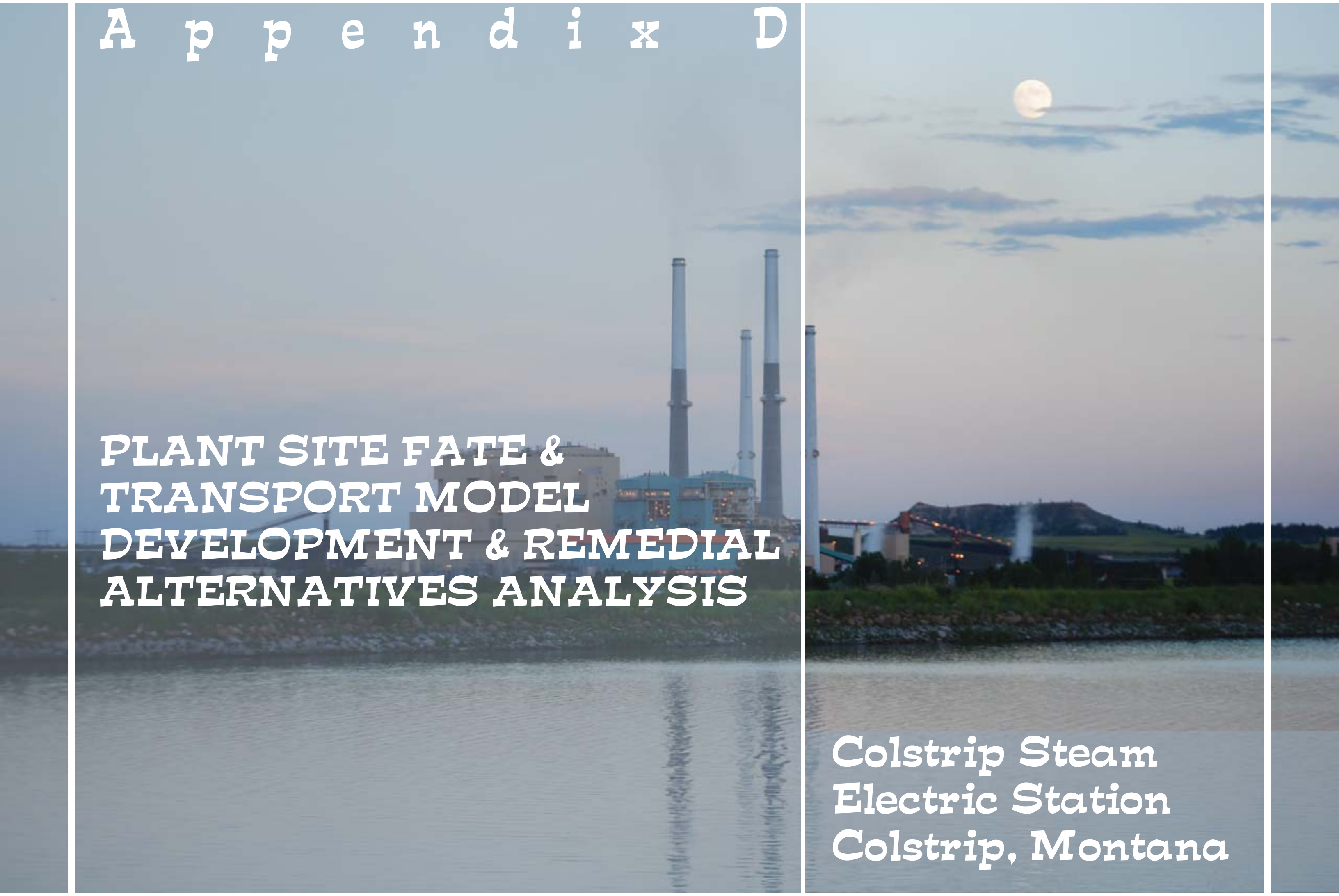
TALEN ENERGY

Appendix D



PLANT SITE FATE & TRANSPORT MODEL DEVELOPMENT & REMEDIAL ALTERNATIVES ANALYSIS

Colstrip Steam
Electric Station
Colstrip, Montana

NewFields

june 2018

Plant Site Fate and Transport Model Development and Remedial Alternative Analysis

Colstrip Steam Electric Station
Colstrip, Montana

Prepared for:
Talen Montana, LLC.
P.O. Box 38
Colstrip, Montana 59323

Prepared by:
NewFields Companies, LLC
700 SW Higgins Suite 15
Missoula, Montana 59803
U.S.A.

NewFields

Revised June 2018

EXECUTIVE SUMMARY

This report describes methods and results of hydrogeologic analysis completed for the Plant Site Area at the Colstrip Steam Electric Station (CSES) in Colstrip, Montana (**Figure 1-1**). The work was completed to provide information to assist with the Plant Site Remedy Evaluation being completed by Geosyntec Consultants (Geosyntec, 2015a) to comply with the Administrative Order on Consent (AOC) regarding impacts related to wastewater facilities at the CSES (MDEQ and PPLM, 2012). The Remedy Evaluation addresses potential actions to remediate impacts to groundwater related to the surface impoundments (ponds or cells) used to manage process wastewater and coal ash (flyash and bottom ash) at the Plant Site. The Plant site is one of the three areas identified in the AOC for the CSES.

A numerical groundwater flow model previously developed for the Plant Site Area was used in the analysis described in this report. Groundwater modeling at the Plant Site Area began in 2004, and conceptual and numerical groundwater models of the groundwater system in the Plant Site Area have been updated periodically as additional data have been collected. NewFields (2015) provides a detailed description of model development along with the latest conceptual model and numerical model that has been approved by the Montana Department of Environmental Quality (MDEQ).

Groundwater Quality

Maps showing the distribution of constituents including boron, sulfate, total dissolved solids (TDS), cobalt, lithium, manganese, molybdenum, and selenium within alluvium and spoils, coal-related and Sub-McKay hydrostratigraphic units were prepared. In addition, maps showing the extent of groundwater exceeding PCC for these constituents in individual model layers (Layers 1 through 5) were developed to provide input for capture analysis. Cobalt, lithium, manganese and molybdenum data are available for CCR wells only, which are currently restricted to the edges of the ponds.

Boron and sulfate isoconcentration contour maps were generated for each model layer to create initial conditions for fate and transport modeling. Sulfate and boron were selected as representative constituents for fate and transport analysis supporting the Plant Site Remedy Evaluation. Sulfate was selected as representative of conservative solutes (constituent that is not affected by adsorption or chemical reactions during transport in groundwater). Boron was selected to represent constituents that are transported in groundwater more slowly due to adsorption to solids in the aquifer.

Several hydrostratigraphic cross-sections showing the distribution of boron and sulfate with depth along with groundwater elevation and flow directions were prepared to present the vertical distribution of these constituents. Deep wells are present in most areas with concentrations below the PCC that adequately define the vertical extent of impacts. There are a few areas (e.g. near well 55D) where deep wells with concentrations below PCC are not available. All these areas are near capture wells where vertical gradients are upward, indicating that further downward migration is unlikely in those areas. Based on cross sections and well screen intervals, the assumed base elevations of the boron and sulfate plumes are 3,180 and 3,201 feet, above mean sea level (amsl), respectively.

Three-dimensional plume imagery was developed to support fate and transport modeling and provide better understanding of the three-dimensional distribution of boron and sulfate in groundwater at the Plant Site. The plume is defined as the area where groundwater concentrations exceed the PCC. Animated plume imagery that illustrates the lateral and vertical distribution of boron and sulfate exceeding PCC under all portions of the Plant site is included.

Flow Model Adjustments

Since the Model Update Report (NewFields, 2015) was issued, additional capture wells have been added to the system and flow rates have been adjusted. The array of capture system wells and average pumping rates from 2016 were used for the capture and fate and transport analysis described in this report. In addition, seepage rates were adjusted to reflect updated seepage estimates for the Units 1 & 2 B Pond and Units 1 & 2 Bottom Ash Clear Well.

Updated Capture Analysis

The capture analysis described in the Model Update Report (NewFields 2015) was updated using new plume maps created for the Plant Site. The capture analysis used particle tracking to evaluate the capture of particles within a 50-year period using a steady-state flow field. Results were similar to previous capture analysis completed in 2015.

Fate and Transport Model Development

A numerical solute transport model was developed to help evaluate fate and transport based on the MDEQ-approved groundwater flow model. The goal was to provide a tool for comparing fate and transport of constituents under a variety of remedial alternatives. The model was developed using the same software as the flow model (MODFLOW-SURFACT).

Sulfate and boron were selected as representative constituents for fate and transport analysis supporting the Plant Site Remedy Evaluation. In selecting these constituents, the goal was to identify two constituents that were widely distributed in groundwater and represented a range of transport velocity. Sulfate was selected as being representative of conservative solutes. Boron was selected to represent constituents that are transported in groundwater more slowly due to adsorption to solids in the aquifer.

Sulfate and boron plume maps for model Layers 1 through 5 were used to assign initial concentrations for fate and transport modeling. Initial concentrations for boundary conditions representing source areas were assigned based on pond water quality data. Solute transport parameters including effective porosity, dispersivity coefficients, and retardation coefficients (for boron) were assigned using estimates form literature values and site data.

A qualitative calibration of the transport model was then completed to demonstrate that the model is generally capable of simulating observed concentrations and distribution of constituents. During calibration, source concentrations were adjusted until simulated concentrations in groundwater generally matched observed concentrations.

Alternatives Analysis

NewFields used the fate and transport model to help evaluate various remedial alternatives to support the Plant Site Remedy Evaluation. Based on MDEQ comments the alternatives analysis considers the edge of the ponds as the point of compliance (POC) for remedy implementation. The analysis discussed in this report evaluates the ability of each remedial alternative to meet PCC for sulfate and boron outside of the POC. Based on MDEQ comments, the goal is to be able to stop operating the groundwater capture system by 2049 (approximately 30 years after remedy implementation) while meeting remedial objectives.

As part of the Remedy Evaluation, Geosyntec developed four remedial alternatives:

- **Alternative 1 – No Further Action**: This alternative assumes those remedial actions implemented by December 2016 will remain in-place and continue to be operated, but no additional remedial measures are taken.
- **Alternative 2 – Source Control Upgrades, Point of Use (POU), Monitored Natural Attenuation (MNA), and Institutional Controls**

  Same as Alternative 1 plus:

  - Upgrade/close ponds per construction schedule in Revised Remedy Evaluation (Geosyntec, 2017a).
  - Consider discontinuing operation of select distal capture wells, where appropriate.
  - Discontinue POU monitoring when no longer needed.
  - Conduct additional field and laboratory investigation, monitoring and modeling to demonstrate MNA of distal groundwater plumes.
  - Implement institutional controls.
- **Alternative 3 – Source Control Upgrades, Enhance/Upgrade Existing Capture System, POU, MNA, and Institutional Controls**

  Same as Alternative 2 plus:

  - Modify pumping rates of existing vertical source area and downgradient (distal) capture wells.
  - Install additional vertical source area and downgradient (distal) capture wells.
  - Add new vertical capture wells to replace wells removed for construction of the new Brine Concentrator Solids Disposal Area.
- **Alternative 4 – Aggressive Source Control Upgrades, Enhance/Upgrade Existing Capture System, POU, MNA, and Institutional Controls**

  Same as Alternative 3 plus:

  - Install horizontal capture wells beneath two source areas, Former Units 1 & 2 A Pond and Former Brine Ponds D1 – D4, that appear to have longer cleanup timeframes in Alternatives 1-3.
  - Evaluate dewatering ash in Former Units 1 & 2 A Pond to further reduce seepage after capping.

    - Install vertical injection wells on either side of the horizontal capture wells and inject clean water to increase the flux of groundwater constituents removed by the enhanced/upgraded capture system and achieve more aggressive cleanup timeframes.
    - Turn off existing vertical capture wells in areas where groundwater constituents achieve Potential Cleanup Criteria (PCC) to maintain water balance for Plant Site operations.
    - As a contingency where MNA cannot be demonstrated, a permeable reactive barrier (PRB) may replace portion(s) of the capture system where boron and sulfate have achieved the PCC, but other less mobile groundwater constituents have not, in order to shut down the injection/capture system sooner.

Transport model simulations were developed for each of the four alternatives. Stress periods were developed to allow for simulation of changes in pumping and seepage rates that are anticipated to occur over time in each of the remedial alternatives. The simulation period runs form the end of 2016 through 2149. This includes the period during operation of the groundwater capture system through 2049 as well as a 100-year post-pumping period.

Interim milestones were established to assess the relative progress of cleanup over time. Milestones are achieved as boron and sulfate concentrations drops below PCC outside of each of the following three areas:

- Distal areas more than 500 feet from the source area;
- Outside the plant property; and
- Beyond the pond perimeter.

The interim milestones for boron are achieved at the following times:

- Distal areas more than 500 feet from the source area
    - Alternative 2 and 3 – not met by the end of 2149
    - Alternative 4 - by end of year 2039
- Outside the plant property
    - Alternatives 2 and 3 - by end of year2129
    - Alternative 4 - by end of year 2049
- Beyond the pond perimeter
    - Alternatives 2 and 3 - not met by end of 2149
    - Alternative 4 - by end of year 2049.

Interim milestones for sulfate are achieved in Alternative 2 at the following times:

- Outside the plant property – by end of year 2034;

- Distal areas more than 500 feet from the source area – by end of year 2039; and
- Beyond the pond perimeter – by end of year 2039.

Alternatives 3 and 4 sulfate simulations were not conducted because simulated sulfate levels dropped below the PCC by the end of 2049 in Alternative 2 and Alternatives 3 and 4 will enhance removal of impacted groundwater from the system.

Quantitative Assessment of Alternatives

Results of predictive simulation for remedial alternatives were evaluated quantitatively to allow for comparison of the effectiveness of each alternative at reducing the amount of dissolved sulfate and boron mass leaving the Plant Site and reducing the overall volume and mass of groundwater exceeding the PCCs. The predicted discharge of sulfate and boron mass flowing through fourteen transects and mass discharge from capture wells was estimated for each alternative. In addition, the volume and mass of groundwater exceeding the sulfate and boron PCC was estimated for different periods for each alternative.

Mass discharge in Alternative 4 is greatly reduced relative to Alternatives 2 and 3 at transects that had PCC exceedances. Alternatives 2, 3, and 4 all meet the PCC by 2069 at all other transects, however, the mass discharge of boron across most of these transects is lowest in Alternative 4.

Table ES-1 summarizes the cumulative rate of mass discharge of boron and sulfate from capture wells calculated from simulations of each alternative at selected periods. Comparison of the cumulative boron mass removal from all wells between Alternatives 2, 3, and 4, shows Alternative 3 cumulative mass discharge is slightly higher than Alternative 2, and Alternative 4 mass discharge is slightly higher in 2029 than Alternative 3. This is likely a result of higher overall pumping in Alternative 3 compared to Alternative 2 and higher overall pumping in Alternative 4 compared to Alternative 3, respectively.

Table ES-1. Predicted Cumulative Rate of Mass Flux of Boron at Wells.

Alternative	Boron (kg/day)		
	Baseline - 2016	End of 2029	End of 2049
Alternative 1	6.15	3.93	3.51
Alternative 2	6.15	2.72	1.97
Alternative 3	6.15	3.47	2.26
Alternative 4	6.15	3.59	1.61
Alternative	**Sulfate kg/day)**		
Alternative 1	5108	3476	2422
Alternative 2	5108	3299	2065

Table ES-2 summarizes the predicted change in volume of groundwater exceeding the PCC for each alternative for boron and sulfate. The volume of the groundwater exceeding the boron PCC calculated from the transport model for the 2016 baseline is 306 acre-feet. The predicted volumes of the boron plume in Alternative 3 are less than the predicted volumes of the plumes in Alternative 2 in comparable years. The boron plume volume under Alternative 4 decreases 93% by 2049, 97%, by 2069, and 100% by 2099. The sulfate plume decreases in volume after 2016 in Alternatives 1 and 2. Because Alternatives 3 and 4 are more aggressive, the sulfate plume volume would decrease even faster. Sulfate plume volumes in Alternative 2 are much less than Alternative 1 volumes. Under Alternative 2 the sulfate plume volume decreases by 100% by the end of 2049.

Table ES-2. Predicted Volume of Groundwater Exceeding PCC

Layer	Baseline (2016)	Alternative 1	Alternative 2		Alternative 3		Alternative 4	
		End of 2049	End of 2049	End of 2069	End of 2049	End of 2069	End of 2049	End of 2069
Volume of Boron (Acre-FT)	306	226	181	348	83	303	21	8
Percent Reduced from Baseline	0	26%	41%	-12%	73%	1%	93%	97%
Volume Sulfate (Acre-FT)	1,079	347	0.3	0				
Percent Reduced from Baseline	0	68%	100%	100%				

Table ES-3 summarizes the predicted change in mass of boron and sulfate exceeding the PCC for each alternative. The mass within the plume above PCC decreases after 2016 in all alternatives; however the mass within the boron plume increases from 2049 to 2069 in Alternatives 2 and 3. This is because after the capture system is shut down in 2049 areas in Layers 1, 2 and 3 are re-saturated (see **Section 6.4.2**).

The predicted boron masses in Alternative 4 are less than the predicted mass of the plumes in Alternatives 2 or 3 in equivalent years. Under Alternative 4, the plume mass above PCC decreases from 5,051 kg in 2016, to 47 kg in 2069 to zero kg in 2099; the plume mass decreases 97% by 2049 and 99% by of 2069. Sulfate plume masses above PCC in Alternative 2 are much less than Alternative 1 in comparable years. Simulation of Alternative 2 shows the mass of the sulfate plume decreases 100% by the end of 2049.

Table ES-3. Predicted Mass Exceeding PCC

Layer	Baseline (2016)	Alternative 1	Alternative 2		Alternative 3		Alternative 4	
		End of 2049	End of 2049	End of 2069	End of 2049	End of 2069	End of 2049	End of 2069
Mass of Boron (Kilograms)	5051	4124	1812	3252	819	3,016	141	47
Percent Reduced from Baseline	0	18%	64%	36%	84%	40%	97%	99%
Mass of Sulfate (Kilograms)	5,598,602	3,015,801	1,121	0				
Percent Reduced from Baseline		46%	100%	100%				

Sensitivity Analysis

A sensitivity analysis was performed on the calibrated transport model by systematically adjusting both boron (Alternative 4) and sulfate (Alternative 2) models. The sensitivity analysis is designed to evaluate the sensitivity in model predictions related to effectiveness of the selected remedial alternative with respect to the following key model inputs: source concentrations; pond seepage rates; hydraulic conductivity; retardation factor; and effective porosity.

Model predictions are not sensitive to the range of changes tested for source concentrations, seepage rates, hydraulic conductivity, or effective porosity. Model predictions for boron are sensitive to retardation coefficient values based on an order of magnitude increase in K_d value; however, empirical data suggest that the higher K_d value tested is not representative of aquifer materials at the Plant Site.

Conclusions

Based on the work described in this report, NewFields offers the following conclusions.

- The overall lateral extent of impacted groundwater based on 2016 data is similar to previous delineations.
- Data available to assess the extent of cobalt, molybdenum, lithium and manganese are spatially limited. More data may be needed to fully characterize the extent of groundwater exceeding PCC for these constituents.
- Lithium, manganese, and cobalt exceed the PCC in groundwater in some wells near source areas;
- Molybdenum concentrations exceeding PCC have been detected in samples from only one well analyzed for this constituent; this suggests that molybdenum concentrations exceeding the PCC are not widespread in groundwater at the Plant Site.
- Selenium concentrations exceeding the PCC are not widespread.
- Concentrations of sulfate, TDS, and selenium in groundwater near well 38SP exceed PCC (or BSL for TDS); the source of constituents detected in this well is not thought to be Plant Site process ponds.
- Surface releases from a flyash slurry pipeline are the likely source of sulfate and TDS exceedances in alluvial groundwater in wells near OT-7. Canty (2017) found that soil remaining in former pipeline release sites does not represent either a human health or ecological risk.
- The vertical extent of groundwater exceeding PCC has been adequately delineated for purposes of remedy selection. There are a few areas (e.g. near well 55D) where the vertical limit of the plume has not been completely defined. All these areas are near capture wells where vertical gradients are currently upward, indicating that further downward migration is unlikely in those areas.
- Updated capture analysis (particle tracking) using 2016 data produced results similar to those in the Model Update Report (NewFields, 2015).

- A qualitative calibration of the solute transport model demonstrates that the model is generally able to simulate the observed extent of boron and sulfate exceeding PCC as well as the general range of observed concentrations. This indicates the model is appropriate for comparing the likely relative effectiveness of different remedial alternatives.
- Based on MDEQ comments, an objective of achieving PCC by 2049 was established.
- By 2049, implementation of Alternative 1 would reduce the volume of groundwater above sulfate and boron PCC by approximately 68 percent and 26 percent, respectively. This reduction would not meet cleanup goals, as boron and sulfate concentrations above the PCC would remain outside pond perimeters after 2049.
- Implementation of Alternatives 2 and 3 would reduce sulfate concentrations below PCC outside pond perimeters by the end of 2049 but would not have the same effect on boron concentrations.
- By 2049, implementation of Alternative 2 is estimated to reduce the volume of groundwater above sulfate and boron PCC by 100 percent and 41 percent, respectively, but the boron plume expands after capture well shutdown in 2049. Alternative 2 does not meet cleanup goals for boron.
- By 2049, implementation of Alternatives 3 would reduce the volume of groundwater above the boron PCC by approximately 73 percent, but the plume expands after capture well shutdown in 2049. Alternative 3 does not meet cleanup goals for boron.
- Alternative 4 reduces the volume of groundwater above the boron PCC by approximately 93 percent by 2049, and the plume does not expand after capture well shutdown.
- Implementation of Alternative 4 would meet cleanup goals and reduce boron and sulfate concentrations outside of pond perimeters below PCC by 2049.
- Alternative 4 reduces the mass of boron above PCC by 97 percent in 2049 and by 99 percent in 2069.
- Alternatives that rely on groundwater capture and source control only do not meet cleanup goals for boron by 2049 because boron mass is trapped in the unsaturated zone due to drawdown from capture and elimination of seepage from source ponds. Implementation of injection combined with extraction (Alternative 4) flushes boron toward capture wells more quickly.
- Model predictions are not sensitive to the range of changes tested for source concentrations, seepage rates, hydraulic conductivity, or effective porosity.
- Model predictions for boron are sensitive to retardation coefficient values based on an order of magnitude increase in K_d value; however, empirical data suggest that the higher K_d value tested is not representative of aquifer materials at the Plant Site.

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ACRONYMS AND ABBREVIATIONS

µmhos/cm	micromhos per centimeter
amsl	above mean sea level
AOC	Administrative Order on Consent
BSL	Background Screening Level
CCRA	Cleanup Criteria and Risk Assessment
COI	Constituent of Interest
CSES	Colstrip Steam Electric Station
EHP	Effluent Holding Pond
FWL5	Fracture Well 5
GHB	General Head Boundary
gpm	gallons per minute
kg/day	kilograms per day
MDEQ	Montana Department of Environmental Quality
MNA	Monitored Natural Attenuation
mg/L	milligrams per liter
PCC	Proposed Cleanup Criteria
PDF	Portable Document Format
POU	Point of Use
PPLM	PPL Montana, LLC
SC	specific conductance
SOEP	Stage I Evaporation Pond
STEP	Stage II Evaporation Pond
Talen	Talen Montana, LLC.
TDS	Total Dissolved Solids
WECO	Western Energy Company

1.0 INTRODUCTION

This report describes methods and results of a hydrogeologic analysis completed for the Plant Site Area at the Colstrip Steam Electric Station (CSES) in Colstrip, Montana (**Figure 1-1**). This report has been prepared by NewFields Consultants, Inc. (NewFields) on behalf of Talen Montana, LLC (Talen), the successor of PPL Montana, LLC (PPLM). The work was completed to provide information supporting a Remedy Evaluation for the Plant Site Area. The Revised Remedy Evaluation (Remedy Evaluation) is being completed by Geosyntec Consultants (Geosyntec, 2017a) to comply with an Administrative Order on Consent (AOC) addressing impacts related to wastewater facilities at the CSES (MDEQ and PPLM, 2012). The Plant Site is one of the three areas identified in the AOC. The Remedy Evaluation addresses potential actions to remediate releases from the wastewater systems that have resulted in concentrations of chemical constituents in groundwater that are elevated relative to Proposed Cleanup Criteria (PCC) identified in the Cleanup Criteria and Risk Assessment Report (CCRA; Canty 2017).

Figure 1-2 is a site map that shows the locations of site features including process ponds and capture system wells. A numerical groundwater flow model developed for the Plant Site Area was used in the analysis described in this report. Groundwater modeling at the Plant Site Area began in 2004, and conceptual and numerical groundwater models of the groundwater system in the Plant Site Area have been updated periodically as additional data have been collected. NewFields (2015) provides a detailed description of model development along with the latest conceptual model and numerical model that has been approved by the Montana Department of Environmental Quality (MDEQ).

Work completed by NewFields to support the Plant Site Remedy Evaluation includes the following general tasks:

- Creating maps showing the extent of groundwater exceeding PCC for selected constituents based on 2016 data;
- Updating capture system analysis completed by NewFields (2015) with particle starting locations within the zones exceeding PCC consistent with the plume maps;
- Developing a fate and transport model using MDEQ-approved groundwater flow model of the Plant Site Area;
- Developing and executing predictive simulations to provide information for comparing various remedy alternatives;
- Calculating volume and mass of groundwater exceeding PCC;
- Calculating mass discharge of selected groundwater constituents across several transects and from capture system wells; and
- Performing sensitivity analysis on model predictions.

The following sections describe:

- Groundwater quality information supporting the Remedy Evaluation;

- Methods and results of updated capture analysis;
- Development of the fate and transport model;
- Methods and results of fate and transport analysis;
- Quantitative assessment of alternatives;
- Sensitivity analysis of fate and transport simulations;
- Model limitations; and
- References.

Referenced figures and tables are presented in **Appendix A** and **Appendix B**, respectively. **Appendix C** contains supporting water quality data. **Appendix D** discusses the selection of representative constituents for fate and transport analysis. **Appendix E** contains cross sections showing boron and sulfate concentrations and groundwater flow across the Plant Site. **Appendix F** contains charts showing the relationship between water quality and groundwater elevations in well 38SP. **Appendix G** contains sulfate and boron concentration data for surface water stations in East Fork Armells Creek.

2.0 GROUNDWATER QUALITY

This section discusses the lateral and vertical extent of groundwater constituent concentrations in various stratigraphic units including alluvium, spoils, overburden, Rosebud Coal, interburden, McKay Coal, and Sub-McKay bedrock at the CSES Plant Site. A detailed description of hydrostratigraphy is provided in NewFields (2015).

Groundwater beneath some portions of the Plant Site contains chemical constituents at concentrations exceeding Background Screening Levels (BSLs; Neptune, 2016). The AOC (MDEQ and PPLM, 2012) lists “regulated substances” that are potentially subject to control actions, including boron, sulfate, specific conductivity (SC), total dissolved solids (TDS), magnesium, sodium, potassium, and selenium. The AOC identifies COIs as those parameters (constituents) found in soil, groundwater, or surface water that: (1) result from Site operations and the wastewater facilities; and (2) exceed background or unaffected reference area concentrations.

Several COIs are present in process water at concentrations higher than in background groundwater and are therefore useful as indicator parameters. Neptune (2016) calculated BSLs designed to help evaluate the extent of groundwater impacted by CSES operations. Historically, this suite of indicator parameters has been used along with multiple lines of evidence to assess whether groundwater has been affected by process ponds (Maxim, 2004; Hydrometrics, 2015a; NewFields, 2015), including TDS, SC, dissolved boron, chloride, sulfate, and calcium-to-magnesium ratio. DEQ and Talen have agreed that chloride will be used as a secondary indicator and will not be used as a standalone indicator of impacted groundwater.

The CCRA Report (Canty, 2017) for the Plant Site lists PCC for groundwater. **Table 2-1** lists groundwater constituents assessed in the Remedy Evaluation and PCC developed for each constituent as part of the risk assessment process. These PCC are used to help evaluate the potential effectiveness of remedial alternatives. Although TDS is considered in the Remedy Evaluation, no PCC is developed for TDS in the CCRA Report (Canty, 2017). All comparisons of TDS in this study are in relation to BSLs developed by Neptune (2016).

2.1 LATERAL EXTENT OF GROUNDWATER EXCEEDING PROPOSED CLEANUP CRITERIA

This section describes the lateral extent of constituents in groundwater exceeding PCC (or exceeding BSL for TDS). Maps showing the extent of boron, sulfate, cobalt, lithium, manganese, molybdenum, and selenium PCC exceedances and TDS BSL exceedances, by hydrostratigraphic unit and by model layer are presented and discussed.

2.1.1 Distribution of Constituents in Groundwater by Unit

Figures 2-1 through **2-17** are maps showing the distribution of boron, sulfate, TDS, cobalt, lithium, manganese, molybdenum, and selenium within alluvium and spoils, coal-related and Sub-McKay hydrostratigraphic units. Data used to create these maps are contained in **Appendix C.** These figures show wells exceeding PCC listed in **Table 2-1** developed by Canty (2017). Groundwater quality data shown are the most recent data available for 2016.

Maps for boron, sulfate, TDS, and selenium show the estimated extent of the constituent concentrations that exceed PCC (or BSL for TDS) in groundwater within each hydrostratigraphic unit. The number of wells sampled for cobalt, lithium, and manganese is more limited making it difficult to fully delineate the extent of groundwater exceeding PCC for these constituents. For this reason, maps for these constituents highlight wells with groundwater containing concentrations that exceed PCC but do not show the estimated extent of groundwater exceeding PCC.

2.1.1.1 Alluvium

Figures 2-1 through **2-8** are maps showing the distribution of boron, sulfate, TDS, cobalt, lithium, manganese, molybdenum, and selenium in wells completed in alluvium and spoils. These figures indicate that groundwater in alluvium above PCC (or BSL for TDS) for one or more constituents extends from south of the Former Units 1 & 2 A Pond near well 147A to north of well 81A. The area of exceedance also extends from east of the Units 1 & 2 B Pond west to wells completed in alluvium along East Fork Armells Creek alluvium (e.g. CA-18, 108A, 49S).

Concentrations exceeding the sulfate PCC and TDS BSL occur in the area west of East Fork Armells Creek between well OT-7 and the City of Colstrip Sewage Lagoons. Concentrations exceeding the PCC for sulfate and BSL for TDS in this area are a result of two surface releases from pipelines in this area (Canty, 2017). The pipeline releases were remediated (Hydrometrics, 2015b). The CCRA Report (Canty, 2017) included a comparison of soil concentrations in surface soil versus near surface soil depth intervals, as well as an analysis of vadose zone travel time, and concluded that the leaching of constituents to groundwater does not constitute a human health or ecological risk.

Figure 2-5 shows that all alluvial wells sampled for lithium exceeded the PCC, including wells 63S and 104A, which are cross gradient (west) and upgradient (southwest), respectively of the Plant Site. Several wells in the Former Units 1 & 2 A and B Pond area exceed PCC for manganese (**Figure 2-6**). Cobalt, molybdenum, and selenium were below PCC in samples from alluvial wells displayed on **Figures 2-4**, **2-7**, and **2-8**, respectively. Although selenium concentrations for wells 42S and 47S shown in **Figure 2-8**, which were collected October 20, 2016, are below the PCC, samples from these wells collected in April 2016 contained concentrations of selenium exceeding the PCC (0.052 mg/L and 0.196 mg/L, respectively).

2.1.1.2 Spoils

The extent of groundwater in spoils where PCC for sulfate and TDS are exceeded extends from well 38SP south of Pond C northeast to near wells 84SP and 86SP (just west of the Units 3 & 4 Bottom Ash ponds). The western limit of the PCC exceedances in spoils is generally constrained by the western limit of the spoils backfill (just west of wells 126SP, 17SP, 71SP, 70SP, and 19SP). A small area of groundwater near well U3-1 (immediately north of Unit 3) and wells 140SP and 141SP (north of the North Plan Area Drain Pond) have sulfate and TDS concentrations exceeding PCC. The extent of boron exceeding PCC in spoil material is more limited, extending from well 26SP northeast to well 111SP. Manganese exceeds the PCC in wells 84SP, 89SP and 152SP-CCR northwest of the Units 3 & 4 Bottom Ash Ponds. Molybdenum exceeds the PCC in well 153SP-CCR near the northeast corner of the Units 3 & 4 Bottom Ash ponds. **Figure 2-5** shows that several spoils wells north of the Units 3 & 4 Bottom Ash Ponds exceed PCC for lithium. **Figure 2-8** shows that 38SP is the only spoils well that exceed the PCC for selenium.

Concentrations of sulfate, TDS, and selenium in spoils near well 38SP exceed PCC (or BSL for TDS); the source of constituents detected in this well is not thought to be Plant Site process ponds. As was described in Geomatrix (2007) and NewFields (2015), groundwater elevations in this area have varied considerably over the last 15 years and are influenced by water management in Western Energy Company (WECO) mine lands south of the Plant Site. For example, in March 2004, groundwater flow in spoils near well 38SP was southward from South Cooling Tower Blowdown Pond C and the Unit 3 & 4 Wash Tray Pond toward 38SP (Maxim, 2004). In April 2004, WECO flooded ponds south and west of SP38. Groundwater elevations in well 38SP increased more than 10 feet between May 2004 and January 2005 in response to that flooding, reversing the direction of groundwater flow in this area Charts comparing sulfate and selenium concentrations in well 38SP to groundwater elevations (**Appendix F**) show that during this period in 2004 concentrations of sulfate and selenium in well 38SP increased as groundwater elevations increased and then decreased for the next several years as groundwater elevations decreased. Since 2005, the flow direction has been from well 38SP toward the Plant Site. Water quality trends along with groundwater flow directions indicate that the source(s) of constituents in this well is not from the process ponds at the Plant Site.

2.1.1.3 Coal-Related

Figures 2-9 through **2-14** are maps showing the distribution of boron, sulfate, TDS, cobalt, lithium, and manganese in wells completed wells within coal-related intervals (Rosebud Overburden, Rosebud Coal, interburden and McKay Coal). Maps of selenium and molybdenum in coal-related groundwater were not included because the most recent selenium and molybdenum concentrations in wells completed in coal-related strata are all below the PCC. Although the selenium concentration in the sample from well 151M-CCR that was collected in December 2016 was below the PCC, a sample from this well collected in September 2016 contained a dissolved selenium concentration (0.066 mg/L) that exceeds the PCC. However, the September 2016 sample had a Total Recoverable Selenium concentration below the reporting limit (0.002 mg/L.) According to Hydrometrics, the discrepancy is thought to be a function of sampling technique.

Figures 2-10 shows that sulfate above PCC in groundwater of coal-related strata extends from south of the South Cooling Tower Blowdown Pond C near well 6M north to well U3-2 and extends from the western extent of coal-related strata (wells 98M, 61M, 57M-P, 56M-P, and 31M) to the eastern extent of Rosebud Coal (wells 90R, 12R-2) and east of the Wash Tray Pond (near wells 17M, 16M). **Figure 2-11** shows that the extent of TDS concentrations exceeding the BSL is similar to the extent of sulfate exceeding the PCC. **Figure 2-9** shows the extent of groundwater exceeding the boron PCC is more limited and includes the area beneath Former Units 1 & 2 A Pond to the western extent of the saturated McKay and north to well 31M and a small area east of the 3 & 4 Wash Tray pond (wells 9M and 142R). Most wells adjacent to the Units 1 & 2 B Pond and the Units 1 & 2 Bottom Ash Ponds exceed the PCC for cobalt, lithium, and manganese (**Figures 2-12** through **2-14**).

2.1.1.4 Sub-McKay

Figures 2-15 and **2-16** show the lateral extent of groundwater exceeding PCC for boron and sulfate. **Figure 2-17** shows the lateral extent of TDS above the BSL. Maps are not included for cobalt, lithium, manganese, and molybdenum because samples from Sub-McKay wells have not been analyzed for those constituents.

In addition, a map for selenium in Sub-McKay groundwater was not included because selenium concentrations in all Plant Site Sub-McKay wells sampled in 2016 were below the PCC.

The area of TDS exceedance in the Sub-McKay unit is relatively small and narrow, extending from well 110D west of Former Units 1 & 2 A Pond north to well 80D and west to well 15S. In addition, TDS concentrations from samples from well 24S are greater than the BSL. Well 55D is the only well exceeding the boron PCC in the Sub-McKay interval, and well 110D is the only Sub-McKay well exceeding the sulfate PCC.

2.1.2 Extent of Groundwater Exceeding PCC by Model Layer

To provide a general understanding of overall groundwater impacts at different depths, maps showing wells exceeding the BSL for TDS, and exceeding PCC for boron, sulfate, cobalt, lithium, manganese, molybdenum, and/or selenium in individual model layers (Layers 1 through 5) were developed as shown in **Figures 2-18** through **2-22.** Several steps were completed in creating these figures. First, wells were assigned to model layers based on the hydrostratigraphic unit(s) they are screened in. Wells that are screened across more than one model layer were included in each layer in which they are screened. Then, concentrations of each constituent at each well in each layer were plotted. For each model layer, polygons were drawn encompassing all PCC exceedances for all constituents. Most model layers contain more than one stratigraphic unit; and therefore, multiple PCC may apply to different portions of a single layer. The extent of these polygons was then compared to the maps of PCC exceedance by stratigraphic unit (**Figures 2-1** through **2-17**) to assure consistency. Information used to create **Figures 2-18** through **2-22** are summarized below:

- Layer 1 (**Figure 2-18**) – PCC exceedances in wells screened in Layer 1 and plume maps for alluvium, coal-related, and spoils (**Figures 2-1** through **2-14**).
- Layer 2 (**Figure 2-19**) – PCC exceedances in wells screened in Layer 2 and plume maps for alluvium, coal-related, and spoils (**Figures 2-1** through **2-14**).
- Layer 3 (**Figure 2-20**) – PCC exceedance measured in wells completed in Layer 3 and plume maps for alluvium and coal-related (**Figures 2-1** through **2-14**). Due to the smaller number of wells screened in interburden, it was assumed that areas exceeding PCC in the McKay Coal would also exceed PCC in the overlying interburden.
- Layer 4 (**Figure 2-21**) – PCC exceedances in wells screened in Layer 4 and the plume maps for alluvium and coal-related strata (**Figures 2-1** through **2-14**).
- Layer 5 (**Figure 2-22**) – PCC exceedances in Layer 5 Sub-McKay wells and plume maps for Sub-McKay (**Figures 2-15** through **2-17**).

2.2 SELECTION OF CONSTITUENTS FOR FATE AND TRANSPORT ANALYSIS

Sulfate and boron were selected as representative constituents for fate and transport analysis supporting the Plant Site Remedy Evaluation. The process used to select these representative constituents is described in **Appendix D**. The goal was to identify constituents that were widely distributed in groundwater and represented a range of transport velocity. Sulfate was selected as being representative of conservative solutes (constituent that is not affected by adsorption or chemical reactions during transport in groundwater). Boron was selected to represent constituents that are transported in groundwater more slowly due to adsorption to solids in the aquifer.

Plume maps for model Layers 1 through 5 were generated for both sulfate and boron to provide inputs for fate and transport modeling. The process of generating these maps is described in the following section.

2.3 DISTRIBUTION OF BORON AND SULFATE IN THREE DIMENSIONS

This section describes mapping and imagery developed to provide better understanding of the distribution of boron and sulfate with depth in groundwater and provide concentration inputs for fate and transport modeling.

2.3.1 Extent of Sulfate and Boron PCC Exceedances with Depth

To help evaluate the extent of impacted groundwater with depth, cross sections were constructed showing sulfate and boron concentrations. Two north-south cross sections and four east-west cross sections were constructed for both boron and sulfate constituents. **Appendix E** includes the cross sections along with a map showing cross section locations (**Figure E-1**).

Figures E-2 through **E-13** present the cross sections. The cross sections were prepared using 2016 water quality data in **Appendix C.** The cross sections include the water table and flow nets with equipotential contours depicting groundwater flow directions based on posted groundwater elevations from the Conceptual Model and Numerical Model Update (NewFields, 2015). In locations without deeper groundwater elevation data, the results of the numerical model (NewFields, 2015) were used to assist in the drawing of equipotential contours.

Well screened intervals on the cross sections are color coded to reflect the range of boron or sulfate concentration detected in 2016 samples from each well. Yellow, orange, red and pink screen intervals indicate the concentration in the well exceeds PCC. Blue screened intervals indicate the concentration is below the PCC but generally above the background screening level (BSL). A grey screened interval indicates that concentrations are below BSLs. It is important to note that most wells are screened within a single hydrostratigraphic unit; the stratigraphy shown on the cross section may not align exactly with the well stratigraphy due to projection onto the cross section.

Cross sections indicate the presence of interburden below the Rosebud Coal in the central portion of the site and below the spoils in the eastern portion of the site. Interburden in the Plant Site area consists chiefly of fine-grained bedrock (siltstone, claystone, and shale) and exhibits low permeability. Interburden, where present, inhibits vertical groundwater flow and therefore transport of constituents.

Cross sections presented in **Figures E-2** through **E-7** show the vertical distribution of boron. Deep wells are present in most areas with concentrations below the PCC that adequately define the vertical extent of impacts. An exception is boron in well 149M-CCR. **Figure E-5** indicates that flow is from 149M-CCR toward capture wells SRP-2, SRP-3, 55D, and 1D. This suggests that any potential migration from well

149M-CCR would be captured. Another area where deep wells are not available to delineate the vertical extent of boron exceeding PCC is in well 55D which is a capture well that exceeds the PCC. However, **Figures E-2** and **E-5** indicate that flow is upward toward this capture well, and therefore further downward migration of boron is unlikely in that area. Well 55D has a well screen bottom at 3,180 feet amsl, it is the deepest well within the plume, and has boron concentrations that are near the applicable PCC. Therefore 3,180 feet amsl is the assumed lowest elevation of the boron plume.

Cross sections presented in **Figures E-8** through **E-13** show the vertical distribution of sulfate. Although there are deep wells in most areas with concentrations below the PCC that adequately define the vertical extent of impacts, there are more exceptions for sulfate. Exceptions include the wells presented on **Figure E-8** between well 10M and well 56M-P. Most wells shown are capture wells, the groundwater model suggest that these wells are capturing impacted groundwater from beneath the Former Units 1 & 2 A Pond and the Units 1 & 2 Bottom Ash Clear Well. Therefore, continued migration of sulfate below the capture wells is unlikely. Another area where deep wells are not available to delineate the vertical extent of sulfate impacts is beneath wells OT-7, 135A and 136A (**Figure E-10**). Deep wells are also not available beneath 149M-CCR, 150M-CCR, and 151M-CCR (**Figure E-11**). However, flow from the area near wells 149M-CCR, 150M-CCR, and 151M-CCR is toward capture wells SRP-2, SRP-3, 55D, and 1D, suggesting that any migration from these wells would be captured. Wells 84SP and 86SP (**Figure E-11**) both have concentrations exceeding the PCC for sulfate. Because interburden underlies these wells screened in spoils, downward migration of sulfate is inhibited in this area. In addition, there is no deeper well near well 58M (**Figure E-12**), which is a capture well, with upward gradients suggesting sulfate would not migrate deeper at this location. Well 110D (**Figure E-12**) has sulfate concentrations above the PCC and no deeper monitoring well nearby. However, there is an upward gradient between well 110D and the adjacent alluvial capture well 107A, therefore, concentrations exceeding the sulfate PCC are not likely to occur below the elevation of well 110D. All wells exceeding the PCC on **Figure E-13** have deeper monitoring wells nearby exhibiting concentrations below the BSL. Well 110D, which has a well screen bottom at 3,201 feet amsl, is the deepest well within the plume and has sulfate concentrations near the applicable PCC. Therefore 3,201 feet amsl is the assumed lowest elevation of the sulfate plume.

2.3.2 Boron and Sulfate Distribution by Model Layer

Boron and sulfate isoconcentration contour maps were generated for each model layer as shown in **Figures 2-23** through **2-32** for initial concentration input values for fate and transport modeling. The isoconcentration contours for each model layer were created using the same data sets used to develop plume maps for boron and sulfate in alluvium, spoils, coal-related strata, and Sub-McKay bedrock discussed in **Section 2.2**. Plume maps shown in **Figures 2-1**, **2-2**, **2-9**, **2-10**, **2-15**, and **2-16** were used to guide the general development of initial concentration inputs shown in **Figures 2-23** through **2-32.** The following describes how sulfate and boron concentrations were assigned to each layer:

- Layer 1 – Boron and sulfate isoconcentration contour maps for Layer 1 (**Figures 2-23** and **2-28**) were created using concentrations measured in Layer 1 wells, which includes wells screened in alluvium, overburden, and spoils.

- Layer 2 – Boron and sulfate isoconcentration contour maps for Layer 2 (**Figures 2-24** and **2-29**) were created using concentrations measured in Layer 2 wells, which includes wells screened in alluvium, Rosebud Coal, and spoils.
- Layer 3 – **Figures 2-25** and **2-30** are isoconcentration contour maps for boron and sulfate in Layer 3, respectively**.** Layer 3 generally consists of alluvium near the center of the model domain (along East Fork Armells Creek) and interburden elsewhere. Several wells are screened in alluvium in Layer 3, but only a few wells are screened in interburden. Due to the scarcity of wells screened in the interburden, the isoconcentration contours for interburden groundwater were developed based on data from wells partially screened in Layer 3. In many cases, wells screened through Layer 2 penetrate the top few feet or more of interburden; these wells were used to help delineate the plume in Layer 3 interburden. Data from some Layer 4 wells were also considered. In areas lacking Layer 3 wells, concentrations in Layers 2 and Layer 4 wells were interpolated to develop Layer 3 concentrations. This strategy was employed near the Former D1 - D4 Brine Ponds, Sediment Retention Ponds, Former Units 3 & 4 Wash Tray Pond, North and South Cooling Tower Blown Pond C, and Former Units 1 & 2 A and B Ponds.
- Layer 4 – Boron and sulfate isoconcentration contour maps for Layer 4 (**Figure 2-26** and **2-31**) were created using concentrations measured in wells screened in Layer 4. This includes wells screened in alluvium near the center of the model domain (along East Fork Armells Creek) and McKay Coal elsewhere.
- Layer 5 –Boron and sulfate isoconcentration contour maps for Layer 5 (**Figure 2-27** and **2-32)** were created using concentrations measured in wells screened in Layer 5, which consists of shallow Sub-McKay bedrock

2.3.3 Three Dimensional Plume Imagery

Three-dimensional plume imagery was developed to support fate and transport modeling and provide better understanding of the three-dimensional distribution of boron and sulfate in groundwater at the Plant Site. **Figures 2-33** and **2-34** present three-dimensional representations of the boron and sulfate plumes, respectively, developed based on isoconcentration contours and observed concentrations. Electronic (PDF) versions of **Figures 2-33** and **2-34** include animation that cut through the plume in east-west slices moving from the southern to the northern end of the plume. Minimum concentrations displayed are the PCC for sulfate and boron. Three-dimensional plume imagery was created by interpolation using three-dimensional kriging. In order to provide 3-D data to create **Figures 2-33** and **2-34**, actual boron and sulfate concentration data from wells were assigned horizontal x and y coordinates, and vertical z coordinates based on surveyed locations; z coordinates were assigned to the mid-point elevation of the well screen. Additionally, isoconcentration contours for boron and sulfate presented in **Figures 2-23** through **2-32** were converted to equally-spaced points using GIS. Elevations were assigned to the point data to represent the middle of the saturated portion of the model layer. For Layers 1 through 4, the elevation was assigned to be equivalent to halfway between the layer bottom and either the layer top or the water table (for cells not fully saturated). Layer 5 points were assigned elevations of 3,180 feet amsl (bottom screen elevation of 55D).

3.0 FLOW MODEL ADJUSTMENTS

The numerical flow model described in the Model Update Report (NewFields, 2015) was used as the basis for fate and transport modeling. To provide the best representation of current conditions, capture system flow rates and process pond seepage rates from the 2014 calibration were adjusted.

The flow model described in Model Update Report (NewFields, 2015) was calibrated using average capture system pumping rates from 2014. Since 2014, additional capture wells have been added to the system and flow rates have been adjusted. The array of capture system wells and average pumping rates from 2016 were used for the capture and fate and transport analysis described below. **Table 3-1** presents the 2016 average pumping rates for the capture wells.

Since the Model Update Report (NewFields, 2015), Hydrometrics (2016a) refined estimates of seepage rates for a two process ponds. Seepage rates in the model were adjusted to reflect these updated estimates. Seepage rates for the Units 1 & 2 B Pond were adjusted from 7.9×10^{-4} gallons per minute (gpm) to 3.6 gpm. Seepage rates for the Units 1 & 2 Bottom Ash Clear Well were adjusted from 5.76×10^{-5} gpm to 0.4 gpm.

4.0 UPDATED CAPTURE ANALYSIS

NewFields (2015) completed a capture analysis to evaluate the effectiveness of the capture system in intercepting groundwater impacted by process pond water. The capture analysis was based on 2014 capture well pumping rates and maps showing the extent of groundwater exceeding BSLs for indicator parameters. This section describes an updated capture analysis based on the new maps of constituents exceeding PCCs as well as the revised pond seepage estimates and average 2016 pumping rates.

Particle tracking is used to forecast the fate of constituents in source areas and areas where groundwater is impacted by process water. These forecasts should be considered approximations. Primary lines of evidence such as field-measured pumping drawdown and trends in water quality should be consulted first in a weight-of-evidence approach for evaluating capture system effectiveness.

Particle tracking simulates advective transport of dissolved constituents in groundwater, with particles representing the solute. Advective transport is the movement of particles calculated only on the average linear velocity of groundwater (Anderson et al., 2015). Particle tracking does not take into account other hydrodynamic processes that can affect the movement of solutes in groundwater including diffusion, dispersion, retardation (adsorption), or decay (chemical reactions).

4.1 METHODS

As with previous capture analyses, the computer program MODPATH (Pollock, 1994) was used to complete particle tracking simulations. Head outputs and inter-cell flow rates from MODLFOW are used to generate a continuous velocity vector field for MODPATH. MODPATH was then used to calculate particle pathlines based on advective flow.

Particle tracking simulations were completed for each of model Layers 1 through 5. Particle tracking was not completed for Layer 6 because there are no wells screened within this layer at the Plant Site, and groundwater concentrations exceeding the PCC are not thought to extend to the deep Sub-McKay system represented by this layer (see **Section 2.1.2**). For each simulation, particles were input into an area that encompasses the known extent of groundwater exceeding PCC for each layer in the areas indicated in **Figures 2-18** through **2-22** and described in **Section 2.1.2**. One particle was placed in every saturated model cell in Layers 1 through 5, in the areas shown in **Figures 4-1** through **4-5**, respectively. Particle starting locations were set to the vertical center of each cell except for Layers 1 and 5. The vertical starting location in Layer 1 was set to the bottom of the cell. Layer 5 is 75 to 135 feet thick and most of the wells in this layer that exceed PCC only partially penetrate the layer. For this reason, particles in Layer 5 were placed at the top of each cell. Forward particle tracking was then executed, and the particles were moved through the steady-state flow field over a 50-year period.

Endpoint analysis was used to identify starting locations of any uncaptured particles, similar to the process described in NewFields (2015). While the analysis described in NewFields (2015) evaluated particles that were not captured after 500 years, the endpoint analysis described below considers starting location of particles not captured within 50 years.

4.2 RESULTS

Most of particles initiated in Layers 1 and 2 are captured within 50 years, and the vast majority of particles initiated in Layers 3, 4, and 5 are also captured**. Figures 4-1** through **4-5** present the starting locations of particles released in Layers 1 through 5 that are not captured. The following summarizes starting locations of uncaptured particles and their direction of travel:

- Particles initiated in Layers 1, 2, and 3 west of East Fork Armells Creek between well OT-7 and the City of Colstrip Sewage Lagoons are not captured by extraction wells. Most of these particles are transported towards East Fork Armells Creek, as was described in **Section 2**. As discussed in **Section 2.1.1**, the source of constituents exceeding PCC in this area was likely past releases from flyash slurry pipeline spills. Canty (2017) determined that leaching of constituents in soil to groundwater in the OT-7 area does not constitute a human health or ecological risk.
- Particles initiated in Layer 3 and Layer 4 near the North Plant Area Drain Pond are not captured within 50 years. These particles are transported towards East Fork Armells Creek.
- A few particles released on the east side in Layers 1 and 2 of the 3 & 4 Bottom Ash Ponds area are transported east-southeast in spoils toward the Cow Creek drainage and are not captured.
- A few particles released beneath the 3 & 4 Bottom Ash Clear Well in Layers 1 and 2 are not captured within 50 years. These particles migrate downward eventually reaching the Sub-McKay.
- A few particles initiated south of the Units 3 & 4 Cooling Tower Blowdown Pond C are not captured with 50 years. These particles slowly migrate downward toward Sub-McKay.
- Most particles that originate in Layers 1 through 4 in an area extending from Units 3 & 4 Bottom Ash Ponds south to the Former Units 3 & 4 Wash Tray Pond travel west and northwest.
- Particles originating in a small area south and southeast of the Former Units 3 & 4 Wash Tray Pond travel slowly downward toward the Sub-McKay.

The updated capture analysis results are similar to results from the NewFields (2015) at 50 years, as the flow fields and pumping rates are similar in most areas. Four new captures wells installed around the North and south Cooling Tower Blowdown Pond C since 2015 have resulted in improved capture in this area. The current capture analysis also differs somewhat from that presented in NewFields (2015) because it is based on updated plume maps that are based on PCC rather than BSLs.

Although capture analysis suggests some particles reach the Sub-McKay within 50 years, constituent concentrations in most Sub-McKay wells are less than PCCs (see **Section 2.3**). Particle tracking traces the pathways that a solute would be transported along, but it does not account for the mass or concentration of contaminants in groundwater. The fact that the model shows particles would be transported to the Sub-McKay interval does not necessarily indicate that enough constituent mass would be transported to produce concentrations above the PCC. As is described in **Section 5.0**, fate and transport modeling is necessary to predict concentrations within groundwater.

5.0 FATE AND TRANSPORT MODEL DEVELOPMENT

The following subsections discuss development of the fate and transport numerical model to support the Remedy Evaluation. Particle tracking is helpful for evaluating capture system effectiveness but it does not account for the mass or concentration of contaminants in groundwater. A solute transport model was developed to provide a more robust tool for evaluating fate and transport of contaminants and comparing potential remedy options.

The 2014 Plant Site steady-state numerical flow model (NewFields, 2015) with revised pond seepage rates and average 2016 capture rates (described in Section 3.0) served as the basis for the fate and transport numerical model used to support the Remedy Evaluation. The following sections discuss model code selection, initial input parameters, source boundary conditions, and qualitative model calibration.

5.1 CODE SELECTION

The fate and transport model was developed with Groundwater Vistas© graphical user interface using the MODFLOW-SURFACT Version 3 (HydroGeoLogic, 1998) transport module to simulate solute transport through the groundwater system for the Remedy Evaluation. MODFLOW-SURFACT is the groundwater flow code used to develop the flow model described in NewFields (2015) that is based on the U.S. Geological Survey groundwater flow modeling code, MODFLOW. MODFLOW-SURFACT also has the capability of simulating solute transport in groundwater and does account for stored pore water and stored mass when areas become unsaturated such as when pumping intensifies and/or seepage decreases. The transport modules are integrated into MODFLOW-SURFACT to perform a numerical solution of the advective-dispersive transport equation in transient or effective steady-state flow fields for up to five solute species. The numerical schemes used in a transport analysis are strictly mass-conservative. The block-centered finite-difference spatial discretization is fully compatible with the MODFLOW formulation.

5.2 INITIAL TRANSPORT PARAMETER INPUTS

Subsections below describe development initial transport parameter inputs.

5.2.1 Initial Concentrations

As described in **Section 2.2** and **Appendix D**, boron and sulfate were selected as the representative constituents for fate and transport modeling. Isoconcentration contours for boron and sulfate in Layers 1 through 5 shown on maps in **Figure 2-23** through **Figure 2-32** were converted to a set of points. These points were combined with point data from individual monitoring wells. Natural neighbor interpolation was applied to this data set to create continuous concentration (raster) coverage for each model layer within the interpolated data. Model nodes outside of interpolated data were assigned concentrations using the following method. The sulfate concentration in all wells less than 2200 mg/L (Sub-McKay BSL) and the boron concentration in all wells less than 0.818 mg/L (Spoils BSL) were averaged for each layer. The following concentrations were then assigned to areas outside of interpolated data in each layer:

Layer	Sulfate	Boron
1	1,772 mg/L	0.518 mg/L
2	1,847 mg/L;	0.571 mg/L
3	1,773 mg/L	0.586 mg/L
4	1,068 mg/L	0.574 mg/L
5&6	1,139 mg/L	0.475 mg/L

5.2.2 Source Boundary Conditions

The primary source of elevated boron and sulfate concentrations in groundwater above BSLs are process ponds. The Recharge Package in MODFLOW SURFACT was used to simulate infiltration from designated source areas shown in **Figure 1-2**. Recharge rates used to calibrate the 2014 Plant Site model described in NewFields (2015) along with revised recharge rates for Units 1 & 2 B Pond and the Units 1 & 2 Bottom Ash Pond Clear Well discussed in **Section 3.0** were used to represent initial seepage from these source areas.

Initial source concentrations were assigned to recharge package cells for each source area based on site data. The initial assignment of concentrations for source areas was based on the most recent pond water quality data and/or historic averages (see Table 1 in Appendix H Geosyntec 2017a). Source concentrations assigned to recharge zones were then adjusted during qualitative calibration within range of the minimum and maximum concentrations historically detected from the sources provided in Hydrometrics (2015a). The calibration is discussed further in **Section 5.3**. The initial extent for defined source areas was based on the process pond footprints as shown on **Figure 1-2**. The shape and extent of the source areas were then adjusted slightly during calibration to better match observed plume shapes and concentrations. **Figure 5-1** shows the final distribution of the recharge zones; and **Table 5-1** lists seepage rates and boron and sulfate concentrations assigned to the individual recharge zones in the simulation.

General head boundary (GHB) cells represent underflow into the model domain. In order to maintain background concentrations in the model representative of natural conditions, background concentrations were set in the general head boundaries of the model. For sulfate these concentrations were set specific to each layer using the 2016 data presented in **Appendix C**. Sulfate concentrations were assigned to GHBs as follows:

- Layer 1 – 1,772 mg/L;
- Layer 2 – 1,847 mg/L;
- Layer 3 – 1,773 mg/L;
- Layer 4 – 1,068 mg/L; and
- Layer 5 and 6 – 1,139 mg/L

For boron there was less layer by layer variability in the background concentrations. Therefore, general head boundaries in all layers were assigned the same concentration (0.5 mg/L, the average of all boron concentrations less than 0.818 mg/L).

Source concentrations were also assigned to River Package cells along East Fork Armells Creek. The assigned concentrations (1.38 mg/L for boron and 2,349 mg/L for sulfate) represent the average boron and sulfate concentrations reported from 1985 through 2016 at monitoring stations along East Fork Armells Creek within the model domain (AR-12, AR-2SF, AR-3, AR-4, AR-5; **Appendix G**).

5.2.3 Solute Transport Parameters

Transport of solutes in groundwater is affected by advection and dispersion. Advection is the bulk movement of solutes by groundwater. It occurs at the average linear velocity of groundwater, which is a function of hydraulic conductivity times the hydraulic gradient divided by the effective porosity. Hydraulic conductivity is an input to the calibrated flow model and gradient is calculated by the flow model. Estimates of effective porosity are required inputs for the transport model. The same effective porosity values that were used in the 2015 Plant Site Model Report (NewFields, 2015) were used in transport simulations:

- Fine-grained alluvium – 0.15 to 0.2
- Coarse-grained alluvium – 0.2
- Spoils – 0.15
- Interburden – 0.15
- Rosebud Coal and McKay Coal – 0.09
- Sub-McKay bedrock – 0.15

Dispersion is the spreading and mixing of solutes in groundwater due to microscopic variations in velocities within pore spaces in the aquifer. Simulation of this process in three dimensions requires estimates of dispersion coefficients. The longitudinal dispersity coefficient was calculated using the following equation developed by Xu and Eckstein (1995):

$$\alpha_l = 0.83(\log L)^{2.414}$$

Where: α_l = longitudinal dispersivity (meters)

L = representative travel distance (meters)

The equation uses a representative travel distance (L) to calculate longitudinal dispersivity (αl) and is based on a compilation of dispersivity results from Gelhar et al. (1992). The distance from the sulfate source area at the northern end of the Former Units 1 & 2 A Pond to the downgradient edge of the sulfate plume, defined as the 3000 mg/L contour line, was used as the representative travel distance to calculate longitudinal dispersivity for the model. This length is approximately 1,400 feet resulting in a longitudinal dispersivity of 28 feet. Bear and Cheng (2010) and Gelhar et al. (1992) note that horizontal transverse dispersivity (αH) is approximately an order of magnitude less and vertical dispersivity (αV) is two orders of magnitude less than longitudinal dispersivity. Based on this, values of 2.8 feet and 0.28 feet were assigned in the transport model for αH and αV, respectively.

The transport of some dissolved constituents is not conservative, and is affected either by adsorption or chemical reactions within the aquifer. As was discussed in **Section 2.2** and **Appendix D**, boron is affected by adsorption and was selected as a representative non-conservative constituent for fate and transport modeling. A retardation factor is used in transport modeling to simulate adsorption of boron to solids in the aquifer. The retardation factor is the ratio of average groundwater velocity to average contaminant transport velocity. The retardation factor is a function of bulk soil density, moisture content, and chemical adsorption properties and is calculated using the following equation:

$$R = 1 + (\frac{\rho_b}{\theta})K_d$$

Where:

R = Retardation factor

ρ_b = dry bulk density of the soil (mass per volume)

θ = volumetric moisture content of the soil (dimensionless)

K_d = distribution coefficient for the solute with the soil (volume per mass)

Retardation of boron was simulated using linear sorption. Dry bulk density (p_b) was assigned based on values reported by Manger (1963) for the Tongue River Formation (1.63 gm/cm^3), the alluvium (1.36 gm/cm^3), and coal units (0.673 gm/cm^3) in the model. Dry bulk density for spoils was assigned a value of 1.63 gm/cm^3. The volumetric moisture content (θ) is equivalent to the maximum porosity of soil; values of θ were assigned form porosity values used in the 2015 Plant Site Model Report (NewFields, 2015). Distribution coefficients (K_d) for boron were estimated from literature (EPRI, 2006) ranging between 0.4 and 3 (Appendix D). As discussed in **Appendix D**, boron appears to be moving 3.5 to 5.2 times slower than conservative solutes such as SC and sulfate. Assuming conservative solutes move at the average groundwater velocity, the retardation factor for boron would range between 3.5 and 5.2. As shown in **Table 5-2,** use of a K_d value of 0.4 for all units resulted in retardation factor values consistent with that range.

5.3 QUALITATIVE CALIBRATION

A qualitative calibration of the transport model was completed to demonstrate that the model is generally capable of simulating observed concentrations and distribution of constituents. There is uncertainty associated with source terms in the solute transport model, including seepage rates, source concentrations, and changes in water management, which all vary considerably over a period of tens of years. For these reasons, it would be difficult to complete a useful quantitative calibration.

The overall objective was to calibrate the model so that source concentrations of boron and sulfate would result in simulated concentration in groundwater that generally match observed concentrations. This assumes that the extent and magnitude of boron and sulfate in groundwater is stable.

The qualitative calibration was conducted iteratively and included the following general steps:

1. Source area boundary conditions were input and transport simulations were run for 2 years.
2. Results were compared to isoconcentration maps based on field-measured values to evaluate how well they matched. (**Figures 2-23** through **2-32**).
3. Source concentrations in Recharge Package cells representing source areas were adjusted in an attempt to match simulated isoconcentration contours with those interpolated from field measured values. As indicated in **Table 5-1**, higher concentrations were applied to specific areas of some source areas (Units 1 & 2 Pond A, South Cooling Tower Blowdown Pond C, Units 3 & 4 Scrubber Drain Collection Pond, and Former D1-D4 Brine Ponds), to improve the match.
4. These steps were repeated until simulated isoconcentration contours matched those based on observed concentrations reasonably well.

Figures 5-2 through **5-7** are concentration maps for boron and sulfate resulting from qualitative model calibration. Comparison of these maps to **Figures 2-23** through **2-32** indicates a good overall match between simulated and observed boron concentrations. The following is a list of most notable differences between the initial concentrations and the calibrated concentrations.

Simulated sulfate concentrations in Layer 3 beneath the Former D1 - D4 Brine Ponds are higher than in **Figure 2-30**. There are few interburden wells in this area to confirm actual concentration in Layer 3. The model might be over-simulating sulfate concentrations in this area, or **Figure 2-30** does not accurately represent sulfate concentrations in this area. If the former is the case then sulfate results in this small area are conservative.

Simulated sulfate concentrations in Layer 2 beneath South Cooling Tower Blowdown Pond C are slightly higher than in **Figure 2-29,** making the model slightly more conservative in this area for sulfate**.**

Simulated sulfate concentrations in Layers 1 and 2 above the PCC in the area south of South Cooling Tower Blowdown Pond C are less than currently observed concentrations. As is discussed in **Section 2.1.1**, the source of sulfate and other constituents in groundwater in this area likely not Plant Site process water.

Simulated sulfate concentrations in Layers 1 and 2 near wells 140SP and 141SP north and east of the North Plant Area Drain Pond (**Figure 5-5**) are below the PCC, whereas actual concentrations (**Figure 2-2**) exceed the PCC. The source of sulfate in these wells is unknown and is not simulated in the model.

Simulated concentrations of sulfate in Layers 2, 3, and 4 west of East Fork Armells Creek and south of the City of Colstrip Sewage Lagoons near well OT-7 are below PCC (**Figures 5-5** and **5-6**), whereas sulfate concentrations measured in these wells are above PCC (**Figure 2-2**). As discussed in **Section 2.1.1**, the source of elevated boron concentrations in this area is past releases from flyash slurry pipeline spills and was not identified as risks to groundwater in the CCRA (Canty, 2017) and therefore was not simulated or evaluated.

6.0 ALTERNATIVES ANALYSIS

Geosyntec (2017a) has developed four remedial alternatives for the Plant Site, which are described in **Section 6.1** below. NewFields simulated these remedial alternatives to support the Plant Site Remedy Evaluation. Predictive simulations were used to evaluate changes in boron and sulfate concentrations in groundwater over time that would result from implementation of remedial alternatives.

The 2014 steady-state groundwater flow model (NewFields, 2015) along with the transport model described in **Section 5.0** were used as the base case for comparison of predictive simulations. Most hydraulic input parameters and boundary conditions used in the calibrated model were also used in predictive simulations. Changes to model inputs used in the alternatives analysis include:

- reductions in assigned seepage rates to simulate reduced pond seepage over time;
- adjustments to recharge zone geometry to simulate the removal of ponds and installation of new lined impoundments; and
- adjustments to capture well pumping rates as pond seepage is reduced and new pumping and injection wells are added.

Based on MDEQ comments this alternatives analysis considers the edge of the ponds as the point of compliance (POC) for all ponds for remedy implementation. The analysis below evaluates the ability of each remedial alternative to meet PCC for sulfate and boron outside of the POC. Based on MDEQ comments, the goal is to be able to stop operating the groundwater capture system by 2049 (approximately 30 years after remedy implementation) while meeting remedial objectives.

6.1 REMEDIAL ALTERNATIVES

Predictive simulations were developed in consultation with the project team (consisting of staff from Geosyntec, NewFields, and Hydrometrics) based on completed or planned remedial measures. The simulations were used to evaluate relative effectiveness of Alternatives 1 through 4 developed by Geosyntec in the Revised Remedy Evaluation (2017a). To support the assessment of the remedial alternatives, the site was spatially divided into different source and near source areas and distal areas as shown on **Figure 6-1**.

The remedial actions proposed under each alternative are summarized below.

- **Alternative 1 – No Further Action**: This alternative assumes those remedial actions implemented by December 2016 will remain in-place and continue to be operated, but no additional remedial measures are taken.
- **Alternative 2 – Source Control Upgrades, Point of Use (POU), Monitored Natural Attenuation (MNA), and Institutional Controls**

  Same as Alternative 1 plus:

  - Upgrade/close ponds per construction schedule in Revised Remedy Evaluation (Geosyntec, 2017a).
  - Consider discontinuing operation of select distal capture wells, where appropriate.
  - Discontinue POU monitoring when no longer needed.
  - Conduct additional field and laboratory investigation, monitoring and modeling to demonstrate MNA of distal groundwater plumes.
  - Implement institutional controls.

- **Alternative 3 – Source Control Upgrades, Enhance/Upgrade Existing Capture System, POU, MNA, and Institutional Controls**

  Same as Alternative 2 plus:

  - Modify pumping rates of existing vertical source area and downgradient (distal) capture wells.
  - Install additional vertical source area and downgradient (distal) capture wells.
  - Add new vertical capture wells to replace wells removed for construction of the new Brine Concentrator Solids Disposal Area.

- **Alternative 4 – Aggressive Source Control Upgrades, Enhance/Upgrade Existing Capture System, POU, MNA, and Institutional Controls**

  Same as Alternative 3 plus:

  - Install horizontal capture wells beneath two source areas, Former Units 1 & 2 A Pond and Former Brine Ponds D1 – D4, that appear to have longer cleanup timeframes in Alternatives 1-3.
  - Evaluate dewatering ash in Former Units 1 & 2 A Pond to further reduce seepage after capping.
  - Install vertical injection wells on either side of the horizontal capture wells, and inject clean water to increase the flux of groundwater constituents removed by the enhanced/upgraded capture system and achieve more aggressive cleanup timeframes.
  - Turn off existing vertical capture wells in areas where groundwater constituents achieve Potential Cleanup Criteria (PCC) to maintain water balance for Plant Site operations.
  - As a contingency where MNA cannot be demonstrated, a permeable reactive barrier (PRB) may replace portion(s) of the capture system where boron and sulfate have achieved the PCC, but other less mobile groundwater constituents have not, in order to shut down the injection/capture system sooner.

6.2 PREDICTIVE SIMULATION SETUP

The general setup of predictive transport simulations is discussed below. Discussion includes stress period setup and model modifications to simulate source control and capture system configurations.

6.2.1 Stress-Periods

Table 6-1 summarizes stress period setup. Simulations include 28 stress periods covering the period from November 2016 through 2149 (Alternative 1 extends from November 2016 through 2049). The first 18 stress periods cover the period from November 2016 through 2049, when active groundwater capture is anticipated (see **Section 6.0**). The remaining stress periods simulate the post-pumping period, which allows evaluation of whether remedial measures will meet cleanup criteria after cessation of groundwater capture. Simulations assume that elements of each remedial alternative will be implemented instantaneously at the beginning of the year in which they are planned.

6.2.2 Source Control Measures

Alternatives 2, 3, and 4, incorporate several proposed source control measures including capping and closure of several process ponds. It is estimated that capped and closed ponds will continue to seep water for some period following closure. Seepage rates for ponds from 2014 through 2029 were estimated by Geosyntec (2017b) and are summarized in **Tables 6-2** and **6-3**.

The following is a summary source control measures and assumptions regarding seepage for each process pond:

- Units 1 & 2 A Pond
    - Pond A was decanted to the extent practicable and filled with solids in 2015 reducing the seepage rate.
    - Pond A will be capped in 2019.
    - Alternatives 2 and 3 assume pond solids will drain passively, and seepage will continue until 2028.
    - Alternative 4 includes active, more aggressive dewatering of pond solids, which will result in the elimination of seepage by 2026.
- Units 1 & 2 B Pond
    - Process water will be removed from B pond after it is taken out of service.
    - Seepage from pond will end in 2023 after it is closed by filling with solids and capping.
- Units 1 & 2 Bottom Ash Ponds
    - Active use of ponds will be discontinued in 2022.
    - The ponds will be capped and closed in 2022.
    - Seepage from pond is projected to cease in 2023.
- Units 1 & 2 Bottom Ash Ponds Clear Well

  - Active use of the clear well will be discontinued in 2022.
  - Clear well will be capped and closed in 2022.
  - Seepage from clear well is projected to cease in 2026.
- North and South Cooling Tower Blowdown Pond C
  - Water will be drained from North and South Pond C and either used as makeup water for the plants and/or evaporated beginning in 2023 and ending in 2027.
  - Seepage from North and South Pond C is assumed to decrease between 2023 and 2027.
  - After 2027, the seepage rate is assumed to be equivalent to recharge from background areas surrounding the Plant Site (0.0025 inches/year; NewFields 2015).
- Units 3 & 4 Bottom Ash Ponds with Clear Well
  - The eight cells in the 3& 4 Bottom Ash Pond Area are being phased out between 2016 and 2018; in the model seepage is simulated to decline in 2017.
  - Ponds will be capped and closed in 2020.
  - Seepage from ponds is projected to cease in 2023 (based on NewFields analysis as described below).

Comparison of calibrated seepage rates from the revised 2014 Plant Site Model (NewFields, 2015) to estimated seepage rates from Geosyntec (2017b) indicates that the rates are similar. **Table 6-2** presents the schedule of decreasing seepage rates for the predictive simulations for all ponds listed above except the Units 3 & 4 Bottom Ash Ponds. Geosyntec (2017b) presented rates of declining seepage for ponds based on the schedule of proposed source control measures. To account for the slight differences between calibrated and estimated pond seepage rates, a schedule of decreasing rates for fate and transport simulations was developed by the following procedure: first, the ratio of seepage rates from the revised 2014 flow model to estimates for 2014 from Geosyntec (2017b) were calculated; then, the Geosyntec (2017b) seepage estimates for 2015 through 2029 were multiplied by this ratio to yield model seepage rates.

A schedule of decreasing seepage rates for the predictive simulations of Units 3 & 4 Bottom Ash Ponds and Clear Well (**Table 6-3**) was developed differently. Projected seepage reduction over time from these ponds is based on the following assumptions:

- No water will be added to the ponds after 2016; after this only direct precipitation will be added to the ponds.
- Following capping of the ponds in 2020, no more water will be added to the ponds.

Since fate and transport modeling was initiated, shutdown of the 3&4 Bottom Ash Ponds and Clear Well was delayed, and some cells will continue to receive water until 2018.

Minor differences regarding assumed timing of when individual cells of the 3 & 4 Bottom Ash Ponds will be taken out of service have minimal effects on predictive results used for the alternatives analysis.

Concentrations of constituents in these ponds are low, and in most cases below the PCC. As a result, having higher seepage rates in these cells for an additional year would not change interpretation of fate and transport modeling results in the alternatives analysis.

Eight recharge zones were assigned to the transport model to represent the different cells of the Units 3 & 4 Bottom Ash Ponds and Clear Well (**Figure 5-1**). Seepage estimates for the 3 & 4 Bottom Ash Ponds and Clear Well were divided into two groups: Group 1 includes ponds with seepage rates that result in the ponds not draining before 2020; Group 2 includes ponds with seepage rates that result in ponds draining prior to 2020. Calculations for each group of recharge zones were conducted using the following methods and assumptions:

- **Group 1** (Recharge Zones 18, 19, 20 and 21) - Most assigned seepage rates for these zones are the same as used in the 2014 steady-state model calibration (NewFields 2015) except during the year that the ponds are calculated to drain completely. The volume of water stored in the ponds from 2016 through 2019 was assumed to decrease; the volume stored for each year was calculated by adding the annual volume of net precipitation to the volume stored from the previous year and then subtracting the volume infiltrated for that year. The 3&4 Bottom Ash Ponds will be capped in 2020. Ponds still having stored volume after capping are assumed to seep until the volume stored has drained. Recharge zones 18 and 21 are expected to drain completely by the end of 2020; Zone 19 is expected to drain by the end of 2022; and Zone 20 is estimated to drain by 2023. In the final year that each pond contains water, the seepage rate is calculated as the remaining volume over the entire year.
- **Group 2** (Recharge Zones 7, 17, 22, and 33) **-** Seepage rates assigned to Group 2 zones for 2016 are consistent with pond seepage rates from the calibrated groundwater model. For Year 2017, seepage rates are high enough that the water stored in the ponds would be drained before the end of the year. In 2017 the volume of water stored in the pond (plus precipitation) is assumed to seep over the entire year. For years 2018 through 2020, the annual seepage rate equals annual net precipitation captured in the pond. Seepage is zero following capping.

The Revised Remedy Evaluation Report (Geosyntec, 2017a) indicates that the Units 3 & 4 Bottom Ash Dewatering System container was constructed in 2017 south of the 3 & 4 Bottom Ash Ponds (**Figure 6-2**). This container will replace the Units 3 & 4 Bottom Ash Pond and Clear Well. Projected seepage rates assigned to the model for the new container following construction are presented in **Table 6-4**.

The Brine Concentrator Solids Disposal Area is planned to be constructed in 2018 in the location of the Former D1-D4 Brine Ponds (**Figure 6-2**). The area will be constructed with a double liner with underdrain collection systems between each layer and will store solids from the Brine Concentrator. The lined area will be constructed above the water table and is not expected to have any seepage. Recharge zones in this area are assigned a value of zero for stress periods representing 2018 through the end of the predictive simulations.

Concentrations for Recharge Package zones representing the Former Units 3 & 4 Wash Tray Pond, Former Units 3 & 4 Scrubber Drain Collection Pond, and Sediment Retention Pond are assigned the lowest BSL for boron and sulfate in the predictive transport simulations. As discussed in the Facility Closure Plan (Geosyntec, 2017c) the Former Units 3 & 4 Wash Tray Pond and the Former Units 3 & 4 Scrubber Drain Collection Pond were excavated and no longer contain ash. In addition, the east side of the Sediment Retention Pond was cleaned out in 2015 and the pond and will no longer receive overflow process water. Several holes in the liner of the Sediment Retention Pond, attributed to penetrations from vegetation and animals, were also patched in 2015. With the exception of the North and South Cooling Tower Blowdown Pond C, all remaining ponds with source material (Units 1 & 2 A Pond, Units 1 & 2 B Pond, Units 1 & 2 Bottom Ash Pond, Units 1 & 2 Bottom Ash Clear Well, and Units 3 & 4 Bottom Ash Ponds with Clear Well), will be removed from service, free water above the ash will be removed, and the ponds will be capped. If groundwater monitoring and subsequent soil sampling indicate the North and South Cooling Tower Blowdown Pond C continue to contribute concentrations of constituents above the PCC to groundwater following forced evaporation, material will be excavated from the ponds.

6.2.3 Capture System

Simulation of the groundwater capture system varies among the four remedial alternatives. Simulation of existing wells, new wells, and modification of pumping rates are described in the following subsections.

6.2.3.1 Existing Wells

Figure 6-2 shows the location of existing pumping wells used in the predictive simulations. Existing capture wells were represented using a combination of the Well and the Fracture-Well (FWL5) packages in MODFLOW SURFACT. **Table 6-5** presents initial pumping rates assigned to existing capture wells for each predictive simulation. Initial assigned pumping rates are based on average 2016 rates. Pumping rates for Alternative 1 are constant throughout predictive simulations. During the simulation process for Alternatives 2, 3, and 4, some pumping rates were reduced during later stress periods to account for lower seepage rates and the addition of new capture wells. In Alternative 4, pumping wells were turned off if they were pumping in an area where groundwater concentrations dropped below the PCC.

6.2.3.2 Modification of Pumping Rates in Existing Wells

The potential for existing capture wells to pump at higher rates was assessed to support Alternative 3 and 4 simulations. Hydrometrics (2017) suggests that pumping rates established in the first few years of a well's operation are a good indicator of the maximum potential sustainable pumping rate for a given well. Well pumping records were reviewed to evaluate if any capture wells could potentially be pumped at greater rates. Pumping rates were not increased in any wells where rates had been reduced in later stress periods in the Alternative 1 and Alternative 2 simulations. In addition, pumping was not increased in capture wells in areas where additional capture did not appear to be necessary. For example, pumping was not increased in a well if the well was located in an area where concentrations were less than the PCC or if concentrations dropped below the PCC in a reasonable timeframe.

Increased pumping rates assigned to existing wells in Alternative 3 and 4 are listed in **Table 6-5**. In Alternative 4, capture in a well was terminated if the well was located in an area where concentrations were less than the PCC or if concentrations dropped below the PCC in a reasonable timeframe. Wells identified to have potential to increase pumping rates in other areas (East Area and Central Area) were assigned modified pumping rates in 2019.

6.2.3.3 New Capture System Wells and Injection Wells

Alternatives 3 and 4 included adding hypothetical wells to evaluate whether groundwater capture could be increased in areas where capture does not appear to be complete. The Alternative 3 simulation includes the addition of hypothetical vertical capture wells only. The Alternative 4 simulation includes addition of hypothetical vertical capture wells, horizontal capture wells, and injection wells. Components of the conceptual model, existing data, well performance, and modeling results (including particle tracking) were used to guide the initial placement of additional hypothetical capture wells. Hypothetical well locations were then adjusted in an iterative process to help optimize the new wells ability to capture groundwater with concentrations exceeding the PCC.

Alternative 3: Ten new hypothetical capture wells (C-1 through C-10) were added in locations shown on **Figure 6-3** and summarized in **Table 6-6**. Two new capture wells (C-1 and C-2) are located in the spoils in the Central Area-Near to replace capture wells that will be removed following the installation of the Brine Concentrator Solids Disposal Area in 2019. In the West Area-Near; three new capture wells were placed in the alluvium and five wells were placed in the McKay. Pumping in new capture wells in alluvium and spoils is initiated in 2019 in the simulation. Pumping in new capture wells in the McKay is not initiated until 2029, when seepage from the Former Units 1 & 2 A Pond is estimated to stop. Pumping in new McKay wells is not initiated until 2029, after seepage from Former Units 1 & 2 A Pond is estimated to stop, to avoid the potential of drawing dissolved boron directly from the source down into interburden (Layer 3) and McKay (Layer 4) units. Pumping rates were assigned to the hypothetical vertical captures wells in an iterative process, where the initial pumping rate was assigned and then adjusted up or down depending on whether or not the well was capable of pumping at a greater rate in the model or if new capture wells achieved cleanup in the area.

Alternative 4: Includes the following:

- Adding two new horizontal capture wells in areas with the greatest boron concentrations. One horizontal capture well extends beneath the north side of the Units 1 & 2 Clear Well to the south end of the Former Units 1 & 2 A Pond. The other horizontal well extends from a point northeast of the Sediment Retention Pond under the Brine Concentrator Solids Disposal Area. In both cases, the horizontal wells were simulated using the Drain Package with the drain elevation set equivalent to the top of the interburden (Layer 3).
- Adding 50 injection wells. Parallel lines of injection wells were placed west and east of the horizontal capture wells to flush water toward the horizontal wells. Additional injection wells were placed upgradient of capture wells in areas that were not meeting remedial goals by 2049 in Alternatives 1 through 3.
- Converting four capture wells located west of Former Units 1 & 2 A Pond to injection wells.
- Three new vertical capture wells (C4, C11 and C-12) were added northeast of the Sediment Retention Pond.

These actions are implemented in the simulation in 2019. Locations and pumping/injection rates of the new wells are summarized in **Table 6-7**. **Figure 6-4** shows the locations of the new capture and injection wells.

Pumping rates for vertical capture wells were assigned and adjusted in a manner similar to Alternative 3. Injection well pumping rates were assigned initial rates based on capture rates of nearby wells and then adjusted if more injection was needed. Injection wells were simulated with the assumption that injection water has background concentrations of boron (0.818 mg/L).

6.3 CRITERIA FOR EVALUATION OF PREDICTIVE RESULTS

Predictive simulations were evaluated qualitatively by visually comparing changes in plume extent and the time that boron and sulfate concentrations outside of the POC drop below the PCC. As discussed above, based on MDEQ comments, a goal was established for turning off the groundwater capture system by 2049 (approximately 30 years following final remedy implementation). Therefore, the ability of each alternative to reduce boron and sulfate concentrations in groundwater outside of POCs by 2049 was evaluated. Interim milestones (discussed in **Section 6.5**) were also developed to qualitatively assess the reduction in the plume extent with time.

Animations showing the predicted extent of sulfate and boron in groundwater exceeding the PCC over time were generated to help compare the effectiveness of remedial alternatives. Because the sulfate PCC for the spoils stratigraphic unit is different than the other units, the outer delineated boundary of the plume in spoils is slightly different than in other units (3,045 mg/L for spoils and 3,000 mg/L for other units). Spoils are present in Layers 1 and 2 only.

6.4 PREDICTIVE RESULTS

The following subsections discuss results for Alternatives 1 through 4. Results for each alternative are assessed based on the time frame for the predicted boron and sulfate concentrations to decrease below the PCC in the different sub-areas. Predicted time frames are relative and actual time frames may vary.

6.4.1 Alternative 1 Predictive Results

Alternative 1 does not meet remedial objects by 2049. **Figure 6-5** through **Figure 6-9** are animations of Alternative 1 simulations showing the reduction of boron concentrations over time for Layers 1 through 5, respectively. **Figure 6-10** through **Figure 6-14** are animations of Alternative 1 simulations showing the reduction of sulfate concentrations over time for Layers 1 through 5, respectively. Printed versions of these figures show boron concentrations at the end of the 2016 year simulation only. These figures show areas in which the PCC concentration for boron and sulfate is exceeded within each model layer.

The following is a summary of Alternative 1 simulation results:

- Layers 1, 2, and 3: By 2049, the extent of groundwater with boron and sulfate concentrations exceeding the PCC is reduced in all areas, and the capture system contains the plume within the boundaries of the capture system. In Layer 3 boron and sulfate concentrations beneath the Former D1 - D4 Brine Ponds increase with time.
- Layer 4: The extent of groundwater exceeding the boron PCC recedes north of the Former Units 1 & 2 A pond. The extent of sulfate exceeding the PCC shrinks in all directions. The extent of

groundwater with sulfate concentration exceeding the PCC expands over time in the South Area-Near and Central Area-Near.

- Layer 5: The extent of groundwater exceeding the PCC is reduced for boron and is gone for sulfate by the end of 2049.

6.4.2 Alternative 2 Predictive Results

Final simulated pumping rates for Alternative 2 are shown in **Table 6-8**.

Figure 6-15 through **Figure 6-19** show animated results for Alternative 2 boron simulations for Layers 1 through 5, respectively. **Figure 6-20** through **Figure 6-24** shows sulfate results for Layers 1 through 5, respectively. Printed versions of these figures show boron and sulfate concentrations at the end of the 2016 only. These figures show areas in which the PCC for boron and sulfate is exceeded within each model layer.

Figure 6-25 through **Figure 6-29** are charts showing when predicted sulfate and boron concentrations drop below the PCC in the different sub-areas. **Table 6-9** and **Table 6-10** summarize the time when sulfate and boron concentrations are predicted to drop below the PCC for each sub-area, respectively.

The following is a summary of Alternative 2 simulation results:

- Alternative 2 meets remedial objectives for sulfate.
- Alternative 2 does not meet remedial objectives for boron.
- Layers 1, 2, and 3: The areas exceeding boron PCC are reduced by 2049, but did not meet PCC. Animations on **Figures 6-15** through **6-17** and charts on **Figures 6-25** through **6-27** show that when the capture system shuts down, the boron plume reemerges where the shallow aquifer had been previously dried up by the capture system. This is caused by the release of mass that was stored in the unsaturated zone and sorbed to aquifer solids. After the groundwater levels rebound, the plume in the West Area-Near migrates to the northwest. Boron concentrations above the PCC remain in the Central Area-Near and Distal and East Area-Near at the end of 2149.
- Layer 4: The areas exceeding boron PCC did not migrate from the site while the capture system was running and they reduced in size but did not cleanup by 2049. By the end of 2049 most of the plume is within the West Area-Near and Off-site Area-Distal. After the pumps shutoff the plume migrates to the northwest. There are no boron concentrations exceeding the PCC in Layer 4 by the end of 2119.
- Layer 5: The boron plume is gone by 2059.

6.4.3 Alternative 3 Predictive Results

Boron was the only constituent simulated for Alternative 3 because simulated sulfate levels dropped below the PCC by the end of 2049 in Alternative 2 and Alternative 3 will enhance removal of impacted groundwater from the system.

Final simulated pumping rates for Alternative 3 are shown in **Table 6-11**. The total additional volumetric pumping rate from new capture wells was 24 gpm.

Figure 6-30 through **Figure 6-34** are animations of Alternative 3 results for Layers 1 through 5, respectively. Printed versions of these figures show boron concentrations at the end of the 2016 year simulation only. These figures show areas in which the PCC for boron is exceeded within each model layer.

Table 6-10 summarizes the year boron concentrations are predicted to drop below the PCC for each sub-area. Results are similar to Alternative 2, with minimal improvements.

The following is a summary of Alternative 3 simulation results:

- Alternative 3 does not meet remedial objectives for boron.
- Layers 1, 2, and 3: Similar to Alternative 2, the areas exceeding boron PCC are reduced by 2049, but did not meet remedial objectives. **Figures 6-30** and **6-31** show that in 2029 in Layers 1 and 2, the plume near Former Units 1 & 2 A Pond disappears. This is due to the addition of capture wells east of the pond that dewater the shallow aquifer in this area. The pumping in Layer 4 draws some mass from the upper layers down into Layer 3. Similar to Alternative 2, when the capture system shuts down, the boron plume reemerges where the shallow aquifer had been previously dried up by the capture system. This is caused by the release of mass that was stored in the unsaturated zone sorbed to aquifer solids. After the groundwater levels rebound, the plume in the West Area-Near migrates to the northwest. Boron concentrations above the PCC remain in the Central Area-Near and Distal and East Area-Near at the end of 2149.
- Layer 4: Similar to Alternative 2, areas exceeding boron PCC did not migrate from the site while the capture system was running and reduced in size but did not cleanup by 2049. By the end of 2049 most of the plume is within the West Area-Near and Off-site West Area-Distal. After the pumps shutoff the plume migrates to the northwest. There are no boron concentrations exceeding the PCC in Layer 4 by the end of 2119.
- Layer 5: The extent of groundwater exceeding the PCC is reduced for boron by the end of 2039.

6.4.4 Alternative 4 Predictive Results

Similar to Alternative 3, boron was the only constituent simulated for Alternative 4 because simulated sulfate levels dropped below the PCC by the end of 2049 in Alternative 2 and Alternative 4 will enhance removal of impacted groundwater from the system.

Final simulated pumping rates are shown in **Table 6-12**. The total additional volumetric pumping rate from new vertical and horizontal capture wells is a maximum 98 gpm in 2022 (sum of New Wells 1,2 and 4 and HW Brine Pond and HW A pond). The total additional volumetric injection rate of the proposed wells was 138 gpm during each year of injection. Throughout the simulation, the total capture system pumping rate exceeds injection rates by 87 to 136 gpm, assuring that all injected water will be captured.

Figure 6-35 through **Figure 6-39** showing animated results for the Alternative 4 simulation for Layers 1 through 5, respectively. Printed versions of these figures show boron concentrations at the end of the 2016 year simulation only. These figures show areas in which the PCC for boron is exceeded within each model layer. The locations of the capture wells and injection wells are shown on the animations.

Table 6-10 summarizes the year boron concentrations are predicted to drop below the PCC for each sub-area.

The following is a summary of Alternative 4 simulation results:

- Alternative 4 meets remedial objectives for boron.
- Layers 1 through 4: In 2019, injection begins and concentrations decrease more rapidly. West of the Former Units 1 & 2 A Pond the western line of injection wells push the boron plume west into coarse grained alluvium, where it turns north and is captured by three wells (78A, 199A, and 43S). Injection and pumping results in meeting remedial objective by 2049, when the capture system is shutdown. Remaining areas that exceed the boron PCC after the capture system is shutdown do not migrate and are gone by 2099.
- Layer 5: The small area of groundwater exceeding the boron PCC is gone by 2049.

6.5 COMPARISON OF REMEDIAL ALTERNATIVE PREDICTIVE SIMULATIONS AND INTERIM MILESTONES

The effectiveness of Remedial Alternatives 2, 3, and 4 were evaluated by comparing the time it takes for boron concentrations to fall below the PCC within each Sub-Area (**Figure 6-1**). Alternative 1 is a not an actionable alternative and does not achieve the remediation goals; therefore it is not used for comparison. **Figure 6-40** through **Figure 6-44** are charts comparing the year in which predicted boron concentrations fall below the PCC in each model layer for the different sub-areas; these results are tabulated in **Table 6-10.** The charts show that Alternatives 2 and 3 are nearly identical with respect to cleanup timeframes; however, the cleanup goal of reducing the boron concentrations below the PCC beyond the POC by the end of 2049 is not achieved. In addition, several areas have concentrations above the boron PCC 100 years after the capture system is shutdown including the Central Area, Central Area under ponds, East Area-Near and Central Area-Distal. Alternative 4 achieves cleanup goals by 2049.

Interim milestones were established to assess the relative progress of cleanup over time. Milestones are achieved as boron and sulfate concentrations drops below PCC outside of each of the following three areas:

- Distal areas more than 500 feet from the source area;
- Outside the plant property; and
- Beyond the pond perimeter.

Figure 6-45 presents a map of the interim milestone areas and charts summarizing the results of when the interim milestones are met; data used to make these charts are tabulated in **Table 6-13**. Alternatives 2 and 3 only meet the outside the plant property milestone for boron within the simulation period. In both Alternatives 2 and 3, the areas outside the plant property clean up by 2129.

The interim milestones for boron are achieved at the following times:

- Distal areas more than 500 feet from the source area

  - Alternative 2 and 3 - not met by the end of 2149
  - Alternative 4 - by end of year 2039
- Outside the plant property
  - Alternatives 2 and 3 – by end of year 2129
  - Alternative 4 - by end of year 2049
- Beyond the pond perimeter –
  - Alternatives 2 and 3 - not met by end of 2149
  - Alternative 4 - by end of year 2049.

Interim milestones for sulfate are achieved in Alternative 2 (Alternative 3 and 4 sulfate simulations were not conducted) at the following times:

- Outside the plant property – by end of year 2034;
- Distal areas more than 500 feet from the source area – by end of year 2039; and
- Beyond the pond perimeter – by end of year 2039.

7.0 QUANTITATIVE ASSESSMENT OF ALTERNATIVES

This section presents quantitative analysis of the different remedial alternatives. Mass discharge through individual transects, mass discharge at wells, and calculated plume volumes and plume mass are presented for different time periods for each alternative.

7.1 MASS DISCHARGE

The mass discharge of boron was estimated across several transects and at wells as a quantitative measure of the reduction of boron at the site that could be achieved by implementing the different alternatives. Mass flux combines flow and concentration into a single metric. Although a reduction in mass discharge is anticipated, the mass will never decrease to zero as sulfate and boron are present in background groundwater.

7.1.1 Mass Discharge Crossing Transects

Geosyntec (2017a) established transects around source areas as a way to quantitatively assess the amount of mass migrating away from source areas. Mass discharge is a measure of mass per unit time crossing a transect. **Figure 7-1** presents the direction in which flow was estimated crossing transects.

Mass discharge across transects was calculated. Only results for the baseline and for 2069 (20 years after the capture system is shut down) for each alternative were compared for the following reasons. The comparison of mass discharge at transects requires that the groundwater flow directions are similar. During the period of active capture, the capture system prevents most impacted groundwater from leaving the Plant Site, groundwater flow across many transects is minimal, and flow directions are different between the various alternatives. Once the capture system is shut down, groundwater moves away from source areas and generally crosses transects perpendicularly. By 2069, groundwater flow directions in each alternative are similar and are generally perpendicular to transects.

Figure 7-2 and **Table 7-1** summarize the predicted mass of boron crossing transects in 2069. **Table 7-2** presents detailed information for each model layer. As shown, mass discharge in Alternative 4 is greatly reduced relative to Alternatives 2 and 3 at transects A-A’, B-B’, D-D’ and E-E’. Alternatives 2, 3, and 4 all meet the PCC by 2069 at all other transects. However, the mass discharge of boron across most of these transects is lower in Alternative 4.

7.1.2 Mass Discharge at Wells

Mass discharge from wells was calculated from model predictions. Mass discharge is a measure of the mass of a constituent removed by a well and was calculated by multiplying the well pumping rate by the concentration of boron or sulfate in the model cell. **Figures 7-3** through **7-11** present the predicted mass of boron and sulfate removed by wells for baseline (2016) conditions and Alternatives 1, 2, 3 and 4 (years 2029 and 2049). Wells are organized geographically by sub-area in numeric order. **Figure 7-12** presents the mass removed by the hypothetical new capture wells and horizontal wells. Predicted mass removal rates for boron and sulfate by capture well are tabulated in **Tables 7-3** and **7-4.**

- Predicted rates of mass removal from individual wells are generally highest in Central Area-Near, West Area-Near and North Area-Distal. Concentrations in wells in the North Area-Distal are typically less than the PCC, but the wells have relatively high pumping rates compared to the rest of the site. Wells in the Central Area-Near and West Area-Near are located near the highest concentrations of boron and sulfate. Wells in Central Area-Near are removed in 2018 in Alternatives 2, 3, and 4 due to the construction of the Brine Concentrator Solids Disposal Area.
- By the end of 2029 in Alternative 4, all of the mass removed in the Central Area-Near is from the horizontal capture well in the Brine Pond area, which replaces the other vertical capture wells (**Figure 7-3** and **7-12**).
- Compared to baseline, the mass removed by wells in the East Area-Near is reduced in Alternatives 2, 3, and 4. As discussed in **Section 6.1,** selected capture wells are shut down in the East Area-Near, where groundwater constituents achieve PCC in Alternative 4. The WECO dewatering well (not part of Plant Site capture system) removes most of the mass in the East Area-Near. All mass removed at the WECO well is below the PCC for both boron and sulfate (**Figure 7-4**); however, this well is not turned off in the simulation because its operation is outside the control of the CSES.
- The rate of boron and sulfate removal declines for all alternatives in the North Area-Distal. Well 74A is the only well pumping and removing mass at end of 2049 in Alternative 4. There are no exceedances in the area at this time (**Figure 7-5**).
- The rate of boron and sulfate removal declines from baseline in all alternatives in the Off-Site West Area. However, wells 107A and 98M remove more mass at the end of 2029 in Alternative 4 than during baseline. The total mass removed by wells in the Off-Site West Area is lowest in 2049 of Alternative 4. (**Figure 7-6**).
- The rate of boron and sulfate removal declines from baseline in all alternatives in the South Area-Near. The mass boron removal rate in Alternatives 2, 3, and 4 is generally consistent (**Figure 7-7**).
- One well (68A) is pumping in the Southwest Distal Area. The mass removal rate declines slightly from baseline in all alternatives (**Figure 7-8**).
- The rate of sulfate mass removal in the West Area-Near declines from baseline in all alternatives (**Figure 7-9** through **Figure 7-11**). Pumping rates in wells 1D, 5M, and 55D are higher in Alternatives 3 and 4 than in Alternatives 1 and 2 resulting in substantial increases in mass removal (**Figure 7-9** and **Figure 7-10**). The mass removed by all SRP wells in West Area-Near declines from baseline and no SRP wells are pumping in Alternative 4 at the end of 2029 (**Figure 7-11**).
- Removal of mass from the horizontal wells in Alternative 4 decreases with time (**Figure 7-12**). The horizontal wells remove a large portion of the mass in Alternative 4. Of the total mass removed by wells in Alternative 4 the horizontal wells remove 50 percent in 2029 and 43 percent in 2049 (**Table 7-3**).
- Removal of mass by new vertical wells decreases with time (**Figure 7-12**). The removal of mass by these wells is most notable in Alternative 3. Of the total mass removed by wells in Alternative 3 the new vertical wells remove 20 percent in 2029 and 15 percent in 2049 (**Table 7-3**).

7.2 VOLUME OF GROUNDWATER EXCEEDING PCC

Model results were processed to calculate the volume of groundwater with boron and sulfate concentrations exceeding the PCC (4 mg/L and 3,000 mg/L for boron and sulfate, respectively). First the saturated thickness of each cell was extrapolated from the model. The saturated thickness of Layer 5 was calculated as the thickness of the model cell above the base elevation of the base of the boron and sulfate plumes (3,180 feet amsl and 3,201 feet amsl, respectively [see **Section 2.3.1**]). The saturated thickness of each model cell was then multiplied by the area of the model cell and the total porosity to yield the volume of water in the cell. The total porosity was assumed to be 0.3 for all stratigraphic units other than coal which was assumed to be 0.09. An assumed total porosity of 0.3 for is reasonable for stratigraphy represented in the model according to values reported by Walton (1988) and Domenico and Schwartz (1990) (cited in Table C.3.2 in Wiedemeier (1998)). An assumed total porosity for coal of 0.09 is based on the upper range of porosity defined for coal as reported by Brown and Parizek (1971) (cited page 39 in Hawkins (1995)). The calculated volume of groundwater for cells with concentrations above the PCC was then summed to get the total volume of groundwater exceeding the PCC.

Figure 7-13 and **Figure 7-14** show the predicted change in volume of groundwater exceeding the PCC through time for each alternative for boron and sulfate, respectively. **Table 7-5** and **Table 7-6** present these volumes in tabulated form along with the percent decrease from baseline

The estimated changes in the volume of the plume are summarized below:

Boron

- The plume decreases in volume after 2016 in all alternatives. However, the volume increases in Alternatives 2 and 3 after the capture system is shut down (2050) due to the rebound of the water table near the West Area – near (see **Section 6.4.2**).
- The predicted volumes of the plume in Alternative 3 are less than the predicted volumes of the plumes in Alternative 2 in comparable years.
- The plume volume under Alternative 4 decreases from 306 acre feet at baseline to 8 acre feet in 2069 and zero acre feet in 2099.
- The plume volume under Alternative 4 decreases 93% by 2049, 97%, by 2069, and 100% by 2099.

Sulfate

- The plume decreases in volume after 2016 in Alternatives 1 and 2. Because Alternatives 3 and 4 are more aggressive than these alternatives, the sulfate plume volume would decrease even faster.
- Sulfate plume volumes in Alternative 2 are much less than Alternative 1 volumes in comparable years.
- Under Alternative 2 sulfate plume volume decreases by 100% by the end of 2049. In Alternative 2 by the end of 2049 the plume volume is near zero (0.3 acre feet).

7.3 MASS OF BORON AND SULFATE IN GROUNDWATER ABOVE PCC

Model results were processed to calculate the mass of boron and sulfate contained in groundwater with concentrations exceeding PCC. Mass was calculated by multiplying the calculated volume of water for each model cell in the plume (See **Section 7.2**) by the concentration reported for the cell. The calculated mass for each cell was then summed to get the total mass.

Figure 7-15 and **Figure 7-16** present charts of the predicted mass exceeding the PCC for each alternative for boron and sulfate, respectively. **Table 7-7** and **Table 7-8** present the tabulated mass of boron and sulfate in groundwater exceeding the PCC for each alternative, respectively, and the percent reduction from baseline.

The estimated changes in the mass of the plume are summarized below:

Boron

- The mass within the plume above PCC decreases after 2016 in all alternatives.
- The mass within the plume increases from 2049 to 2069 in Alternatives 2 and 3. This is because after the capture system is shut down in 2049 areas in Layers 1, 2 and 3 are re-saturated (see **Section 6.4.2**). The mass of boron in groundwater in 2069 is less than the baseline mass in 2016.
- Calculated plume masses under Alternative 3 are all less than under Alternative 2 in comparable years.
- The predicted mass of the plumes in Alternative 4 are generally less than the predicted mass of the plumes in Alternatives 2 or 3 in equivalent years. The one exception is the mass of boron in 2029 in Alternative 4 is greater than the mass of boron in 2029 in Alternative 3.
- Under Alternative 4, the plume mass above PCC decreases from 5,051 kg in 2016, to 47 kg in 2069 to zero kg in 2099; the plume mass decreases 97% by 2049 and 99% by of 2069.

Sulfate

- Sulfate plume masses above PCC in Alternative 2 are much less than Alternative 1 in comparable years.
- The plume mass decreases after 2016 in all simulations.
- In Alternative 2 by the end of 2049 the plume mass above PCC is 0 kg with the exception of Layer 3 which has a plume mass of 1,121 kg (a result of concentrations exceeding the PCC in three model cells beneath the Former D4 Brine Pond).
- Simulation of Alternative 2 shows the mass of the sulfate plume decreases 100% by the end of 2049.

8.0 SENSITIVITY ANALYSIS

A sensitivity analysis was performed on the calibrated transport model by systematically adjusting both boron (Alternative 4) and sulfate (Alternative 2) models. The sensitivity analysis is designed to evaluate the sensitivity in model predictions associated with uncertain model assumptions and inputs. The simulations are designed to evaluate potential uncertainty related to effectiveness of the selected remedial alternative with respect to uncertainty in key model inputs. Through the modeling process, it was observed that predictions of the effectiveness of remedial alternatives appear to be most sensitive to the following inputs:

- Source concentrations;
- Pond seepage rates;
- Hydraulic conductivity;
- Retardation factor; and
- Effective porosity.

Sensitivity analyses were designed and executed for each of these inputs. The extent of boron and sulfate exceeding the PCC resulting from sensitivity simulations in 2049 were compare results for boron (Alternative 4) and sulfate Alternative 2) to evaluate sensitivity of model predictions to each parameter. **Figures 8-1** through **8-6** present isoconcentration maps generated from simulation results in 2049 for each layer and for each sensitivity simulation.

8.1 SIMULATED SOURCE CONCENTRATION

Source concentrations from process ponds in the model are uncertain. Concentrations of constituents in some ponds have varied considerably over the years due to changes in water management and other factors. It is also possible that concentrations of constituents could increase as pond seepage percolates through previously impacted soil in the vadose zone.

Simulations indicate that sulfate will clean up faster than boron. For this reason, most sensitivity analyses were completed on boron. There are some portions of the Plant Site area where current concentrations of boron in groundwater are already below PCC, but sulfate exceeds the PCC (i.e. near South Cooling Tower Blowdown Pond C, Former Units 3 & 4 Wash Tray Ponds, and Former Units 3 & 4 Drain Collection Pond). For this reason, sensitivity of model predictions in Alternative 2 to sulfate source concentrations was analyzed.

Table 8-1 lists source concentrations values that were adjusted during the sensitivity analysis along with the adjusted values. Sensitivity analyses on individual source areas was conducted by multiplying the simulated source concentration by 0.5 and 2 to represent low and high range estimates for sensitivity analysis. All zones were adjusted together.

Process ponds not listed in **Table 8-1** were not adjusted during the sensitivity analysis. Ponds not included fall into two categories: 1) ponds that are already closed or will be closed and capped within 4 years and will therefore no longer be a source after a short period of time; and 2) ponds where surrounding groundwater currently does not exceed PCC.

Figure 8-1 and **Figure 8-2** presents sensitivity analysis results for source concentrations. Predictions are not very sensitive to increases in source concentrations. The higher boron and sulfate source concentration simulations result in slightly increased extents of groundwater exceeding the PCC. However, these extents are generally within the POC; the one exception is that sulfate concentrations greater than the PCC occur slightly outside the POC in the high source concentration sensitivity analysis.

8.2 POND SEEPAGE RATES

There is some uncertainty in seepage rates for some process ponds that are sources of constituents to groundwater.

- Some ponds (North Plant Area Drain Pond, Units 3 & 4 Bottom Ash Ponds, etc.) may have some uncertainty related to seepage rates, but groundwater downgradient of these ponds already has constituent concentrations near or below PCCs, therefore, sensitivity analyses was not run on these ponds.
- Seepage rates for source areas that have been recently taken out of service or cleaned out (i.e. Wash Tray Pond, Units 3 & 4 Scrubber Drain Collection Pond, and Sediment Retention Pond) have simulated source concentration at background in the predictive simulations; seepage rates for these ponds were not adjusted during the sensitivity analysis.
- Furthermore, seepage rates in the location of the Former D1-D4 Brine Ponds (taken out of service several years ago) is simulated to reduce to zero when the Brine Concentrator Solids Disposal Area is constructed over the footprint of the ponds in 2018; seepage rates for these ponds were also not adjusted during the sensitivity analysis.

During the sensitivity analysis, seepage rates for selected source areas were multiplied by a factor of 2 to evaluate uncertainty in model results associated with uncertainty in seepage rates. Seepage rates were not reduced as part of the sensitivity analysis because the model would not converge when seepage rates were reduced. In addition, cleanup goals are achieved in 2049, and reducing the seepage rates would improve the predicted time required for concentrations outside pond perimeters to drop below PCC.

Table 8-2 lists pond seepage rates that were adjusted during the sensitivity analysis along with adjusted along with the MODLFOW Recharge Package zones representing each source and the adjusted seepage values. Most of the ponds have simulated decreasing seepage in each Alternative representing source control; the adjustment factor of 2 was applied to seepage rates in all subsequent stress periods. All source areas listed were adjusted together.

Figure 8-3 presents the results of the sensitivity analysis for pond seepage rates. Though the higher seepage rate tested results in an increased extent of groundwater exceeding the PCC, results indicate cleanup goals would still be achieved by 2049. Increase seepage rates did not result in any predicted sulfate concentrations above the PCC

8.3 HYDRAULIC CONDUCTIVITY

Hydraulic conductivity values within the model domain could vary from the calibrated values. Groundwater in the area around the Former Units 1 & 2 A Pond exhibits some of the highest constituent concentrations, and the model predicts that this area will continue to have elevated concentrations for many decades. Therefore, uncertainty in model results related to uncertainty in hydraulic conductivity of key zones in this area was evaluated. Hydraulic conductivity zones affecting transport from the Former Units 1 & 2 A Pond area include: Zone 13 in Layer 2, Zone 8 in Layer 3, Zone 6 in Layer 4 and Zone 7 in Layer 5. **Table 8-3** lists zones that were tested along with low and high horizontal and vertical hydraulic conductivity values that were used in the sensitivity analysis. Sensitivity of model results to hydraulic conductivity values in each of these zones were evaluated as a group.

Originally, the hydraulic conductivity sensitivity analysis was planned to include order of magnitude adjustments above and below the calibrated value. However, the model would not converge when decreasing the hydraulic conductivity in the selected zones an order of magnitude. As a result, hydraulic conductivity was iteratively adjusted until the model did converge. Hydraulic conductivity Zones 13 and 8, were multiplied by 0.5 Zone 6 was multiplied by 0.33, and Zone 7 (Sub-McKay) was multiplied by 0.75. Most high end adjusted values are an order of magnitude above the calibrated value. The high end value for McKay Coal was set to the maximum value observed in site data (NewFields, 2015), as literature values for this unit do not range an order of magnitude above values in the calibrated values for this unit.

Figure 8-4 presents the results of the sensitivity analysis for hydraulic conductivity. Results show conclusions regarding the effectiveness of Alternative 4 are not sensitive to changes in hydraulic conductivity. An increase in hydraulic conductivity in the selected zones would result in slightly larger areas of boron concentrations exceeding PCC (D4 Brine Pond in Layers 2 and 3. A decrease in hydraulic conductivity in the selected zones results in slightly larger areas of exceedance under the Former Units 1 & 2 A Pond in Layers 3 and 4. However, even with adjusted hydraulic conductivity values, Alternative 4 meets cleanup goals by 2049.

8.4 RETARDATION

As described in **Section 5.2.3**, the retardation factor is a function of several parameters. Of these parameters, K_d has the greatest range of uncertainty. According to EPRI (2006) the K_d for boron ranges from 0.4 to 3.0. Based on site data and model calibration a K_d value of 0.4 was used in the calibrated model. We propose to evaluate the retardation sensitivity for boron using the upper end value of K_d (3.0).

Figure 8-5 presents results of the sensitivity analysis for retardation. Results show an increase in the retardation factor increases the area exceeding the PCC at the end of 2049 and slows the cleanup timeframe. As discussed in **Section 5.2.3**, site data suggests a K_d on the order of 0.4 is appropriate. A K_d for boron at the site of 3.0 would likely result in much slower boron breakthrough and higher boron concentration gradients than has been observed (see **Appendix D**). While the sensitivity analysis suggests the model is sensitive to an order of magnitude increase in K_d value, results predicted using this K_d are probably unrepresentative.

8.5 EFFECTIVE POROSITY

Effective porosity affects groundwater velocity and transport of dissolve constituents. Effective porosity in the model was multiplied by 0.5 and 2 to represent low and high values for sensitivity analysis. **Table 8-4** lists high and low effective porosity values that were used in the sensitivity analysis.

Figure 8-6 presents the results of the sensitivity analysis for effective porosity. Results show the model predictions are not sensitive to changes in effective porosity of 0.5 and 2 times the model assigned values. Higher effective porosity results in only a slight increase the area of groundwater exceeding the boron PCC at the end of 2049 in Layer 4 under the Former Units 1 & 2 A Pond.

9.0 MODEL LIMITATIONS

Models are simplifications of complex systems. In all modeling exercises, some input parameters are not well quantified due to a lack of data, which leads to uncertainty in model predictions. The primary objective of the modeling exercise described in this memorandum was to develop a numerical tool to help evaluate proposed remedial alternative in a relative manner. Actual time frames could vary from these predictions, but the relative performance of alternatives should be reliable.

Because the transport model has not undergone a rigorous quantitative calibration, its ability to accurately predict concentrations of constituents at specific locations at specific times in the future has not been demonstrated. However, qualitative calibration of the model demonstrates that the model is capable of simulating the general extent and magnitude of groundwater impacted by process water from the Plant Site and is therefore appropriate for evaluating the effects of the Alternative Measures on a comparative basis. The ability of the model to predict changes in concentrations over short distances at the scale of tens of feet or less may be limited, particularly in areas with complex flow dynamics and geochemistry. In other words, the fate and transport model is appropriate for comparing the effects of different potential remedial measures on the overall plume geometry and magnitude, but not for predicting concentrations at precise points in space and time.

Site-specific data related to transport parameters such as dispersivity and effective porosity are not available. Where data are missing or insufficient to characterize variability in the system, conservative assumptions were made in developing model inputs based on literature values. To minimize the uncertainties with these parameters, dispersivity was calculated and then adjusted during the qualitative calibration, and the effects of effective porosity were evaluated in the sensitivity analysis.

The model simulates flow through bedrock fractures as an equivalent porous medium. This approximates flow and some units may be more influenced by fracture flow that cannot be modeled as porous flow at this scale.

10.0 CONCLUSIONS

Based on the work described above, NewFields offers the following conclusions.

- The overall lateral extent of impacted groundwater based on 2016 data is similar to previous delineations.
- Data available to assess the extent of cobalt, molybdenum, lithium and manganese are spatially limited. More data may be needed to fully characterize the extent of groundwater exceeding PCCs for these constituents.
- Lithium, manganese, and cobalt exceed PCC in groundwater in some wells near source areas;
- Molybdenum concentrations exceeding PCC have been detected in samples from only one well analyzed for this constituent; this suggests that molybdenum concentrations exceeding the PCC are not widespread in groundwater at the Plant Site.
- Selenium concentrations exceeding the PCC are not widespread.
- Concentrations of sulfate, TDS, and selenium in groundwater near well 38SP exceed PCC (or BSL for TDS); the source of constituents detected in this well is not thought to be Plant Site process ponds.
- Surface releases from a flyash slurry pipeline are the likely source of sulfate and TDS exceedances in alluvial groundwater in wells near OT-7. Canty (2017) found that soil remaining in former pipeline release sites south of the City of Colstrip Sewage Lagoons areas does not present a human health or ecological risk.
- The vertical extent of groundwater exceeding PCC has been adequately delineated for purposes of remedy selection. There are a few areas (e.g. near well 55D) where the vertical limit of the plume has not been completely defined. All these areas are near capture wells where vertical gradients are currently upward, indicating that further downward migration is unlikely in those areas.
- Updated capture analysis (particle tracking) using 2016 data produced results similar to those in Model Update Report (NewFields, 2015).
- A qualitative calibration of the solute transport model demonstrates that the model is generally able to simulate the observed extent of boron and sulfate exceeding PCC as well as the general range of observed concentrations. This indicates the model is appropriate for comparing the likely relative effectiveness of different remedial alternatives.
- Based on MDEQ comments, an objective of achieving PCC by 2049 was established.
- By 2049, implementation of Alternative 1 would reduce the volume of groundwater above sulfate and boron PCC by approximately 68 percent and 26 percent, respectively. This reduction would not meet cleanup goals, as boron and sulfate concentrations above the PCC would remain outside pond perimeters after 2049.
- Implementation of Alternatives 2 and 3 would reduce sulfate concentrations below PCC outside pond perimeters by the end of 2049 but would not have the same effect on boron concentrations.

- By 2049, implementation of Alternative 2 is estimated to reduce the volume of groundwater above sulfate and boron PCC by 100 percent and 41 percent, respectively, but the boron plume expands after capture well shutdown in 2049. Alternative 2 does not meet cleanup goals for boron.
- By 2049, implementation of Alternatives 3 would reduce the volume of groundwater above the boron PCC by approximately 73 percent, but the plume expands after capture well shutdown in 2049. Alternative 3 does not meet cleanup goals for boron.
- Alternative 4 reduces the volume of groundwater above the boron PCC by approximately 93 percent by 2049, and the plume does not expand after capture well shutdown. The remaining 7% of PCC exceedances are beneath the ponds, which is within the POC.
- Implementation of Alternative 4 would meet cleanup goals and reduce boron and sulfate concentrations outside of pond perimeters below PCC by 2049.
- Alternative 4 reduces the mass of boron above PCC by 97 percent in 2049 and by 99 percent in 2069.
- Alternatives that rely on groundwater capture and source control only do not meet cleanup goals for boron by 2049 because boron mass is trapped in the unsaturated zone due to drawdown from capture and elimination of seepage from source ponds. Implementation of injection combined with extraction (Alternative 4) flushes boron toward capture wells more quickly.
- Model predictions are not sensitive to the range of changes tested for source concentrations, seepage rates, hydraulic conductivity, or effective porosity.
- Model predictions for boron are sensitive to retardation coefficient values based on an order of magnitude increase in K_d value; however, empirical data suggest that the higher K_d value tested is not representative of aquifer materials at the Plant Site.

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