Transient Simulation of Dewatering to Estimate Potential Effects to Water Resources for an Open Pit Lithium Mine in NC

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Abstract

Piedmont Lithium Carolinas, Inc. (PLL) is proposing to construct an open-pit mine in the Carolina Tin-Spodumene Belt (TSB) of North Carolina where lithium-bearing spodumene pegmatites occur. PLL intends to extract lithium-bearing spodumene for refinement to battery grade lithium hydroxide, to support manufacturing of lithium-ion batteries. The approximately 1,548-acre Site is in an unincorporated area of Gaston County, near Cherryville, North Carolina. On behalf of PLL, HDR Engineering, Inc. of the Carolinas (HDR) performed groundwater modelling to estimate water withdrawal rates for pit dewatering and evaluate possible effects pit dewatering may have on local water resources.

The mine will be comprised of four 600-feet deep mine pits excavated at different rates and times over 20 years. RQD from 288 rock cores was evaluated as a surrogate for hydraulic conductivity, 10 monitoring wells were installed, stream flows were monitored, and an aquifer test was conducted in support of the model. A geologic model based on the rock core was used as the stratigraphic basis of the groundwater model. Because the bulk hydraulic conductivity is low, dewatering will be done in-pit by sumps. The mined rock is spodumene pegmatites in a deformed massive granite with almost no intrinsic and limited secondary permeability, so deep rock hydraulic conductivities is very low. Simulating the material changes and competing dewatering in multiple changing pit shells over the mine's life is a complex task. A series of transient models were undertaken to simulate mine pit excavation and backfilling over time. This complex model was conceptually challenging and mathematical instabilities occurred during some simulations.

The groundwater flow model was constructed with six hydrostratigraphic layers. The model domain encompassed the area that potentially contributes water to the mine pits during dewatering or that could be affected by dewatering. Mine pit shell extents were represented in the transient models through a change of aquifer materials. MODFLOW drain cells are varied in elevation over the modelled period to reflect changing dewatering conditions as pit extents expanded. The series of transient groundwater models that simulated dewatering through the 20-year anticipated life of the mine were used to estimate water withdrawal necessary to dewater the mine pits as they are excavated and associated drawdown in the adjacent aquifer. Each change in mine pit configuration and dewatering operations altered groundwater flow paths and resulted in re-evaluation of the site conceptual model.

Model results indicated that withdrawals would range between 575 and 2,300 gallons per minute and drawdown greater than 1 foot would be limited to areas near the pits (within less than a half mile) as they are excavated. Discharge of pumped water through permitted National Pollutant Discharge Elimination System (NPDES) outfalls to streams and wetlands was found to reduce impacts to baseflow conditions. Additional site characterization studies in support of the model and additional modelling are under way. Moving forward, the model will be used to site sentinel monitoring wells, size dewatering pumps, make decisions regarding the mine process water budget, and evaluate potential mitigation measures for impacts to surface water bodies and nearby private water supply wells.

Introduction

PLL is proposing to construct an open-pit mine in the Carolina TSB of North Carolina where lithium-bearing spodumene pegmatites occur. PLL intends to extract lithium-bearing spodumene for refinement to battery grade lithium hydroxide, to support the manufacturing of electric vehicle (EV) lithium-ion batteries. The approximately 1,548-acre Site is in an unincorporated area of Gaston County, approximately one mile east of Cherryville, North Carolina. The mine will be comprised of four pits that are excavated at different rates to approximately 600 feet over a 20-year period. On behalf of PLL, HDR performed groundwater modelling to estimate the rate of water withdrawal during pit dewatering operations and evaluate possible effects pit dewatering may have on local water resources and water users. The model was also used to site sentinel wells around the permitted boundary to provide early detection of drawdown prior to drawdown in private supply wells. Post-mining recovery will be the subject of future modelling.

Conceptual Model

The groundwater flow model domain includes the southern portion of Indian Creek watershed, Beaverdam Creek watershed, and a reach of the South Fork Catawba River. The 32.5 square mile (mi^2) model domain and Site boundary are shown in Figure 1. PLL plans to mine resource from four 600-feet deep mine pits (North, South, East, and West pits) within the permitted mine boundary. Mine pits are separated by existing streams and wetlands that will largely remain intact during and after mining.

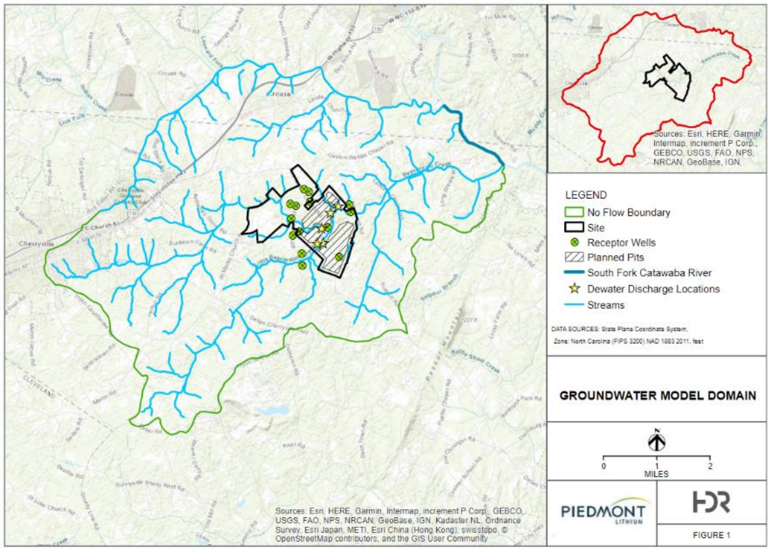

Figure 1 Groundwater Model Domain

Hydrostratigraphy

The Site is located within the TSB, which is comprised of metamorphic and igneous rocks overlain by weathered by-products of the rock and residuum (Kessler 1942, Schaeffer 2019). These materials can be divided into the following hydrostratigraphy:

1. *Overburden* is generally residuum consisting of alluvial and regolith deposits composed of silt from weathered bedrock, with some rock fragments as gravel and sand.
2. *Saprolite* is derived from weathering of bedrock in-situ where some of the original rock texture and structure remain, yet the minerals have been altered to a consistency of soil.
3. *Transition Zone* is a thin zone between the saprolite and the underlying bedrock where there is less weathering, but the rock is highly fractured, weathered, and not competent.
4. *Bedrock* is generally metavolcanic amphibolite intruded by pegmatites (some of which are spodumene bearing). The amphibolite exhibits little foliation or other structures. Other areas within the model domain are comprised of foliated metasedimentary rocks, which at some places, have relict bedding. Neither the metavolcanics nor the metasedimentary rocks have significant primary porosity, so almost all the water in these units exists in joints and fractures. At some locations, Triassic diabase dikes have intruded the crystalline bedrock and may be responsible for some of the lineations described below. As reported by Daniel, Smith, and Eimers (1997), groundwater flow in the bedrock

aquifers is controlled by fracturing and further, it is likely that erosion results along fractures so that streams and rivers are associated with areas of higher fracturing and hence more transmissive fractured bedrock.

5. *Lineations*, including valleys and linear topographic expressions visible in aerial photographs and topographic maps, are likely due to weakness in the bedrock such as faults and fractures and more easily eroded folded rock units and may indicate zones of higher hydraulic conductivity. These lineations can be simulated as higher-hydraulic conductivity material, however, their attitude in the subsurface is uncertain. Daniel, Smith, and Eimers (1997) found that valley floors had higher hydraulic conductivity than hill tops and that the valley walls transition between the two. This variation in hydraulic conductivity is consistent with valleys being coincident with subsurface fractures.
6. *Mine Pits* become open holes that are dried by dewatering. Mine pits that were dried during dewatering either will rewet as pit lakes after dewatering or will be filled with low hydraulic conductivity fill consisting of native waste rock material and non-hazardous mine tailings.

Boundary Conditions

Groundwater flows are generally from inflow to storage to discharge; boundary conditions describe the specific features that make up these processes. Inflow to the model domain is generally from recharge due to precipitation, although under stress, water may be diverted from adjacent systems or captured from surface water. Storage is the quantity of water occupying space in the system and from compressibility of the aquifer matrix. Discharge under natural conditions is usually to surface water bodies (streams, wetlands, rivers, and lakes) and evapotranspiration. At the Site, discharge is to streams (e.g., Beaverdam Creek), wetlands (which typically feed streams), the South Fork Catawba River and evapotranspiration where groundwater is near the ground surface. Also, water is withdrawn from the system by water supply wells, reducing discharge to surface water (no large water supply wells are documented in the model domain). These boundary conditions are accounted for in a groundwater model to assure the appropriate water budget is simulated and are shown in general on Figure 1 (more detailed wetlands were simulated than shown).

Temporal Constraints

The calibrated steady state model of natural state conditions described below provided the initial conditions for the transient modelling. Pit dewatering was simulated with a series of transient models to account for the changing pit geometries and locations of dewatering. The transient models represent annual mine pit extents with portions of different pits open at the same time. The pit dewatering sequence simulated is shown in Table 1. Drawdown due to dewatering is greatest when the mine pits have been excavated to the designed terminal depth. After completion of mining, pits either fill with water or are filled with low hydraulic conductivity material. Multiple stress periods were simulated in the multi-year phases to account for changing pit geometries when the same set of pits were mined over multiple years.

Table 1 Transient Model Sequence of Mine Pits

	Pits with Dewatering			
Model Year	South Pit	East Pit	West Pit	North Pit
1	Mining			
2	Mining	Mining		
3	Mining	Mining		
4	Filling	Mining		
5	Filling	Mining		
6-10	Filling	Mining		
11	Filling	Mining		
12	Filling	Mining	Mining	
13	Filling	Filling	Mining	Mining
14 – 20	Filling	Filling	Pits Merged Mining	

Dewatering and Water Handling

Water was assumed to passively seep into the mine pit then be pumped from the lowest levels of the mine pit into settling basins prior to being discharged to adjacent streams or wetlands. Dewatering was simulated by MODFLOW drain return cells (DRT) which estimate the amount of water removal necessary to dewater the mine pits. Drain elevations were set equal to the bottom of the pit. The water removed by drain cells was returned to the model at the planned discharge locations. Water from mine pit dewatering returned to the model infiltrates to groundwater or flows out of the model domain through streams and wetlands. Using the DRT cells to return water from dewatering operations to the model allowed the evaluation of water handling effects on water balances for wetlands and streams, drawdown at nearby wells, and recovery of water levels in adjacent idle mine pits.

Model Development and Calibration

Modelling Software

Groundwater modelling was performed using the USGS groundwater model software, MODFLOW-NWT (Niswonger, 2011) which allowed a variable spaced grid that focused on areas of interest, while staying generalized in remote areas. Aquaveo's model pre- and post-processing software, GMS (Aquaveo, 2021), was used to develop the groundwater flow model.

Discretization

The model grid was refined both horizontally and vertically so that features of the CSM and the focus area near the Site could be simulated with greater detail than remote areas which are generalized.

Cells in the model range between 50 feet on a side where the grid is focused around the mine pits, to 500 feet on a side where the model is generalized further away from the Site.

Model Layers

The model was constructed using the following six layers to represent hydrostratigraphy within the model domain.

Table 2 Layer Description

Layer	Hydraulic Conductivity (ft/d)	Vertical Anisotropy (ft/d)	Specific Storage (1/ft)	Specific Yield	Description
1	1.5	2	0.01	0.2	Overburden: regolith and fluvial deposits
2	1	2	0.001	0.15	Saprolite: bedrock eroded to soil
3	2	2	0.001	0.2	Transition Zone: highly fractured and weathered rock beneath the saprolite
4 / 5 Hard Rock	0.0075	1	0.0004	0.01	Bedrock: Hard rock found between streams
4 / 5 Soft Rock	0.25	1	0.0004	0.1	Bedrock: Soft rock found near streams
6	0.0075	1	0.0004	0.01	Deep Bedrock: Hard rock with closed fractures
Pits	5000	1	0.001	0.1	Mine Pits: Simulated as high hydraulic conductivity material as pits were excavated, once dried, cells representing mine pits are represented by dry-cells. After dewatering, the pits are simulated as either rewetted high hydraulic conductivity (mine pit lakes) or with rewetted low hydraulic conductivity material (backfill)

Boundary Conditions

Recharge was based on studies done in the adjoining Indian Creek watershed by Daniel, Smith, and Eimers (1997), who estimated recharge at 10 inches per year within the model domain. Recharge was simulated using constant flux in the MODFLOW Recharge package.

Streams were based on the USGS National Hydrographic Dataset (NHD) flow lines shapefile (USGS, 2019) for generalized model areas and the detailed digitized stream map shapefile (HDR, 2018) at the Site. Streams were simulated using the MODFLOW Stream package which allows individual stream segments to gain or lose water and connects flow between reaches. Each node along the streams was referenced to the surface elevation from a digital elevation model (DEM) (USGS 2013). The bottom conductance, roughness, width, and connection to incoming upstream flow were added to each stream segment. Beaverdam Creek, the largest stream in the domain, was simulated as 25 feet wide and Little Beaverdam

Creek was simulated as 15 feet wide. Smaller tributaries were simulated to be 5 feet wide. Stream bottom conductance was set to 1_(ft^2/d)/ft.

Ponds in the model domain are generally created by small dams on streams and creeks. Although they may affect groundwater flow locally, the effect is similar to that of the stream at the same location. For that reason, changes in simulated base flow in streams was used to assess impacts on ponds.

South Fork Catawba River is the down-gradient model boundary and was simulated using the MODFLOW River package. This package uses the riverbed elevation based on the DEM (USGS 2013) along the stretch of the river and an estimated conductance value for the riverbed.

No-flow cells are inactive model grid cells (water can pass through vertically as recharge). Since the domain is larger than the effects of dewatering, the domain is bounded by no-flow cells (inactive cells in the grid beyond the domain). Also, no-flow cells are used to simulate the empty space of dewatered pits.

Steady-State Calibration

Once constructed, the groundwater model results were compared to mean water levels from 10 monitoring wells at the Site, base flow estimates for streams in the Indian Creek watershed as documented by Daniel, Smith, and Eimers (1997), and stream flows measured in May 2019 within the Site boundary. An aquifer test conducted was influenced by a recharge event (i.e., hurricane) making it unusable as a transient calibration target, however, estimates for storativity and hydraulic conductivity from the test were used to guide the modelling. A second aquifer test is planned during the second quarter 2022.

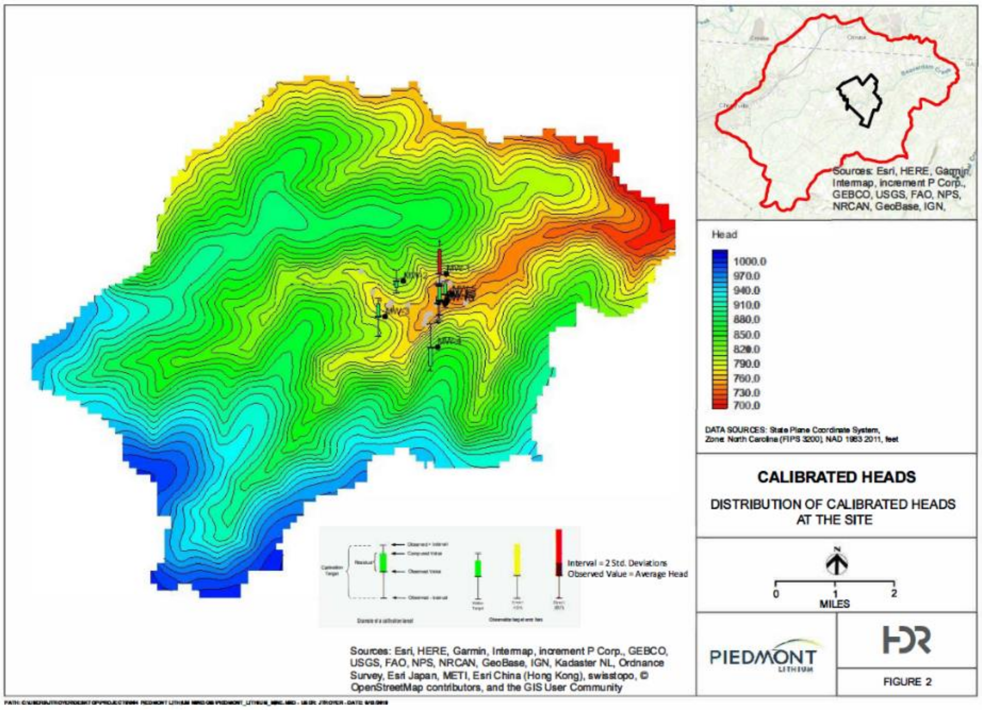

Figure 2 Calibrated Heads

The means and ranges of variability in groundwater levels measured in 10 monitoring wells over a one-year monitoring period were calculated and compared to simulated water levels. Simulated levels at 9 of 10 wells were within the range of observed levels within two standard deviations of the mean water level and within one standard deviation of the mean in four of these wells. The Root Mean Squared error for the base simulation is 3.6 feet, while the mean square of the observed standard deviation is 4.3 feet showing the water levels simulated are within the variability of the observed water levels. Water levels in one well on a hillside were off by 28 feet. This water level variation could be due to a nearby fracture, spring or other condition not simulated by the model. Adjusting the model to match the one well would cause loss of calibration at the other wells. Hydraulic conductivity simulated by the calibrated model was at the low end of the values observed during the aquifer test, however, the pumping test was hampered by a recharge event and likely overestimated hydraulic conductivity.

Total flow in a stream includes runoff into the streams, lateral flow from the soil, and base flow. Baseflow is the portion of stream flow which is discharged from the groundwater. Baseflows were estimated by Daniel, Smith, and Eimers (1997) at four locations on Indian Creek within the model domain. The baseflow simulated by the base model was compared to these locations (Table 3). Stream flow (specifically baseflow) measurement locations that were compared to the calibrated model are shown on Figure 3.

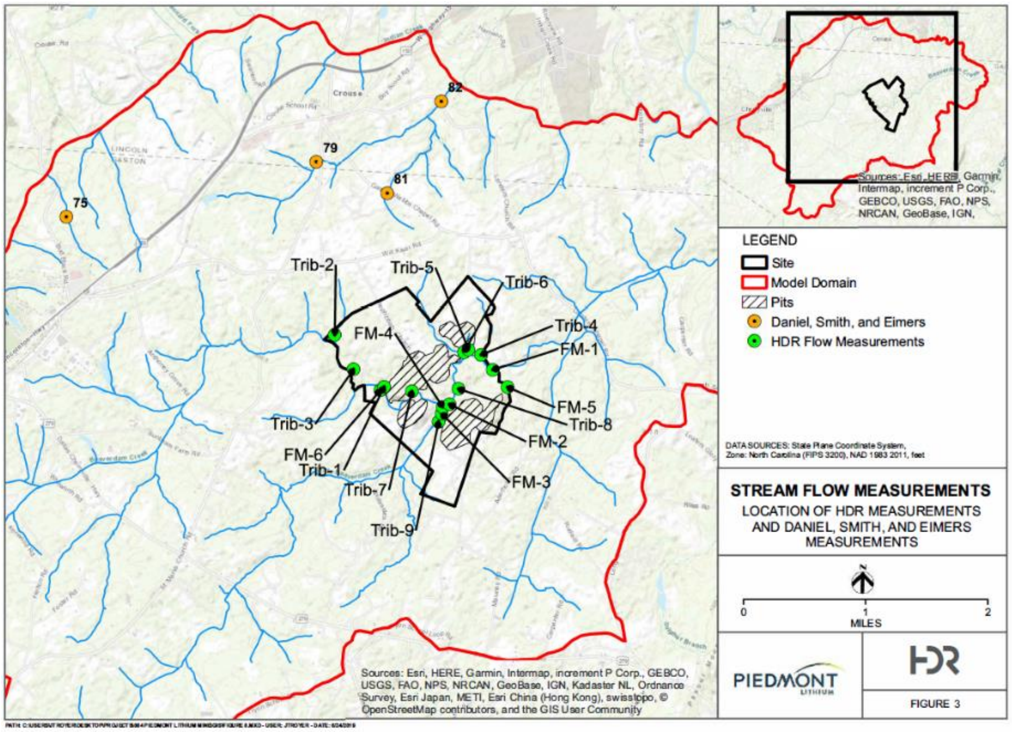

Figure 3 Stream Flow Measurements

Table 3 Simulated Baseflow and Baseflow Reported by Daniel, Smith, and Eimers (1997)

Measurement Location (see Figure 3)	Reported Flow (ft3/s) (1997)	Modelled Flow (ft^3/s)	Percent Difference
81	0.16	0.17	5.6
79	0.75	0.69	7.3
82	1.79	1.77	1.4
75	0.28	0.26	6.5

Stream flows within the Site were measured on May 13 and 15, 2019. The USGS stream gage on Indian Creek (the adjacent watershed) was at the 95th percentile and 85th percentile daily flows for those two days, meaning elevated total flow was measured and not baseflow. When these stream flows are compared to model output (baseflow, so likely less than 50th percentile), all simulated flows were less than measured and most at about 50 percent of observed. While this is a qualitative comparison, the model-predicted base flows are within observed flows and likely approaching actual baseflow values.

Determining Mine Pit Shells Through Time

PLL’s most recent estimate of resource extent was used to establish the potential extents of pit excavation used in the transient model (see Figure 1). Annual mine pit geometries were estimated by the mining engineer, Marshall Miller & Associates (MMA), in 2021 and provided as 3-dimensional shapefiles of surface topography. MMA used MiningMath SimSched software to optimize pit geometries and Maptek’s Vulcan Evolution software to establish the mine operations schedule (MMA, 2021).

The mine pit topography was subtracted from the modelled ground surface topography for each annual change in mine pit geometry. Mine pit extents for model layers were based on contours from the pit excavation geometries that coincide with model layers. Pit excavation depths did not always coincide with established model layering, so a layer was considered excavated where the pit shell was deeper than 50% of the modelled layer thickness and the material was changed to open pit.

Simulating Mine Dewatering Through Time

The complexity of the model required the model approach and solution method to be re-evaluated with each change in mine pit and dewatering geometry. A series of transient models simulated annual configuration of each pit over a 20-year anticipated mine life (Table 1). Model cells within mine footprints were represented with water-filled, high conductivity cells which are allowed to go dry when water levels drop beneath them. Additionally, drains placed in the model to collect simulated groundwater seepage through the face of the pit or flow through a lower layer were reconfigured to fit each new mine pit footprint. The model runs were more successful when each footprint change and drain configuration were conducted with an independent transient simulation. Often, the solver scheme used in one phase of mining needed adjustment to accommodate the next phase of mining. Final heads generated from a simulation became the starting heads for the next simulation in the sequence. Final drawdown at the end of the 20 years of simulated dewatering is shown on Figure 4.

A volumetric water budget analysis for each transient model was performed. Dewatering rates at various stages of mine pit operations were estimated based on the volume of water removed by the drains and the time period of the simulation. Estimated dewatering rates ranged from 575 gallons per minutes (gpm) to 2,300 gpm for the largest mine pit footprint as presented in Table 4.

Simulated drawdowns at two wells located off the mine property resulted in significant loss of water in the well column. PLL plans to place sentinel wells at strategic locations along the site boundary to provide early detection of excessive drawdowns. Mitigation for wells that experience water column loss will be addressed case by case.

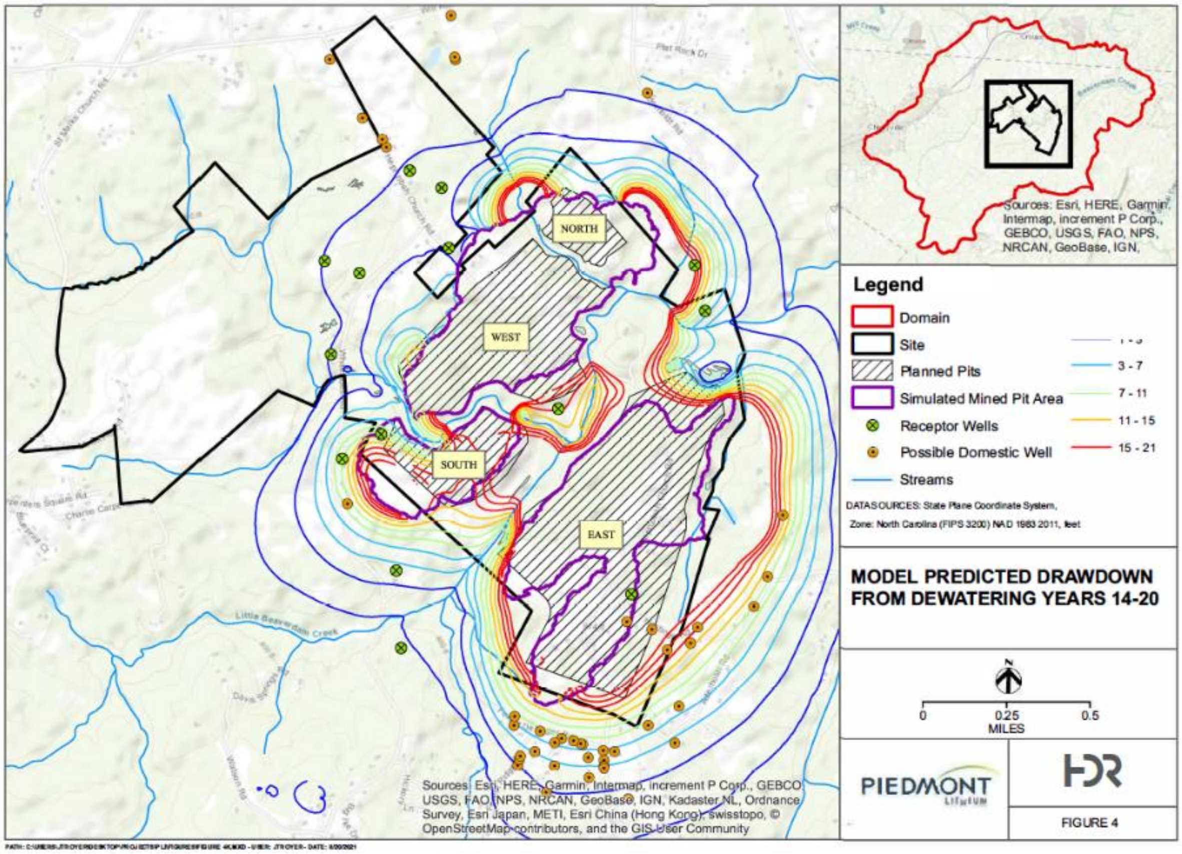

Figure 4 Model Predicted Drawdown at the End of the 20 Years of Simulated Dewatering

Table 4 Model Predicted Dewatering Withdrawal Rates

	Pumping Rate (gpm)				
Model Year	South Pit	East Pit	West Pit	North Pit	Total
1	525	50			575
2	975	1,225			2,300
3	725	775			1,500
4	25[1]	1,025			1,050
5	75[1]	950			1,025
6-10	N/A[2]	1,250			1,250
11	N/A[2]	1,575			1,575
12	N/A[2]	1,050	950		2,000
13	N/A[2]	0	500	850	1,350
14 – 20	N/A[2]	N/A[2]	1,075[3]		

[1] Pumping to maintain drawdown while filling pit with excavated material.

[2] Pit complete, no dewatering modelled.

[3] West and North Pits are merged.

The potential changes of discharge to wetlands and stream baseflow due to dewatering were assessed for each variation of the mine pit footprint and drain configuration by comparing water budgets for each wetland or stream reach with the base simulation (no mine pits or dewatering). Several wetlands were predicted to go dry during dewatering and baseflow to three streams crossing the site is expected to be significantly reduced. PLL plans to return groundwater collected during dewatering to stream locations downstream of the mine pit near the site boundaries to reduce downstream effects of dewatering. These processes were explicitly simulated in the model. Discharge to streams will comply with NPDES requirements. Some discharge water may be released to the most potentially impacted wetlands.

Subsurface conditions are varied and complex with fractured bedrock being simulated with a porous media model. Sensitivity analyses were not conducted due to the long run times associated with each model step but may have shown which parameters model results were sensitive to and are planned for the future. Identifying sensitive parameters may improve model performance and reduce run times as well as estimating potential variability in the modelled outcome.

Conclusion

Dewatering for the planned mine life at a multiple-pit lithium mine in the Carolina TSB, including the complexities of overlapping mine pit excavation schedules, was successfully modelled using a series of linked transient models based on a well-calibrated steady state model and storativity values from aquifer testing. Each phase model outcome was used as the starting point for the next step, which was modified to include the new pit geometry. Model results indicated that impactful drawdown would be limited to the areas near the pits as they are excavated. Withdrawal rates needed to dewater the pits ranged from 575 to 2,300 gpm. Discharge of pumped water through permitted NPDES outfalls to streams and wetlands was found to reduce impacts to baseflow conditions. Mitigation of impacts to wetlands may include discharging portions of the dewatering water directly to potentially wetlands during dry periods. Moving forward, this complex model will be used to site sentinel groundwater monitoring wells, size pumps necessary to dewater the pits, make decisions regarding the mine process water budget, and evaluate potential mitigation measures for affected surface water bodies and nearby private water supply wells. Additional aquifer testing is being conducted at a location within a planned mine pit to verify and update the model parameters used and inform needed adjustments to the current model and transient calibration.

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