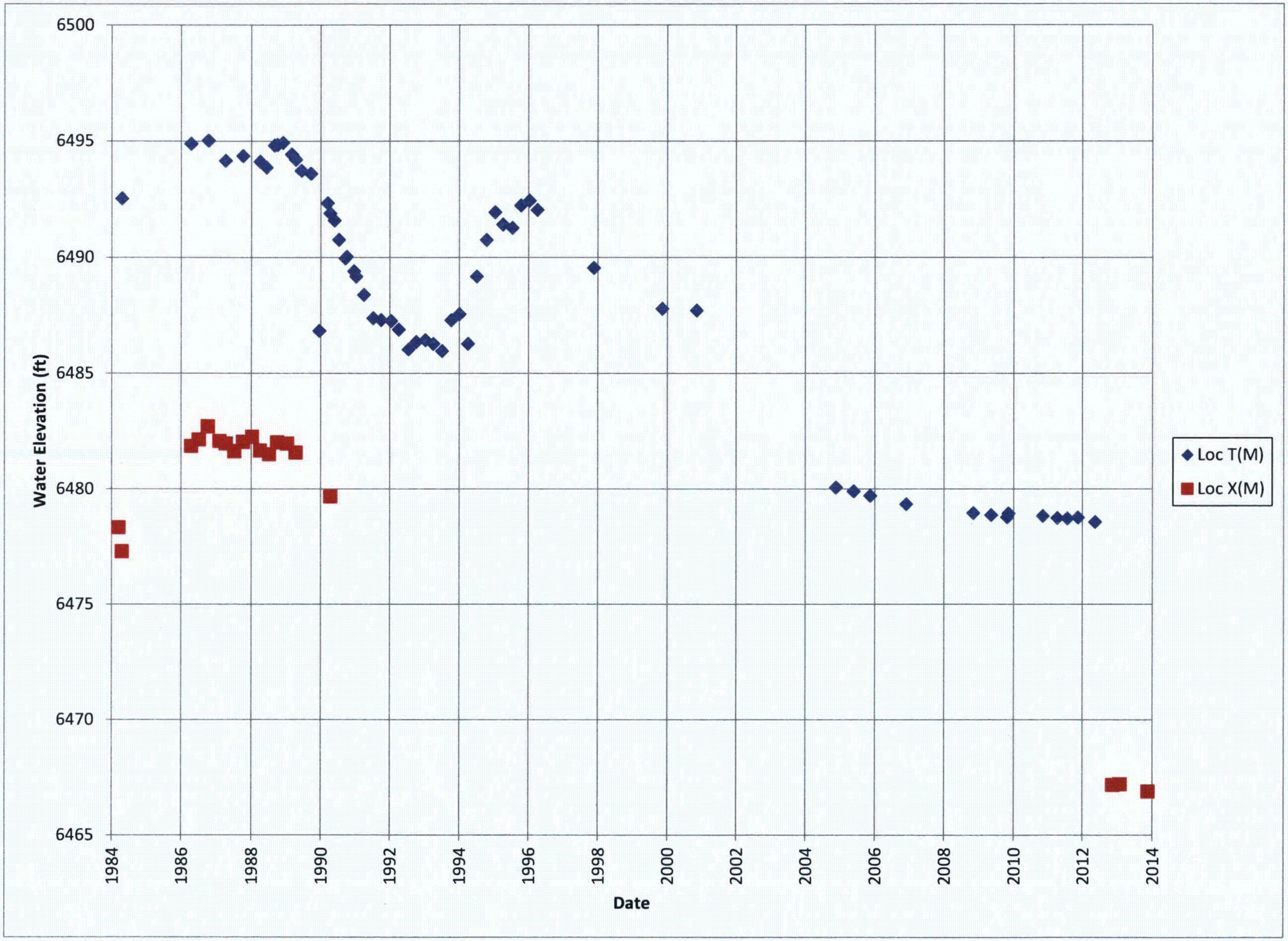

Figure 13. Hydrographs for Alluvial Aquifer Wells T(M) and X(M)

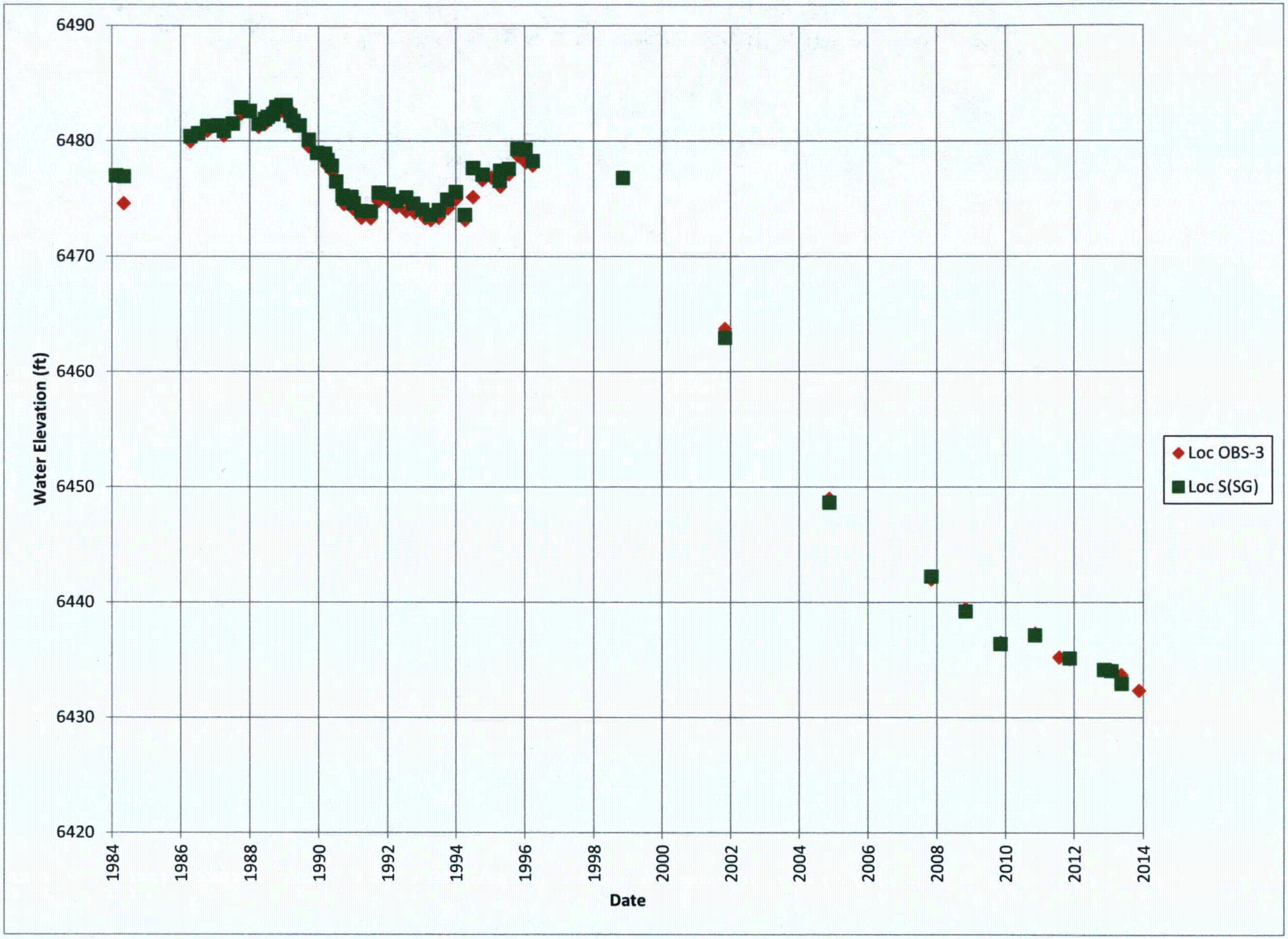

Figure 14. Hydrographs for San Andres Aquifer Wells OBS-3 and S(SG)