Pawnee Station North CCR Landfill

Notification of Completion of Assessment of Corrective Measures

Public Service Company of Colorado (PSCo), an Xcel Energy Company, is the owner of Pawnee Station which is a coal-fired, steam turbine electric generating station and is subject to requirements of the Disposal of Coal Combustion Residuals from Electrical Utilities Rule (Federal CCR Rule), finalized on April 17, 2015.

Protecting the environment is a priority for Xcel Energy

Xcel Energy conducts all of its business in an environmentally responsible manner and that includes regularly monitoring operations and taking steps to protect air, water and other natural resources. Pursuant to 257.95(g), Xcel Energy previously made a determination that one or more constituents listed in Appendix IV were detected at Statistically Significant Levels (SSLs) above the Groundwater Protection Standards (GPS) established for the site pursuant to 257.95(h). These results do not indicate there is any impact on local drinking water, and Xcel Energy will continue to monitor groundwater at the site in accordance with the assessment monitoring program as specified in 257.95.

Xcel Energy also previously initiated an Assessment of Corrective Measures to identify and evaluate potential corrective measures to address groundwater conditions. The assessment is complete and the results are presented in the attached document, *Conceptual Site Model and Assessment of Corrective Measures*. The assessment involved development of a site-specific groundwater model for use in predicting the transport of these constituents in groundwater and evaluating the effectiveness of various alternatives to curtail this transport and meet groundwater protection standards. The model was validated by comparing model results to observed site conditions, and it was determined that additional data should be collected to help more accurately evaluate corrective measure alternatives. Field work to obtain this additional data is underway. The data will be used to update the model after which a final corrective measure will be selected.

Conceptual Site Model and Assessment of Corrective Measures

for Compliance with the Coal Combustion Residuals (CCR) Rule

Pawnee Station

Public Service Company of Colorado

August 30, 2019

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Certification

Pawnee Landfill Assessment of Corrective Measures Report

I hereby certify to the best of my knowledge that this assessment of corrective measures for the Pawnee Station North Landfill is an accurate demonstration of the potential corrective measures under consideration for the landfill and is in compliance with 40 CFR Part 257 of the Federal Coal Combustion Residuals (CCR) Rule.

I am duly licensed Professional Engineer under the laws of the State of Colorado.

Matthew Rohr, PE
Colorado PE License 0053467
License renewal date October 31, 2019

1 Introduction

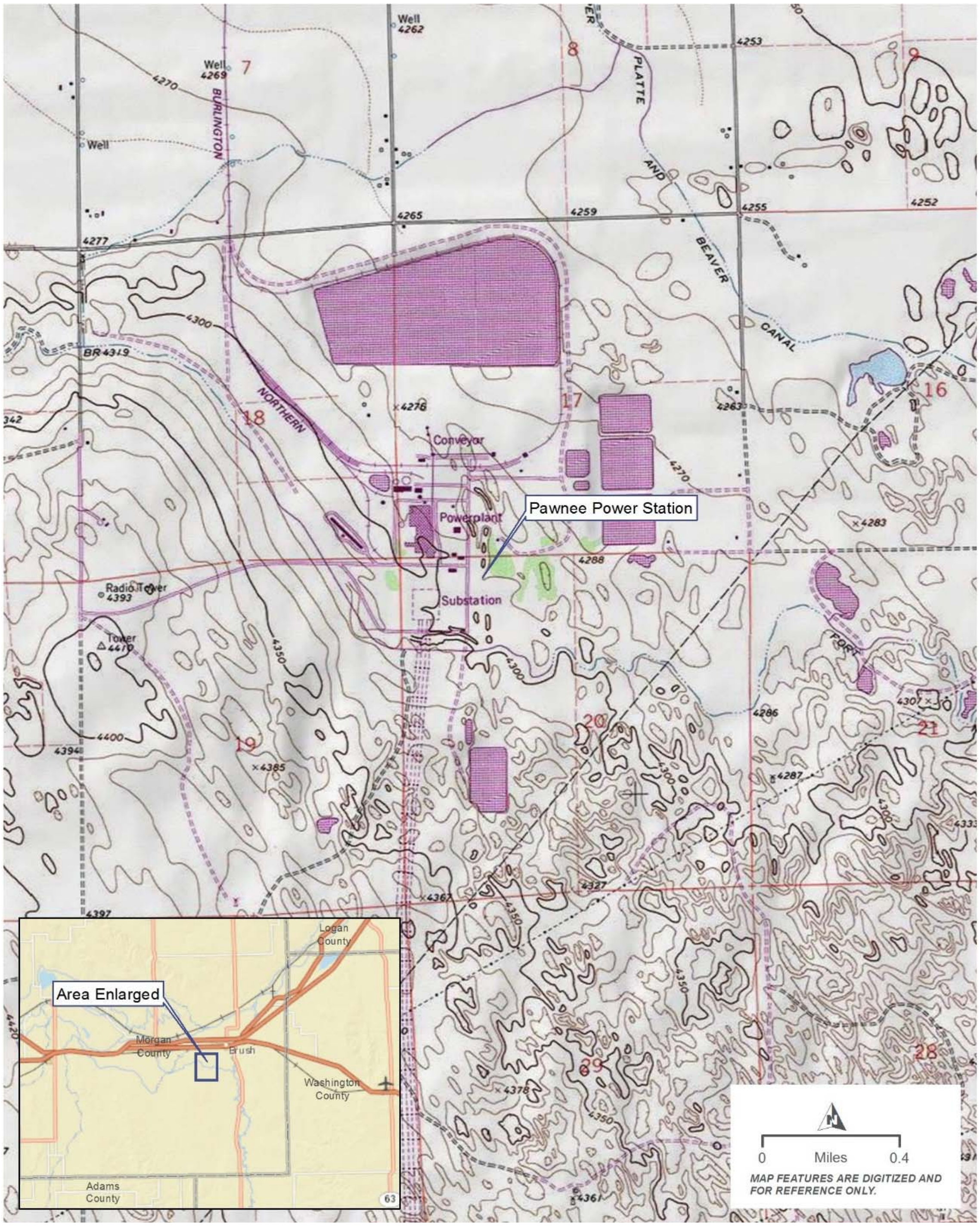
This assessment of corrective measures was performed for groundwater conditions at the Public Service Company of Colorado (PSCo) Pawnee Generating Station site in Brush, Colorado (Figure 1-1). The purpose of the assessment was to identify and evaluate potential groundwater corrective measures for the North Landfill, showing benefits and limitations associated with each alternative. The corrective measure alternatives were evaluated with the goal of reducing groundwater concentrations to levels below the groundwater protection standards (GPS) developed for the site. The GPS values for each constituent of interest are either the 1) federal Maximum Concentration Limits (MCLs), as established under 40 CFR §141.62 and 141.66; or 2) background concentrations developed in accordance with 40 CFR §257.91, whichever is greater.

In accordance with 40 CFR §257.96(c), this assessment of corrective measures includes a preliminary analysis of the feasibility of potential corrective measures in meeting all of the requirements and objectives of the remedy as described under § 257.97. Seven potential corrective measure alternatives were evaluated for the North Landfill.

In order to assess the potential effectiveness and time to complete the remedy of each corrective measure alternative for the landfill, HDR developed a numerical groundwater flow and transport model. The conceptual site model (CSM) is a narrative description of the hydrologic flow system that forms the basis of the numerical groundwater flow and transport model. This report describes the CSM for the Pawnee Station, the groundwater model objectives, model construction, additional data collected to fill recognized data gaps, and additional data that would be beneficial to collect moving forward.

The purpose of modeling is to predict the groundwater flow and constituent transport that will occur as a result of different corrective measure alternatives at the landfill. The study for the landfill consists of three main activities: development of a calibrated steady-state flow model to current conditions, development and calibration of a transport model for constituents identified as constituents of interest (COIs), and preliminary simulation of transport for multiple corrective measure scenarios. These steps were completed; however as described herein, transport model calibration identified additional data collection that would be beneficial before model simulations may be used to further analyze the alternatives and later select the appropriate remedies.

Figure 1-1. Pawnee Station Vicinity Map



2 Background

Pawnee Station has one CCR unit that is the subject of this assessment, the North Landfill (Figure 2.1-1). Adjacent to the North Landfill is the South Landfill, which is a non-CCR landfill operated under an Engineering Design and Operations Plan (EDOP) approved by the Colorado Department of Public Health and Environment (CDPHE). The two landfills are physically separated by a clay lined evaporation pond used to contain contact stormwater from the North Landfill. The Station previously had two inactive CCR impoundments, the former Bottom Ash Storage Pond (BASP) and former Ash Water Recovery Pond (AWRP). Both impoundments were physically closed in 2017 by removal of CCR, with ongoing groundwater monitoring under CCR Rule Part 257. A new lined CCR landfill, the East CCR Landfill was constructed in 2018 in the same footprint of the former BASP, but did not take receipt of CCR until July 2019 (Figure 2.1-1).

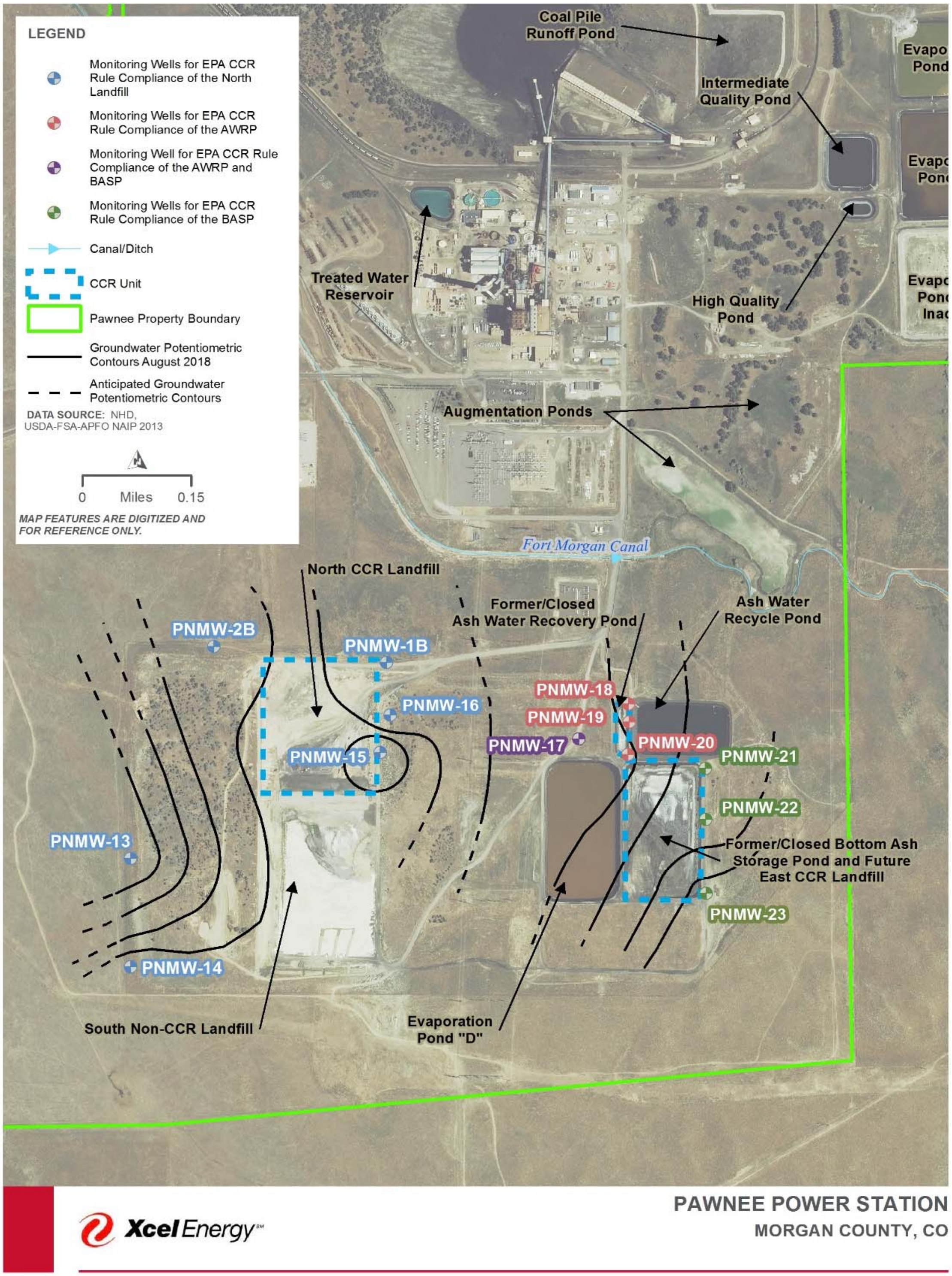
2.1 North Landfill

For the North Landfill, detection monitoring water quality data collected in 2017 were compared against the background threshold values (BTVs) as specified under CCR Rule Part 257.94, and SSIs were identified. Groundwater monitoring was subsequently conducted for assessment monitoring as specified under Part 257.95. In accordance with CCR Rule 257.95(h), GPS were established for each detected Appendix IV COI and documented in the January 2, 2019 memorandum *Groundwater Protection Standards and Determination of SSLs per 257.95(g)*. Two downgradient wells were found to have concentrations of lithium at statistically significant levels (SSLs) above the GPS. However, the lithium concentrations meet State agricultural water standard and there are no drinking water standards for lithium. PSCo will select, design, and implement a remedy for the landfill based upon the corrective measures assessment herein compliant with 257.96-97.

Operation of the Pawnee North Landfill commenced in 1981. The Pawnee Station North CCR Landfill is located approximately ½ mile south-southwest of the power plant. The North CCR Landfill has been used for storage of CCR and has been in use since operations began in 1981. The North Landfill is 15 acres and receives fly ash and bottom ash. Filling since 2014 has proceeded from the south to the north in 5-foot lifts, tying into the toe of the historically placed ash.

Contact stormwater is directed to a diversion berm and rip rap discharge channels that route the water to the existing lined evaporation pond at the south toe of the ash disposal area. Pond water is evaporated or pumped to adjacent Evaporation Pond D, as needed.

Figure 2.1-1. Pawnee Station—CCR Units and Certified Monitoring Well System



3 Conceptual Site Model

The CSM is a narrative description of the groundwater flow system that forms the basis of the numerical groundwater flow and transport model. The purpose of the CSM is to identify all relevant hydrogeologic components of the local groundwater system, including all inflows and outflows, in order to later translate this information into a numerical model that is representative of the physical processes within the groundwater system under the landfill. The model domain encompasses the ash landfill and surrounding area, extending 3,760 feet north to south and 6,360 feet east to west, as shown on Figure 3.4-1.

In addition to the narrative description and to corroborate the CSM, a three-dimensional (3D) hydrogeologic model of the subsurface underlying the Pawnee North Landfill and the surrounding area was created using geologic interpretations of well boring lithologic logs from monitor wells and geotechnical exploratory borings. The geological model was created in Leapfrog Hydro version 2.5.2 (ARANZ Geo Limited, 2006) and can be directly translated into the numerical groundwater flow and transport model pre- and post-processing software; Groundwater Vistas Version 7 (Environmental Simulations, Inc., 2017).

3.1 Climate

The climate of the station location can be described as semi-arid continental steppe.

Annual total precipitation is 13.34 inches per year in Fort Morgan, which is approximately 7 miles west of the site, with annual mean snowfall of 21.8 inches (Western Regional Climate Center). The wettest month is May, with an average of 2.47 inches of total precipitation. The average maximum temperature is 64.3 degrees Fahrenheit (°F) and the average minimum temperature is 34.9 °F. The warmest month is July with an average high of 90.1 °F and an average low of 60 °F. The coldest month is January with an average high of 39.0 °F and an average low of 10.3 °F. Table 3.1-1 summarized key characteristics.

The groundwater model will use net recharge, which is a combination of rainfall and evaporation as one model variable. Typically, the net recharge is approximately 10% to 50% of rainfall. However, the net recharge variable may be modified to calibrate the model to actual measured monitor well water levels.

Table 3.1-1. Key Climate Characteristics at Pawnee Station

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
Monthly Average Temperature (Fort Morgan 1896-2018)	24.53	29.55	37.79	47.87	57.67	67.74	74.12	71.76	62.63	50.38	36.78	26.65	48.72
Monthly Average Precipitation (Fort Morgan 1896-2016)	0.25	0.25	0.73	1.49	2.36	1.94	2.07	1.55	1.17	0.83	0.40	0.30	13.34
Monthly Average Pan Evaporation (Inches) (Akron 1918-2005)	0.00	0.00	0.00	7.30	9.29	11.43	13.26	11.16	9.09	6.16	0.00	0.00	67.69

3.2 Topography

The geological model created in Leapfrog Hydro, and thus the groundwater flow and transport model, requires a digital elevation model (DEM) file (or similar) to reflect the top boundary of the model. The topographic surface for the model area is a 10-meter digital elevation model (DEM) downloaded from the Nebraska Department of Natural Resources in a work-share agreement with the U.S. Geological Survey. The DEM data was replaced in select areas of the site with more recent LiDAR data collected by Great Lakes Environmental and Infrastructure on September 8 and 13, 2018. After a complete surface was compiled, the surface was compared to surveyed ground elevations at the monitor wells and boreholes for accuracy. The completed surface corresponded with surveyed ground elevations at the monitor wells and boreholes with minimal error.

For imagery HDR will use high-resolution aerial photograph from ESRI World Imagery from January 2019.

3.3 Surface Water

Two surface water drainages are located in the vicinity of Pawnee Station. The South Platte River is located about 3.5 miles north of the Station and Brush Creek about 3.5 miles to the east. The South Platte River flows east-northeast and Brush Creek flows in a northerly direction, joining the South Platte about 7 miles beyond Brush, Colorado.

One irrigation ditch, Fort Morgan Canal, managed by the Fort Morgan Irrigation Company runs west to east through the Pawnee Station north of the landfill and south of the plant. The ditch is concrete lined through most of the property, and discharges from the concrete lined ditch to unlined irrigation ditches near the augmentation ponds on the east side of the Station (Figure 2.1-1). Small artificial wetland areas have been created on and immediately east of Pawnee Station by the augmentation ponds, which were created and are operated by the Fort Morgan Irrigation Company. The ponds are downgradient of the North Landfill. The Fort Morgan Canal is used, in part, to fill these ponds, which are consequently used for groundwater recharge. The augmentation pond bottoms are above the water table.

3.4 Geology

Dune sand deposits are present under the entire Pawnee Station, which overlie a fine-grained residual soil and shale bedrock (the Pierre Shale Formation).

- The dune sand deposit is a well-sorted fine sand and ranges from approximately 8 to 70 feet thick from the land surface (Xcel Energy, 2018).
- The fine-grained deposit underlying the dune sand is unconsolidated very fine sand, silt, and clay derived from in-situ weathering of the Pierre Shale and is approximately 8 to 125 feet thick (Xcel Energy, 2018). The thickness of the residual soil is greatest in the

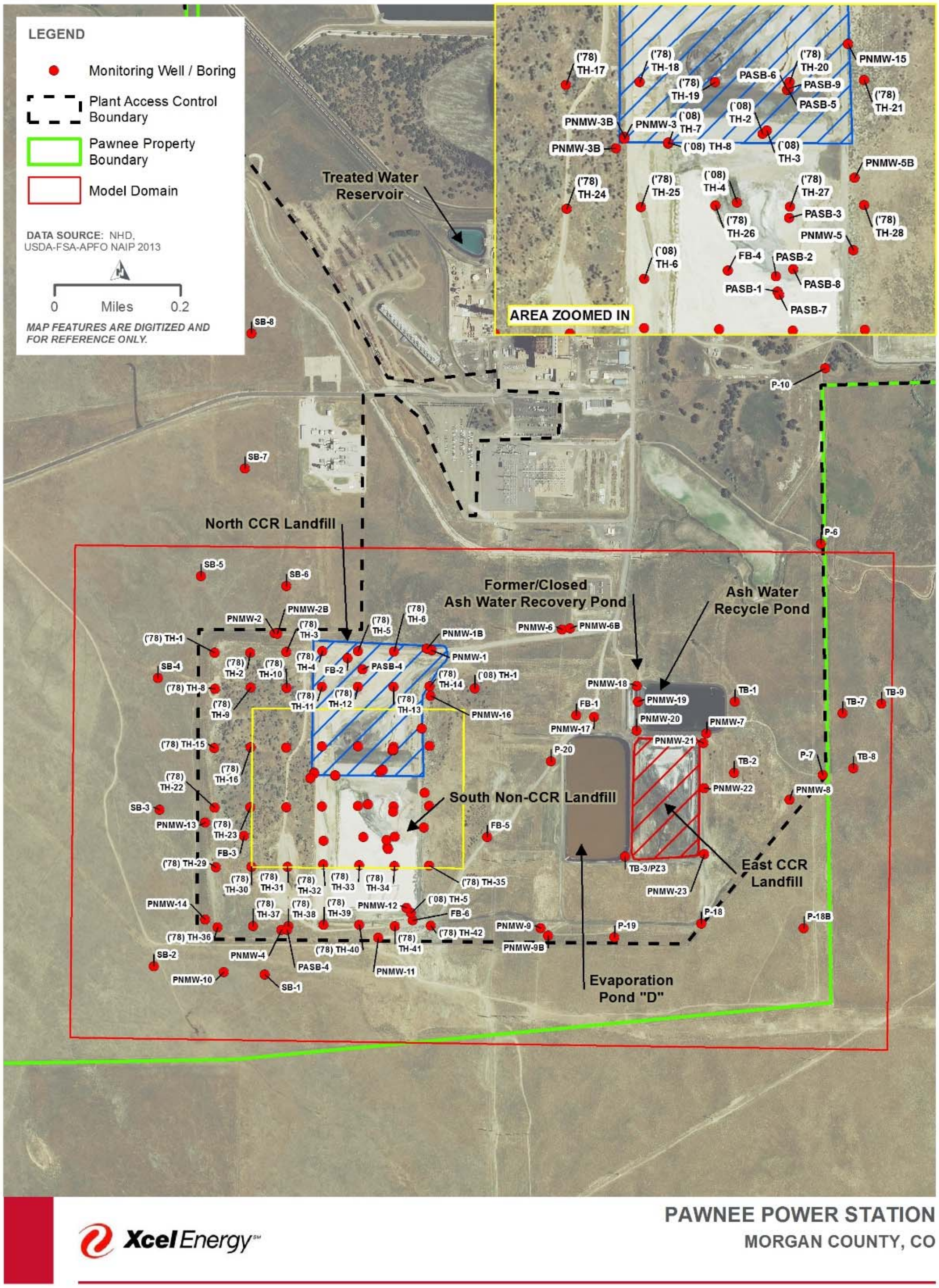
northeast portion of the power station. The base of the residual soil is characterized by a transition zone from partially weathered bedrock to the underlying competent bedrock.

- The Pierre Shale bedrock underlies the units described above and consists of shale to sandy shale (claystones and siltstones), and is approximately 4,500 to 5,000 feet thick in this region of Colorado. The depth to the Pierre Shale at the site ranges from approximately 40 to 80 feet in the southern portion of the site to approximately 110 to 140 feet in the northeastern portion of the property (Xcel Energy, 2018).

HDR reviewed available boring logs from geotechnical studies and boring logs from well installations. HDR reviewed all available studies, gathered and interpreted the boring logs to consolidate the logged lithologies into units for use in developing the geologic model in Leapfrog that will be the framework for the groundwater model in MODFLOW. In addition to existing boring logs and wells, HDR completed an additional 8 borings in the landfill to satisfy recognized data gaps and collect ash and ash pore water samples. Figure 3.4-1 provides the map of borings for building the geologic model. A table of all of the data sources is provided in Appendix A of this document.

An east-west geologic cross section through the landfill was prepared in Leapfrog and is provided in Appendix A of this document. The geologic interpretations presented on the cross section are based on the subsurface conditions encountered in exploratory borings, historical descriptions of the construction of the landfill, measurements of the cover fill berms, and review of aerial photographs.

Figure 3.4-1. Geotechnical and Monitoring Well Borings Containing Lithologic Data for Use in Developing the Geologic Framework for the Groundwater Model



3.5 Groundwater Flow System

Groundwater flows primarily within the transition zone bedrock located at the base of the residual soil and above the consolidated shale bedrock. Groundwater is recharged from infiltration from above and is confined below by the competent, low conductivity, Pierre Shale bedrock. Dune sands in the North CCR Landfill area overlay the residual soil and generally do not contain water.

Regional groundwater flow is generally to the northeast under the North Landfill towards the South Platte River; however, a bedrock high, trending northwest to southeast, is present beneath the North Landfill area, resulting in an eastern radial flow such that groundwater under the North CCR Landfill flows east northeast, east, and east southeast (Xcel Energy, 2018).

Water level data has been collected in monitoring wells across the site over many years. Water level data was collected by HDR in all monitoring wells within the model domain between May and October 2018 (Table 3.5-1). Figure 3.5-1 provides groundwater elevation data from wells that HDR monitors or has monitored in the past; however monitoring dates are not consistent across the site. Figure 2.1-1 is a potentiometric map of the groundwater surface within the model domain using wells monitored by HDR. This illustrates the flow direction under the North Landfill as northeast and east. Additional wells at Pawnee Station are monitored by AECOM under a separate monitoring program per CDPHE Solid Waste Regulations. AECOM's May 2018 groundwater potentiometric surface map contains more wells spread farther across the property, providing a representation of the water table under the Station (Figure 3.5-2) (AECOM, 2018). This illustrates the flow direction under the North Landfill as east-northeast, consistent with HDR's monitoring.

Table 3.5-1. Water Elevation Data Collected in Monitoring Wells Within the Modeling Boundaries (May 2018)

Well ID	May 2018 (ft amsl)
PNMW-1B	4307.17
PNMW-2B	4319.95
PNMW-13	4331.73
PNMW-14	4314.65
PNMW-15	4310.7
PNMW-16	4305.84
PNMW-17[1]	4304.3
PNMW-18[1]	4298.17
PNMW-19[1]	4299.71
PNMW-20[1]	4300.12
PNMW-21[2]	4291.153
PNMW-22[2]	4289.865
PNMW-23[2]	4283.825
PNMW-5B	4313.858
PNMW-12	4314.323
PNMW-3B	4317.76
PNMW-11	4307.15
PNMW-9B	4287.99
PNMW-6B[3]	4293.00
P7	4283.75
P18B	4279.17
P21	4251.47
P22	4257.03
P23	4261.41
P1	4256.37

[1] Water levels gathered in August 2018.
[2] Water levels gathered in October 2018.
[3] Representative water level from past sampling events.

Figure 3.5-1. Water Level Graph of North and South Landfill Wells

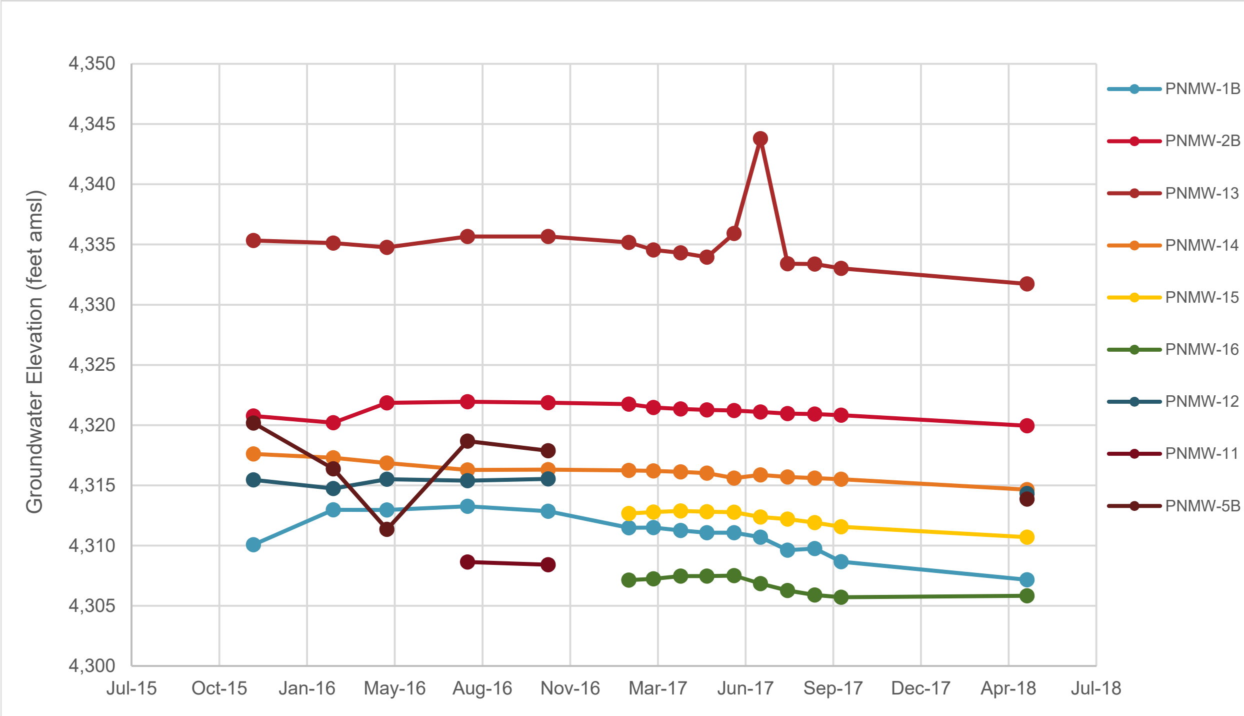
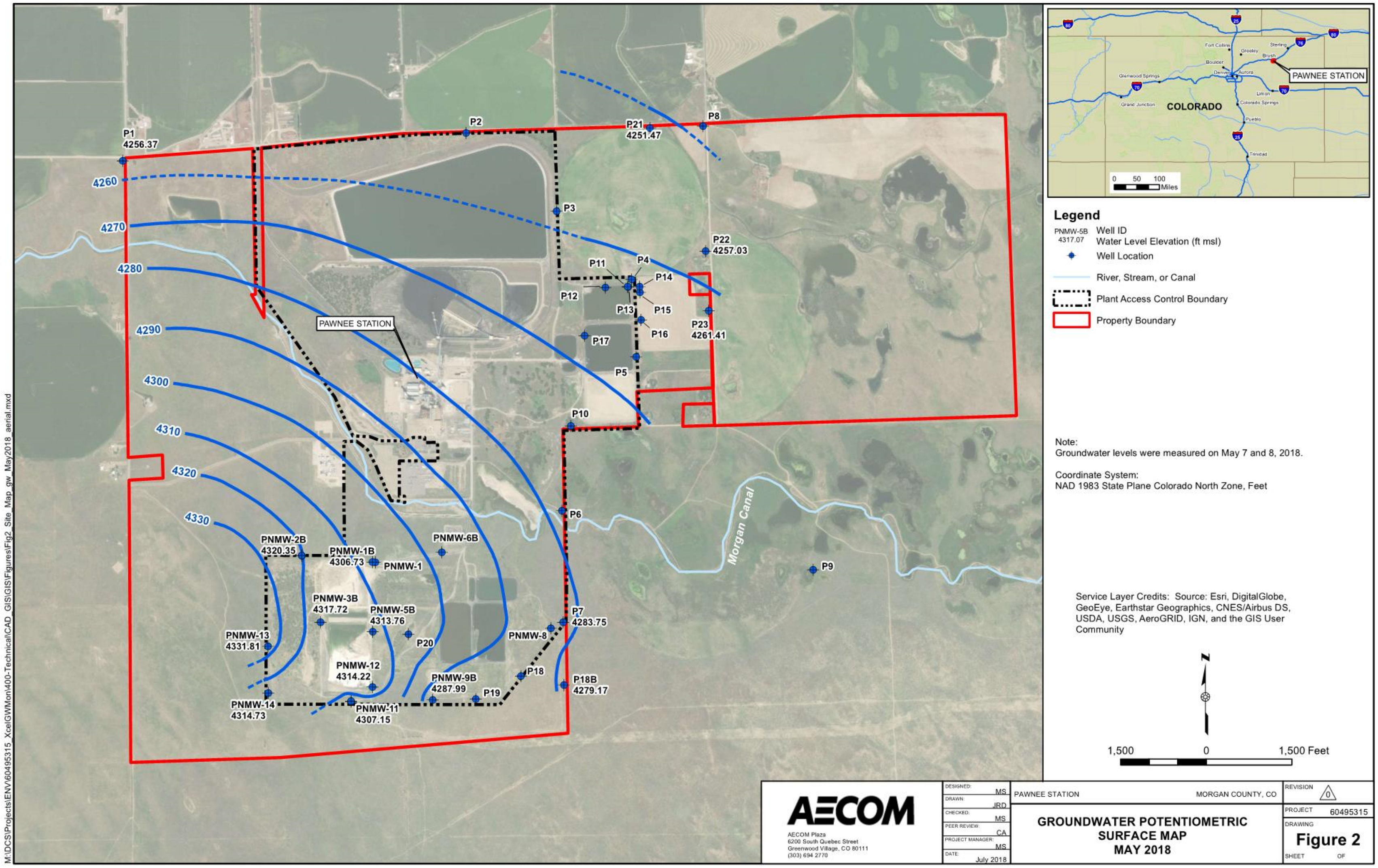


Figure 3.5-2. Groundwater potentiometric surface from May 2018 (from AECOM 2018)



Data from the landfill wells place the first water table in the silty sand (also described as the residual soil) or the weathered bedrock, above the 5,000 foot thick Pierre Shale bedrock. Table 3.5-2 displays all available data for the hydraulic conductivity for geologic units on site.

Table 3.5-2. Hydraulic Conductivity Values for Subsurface Materials at the Landfill

Well I.D.	Depth of Screened Interval (feet below surface)	Screened Interval Lithology	Hydraulic conductivity (ft/day)	Method	Data Source
Two samples from TH-2(08), TH-3(08), and TH-4(08)	Top of Pierre Shale	Pierre Shale Bedrock	1.5×10^{-4}-2.4×10^{-4}	Lab permeability	URS (2009)
3 test borings in landfill	unk	Weathered Bedrock	8.5×10^{-4} - 1.7×10^{-4}	Permeability values on six remolded clayey samples	Dames and Moore (1976)
PNMW-1	34-39	Sand	0.132	Single Well Pump Test	EPRI, 2006. Field Evaluation of the Co-management of Utility Low-Volume Wastes With High-Volume Coal Combustion By-Products: PA Site.
PNMW-5	44-49	Weathered Bedrock	0.128		
PNMW-6	51-56	Weathered Bedrock	0.447		
PNMW-7	59-64	Weathered Bedrock	0.341		
PNMW-10	50-60	Sand	0.056		
PNMW-12	20-50	Sand/Silty Sand/Weathered Bedrock	6.78	Slug Test	HDR, 2018. Monitoring Well Installation Report for Compliance with the Coal Combustion Residuals (CCR) Rule – Pawnee Station.
PNMW-13	20−50	Sand	16.72		
PNMW-14	40−70	Sand/Silty Sand	58.39		
PNMW-15	25−55	Weathered Bedrock	2.49		
PNMW-17	5−35	Silt/Weathered Bedrock	1.05		
PNMW-18	20-55	Silty Sand	2.27		
PNMW-19	23-53	Silty Sand/Clay	0.88		
PNMW-20	20-50	Silty Sand/Weathered Bedrock	16.16		
PNMW-21	30−60	Sand/Silt	1.30		
PNMW-22	30−60	Sand/Weathered Bedrock	0.82		
PNMW-23	30−60	Silt/Silty Sand/Weathered Bedrock	0.91		
P-19	39-69	Silty Sand	1.28	Slug Test	HDR, 2017 Analysis
PZ-3	45.6-55.6	Sand/Weathered Bedrock	0.57	Slug Test	HDR, 2017 Analysis

Using the hydraulic conductivity values between 0.056 and 0.447 feet per day (ft/day) and a representative effective porosity of 30%, the groundwater velocities were calculated to range between 1.8 and 6.0 feet per year (ft/yr) to the east.

According to the Colorado Geological Survey, the Pierre Shale formation is not a viable aquifer due to its low yield and poor water quality and is considered a regional semi-confining unit.

3.6 Groundwater Recharge

Annual average precipitation from 1896-2016, as provided by the Fort Morgan Weather Station, is 13.34 inches per year (in/yr). Annual average pan evaporation, as provided by the Akron Station from the Western Regional Climate Center, is 67.69 in/yr. Evaporation is more than four times the precipitation. However, it is unlikely that all precipitation that falls onto the ground evaporates before entering the groundwater system.

The groundwater model will use net recharge, which is a combination of precipitation and evaporation as one model variable. An initial recharge value of approximately 10% to 50% of precipitation will be used. However, the net recharge variable may be modified to calibrate the model to actual measured monitor well water levels, due to the absence of site-specific recharge measurements.

3.7 Groundwater Withdrawal

No groundwater withdrawal wells were located within or near the model domain.

3.8 Water Quality

A total of six monitoring wells were originally sited at the landfill for CCR compliance: three upgradient monitoring wells (PNMW-2B, PNMW-13, and PNMW-14) and three downgradient monitoring wells (PNMW-1B, PNMW-15, and PNMW-16) (Figure 2.1-1). The network is described in detail in the Groundwater Monitoring System Certification report (HDR, 2018). As stipulated in the CCR Rule, eight rounds of background groundwater sampling and the initial round of detection monitoring were completed before October 17, 2017 for the landfill. Background values were calculated and described in detail in the *Background Water Quality Statistical Certification* (HDR, 2018b). The initial round of detection monitoring was conducted in September 2017. In the January 15, 2018 PSCo memorandum, *Determination of Statistically Significant Increases over Background per 257.93(h)(2)*, concentrations of COIs at downgradient monitoring wells at the North Landfill were compared against background values and COIs were shown to have SSIs over background concentrations. These SSIs triggered the assessment monitoring program for the landfill. As stipulated in CCR Rule 257.95 assessment monitoring was completed in 2018 and GPS were established and documented in *Groundwater Protection Standards and Determination of SSLs per 257.95(g)* (HDR, 2019b). In 2019 three existing wells were added to the monitoring network (P-6, P-7, and P-18B) to provide downgradient property boundary wells (Figure 2.1-1). The water quality of groundwater at the landfill has been well established and a database is available for use in calibrating the transport model. Monitoring wells PNMW-17 through PNMW-23 located around the former AWRP and BASP were installed to monitor for groundwater impacts from those former ponds. Water quality data from those wells was used in calibrating the transport model, which covers this area to the east of the North Landfill. Due to the formerly inactive and current closed status of the AWRP and BASP, the monitoring programs for these former CCR units is operated under a separate schedule and is in a different phase of the CCR compliance monitoring than the North Landfill.

4 Constituents of Concern in Groundwater

4.1 Constituents Exceeding the Groundwater Protection Standard

In accordance with CCR Rule 257.95(f), downgradient well concentrations from the assessment monitoring events were compared against GPS and found to exceed GPS. Therefore, following CCR Rule 257.95(g), downgradient well concentrations were compared against GPS to determine "if one or more constituents in Appendix IV to this part are detected at statistically significant levels above the groundwater protection standard." To determine if an exceedance of a GPS was statistically significant, the lower confidence limit (LCL) was calculated for each of the downgradient wells at the North Landfill for each of the detected Appendix IV COIs. Downgradient wells MW-15 and MW-16 were both found to have concentrations of lithium at statistically significant levels (SSLs) above the GPS. All other detected Appendix IV COIs are below the GPS. Therefore the constituent that will be modeled and evaluated moving forward is lithium (this constituent is referred to herein as the constituent of concern (COC)).

The groundwater transport model will utilize the total lithium concentrations for wells at the landfill collected in August and October 2018 as the starting point for transport model calibration. Table 4.1-1 lists the MCL, the BTV, and the GPS for lithium. Since there is no EPA established MCL for lithium from 40 CFR 141.62, the MCL value is the EPA adopted health-based value for lithium, per the amended rule.

Table 4.1-1. Groundwater Protection Standard for Appendix IV COIs with SSLs above the GPS at the North Landfill 257.95(d)(3)

Constituent	Unit	Maximum Contaminant Level	Background Concentration (UTL)	Groundwater Protection Standard
Lithium	mg/l	0.0400*	0.094	0.094

*EPA adopted health-based value in place of MCL.

4.2 Constituents of Concern Source Areas

Fly ash and bottom ash have been deposited in the North Landfill since the beginning of Station operations. By design, the landfill was constructed with the base cut to the Pierre shale bedrock. The bedrock has low permeability and acts as a natural barrier to potential seepage; therefore no engineered liner was constructed on the landfill bottom.

The east-west cross section prepared by HDR (Appendix B), based on borehole lithology and groundwater elevations measured in wells surrounding the landfill, demonstrate ash in contact with groundwater within the weathered bedrock zone at the base of the landfill, above the consolidated Pierre shale bedrock. Borehole drilling was conducted in 2019 within the landfill footprint that observed free water within the boreholes that allowed for water sample collection.

This water is referred to as pore water for waste characterization purposes, but the elevation is consistent with the water table across the Station.

Table 4.2-1 provides the potential pathways for groundwater impacts and likelihood for each pathway at the North Landfill given operating conditions.

Table 4.2-1. Potential Pathways for Impacts to Groundwater at the North Landfill

Potential Pathways for Impacts to Groundwater/ Recharge Sources	Potential for each Pathway at North Landfill
Precipitation infiltration through the dry ash leaching metals and discharging to groundwater	Occurs on site, though precipitation would not be expected to build-up saturated conditions to drive enough transport through the compacted ash. This impact would be expected to be minor and would not be anticipated to have caused an SSI.
Ash contact stormwater ponding in the clay lined evaporation pond at the south end of the North Landfill leaking to groundwater	Ponding could provide sufficient head and saturated conditions to drive pore water through the clay liner if weak points were to exist, and potentially impact groundwater.
Ash in direct contact with groundwater	Borehole drilling data was used to develop the cross-section of the North Landfill provided in Appendix B, including the base of the ash that confirm ash in contact with groundwater within the weathered bedrock zone at the base of the landfill. Saturated ash was observed in boreholes drilled within the landfill at elevations consistent with the groundwater elevations across the Station. The base of the landfill in contact with groundwater is consistent with the groundwater elevations of the wells adjacent to the landfill screened in the weathered bedrock and sandy silts that lay above the Pierre Shale consolidated bedrock. This is the most likely potential pathway for the site.

4.3 Source Characterization

For the groundwater modeling of the landfill, the source characterization is an input for the model. Pore water was collected for analysis from four temporary wells where the ash was saturated in the North Landfill.

Borings were drilled in four locations distributed across the North Landfill, and a temporary well was installed and screened in the saturated ash for pore water collection. This approach yielded pore water in three of the four boreholes. Dry ash samples were also collected.

The saturated ash pore water samples were analyzed for concentrations of lithium, which were ultimately used in the groundwater transport model to establish the COC source concentration. Pore water lithium concentrations were higher than the observed groundwater concentrations downgradient of the landfill, which indicates the ash as a source for the lithium in groundwater. Dry ash samples were collected and submitted to the lab for Synthetic Precipitation Leaching Procedure (SPLP) and analysis for lithium concentrations. Results of SPLP testing of the ash resulted in highly variable concentrations around the landfill and lower concentration of leachate lithium than the pore water results and therefore were not used for source terms in the model.

4.4 Potential Receptors

There is no primary or secondary drinking water standard for lithium. The agricultural water quality standard for lithium in Colorado is 2.5 mg/L. Therefore, the locations where groundwater concentrations of lithium exceed the CCR Rule GPS, all of which are on Pawnee Station property meet agricultural standards for lithium.

The City of Brush obtains its municipal water supply from six wells drilled into the Beaver Creek Alluvium about 3 miles east of the south boundary of the plant site. The Brush Wellfield area is classified for Domestic Use and Agricultural use.

The Fort Morgan Canal is used for delivery of irrigation water to farmers in the region and water is supplied to augmentation ponds operated by the Fort Morgan Canal. The Fort Morgan Canal traverses the plant site from west to east, bisecting the plant property. The Fort Morgan Canal is contained within a concrete culvert across the plant property, except for a short section at each end. There are two augmentation ponds on the Pawnee Station property, one on the northwest side of the property, near where the canal enters the plant site, and one on the east side where the Fort Morgan Canal exits the property. These ponds are used to provide wildlife habitat, and to recharge the groundwater. In addition, more augmentation ponds are located east of the power plant, in close proximity to the plant property and along the canal, out to a distance of approximately two miles. The canal water is obtained from the South Platte River, about 20 miles northwest of the plant (13 miles northwest of Fort Morgan), and shows seasonal water quality variations typical of the South Platte River. The augmentation pond on the east side of the property is downgradient of the North Landfill but recharges groundwater. Therefore this pond is not a potential receptor for potentially contaminated groundwater from the North Landfill.

4.4.1 Domestic Wells and Springs Distances

There are 98 well permits within 1 mile of the eastern property boundary, 18 of which are domestic well permits (Xcel Energy, 2018). The closest downgradient domestic well (permit number 64719) is located 316 feet east of the eastern property boundary. No wells are located south of the Station within one mile.

5 Groundwater Flow and Transport Model

The groundwater flow and transport model is the numerical representation of the CSM. The 3D geological model created in Leapfrog Works (ARANZ Geo Limited t/a Seequent, 2017) was used as input for the elevations and thicknesses of aquifer units in the numerical groundwater flow and transport model. The numerical groundwater flow and transport model uses the graphical user interface (GUI) Groundwater Vistas Version 7 (Environmental Simulations, Inc.,

2017) as the pre- and post- processor for the groundwater flow code MODFLOW-NWT and the transport code MT3DMS.

The specific MODFLOW code chosen for the study is MODFLOW-NWT, a Newton formulation of MODFLOW-2005 that is specifically designed to improve the stability of solutions involving drying and re-wetting under conditions present at the water table (Niswonger et al. 2011). The numerical code selected for the transport model is MT3DMS (Zheng and Wang 1999). MT3DMS is a multi-species three-dimensional (3D) mass transport model that can evaluate advection, dispersion/diffusion, and chemical reaction of COIs in groundwater flow systems, and has a package that provides a link to the MODFLOW codes. The MODFLOW-NWT and MT3DMS input packages used to create the groundwater flow and transport models, as well as a brief description of their use, are provided in Table 5.2-1.

5.1 Modeling Objectives

The primary modeling objectives are to simulate the rate of movement, potential pathway(s) and the potential offsite migration of lithium within the local groundwater system. Predictive simulations will estimate the movement of this COC over a pre-determined time period and determine if offsite migration is likely or unlikely. Simulation of corrective action alternatives (such as, source removal, injection, barriers) will be performed for alternatives that are not removed from consideration. Predictive simulations will be completed after further data is gathered to confirm the calibrated results to current conditions.

5.2 Model Domain and Grid

The 3D geological model was used as input for the elevations and thicknesses of aquifer/lithology units in the groundwater flow and transport model. The geological model constructed in Leapfrog Hydro was imported into Groundwater Vistas, Version 7, which is the pre and post-processor for the groundwater modeling software used to simulate groundwater flow (MODFLOW) and contaminant transport (MT3DMS). The imported geologic units include top and bottom elevations of each layer beginning at ground surface to a pre-determined bottom elevation of bedrock. The following geologic units were used in the Leapfrog geological model and the groundwater flow and transport model:

- Ash
- Silt
- Sand
- Sandy silt
- Sandy clay
- Gravelly sand
- Clay
- Clayey sand
- Silty gravel
- Weathered bedrock
- Bedrock

Table 5.2-1. MODFLOW and MT3DMS Input Packages Utilized

MODFLOW Input Package	Description
Name (NAM)	Contains the names of the input and output files used in the model simulation and controls the active model program
Basic (BAS)	Specifies input packages used, model discretization, number of model stress periods, initial heads and active cells
Discretization (DIS)	Contains finite-difference grid information, including the number and spacing of rows and columns, number of layers in the grid, top and bottom model layer elevations and number of stress periods
Specified Head and Concentration (CHD)	Specifies a head and/or a concentration that remains constant throughout the simulation
Recharge (RCH)	Simulates areal distribution of recharge to the groundwater system
Newton Solver (NWT)	Contains input values and the Newton and matrix solver options
Upstream Weighting (UPW)	Replaces the LPF and/or BCF packages and contains the input required for internal flow calculations
Flow Transfer Link File (LMT)	Used by MTDMS to obtain the location, type, and flow rates of all sources and sinks simulated in the flow model
MT3DMS Input Package	**Description**
Flow Transfer Link File (FTL)	Reads the LMT file produced by MODFLOW
Basic Transport Package (BTN)	Reads the MODFLOW data used for transport simulations and contains transport options and parameters
Advection (ADV)	Reads and solves the selected advection term
Dispersion (DSP)	Reads and solves the dispersion using the explicit finite- difference formulation
Source and Sink Mixing (SSM)	Reads and solves the concentration change due to sink/source mixing using the explicit finite-difference formulation
Chemical Reaction (RCT)	Reads and solves the concentration change due to chemical reactions using the explicit finite-difference formulation
Generalized Conjugate Gradient (GCG) Solver	Solves the matrix equations resulting from the implicit solution of the transport equation

The model domain encompasses the ash landfill and surrounding property and extends to slightly beyond the Xcel Energy property boundaries to the east and west, and is within 100 feet inside the property boundary to the south. The model boundary to the north terminates on Xcel Energy property at a sufficient distance from known extents of Lithium concentrations above the

GPS. The model domain extends 3,760 feet north to south and 6,360 feet east to west and has a grid consisting of uniform 20 foot grid cells in 20 layers. (Figure 5.3-1) The bedrock unit in the model is divided into 2 layers; the upper layer has a 10 foot uniform thickness and the lower layer is assigned a thickness of 90 feet.

The geologic units identified in the boring logs are not always continuous across the site and may be modeled as one or more layers with different hydraulic conductivity values to designate discontinuities and spatial changes of geologic units.

5.3 Hydraulic Parameters

Horizontal hydraulic conductivity and the ratio of horizontal to vertical hydraulic conductivity, which are specific for each hydrostratigraphic unit, are the primary determinants of groundwater flow for a given configuration of boundary conditions and sources and sinks, including recharge. Field measurement of these parameters have been performed through slug testing of onsite monitor wells and are included in consultant reports associated with the drilling (Xcel Energy, 2018; HDR, 2018c). Measured values are available for most encountered geologic units, including, sand, silt, weathered bedrock, and bedrock. A portion of geologic units above the weathered bedrock are unsaturated. MODFLOW does not simulate flow in unsaturated sediments, so does not use the hydraulic conductivity of unsaturated units in the flow and transport computation. However, values were assigned to the unsaturated units for completeness.

Values assigned to the model, with a comparison of literature and measured values are provided in Table 5.3-1.

Figure 5.3-1. Model Domain

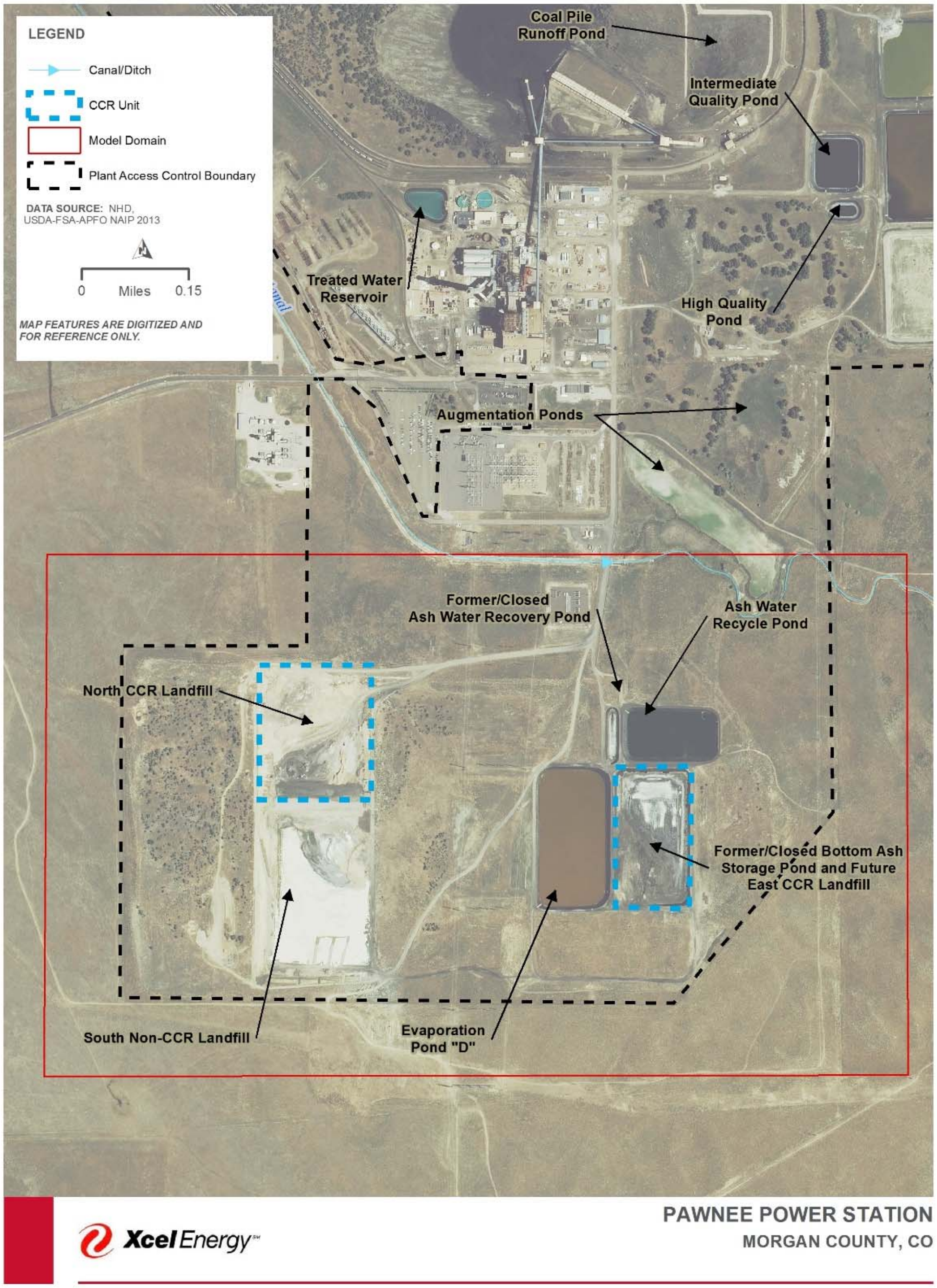


Table 5.3-1. Summary of Hydraulic Conductivity Values Used in the Calibrated Model

Geologic Unit	Model Values			Measured Values
	Horizontal Hydraulic Conductivity (ft/d)	Vertical Hydraulic Conductivity (ft/d)	Model Zone	Horizontal Hydraulic Conductivity (ft/d)
Ash/Lime	0.35	0.035	1-3	0.35
Bedrock	0.01	0.01	18	0.1 - 0.001
	0.001	0.0001	19	
Clay	0.01	0.01	8	Literature Value
	0.01	0.001	15	
	0.01	0.01	24	
Clayey Sand	0.9	0.9	10	0.88
Sand	10	1	4	0.06 – 16.7
	10	1	6	
	15	1.5	14	
	20	2	22	
Sand/Silty Sand	60	6	21	58.4
Sandy Clay	0.9	0.09	11	0.88
	0.9	0.09	13	
Sandy Silt	15	1.5	9	16.2
Silt	0.9	0.09	7	0.91
	0.9	0.8	16	
Silty Sand	2.3	0.2	5	1.3 - 2.27
	2	0.2	12	
	1	0.1	23	
Weathered Bedrock	15	1.5	17	0.13 – 58.4
	50	25	20	
	0.1	0.01	25	
	6	0.6	26	
	1	0.1	27	

5.4 Boundary Conditions

The outer model boundary is simulated with Constant Head boundary conditions set to elevations that approximately represent late 2018 water level elevations that align with the water level contours developed for the site.

A constant recharge rate of 0.0013 feet/day was assigned to the entire model domain, which is about 43% of average annual rainfall. This rate was determined through model calibration to measured water levels in on-site monitor wells.

5.5 Contaminant Transport Properties

The calibrated, steady-state flow model was used to apply flow conditions for the transport model at the North Landfill using groundwater quality data obtained from monitor wells during the November 2018 sampling event. The relevant transport input parameters were constant concentrations at the source zone, effective porosity, advection and dispersion.

5.5.1 Constant Concentration Source Zones

The flow model hydrogeologic properties (hydraulic conductivity) were slightly modified during transport calibration to better match measured lithium concentrations. To calibrate the transport model to existing conditions, constant concentration source zones were applied to ash in the North Landfill.

Concentrations were based on measured pore water samples, adjusted as needed, as areas of the North Landfill required variability in source concentrations to achieve transport calibration.

The background concentration for lithium is the calculated GPS value of 0.094 milligrams per liter (mg/L) (HDR, 2019). This value was applied to the saturated weathered bedrock and bedrock layers.

Constant concentration source zones in the North Landfilll area are activated in the model at the date the landfill was placed in service. The model terminated in October 2018 to match the water quality calibration sample date, which resulted in a transport model total time length of 37.75 years (1981 to October 2018)

5.5.2 Effective Porosity

No effective porosity measurements of the saturated sediments have been collected at the Pawnee Site, so the following literature values provided in Table 5.5-1 (Freeze and Cherry, 1979, Domenico and Schwartz, 1990) were used. Effective porosity is a fraction of the total porosity.

Table 5.5-1. Effective Porosity Values used in the Transport Model

Geologic Unit	Model Values	
	Effective Porosity (%)	Model Zone
Ash	30	1,2,3
Bedrock	10	18,19
Clay	10	8,15,24
Clayey Sand	20	10
Sand	25	4,6,14,22
Sand/Silty Sand	25	21
Sandy Clay	20	11,13
Sandy Silt	25	9
Silt	15	7,16
Silty Sand	25	5,12,23
Weathered Bedrock	10	20,25,26,27

5.5.3 Advection and Dispersion

Contaminants move through the groundwater system via advection and dispersion. Advection is the movement of contaminant mass due to the flow of water in which the mass is dissolved. Dispersion is the process of mixing that occurs with the native groundwater, in which the mass is spread. Advection does not have specific parameters outside of the hydraulic gradient, hydraulic conductivity and porosity.

Dispersion is a physical property of the aquifer medium and is normally a fraction of the field scale condition (i.e., plume length), commonly considered to be approximately 10 percent (Zheng and Bennett 2002). The dispersivity quantifies the degree to which mechanical dispersion of COIs occurs. Dispersion is site dependent and since plume length is usually unknown, this parameter is usually determined through the transport model calibration process. Dispersion is measured in the longitudinal, horizontal transverse, and vertical transverse tensors. These values usually have a ratio of 100/10/1 and are measured in feet. Consistent with this ratio, values of 30/3/0.3 were used in the transport model.

5.6 Calibration to Current Conditions

Model calibration is the process of adjusting hydraulic parameters, transport parameters, and boundary conditions within reasonable ranges to achieve an acceptable match between modeled and measured calibration targets. The flow model was calibrated to monitoring well water levels from May 2018 thru October 2018 (Table 3.5-1). The transport model was calibrated to porewater and monitor well concentrations from late August 2018 thru February 2019.

5.6.1 Flow Model Calibration

The flow model was calibrated to groundwater elevations calculated from depth to water measurements in all wells obtained from May 2018 thru October 2018. Multiple observation data points were used to provide a more robust steady-state flow model calibration data set.

The initial iterative calibration assumed homogeneous conditions in each hydrostratigraphic layer (model layers received varying hydrogeologic parameters from the 3D geologic model). Recharge was also fixed at reasonable values early in the calibration process, and then refinements were made by adjusting hydraulic conductivity and the recharge rate.

Modeled and observed water levels (post-calibration) are compared in Table 5.6-1 and on Figure 5.6-1. The calibrated flow model is assumed to represent long-term, steady-state flow conditions for the site and the area beneath the North Landfill under long-term, average conditions. Iso-contours for each calibrated Lithium concentrations are also provided in Figure 5.6-2.

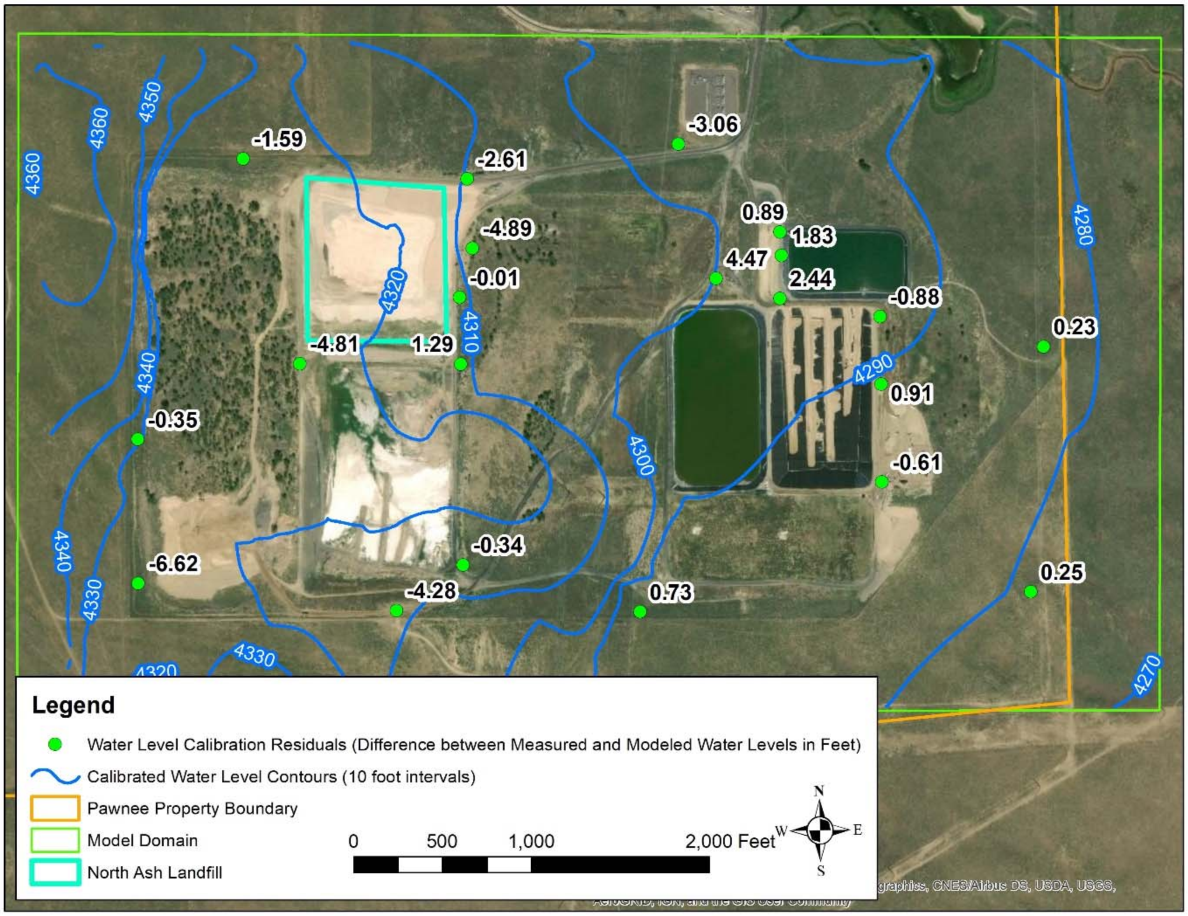
The square root of the average square error (also referred to as the root mean squared error, or RMS error) of the modeled versus measured water is an industry standard means to validate model calibration to water levels. The model calibration goal is an RMS error less than 10 percent of the change in head across the model domain. The ratio of the average RMS error to total measured head change is the normalized root mean square error (NRMSE). The NRMSE of the calibrated model is 5.3 percent. The range in water level residuals (feet) is -6.62 to 4.47, with a mean residual of -0.81. These statistics indicate a well calibrated model to steady-state water levels.

Table 5.6-1. Measured vs. Model Calibrated Water Levels

Monitor Well ID	Measured Water Level (Feet) (May 2018)	Model Calibrated Water Level (Feet)	Residual (Feet)
PNMW-1B	4307.17	4309.78	-2.61
PNMW-2B	4319.95	4321.54	-1.59
PNMW-13	4331.73	4332.08	-0.35
PNMW-14	4314.65	4321.27	-6.62
PNMW-15	4310.70	4310.71	-0.01
PNMW-16	4305.84	4310.73	-4.89
PNMW-17	4304.30[1]	4299.83	4.47
PNMW-18	4298.17[1]	4297.28	0.89
PNMW-19	4299.71[1]	4297.88	1.83
PNMW-20	4300.12[1]	4297.68	2.44
PNMW-21	4291.15[2]	4292.03	-0.88
PNMW-22	4289.87[2]	4288.95	0.91
PNMW-23	4283.83[2]	4284.43	-0.61
PNMW-5B	4313.86	4312.57	1.29
PNMW-3B	4317.76	4322.57	-4.81
PNMW-11	4307.15	4311.43	-4.28
PNMW-12	4314.22	4314.56	-0.34
PNMW-9B	4287.99	4287.26	0.73
P7	4283.75	4283.52	0.23
P18B	4279.17	4278.92	0.25
PNMW-6B	4293.00	4296.06	-3.06

[1]August 2018, [2]October 2018

Figure 5.6-1. Water Level Calibration Residuals (Feet Difference between Measured and Modeled Water Levels)



5.6.2 Transport Model Calibration

For the transport model calibration, the calibration parameters consisted of constant source concentrations in the North Landfill, porosity, and slight modifications to the flow model parameters that improved both flow and transport calibrations. These parameters were adjusted to minimize residual lithium concentrations (difference between modeled and measured) in monitor wells. The model assumed an initial concentration matching the GPS within the groundwater system for lithium at the beginning of the model simulation. Constant concentration source zones (concentration areas) within the porewater concentration range for lithium were applied within the North Landfill area at the start of the calibration period. The source concentrations were adjusted in order to match measured porewater concentrations with the observed groundwater concentrations in downgradient monitoring wells. Some of these downgradient wells used to calibrate the model (PNMW-17 through PNMW-23) are not part of the North Landfill monitoring system; rather they are for monitoring groundwater at the two former CCR impoundments (BASP and AWRP) and the newly constructed East CCR Landfill. The monitoring program for the former CCR impoundments follows a separate schedule than the North Landfill and is currently in the assessment monitoring phase of the CCR compliance monitoring. Therefore, the former AWRP and BASP are not being assessed for the corrective measures discussed in this report.

Modeled and observed groundwater concentrations for lithium (post-calibration) are compared in Table 5.6-2. Overall, the calibration to measured concentrations shows a good match and is acceptable as a starting point for predictive simulations.

Table 5.6-2. Measured vs. Model Calibrated Lithium Concentrations

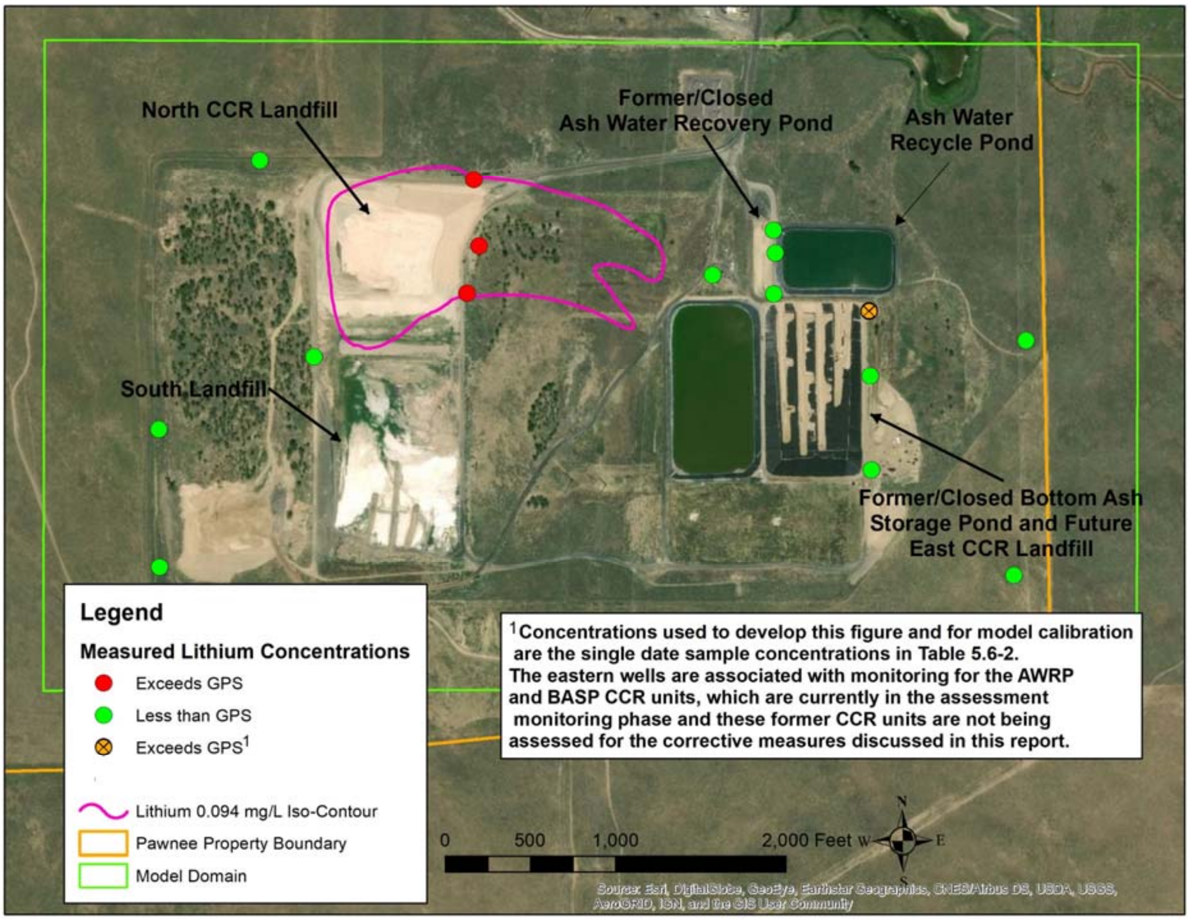
Monitor Well ID	Measured Concentration (mg/L) (August 2018)	Model Calibrated Concentration (mg/L)	Residual (mg/L)
PNMW-1B	0.098[1]	0.098	0.000
PNMW-2B	0.037[1]	0.002	0.035
PNMW-13	0.061	0.006	0.055
PNMW-14	0.044	0.006	0.038
PNMW-15	0.110	0.107	0.003
PNMW-16	0.140	0.139	0.001
PNMW-17	0.037	0.064	-0.027
PNMW-18	0.031	0.040	-0.009
PNMW-19	0.024	0.032	-0.008
PNMW-20	0.064	0.023	0.041
PNMW-21	0.095[1]	0.008	0.087
PNMW-22	0.053[1]	0.020	0.033
PNMW-23	0.044[1]	0.009	0.035
PNMW-3B	0.053[1]	0.002	0.051
P7	0.031[2]	0.070	-0.039

Table 5.6-2. Measured vs. Model Calibrated Lithium Concentrations

Monitor Well ID	Measured Concentration (mg/L) (August 2018)	Model Calibrated Concentration (mg/L)	Residual (mg/L)
P18B	0.021[2]	0.018	0.003

[1] October 2018, [2] February 2019

Figure 5.6-2. Calibrated Lithium Concentrations



5.7 Data Limitations

The following limitations, based on necessary assumptions, will be inherent within the completed groundwater flow and transport model. Where data was unavailable, use of published literature values, appropriate assumptions and professional judgment are routinely employed in modeling and are sufficient to complete the model.

- The geological interpretation of boring logs has been completed by multiple people from different engineering companies over a 10-year period. It's possible that geological interpretations are not uniform.
- The development of the geological model requires interpolation of geologic units between boreholes that may be inaccurate despite professional judgment and reasonable interpretations.
- Hydraulic conductivity values are sparse and are likely not representative of each entire geological unit underlying the site, as most geological units are heterogeneous.
- Site-specific aquifer recharge is not known and testing has not been conducted.
- Dispersion or dispersivity of a contaminant within the subsurface is difficult to quantify.
- Site-specific effective porosity values are not known. However, literature values are extensive and can be correlated to known site specific soil characteristics.
- Groundwater levels at the model boundaries are inferred from interpreted groundwater level contour maps, but actual groundwater levels at the model boundaries are non-existent.
- Pore water measurements may not represent the concentration of lithium over the entire North Landfill, as these concentrations may vary spatially.
- The model will represent steady-state conditions and does not account for transient impacts, such as aquifer storage or fluctuations of water level gradients over time.
- The model predicts groundwater flow and transport onsite, and predicts the direction and velocity of flow, but does not evaluate the extent or velocity of offsite movement beyond the model boundaries.

5.8 Data Gaps

It has been determined that further sampling and analysis will better determine the extent of lithium transport.

After additional sampling and analysis, the transport model will be re-calibrated and predictive simulations can then be run and reviewed. For each alternative simulated the re-calibrated model will:

- Evaluate concentrations of the COC over time, transport directions, potential for movement offsite and quantify mass flux moving offsite; and
- Evaluate the time required for each alternative to "complete the remedy" (per 257.96(c)(2)).

5.9 Plume Evaluation

Based on the current understanding of the site hydrogeology, water quality sampling and preliminary model simulations, groundwater is impacted by lithium east of the North Landfill. Therefore it appears that groundwater is impacted under the North Landfill, where ash appears to be below the water table. The extent of the modeled plume is shown on Figure 5.6-2.

The vertical extent of impacted groundwater is limited to the saturated portion of the weathered bedrock and possibly the upper portions of the bedrock, as the bedrock becomes less permeable with depth.

5.10 Potential for Offsite Transport

Water quality sampling and preliminary model simulations demonstrate that the potential for concentrations of lithium to move offsite from the North Landfill is unlikely. This potential for offsite transport will be confirmed through long-term predictive model simulations after further data collection.

6 Corrective Measures Alternatives

Corrective measure alternatives are described for consideration at the North Landfill to address CCR-related impacts to groundwater. The alternatives are listed and compared with respect to their anticipated effectiveness, ease of implementation, institutional requirements, and time table for implementation per 257.96(c). Additional data inputs are also identified. The time required to complete the remedy (257.96(c)(2)) will be better estimated after the model updates have been made, as described in Section 5.8. Results of additional modeling and final alternative selection will be compiled in a Remedy Selection Report.

6.1 North Landfill Corrective Measure Alternatives

Table 6.1-1 provides brief descriptions of seven potential corrective measure alternatives for consideration at the North Landfill to address CCR-related impacts to groundwater. The selection of the remedy will take into consideration the COC lithium identified at the landfill wells MW-15 and MW-16 and the transport pathways identified in the model. Of the alternatives reviewed, most appear to be feasible and will be carried forward for further consideration after the data gaps identified during initial calibration have been addressed. Certain natural site-specific characteristics, such as groundwater velocities and depth to bedrock are common to multiple alternatives and will factor in the effectiveness, feasibility, and timeliness of each, and therefore warrant additional evaluation. The alternatives are briefly discussed in the sections below.

6.1.1 Alternative 1—Monitored Natural Attenuation

Description. Monitored natural attenuation (MNA) is well accepted as an appropriate mitigation factor that should be considered when evaluating passive and active remedial options (USEPA, 1999, 2007a, b). The USEPA has established a tiered series of steps to determine whether MNA would sufficiently lower concentrations of COIs on an appropriate timescale, and whether there is sufficient system capacity and stability for MNA mechanisms (USEPA, 1999, 2007a, b). Natural attenuation mechanisms include adsorption of COIs, ion exchange, precipitation of COI-containing minerals, and dispersion. In addition to adsorption to soil, clay particles, and organic matter, iron and manganese oxides that commonly precipitate down-gradient of CCR disposal sites will, in turn, remove other COIs by adsorption. While model predictions can simulate long-term attenuation using a soil-water partitioning coefficient to estimate adsorption, natural conditions will dictate how COIs migrate through the strata and how much is removed en route. Empirical data are the best indicator of natural attenuation mechanisms, but long-term groundwater monitoring is required. (EPRI, 2015; USEPA, 1999, 2007a, b). Dispersion of COIs should also be fully considered, modeled, and if possible, validated using naturally present ions like chloride and sulfate that are generally not affected by interactions with soil, clay particles, and mineral precipitates.

Considerations. MNA as an alternative is primarily carried forward as a comparative tool to evaluate concentrations of COC without any source control or groundwater treatment.

Additional Data Needs. This alternative will require additional modeling simulations to be run after the additional data collection efforts have been completed.

6.1.2 Alternative 2—Landfill Cover

Description. The final cover design for the North Landfill is a engineered turf synthetic cover. The cover system will be installed to prohibit vertical migration of precipitation into ash to cut off that continued source of lithium to groundwater. After the cover is installed, MNA will occur and groundwater monitoring will continue to evaluate the predicted decrease in the COC leaching to groundwater.

Considerations. Covering the landfill should eliminate infiltration of precipitation through the ash thereby decreasing leaching of the COC into groundwater. This alternative would not address the ash located below the water table. It also may take a long time to meet GPS; however this alternative decreases one potential source of the COC to groundwater.

Additional Data Needs. The landfill cover will be modeled, including reducing vertical recharge rates to zero recharge. The model results will demonstrate the timeline to achieve the decrease in the COC required to meet the relevant criteria followed by MNA.

6.1.3 Alternative 3—Ash Removal

Description. The ash removal alternative assumes that all or a large portion of ash from the landfill will be excavated and moved offsite or onsite to CCR Rule-compliant landfill for disposal or beneficial use.

Considerations. This alternative would provide source removal and MNA. MNA will continue after the ash is removed and groundwater monitoring will continue to evaluate the predicted decrease in the COC in groundwater over time. Removal of the ash will take time, and MNA may prove slow to meet GPS due to low groundwater transmissivity. This alternative removes the source of the COC to groundwater.

Additional Data Needs. Different scenarios of ash removal will be modeled, including ash removal to various depths.

6.1.4 Alternative 4—Groundwater Extraction and Treatment

Description. As an alternative to in-situ groundwater treatment methods, impacted groundwater could be pumped to the surface and treated above grade (pump-and-treat) in order to provide hydraulic containment and prevent the COC from migrating. Following treatment, the water could be discharged directly to a surface water body or reinjected underground, depending on the site conditions and permitting requirements. Active treatment systems are generally costly to construct and operate but can be designed to effectively lower the concentration of lithium.

Considerations. Use of sorbents for chemical fixation of the COC or use of reverse osmosis is a well-established method to reduce COC concentrations in groundwater. However, this method has never been used for lithium or at CCR sites. While the operation of a groundwater extraction system would effectively provide hydraulic containment of impacted groundwater, it is anticipated that a groundwater extraction and treatment system would have to operate into perpetuity unless source control was also implemented.

Additional Data Needs. Geochemical modeling to evaluate reduction in COC concentrations. Bench-scale screening and treatability testing would be required.

6.1.5 Alternative 5—Permeable Reactive Barrier

Description. Form of in-situ groundwater treatment that can be constructed to remove contaminants. Constructed by excavating a trench that penetrates the saturated zone perpendicular to the direction of groundwater flow, which is keyed into an underlying barrier to groundwater movement such as bedrock. The trench is then backfilled with reactive material while maintaining a transmissivity greater than the surrounding subsurface so that groundwater continues to flow through, rather than around the PRB. The reactive material would likely be media that adsorbs the COC or precipitates the COC to reduce downgradient concentrations. The design of a PRB can involve the use of multiple types of reactive material depending on the target COC. Depending on the COC, multiple types of reactive material may be mixed together to create a single reactive zone or sequentially so that the groundwater passes through several different reactive zones. Example reagents for Pawnee include manganese-oxide, zero valent iron (ZVI), and apatite (phosphate) to precipitate lithium.

A variation of the conventional PRB is a trenchless PRB, which involves the injection of reactive components, in a starch medium that subsequently breaks down, leaving the reactive components behind. The reactive components are injected at the desired depth(s) using a series of wells.

Considerations. The depth to consolidated bedrock is approximately 60 feet below ground surface at the east side of the landfill, this required depth of trench may limit the feasibility. A trenchless PRB would not have this difficulty. First, a trenchless PRB can be installed to depths greater than that achievable using traditional trenching technologies. A funnel-and-gate system can be used to channel the contaminant plume into a gate that contains the reactive material (Obiri-Nyarko et al., 2014). The funnels are non-permeable (e.g., slurry wall), and the simplest design consists of a single gate with walls extending from both sides. The main advantage of the funnel-and-gate system is that a smaller reactive zone can be used to treat the plume, thereby, potentially reducing costs. This alternative treats groundwater downgradient of the landfill; however this alternative will not remove or control the source of the COC to groundwater.

Additional Data Needs. Geochemical, bench-scale, and possible pilot-scale testing will be required to evaluate the optimal reactive media composition, PRB lifespan, selection of the most appropriate reagent(s), and to evaluate potential additional contaminant mobilization.

6.1.6 Alternative 6—In-Situ Solidification

Description. Injection of Portland cement or other binding agent to physically bind ash below the localized water table via creation of a monolith. The mixture is intended to encapsulate the source material resulting in the COC becoming inert. This is accomplished through bench testing of the ash and surrounding soils with potential binding agents to determine the effectiveness of the mixture in immobilizing the COC. Multiple injection techniques are available depending on the binding agent used.

Considerations. In-situ solidification is a potential option to immobilize the COC in the source below the water table rendering it inert.

Additional Data Needs. Additional groundwater flow modeling would be needed to evaluate potential changes to the physical setting. Geochemical, bench-scale, and possible pilot-scale testing will be required to evaluate the optimal binding agent.

6.1.7 Alternative 7—Slurry Wall/Cutoff Wall

Description. Excavation of a trench system coupled with injection of a high slump slurry that when solidified forms an impermeable cutoff wall to prevent groundwater flow from off-site to beneath the landfill and become in contact with ash. The slurry is typically a combination of the excavated trench soils, bentonite, and other potential additives. The slurry mixture forms into a material similar to a soft, clayey soil. This method typically results in a cutoff wall with a permeability ranging from $1x10^{-6}$ to $1x10^{-8}$ cm/sec.

Considerations. Could have some benefit along the west perimeter of the landfill. The wall may result in groundwater mounding on the west side as the gradient changes to flow around the wall. Potential impacts of mounding would need to be evaluated as well as potential mounding impacts to the South Landfill to ensure that the change in groundwater flow does not result in additional impacts to groundwater from the non-CCR landfill. Also, depth to bedrock is greatest in this area, and slurry wall would need to be keyed into bedrock.

Additional Data Needs. This alternative will require modeling scenarios to be run.

Table 6.1-1. Summary of the Corrective Measure Alternatives at the Landfill

Alternative	Description	Performance and Reliability	Additional Data Needs	Relative Ease of Implementation 1 = easy 2 = moderately easy 3 = moderate 4 = moderately difficult 5 = difficult)	Potential Impacts of the Remedy (Safety, cross-media impacts, exposure to residual contamination)	Relative Time Required for Implementation/ Completion of Remedy 1 = 1-5 yrs 2 = 5-10 yrs 3 = 10-50 yrs 4 = 50-100 yrs 5 = 100+ yrs	Institutional Requirements (Permits or other environmental or public health requirements	Recommended for Further Evaluation
Monitored Natural Attenuation (MNA)	Well accepted by state and federal regulators as an appropriate mitigation factor that should be considered when evaluating passive and active remedial options (USEPA, 1999, 2007a, b). Natural attenuation mechanisms include adsorption of COIs, ion exchange, precipitation of COI-containing minerals, and dilution/dispersion. In addition to adsorption to soil, clay particles, and organic matter, iron and manganese oxides that commonly precipitate downgradient of CCR disposal sites will, in turn, remove other COIs by adsorption.	• Accepted as a valid remedial approach. COC concentrations in groundwater should decrease over time if leaching of the COC is reduced or eliminated by source control. • O&M is limited to performance monitoring and would not be reliant on operation or periodic maintenance of engineered systems. • Requires a determination of the existence of sufficient aquifer materials down-gradient of the landfill to attenuate the COC in groundwater within the property boundary. • Transport modeling with slow groundwater flow velocities on site may predict long term presence of elevated COC in groundwater.	This alternative will require modeling scenarios to be run after it is paired with various other alternatives.	1	No additional impacts	1/5 with source control	Notification to adjacent property owners of COC in groundwater being transported onto their properties. Landfill will continue to be monitored per state regulations. Selected alternative will require approval from the State.	Yes
Landfill Cover (partial or complete)	Impermeable cap(s) are placed over existing ash landfill cells. Currently D and E cells have a geosynthetic cover detailed in the closure plan; however remaining cells with existing cover could be reinforced to limit recharge to groundwater, thus limiting the ash leachate to groundwater from the unsaturated ash above the water table.	• Partial source control. • Recharge to groundwater and leaching of the COC is reduced or eliminated from the ash above the water table. • Transport modeling with slow groundwater flow velocities on site may predict long term presence of elevated COC in groundwater. Model simulations may show ash below the water table continuing to be a source of COC to groundwater.	Additional groundwater modeling scenarios will allow for determination of most effective: • Cover materials • Cover thickness	2	No additional impacts	1/5	Landfill will continue to be monitored per state regulations. Selected alternative will require approval from the State.	No, assumed that the primary source of COC to groundwater is the ash below the water table.
Ash Source Removal (partial or complete)	Removal of landfill ash.	• Ash removal will result in a reduction or elimination of the COC from the ash leaching to groundwater. • COC concentrations in groundwater should decrease over time after removal of the source. • Complete or partial source control, including ash below the water table. • Transport modeling with slow groundwater flow velocities on site may predict long term presence of elevated COC in groundwater.	Additional groundwater modeling scenarios will allow for determination of effectiveness of varying the volume and locations of ash removed.	2	No additional impacts	1/4-5	Landfill will continue to be monitored per state regulations. Selected alternative will require approval from the State.	Yes
Pump and Treat	Extraction of groundwater from areas with COC discharging offsite, or newly installed extraction wells targeting the weathered bedrock, and above-ground treatment of COCs.	• Does not remove the source therefore required into perpetuity, or until the COC was completely leached out of the ash.	Geochemical, modeling and bench-scale testing to evaluate the optimal treatment train/reagents (e.g. RO), operational lifespan. Source	5	No additional impacts	1/3 with source control	Landfill will continue to be monitored per state regulations. Selected alternative will require approval from the State.	Yes

Table 6.1-1. Summary of the Corrective Measure Alternatives at the Landfill

Alternative	Description	Performance and Reliability	Additional Data Needs	Relative Ease of Implementation 1 = easy 2 = moderately easy 3 = moderate 4 = moderately difficult 5 = difficult)	Potential Impacts of the Remedy (Safety, cross-media impacts, exposure to residual contamination)	Relative Time Required for Implementation/ Completion of Remedy 1 = 1-5 yrs 2 = 5-10 yrs 3 = 10-50 yrs 4 = 50-100 yrs 5 = 100+ yrs	Institutional Requirements (Permits or other environmental or public health requirements	Recommended for Further Evaluation
			control also required.					
Permeable Reactive Barrier (PRB)	A form of in-situ groundwater treatment that can be constructed to remove contaminants. Constructed by excavating a trench that penetrates the saturated zone perpendicular to the direction of groundwater flow, which is keyed into an underlying barrier to groundwater movement such as bedrock. The trench is then backfilled with reactive material while maintaining a transmissivity greater than the surrounding subsurface so that groundwater continues to flow through, rather than around the PRB.	• Remedial alternative that, once installed, will prevent discharge of the COC beyond the landfill. • Has been successfully implemented at other sites nationwide, has not been implemented for lithium. • Depth to consolidated bedrock (approximately 60 feet below ground surface). • Effectiveness and frequency of reactive material recharge unknown without laboratory bench-scale testing. • Conventional PRB design life is commonly based on decades; therefore, if it is anticipated that the COC will be present long term in groundwater.	Geochemical, bench-scale and possible pilot-scale testing to evaluate the optimal reactive media composition, PRB lifespan, select the most appropriate reagent(s), and evaluate potential additional contaminant mobilization. Availability and quantity of material required for the respective application locations will drive feasibility.	3-4	Addition of reagents or adjustment of pH/redox conditions may mobilize other contaminants in groundwater.	1-2/3	EPA application may be required. Landfill will continue to be monitored per state regulations. Selected alternative will require approval from the State.	Yes
In-situ solidification	Injection of Portland cement or other mixture to physically bind ash below the water table via creation of a monolith. Encapsulates source material and immobilizes the COC.	• Encapsulates the source of the COC below the water table, and limits further migration. • One time implementation with no ongoing O&M. • Ease of implementation when compared to some other remedial alternatives, e.g., ash removal. • Contaminants are not destroyed or removed. • Modeling simulations may show groundwater mounding potential. • Transport modeling with slow groundwater flow velocities on site may predict long term presence of the COC in groundwater. • Leaching of COIs still occurring from the ash above the water table through precipitation infiltration not bound in cement.	Groundwater flow modeling to evaluate potential changes in physical setting.	3	Groundwater mounding potential	1/2-3	Landfill will continue to be monitored per state regulations. Selected alternative will require approval from the State.	Yes
Slurry Wall	Cutoff wall to prevent upgradient, background groundwater to flow beneath the landfill in contact with ash. The wall will serve as an impermeable barrier, sending groundwater flow around the	• Reduces groundwater contact with ash and leaching of the COC. • Low maintenance once installed. • Modeling simulations may show groundwater mounding potential.	This alternative will require modeling scenarios to be run to evaluate degree of effectiveness and.	3	Groundwater mounding potential	1/additional remedy dependent	Landfill will continue to be monitored per state regulations. Selected alternative will require	Yes

Table 6.1-1. Summary of the Corrective Measure Alternatives at the Landfill

Alternative	Description	Performance and Reliability	Additional Data Needs	Relative Ease of Implementation 1 = easy 2 = moderately easy 3 = moderate 4 = moderately difficult 5 = difficult)	Potential Impacts of the Remedy (Safety, cross-media impacts, exposure to residual contamination)	Relative Time Required for Implementation/ Completion of Remedy 1 = 1-5 yrs 2 = 5-10 yrs 3 = 10-50 yrs 4 = 50-100 yrs 5 = 100+ yrs	Institutional Requirements (Permits or other environmental or public health requirements	Recommended for Further Evaluation
	perimeter of the landfill.	• Feasibility of installation should be evaluated due to depth of bedrock, may be too deep as wall must be keyed into bedrock. • Modeling simulations may show incomplete diversion of groundwater flow from off-site.	assist in assessing potential for groundwater mounding.				approval from the State.	

7 References

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Appendix A.
Boring Data

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Geotechnical boring and monitoring well boring lithology data that was used to develop the geologic model

Boring ID	Source File Name	Citation
PNMW-1 (PAMW-1)	URS Final North Landfill Eval rpt Xcel_Complete.pdf	URS, 2009. Pawnee North Landfill Evaluation, Pawnee Station Brush, Colorado. Prepared for Public Service Company of Colorado (PsCo).
PNMW-2 (PAMW-2)		
PNMW-3 (PAMW-3)		
PNMW-4 (PAMW-4)		
PNMW-5 (PAMW-5)		
PNMW-6 (PAMW-6)		
PNMW-7 (PAMW-7)		
PNMW-8 (PAMW-8)		
PNMW-9 (PAMW-9)		
PNMW-1B	Pawnee North Landfill EDO Plan February 2011 Rev. 2.0 Final.pdf	Xcel Energy, 2010. Pawnee Station North Landfill Engineering Design and Operations Plan. Revised 2011.
PNMW-2B		
PNMW-3B		
PNMW-5B		
PNMW-6B		
PNMW-9B		
PNMW-11		
PNMW-10	Pawnee North Landfill EDO Plan_Revised Feb 2017.pdf	Xcel Energy, 2010. Pawnee Station North Landfill Engineering Design and Operations Plan. Revised 2017.
PNMW-12	Pawnee_DRAFT_CCR Amended Well_Install_Report.pdf	HDR, 2017. Monitoring Well Installation Report: for Compliance with the Coal Combustion Residuals (CCR) Rule. Prepared for Xcel.
PNMW-13		
PNMW-14		
PNMW-15		
PNMW-16		
TB-4/PNMW-21		
TB-5/PNMW-22		
TB-6/PNMW-23		
PNMW-17	Eastern_CCR_LF_Geotechnical_Report _Final.pdf	HDR, 2017. Consolidation, Slope Stability and Liquefaction Analysis, Pawnee Station – East CCR North Landfill. Prepared for Xcel.
TB-3/PZ-3		
PNMW-20	Pawnee_CCR Well_Install_Report_12262018.pdf	HDR, 2016. Monitoring Well Installation Report: For Compliance with the Coal Combustion Residuals (CCR) Rule: Pawnee Station. Revised 2018. Prepared for Xcel.
P-19		
PNMW-18		
PNMW-19		
SB-1	Background Study Field Summary_Pawnee_050217.pdf	HDR, 2017. Pawnee Background Soil Study Results Memo. Prepared for Xcel.
SB-2		
SB-3		
SB-4		

SB-5		
SB-6		
PASB-1	EPRI 1996 Boring Logs.pdf	URS, 2009. Pawnee North Landfill Evaluation, Pawnee Station Brush, Colorado. Prepared for Public Service Company of Colorado (PsCo). (in Appendix 3.4)
PASB-2		
PASB-3		
PASB-4		
PASB-5		
PASB-6		
TH-4	1978 Lincoln Devore Boring Logs.pdf	URS, 2009. Pawnee North Landfill Evaluation, Pawnee Station Brush, Colorado. Prepared for Public Service Company of Colorado (PsCo). (in Appendix 3.4)
TH-5		
TH-6		
TH-11		
TH-12		
TH-13		
TH-15		
TH-16		
TH-18		
TH-25		
TH-26		
TH-27		
TH-28		
TH-32		
TH-33		
TH-34		
TH-41		
FB-1	Dames & Moore Test Boring Logs.pdf	URS, 2009. Pawnee North Landfill Evaluation, Pawnee Station Brush, Colorado. Prepared for Public Service Company of Colorado (PsCo). (in Appendix 3.4)
FB-2		
FB-3		
FB-4		
FB-6		
('08) TH-1	URS Test Hole Logs.pdf	URS, 2009. Pawnee North Landfill Evaluation, Pawnee Station Brush, Colorado. Prepared for Public Service Company of Colorado (PsCo). (in Appendix 3.2)
('08) TH-2		
('08) TH-3		
('08) TH-4		
('08) TH-5		
('08) TH-6		
('08) TH-7		
('08) TH-8		
PAW-N1	Pawnee Boring Logs.pdf	HDR, 2019. Pawnee Landfill Draft Boring Logs.
PAW-N2		
PAW-N3		
PAW-N4		

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PAW-S1		
PAW-S2		
PAW-S3		
PAW-S4		

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Appendix B.

North Landfill Geologic Cross-Section

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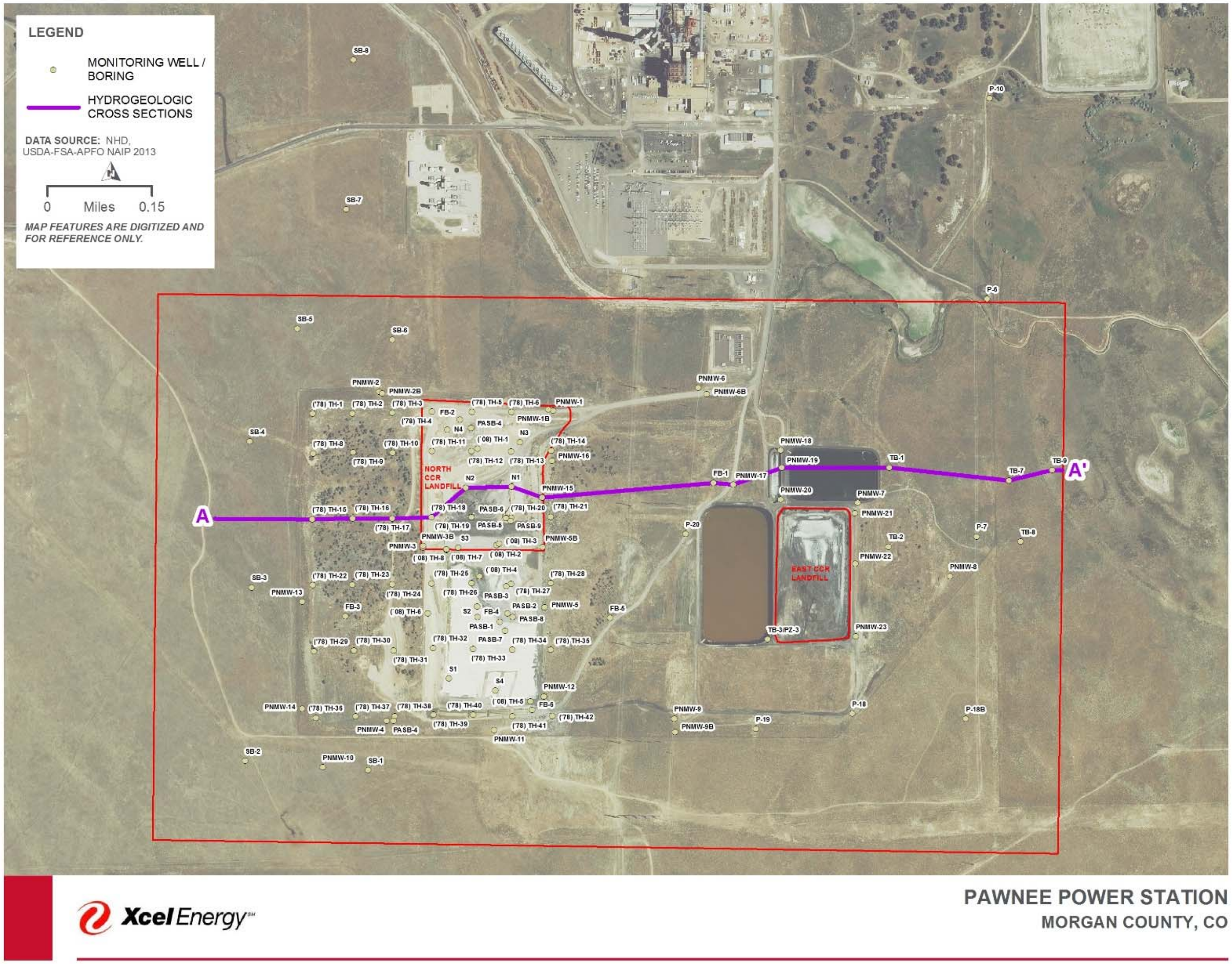
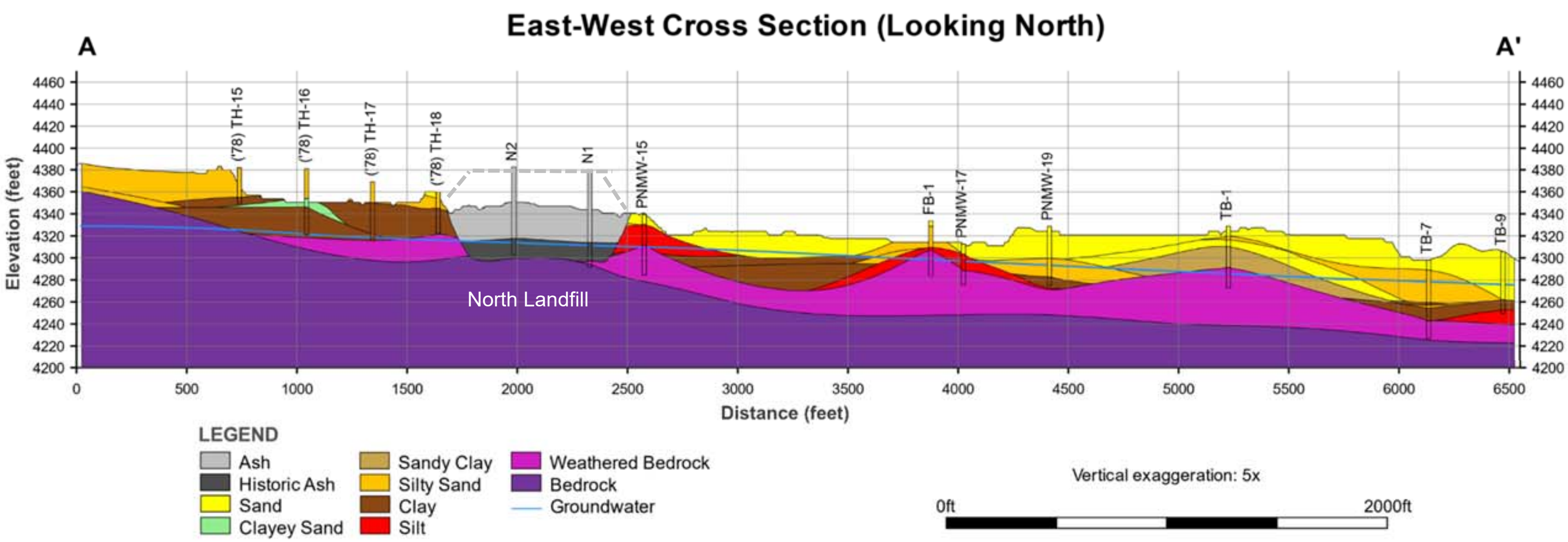

LEGEND
MONITORING WELL / BORING
HYDROGEOLOGIC CROSS SECTIONS
DATA SOURCE: NHD, USDA-FSA-APFO NAIP 2013
0 Miles 0.15
MAP FEATURES ARE DIGITIZED AND FOR REFERENCE ONLY.
A
A'
NORTH CCR LANDFILL
EAST CCR LANDFILL
PAWNEE POWER STATION
MORGAN COUNTY, CO


East-West Cross Section (Looking North)
A
A'
('78) TH-15
('78) TH-16
('78) TH-17
('78) TH-18
N2
N1
PNMW-15
FB-1
PNMW-17
PNMW-19
TB-1
TB-7
TB-9
North Landfill
Elevation (feet)
Distance (feet)
4460
4440
4420
4400
4380
4360
4340
4320
4300
4280
4260
4240
4220
4200
0
500
1000
1500
2000
2500
3000
3500
4000
4500
5000
5500
6000
6500
LEGEND
Ash
Historic Ash
Sand
Clayey Sand
Sandy Clay
Silty Sand
Clay
Silt
Weathered Bedrock
Bedrock
Groundwater
Vertical exaggeration: 5x
0ft
2000ft