MODELING THE GROUNDWATER FLOW SYSTEM AT THE PROPOSED TWIN PINES MINE ON TRAIL RIDGE

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Proposed Heavy Minerals Mine
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1.0 EXECUTIVE SUMMARY

Twin Pines Minerals, LLC (TPM) has submitted a permit application to the Georgia Environment Protection Division (GA EPD) for a surface mining permit to develop a heavy mineral sand mine along Trail Ridge in Charlton County, Georgia. The proposed mine is located 3.2 miles west of St. George, Georgia, on Georgia State Highway Route 94 as shown on Figures 1 and 2.

The objective of this report is to document the revised groundwater modeling efforts conducted to evaluate the impact of the proposed TPM mine on the Trail Ridge hydrologic system. The revised model addresses issues raised by GA EPD, which include (1) the addition of a continuous consolidated black sand unit within the model, and (2) the placement of a bentonite soil amendment layer in order to reconstitute the consolidated black sand unit post-mining.

This modeling report also assesses the impact of varying bentonite mixtures in a soil amendment layer within the reclaimed sands on the system hydrogeology. This was done by conducting a sensitivity analysis of the system to the hydraulic conductivity of the bentonite mixture. The model does not simulate the physical process of placing the bentonite-enhanced soil layer. The modeling suggests a 10.9% bentonite mixture in the amended sand layer provides the least amount of hydrogeologic impact at the mine site.

The results of modeling efforts presented in this report indicate that post-mining conditions will have no significant impact on water levels in and near the Okefenokee National Wildlife Refuge. Additionally, the existing Trail Ridge hydrologic divide separating the Okefenokee Swamp to west from the Saint Mary’s River to the east will be maintained.

2.0 BACKGROUND

The location of the proposed TPM mine is shown on Figure 1. The proposed mining area is approximately 582 acres and is located about 2.9 miles southeast of the Okefenokee National Wildlife Refuge (ONWR). The overall project study area consisted of approximately 12,000 acres that include five tracts identified as Loncala, Dallas Police & Fire, Keystone, TIAA, and Adirondack as shown on Figure 2. TPM no longer has access to the TIAA tract.

Heavy mineral sands will be excavated to a maximum depth of 50 feet in the surficial aquifer within the proposed mining area, with about 98% of the post-processed sand (sand tailings) returned to the mine pit. The depth of mining will not exceed the water surface elevation of the swamp. The dragline will move through the mining area excavating approximately 100-feet wide by 50-feet-deep cuts, in an east to west or west to east direction. Mining rates are anticipated to vary from approximately 100-200 feet of pit length excavation per day. As the pit advances into unmined areas, the inactive portion of the pit will be filled with sand tailings.

Within one to two weeks of the commencement of mining, sand tailings will be returned to the pit as mining continues to advance. Mine reclamation will include placement of a low-permeability layer (bentonite-sand mixture) approximately 3 feet thick, placed approximately 8-25 feet below the reclaimed land surface. The topography of the reclaimed mine spoils will be returned as close as possible to pre-mining elevations. The extraction of heavy minerals is estimated to be completed in about 4 years as shown on Figure 3.

TPM has conducted several studies related to this permit application including:

1. Field activities were conducted to characterize the local hydraulic properties of the surficial aquifer within the proposed study area documented by Holt et al., (2019a). Aquifer pumping tests and slug tests were conducted on wells within the study area to determine the areal and vertical distribution of hydraulic conductivity of the surficial aquifer materials.
2. The geology of the surficial aquifer within the proposed study area was characterized and documented by Holt et al., (2019b). The boring logs of wells within the proposed study area were evaluated to characterize the subsurface geology.
3. Water quality analyses of groundwater and surface water within the proposed study area documented by Holt et al., (2019c). Water samples were analyzed for pH, dissolved oxygen, specific conductance, Oxidation Reduction Potential and major constituents with groundwater protection standards. The analyses serve to provide background conditions for a pre-mining state of water quality at the site.
4. Local and regional climate data were evaluated and documented by Holt et al., (2019d). Precipitation and evapotranspiration were evaluated to estimate groundwater recharge to the surficial aquifer within the study area.
5. A hydrogeologic conceptual model was developed and documented by Holt et al., (2019e). Water level data from piezometers and observation wells, water level differences between shallow and deep piezometer pairs, and potentiometric surface maps were developed to understand subsurface hydrogeologic conditions.
6. Laboratory testing was conducted to evaluate hydrogeologic properties of the soil types as documented by Holt et al., (2019f). Measurements for the various subsurface units helped to quantify the hydraulic conductivity, and to understand contrast between the hydrogeological units and variability within each unit.
7. A geologic conceptual model was developed and documented by Holt et al., (2019g). The major subsurface lithologies of the surficial aquifer includes (with increasing depth) an unconsolidated and semi-consolidated sand unit; a consolidated black sand unit; a silty-clayey sand unit; and a sandy clay unit overlying the Hawthorn Group.
8. A groundwater flow model was developed and documented by Holt et al., (2020a). The groundwater flow model was the culmination of all the data collection and model conceptualization efforts, meant to evaluate the pre- and post-mining hydrogeologic conditions in the study area.
9. A United States Army Corps of Engineers individual permit application submitted by TPM summarizes the data assimilation, conceptual model development, and groundwater modeling efforts along with other required studies as documented by TTL (2020a).
10. Additional modeling conducted to evaluate the impact of adding soil amendments to the reclamation process as documented by Holt et al., (2020b). The groundwater modeling conducted by Holt et al., (2020a) did not include a layer of bentonite treated sand to maintain higher water levels beneath Trail Ridge and minimize impacts to the groundwater divide. Therefore, further analyses were conducted to note the impact on water levels and flows as suggested by the State Geologist Dr. James Kennedy, during an August 2020 meeting.

These documents have gone through several rounds of review and comments by Georgia Environmental Protection Division (GA EPD). The reviews and responses include:

1. A letter dated March 23, 2020, from GA EPD (Dr. James Kennedy) to Mr. Stephen C. Wiedl submitting comments to TTL's report "Impact of the Proposed Twin Pines Mine on the Trail Ridge Hydrologic System" (Kennedy 2020a).
2. A response by TTL on November 13, 2020, to GA EPD's comments of March 23, 2020. (TTL, 2020b).
3. Comments provided by GA EPD on November 25, 2020, to the TTL submittal of November 13, 2020 (Kennedy 2020b).
4. Response by TTL on January 25, 2021, to review comments from GA EPD of November 25, 2020 (TTL, 2021).
5. Comments provided to TTL on April 14, 2021, by GA EPD (Kennedy, 2021) as part of a Twin Pines Permit Coordination Document.

The back and forth of comments and responses led to resolution of several concerns; however, other issues remain as noted in the last set of comments provided by GA EPD on April 14, 2021 (Kennedy, 2021). The primary remaining concerns regarding the groundwater flow model were: (1) to justify and address recharge values used in the model that deviated from both local studies and a regional USGS evaluation of recharge in the area; (2) to provide a better structural representation of the consolidated black sand unit within the groundwater model; and (3) to constrain modeled parameter values to those observed from field studies and laboratory tests that have been conducted. To address these groundwater flow model related issues and concerns, a new numerical model was developed that is consistent with the consolidated black sand unit structural representation in the geologic conceptual site model, includes hydrogeologic properties consistent with field and laboratory measurements, implements wetland and surface drainage features indicated by the National Hydrograph Dataset (NHD, USGS, 2021), and simulates hydrogeologic conditions represented by the conceptual model. The study evaluates a range of potential recharge conditions at the site and further addresses impact of uncertainties in the data via a sensitivity analysis.

3.0 CONCEPTUAL SITE MODEL

The studies conducted by TPM related to site geology and hydrogeology were evaluated to develop a conceptual site model for the study area of interest. The modeling study area is indicated on Figure 2. Only the Surficial Aquifer is of concern for the current evaluations; therefore, the clays of the upper Hawthorn Group at the base of the Surficial Aquifer form the lower boundary of the study domain.

3.1 Hydrostratigraphic Units

The subsurface soil sediments that comprise the Surficial Aquifer include unconsolidated and semi-consolidated sand units that extend from land surface down to the Hawthorn Formation. A layer of consolidated black sands lies generally from 8 to 25 feet beneath the land surface. The unconsolidated sands are further interlayered unconformably with zones of semi-consolidated to consolidated sands, silty-clayey sands, and sandy clays. Aquifer tests conducted on deeper wells indicate that the hydraulic conductivity of the unconsolidated sands is lower, at elevations below 120 ft above mean sea level. The Hawthorn Group forms the base of the Surficial Aquifer.

The geologic conceptual model previously developed in Holt (2020a) did not include a continuous black sand layer and instead attempted to produce statistically similar geologic conditions for the Surficial Aquifer. This was noted by GA EPD who indicated that the environment of deposition for the aeolian sands would allow for horizontal continuity (Kennedy 2020a). The TTL (2020b) response was that the black sands are diagenetic and originate due to circulation of groundwaters through the sediments. The response further noted that indicator kriging suggested small horizontal correlation lengths for the consolidated black sand units. In response, GA EPD indicated that the paleo-groundwater condition would cause the black sands to be continuously distributed across the site (Kennedy, 2020b). In addition, GA EPD evaluated that the cross-sections developed in Holt et al, (2019g) showing on average, that the consolidated black sands cover approximately 69% of the study area. Table 1 reproduces the work of the State Geologist Dr. Kennedy, and a check of these estimates confirms the calculations. However, there was disagreement as to the continuity of the consolidated black sand unit expressed by TTL (2021). Finally, in response, GA EPD provided the following reasons as to why a layer of consolidated black sands should be considered (Kennedy, 2021) in the numerical model:

1. Because units in adjacent boreholes should be connected as per standard geological practice.
2. Because there is no evidence that consolidated black sand is not present between borings that do show its presence and therefore it should be included to be conservative.
3. Because the effective hydraulic conductivity in the model did not correspond to site conditions unless a consolidated black sand unit was included in the numerical model.
4. Because even if it is discontinuous, a layer of consolidated black sand should be incorporated to cover 69% of the study area as noted from Table 1 and the TTL cross-sections.
5. Because even with a discontinuous layer for the consolidated black sand, it should be continuous enough to affect the presence of the shallow water table along Trail Ridge.

The model has been revised accordingly. The stratigraphic units identified from soil borings, piezometers and wells were assimilated into a database for the current modeling effort. Figure 4 shows the locations where consolidated black sands were present in the log. There are distinct zones (demarcated visually on the figure) where consolidated black sands do exist in the logs and where they do not exist. There is also an area just to the west of Trail Ridge, which may be a transition zone. This is also a location of highest density of data. The consolidated black sands are present in 65 % of the borings and they cover approximately 77 % of the study area (Figure 4).

As shown by these findings and noted by GA EPD, a modified hydrogeologic conceptual model is considered with a continuous layer of consolidated black sands as shown on Figure 5. The hydrogeologic units (also called hydrostratigraphic units) within the study area are as follows:

- The uppermost hydrogeologic unit beneath the land surface consists of unconsolidated and semi-consolidated sands and is labeled hydrostratigraphic (HSU) unit 1. Figure 6 shows the land surface elevation, and Figure 7 shows the thickness of this hydrostratigraphic unit. This unit has a fairly high hydraulic conductivity value and is generally between 10 and 20 feet thick except along the lateral extents of the study area where it is thinner because the Hawthorn Group is closer to land surface with increasing distance from the crest of Trail Ridge.
- The consolidated black sands layer is considered as hydrostratigraphic unit 2 with a top elevation and thickness shown on Figure 8 and Figure 9, respectively. The layer elevation and thickness were evaluated from the shallowest occurrence of consolidated black sands noted in the boring logs, that are greater than 1 foot in thickness, which were then interpolated across the site. The consolidated black sands have a low value of hydraulic conductivity and act as an aquitard or barrier to flow between the surficial sands and the sand units below.

- The sands that lie beneath the consolidated black sands forms hydrostratigraphic unit 3 with a top elevation and thickness shown on Figure 10 and Figure 11, respectively. Hydrostratigraphic unit 3 is also denoted as the silty clayey sand unit.
- The lower permeability sands and sandy clay materials that overlie the Hawthorn Group form hydrostratigraphic unit 4 with a top elevation, thickness, and bottom elevation shown on Figure 12, Figure 13, and Figure 14, respectively. It is noted that hydrostratigraphic unit 4 is not a well-defined conforming unit but has been defined from the aquifer tests at deeper wells that indicate a lower hydraulic conductivity.

Layer elevations and thicknesses were evaluated and interpolated from the available boring log information. These elevations and thicknesses were used for layer discretization in the numerical model.

3.2 Hydrogeologic Properties

Hydraulic properties of the various hydrogeologic units were assimilated from field and laboratory information collected by Holt et al., (2019a, 2019b, 2019f, 2019g). Figures 15, 16, 17, and 18 show the hydraulic conductivity values in hydrostratigraphic units 1, 2, 3 and 4, respectively, as obtained from available tests. The horizontal hydraulic conductivity is of greater significance in units considered as aquifers since it governs the flow of water within the aquifer. The vertical hydraulic conductivity is of greater importance in aquitard units since it controls the flow across the aquitard unit.

The horizontal hydraulic conductivity value of hydrostratigraphic unit 1 (the unconsolidated / semi-consolidated sand unit) ranges from generally 30 to 50 feet/day with some lower horizontal hydraulic conductivity values of about 1 to 10 ft/day to the south of the study area. This unit acts as an aquifer considering its high hydraulic conductivity values.

Hydrostratigraphic unit 2 (the consolidated black sands) has a vertical hydraulic conductivity value ranging from 4.6×10^{-6} to 7.4×10^{-3} feet/day. Higher values previously reported from aquifer and/or slug tests may not be representative of the consolidated black sands alone, considering that the consolidated black sands are very tight geological materials. Therefore, only data with ranges of K shown in Figure 16 are considered as part of this study. Hydrostratigraphic unit 2 acts as an aquitard between units 1 and 3, considering its low hydraulic conductivity values. Laboratory values of hydraulic conductivity for the consolidated black sands were generally in the range of 0.003 feet/day to 4×10^{-5} feet/day (10^{-6} to 10^{-8} cm/second).

The horizontal hydraulic conductivity value for hydrostratigraphic unit 3 (the silty clayey sand unit) ranges from 20 to 54 feet/day along the ridge, with lower hydraulic conductivity values of about 1 to 10 ft/day off the ridge. This unit acts as an aquifer considering its high hydraulic conductivity values.

The horizontal hydraulic conductivity value for hydrostratigraphic unit 4 (the sandy clay unit) ranges from 1 to 10 feet/day. This unit acts as an aquifer even with its lower hydraulic conductivity values. The Hawthorn Group at the bottom of Surficial Aquifer has even lower hydraulic conductivity values and it acts as an aquitard separating the Surficial Aquifer from the underlying Floridan Aquifer units.

3.3 Groundwater Flow

Groundwater flow occurs within the study area due to recharge from precipitation. Water flows mainly from the centerline of Trail Ridge towards the west and the east, discharging into local streams and wetlands. Groundwater may also flow out of the west and east boundaries of the study area as there is no flow barrier at the study area boundary. Measured water levels were as high as 174 feet above mean sea level along the crest of Trail Ridge and drop to about 120 feet along the western boundary of the study area and about 80 feet along the eastern boundary of the study area, following the topography of Trail Ridge.

The hydrogeology of the flow system in the Shallow Aquifer at the site is typically understood as a "Toth Flow" problem (Toth, 1963), where topographically driven flow dominates. Essentially, as shown on Figure 5, groundwater flows along short flow-paths from recharge areas along Trail Ridge, to discharge areas in adjacent wetlands or surface drainage features with the shallow water table closely following ground surface. The consolidated black sands provide resistance to flow between hydrogeologic unit 1 and hydrogeologic unit 3 due to their low vertical hydraulic conductivity and affect the presence of the shallow water table along Trail Ridge.

Figure 19 shows the water level elevations in wells and piezometers within the study area averaged for 2019 conditions. The data were assimilated through the first 10 months of 2019 by Holt et al., (2019e). Depth to groundwater generally ranged from just below ground surface to five feet below ground surface; however, during periods of increased precipitation, water levels in some piezometers were above the top of well casing. Hydrographs plotted by Holt et al., (2019e) indicate that water level elevations generally declined from January through June 2019, followed by a sharp increase in July with subsequent decline from August through October. These water level changes follow rainfall periods.

Figure 20 shows the potentiometric surface map for July 26, 2019 (from Holt et al., 2019e). Groundwater elevations at the site generally mimic land surface topography with groundwater flowing to the west and east of Trail Ridge which forms a hydrologic divide within the underlying Surficial Aquifer. Thus, groundwater flow along the west side of Trail Ridge is to the west, and along the east side of Trail Ridge is to the east.

Figure 21 shows the average water level differences in shallow and deep piezometer pairs as evaluated by Holt et al., (2019e). Gradients are noted to be downward through most of the study area (negative values) indicating recharge from hydrogeologic unit 1 into hydrogeologic units 3 and 4 below. Upward gradients are noted in western and northern portions of the study area below the ridge, where the deeper sands of the Surficial Aquifer discharge to streams and wetlands. The water level differences are largest along Trail Ridge and are smaller to the west than to the east.

3.4 Recharge

Groundwater recharge occurs due to precipitation water that infiltrates into the soil after consideration of evaporation or runoff from the land surface. Groundwater recharge was evaluated by Holt et al., (2019d) to be about 3.5 inches/year by subtracting evapotranspiration estimates (39.5 inches/year) from local precipitation values (43 inches/year). The numerical groundwater flow model of Holt et al., (2020a) used an initial estimate of 4.5 inches/year, which was reduced to 2.8 inches/year during the calibration process. During review of the model, GA EPD performed their own investigation of recharge at the location of the proposed mine site. Using information from USGS (2008), and the source of that information from USGS (2003), Dr. James Kennedy estimated through personal communication with the author of the published dataset that recharge in the area of the proposed mine site was about 4.1 inches/year. Since this rate is more aligned with the initial estimates from Holt et al., (2019d), GA EPD (Kennedy, 2021) requested further information on the model that assigned a reduced rate of 2.8 inches/year.

Average groundwater recharge is a difficult parameter to estimate accurately and more so at a local scale the size of the study area. There can be spatial variability due to local hydrogeologic and topographic conditions as well as temporal variability considering long-term climatic conditions. Therefore, we further evaluated the data to estimate a reasonable recharge rate or range of possible recharge rates at the site.

A regional recharge estimate of about 4.13 inches/year was derived by Dr. Kennedy from the USGS (2003) data and approach. The approach is based on the consideration that long-term average recharge in a watershed is equal to the baseflow to streams within that watershed, absent any other sinks such as diversions or pumping. The estimated value of recharge was based on streamflow that occurred during the period 1951 – 1980 at the St. Mary's gage near Gross, Florida. The approach accounts for groundwater recharge after consideration of runoff, evaporation, or pumping. Since this value lies between the earlier site estimates, it seems to be a reasonable value of recharge to use in the model. A sensitivity analysis was conducted on the range of recharge values with the numerical model, to note the impact.

3.5 Discharge

Groundwater within the study area discharges to wetlands and stream channels. The stream channels are dry or may contain very little flow except during wet periods. Figure 22 shows the NHD delineation of wetlands and stream channels in the study area. Groundwater may also discharge laterally across the study area lateral boundaries as there are no hydraulic barriers located along the study area boundary.

4.0 NUMERICAL MODEL CONSTRUCTION

The conceptual model discussed above forms the basis for development of the numerical groundwater flow model. The model was used to assess the pre- and post-mining conditions within the study area.

The three-dimensional modular groundwater-flow model software MODFLOW-NWT (Niswonger et al., 2011), developed by the U.S. Geological Survey, was used for the simulations. The Groundwater Vistas, Version 8 (Rumbaugh and Rumbaugh, 2020), graphical user interface was used to interface with MODFLOW-NWT for pre-processing the data and constructing the model, for post-processing and evaluating results, and to create figures and maps. Construction of the numerical model required evaluating the objectives and the conceptual site model, establishing the time period of the simulation, and designing the spatial resolution necessary to perform the simulation. The site location is shown on Figure 1.

MODFLOW-NWT (Niswonger et al., 2011) was selected for this study because it has the capabilities required for the evaluation, is readily available as an open-source, public domain software, and has robust simulation routines to handle numerical difficulties associated with drying and rewetting of model areas, varying topography, or contrasting hydrogeologic properties.

MODFLOW-NWT solves for three-dimensional flow of water in the subsurface using the finite-difference approach. The finite-difference numerical method "discretizes" the modeled domain into model cells that are rectangular in map view but whose top and bottom elevations may vary vertically to conform to stratigraphic geometries. Each model cell represents a part of the domain that is encompassed by that model cell and model inputs and outputs are generated for this discretized system for each cell within the model domain. Groundwater flow simulations can be performed on this discretized domain using a steady-state or transient approach. In a steady-state approach, the groundwater flow equations are solved for long-term average conditions, while a transient approach solves for the groundwater flow at different times, as flow conditions and water levels change through time due to changing recharge or discharge conditions. Modeling objectives, and the behavior of the hydrogeologic system determine how a numerical groundwater model is discretized in space and whether steady-state or transient simulations are necessary.

4.1 Model Discretization

The model domain was discretized for the current study as shown on Figure 23. The study area was divided into 64 columns and 62 rows of cells. The grid block size is a uniform 500 feet in the x- and y- coordinate directions and the proposed mine area contains 100 model cells in the aerial direction (Figure 23). The grid block thickness is variable, to enable the grid to conform to hydrogeologic units and to post-mining backfill conditions.

The stratigraphic layer elevations and thicknesses of the numerical model honor the hydrogeologic conceptual model depicted on Figures 6 through 14, though additional numerical layers have been added so as to allow post-mining conditions to be accurately represented – mining is anticipated to occur up to different depths from stratigraphic contacts between the hydrogeologic units and therefore additional numerical layers were included in the model to accommodate those post-mining conditions. Figure 24 shows the model layering in relation to the hydrostratigraphic layers. If a hydrostratigraphic layer is divided into more than one numerical layer, the sub-discretization is performed with equal thickness allocated to the numerical layers that represent a hydrostratigraphic layer, except where it is specifically allocated to represent the bottom of post-mining back-fill materials. Figure 25 shows N-S and E-W cross-sections of the numerical model grid (cross-section locations are also depicted on Figure 23).

The numerical model was run using a steady-state approach. Though fluctuations were noted in the water level hydrographs, they were seasonal and did not exhibit long-term trends. GA EPD has further examined the State Water Plan model which showed little change in hydraulic heads between high and low recharge periods and noted that steady-state simulation conditions could be used to evaluate conditions at the mine (Kennedy, 2020b).

4.2 Model Parametrization

The numerical model cells are all assigned with initial horizontal and vertical hydraulic conductivity values for the associated hydrogeologic units. Figures 15 through 18 show initial estimates of hydraulic conductivity at wellbore locations from various aquifer and laboratory tests, which were then interpolated across the site to provide values for the entire domain. The anisotropy (horizontal to vertical hydraulic conductivity ratio) of the units was taken as 1:1 for the consolidated black sands and 10:1 for the other hydrogeologic units. Layers containing the consolidated black sand were zoned into regions where the consolidated black sands did and did not exist, and a transition zone as depicted on Figure 4. Initial hydraulic conductivity values in the transition zone were in between those of the unconsolidated sand and the consolidated black sand. The initial hydraulic conductivity distributions were then changed during the model calibration process.

4.3 Model Boundary Conditions

Model boundary conditions applied on the top surface of the model included recharge of precipitation and discharge to stream channels and wetlands within the model domain. Model boundary conditions also include prescribed water levels along the east and west lateral boundaries in all layers of the model to allow water to migrate out of the domain laterally. Since the groundwater flow system is mainly in the east-west direction with Trail Ridge acting as a hydrogeologic divide, there is no flow occurring across the north and south boundaries of the model domain or through the Hawthorn Group at the bottom. The boundary conditions on the top model layer are noted on Figure 23.

Recharge was applied uniformly to the land surface at a rate of 4.13 inches/year, which is based upon estimates for the proposed mine area calculated by the USGS (2003). The conceptual model evaluations above, noted that estimates can range from 3.5 to 4.5 inches/year (Holt, 2019d and Holt 2020a). A sensitivity analysis was conducted to note the impact of recharge uncertainty on model results.

The bottom boundary was considered a no-flow boundary because the Hawthorn Formation at the base of the Surficial Aquifer has very low permeability and flow through it is negligible in comparison to flow conditions in the Surficial Aquifer.

Wetlands are discharge areas for groundwater. Stream channels in the area may recharge groundwater during periods of rainfall events but are otherwise locations of groundwater discharge. The drain boundary in MODFLOW-NWT was used to represent wetlands and streams. The drain boundary allows water to flow out of the groundwater system when water levels are at or above a prescribed “drain” elevation – no flow occurs when groundwater levels are below the “drain” elevation. Thus, for MODFLOW models, drains can receive water from the modeled aquifer but cannot simulate losses from surface water features to the aquifer. A river boundary condition in MODFLOW can receive water from the modeled aquifer as well as discharge water to the modeled aquifer. Drains were used to simulate the surface water features shown in Figures 22 and 23 and no rivers were represented since there are no rivers within the model domain. The streambed elevation or the elevation of the wetland were assigned as the “drain” elevations. The drain boundary includes a conductance term to represent sediments at the bottom of the streams, wetlands, or lining of the streambed. A high conductance value (10^7 ft^2/d) was used for the drains to allow water to freely drain without resistance from near surface depositions or alterations

Prescribed water level conditions (prescribed head conditions of MODFLOW-NWT) were provided along the east and west lateral model boundaries in all model layers. The prescribed water level elevation was set to land surface at the location of wetlands, and to 1 foot below land surface where there were no wetlands along the boundary. The prescribed water level conditions were not provided in layer 1 at locations also coincident with drain boundary conditions. The northern and southern lateral boundaries were no-flow conditions because they are parallel to the direction of groundwater flow with minimal flow across them.

5.0 MODEL CALIBRATION

The numerical model was constructed using Groundwater Vistas Version 8 (Rumbaugh and Rumbaugh, 2020). Model files were then generated for MODFLOW-NWT, which runs the model and creates output files that were then imported into Groundwater Vistas for further analysis. A model developed with preliminary estimates of the hydrogeologic properties usually does not match site conditions very well and requires “calibration”, which is done by adjusting the model parameters to obtain a best fit between the model calculations and the field data. Model calibration was performed using expert hydrogeological judgement aided with automatic calibration tools provided by the computer software PEST (Doherty, 2010). Consistency with the conceptual model was also evaluated and adjustments were made to modeled hydraulic conductivity values within reasonable ranges for each of the hydrogeologic units, until the model was considered calibrated.

All available field data were used for model calibration and include average water level measurements of Figure 19 and water level differences between piezometer pairs noted on Figure 21. The water level contour maps of Figure 20 were also evaluated visually during calibration. Finally, in areas outside of wetland or stream channels, the calibration was constrained to try and keep water levels below land surface.

Model calibration was evaluated quantitively as well as qualitatively. Quantitative calibration metrics include evaluating that the basic statistics of the goodness of fit between modeled water levels and measured water levels of Figure 19 are within acceptable professional standards. The errors were also displayed on a map to note if there was any spatial bias in the calibration (i.e., if there were regions that consistently overpredict or underpredict water levels). Water level differences of Figure 21 were considered during calibration but were not evaluated further. Qualitative metrics include visual comparison of simulated water level contours against estimates of Figure 20. Modeled depth to water and standing water above land surface in locations where stream channels or wetlands do not exist were also evaluated to note consistency of the model with conditions at the site; this was done by plotting the difference between the top elevation of model layer 1 and the water level in model layer 1, where negative values represent ponded water depth and positive values represent depth to water.

The hydraulic conductivity values of the hydrostratigraphic units were varied to calibrate the model. Estimates derived from aquifer tests and laboratory studies shown on Figures 15 through 18 were assigned as initial values within each respective hydrostratigraphic unit and hydraulic conductivity values were then adjusted by the automatic calibration software PEST on a set of interpolation points termed “pilot points”. The hydraulic conductivity field was constrained to stay within reasonable limits of measured conditions. The results of a PEST automated parameter estimation simulation were evaluated for the quantitative and qualitative calibration metrics discussed in the previous paragraph. Each parameter estimation simulation was also evaluated to note that hydraulic conductivity values for the various hydrogeologic units were reasonable and that the conceptual model was represented appropriately by the numerical model. Calibration proceeded in this manner until satisfactory results were obtained for the calibration metrics, hydrogeologic property values, and conceptual flow conditions.

6.0 MODEL CALIBRATION RESULTS FOR PRE-MINING CONDITIONS

The Trail Ridge hydrologic system model was developed for steady-state conditions and calibrated as discussed above. The model represents pre-mining conditions of groundwater flow and its interaction with surface-water features in the study area.

Figures 26, 27, 28 and 29 show the calibrated horizontal hydraulic conductivity distribution of the four hydrogeologic units in the model. The values are within the range of observed conditions for the various hydrogeologic layers. Specifically, it is noted that the consolidated black sands layer hydraulic conductivities range from 0.0028 feet/day 4 x 10^{-5} feet/day (10^{-6} to 10^{-8} cm/second) as was obtained in laboratory and field tests. The other hydrogeologic units also had calibrated hydraulic conductivity values within similar ranges to their field or laboratory estimated values.

Figure 30 shows the fit between modeled water levels and measured water levels and Table 2 shows the model calibration statistics. The match between simulated and observed water levels is noted to be good for the range of water levels at the site. The mean of the residual error was small 3.23 ft compared to the range of observed heads (over 60 ft), and the normalized root mean squared error was 5.1 %.

Figure 31 shows the simulated water level contours. The simulated water levels reflect the topography of Trail Ridge and show the influence of stream channels. The simulated water levels also resemble the potentiometric surface map for July 2019, depicted in Figure 20.

Figure 32 shows the modeled depth to water, which is 1-5 feet below land surface within most of the study area. There are a few small areas off from the ridge where the model simulated water levels above ground surface (simulated ponding). It is likely that since these ponded areas are adjacent to either streams or wetlands (Figure 22 and 32), they may also be seepage locations not identified on the NHD dataset.

Considering all the above metrics, the pre-mine model is determined to be well calibrated to long-term steady-state conditions at the site.

The water budget for the pre-mining simulation is shown on Table 3. 52% of groundwater recharge is noted to flow into streams and wetlands on the west of Trail Ridge while 42% flows into wetlands and streams on the east side of the ridge. Figure 33 provides a map of the areas east and west of Trail Ridge for water budget evaluations.

7.0 POST-MINING ANALYSIS

For post-mining conditions, the mined volume will be backfilled with homogenized reclaimed sand. The geometry of the mine pit and mine advancement conditions are shown on Figure 3. The sands will be mined to a maximum depth of 50 feet below ground surface. Mine reclamation will include a layer of bentonite treated sand approximately 3 feet thick, where the top of the bentonite treated sand will be placed as close as possible to top of the consolidated black sands of pre-mining conditions. The model does not simulate the physical process of placing the bentonite-enhanced soil layer. The topography of the reclaimed mine spoils will be returned as close to pre-mining elevations as possible. The additional numerical layers included in the model were intended to account for the natural occurring transitions between hydrostratigraphic units, the demarcation between unmined and mined volumes, and to explicitly account for the placement of 3 feet of bentonite treated sand. Figure 34 shows a cross-section of the model through the mine pit indicating the various mined and unmined layers.

The hydraulic conductivity of reclaimed sands was evaluated to be approximately 2.8 feet/day (1 x 10^{-3} cm/s) from experiments conducted on homogenized sands from the area (Holt et al., 2019f). Experiments were also conducted on evaluating the hydraulic conductivity of a sand mixture with different percentages of bentonite. Holt et al., (2020b) further fit a regression equation to the hydraulic conductivity as a function of the percent of bentonite in the mixture, reproduced here as:

$\mathrm{Log}\ (K_{sb}) = (-0.3567\ pB - 3.108)$

Where K_{sb} is the hydraulic conductivity of the sand-bentonite mixture in units of cm/sec, and pB is the percent of bentonite added to the sand. This equation indicates a hydraulic conductivity value for sand of 7.8 x 10^{-4} cm/sec (2.2 feet/day), with no bentonite present. This is in line with the 1 x 10^{-3} cm/s (2.8 feet/day) value estimated by Holt et al., (2019f) for homogenized sands. Hydraulic conductivity of the sand-bentonite mixture is 1 x 10^{-4} cm/s (0.28 feet/day) with 2.5% bentonite; 1 x 10^{-5} cm/s (0.028 feet/day) with 5.3% bentonite; 1 x 10^{-6} cm/s (2.8 x 10^{-3} feet/day) with 8.1% bentonite; and 1 x 10^{-7} cm/s (2.8 x 10^{-4} feet/day) with 10.9 % bentonite (Holt et al., 2020b).

The groundwater model for post-mining conditions was developed using the calibrated model for pre-mining conditions. The mined volume was replaced by homogenized reclaimed sand spoils with a hydraulic conductivity value of 1 x 10^{-3} cm/s (2.8 feet/day) and included a layer of bentonite treated sand approximately 3 feet thick and 8 to 25 feet below the reclaimed land surface. The reclaimed homogenized sand spoils and bentonite treated sands were only simulated within the proposed mining area as shown on Figure 3 (and select subsequent report figures).

Four different values of hydraulic conductivity for bentonite treated sand layer were evaluated to assess the impact of varying amounts of bentonite in the amended soil layer mix. These include:

- 1 x 10^{-3} cm/sec (2.8 feet/day) representing no bentonite;
- 1 x 10^{-5} cm/s (0.028 feet/day) representing a 5.3% bentonite mix;
- 1 x 10^{-7} cm/s (2.8 x 10^{-4} feet/day) assuming a 10.9% bentonite mix; and
- 2.7 x 10^{-8} cm/s (7.7x 10^{-5} feet/day) representing 12.5% bentonite in the mix.

These analyses help to assess the changes in hydrogeologic conditions due to different bentonite mixtures in the amended sand/bentonite layer and are useful to provide input to the bentonite mixture percentages that would be most beneficial in reducing post-mining hydrogeologic impacts.

Figures 35, 36, 37, and 38 show the simulated water level contours for post-mining conditions with 0%, 5.3%, 10.9% and 12.5% bentonite mixture respectively in the 3-feet thick treated sand layer. The water levels are generally similar to pre-mining conditions for all cases of bentonite mix, except in the immediate vicinity of the mine. The groundwater divide is similarly maintained to the pre-mining simulation (Figure 31) across all scenarios and simulations though water levels are generally noted to be higher within the mined area, with increasing bentonite content of the amended sands.

Figures 39, 40, 41, and 42 show the difference in simulated water level contours between pre-mining and post-mining conditions with 0%, 5.3%, 10.9% and 12.5% bentonite mixture, respectively, in the 3-feet thick treated sand layer. Both the 0% and 5.3% bentonite amended soil scenarios exhibit similar results where water levels are generally maintained through much of the proposed mine footprint but decrease by as much as 6 feet relative to pre-mining conditions on the northeast side of the proposed mine area.

The 10.9% bentonite mixture results in a 2-5 feet rise in groundwater elevation within the mine footprint. Along and adjacent to the mine boundary, declines in water level elevations following mining are generally less than 1 foot with one model cell showing a decline of approximately 2 feet.

The high bentonite mixture scenario (12.5%) causes as much as 9 feet of water level rise within the mine footprint, which results in simulated groundwater elevations greater than 5 feet above ground surface. This scenario also shows declines adjacent to the mine boundary that are consistent in magnitude with the 10.9% bentonite soil amendment scenario but spread over a slightly increased area.

For all scenarios, water level changes were negligible in and near the Okefenokee National Wildlife Refuge.

The water level rise for post-mining conditions increases with increase in percent of bentonite in the amended sands because it increasingly acts as a barrier to downward flow thus affecting the shallow water table along the ridge. Water levels are noted to decline just outside of the mine footprint, with those declines being largest under the no bentonite scenario. The modeled water levels did not change near the eastern or western model boundaries. The water level changes for post-mining conditions are influenced by the groundwater flow system adjusting to homogeneous sand spoils and the amended sand layer replacing the original hydrogeology within the mined area.

Table 4 shows the water budget components for pre- and post-mining conditions. It is noted that discharge to the wetlands changes minimally across all scenarios.

In conclusion, it is noted that for post-mining conditions, bentonite amended soils perform best to approximate pre-mining conditions at around 10.9% for both water levels and groundwater discharge to streams and wetlands.

8.0 SENSITIVITY ANALYSIS

A sensitivity analysis was conducted on the calibrated model to determine the impact of parameter changes to the calibration results as well as to the post-mining predictions. For these sensitivities, the parameter values were raised and lowered by prescribed factors and the change in model calibration errors was evaluated for each case. These parameters were then categorized into high, medium, and low sensitivity groups based on the change in calibration statistics resulting from the change in the parameter value. For each parameter, the resulting post-mining predictions are also evaluated and categorized into high, medium, and low sensitivity groups. The parameters are then categorized into “sensitivity types” as defined by ASTM International (formerly the American Society for Testing and Materials) (ASTM, 1994, 2000) for uncertainty evaluations of the post-mining predictions. The sensitivity types categorize how parameters change the model calibration versus the model predictions and are as follows:

- Type I sensitivity is defined for parameters that cause insignificant changes to the calibration residuals as well as to model conclusions/predictions of interest. Type I sensitivity is of no concern because regardless of the value of the input, the prediction is also insensitive.
- Type II sensitivity is defined for parameters that cause significant changes to the calibration residuals but insignificant changes to model conclusions/predictions of interest. Type II sensitivity is of no concern because the prediction is not sensitive to the calibration.
- Type III sensitivity is defined for parameters that cause significant changes to the calibration residuals as well as to the model conclusions/predictions. Type III sensitivity is of no concern because even though the model’s predictions change as a result of variation of the input variable value, the calibration residuals are also sensitive, and the model becomes uncalibrated as a result. Thus, model calibration ensures that the predictions considered are appropriate for the modeled system.
- Type IV sensitivity is defined for parameters that cause insignificant changes to model calibration residuals but significant changes to the model predictions. Type IV sensitivity is of concern because, over the range of that parameter in which the model can be considered calibrated, the conclusions or predictions of the model can change.

The parameters that were evaluated for the sensitivity study include the recharge rate, the hydraulic conductivity of the consolidated black sand hydrogeologic unit, and the hydraulic conductivity value for the unconsolidated and semi-consolidated sand layers.

8.1 Sensitivity to Recharge Rate

The first set of sensitivity simulations was conducted on the recharge rate applied to the steady-state models. For this sensitivity analysis, the recharge rate was varied within the estimated range of recharge values noted from various studies in the area. Two model runs were performed, one with the recharge rate raised to 4.5 inches/year, and the other with the recharge rate lowered to 3.5 inches/year (the calibrated model had a recharge rate of 4.13 inches/year). The mean residual and root-mean-square (RMS) error for this sensitivity are noted on Figure 43. It is noted that the calibration (pre-mining) water level errors are generally not sensitive to the recharge rates and therefore, the water levels would be similar if a different value were assigned to the model. Increasing the recharge raises average water levels slightly while decreasing recharge creates a greater relative decline in simulated water levels although, overall, this decline remains small. Therefore, given the minimal difference in changes in simulated head values across the simulations, sensitivity of the model calibration to recharge is low.

Table 5 shows the water budget components for the sensitivity analysis. It is noted that even though recharge rates vary between the simulations, the percent of discharge to the different boundaries was not significantly affected. Thus, sensitivity of the model predictions (discharge percentages and pre- versus post-mining water level changes) to recharge is low.

Considering a low sensitivity to calibration and low sensitivity to the predictions, recharge may be categorized as a Type I sensitivity. This sensitivity is not of concern because a change in the parameter value does not cause a significant change in the calibrated model or the results.

8.2 Sensitivity to Hydraulic Conductivity of Consolidated Black Sand Layers

The next set of sensitivity simulations was conducted on the hydraulic conductivity of the consolidated black sand numerical layers. For this sensitivity analysis, the hydraulic conductivity of the consolidated black sand hydrogeologic unit was varied up and down by a factor of 5. The mean residual and RMS error for this sensitivity are noted on Figure 44. It is noted that the calibration (pre-mining) water level errors are minimally sensitive to the hydraulic conductivity of the consolidated black sand and therefore, simulated water levels would be similar over this range of tested K values. Decreasing the hydraulic conductivity of the consolidated black sand results in a slightly higher simulated water level on average, which leads to a slight increase in the RMS error. Increasing the hydraulic conductivity of the consolidated black sands has a lesser relative effect on the RMS error and the change in residual mean is still quite small. Thus, sensitivity of the model calibration to hydraulic conductivity of the consolidated black sands layer is low within a factor of 5.

Table 6 shows the water budget components for the sensitivity analysis. It is noted that the percent of discharge to the different boundaries was not significantly affected. Thus, sensitivity of the model predictions (discharge percentages and pre- versus post-mining water level changes) to hydraulic conductivity value of the consolidated black sands hydrogeologic layer is low.

Considering a low sensitivity to calibration and low sensitivity to the predictions, hydraulic conductivity values of the consolidated black sands may be categorized as a Type I sensitivity. This sensitivity is not of concern because a change in the parameter value, within the range evaluated, does not cause a change in the calibrated model or the results.

8.3 Sensitivity to Hydraulic Conductivity of Unconsolidated and Semi-Consolidated Sand and the Silty Clayey Sand

The next set of sensitivity simulations was conducted on the hydraulic conductivity of the unconsolidated sand layers (hydrogeologic units 1 and 3). For this sensitivity analysis, the hydraulic conductivity of hydrogeologic units 1 and 3 was varied up and down by a factor of 5. The mean residual and RMS error for this sensitivity are noted on Figure 45. It is noted that the calibration (pre-mining) water level errors are sensitive to the hydraulic conductivity of the sandy units and therefore, the water levels would change if values were used outside of the range used in the calibrated model and/or observed data. Decreasing the hydraulic conductivity of the unconsolidated sand results in high simulated groundwater elevations while increasing hydraulic conductivity causes a substantial decline in the water level elevations as noted by the residuals. Thus, sensitivity of the model calibration to the hydraulic conductivity of the unconsolidated and semi-consolidated sand and the silty clayey sand layer is high.

Table 7 shows the water budget components for the sensitivity analysis. It is noted that the percent of discharge to the different boundaries was affected by lowering or raising the hydraulic conductivity of the sands. Thus, sensitivity of the model predictions (discharge percentages and pre- versus post-mining water level changes) to hydraulic conductivity value of the unconsolidated sands hydrogeologic layers is relatively high. However, it is noted that the discharge percentages for post-mining conditions are similar to those of the respective pre-mining condition indicating that there may be some uncertainty in the discharge depending on uncertainty in the parameter value. However, it is also noted that pre- and post-mining conditions are similar for each sensitivity indicating that mining does not change those percentages.

Considering a high sensitivity to calibration and high sensitivity to the predictions, the hydraulic conductivity value of the unconsolidated sands may be categorized as a Type III sensitivity. This sensitivity is not of concern because although the model's predictions would change as a result of variation of the input variable value, the calibration residuals are also sensitive, and the model becomes more uncalibrated as a result and model calibration ensures that the predictions considered are appropriate for the modeled system. Furthermore, as indicated in Table 7, pre- and post-mining discharges are similar no matter the sensitivity being evaluated.

8.4 Summary of Sensitivity Simulations

Table 8 shows the sensitivity simulations categorized as per the ASTM (1994, 2000) approach. It is noted that recharge and hydraulic conductivity of the consolidated black sands have a Type I sensitivity, while hydraulic conductivity of the unconsolidated and semi consolidated sand units (hydrogeologic units 1 and 3) have a Type III sensitivity. These types of sensitivities indicate that the variations or uncertainties in the parameter values are not of concern to the results of the model within the ranges tested.

9.0 SUMMARY AND CONCLUSIONS

This report documents the numerical groundwater flow modeling effort conducted to evaluate the impact of the proposed mine on the hydrogeologic system of Trail Ridge and surrounding areas including the Okefenokee National Wildlife Refuge. Available hydrologic, hydrogeologic and climate data were assimilated and evaluated to develop a conceptual model of the flow system. A numerical model was then developed based on the conceptual model and calibrated to available data for steady-state, pre-mining conditions. The model was then used to evaluate post-mining conditions and how the hydrogeologic system may have changed as a result of mining. The model also assessed the impact of different bentonite mixtures in a soil amendment layer within the reclaimed sands, on the system hydrogeology. This was done by conducting a sensitivity analyses of the system to the hydraulic conductivity of the bentonite mixture. A 10.9% bentonite mixture in the amended sand layer provides the least amount of hydrogeologic impact around the mine site.

Sensitivity analyses were also conducted on key inputs to the model including recharge rate, hydraulic conductivity of the consolidated black sand, and hydraulic conductivity of the unconsolidated and semi-consolidated sands. The recharge rate was changed from 4.13 inches/year to 3.5 inches/year and to 4.5 inches per year, which is the general range of estimated average recharge conditions in the vicinity of the proposed mine. The hydraulic conductivity values were varied by a factor of 5 to estimate a bound for its range of uncertainty. These sensitivity analyses indicate that the results are reliable. The water budgets for pre- and post-mining conditions are similar for the different sensitivity analyses indicating that mining does not impact these water budget values for the various sensitivity cases.

In conclusion, the current model has been completed to address the concerns of the GA EPD and results indicate that mining activities will have no significant impact on water levels in and near the Okefenokee National Wildlife Refuge. Additionally, the existing Trail Ridge hydrologic divide separating the Okefenokee Swamp to west from the Saint Mary’s River to the east will always be maintained.

10.0 REFERENCES

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