DRAFT REPORT

Monitored Natural Attenuation Evaluation for Boron and Sulfate

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MNA Checklist

Elements of MNA Evaluation	Characterization	Applicable Section(s)
Pre-Tier 1 - Site Background Information		
Site Layout	Identify potential source(s)	2.0, 2.1, 3.1
	Identify potential exposure points/receptors	2.0, 2.1, 3.1
Site History	History and Inventory of contaminants released	1.0, 2.1
	Mode of contaminant release	1.0, 2.1
	Chemistry of CCR source and release	3.1, 3.2, 4.1, 4.2
Tier 1 - Demonstrate Active Contaminant Removal from Groundwater		
Hydrogeologic Elements	Potential migration pathways identified	2.1
	Nature and extent of contaminant plume	2.1, 3.1, 5.0, 6.3
	Basic groundwater flow direction and aquifer hydrostratigraphy	5.0, App. A
General Site Chemistry	General chemistry (groundwater, surface water, and/or aquifer solids) for preliminary evaluation of contaminant degradation	3.1, 3.2, 4.1, 4.2
	Trend evaluation of groundwater data	3.1, 3.2, 4.1
	Distribution of contaminants between aqueous and solid phases	4.1, 4.2
Tier 2 - Determine Mechanisms and Rate of Attenuation		
Define Contaminant/Aquifer Solid Interactions	Identify aquifer mineralogy, attenuation mechanisms, and microbiological processes (if applicable)	4.1, 4.2, 6.1, 6.2, 6.3
Chemistry and Spatial Distribution of Contaminants	Groundwater characteristics for source(s) and contaminant plume, including field parameters, Appendix III parameters, Appendix IV parameters, major cations and anions, and speciation data (if applicable)	3.1, 3.2, 4.1, 5.0
Detailed Hydrogeology	Groundwater flow regime, including direction, velocity, potentiometric surface, gradients, etc.	2.1, 5.0, App. A
Tier 3 – Determine System Capacity and Stability of Attenuation		
Measurement of Attenuation Capacity	Determination of contaminant and dissolved reactant fluxes (concentration data and water flux)	6.1, 6.2, 6.3
	Determination of mass of available solid phase reactant(s)	4.2, 6.2, 6.3
Stability of Attenuated Contaminated Mass	Laboratory testing of immobilized contaminant stability	4.2, 6.2
	Model analyses to characterize aquifer capacity and evaluation of immobilized contaminant stability	6.2, 6.3
Tier 4 - Design of Performance Monitoring Program and Identify Alternative Remedy		
Long-Term Monitoring Program	Selection of monitoring locations and sampling frequency based on site conditions	Not applicable - provided in separate report.
	Selection of key monitoring parameters used to assess effectiveness of the remedy	
	Selection of monitoring criteria that would trigger re-evaluation of adequacy of the monitoring program and the remedy selected	

Note: Table based on summaries provided in United States Environmental Protection Agency (USEPA) *Monitored Natural Attenuation of Inorganic Contaminants in Ground Water* (USEPA 2007a, b), and Interstate Technology & Regulatory Council (ITRC) *A Decision Framework for Applying Monitoring Natural Attenuation Processes to Metals and Radionuclides in Groundwater* (ITRC 2010).

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1.0 INTRODUCTION

Groundwater and coal combustion residual (CCR) porewater were characterized and the results evaluated to determine the effectiveness of Monitored Natural Attenuation (MNA) as a component of remedial strategy assessment for Ameren Missouri's (hereafter, "Ameren") LCPA bottom ash surface impoundment (hereafter, "LCPA" or "CCR Unit") located at Labadie Energy Center (LEC) in Franklin County, Missouri (hereafter, the "Site", "LEC", "Facility" or "Labadie"). The structure of this evaluation closely follows the United States Environmental Protection Agency (USEPA) guidance on using MNA as a remedial strategy (USEPA 2007a, b) and considers best practices from the Interstate Technology Regulatory Council (ITRC) document: "A Decision Framework for Applying Monitored Natural Attenuation Processes to Metals and Radionuclides in Groundwater" (ITRC 2010). This MNA evaluation was completed using the following tiers (USEPA 2007a, b):

1) Demonstrate active constituent removal from groundwater and dissolved plume stability (Tier I)
2) Determine the mechanism(s) and rate(s) of the operative attenuation processes (Tier II)
3) Determine the long-term capacity for attenuation and the stability of immobilized constituents (Tier III)

Following the completion of this multi-tier evaluation, the fourth and final tier of an MNA program, which involves the design of a performance monitoring program and the development of contingency plan, will be updated as needed, based on the findings of this evaluation.

2.0 SITE BACKGROUND

The LEC is located approximately 35 miles west of downtown St. Louis in Franklin County, Missouri. The Site encompasses approximately 2,400 acres and is situated within the Missouri River Valley. The Site is bounded to the north by the Missouri River, to the west by Labadie Creek, to the northeast and east by agricultural land and to the south by a railroad line and bedrock bluffs. Figure 1 shows the CCR Unit, along with Site wells and the Missouri River.

For groundwater compliance, the LEC either currently has, or expects to have in the future, three different programs that all have different groundwater compliance limits, as follows:

1) USEPA CCR Rule regulations which have site-specific Groundwater Protection Standards (GWPS).

2) A future Missouri Department of Natural Resources (MDNR) National Pollutants Discharge Elimination System (NPDES) permit for the Labadie Energy Center. Proposed groundwater sampling requirements associated with this program are available under special condition 11 of the proposed permit MO-0004812.

3) A future MDNR Underground Injection Control (UIC) permit for groundwater treatment at the LEC. The effluent limitations and monitoring requirements are expected to be similar to those of the current Rush Island Energy Center (RIEC) UIC permit (number UI-0000043).

An initial investigation into the parameters associated with each of these different programs, as well as what constituents are expected to be present at a level that would require either remediation or an Alternative Source Demonstration (ASD), was initially conducted by Golder in February 2021. Based on that evaluation, the constituents of concern (COC) that required further assessment are as follows:

- Arsenic
- Boron
- Cobalt
- Lithium
- Molybdenum
- Manganese
- Sulfate
- Selenium

An MNA evaluation for molybdenum has been prepared and provided to Ameren (Golder, 2021). Based on review of the other COCs, an ASD appears to be applicable for arsenic, cobalt, lithium, manganese, or selenium. Therefore, the effectiveness of MNA as a remedial option was evaluated for boron and sulfate.

Data from the CCR Rule and NPDES monitoring well networks were utilized for the MNA assessment. The well networks are summarized in Table 1 and shown on Figure 1.

Table 1: LEC Monitoring Well Networks

Monitoring Well Networks	Well ID
Background Monitoring Wells	BMW-1D, BMW-2D, BMW-1S, BMW-2S
LCPA Detection and Assessment (Compliance) Monitoring Wells	UMW-1D, UMW-2D, UMW-3D, UMW-4D, UMW-5D, UMW-6D, UMW-7D, UMW-8D, UMW-9D
LCPA Corrective Action Monitoring Wells	LMW-1S, LMW-2S, LMW-4S, LMW-7S, LMW-8S, MW-24, MW-26, S-1, AM-1S, AM-1D, TP-1D, TP-2M, TP-2D, TP-3M, TP-3D, TP-4D, MW-33(D), MW-34(D), MW-35(D), AMW-8*
NPDES Site Characterization Wells	AMW-1, AMW-2, AMW-3, AMW-4, AMW-5, AMW-6, AMW-7, AMW-8*, AMW-9, TGP-A**

Notes:
* AMW-8 is included in both the corrective action monitoring well network and the NPDES site characterization network.
**TGP-A is a bedrock aquifer well and was not used for this evaluation of the Missouri River Alluvial Aquifer.

Under the CCR Rule, boron and sulfate are both Appendix III parameters, meaning that they are used in detection monitoring. Statistically, in CCR Rule monitoring, these constituents are compared to background values, and if they are found to have demonstrated a Statistically Significant Increase (SSI) over background levels, then Assessment Monitoring is triggered. Corrective Action under the CCR Rule, however, is only required if an Appendix IV parameter (for example, molybdenum) is found at a Statistically Significant Level (SSL) over the site-specific GWPS. Therefore, exceedances of these parameters alone have not required remediation at the site.

A draft NPDES permit was prepared by the MDNR for the LEC in 2020 that has special conditions for groundwater monitoring of historical ash impoundments. This draft permit requires quarterly groundwater monitoring and has set compliance limits in groundwater as follows:

- Boron at 2,000 micrograms per liter (µg/L)
- Sulfate at 250 milligrams per liter (mg/L)

These limits are from the MDNR Division 20 – Clean Water Commission Chapter 7 – Water Quality (MDNR 2019) regulations. If these limitations are exceeded, the NPDES permit states that the facility must develop a plan for remediation. Based on historical data at the site for the well networks provided in Table 1, at least one exceedance of the NPDES permit compliance limitations for boron and/or sulfate has been observed at the following wells:

- **Boron** – UMW-2D, UMW-3D, UMW-4D, UMW-5D, UMW-6D, UMW-7D, UMW-8D, LMW-1S, LMW-2S, LMW-4S, LMW-7S, LMW-8S, AM-1D, TP-2M, TP-2D, TP-3M, TP-3D, TP-4D, MW-33(D), MW-34(D), MW-35(D), AMW-8, AMW-2, AMW-4, AMW-5, AMW-6, AMW-7, AMW-9

- **Sulfate** -UMW-2D, UMW-3D, UMW-4D, UMW-5D, UMW-6D, UMW-7D UMW-8D, LMW-1S, LMW-2S, LMW-4S, LMW-7S, LMW-8S, AM-1D, TP-3D, MW-33(D), MW-34(D), MW-35(D), AMW-2, AMW-4, AMW-5, AMW-6, AMW-7, AMW-8, AMW-9

This MNA report has been prepared to further evaluate the effectiveness of MNA as a groundwater remedy at the LEC for boron and sulfate.

In addition to MNA, a pilot study to evaluate the effectiveness of a pump, treat and re-injection system is currently underway. A similar system was installed at the RIEC and the test demonstrated a 99% reduction in key CCR constituent concentrations. At the LEC, an underground injection permit has been submitted to the state, and if the pilot test displays favorable results like those at the RIEC, a full-scale treatment system will be installed on the downgradient sides of the LCPA. The current plan is for the treatment system to be fully operational by the end of 2023.

2.1 Summary of Site Hydrogeologic Conditions

A detailed discussion of the Site hydrogeology is presented in the Groundwater Monitoring Plan (GMP; Golder 2017), the Corrective Action Groundwater Monitoring Plan (CAGMP; Golder 2020b) and the initial 2019 modeling report (Gredell 2019). In summary, geological and hydrogeological units exposed at the Site include two different geologic terrains: (1) floodplain deposits of the Missouri River Valley and (2) older sedimentary bedrock formations. The alluvial floodplain deposits are typically comprised of sands and gravels with lesser amounts of silts and clays, generally resulting in an overall fining-upward sequence. The bedrock formations are comprised of relatively flat-lying Ordovician-aged limestones, sandstones, and dolomites.

The alluvial deposits represent the primary aquifer at the Site and are influenced by the nearby Missouri River. Water flows into and out of the alluvial aquifer because of fluctuating river water levels that produce “bank recharge” and “bank discharge” conditions. Under typical aquifer conditions, groundwater in the alluvial aquifer flows towards the river and away from the bedrock bluffs, with a net flow direction generally to the north or northeast.

Horizontal and vertical groundwater flow within the uppermost aquifer have been locally influenced by operation of the LCPA surface impoundment prior to commencing closure. Prior to closure, ponding of water in the LCPA at elevations higher than the static water levels in the underlying alluvial aquifer groundwater created a localized mounding effect, resulting in localized downward gradients and localized radial groundwater flow outward from the impoundment. Since closure, these artificial downward gradients have been eliminated and alluvial aquifer flow has returned to more natural flow conditions.

3.0 DATA USED FOR MNA EVALUATION

This evaluation was performed to further assess the mechanisms, rates, and stability of MNA as a remedy for groundwater impacts for the LCPA. To conduct this evaluation, analytical results for groundwater and CCR porewater collected since 2011 were reviewed. Supplemental data collection and evaluation in support of the MNA assessment included:

- Groundwater characterization (including major cations and anions) to identify water types and temporal and geographical trends, where present.
- Geochemical modeling to identify the major aqueous species and evaluate saturation indices of minerals relevant to attenuation of boron and sulfate.

The results generated by this supplemental assessment were used by Golder to complete the Tier I, Tier II, and Tier III evaluations in accordance with USEPA (2007a, b). The results of the Tier I, Tier II, and Tier III are summarized in the subsequent sections.

3.1 Groundwater and Porewater Sampling

Numerous groundwater samples have been collected at the Site in support of CCR Rule, NPDES Permit, and State Utility Waste Landfill (UWL) monitoring programs. For this evaluation, monitoring wells from the compliance, corrective action, and NPDES site characterization networks as well as porewater from the CCR Unit piezometers were evaluated. The network sampling locations and designations are presented on Figure 1 and in Table 2.

Table 2: Sampling Locations Used for the MNA Assessment

Detection and Assessment (Compliance) Monitoring Network Wells	Corrective Action Monitoring Network Wells	NPDES Site Characterization Wells	CCR Unit Porewater Piezometers
BMW-1D*, BMW-2D*, UMW-1D, UMW-2D, UMW-3D, UMW-4D, UMW-5D, UMW-6D, UMW-7D, UMW-8D, UMW-9D	BMW-1S*, BMW-2S*, LMW-1S, LMW-2S, LMW-4S, LMW-7S, LMW-8S, MW-24, MW-26, S-1, AM-1S, AM-1D, TP-1D, TP-2M, TP-2D, TP-3M, TP-3D, TP-4D, MW-33(D), MW-34(D), MW-35(D), AMW-8**	AMW-1, AMW-2, AMW-3, AMW-4, AMW-5, AMW-6, AMW-7, AMW-8**, AMW-9, TGP-A***	LCPA-1D, LCPA-1S, LCPA-2D, LCPA-2S, LCPA-3D, LCPA-3S

Note: * - Denotes background well.
** - AMW-8 is included in both the corrective action monitoring well network and the NPDES site characterization network.
*** - TGP-A is a bedrock aquifer well and was not used for this evaluation of the Missouri River Alluvial Aquifer.

3.1.1 Groundwater and Porewater Analysis

Geochemical analysis of groundwater and porewater samples included the determination of field parameters and the concentrations of total metals and major cations and anions. The rationale and methods used were as follows:

- **Field Parameters:** Parameters measured in the field included pH, dissolved oxygen, oxidation reduction potential (ORP), conductivity, and temperature. These parameters were used to determine general geochemical conditions in the groundwater and support geochemical modeling.
- **Metals:** Analysis of Appendix III and IV metals concentrations was conducted to understand the geochemical composition of groundwater and CCR Unit porewater. Metals analysis allows for the delineation of a potential plume, evaluation of mineral saturation indices through geochemical modeling, and evaluation of contributions from natural or anthropogenic sources.
- **Major Cations and Anions:** Geochemical modeling of mineral solubility, metals attenuation, and background contributions requires analysis of major cations and anions because they affect and participate in sorption and mineral dissolution or precipitation reactions.

The results and methods for analysis of the groundwater and porewater samples are provided in the Annual Reports for the LCPA, LCPB, and LCL1 from 2017 to 2020.

4.0 GROUNDWATER AND POREWATER CHARACTERIZATION

4.1 Geochemical Evaluation

The water quality monitoring data used for the geochemical evaluation were obtained from Site monitoring wells and CCR Unit piezometers. The results discussed in this section apply to the compliance monitoring wells, the corrective action monitoring wells, and the NPDES site characterization wells. Data used are provided in the Annual Reports produced by Golder from 2017 through 2021 and Gredell's ongoing NPDES permit sampling.

On September 28th, 2019, Ameren commenced Phase 1 of Corrective Action by initiating closure at the LCPA and completed Phase 1 with the installation of a geomembrane liner system by December 30th, 2020. As such, the discussion of water quality results addresses the periods before and after closure. The following is noted with respect to groundwater quality:

- **pH:** The pH of groundwater samples collected from CCR compliance monitoring network wells after closure (between January and June 2021) ranged from 6.8 to 9.4 (Figure 2a). Historically, the pH in the compliance monitoring well network has ranged from 6.2 to 9.6. Pre-closure groundwater samples collected from the corrective action and the NPDES site characterization well networks reported pH values ranging from 5.8 to 9.8. Samples collected from the corrective action and the NPDES site characterization network since the closure of the LCPA display pH values ranging from 6.6 to 9.4 (Figure 2b, 2c). In 2018, the pH of LPCA porewater ranged from 8.9 to 10.8.

- **ORP (Redox):** The ORP of groundwater samples collected from compliance monitoring wells after closure ranged from -181 to +53 millivolts (mV) (Figure 3a). Historically, the ORP in the compliance monitoring well network has ranged from –242 to +159 mV. The ORP of corrective action and NPDES site characterization monitoring wells ranged from -183 to +94 mV after closure. Pre-closure ORP values within the corrective action and NPDES site characterization monitoring network were variable, ranging from -297 to +311 mV (Figure 3b, 3c). In 2018, the ORP of porewater ranged from -90 to +170 mV.

- **Total Dissolved Solids (TDS):** Groundwater TDS concentrations in the compliance monitoring well network were variable after the LCPA closure and ranged from 324 to 1050 mg/L. The lowest TDS concentration (324 mg/L) was observed in the compliance monitoring well UMW-4D (where there is an exceedance of the draft NPDES permit level for boron and sulfate) and the highest TDS concentration (1,050 mg/L) was reported at CCR compliance monitoring well UMW-8D (where the same exceedances are observed). TDS concentrations in groundwater samples collected from the corrective action and the NPDES site characterization networks prior to closure ranged from 366 to 1,820 mg/L. After closure, TDS concentrations in the corrective action and NPDES site characterization networks ranged from 274 to 1,270 mg/L. In 2018, the TDS of LPCA porewater ranged from 528 to 642 mg/L.

- **Major ion chemistry:** A Piper plot was generated for groundwater and porewater samples to facilitate the identification of water types and source contributions (Figure 4a, 4b). All background water samples, and most compliance monitoring well network downgradient water samples were water type Ca-HCO_3. The remainder of the downgradient wells had a water type of Ca-SO_4 or Na-SO_4 and demonstrated a similar major ion relative abundance as LPCA porewater (water type Ca-SO_4). The major ion characteristics of samples from the corrective action well network were similar to those of downgradient samples from the compliance monitoring network. A ternary plot evaluating the relative abundance of CCR indicators magnesium, chloride, and boron was generated for groundwater samples collected from the NPDES site characterization network (Figure 5). Boron relative abundance in samples from the NPDES wells ranged from <1% to 50% and magnesium relative abundance ranged from 4% to 72%.

The majority of LPCA porewater samples contained a higher relative abundance of boron (>50%) and a lower relative abundance of magnesium (<12%) than NPDES samples.

- **Boron:** Historically, boron concentrations in groundwater surrounding the LCPA CCR Unit have ranged from non-detect (<0.001 mg/L) to 18.2 mg/L (Figure 6a). Boron concentrations exceeded the draft NPDES permit requirements in 28 out of 41 wells evaluated at the Site. However, since the installation of a closure liner system at the LCPA (December 2020), boron concentrations in only 19 wells continue to exceed the proposed NPDES permit requirements (Figure 6a, 6b, 6c).

  Using available historical data, Mann-Kendall tests of boron concentrations at LMW-7S, UMW-7D, and UMW-8D show a statistically significant increasing trend. However, since the initial closure activities began (September 2019), a significant increasing trend is no longer observed at any of these wells. Instead, boron concentrations appear to be only slightly increasing at LMW-7S, and UMW-8D, and decreasing at UMW-7D. However, these trends are not considered statistically significant. Nearly all other wells with an exceedance of the draft NPDES permit for boron show a visually decreasing or stable trend. It is anticipated that boron concentrations will continue to decrease due the closure of the LCPA and the installation of a groundwater treatment system.

- **Sulfate:** Historically, sulfate concentrations in groundwater across the Site have ranged from non-detect (0.075 mg/L) to 1,720 mg/L. Sulfate concentrations exceeded the draft NPDES permit limit of 250 mg/L in 24 of the 41 wells evaluated for this investigation across the Site. However, since the installation of the closure liner system at the LCPA, sulfate concentrations in only 10 wells continue to exceed the draft NPDES permit requirements (Figure 7a, 7b, 7c).

  Since 2014, sulfate concentrations in groundwater have increased in wells MW-35(D), UMW-6D, UMW-7D, and UMW-8D. However, since closure activities at the Site began (September 2019), sulfate concentrations at these wells have decreased substantially. For example, sulfate concentrations decreased from 926 mg/L to 634 mg/L in MW-35(D) between November 2019 and April 2021. It is anticipated that sulfate concentrations will continue to decrease due the closure of the LCPA and the installation of a groundwater treatment system.

5.0 GROUNDWATER MODELING

In 2019, a groundwater model and draft report was prepared by Gredell Engineering, Inc (Gredell 2019) to predict groundwater flow at the LEC for the Corrective Measures Assessment. In 2021, this groundwater model was updated by XDD Environmental, LLC to provide predictive analysis for groundwater flow at the LEC for the design of a pump, treat, and re-injection system for LCPA Corrective Action. For the present evaluation, Golder updated the XDD model to assess the conservative transport of boron and sulfate under different corrective action scenarios. The transport model used for this evaluation is considered conservative in the context of not considering chemical attenuation (that is, no formation of mineral precipitates and no sorption [i.e., K_d = 0]). However, physical attenuation (i.e., dilution and dispersion) was accounted for in the transport model. An evaluation of the potential for chemical attenuation of boron and sulfate was conducted as described in Section 6.2, with the results presented in Section 6.3.2. A Technical Memorandum summarizing the groundwater model is provided in Appendix A.

The numerical computer code MODFLOW, developed by the United States Geological Survey (USGS), was selected for the groundwater modeling because it is well suited to represent a wide range of hydrologic and hydrogeologic conditions, has been widely tested and accepted in the professional hydrology community and by regulatory agencies, and has been scrutinized closely in a number of legal proceedings over the past 20 years. In total, five software packages were used for the groundwater investigation:

- Groundwater flow: USGS software package MODFLOW (McDonald and Harbaugh 1988, Harbaugh and McDonald 1996, Harbaugh et al. 2000, Harbaugh 2005). MODFLOW-2005 was the version used in the analyses presented here
- Groundwater transport: USGS software package MT3DMS (Zheng and Wang, 1999)
- Particle tracking: USGS software package MODPATH (Pollock 2012)
- Parameter estimation: PEST (Doherty 2010 and 2016)
- Graphical user interface: Groundwater Vistas (Environmental Simulations 2020, Rumbaugh and Rumbaugh 2011)

The groundwater model simulates steady-state and transient flow conditions for the site area. The groundwater model was developed and updated based on the following:

- Natural hydrologic boundaries wherever possible
- Ground surface topography and CCR unit geometries
- Geologic layers with representative hydrogeological properties based on boring logs
- Hydraulic properties of geologic layers based on historical aquifer tests conducted at the site
- Historical groundwater elevation measurements

Details of the flow model development and results are presented in Appendix A. The results of the model were used to support the geochemical evaluation, as discussed in Section 6

6.0 GEOCHEMICAL EVALUATION AND MODELING

6.1 Empirical Attenuation Rates

To evaluate the attenuation of boron and sulfate in groundwater at the Site and to assess the rate of attenuation, Golder applied the point decay method (Newell et al. 2002). The point decay method is used to determine the rate at which a constituent's concentrations are increasing or decreasing in groundwater at a single well between sampling events. This method can thus be used to predict when the constituent's concentrations will fall back below regulatory limits.

Equation 1 describes first-order decay for a constituent:

$$Ln(Ct) = kt + Ln(C0) \qquad \text{(Equation 1)}$$

where C0 is the initial constituent concentration, Ct is the constituent concentration at time t, t is the amount of time in years that has passed since the initial concentration measurement, and k is the first-order decay rate constant (1 per year). Equation 2 shows Equation 1 reorganized to solve for the decay rate constant:

$$k = (Ln(Ct)- Ln(C0))/t \qquad \text{(Equation 2)}$$

Groundwater water quality data from the background and downgradient wells collected between March 2015 and April 2021 were used to determine the mean first-order decay rate for each constituent of interest. A first-order decay rate was also calculated using data collected from September 2019 to June 2021 to evaluate the effect of changing conditions at the Unit since initial closure activities began. Due to variable detection limits, results that were reported as below detection limits were not used in the point decay analysis. Using Equation 1 and the mean first-order decay rate, Golder calculated the approximate number of years that it would take for boron and sulfate concentrations higher than their NPDES compliance limitations to decline below these values and these results are provided in Section 6.3.1.

6.2 Geochemical Modeling

Geochemical modeling was conducted to evaluate general groundwater and porewater quality and determine the potential for mineral precipitation. The geochemical computer code developed by the USGS, PHREEQC, was used for these simulations (Parkhurst and Appelo 2013). PHREEQC version 3.6 is a general-purpose geochemical modeling code used to simulate reactions in water and between water and solid mineral phases (e.g., rocks and sediments). Reactions include aqueous equilibria, mineral dissolution and precipitation, ion exchange, surface complexation, solid solutions, gas-water equilibrium, and kinetic biogeochemical reactions. The widely accepted thermodynamic database Minteq.v4, 2017 edition (USEPA 1998, as amended) was used as a basis for the thermodynamic constants required for modeling, with additions and modifications from recent literature as required. The Geochemist's Workbench (Release 15; Bethke et al. 2021) was used to generate graphical representations of geochemical modeling outputs for the species of interest (i.e., boron and sulfate) and trilinear plots (also known as Piper plots) displaying the relative abundance of major ions.

Over the range of groundwater pH and redox conditions present at the site, only trace amounts of boron and sulfate are expected to adsorb on ferrihydrite (Dzombak and Morel 1990; Smith 1999). Therefore, integrated geochemical attenuation modeling was not conducted for boron and sulfate and the conservative transport modeling approach described in Section 5.0 and Appendix A was considered more appropriate.

6.2.1 Mineral Precipitation and Co-precipitation

The potential for mineral precipitation was assessed in PHREEQC using a saturation index (SI) calculated according to Equation 4.

$$SI = \log (IAP/Ksp) \quad \text{(Equation 4)}$$

The saturation index is the ratio of the ion activity product (IAP) of a mineral to the solubility product (Ksp). An SI value greater than zero indicates that the solution is supersaturated with respect to a particular mineral phase and, therefore, precipitation of this mineral may occur. An evaluation of precipitation kinetics is then required to determine whether the supersaturated mineral will indeed form. An SI value less than zero indicates the solution is undersaturated with respect to a particular mineral phase. An SI value close to zero indicates equilibrium conditions exist between the mineral and the solution. SI values between -0.5 and 0.5 are considered to represent 'equilibrium' in this report to account for the uncertainties inherent in the analytical methods and geochemical modeling.

6.2.2 Geochemical Modeling Assumptions and Data Handling

Geochemical modeling assumptions and data handling included the following:

- **Groundwater continuity:** Groundwater quality samples were collected from each well during sampling events conducted between January and May 2021. Samples from this period were selected for the geochemical modeling because all wells within the compliance, NPDES site characterization, and corrective action monitoring well networks were sampled and analyzed for the full suite of parameters required and the resulting data are assumed to provide a comprehensive overview of groundwater conditions. Temporal trend analysis for boron and sulfate made use of all available sampling events between March 2016 and April 2021.

- **Porewater chemistry:** Porewater samples collected from LCPA-1D, LCPA-1S, LCPA-2D, LCPA-2S, LCPA-3D, and LCPA-3S in February 2018 were assumed to be representative of porewater found in the CCR Unit.

- **Redox values:** ORP values measured in the field were converted to Eh by adding 200 mV to the field-measured values as per YSI Tech Note (YSI 2015).
- **Non-detect values:** Constituents with concentrations less than their respective method reporting limits were assumed to have a concentration equal to half the reporting limit in model simulations.
- **Total recoverable concentrations:** Total recoverable fraction results were used for geochemical modeling.
- **Charge balance:** Groundwater and porewater compositions with charge balance errors less than 10% were considered valid. Compositions with charge balance errors greater than 10% were flagged as potentially less reliable, but still included in the geochemical modeling effort.

6.3 Results

6.3.1 Empirical Attenuation Rate

The results of a combined point decay analysis for groundwater at downgradient wells from all three well networks between March 2015 and May 2021 are provided in Table 3. By combining the networks, the results represent a mean, site-wide attenuation rate for both boron and sulfate.

This evaluation demonstrates that in downgradient wells (from the compliance, corrective action, and NPDES networks), a net decrease in the concentration of boron and sulfate at downgradient monitoring wells has been occurring, as indicated by negative point decay constants. A second point decay analysis for data collected between September 2019 and May 2021 was conducted to represent boron and sulfate concentration trends throughout and following recent Site closure activities. In this dataset, boron and sulfate concentrations reported a stronger decreasing trend (i.e., a more negative point decay constant), shortening the expected time to compliance.

Table 3: Empirical Attenuation Rate of Boron and Sulfate in Site Groundwater

Constituents	Units	Average Point Decay Rates	
		Downgradient Wells	Time to Compliance (years)
March 2015 to May 2021			
Boron	yr^{-1}	-0.08	23.9
Sulfate	yr^{-1}	-0.07	12.9
September 2019 to May 2021			
Boron	yr^{-1}	-0.10	19
Sulfate	yr^{-1}	-0.17	5.5

The mean downgradient decay rates can be used to estimate the number of years it would take for elevated groundwater boron and sulfate concentrations to decrease below the draft NPDES permit requirements in Site wells. At the maximum concentration of boron and sulfate observed in downgradient wells in 2021 (12.8 and 634 mg/L, respectively), achieving compliance would require approximately 19 years for boron and 5.5 years for sulfate based on the site decay rate that has been observed since September 2019. This estimate is conservative, as it does not account for various physical or chemical attenuation processes (e.g., dilution, dispersion, or sorption). Also, this evaluation is based on mean current rates and assumes that enhanced MNA with treatment is not in place. As discussed further in Section 6.3.2, modeling that accounts for the proposed treatment system results in shorter predicted times to compliance.

6.3.2 Mineralogical Controls in Groundwater and Porewater

The results of saturation index modeling for minerals potentially relevant to boron and sulfate attenuation in porewater and groundwater at upgradient, downgradient, and corrective action wells are presented in Table 4. Mineral saturation can play an important role in the attenuation of COCs directly by their removal through precipitation (e.g., sulfate minerals) or by providing sorptive surfaces or opportunities for co-precipitation (e.g., boron co-precipitation on calcite). The results of the saturation index modeling can be summarized as follows:

- Iron-bearing minerals: Ferrihydrite was indicated to be at equilibrium with groundwater or oversaturated in all monitoring well and porewater samples, indicating a strong potential for ongoing precipitation of solid-phase iron oxides. However, sequestration of boron and sulfate through sorption onto ferrihydrite is known to be minimal at the pH range of site groundwater (see Section 6.2).
- Other minerals: All groundwater and porewater samples were simulated to be in equilibrium or oversaturated with respect to calcite ($CaCO_3$). Other carbonate minerals, i.e., rhodochrosite ($MnCO_3$) and siderite ($FeCO_3$), were oversaturated or in equilibrium in most groundwater and some porewater samples. Barite ($BaSO_4$) was simulated to be in equilibrium or oversaturated in all porewater samples and nearly all groundwater samples (except for UMW-9D).

In summary, several mineral phases likely control groundwater composition at some or all wells: barite, calcite, ferrihydrite, rhodochrosite, and siderite. In the case of barite, the dissolved concentrations of sulfate may be reduced through its formation, and very small amounts of boron may be attenuated through sorption onto ferrihydrite. Boron co-precipitation with calcite is theoretically possible based on the literature (e.g., Goldberg 1997). However, the amount of boron potentially removed from groundwater through this mechanism is unlikely to appreciably affect dissolved concentrations at the site.

6.3.3 Model Predicted Attenuation Rate

The attenuation rates for boron and sulfate in groundwater were also modeled using a conservative transport model (described in Section 5.0 and Appendix A) that considers groundwater flow and Site closure (in contrast to empirical decay rates that do not). Based on the results of the conservative groundwater modeling, boron and sulfate concentrations are predicted to decrease in wells both adjacent to the LCPA (Detection and Assessment Network) and within the existing plume (Corrective Action Network).

As shown in Figure 8, sulfate concentrations in monitoring wells currently above the proposed NPDES compliance limit of 250 mg/L that are adjacent to the LCPA and will be immediately affected by the installation of the treatment system (i.e., UMW-3D, UMW-4D, UMW-5D, UMW-6D, UMW-7D and AMW-7) are predicted to be below the proposed compliance limit within 1 to 2 years of the start of treatment system operation. As presented in Figure 9, sulfate concentrations in monitoring wells currently above the proposed NPDES limit that are not immediately affected by the treatment system in the NPDES compliance or corrective action networks (i.e., TP-3D, MW-33D, MW-34D, MW-35D, AM-1D, AMW-5, AMW-8 and AMW-9) are predicted to be below the proposed limit within 1 to 13 years of the start of operation.

Figure 10 displays model predicted boron concentrations in the monitoring wells currently above the proposed NPDES limit of 2,000 µg/L that are adjacent to the LCPA and will be immediately affected by the installation of the treatment system (i.e., UMW-3D, UMW-4D, UMW-5D, UMW-6D, UMW-7D, UMW-8D, AMW-4, and AMW-7). As shown in Figure 10, boron concentrations in these monitoring wells are predicted to be below the proposed limit within 1 to 8 years of the start of treatment system operation. The model calculated attenuation rate in these wells is approximately 646 to 4,800 µg/L per year, with an average decrease in concentration of approximately 1,600 µg/L per year.

Figure 11 presents model predicted boron concentrations at the monitoring wells currently present above the proposed NPDES limit that are not adjacent to the LCPA and are not immediately affected by the installation of the treatment system (i.e., LMW-2S, LMW-4S, LMW-7S, LMW-8S, AM-1D, TP-2D, TP-3D, TP-3M, TP-4D, AMW-6, AMW-8, AMW-9, MW-33D, MW-34D, and MW-35D). As shown in Figure 11, these monitoring wells are predicted to be below the proposed limit within 1 to 37 years of the start of the treatment system operation. The model calculated attenuation rate in these wells is approximately 72 to 2,000 µg/L per year, with an average decrease in concentration of approximately 600 µg/L per year.

To further evaluate the reduction of boron in the system, an assessment of boron mass over time was completed for the alluvial aquifer. This evaluation made use of the modeled concentration in each cell multiplied by the saturated thickness of each cell and the porosity to calculate the estimated mass of boron in the alluvial aquifer over time. As shown in Figure 12, after 10 years of active treatment, almost half of the mass of boron present in the alluvial aquifer system was estimated to have been physically attenuated (i.e., diluted, dispersed, or removed by pumping adjacent to the LCPA). After 30 years of active treatment, the model predicts that 80% of the boron will be physically attenuated.

6.3.4 Aquifer Capacity and Long-term Stability

Enhanced MNA is planned to be used as the Corrective Action remedy at this site, with a pump, treat and re-injection system expected to be fully operational by the end of 2023 on the downgradient side of the surface impoundments. This system supplements the already installed geosynthetic liner capping system and is designed to capture porewater from the LCPA that would discharge into the alluvial aquifer after closure, treat the water such that concentrations of CCR constituents (including boron and sulfate) are below drinking water standards, and then re-inject the water into the alluvial aquifer. As discussed in Section 6.3.3, groundwater modeling using this design predicts that boron concentrations associated with the surface impoundments will physically attenuate below its proposed NPDES compliance limit in 1 to 37 years and sulfate will attenuate below its proposed NPDES compliance limit in 1 to 13 years, depending on the location in the alluvial aquifer.

Boron and sulfate are relatively unaffected by geochemical changes to the aquifer. As such, the pH and redox conditions at the site will have little to no impact on boron and sulfate concentrations or the capacity of the aquifer for their attenuation. Therefore, once levels decline below the GWPS for each, boron and sulfate concentrations are expected to remain stable or further decrease as predicted in the conservative transport model.

7.0 TIER I EVALUATION

The evaluation of natural attenuation of boron and sulfate was completed in accordance with recommended practices and guidance promulgated by the USEPA and the ITRC (USEPA 2007a, b; ITRC 2010). According to USEPA (USEPA 2007a), the purpose of the Tier 1 evaluation is to “Demonstrate that the groundwater plume is not expanding and that sorption of the contaminant onto aquifer solids is occurring where immobilization is the predominant attenuation process.” Based on this definition, the following observations support further MNA for the CCR Unit in coordination with other closure and corrective measure efforts (treatment) that are currently being undertaken:

- **Plume Stability:** Based on the water quality monitoring data presented in this assessment, groundwater concentrations of boron and sulfate outside of the CCR Unit appear to be stable or decreasing. Boron and sulfate concentrations exceeded the draft NPDES permit requirements in twenty-eight and twenty-four wells across the Site, respectively. Since installation of a liner at LCPA (December 2020), only nineteen and ten wells exceeded the NPDES permit requirements for boron and sulfate, respectively. Based on the results from the Mann-Kendall tests, boron and sulfate concentrations in groundwater have generally decreased since site closure activities began (September 2019), even in wells with historically increasing trends.

- **Magnitude of Exceedances:** The highest boron concentration (since monitoring began) across all three well networks were observed at downgradient well UMW-6D in March 2016 at 18.2 mg/L. However, results from the most recent sampling event show that the concentration in this well has decreased to 11.5 mg/L. A similar trend is observed in sulfate across Site wells, where concentrations reached as high as 1,720 mg/L in TP-3D in April 2020 but were below 450 mg/L during the most recent sample event (April 2021). Additionally, only four of twenty-eight downgradient wells with exceedances for boron show increasing trends since closure efforts began in September 2019. The effects of closure were more pronounced for sulfate, since nearly all wells with groundwater exceedances for sulfate show visually stable or decreasing trends since September 2019.
- **Porewater:** Historical records are not available for ash additions or porewater concentrations over the lifespan of the LCPA surface impoundment. However, based on 2018 porewater data, boron and sulfate concentrations in porewater ranged from 3.4 mg/L to 21.7 mg/L and 254 to 306 mg/L, respectively. This indicates variable concentrations of boron and sulfate in the CCR Unit. While the LCPA may have been a source for boron and sulfate in groundwater in the past, due to the leaching characteristics of CCR, and groundwater predominantly flowing around instead of into the LCPA after closure, it is currently not considered to be an active source of boron and sulfate, as demonstrated by decreasing site-wide boron and sulfate concentrations in the various well networks that are immediately adjacent to the LCPA. Installation of a treatment system will also capture any future discharges from the LCPA, further reducing the potential for the LCPA to be a source of future impacts.
- **Groundwater Chemistry:** The groundwater monitoring results and the findings of the geochemical modeling support the potential for limited natural chemical attenuation of boron and sulfate. Groundwater was modeled to be in equilibrium with the mineral phase ferrihydrite for all monitoring wells included in this assessment, which may result in sorption of trace amounts of boron. Additionally, the sulfate bearing mineral barite ($BaSO_4$) was simulated to be in equilibrium or oversaturated in all porewater samples and nearly all groundwater samples (except for UMW-9D). This likely indicates the removal of minor amounts of sulfate in groundwater through mineral precipitation.
- **Confirmation of Attenuation:** Based on empirical attenuation calculations, it is demonstrated that attenuation of boron and sulfate is occurring. Additional attenuation is likely taking place because of a reduced contribution from porewater around the LCPA due to liner placement, which will be further aided by the installation of a groundwater treatment system.

Based on these findings, boron and sulfate are considered to be viable candidates for an MNA remedy application due to the aquifer response observed from closure activities and are, therefore, deemed to meet the criteria for Tier I MNA in accordance with USEPA guidance (USEPA 2007a, b).

8.0 TIER II EVALUATION

The purpose of the Tier II evaluation is to "Identify mechanisms and rates of the operative attenuation process." Based on this definition, the following modeling results and observations support MNA as a viable corrective measure for the CCR Unit:

- **Attenuation Mechanisms:** Geochemical modeling results show that precipitation of the sulfate bearing mineral barite is likely leading to some chemical attenuation of sulfate within downgradient wells. The compliance monitoring network (located immediately adjacent to the LCPA) shows significant additional attenuation capacity based on empirical calculations. The corrective action network, which is more distant from the LCPA, currently shows less capacity for additional attenuation of boron and sulfate. However, additional capacity will likely be created as the porewater flux decreases due to closure activities. Clay minerals and/or particulate organics can also act as a substrate for attenuation (Goldberg et al. 1993), but these mechanisms were not directly addressed in the current evaluation.

- **Estimated Site Attenuation Rates:** Concentrations of boron and sulfate are decreasing at downgradient compliance monitoring network wells, resulting in negative calculated point decay rates. Using the mean empirical decay rate, the maximum 2021 concentrations of boron and sulfate observed in downgradient monitoring wells would take approximately 19 and 5.5 years, respectively, to attenuate to below the draft NPDES permit compliance limit (based on the trend since September 2019) without further corrective measures. Modeled attenuation rates are estimated to result in concentrations below the GWPS in the detection and assessment monitoring well network within 1- to 2 years after installation of the treatment system for sulfate and 1 to 8 years for boron. Concentrations in monitoring wells within the corrective action well network are estimated to be under the proposed compliance limit in 1 to 13 years of installing the treatment system for sulfate and within 1 to 37 years for boron, depending on well location. Additionally, an evaluation of boron mass in the alluvial aquifer predicts a 45% reduction in 10 years, and greater than 80% reduction in 30 years.

Based on these findings, boron and sulfate are considered viable candidates for an MNA remedy application in combination with closure activities and deemed to meet the criteria for Tier II MNA in accordance with USEPA guidance (USEPA 2007a, b).

9.0 TIER III EVALUATION

According to USEPA (USEPA 2007a), the purpose of the Tier III evaluation is to eliminate sites for an MNA remedy where (1) “Capacity of the aquifer is insufficient to attenuate the COC mass to regulatory standards” and/or (2) “Stability of the immobilized COC is insufficient to prevent remobilization due to future changes in groundwater chemistry”. Based on this definition, the following observations support MNA as a viable corrective measure for the CCR Unit:

- **Capacity Modeling:** Conservative transport modeling has demonstrated that with enhanced MNA efforts (i.e., pump and treat; described in Section 6.3.3), concentrations of boron and sulfate at downgradient monitoring wells of the compliance monitoring network will be below their proposed NPDES limits in a reasonable time frame. The time frame is defined here as “reasonable” when it is comparable to time frames associated with other active remediation options described in an assessment of corrective measures (ITRC 2010). The pH and redox conditions at the site will have little to no impact on boron and sulfate concentrations at the site or the overall capacity of the aquifer for attenuation. The decreasing trend in groundwater boron and sulfate concentration at the Site is expected to continue in the corrective action monitoring network, as supported by conservative transport modeling.

- **Stability Modeling for Adsorbed Constituents:** Boron and sulfate are relatively unaffected by geochemical changes to the aquifer and, once levels decline to below the GWPS for each, are expected to remain stable or further decrease based on conservative transport modeling and the geochemical nature of the constituents. Stability of the site was specifically evaluated during conservative transport modeling and considered the planned Enhanced MNA efforts (Section 6.3.3) that will be designed to capture porewater that discharges to the alluvial aquifer, treat the impacted groundwater to below site GWPS, and re-inject the water into the alluvial aquifer. Therefore, no further impacts will affect the alluvial aquifer outside of the treatment system and once concentrations decrease below the GWPS, they are predicted to remain stable or further decrease.

Based on these findings, boron and sulfate are considered viable candidates for an MNA remedy application in combination with closure activities and deemed to meet the criteria for Tier III MNA in accordance with USEPA guidance (USEPA 2007a, b).

10.0 CONCLUSIONS

This evaluation has been completed in accordance with guidance and best practices promulgated by the USEPA (USEPA 2007a, b) and the ITRC (ITRC 2010). Based on the results of this evaluation, the following is concluded for boron and sulfate in Site groundwater:

- Physical and (minor) chemical attenuation is occurring, and concentrations are stable or declining across the site.
- Modeling indicates that boron and sulfate attenuation will be efficient and stable in the long term.
- Boron and sulfate concentrations in corrective action wells outside of the treatment capture zone are predicted by Golder's modeling to decrease below the draft NPDES permit within 1 to 13 years for sulfate and 1 to 37 years for boron.
- An evaluation of boron mass in the alluvial aquifer predicts a 45% reduction in 10 years, and a greater than 80% reduction in 30 years.
- Boron and sulfate meet the USEPA requirements (Tiers I, II, and III) and are considered viable candidates for an MNA remedy application in combination with the capping and closure of the LCPA. This conclusion is further supported by conservative transport modeling to predict future boron and sulfate concentrations at the Site while considering the effects of the proposed groundwater treatment system.

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TABLES

TABLE 4
GEOCHEMICAL MODELING
RELEVANT MINERAL PHASES - Saturation Indices
LCPA SURFACE IMPOUNDMENT, LABADIE ENERGY CENTER

MINERAL PHASES - Saturation Indices		LCPA-1D	LCPA-1S	LCPA-2D	LCPA-2S	LCPA-3D	LCPA-3S	BMW-1D	BMW-2D	UMW-1D	UMW-2D	UMW-3D	UMW-4D	UMW-5D	UMW-6D	UMW-7D	UMW-8D	UMW-9D
Ferrihydrite	Fe(OH)3	**3.36**	**1.51**	**2.33**	**2.21**	**2.43**	**1.83**	**1.60**	**2.48**	**3.71**	**3.37**	**3.27**	**1.91**	**2.37**	**3.74**	**3.43**	**4.48**	**3.95**
Siderite	FeCO3	-4.51	-9.92	-5.56	-7.27	-6.47	-11.70	**0.49**	**0.62**	**0.96**	**0.43**	-2.26	-0.90	-3.90	-1.10	**0.68**	**0.45**	**0.92**
Melanterite	FeSO4: 7H2O	-10.63	-16.77	-11.98	-13.65	-13.12	-18.48	-5.45	-5.67	-5.91	-5.56	-8.40	-6.01	-10.38	-6.28	-4.82	-4.75	-7.09
Anglesite	PbSO4	-4.87	-7.71	-5.56	-5.45	-6.02	-6.81	-4.82	-5.03	-5.63	-4.39	-4.64	-3.82	-5.27	-3.92	-3.99	-3.76	-6.51
Rhodochrosite	MnCO3	-1.35	-0.90		**0.02**	-1.14		**-0.32**	**-0.35**	**-0.16**	**0.02**	**0.21**	**-0.42**	-0.79	**-0.13**	**0.43**	**-0.01**	**-0.30**
Birnessite	MnO2	-8.53	-4.08		-2.97	-8.00		-17.95	-16.91	-14.75	-14.69	-11.17	-16.88	-11.90	-12.60	-14.31	-12.18	-14.39
Manganite	MnOOH	-2.36	**1.62**		**1.20**	-1.30		-7.91	-7.20	-6.28	-5.94	-3.31	-6.58	-3.49	-4.06	-5.56	-4.76	-6.06
Anhydrite	CaSO4	-1.49	-1.44	-1.36	-1.61	-1.41	-1.51	-2.25	-2.24	-2.76	-1.73	-1.19	-1.41	-1.60	-1.24	-1.32	-1.30	-4.13
Gypsum	CaSO4:2H2O	-1.19	-1.14	-1.05	-1.26	-1.13	-1.21	-1.94	-1.93	-2.46	-1.44	-0.91	-1.12	-1.31	-0.93	-1.01	-0.99	-3.82
Calcite	CaCO3	**0.93**	**1.70**	**1.43**	**1.28**	**1.46**	**1.54**	**0.04**	**0.40**	**0.41**	**0.54**	**1.18**	**-0.04**	**1.13**	**0.27**	**0.51**	**0.23**	**0.21**
Magnesite	MgCO3	-0.94	-1.66	**-0.42**	**0.59**	-0.96	-1.33	-1.19	-0.93	-0.81	-0.76	-0.89	-1.61	-2.81	-1.64	-0.96	-0.96	-0.95
Barite	BaSO4	**0.63**	**0.60**	**0.89**	**0.97**	**0.63**	**0.53**	**1.00**	**0.46**	**0.07**	**0.61**	**1.03**	**1.03**	**0.71**	**1.16**	**0.66**	**1.10**	-1.18

MINERAL PHASES - Saturation Indices		BMW-1S	BMW-2S	LMW-1S	LMW-2S	LMW-4S	LMW-7S	LMW-8S	MW-24	MW-26	S-1	AM-1S	AM-1D	TP-1D	TP-2M	TP-2D	TP-3M	TP-3D
Ferrihydrite	Fe(OH)3	**3.99**	**1.42**	**1.60**	**2.15**	**2.64**	**1.46**	**2.61**	**0.64**	**1.01**	**2.02**	**1.45**	**1.56**	**1.22**	**1.62**	**2.50**	**2.99**	**4.11**
Siderite	FeCO3	**0.44**	-2.12	**0.31**	-5.54	**0.43**	**-0.11**	**0.24**	-2.37	-2.29	-1.27	**0.19**	**0.27**	**0.66**	**0.35**	**0.78**	**0.28**	**-0.42**
Melanterite	FeSO4: 7H2O	-5.22	-7.95	-5.44	-11.77	-4.72	-4.89	-4.44	-8.27	-8.46	-7.50	-6.29	-4.81	-6.02	-5.32	-4.83	-4.78	-5.26
Anglesite	PbSO4	-4.62	-4.60	-4.58	-5.13	-3.98	-3.44	-3.53	-4.79	-4.81	-5.00	-5.17	-3.61	-5.46	-4.31	-4.32	-3.77	-3.62
Rhodochrosite	MnCO3	**0.24**	-2.86	**0.04**	-1.50	**0.19**	**-0.23**	**0.14**	-2.27	**0.07**	**-0.36**	**0.18**	-0.53	**-0.44**	**-0.04**	**0.53**	**-0.02**	-0.91
Birnessite	MnO2	-12.20	-16.04	-17.49	-10.04	-15.61	-17.21	-15.44	-16.06	-13.32	-13.66	-17.01	-19.02	-19.37	-18.32	-16.79	-14.89	-12.94
Manganite	MnOOH	-4.95	-8.10	-7.43	-2.78	-6.40	-7.47	-6.26	-7.93	-5.34	-5.86	-7.41	-8.10	-8.65	-7.54	-6.49	-6.17	-5.22
Anhydrite	CaSO4	-1.79	-1.91	-1.98	-1.69	-1.47	-1.33	-0.92	-2.25	-2.32	-2.47	-2.52	-1.31	-2.64	-1.65	-1.60	-1.50	-1.26
Gypsum	CaSO4:2H2O	-1.49	-1.61	-1.68	-1.40	-1.17	-1.03	-0.61	-1.94	-2.01	-2.17	-2.23	-1.02	-2.34	-1.35	-1.29	-1.20	-0.97
Calcite	CaCO3	**0.20**	**0.25**	**0.10**	**0.81**	**0.00**	**-0.24**	**0.08**	**0.02**	**0.20**	**0.08**	**0.25**	**0.07**	**0.37**	**0.34**	**0.35**	**-0.14**	**-0.12**
Magnesite	MgCO3	-1.08	-1.18	-1.24	-2.61	-1.25	-1.48	-1.25	-1.25	-1.09	-1.32	-1.04	-1.43	-0.82	-1.08	-0.91	-1.43	-1.37
Barite	BaSO4	**0.75**	**0.66**	**0.29**	**0.37**	**1.02**	**1.28**	**1.32**	**0.24**	**0.16**	**0.22**	**0.25**	**0.88**	**0.69**	**0.80**	**0.88**	**1.18**	**0.99**

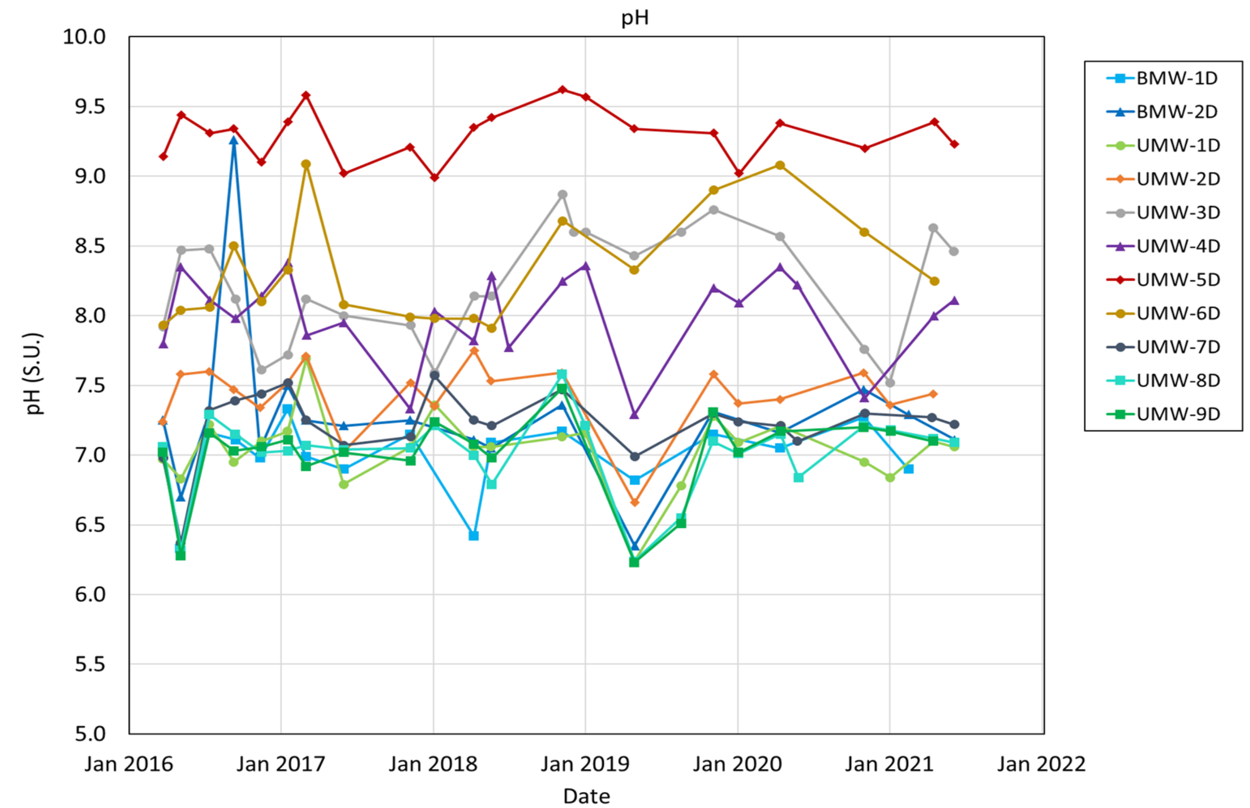
MINERAL PHASES - Saturation Indices		TP-4D	MW-33[D]	MW-34[D]	MW-35[D]	AMW-8
Ferrihydrite	Fe(OH)3	**4.02**	**3.38**	**3.46**	**1.29**	**3.88**
Siderite	FeCO3	-0.79	**-0.04**	**0.02**	**-0.04**	-0.56
Melanterite	FeSO4: 7H2O	-6.17	-5.06	-4.92	-4.59	-6.09
Anglesite	PbSO4	-3.99	-3.79	-3.74	-3.42	-4.25
Rhodochrosite	MnCO3	**-0.46**	-0.76	-0.77	-0.69	**-0.40**
Birnessite	MnO2	-11.14	-14.80	-14.65	-18.85	-13.03
Manganite	MnOOH	-4.46	-6.14	-6.11	-8.15	-4.74
Anhydrite	CaSO4	-1.54	-1.56	-1.41	-1.03	-1.88
Gypsum	CaSO4:2H2O	-1.24	-1.25	-1.11	-0.73	-1.58
Calcite	CaCO3	**0.16**	**-0.23**	**-0.16**	**-0.16**	**-0.03**
Magnesite	MgCO3	-1.01	-1.48	-1.37	-1.40	-1.52
Barite	BaSO4	**1.33**	**0.91**	**0.97**	**0.91**	**0.66**

Notes:

Saturation indices >-0.5 identified by red bold type and grey shading

FIGURES

(a)



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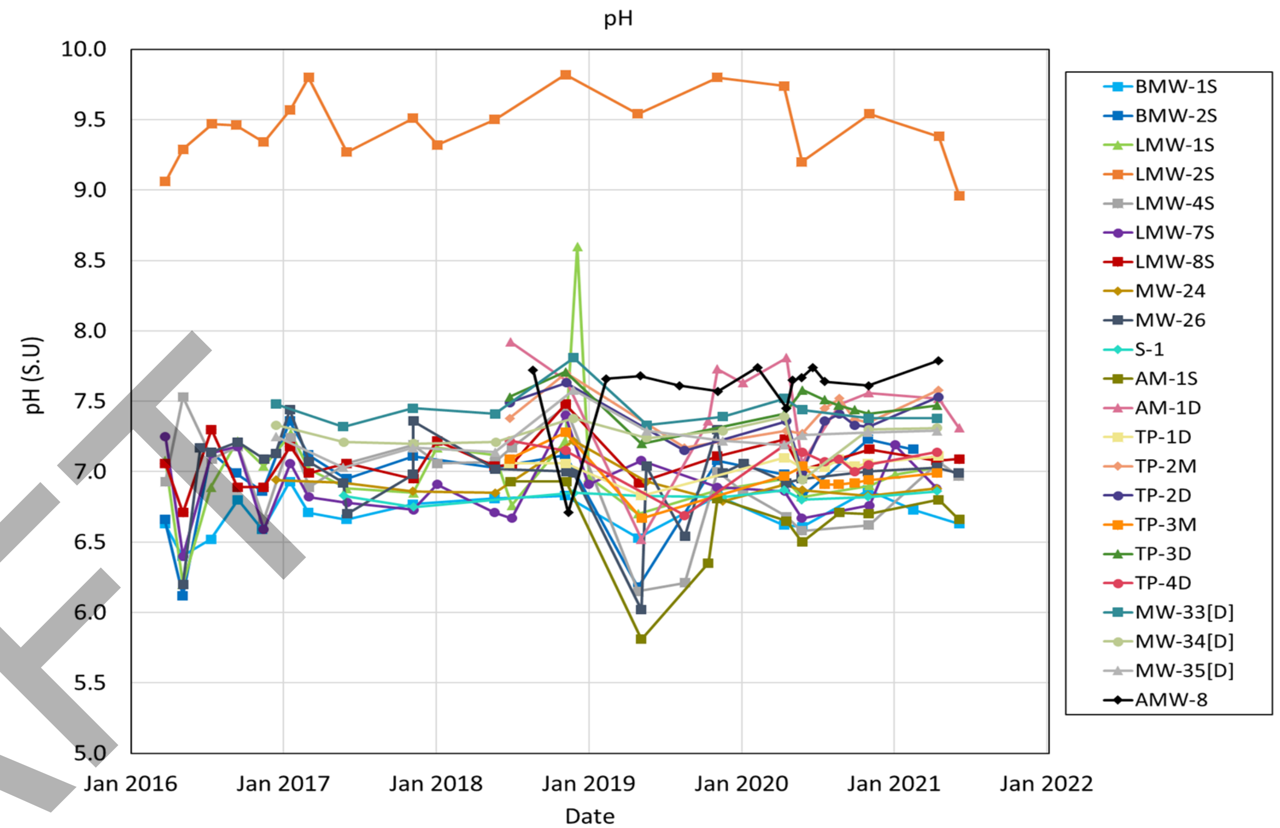

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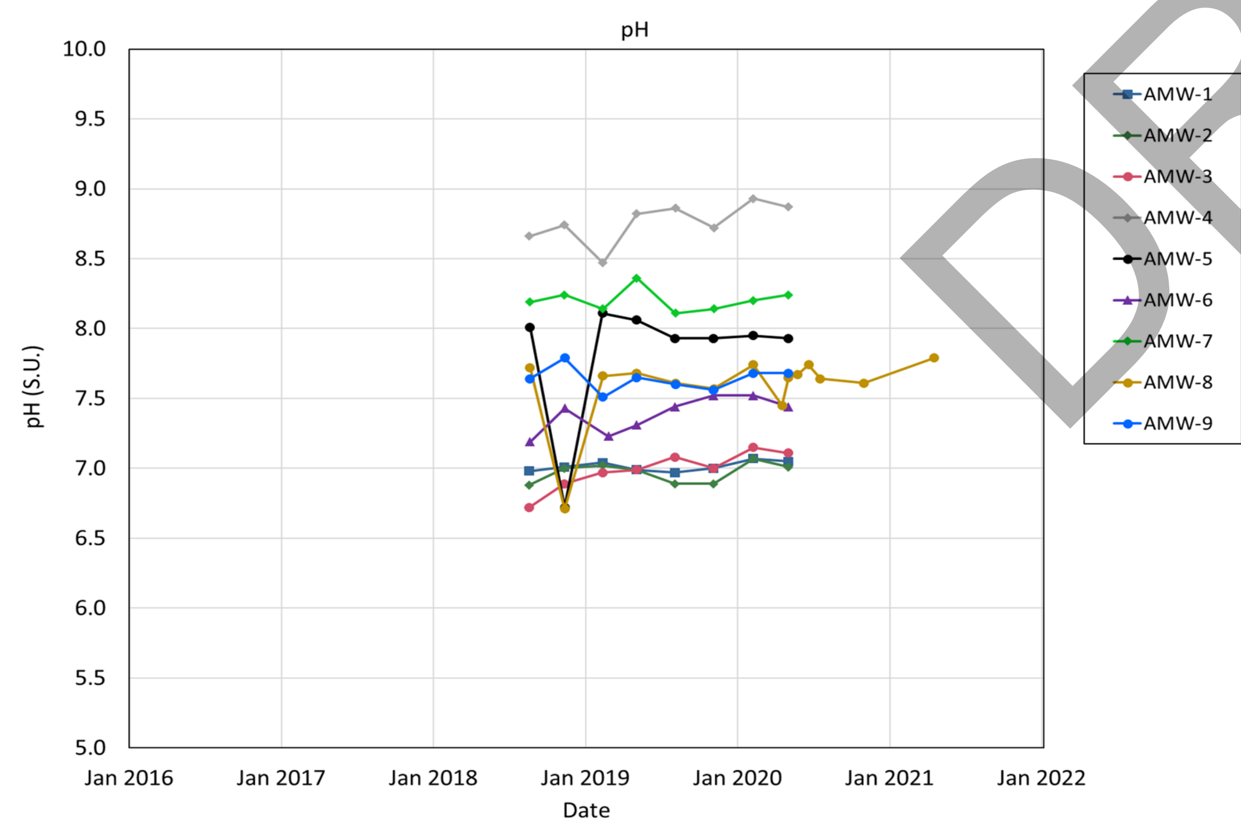


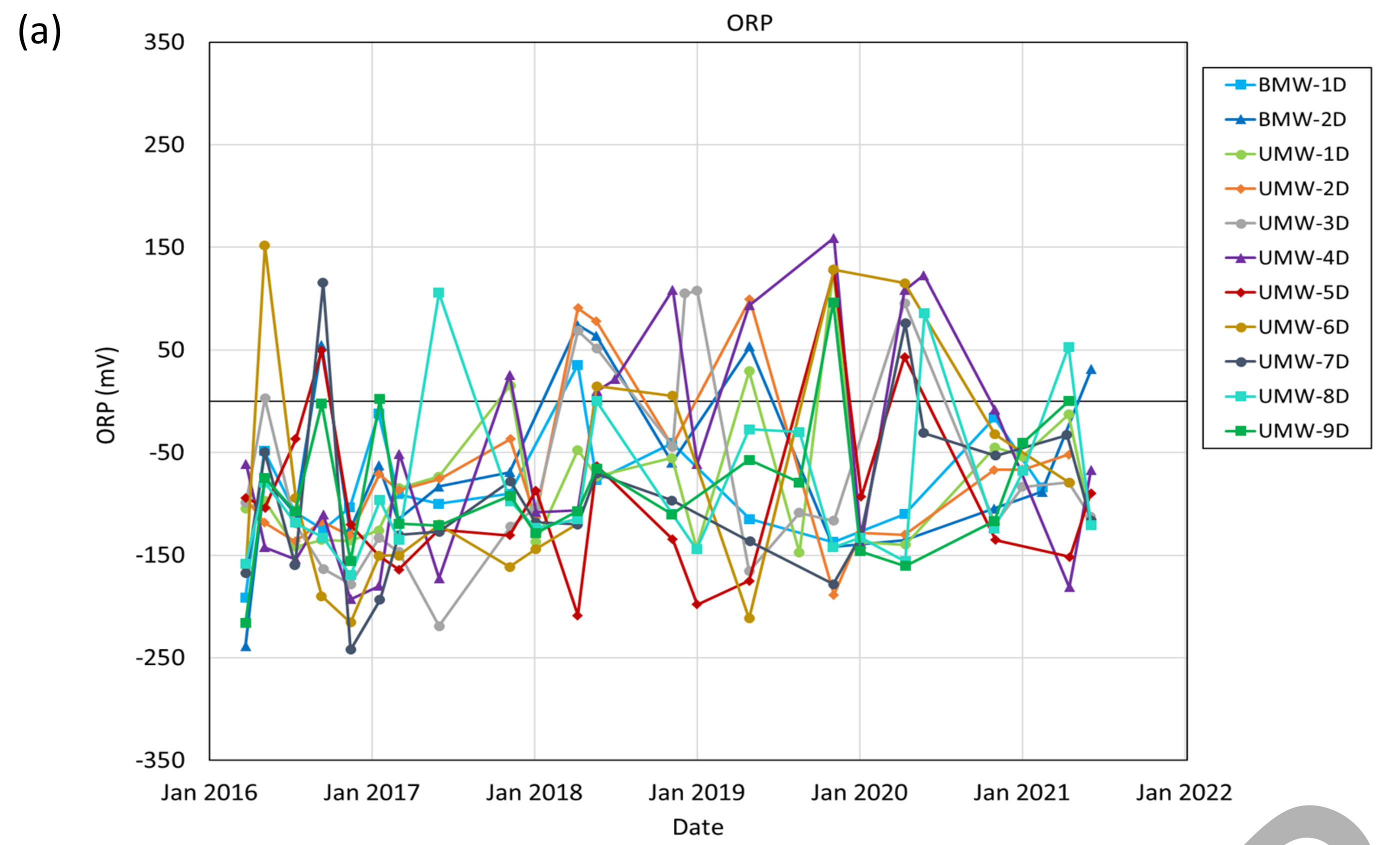
CLIENT
AMEREN MISSOURI
LCPA SURFACE IMPOUNDMENT, LABADIE ENERGY CENTER

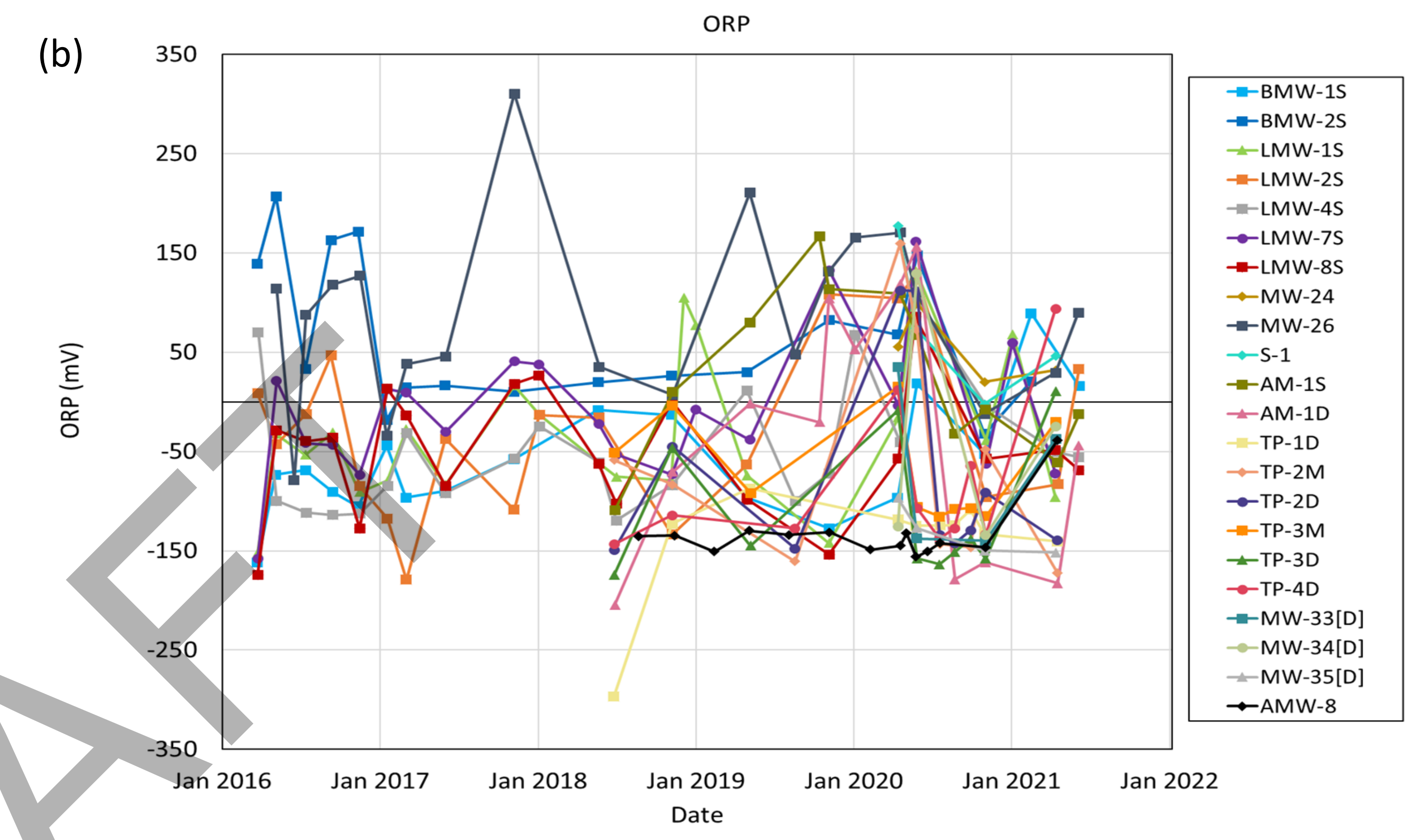
PROJECT
TIER I – TIER III MNA GEOCHEMICAL EVALUATION

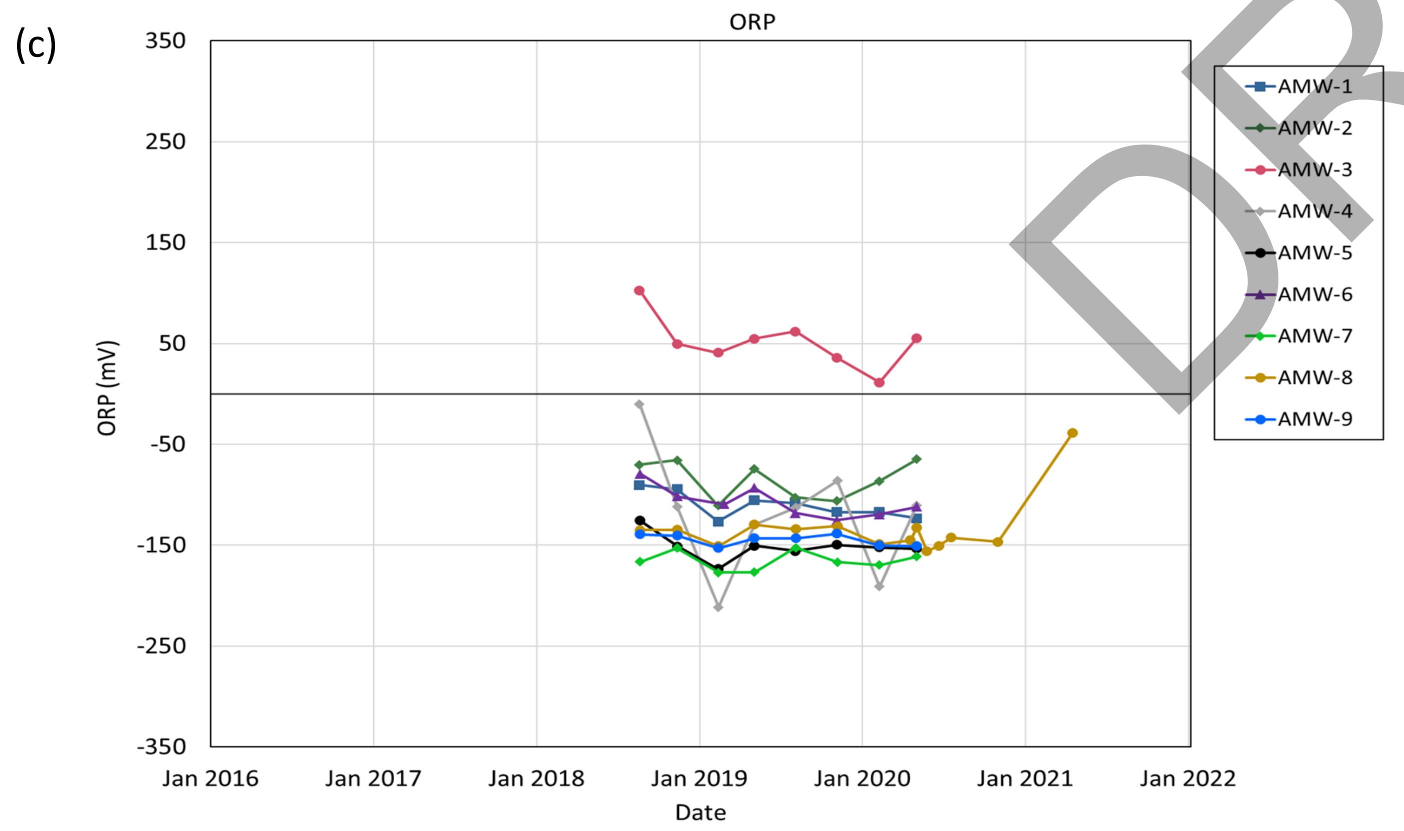
CONSULTANT
GOLDER
MEMBER OF WSP

TITLE
Historical pH Values of Groundwater in (a) Compliance Monitoring (b) Corrective Action and (c) NPDES Wells

PROJECT NO.	PHASE	REV.	FIGURE
153140603	0001D	A	2







CLIENT
AMEREN MISSOURI
LCPA SURFACE IMPOUNDMENT, LABADIE ENERGY CENTER

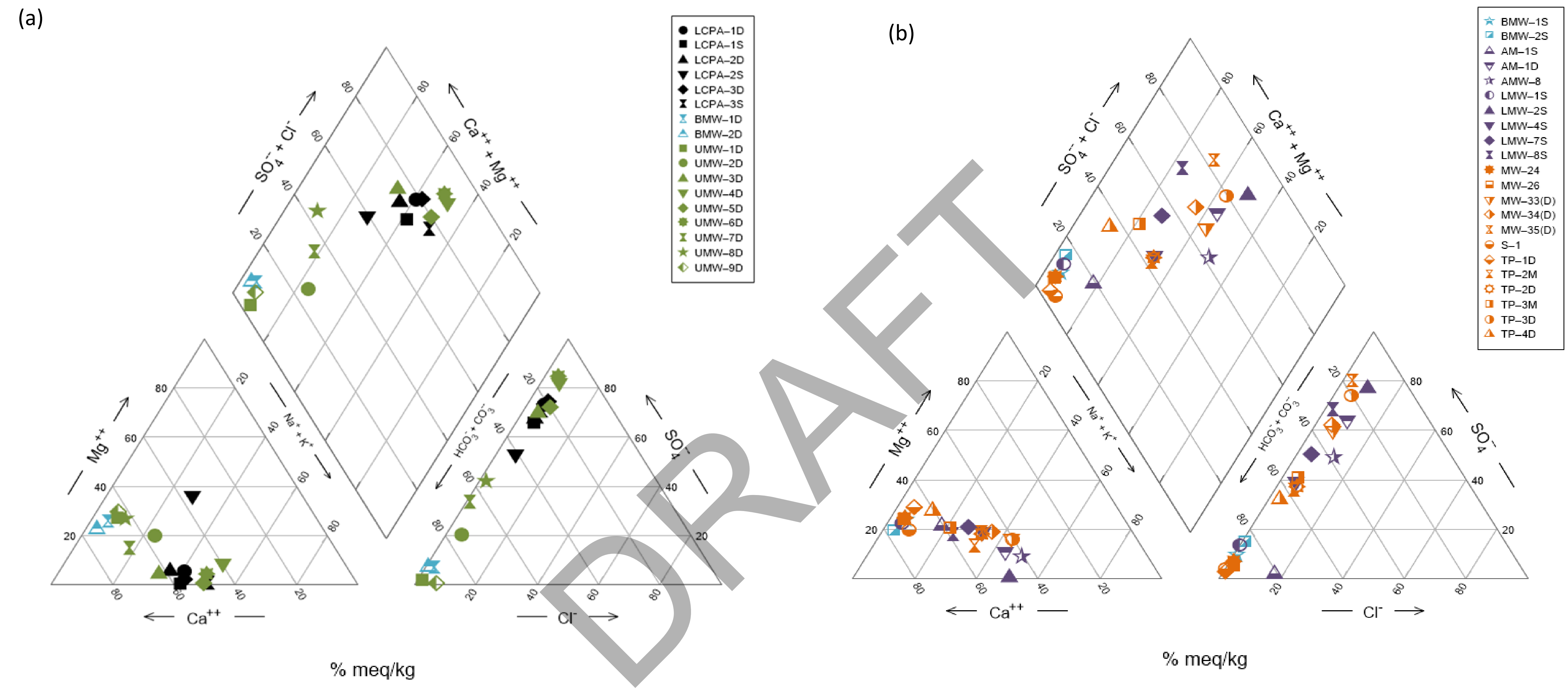
PROJECT
TIER I – TIER III MNA GEOCHEMICAL EVALUATION

CONSULTANT
GOLDER
MEMBER OF WSP

TITLE
Historical Redox Values of Groundwater in (a) Compliance Monitoring (b) Corrective Action and (c) NPDES Wells

PROJECT NO.	PHASE	REV.	FIGURE
153140603	0001D	A	3

PATH: https://golderassociates.sharepoint.com/sites/123667/Project Files/APF/6 Deliverables/153-1406-03/Phase 0001 - Labadie/202109-MNA-Evaluations/B and SO4 MNA/Figures | FILE NAME: Figure Book.xlsx



CLIENT
AMEREN MISSOURI
LCPA SURFACE IMPOUNDMENT, LABADIE ENERGY CENTER

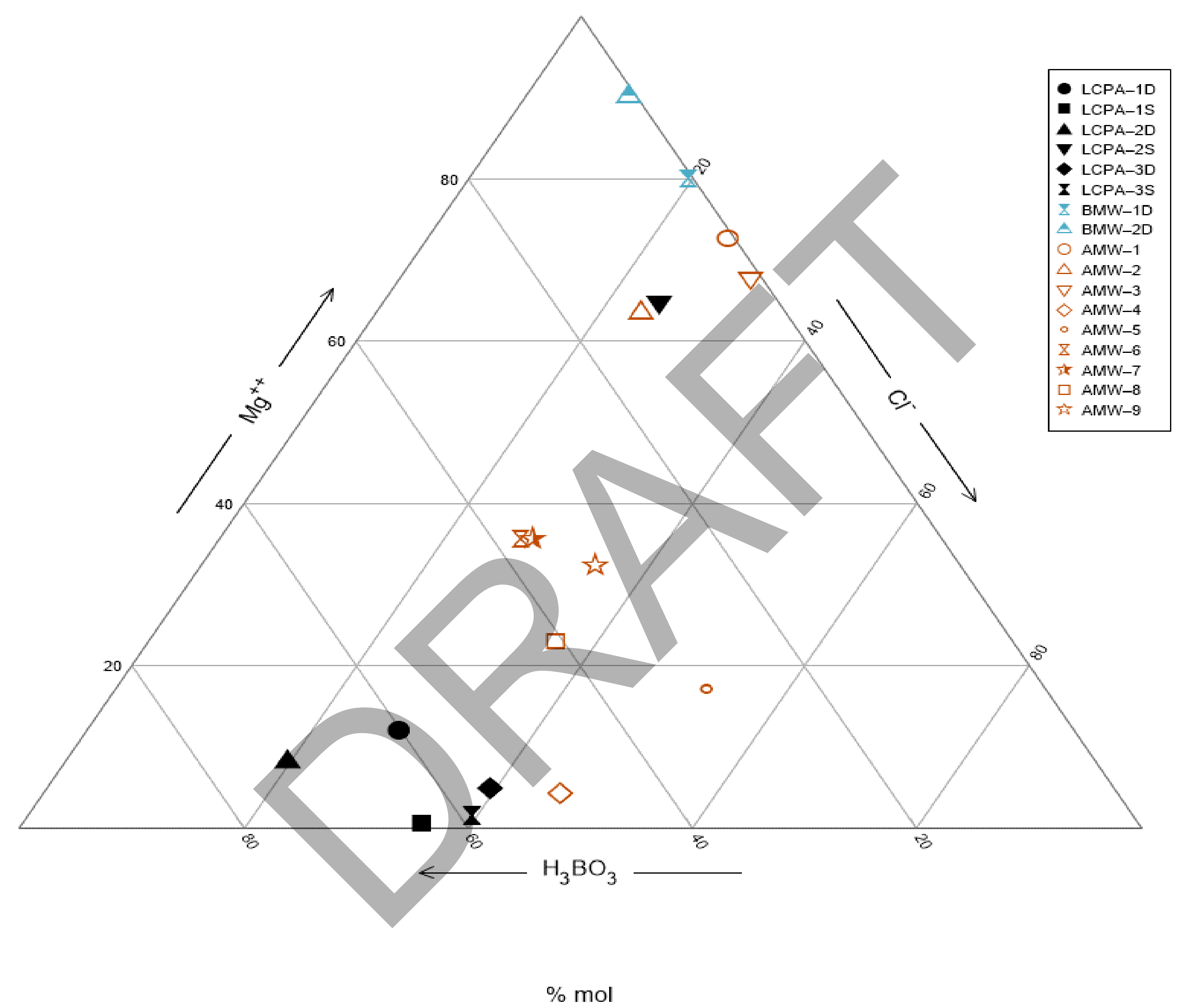
PROJECT
TIER I – TIER III MNA GEOCHEMICAL EVALUATION

CONSULTANT
GOLDER
MEMBER OF WSP

TITLE
Trilinear Diagrams - Groundwater Characterization of (a) Compliance Monitoring and (b) Corrective Action Wells

PROJECT NO.	PHASE	REV.	FIGURE
153140603	0001D	A	4

PATH: https://golderassociates.sharepoint.com/sites/123667/Project Files/APF/6 Deliverables/153-1406-03/Phase 0001 - Labadie/202109-MNA-Evaluations/B and SO4 MNA/Figures | FILE NAME: Figure Book.xlsx



CLIENT
AMEREN MISSOURI
LCPA SURFACE IMPOUNDMENT, LABADIE ENERGY CENTER

PROJECT
TIER I – TIER III MNA GEOCHEMICAL EVALUATION

CONSULTANT
GOLDER
MEMBER OF WSP

TITLE
Ternary Diagram - Groundwater Characterization of NPDES Wells

PROJECT NO.	PHASE	REV.	FIGURE
153140603	0001D	A	5

PATH: https://golderassociates.sharepoint.com/sites/123667/Project Files/APF/6 Deliverables/153-1406-03/Phase 0001 - Labadie/202109-MNA-Evaluations/B and SO4 MNA/Figures | FILE NAME: Figure Book.xlsx

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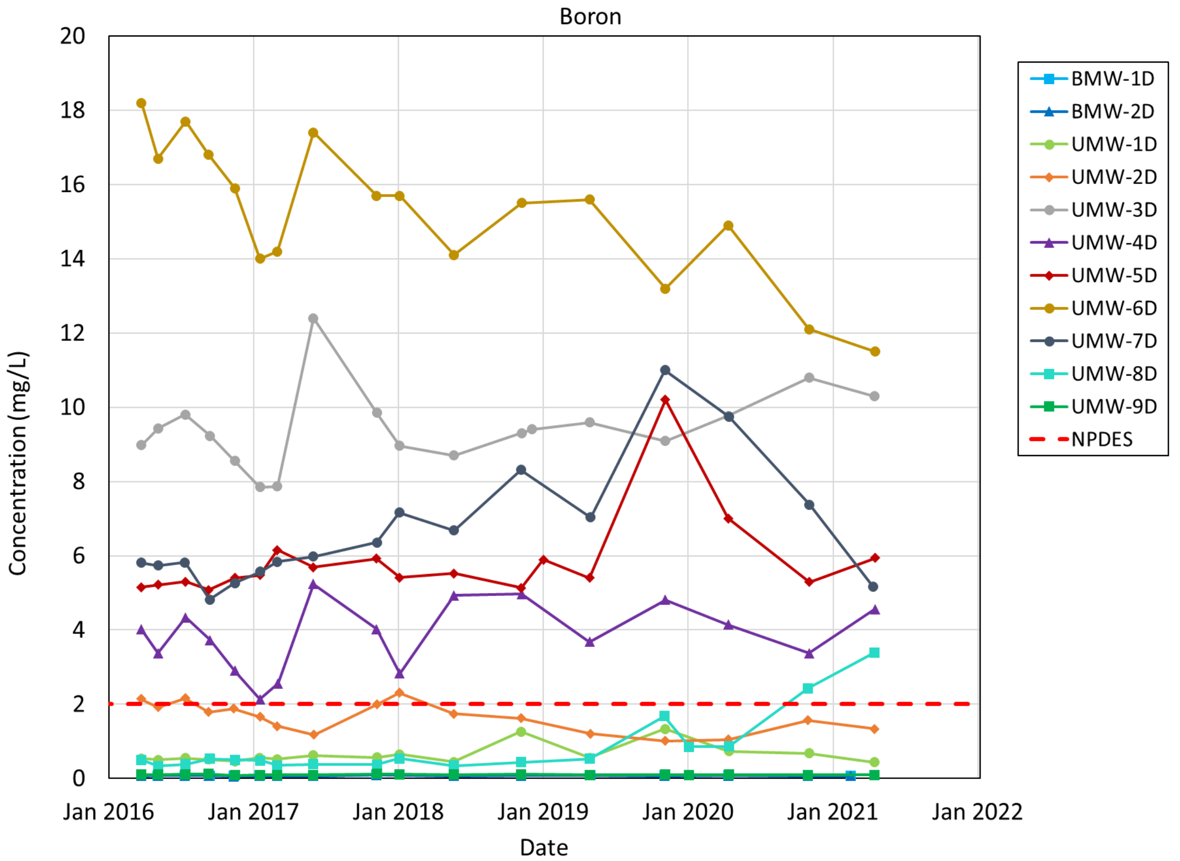

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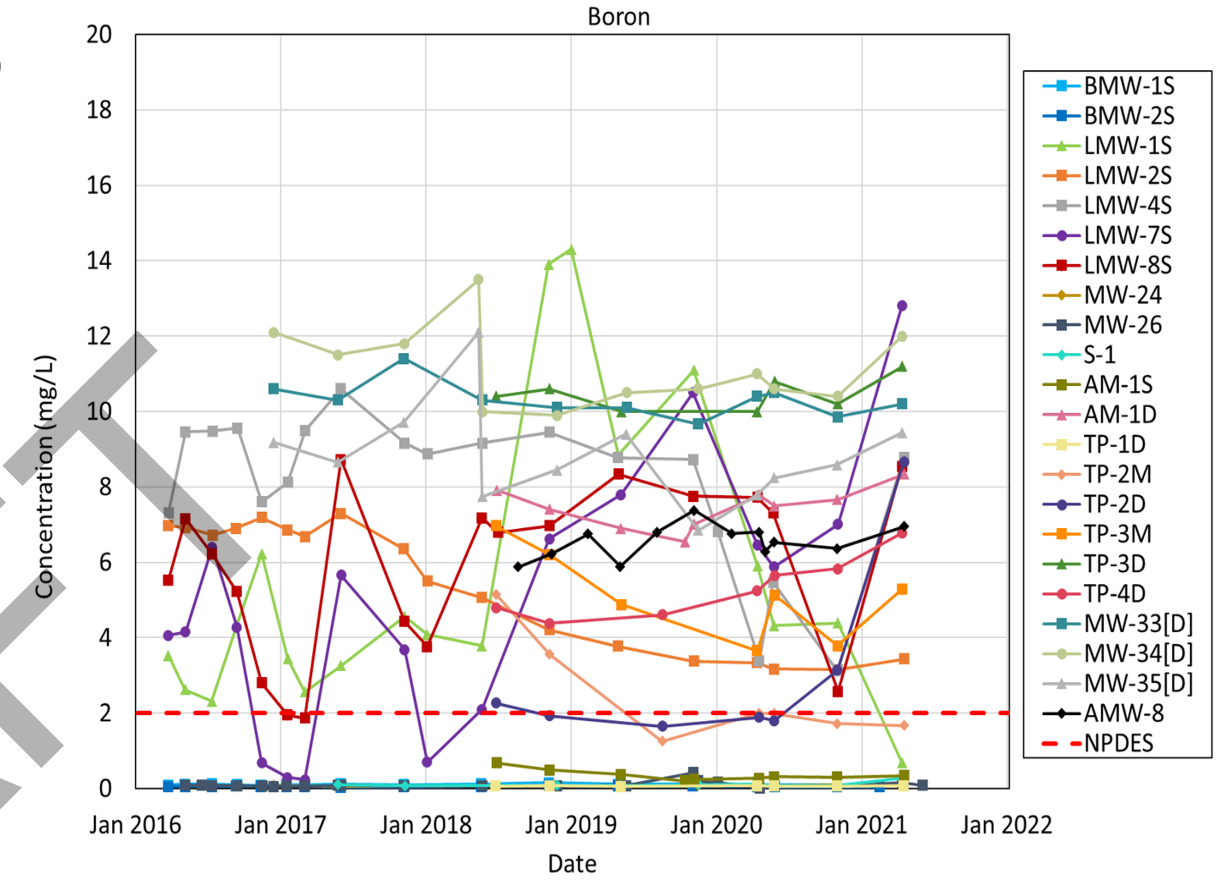

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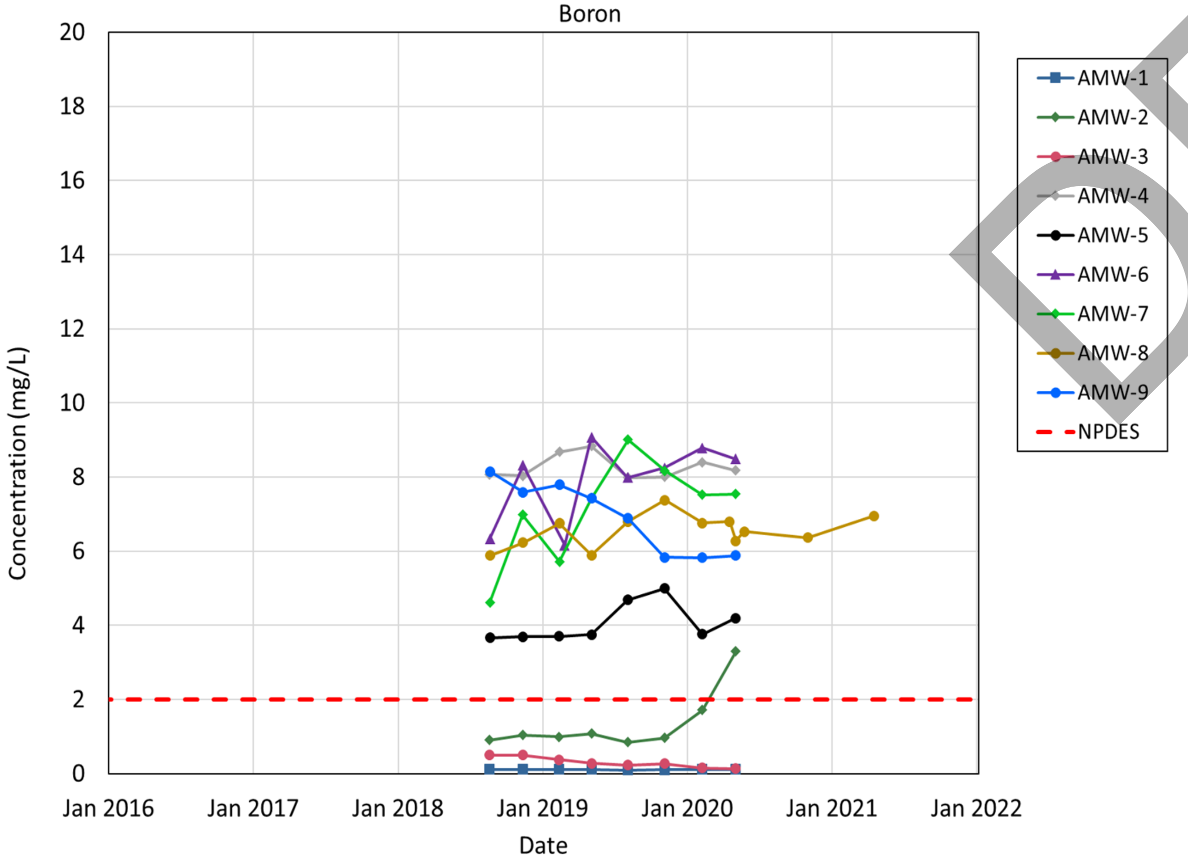

Note(s)

1) mg/L – Milligrams per liter.
2) NPDES – National Pollution Discharge Elimination System.

CLIENT
AMEREN MISSOURI
LCPA SURFACE IMPOUNDMENT, LABADIE ENERGY CENTER

PROJECT
TIER I – TIER III MNA GEOCHEMICAL EVALUATION

CONSULTANT
GOLDER
MEMBER OF WSP

TITLE
Historical Boron Concentrations of Groundwater in (a) Compliance Monitoring (b) Corrective Action and (c) NPDES Wells

PROJECT NO.	PHASE	REV.	FIGURE
153140603	0001D	A	6

PATH: https://golderassociates.sharepoint.com/sites/123667/Project Files/APF/6 Deliverables/153-1406-03/Phase 0001 - Labadie/202109-MNA-Evaluations/B and SO4 MNA/Figures | FILE NAME: Figure Book.xlsx

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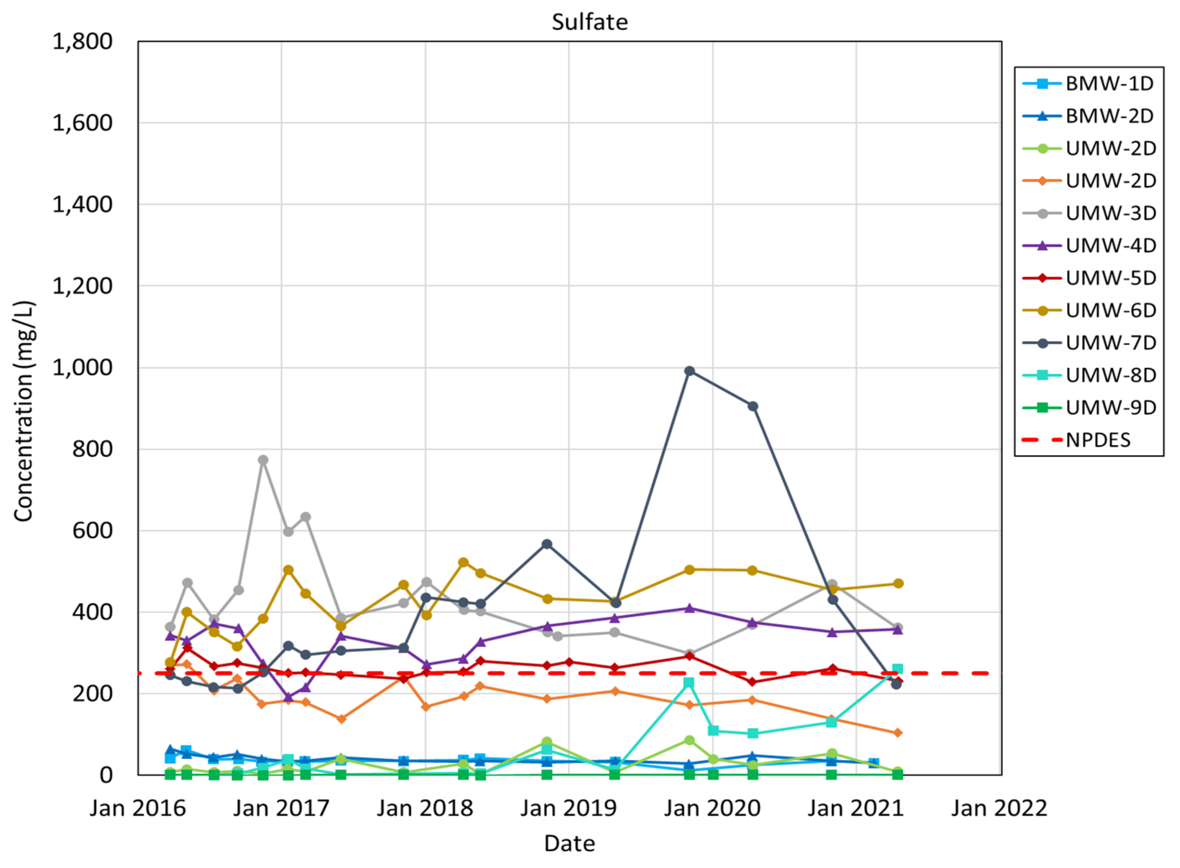

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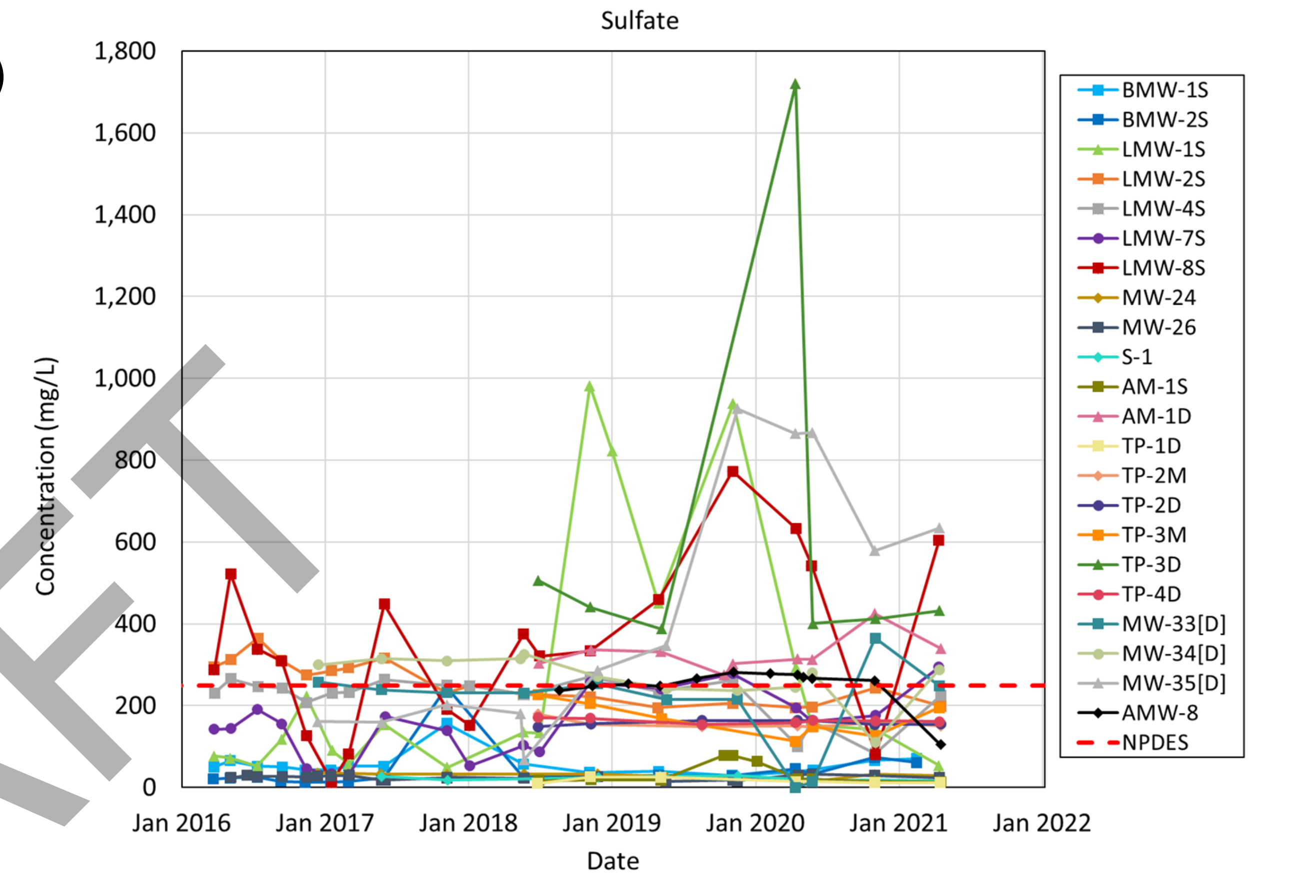

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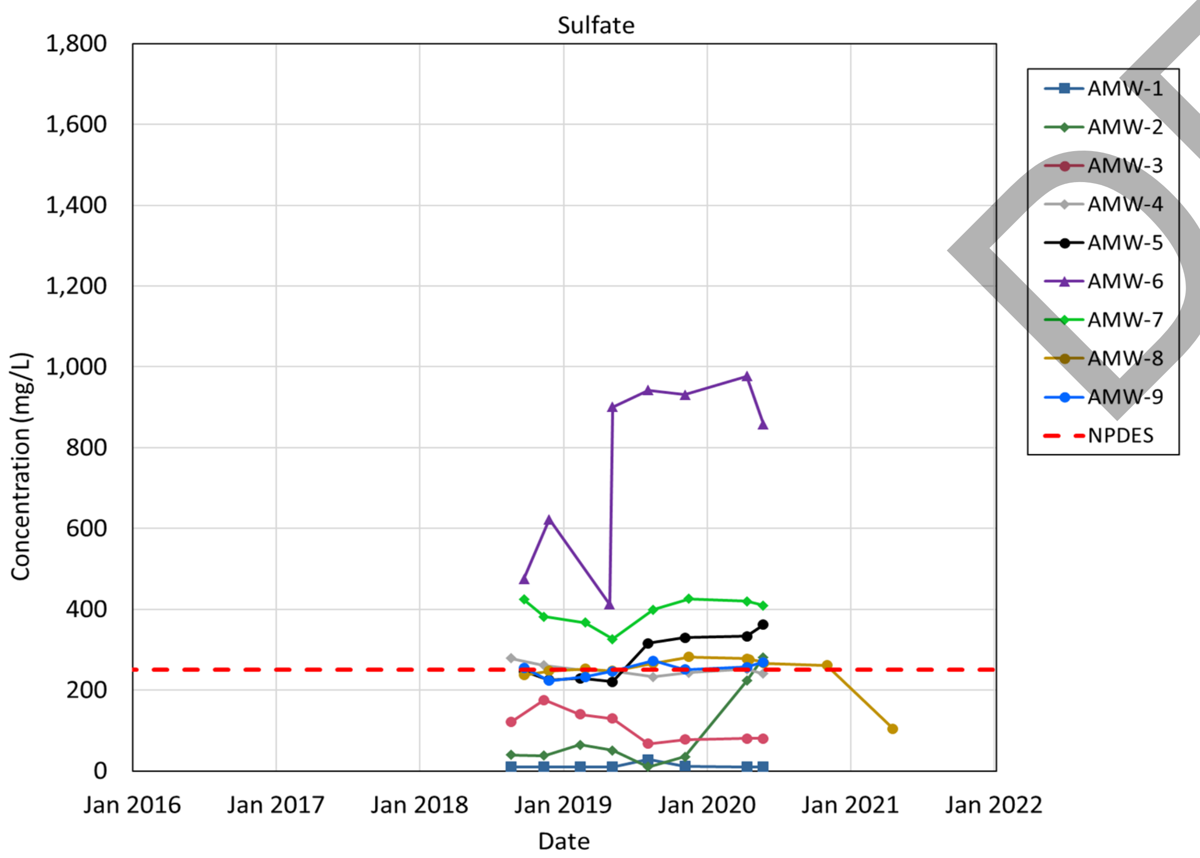


DRAFT

Note(s)
1) mg/L – Milligrams per liter.
2) NPDES – National Pollution Discharge Elimination System.

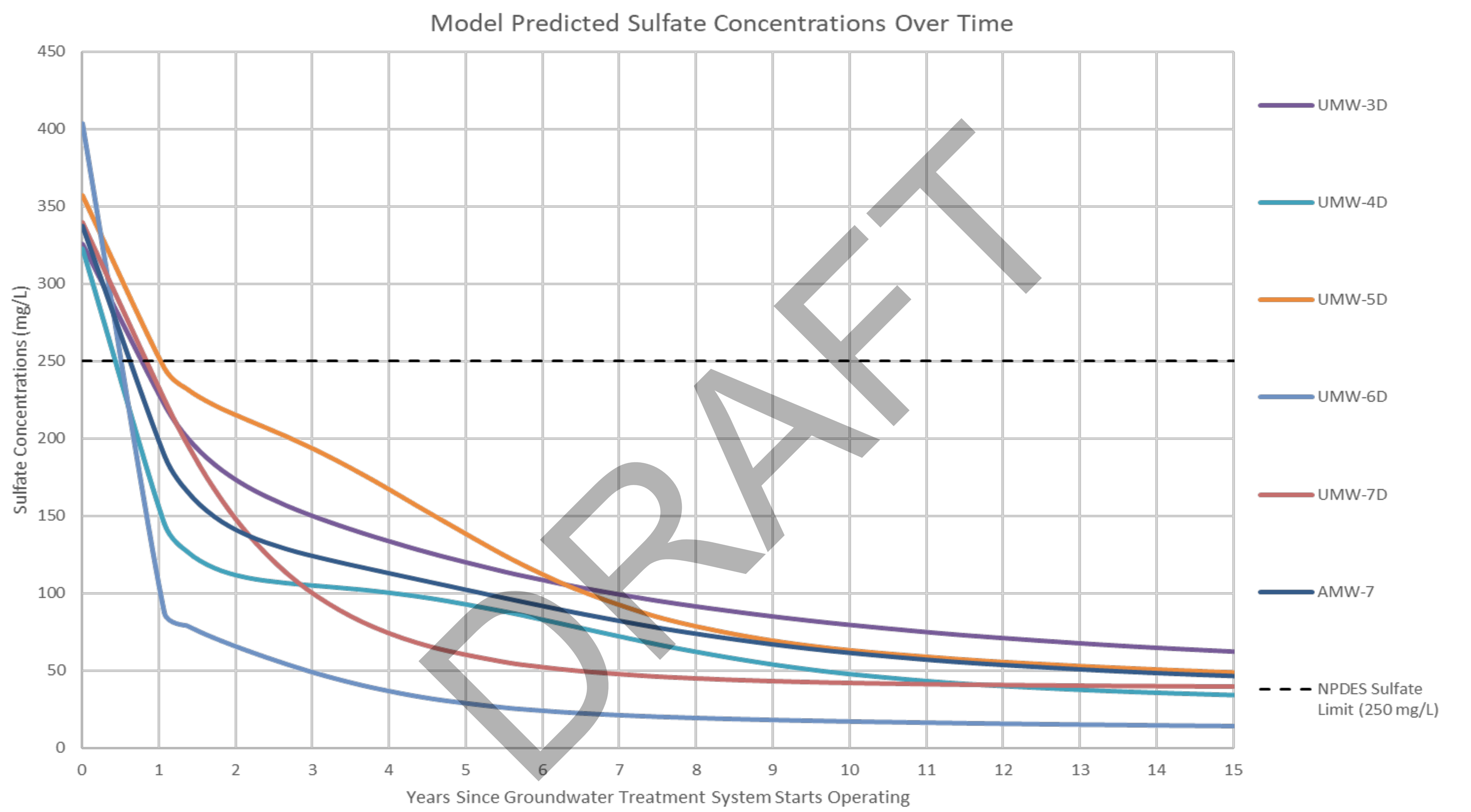
CLIENT
AMEREN MISSOURI
LCPA SURFACE IMPOUNDMENT, LABADIE ENERGY CENTER

PROJECT
TIER I – TIER III MNA GEOCHEMICAL EVALUATION

CONSULTANT
GOLDER
MEMBER OF WSP

TITLE
Historical Sulfate Concentrations of Groundwater in (a) Compliance Monitoring (b) Corrective Action and (c) NPDES Wells

PROJECT NO.	PHASE	REV.	FIGURE
153140603	0001D	A	7



Note(s)

1) mg/L – Milligrams per liter.
2) NPDES – National Pollution Discharge Elimination System.

CLIENT
AMEREN MISSOURI
LCPA SURFACE IMPOUNDMENT, LABADIE ENERGY CENTER

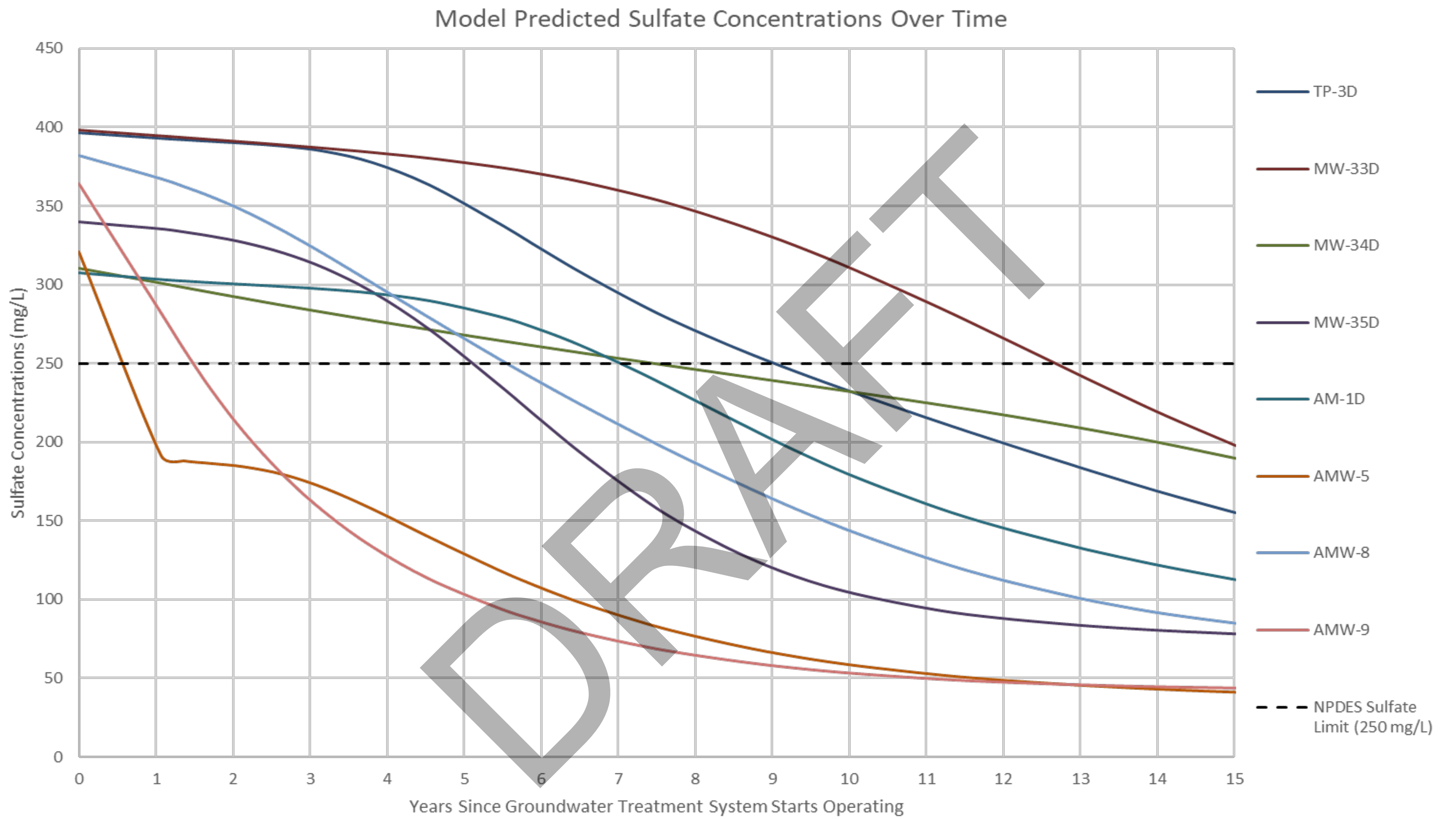
PROJECT
TIER I – TIER III MNA GEOCHEMICAL EVALUATION

CONSULTANT
GOLDER
MEMBER OF WSP

TITLE
Model Predicted Sulfate Concentrations Over Time – Monitoring Wells Adjacent to LCPA

PROJECT NO.	PHASE	REV.	FIGURE
153140603	0001D	A	8

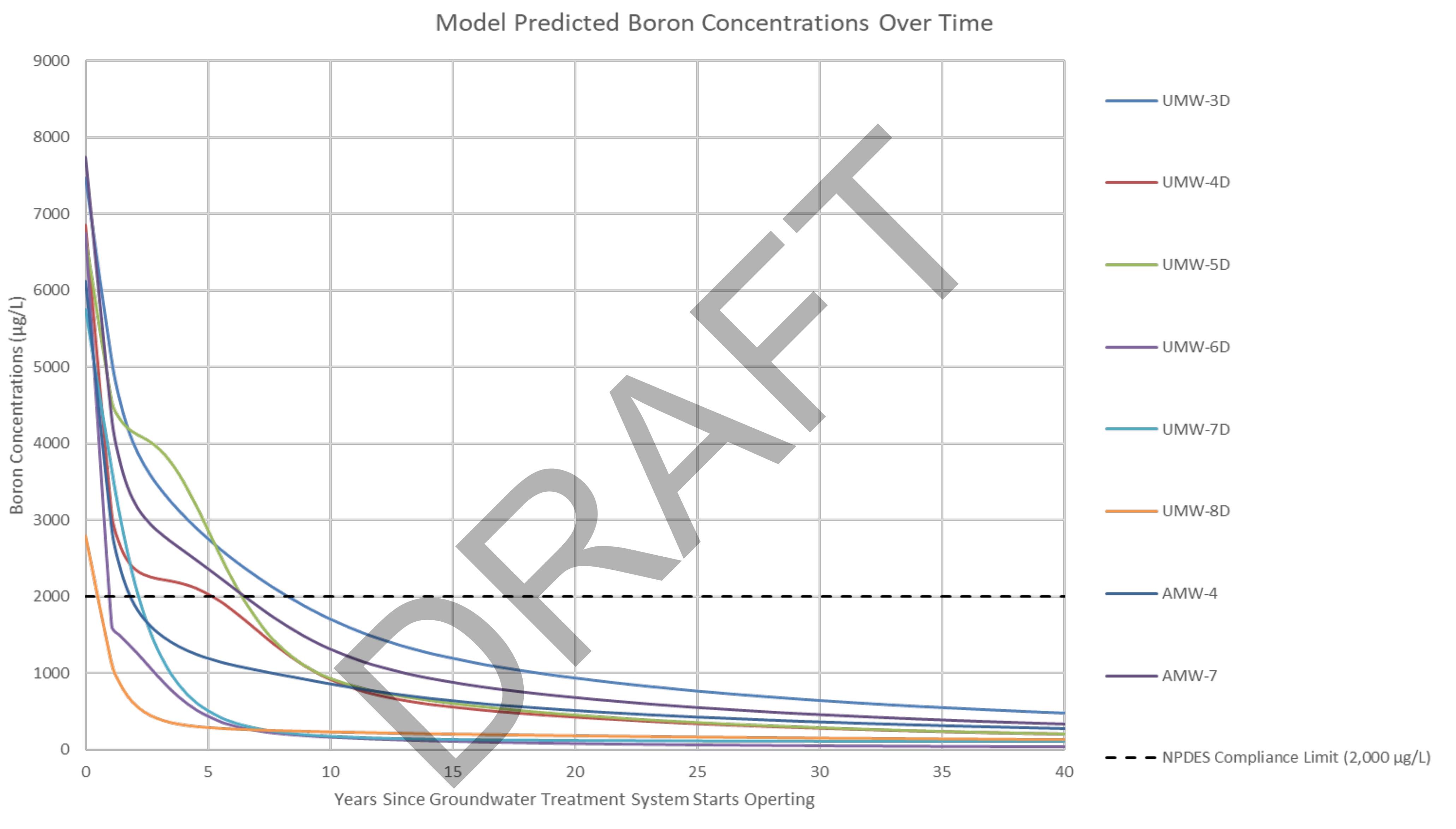
PATH: https://golderassociates.sharepoint.com/sites/123667/Project Files/APF/6 Deliverables/153-1406-03/Phase 0001 - Labadie/202109-MNA-Evaluations/B and SO4 MNA/Figures | FILE NAME: Figure Book.xlsx



Note(s)
1) mg/L – Milligrams per liter.
2) NPDES – National Pollution Discharge Elimination System.

CLIENT AMEREN MISSOURI LCPA SURFACE IMPOUNDMENT, LABADIE ENERGY CENTER	PROJECT TIER I – TIER III MNA GEOCHEMICAL EVALUATION
CONSULTANT GOLDER MEMBER OF WSP	TITLE **Model Predicted Sulfate Concentrations Over Time** **– Monitoring Wells Not Immediately Affected by Treatment System**

PROJECT NO.	PHASE	REV.	FIGURE
153140603	0001D	A	9



Note(s)

1) µg/L – Micrograms per liter.
2) NPDES – National Pollution Discharge Elimination System.

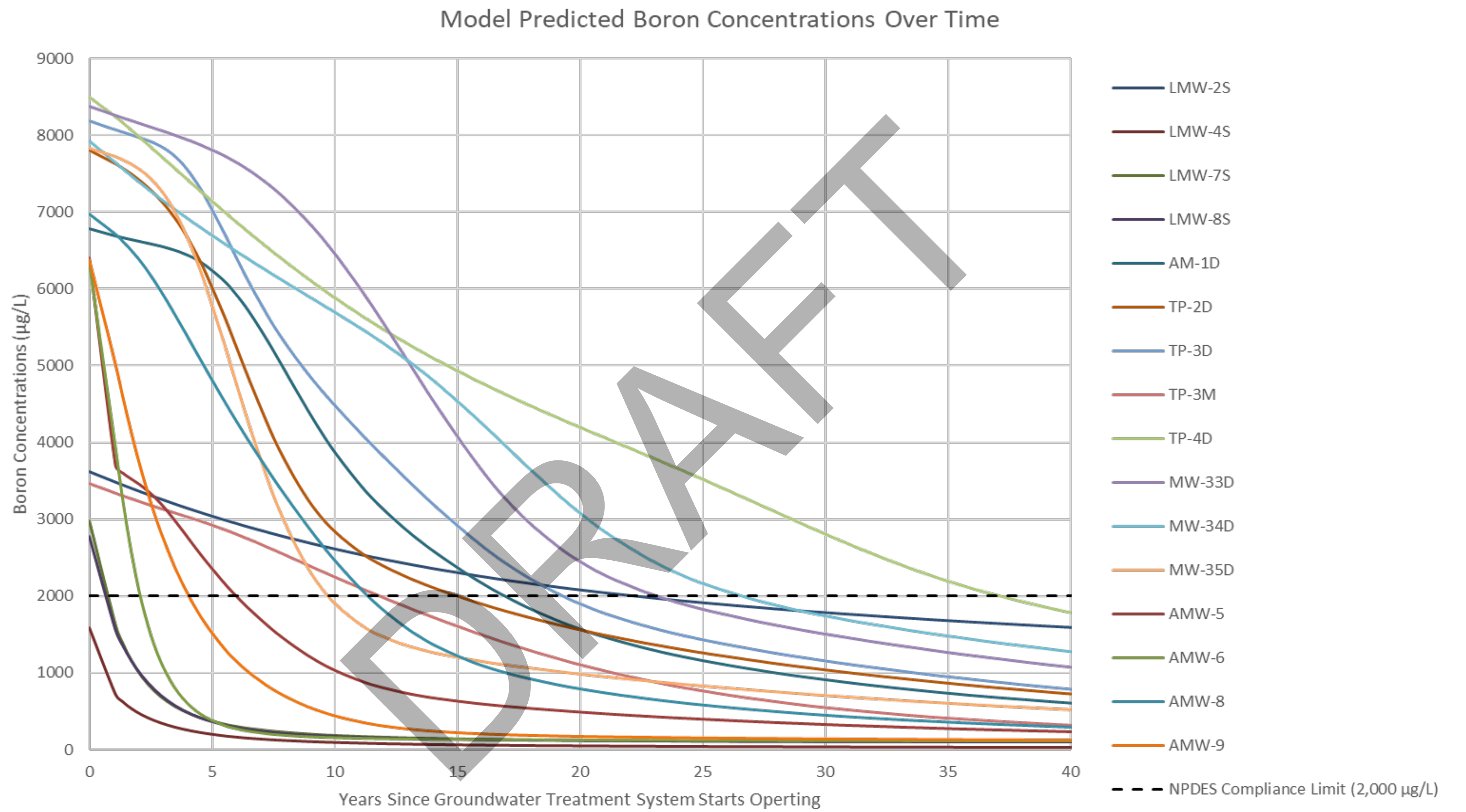
CLIENT
AMEREN MISSOURI
LCPA SURFACE IMPOUNDMENT, LABADIE ENERGY CENTER

PROJECT
TIER I – TIER III MNA GEOCHEMICAL EVALUATION

CONSULTANT
GOLDER
MEMBER OF WSP

TITLE
Model Predicted Boron Concentrations Over Time – Monitoring Wells Adjacent to LCPA

PROJECT NO.	PHASE	REV.	FIGURE
153140603	0001D	A	10



Note(s)
1) µg/L – Micrograms per liter.
2) NPDES – National Pollution Discharge Elimination System.

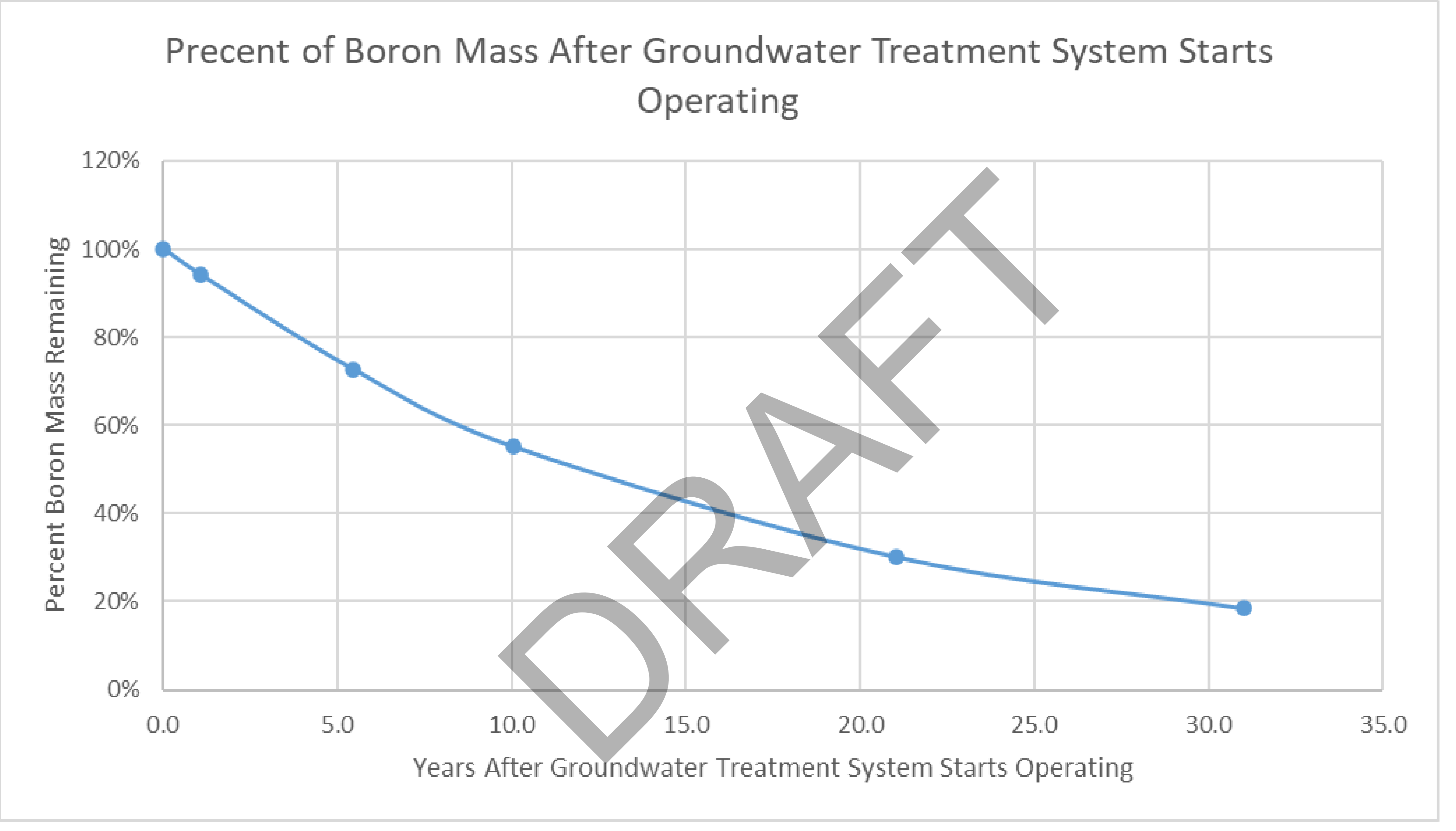
CLIENT
AMEREN MISSOURI
LCPA SURFACE IMPOUNDMENT, LABADIE ENERGY CENTER

CONSULTANT
GOLDER
MEMBER OF WSP

PROJECT
TIER I – TIER III MNA GEOCHEMICAL EVALUATION

TITLE
Model Predicted Boron Concentrations Over Time
– Monitoring Wells Not Immediately Affected by Treatment System

PROJECT NO.	PHASE	REV.	FIGURE
153140603	0001D	A	11



Note(s)

1) NPDES – National Pollution Discharge Elimination System.

CLIENT
AMEREN MISSOURI
LCPA SURFACE IMPOUNDMENT, LABADIE ENERGY CENTER

PROJECT
TIER I – TIER III MNA GEOCHEMICAL EVALUATION

CONSULTANT
GOLDER
MEMBER OF WSP

TITLE
Percent of Boron Mass Remaining After Groundwater Treatment System Starts Operating

PROJECT NO.	PHASE	REV.	FIGURE
153140603	0001D	A	12

APPENDIX A

Groundwater Modeling Report

TECHNICAL MEMORANDUM

DATE January 2022 **Project No.** 153140603

TO Ameren Missouri
1901 Chouteau Avenue, St. Louis, Missouri 63103

CC

FROM Jeffrey Ingram, Joanna Moreno, Mark Haddock **EMAIL JIngram@Golder.com**

GROUNDWATER MODELING SUMMARY FOR BORON AND SULFATE TRANSPORT AT THE LABADIE ENERGY CENTER BASED ON DIFFERENT CLOSURE SCENARIOS

Golder Associates USA Inc. (Golder) is pleased to provide this Technical Memorandum summarizing modeling results for closure scenarios at the Ameren Missouri (Ameren) Labadie Energy Center (LEC) in Franklin County, Missouri. As part of the Monitored Natural Attenuation (MNA) Evaluation, the fate and transport of boron and sulfate after closure of the bottom ash basin (LCPA) was investigated through groundwater modeling and this memo summarizes the tasks conducted in support of the MNA Evaluation.

This Technical Memorandum supplements the LEC MNA Groundwater Technical Memorandum for molybdenum, (Golder 2021). Details on the groundwater modeling development and flow calibration are discussed in the Technical Memorandum for Molybdenum and are not included in this Technical Memorandum. This memo focuses on the fate and transport of boron and sulfate under various closure scenarios.

1.1 Groundwater Modeling Objectives

The objectives of this modeling analysis are as follows:

- Update the existing groundwater model to predict future boron and sulfate concentrations after capping and closing the LCPA surface impoundment with the addition of the groundwater pump, treat and re-injection system.
- Use the groundwater model to predict future boron concentrations for different closure scenarios including capping and closing with MNA and closure by removal (CBR) with MNA.

1.2 Transport MNA Modeling for Current Corrective Action Plan

This section describes the transport modeling analyses conducted for the LCPA contaminant source area for sulfate and boron under the current Corrective Action remedy plan of capping and closure of the Coal Combustion Residual (CCR) unit along with a groundwater treatment system and MNA. The Fly Ash Surface Impoundment (LCPB) and the Utility Waste Landfill Cell (LCL1) were not modeled as source areas because both units are lined with geomembrane liners, while the LCPA is unlined. Based on drilling data and historical images, the LCPA has historically been managed with the ash materials contained in the southern and eastern portions of the CCR Unit while the ponded area has been historically managed in the western portion of the unit. In 1993, the LCPB was built to the east of the LCPA, and fly ash was then managed in the LCPB and not the LCPA, although the outfall for the LCPB discharged into the southeastern portion of the LCPA during its operation. Table 1 provides the dates and a brief description of the dates of changes in site conditions (stress periods) used in the Transient Model for Closure in place, with a treatment system and MNA.

Table 1: Description of Stress Periods

Stress Period	Start Date	End Date	Length (Days)	Description
1	1/1/1970	12/31/1992	8765	Beginning of LEC operations with LCPA as only active CCR Unit
2	1/1/1993	9/28/2019	9402	LCPB active along with the LCPA. LCPA no longer receives fly ash management water, therefore, constituent of concern concentrations and head on pond and related recharge values reduce
3	9/28/2019	12/29/2020	459	Closure construction on the LPCA. No more active addition of CCR materials to LCPA. Recharge equal to that of surrounding alluvial aquifer.
4	12/30/2020	12/31/2022	732	LCPA closed with geomembrane liner system. No groundwater treatment system in place.
5	1/1/2023	8/1/2120	35652	LCPA closed along with active treatment system.

These transport analyses were completed for both sulfate and boron. The primary transport mechanisms of these constituents are advection and mixing due to natural and pond recharge, and advection and mixing under varying natural hydraulic gradients controlled by river water elevations.

Transport model setup details include:

Aquifer bulk densities based on sampling results from Golder 2017a:

- CCR Materials:1.2 g/mL
- Sandy Alluvial Materials: 1.4 g/mL
- Bedrock: 2.3 g/mL

- Uniform effective porosity of 0.20 based on Gredell, 2019.
- Longitudinal, transverse and vertical dispersivity were assumed to have values of 15, 1.5, and 0.15 ft, respectively. Values were calculated using the Environmental Protection Agency (EPA) on-line tool for estimating longitudinal dispersity (available at: https://www3.epa.gov/ceampubl/learn2model/part-two/onsite/longdisp.html)
- To be conservative, no sorption represented by a partition coefficient (Kd) was included in the model (Kd = 0 mL/g).
- Boron and sulfate recharge concentrations as shown below in Tables 2 and 3.

Table 2: Sulfate Concentration Data Ranges

Applicable Area	Reported Range	Recharge Concentrations Supplied to Model	Data Source
Sulfate Concentrations (mg/L)			
Missouri River	Minimum: 172	192	AECOM 2014, Haley and Aldrich 2018, Kleinfelder 2016
	Maximum: 224		
	Mean: 192.3		
Bedrock Aquifer	Minimum: Non-Detect (<10)	18	Golder 2012, AECOM 2014, Haley and Aldrich 2018, Kleinfelder 2016
	Maximum: 34		
	Mean: 18.49		
Background (BMW-1S, BMW-2S, BMW-1D, and BMW-2D)	Minimum: 12.3	38.5	Golder 2017-2021 (a-c)
	Maximum: 73.4		
	Mean: 38.54		
Ponded portion of LCPA	57	57	2018 NPDES Report
Fly Ash / Mixed Ash	Site Minimum: 254	For Concentrations Below – Location: LCPA only / LCPA + LCPB	Golder 2018b, EPRI 2012
	Site Maximum: 1,060	North central: 950 / 350	
	Site Mean: 493.1	South central: 950 / 300	
	EPRI minimum for multiple CCR Sites: 89	Northeastern: 950 / 300	
	EPRI maximum for multiple CCR Sites: 6,070	Southeastern: 950 / 450	

Table 3: Boron Concentration Data Ranges

Applicable Area	Reported Range	Recharge Concentrations Supplied to Model	Data Source
Boron Concentrations (µg/L)			
Missouri River	Minimum: 78.7 J	100	AECOM 2014, Haley and Aldrich 2018, Kleinfelder 2016
	Maximum: 123		
	Mean: 100.1		
Bedrock Aquifer	Minimum: 6.3 J	28.35	Golder 2012, AECOM 2014, Haley and Aldrich 2018, Kleinfelder 2016
	Maximum: 198		
	Mean: 28.35		
Background (BMW-1S, BMW-2S, BMW-1D, and BMW-2D)	Minimum: Non-Detect (<25.0)	100	Golder 2017-2021 (a-c)
	Maximum: 151		

Applicable Area	Reported Range	Recharge Concentrations Supplied to Model	Data Source
	Mean: 78.25		
Ponded portion of LCPA	1,150	1,150	2018 NPDES Report (MDNR 2018)
Fly Ash / Mixed Ash	Site Minimum: 3,360	For Concentrations Below – Location: LCPA only / LCPA + LCPB	Golder 2018b, EPRI 2005, EPRI 2012
	Site Maximum: 28,200	North central: 28,000 / 8,000	
	Site Mean: 14,511	South central: 28,000 / 8,000	
	EPRI minimum for multiple CCR Sites: 1,100	Northeastern: 28,000 / 6,000	
	EPRI minimum for multiple CCR Sites: 109,000	Southeastern: 28,000 / 6,000	

Sulfate and boron data from 2013 to June 2021 were included as calibration targets in the models for the 115 monitored locations within the alluvial aquifer. The transport model calibration results are summarized in Figures 1 and 2. The average sulfate concentration residual is less than 4 mg/L and the normalized root mean square error is 9.8%. The average boron concentration residual is less than 200 µg/L and the normalized root mean square error is 9.7%[1]. The calibrated models were found to be acceptable for current purposes.

Predictive simulations were used to assess future plume movement under existing and capped-pond conditions with the installation of a groundwater treatment system along the northwestern side of the LCPA and LCPB as well as between the two units. The predicted future boron and sulfate concentrations in groundwater were found to be sensitive to the assumed dispersivity and the hydraulic conductivity parameters. Predicted groundwater concentrations for wells within the LCPA and LCPA Corrective Action networks that are currently above the sulfate limit of 250 mg/L and the boron limit of 2,000 µg/L are provided in Figures 3-6 and discussed in the following sections.

1.2.1 Transport Sulfate Results

As shown in Figure 3, sulfate concentrations in monitoring wells currently above the proposed NPDES compliance limit of 250 mg/L that are adjacent to the LCPA and will be immediately affected by the installation of the treatment system (i.e., UMW-3D, UMW-4D, UMW-5D, UMW-6D, UMW-7D and AMW-7) are predicted to be below the proposed compliance limit within 1 to 2 years of the start of treatment system operation. As presented in Figure 4, sulfate concentrations in monitoring wells currently above the proposed NPDES limit that are not immediately affected by the treatment system in the NPDES compliance or corrective action networks (i.e., TP-

[1] It should be noted that there are several high concentrations within shallow wells S2, S3, MW-31, MW-25, MW-26, LMW-5S, and LMW-4S that display temporarily high boron concentrations in the August-November 2019 sampling results. A further discussion these high results and the impacts of the 2019 Missouri River flooding on boron in this area is provided in the November 2019 Alternative Source Demonstration (ASD) for the LCL1. These observed values were included in the calibration statistics values.

3D, MW-33D, MW-34D, MW-35D, AM-1D, AMW-5, AMW-8 and AMW-9) are predicted to be below the proposed limit within 1 to 13 years of the start of operation.

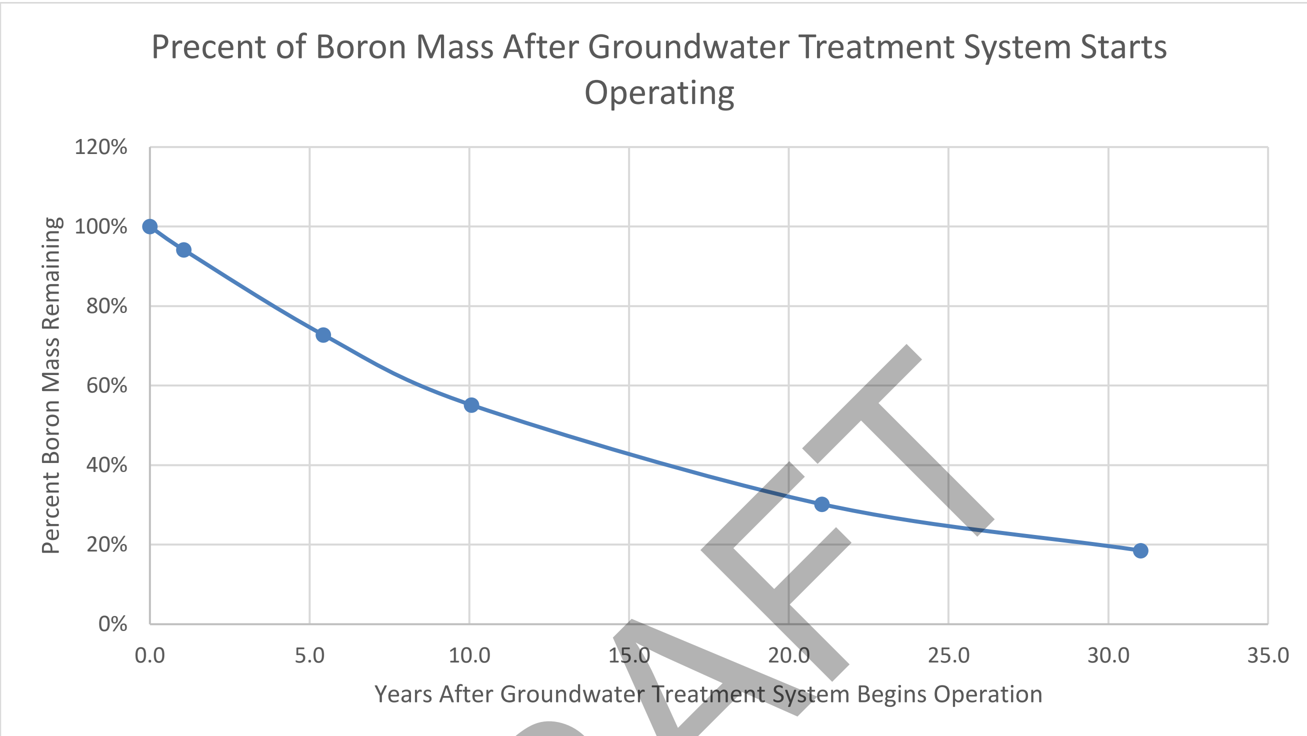
1.2.2 Transport Boron Results

Figure 5 displays model-predicted boron concentrations in the compliance monitoring wells currently above the proposed NPDES Limit of 2,000 µg/L (MDNR, 2021) that are adjacent to the LCPA and will be immediately affected by the installation of the treatment system (i.e., UMW-3D, UMW-4D, UMW-5D, UMW-6D, UMW-7D, UMW-8D, AMW-4D, and AMW-7D). As shown in Figure 5, boron concentrations in these monitoring wells are predicted to drop below the GWPS within 1 to 8 years of the start of treatment system operation. The model calculated attenuation rate in these wells is approximately 646 to 4,800 micrograms (µg/L) per year, with an average decrease in concentration of approximately 1,600 µg/L per year.

Figure 6 presents model-predicted boron concentrations at the monitoring wells currently present above the proposed NPDES Limit that are not adjacent to the LCPA and are not immediately affected by the installation of the treatment system (i.e., LMW-2S, LMW-4S, LMW-7S, LMW-8S, AM-1D, TP-2D, TP-3D, TP-3M, TP-4D, AMW-6, AMW-8, AMW-9, MW-33D, MW-34D, and MW-35D). As shown in Figure 6, concentrations at these monitoring wells are predicted to drop below the NPDES Compliance Limit within 1 to 37 years of the start of the treatment system operation. The model calculated attenuation rate in these wells is approximately 72 to 2,000 micrograms (µg/L) per year, with an average decrease in concentration of approximately 600 µg/L per year.

To further evaluate the reduction of boron in the system, an assessment of boron mass over time was completed for the alluvial aquifer. This evaluation made use of the modeled concentration in each cell multiplied by the saturated thickness of water in each cell and the porosity to calculate the estimated mass of boron in the alluvial aquifer over time. As shown in Figure 7, after 10 years of active treatment, almost half of the mass of boron present in the aquifer system was estimated to have physically attenuated or have been removed via the proposed treatment system. After 30 years, 80% of the boron will have been removed from the alluvial aquifer.

Figure 7: Percent of Boron Mass Remaining After Groundwater Treatment System Begins Operation



1.3 Comparison of MNA and Treatment to Alternative Closure Scenarios

To further evaluate the effectiveness of MNA and treatment, additional modeling scenarios for capping, closure and MNA, as well as Closure by Removal were completed. Boron was selected as the constituent to complete this evaluation, as it is a conservative parameter analyzed due to its mobile nature, and lack of anthropogenic sources. This section describes the model setup for these alternative closure scenarios and compares the results.

The MNA only model uses the same stress periods, recharge concentrations, etc., as the models described above in the current remedy selection section. The only difference between the two models is the removal of the treatment injection and extraction wells.

The closure by removal model was completed as a series of two transient models due to changes in hydraulic conductivities and removal of boron mass after the placement of the unimpacted fill. A summary of the different stress periods is provided in Table 4. Stress periods 1-3 are the same as the previously discussed transient models, as these stress periods have already taken place.

Table 4: Description of Stress Periods – Closure by Removal

Stress Period	Start Date	End Date	Length (Days)	Description
1	1/1/1970	12/31/1992	8765	Beginning of LEC operations with LCPA as only active CCR Unit

Stress Period	Start Date	End Date	Length (Days)	Description
2	1/1/1993	9/28/2019	9402	LCPB now active along with the LCPA. LCPA no longer receives fly ash management water, therefore, boron concentrations and recharge values go down within the LCPA
3	9/28/2019	12/29/2020	459	Closure construction on the LPCA. No more active addition of CCR materials to LCPA. Recharge equal to that of surrounding alluvial aquifer. This has already occurred, so it is included in the transient modeling scenario for closure by removal.
4	12/30/2020	12/31/2036	5840	Dry removal of CCR materials. Based on volume of CCR, it is estimated to take 16 years to excavate down the top approximately 30 feet of dry materials (Lochmuller, 2019). Recharge into CCR during this time is estimated to be equal to that of the surrounding alluvial aquifer. No infiltration basin or treatment wells are present in the CBR modeling scenario.
5	1/1/2037	12/31/2050	5110	Dredging and wet removal of CCR materials. Based on volume of CCR, it is estimated to take 14 years to dredge out the remaining CCR materials (Lochmuller, 2019). During this time, recharge is set to 21 inches per year. This value is equal to the average rainfall/year for the area (approximately 44 inches/year, U.S. Climate Data, Labadie) subtracted by estimated evaporation rates for lakes in Missouri (23 inches per year in Missouri, USDC, 1955).
6	1/1/2051	12/31/2081	11315	Entire former LCPA modeled as being backfilled with materials that have the same conductivity as the shallow alluvium, recharge rate equal to the surrounding alluvium, and an initial concentration equal to background recharge (100 µg/L)

Table 5 displays the model estimated year that each monitoring well with a current boron exceedance from the LCPA, LCPA-CA, or NPDES monitoring well networks will reach the proposed compliance limit of 2,000 ug/L. As displayed in the table, for the monitoring wells immediately downgradient of the proposed treatment system, closure by removal extends the estimated time to reach compliance from 28 to 42 years, with an average of approximately 34 years (by comparison with the current remedy selection plan of closure with treatment and MNA). Monitoring wells further downgradient of the treatment system also display a delay to compliance if closure by removal is selected, with the additional time to reach compliance ranging between 7 and 58 years, with an average of approximately 32 years.

Table 5: Comparison of Corrective Action Remedies and Model-Predicted Time to Compliance for Boron

Well ID	CCR Unit Closure, Groundwater Treatment and MNA	CCR Unit Closure and MNA	Closure by Removal and MNA	Extended Time to Compliance for Closure by Removal
Monitoring Wells Immediately Downgradient of the Proposed Treatment System (Within 500 feet)				
UMW-3D	2031	2038	2059	28
UMW-4D	2028	2036	2063	35
UMW-5D	2029	2032	2064	35
UMW-6D	2023	2028	2065	42
AMW-7D	2030	2038	2061	31
AMW-4D	2025	2034	2057	32
Average Time to Compliance (years after 2022)	**5.7**	**12.3**	**39.5**	**33.8**
Monitoring Wells Downgradient of Proposed Treatment System				
AM-1D	2032	2050	2071	39
TP-2D	2029	2046	2039	10
TP-3D	2042	2049	2100	58
TP-3M	2034	2038	2041	7
MW-33D	2046	2047	2084	38
MW-35D	2033	2033	2054	21
AMW-5D	2029	2038	2069	40
AMW-6D	2025	2025	2040	15
AMW-8D	2034	2034	2081	47
AMW-9D	2027	2027	2073	46
Average Time to Compliance (years after 2022)	**11.1**	**16.7**	**43.2**	**32.1**
Monitoring Wells Upgradient or Not Impacted by Proposed Treatment System				
MW-34D	2049	2049	2053	3
TP-4D	2061	2061	2062	1
UMW-7D	2025	2025	2046	21
UMW-8D	2023	2023	2026	3
LMW-7S	2023	2023	2031	8
LMW-8S	2023	2023	2029	6
LMW-2S	2045	2045	2049	4
Average Time to Compliance (years after 2022)	**13.7**	**13.6**	**20.3**	**9.6**

2.0 GROUNDWATER MODELING SUMMARY

Using industry-standard numerical groundwater modeling procedures, Golder has updated the existing LEC transient groundwater flow model to evaluate boron and sulfate concentrations under various closure scenarios. The following conclusions can be made from these modeling efforts.

- With the current remedy selected (capping/closure of the LCPA, groundwater treatment, and MNA), sulfate concentrations are predicted to be below the proposed NPDES Limit of 250 mg/L within 1 to 13 years after the initiation of the treatment system in monitoring wells within the Corrective Action Network. Those monitoring locations adjacent to the CCR Unit, immediately downgradient of the proposed treatment system are predicted to meet the proposed compliance standard within 2 years of the start of the treatment system operations.
- With the current remedy selected (capping/closure of the LCPA, groundwater treatment, and MNA), boron concentrations are predicted to be below the proposed NPDES Limit of 2,000 µg/L within 1 to 8 years of the start of the treatment system operation for those monitoring well locations immediately adjacent to the CCR Unit and downgradient of the proposed treatment system. Monitoring wells not adjacent to the CCR Unit and the treatment system are predicted to monitor concentrations below the compliance limit within 1 to 37 years of the start of the treatment system operation.
- The boron mass within the alluvial aquifer is predicted to drop by approximately 45% in the first 10 years after the installation of the proposed treatment system, and more than 80% after 30 years due to treatment and physical attenuation.
- Comparisons of the simulations of current selected remedy and closure by removal predict that closure by removal is estimated to delay compliance by up to 42 years adjacent to the LCPA and by up to 58 years within the current boron plume.

3.0 LIMITATIONS

The modeling analyses presented in this report are a simplification of reality and the model-predicted results should be used with this understanding. The limitations associated with analyses such as these are detailed below.

Hydrogeologic investigations and groundwater modeling are dynamic and inexact sciences. They are dynamic in the sense that the state of any hydrological system is changing with time, and in the sense that the science is continually developing new techniques to evaluate these systems. They are inexact in the sense that groundwater systems are complicated beyond human capability to evaluate them comprehensively in detail, and we invariably do not have sufficient data to do so. A groundwater model uses the laws of science and mathematics to draw together the available data into a mathematical or computer-based representation of the essential features of an existing hydrogeologic system. While the model itself obviously lacks the detailed reality of the existing hydrogeologic system, the behavior of a valid groundwater model reasonably approximates that of the real system. The validity and accuracy of the model depends on the amount of data available relative to the degree of complexity of the geologic formations, the site geochemistry, the fate and transport of the dissolved compounds, and on the quality and degree of accuracy of the data entered. Therefore, every groundwater model is a simplification of a reality and the model described in this report is not an exception.

The professional groundwater and geochemical modeling services performed as described in this report were conducted in a manner consistent with that level of care and skill normally exercised by other members of the engineering and science professions currently practicing under similar conditions, subject to the quality and quality of available data, the time limits and financial and physical constraints applicable to the services. Unless otherwise specified, the results of previous or simultaneous work provided by sources other than Golder and quoted and/or used herein are considered as having been obtained according to recognized and accepted professional rules and practices, and therefore deemed valid. This model provides a predictive scientific tool to evaluate the impacts on a real groundwater system of specified hydrological stresses and/or to compare various scenarios in a decision-making process. However, and despite the professional care taken during the construction of the model and in conducting the simulations, its accuracy is bound to the normal uncertainty associated to groundwater modeling and no warranty, express or implied, is made.

4.0 REFERENCES

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Attachments: **Figure 1** - Scatter Diagram for Predicted and Observed Sulfate Concentrations – Transient Conditions

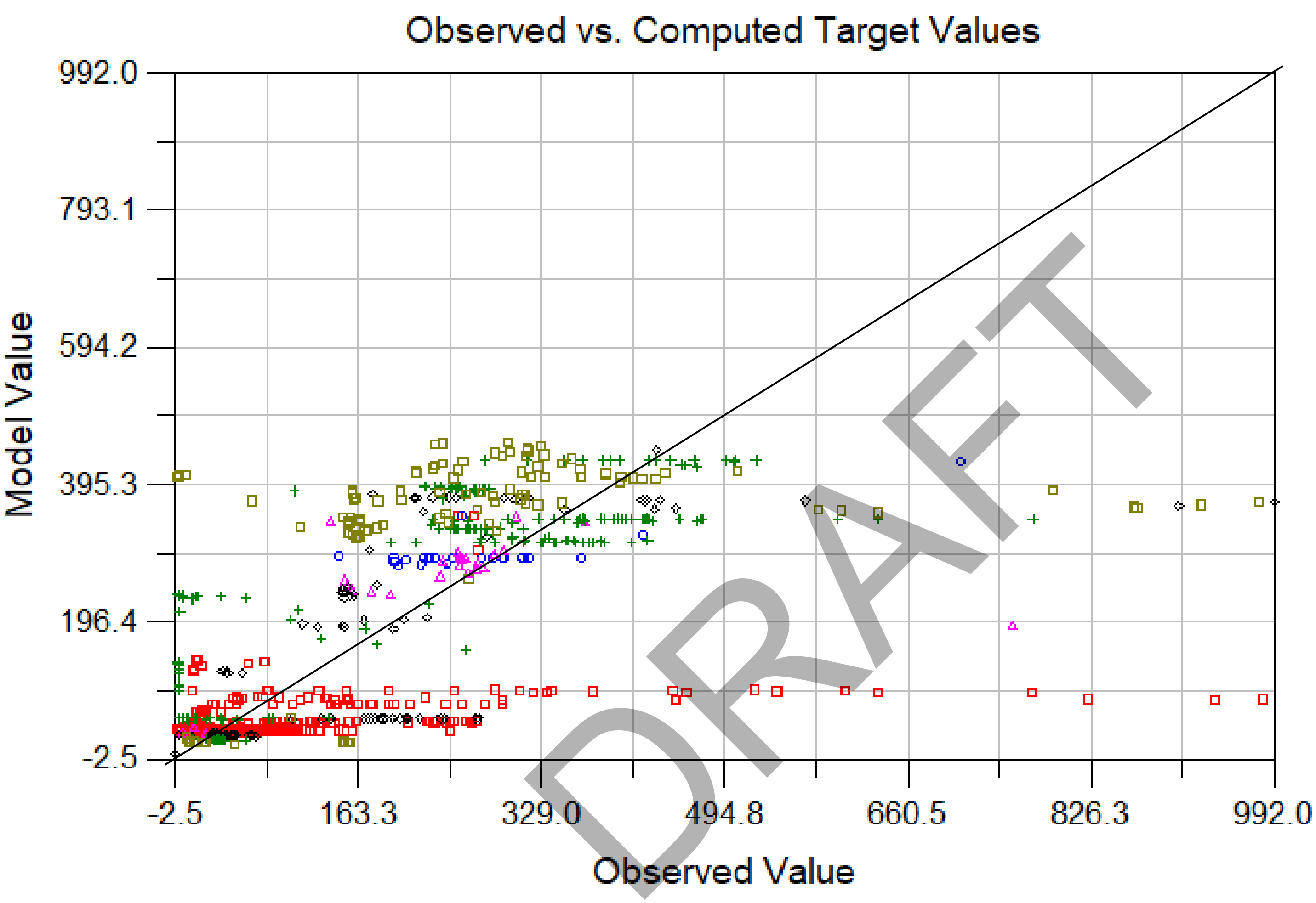
Figure 2 - Scatter Diagram for Predicted and Observed Boron Concentrations – Transient Conditions

Figure 3 - Model Predicted Sulfate Concentrations Over Time – Monitoring Wells Adjacent to LCPA

Figure 4 - Model Predicted Sulfate Concentrations Over Time – Monitoring Wells Not Immediately Affected by Treatment System

Figure 5 - Model Predicted Boron Concentrations Over Time – Monitoring Wells Adjacent to LCPA

Figure 6 - Model Predicted Boron Concentrations Over Time – Monitoring Wells Not Immediately Affected by Treatment System



Residual Mean	= -3.85
Residual Standard Dev.	= 97.87
Absolute Residual Mean	= 52.21
Residual Sum of Squares	=1.42e+007
RMS Error	=97.95
Minimum Residual	= -409.02
Maximum Residual	= 897.58
Range of Observations	= 994.50
Scaled Res. Std. Dev.	= 0.098
Scaled Abs. Mean	= 0.052
Scaled RMS	= 0.098
Number of Observations	= 1477

NOTE(S)

1) Values from groundwater samples collected between 2013 and 2021.

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REVIEW	EMS
APPROVED	JM

TITLE
SCATTER DIAGRAM FOR PREDICTED AND OBSERVED SULFATE CONCENTRATIONS – TRANSIENT CONDITIONS

PROJECT No.	REV.	FIGURE
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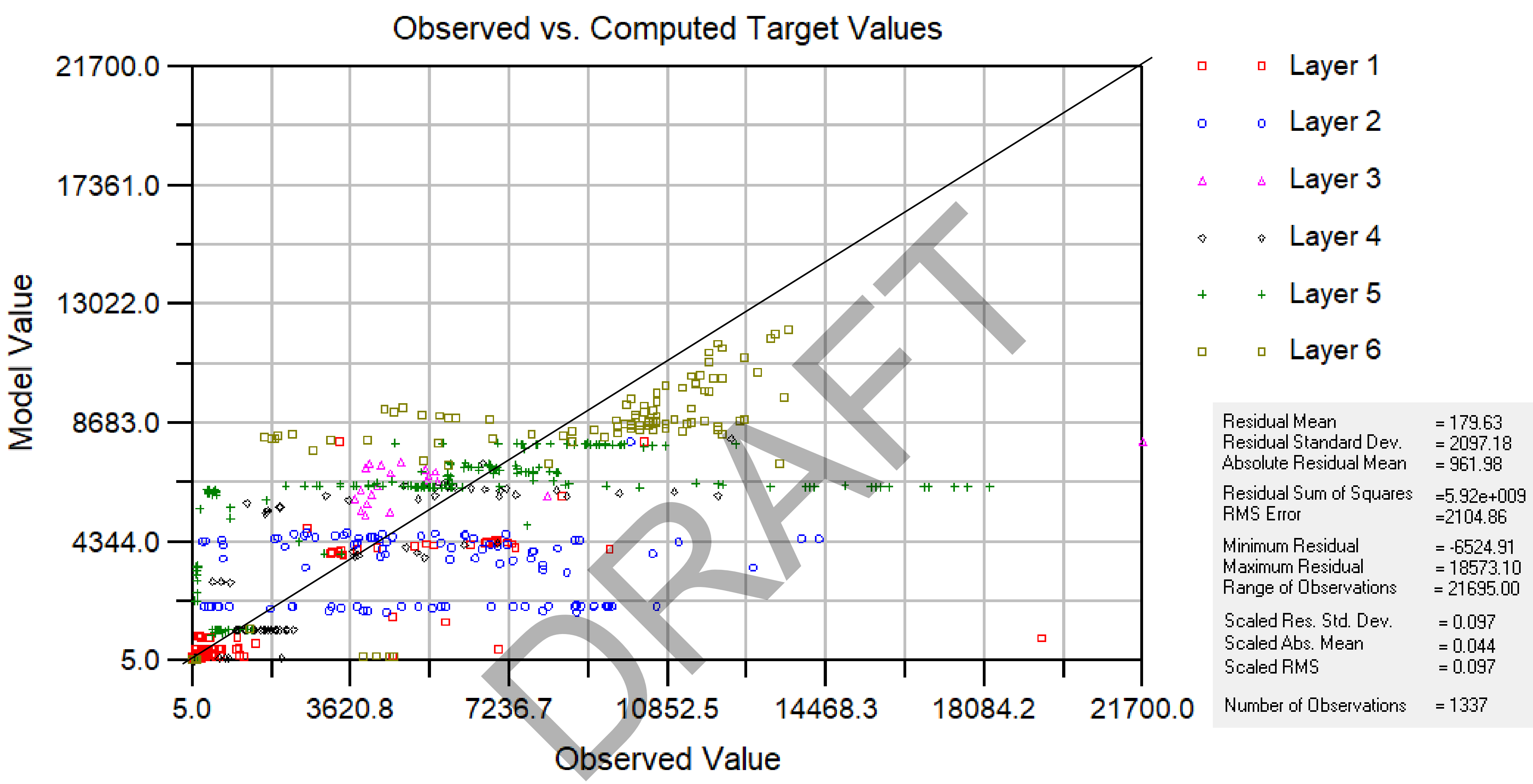

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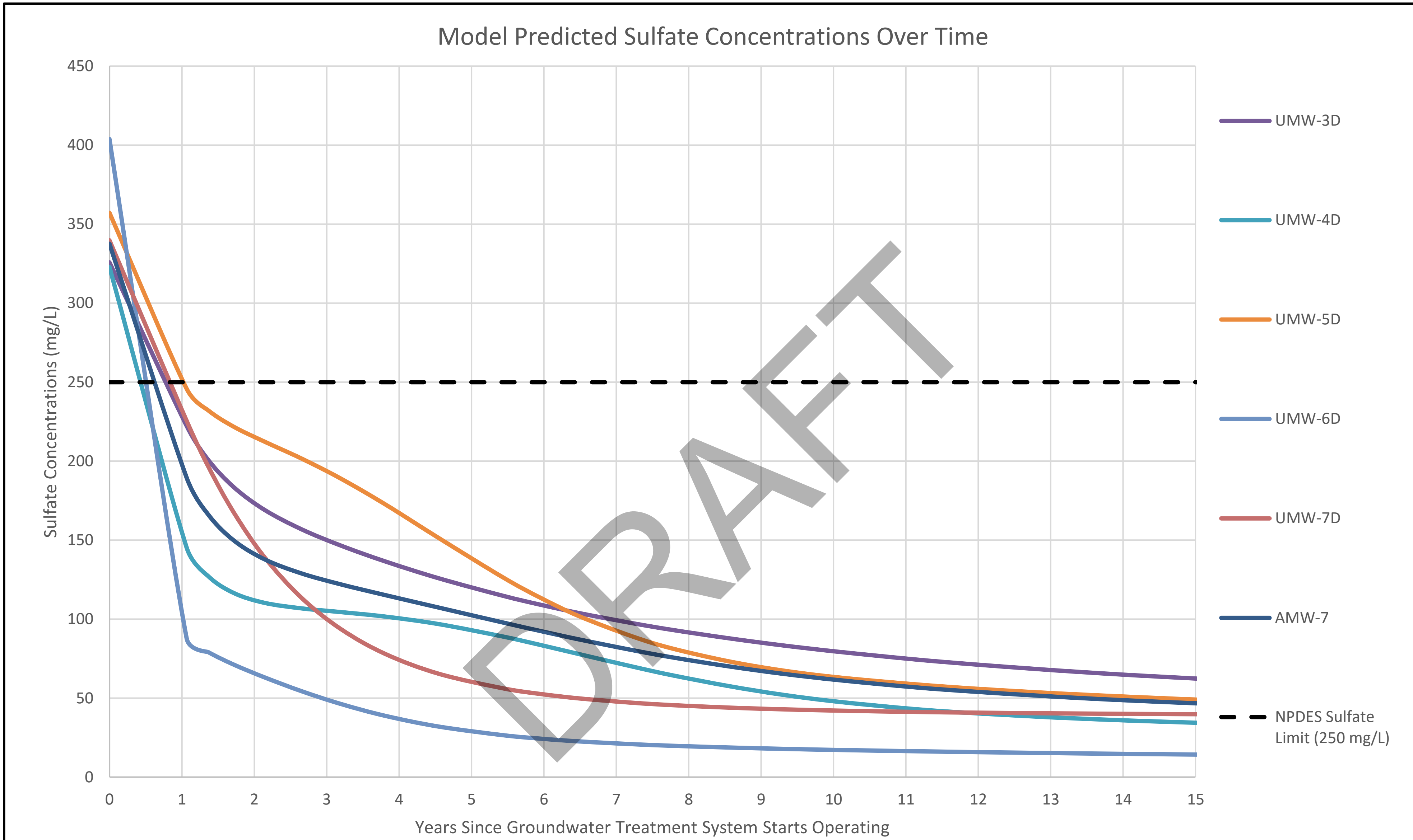
TITLE
SCATTER DIAGRAM FOR PREDICTED AND OBSERVED BORON CONCENTRATIONS – TRANSIENT CONDITIONS

PROJECT No.	REV.	FIGURE
153140603	**0.0**	**2**



NOTE(S)

1) Mg/L – Milligrams per liter.
2) NPDES – National Pollution Discharge Elimination System.

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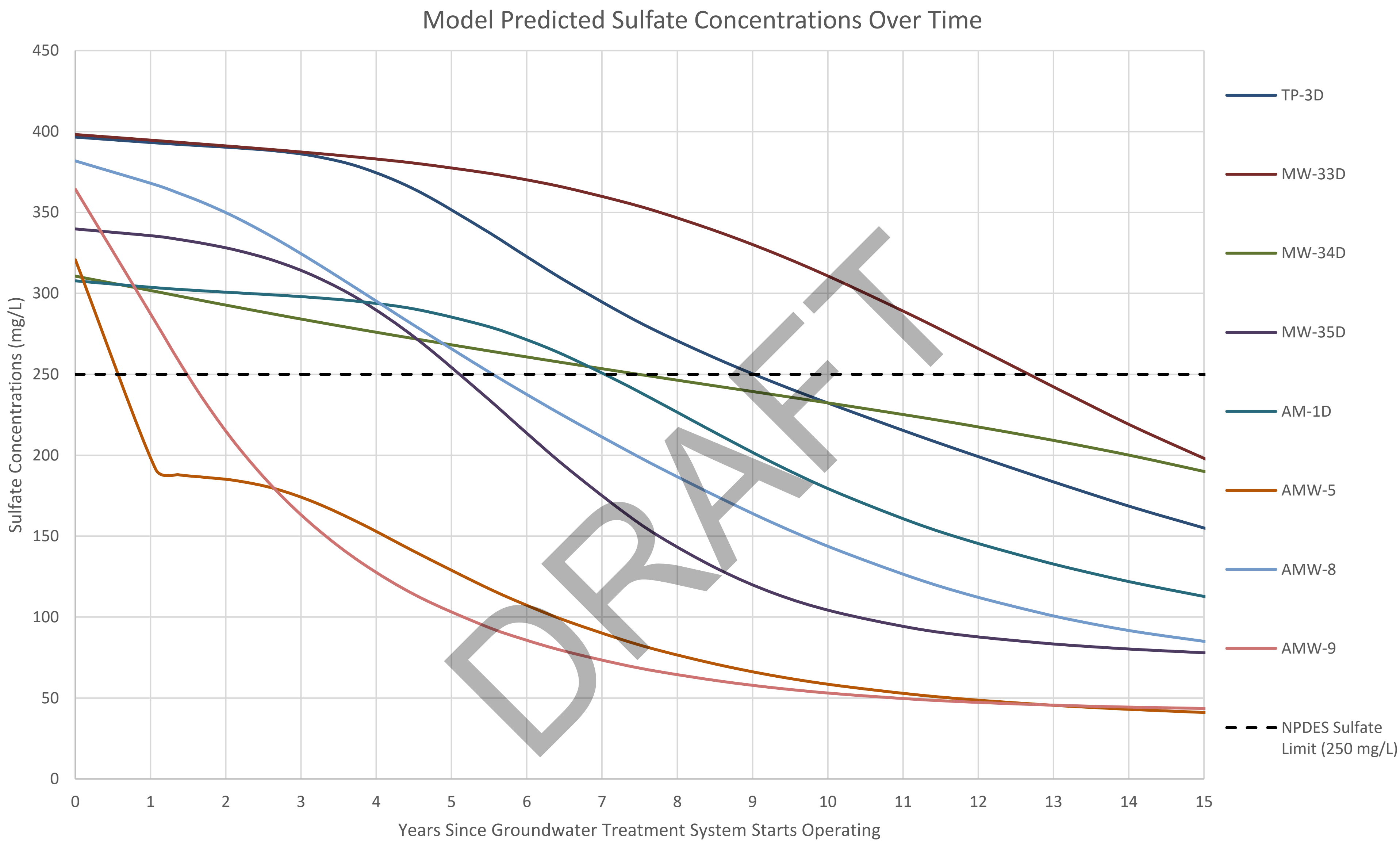
TITLE
MODEL PREDICTED SULFATE CONCENTRATIONS OVER TIME
MONITORING WELLS ADJACENT TO LCPA

PROJECT No.	REV.	FIGURE
153140603	**0.0**	**3**



NOTE(S)

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TITLE
MODEL PREDICTED SULFATE CONCENTRATIONS OVER TIME MONITORING WELLS NOT IMMEDIATELY AFFECTED BY TREATMENT SYSTEM

PROJECT No.	REV.	FIGURE
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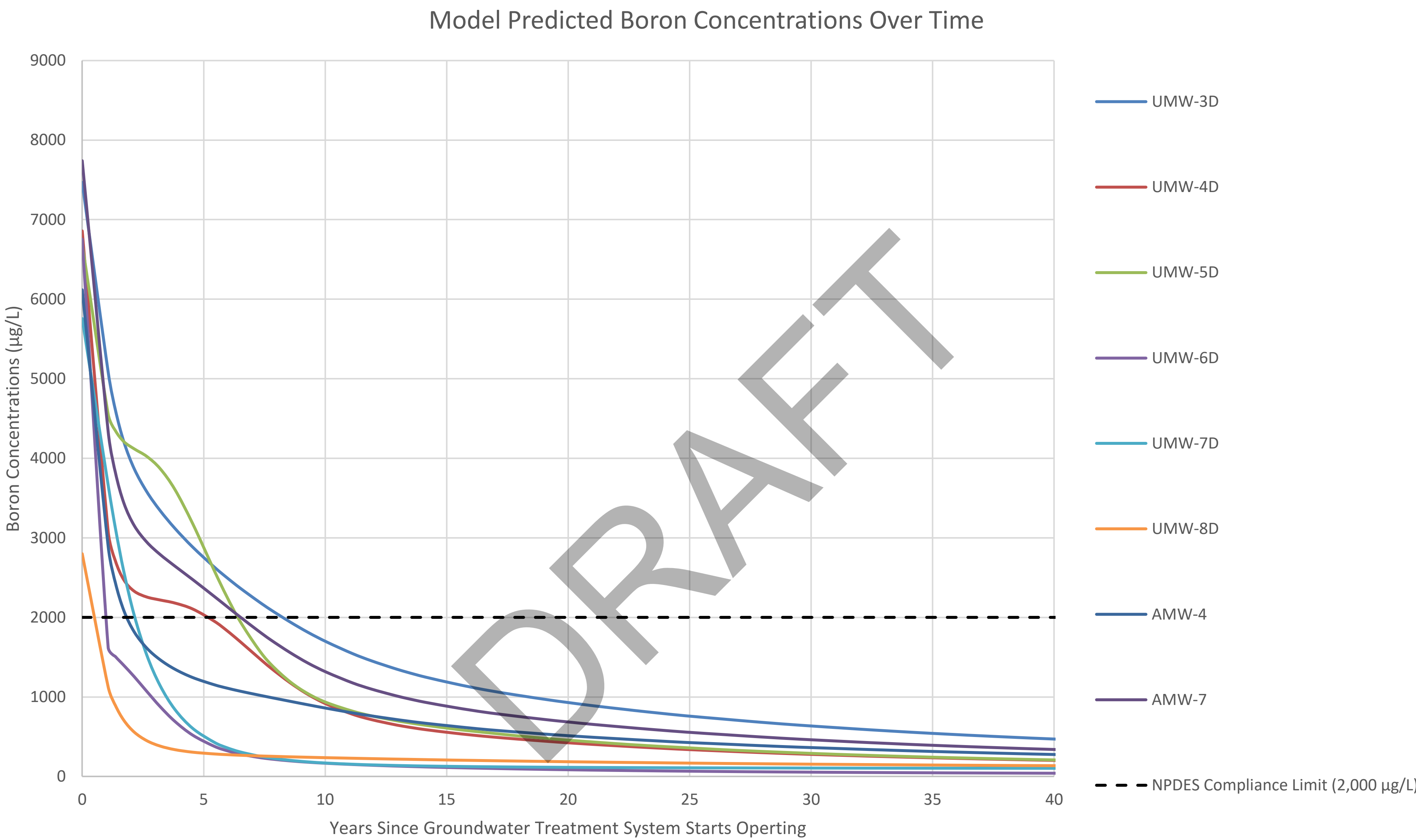

NOTE(S)

1) µg/L – micrograms per liter.
2) NPDES – National Pollution Discharge Elimination System

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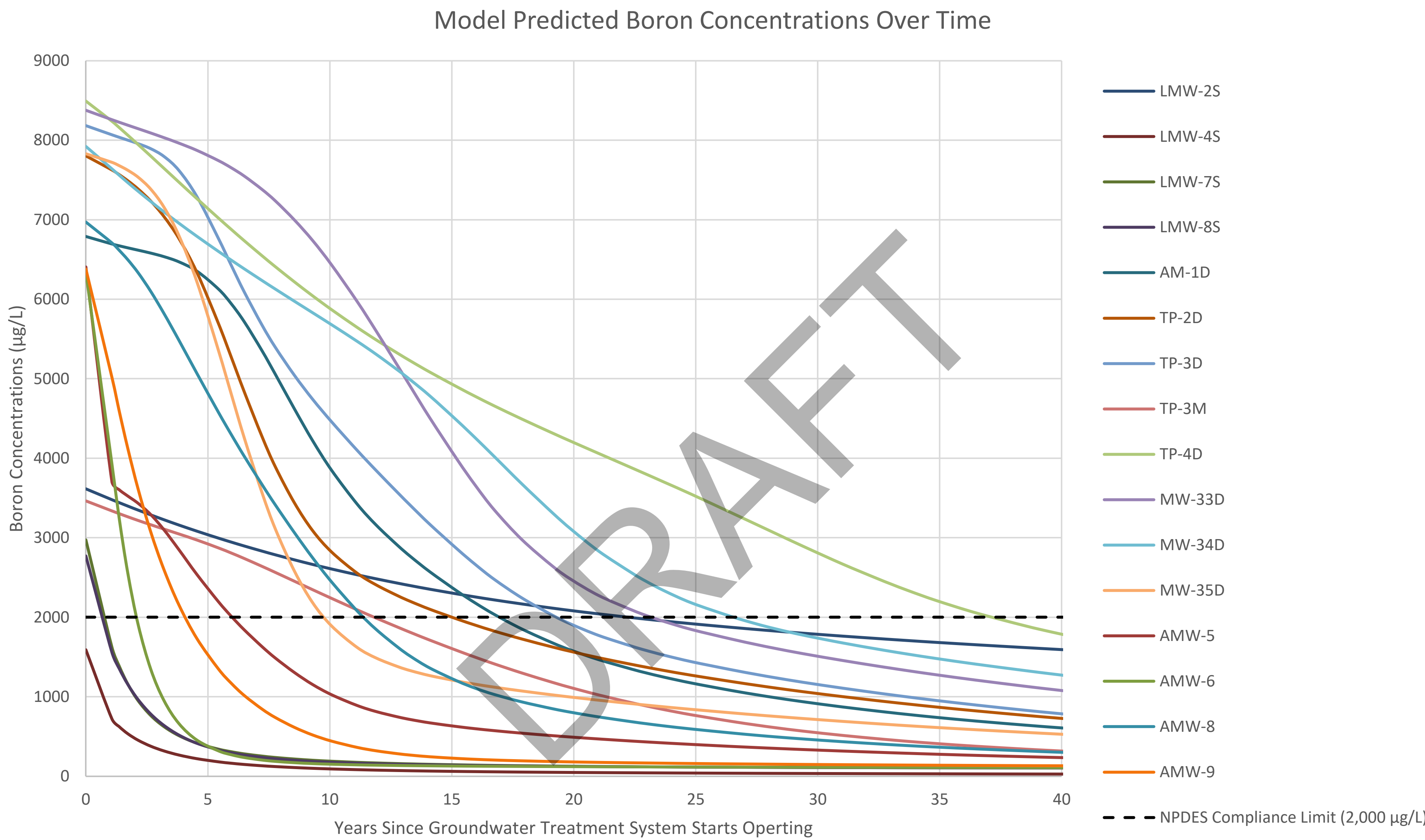
TITLE
MODEL PREDICTED BORON CONCENTRATIONS OVER TIME MONITORING WELLS ADJACENT TO LCPA

PROJECT No.	REV.	FIGURE
153140603	**0.0**	**5**



NOTE(S)

1) µg/L – micrograms per liter.
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TITLE
MODEL PREDICTED BORON CONCENTRATIONS OVER TIME MONITORING WELLS NOT IMMEDIATELY AFFECTED BY TREATMENT SYSTEM

PROJECT No.	REV.	FIGURE
153140603	**0.0**	**6**

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