Prepared for

RI23-00453
Black Mountain Mining (Pty) Ltd
1 Penge Road
Aggeneys, Northern Cape
South Africa, 8893

Prepared by
Knight Piésold (Pty) Ltd.
1 Discovery Place, The Ridge,
Sandhurst, Sandton, Johannesburg
Gauteng, South Africa,2196
T +27 11 806 7111
F +27 11 806 7100
And sandton@knightpiesold.com
www.knightpiesold.com
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GAMSBERG ZINC MINE
NUMERICAL GROUNDWATER MODEL

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Knight Piésold CONSULTING

EXECUTIVE SUMMARY

BMM has appointed Knight Piésold (Pty) Ltd (KP) to develop a Contaminant Transport Model (CTM) as part of the hydrogeological study, for the expansion of the Gamsberg TSF (Phase 2). The numerical model and contaminant transport model was developed in 2023.

The available hydrochemical data from Gamsberg Zinc Mine, shows that the boreholes located north west of the current TSF show elevated concentrations of total dissolved salts (indicated by elevated electrical conductivity or EC), particularly SO_4, Na, and Cl. The geophysical study conducted by KP around the current TSF suggests that the old haul road during construction, may have compromised the liner system. The old road and borrow pits located in the north west during the TSF construction have likely created a preferential flow path for leakage from the TSF to flow.

The current TSF at Gamsberg has been lined with a High-Density Polyethylene (HDPE) geomembrane with a 300 mm thick soil layer modified with 6% bentonite (mineral liner) liner system. BMM intends to extend the TSF to the north, and the Phase 2 TSF will be designed the same with a HDPE geomembrane liner system.

A geochemical model was developed by Millswater, to predict the long-term evolution of any TSF seepage quality and reactions with the groundwater. The model outcomes showed a best case and a worst-case scenario for the TSF seepage. The results from both predicted scenarios were incorporated into the numerical contaminant transport model.

The conceptual hydrogeological model was developed to illustrate the current groundwater conditions around the TSF and the expected groundwater conditions due to the Phase 2 TSF expansion. The current drawdown cone of the pit sumps does not impact the TSF area, it has remained highly localised around the pits. The hydraulic gradient is towards the south for this area and is the expected direction for any potential plume to migrate.

Seepage from the current TSF has migrated to the northwest but is localised (>200m). The Phase 2 TSF extension will be developed further north of the current TSF and will overlie the current plume emanating from TSF1. The mass solute plume formed by the integrated TSFs for the future operational phase is likely to seep towards the south.

A numerical groundwater model of the current TSF at Gamsberg Zinc Mine was constructed to evaluate the potential impacts on the groundwater system and potential receptors surrounding the TSF. The 3-D numerical flow and contaminant transport model was developed using the programme FEFLOW, to determine the possible extent of migration of the contaminant plume for the current and Phase 2 TSF extension at Gamsberg Zinc Mine.

Two scenarios were included in the contaminant transport model:

- The first scenario is representative of the future Phase 2 TSF operational period at Gamsberg Zinc Mine
- The second scenario includes the post operational period at Gamsberg Zinc Mine

To calibrate the model, input data was obtained from various studies, reports (monitoring, geochemical, geotechnical, and hydrological) for the Gamsberg Zinc Mine. The steady-state flow calibration was conducted by making minor changes to the model input parameters, mainly the permeability and recharge as well as the storage coefficients to simulate the current groundwater flow conditions.

The first transient simulation included a 13-year period that represents that expected life of design for the Phase 2 TSF extension at Gamsberg Zinc Mine. The inputs have remained the same as the steady state calibration input, with additional source concentrations applied to the new TSF extension footprint.

The second transient simulation includes a 30-year period that represents the post operational period at Gamsberg Zinc Mine. For this scenario, the TSF at Gamsberg Zinc Mine is no longer in operation, with no new deposition occurring. The model inputs that have changed for this scenario, include lower source concentrations assigned to the TSF facilities as well as removal of the increased recharge component on the TSF (flux).

The modelled simulations (Scenario 1 and 2) show migratory paths of the potential plume from the TSF sources towards the north and north west, as well as towards the south east.

Overall, the spatial extent of the modelled plumes (Sulphate and Zinc) remains within a 250 m radius of the TSF, for both the current TSF and Phase 2 extension. The vertical extent of the plume for the TSF could reach a depth of 65 mbgl, indicating the potential to locally impact the shallow and deep aquifers in the TSF area. The current simulations show that the risk of the potential contaminant plume from the TSF impacting any groundwater users is low.

Following the development of the numerical model at Gamsberg Zinc Mine, KP recommends the following:

- The current borehole monitoring network infrastructure must be maintained at the Gamsberg Zinc Mine, particularly the boreholes surrounding the TSF to identify any increasing trends. Particularly north west of the current TSF.
- Continue the quarterly groundwater monitoring at Gamsberg Zinc Mine, this will ensure that any leak and/or contamination will be detected, and the correct mitigation measure can be implemented effectively.
- The numerical flow and transport model should be updated annually with the new monitoring data as a management tool so that any mitigation that may be required can be modelled and planned timeously.
- Several of the boreholes could be used as potential scavenger boreholes to act as seepage capture for the future operations if required. Particularly the boreholes located south and south east of the TSF (GBTSF 8 and 9).
- Following the construction of the Phase 2 TSF extension, it is recommended that monitoring boreholes are installed north of TSF to ensure that any leak and/or contamination is detected. Four proposed locations are identified in positions further north of the Phase 2 TSF extension (GBTSF 10-13).

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APPENDICES

Appendix A
Gamsberg TSF Waste Assessment
Appendix B
Geochemical Model for Gamsberg TSF Extension

ABBREVIATIONS

BMM – Black Mountain Mining
ARD - Acid Rock Drainage
ABA – Acid Base Accounting
DFO - Fisheries and Oceans Canada
EIS - Environmental Impact Statement
EPC - Engineering, Procurement and Construction management
TSF - Tailings Storage Facility
KP – Knight Piesold
Mbs – metres below surface
Mbgl – metres below ground level
MAMSL – metres above mean sea level
N - North
E - East
S – South
W- West
TDS- Total Dissolved solids
EC- Electrical Conductivity
SO_4 – Sulphate
Zn – Zinc
Cl – Chloride

1. INTRODUCTION

Black Mountain Mining (Pty) Ltd (BMM), which is a subsidiary of Vedanta Zinc International, owns and operates Gamsberg Zinc Mine (Gamsberg). Gamsberg is located approximately 30 km from BBM in the Northern Cape province of South Africa. Zinc deposits in Gamsberg were discovered in 1971 and Gamsberg Zinc Mine has been owned by Vedanta since 2011, to form part of the Black Mountain Mining Complex. The mine has open pit operations and currently produces 400,000 tonnes of ore per month with a planned expansion to double production. This will necessitate an expansion of the tailings storage facility (TSF).

BMM has appointed Knight Piésold (Pty) Ltd (KP) to develop a Contaminant Transport Model (CTM) as part of the hydrogeological study, for the expansion of the Gamsberg TSF (Phase 2). Previous studies conducted by KP (Van Dyk & Duthe, 2022), on the Gamsberg lined TSF, indicate seepage along the northwest boundary of the TSF. The Gamsberg TSF Phase 2 extension will be developed over the current seepage plume from the existing TSF to the north. The Phase 2 TSF will be constructed similar to the current TSF and will be lined. The CTM developed will indicate the maximum extent of the contamination plume from the current lined TSF and the proposed Phase 2 extension. The mine site layout and Phase 2 TSF expansion is shown in Figure 1-1 below.

This report covers the Contaminant Transport Model of the current lined cyclone TSF at the Gamsberg Mine and includes the lined TSF Phase 2 expansion.

1.1 BACKGROUND

Gamsberg Mine is located in the lower Orange River water management area and falls within the D28C quaternary catchment in an arid climate with mean annual rainfall < 100 mm/year (Huisamen & du Toit, 2017).

The ore body at Gamsberg has been split into 3 ore types namely, a pyrite rich ore (py), a pyrrhotite rich ore (Po) and magnetite rich (Mo). The three different ores are mined simultaneously resulting in a blend of tailings processed during the mining operations and deposited in the TSF.

Since the construction of the Gamsberg TSF in 2017, several boreholes have been drilled upgradient and downgradient of the TSF for monitoring purposes. A quarterly groundwater monitoring program has been implemented by Geo-Hydro Technologies (GHT) consultants. The current monitoring results indicate that seepage from the Gamsberg TSF is migrating towards the north-western boundary based on an increase in water levels that has been observed in the borehole(GBTSF 5) at the NW corner (Hough & Rudolph, 2022). There is an increase in the concentration of dissolved salts (particularly as Cl and SO_4) in the boreholes located to the northwest of the TSF (GBTSF 5, MBH 17) as shown in Figure 1-1. GHT consultants recommended ongoing monitoring and that an in-depth hydrogeological investigation be conducted around the TSF area.

KP performed a geophysical survey around the around the current TSF and further north of the TSF at Gamsberg mine (Van Dyk & Duthe, 2022). The survey concluded that the weathered profile in the north west sections shows that the subsurface has been disturbed creating a weaker platform for the liner and compacted TSF floor. During the construction of the TSF, 2 borrow pits were made north west of the TSF, along with a haul road which most likely created a preferential flow path for any seepage from the TSF towards the north west.

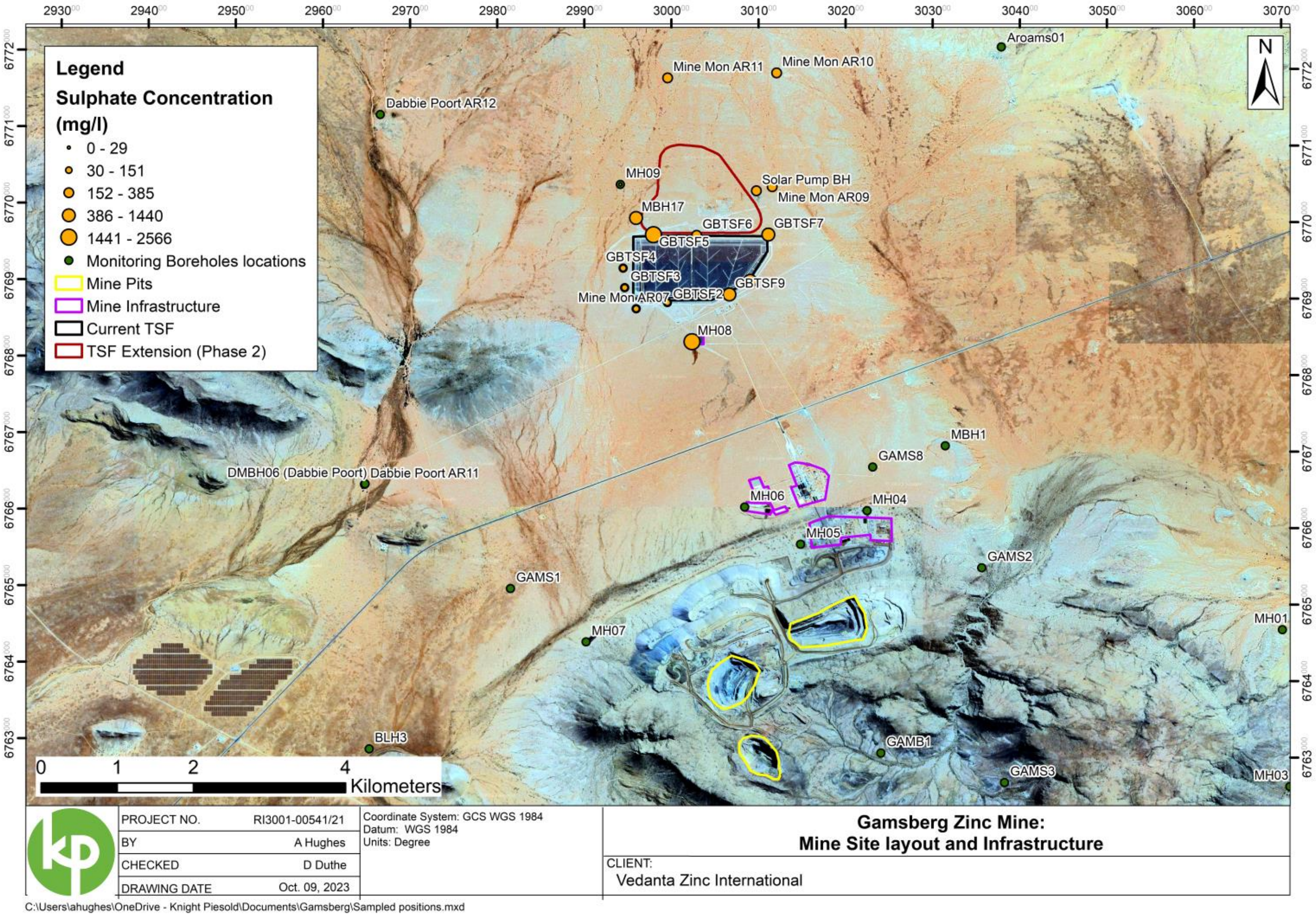

Figure 1-1: Mine Site layout and Infrastructure at Gamsberg Zinc Mine

The current TSF at Gamsberg has been lined with a High-Density Polyethylene (HDPE) geomembrane with a 300 mm thick soil layer modified with 6% bentonite (mineral liner) liner system (du Plessis & Strauss, 2017) . A desk study done by AMEC concluded that a HDPE geomembrane is most favourably for a hot climate and ideal for the climate at Gamsberg mine. BMM plans to extend the current TSF towards the north, KP have previously done geotechnical studies (du Plessis & Strauss, 2017), that confirmed the region north of the TSF is suitable for the extension. The Phase 2 TSF extension will be constructed the same as the current TSF with the same HDPE geomembrane liner system.

Previous geochemical static testing has been conducted for the waste streams at Gamsberg in 2013, by Environmental Resource Management (ERM) (Whyte, 2013). The report showed that the hanging wall, foot wall waste rocks and the tailings are predominantly acid generating. Each tailings type and a composite sample considered representative of the ratio of blended tailings was subjected to static and kinetic testing. The tailings produced from processing of the pyrite and pyrrhotite ore are classified as acid generating whereas the magnetite rich ore tailings was non-acid generating. The study confirmed that the tailings are expected to generate acid rock drainage (ARD) within a short period of deposition, due to the high sulphide and low neutralisation content of the tailings.

ERM recommended that various TSF management protocols be put in place for the Gamsberg TSF including:

- Short deposition cycles to reduce drying out and oxidation of the tailings,
- Cladding TSF side slopes concurrently with deposition,
- Engineered controls to capture and contain TSF drainage and,
- Liming of the tailings to acceptable pH values prior to tailings deposition.

Since 2022 KP has been involved in a waste classification of the Gamsberg tailings and pilot tailings for the TSF extension (Duthe & Hughes, 2023). Various locations (under flow, over flow, penstock, silt trap) were sampled at the Gamsberg TSF including the pilot tailings for the TSF Phase 2 expansion. The waste classification of the TSF materials was done in accordance with the Waste Classification and Management Regulations (WCMR) Government Notice 634 (23 August 2013) The current TSF samples show that dry tailings classify as Potentially Acid Generating (PAG) while the wet tailings classify as Non-Potentially Acid Generating (NPAG).

Following the geochemical assessment of the Gamsberg tailings, a geochemical model was developed by Millswater and the purpose of the model was to predict the potential impacts to groundwater (Mills, 2023). The model results indicate that the long-term impacts of any seepage on the groundwater surrounding the TSF are an increase in total dissolved salts, particularly sulphate and chloride and an increase in trace element concentrations particularly zinc and lead. Various geochemical reactions are controlling the evolution of the seepage mixing with groundwater and the model incorporated these reactions to predict the long term evolution of the TSF seepage water quality. The model results concluded that in the best-case scenario, sulphate, zinc and lead concentrations may increase although the pH will remain near-neutral around the TSF. For the worst-case scenario, the pH of groundwater will become acidic and sulphate and trace element concentrations will increase substantially. The complete Geochemical Modelling report is provided in Appendix B.

The results from the Geochemical model developed by (Mills, 2023), were incorporated into the numerical transport model for the Gamsberg Zinc Mine TSF extension (Phase 2). As the model predicted the long-term evolution of any seepage mixing with groundwater.

1.2 SCOPE OF WORKS

The scope of work undertaken is as follows:

- Data review of the reports made available from the client. Various groundwater monitoring reports, hydrogeological assessments, environmental impact assessments and geochemical assessments provided by the client, and detailed in the reference list.
- Development of a conceptual model to assess the potential risks of contamination and to identify any source-path-receptor linkages, around the TSF facility at Gamsberg Zinc Mine.
- Development of a numerical flow and transport model to determine the rate of migration from the current TSF and Phase 2 TSF (extension) and potential impacts on receptors, with mitigation measures
- Three scenarios have been developed for the contaminant transport model:
  - Scenario 1: Current status of the groundwater and plume around the existing TSF
  - Scenario 2: Future TSF Phase 2 development and associated plume that could migrate from the lined TSF facility.
  - Scenario 3: Post operational phase

2.0 SITE SPECIFIC DATA AND INFORMATION

The available data review and the additional site assessments were analysed and used as site specific inputs to the development of the conceptual model which describes the current hydrogeological status and the anticipated future groundwater status when the TSF Phase 2 gets developed. The conceptual model was used in the development of the numerical groundwater model to incorporate the site-specific data as input to the construction and calibration of the numerical groundwater model.

The following site-specific data was used to develop the conceptual and numerical groundwater model:

2.1 TOPOGRAPHY AND SURFACE DRAINAGE

The Gamsberg TSF is located on an extensive peneplain approximately 3.5 km north of the Gamsberg inselberg (Gamsberg mountain). The land slopes gently (0.4%) to the south, with the higher elevations recorded in the north west (980 mamsl) and the lowest elevations recorded in the south (845 mamsl). The Gamsberg inselberg records the highest elevation at 1156 mamsl. The topography and drainages are shown in Figure 2-1. The model boundary follows the watersheds between the sub catchments, as these natural ridges create a boundary condition in terms of groundwater flow.

The mine is located on the boundary between the D82A and the D82C quaternary catchments. The D82A catchment drains northwards into the Orange River, approximately 30 km to the north of the mine. The D82C catchment is an internal catchment with no major outflow river like the Orange in the adjacent catchment (D28C), however the stormwater flow is in a southerly direction. Both of these catchments are dominated by ephemeral rivers that only flows after heavy rainfall events (WSP Golder, 2022).

The Klein Pella River is the main drainage of the D82A catchment and also considered an ephemeral river that flows after heavy rain falls. Although this river is located outside of the model boundary, the start of the Klein Pella is just north of the current model boundary. The Klein Pella River drains towards the north before joining the Pella river which subsequently joins the Orange River, which flows West towards the Atlantic Ocean.

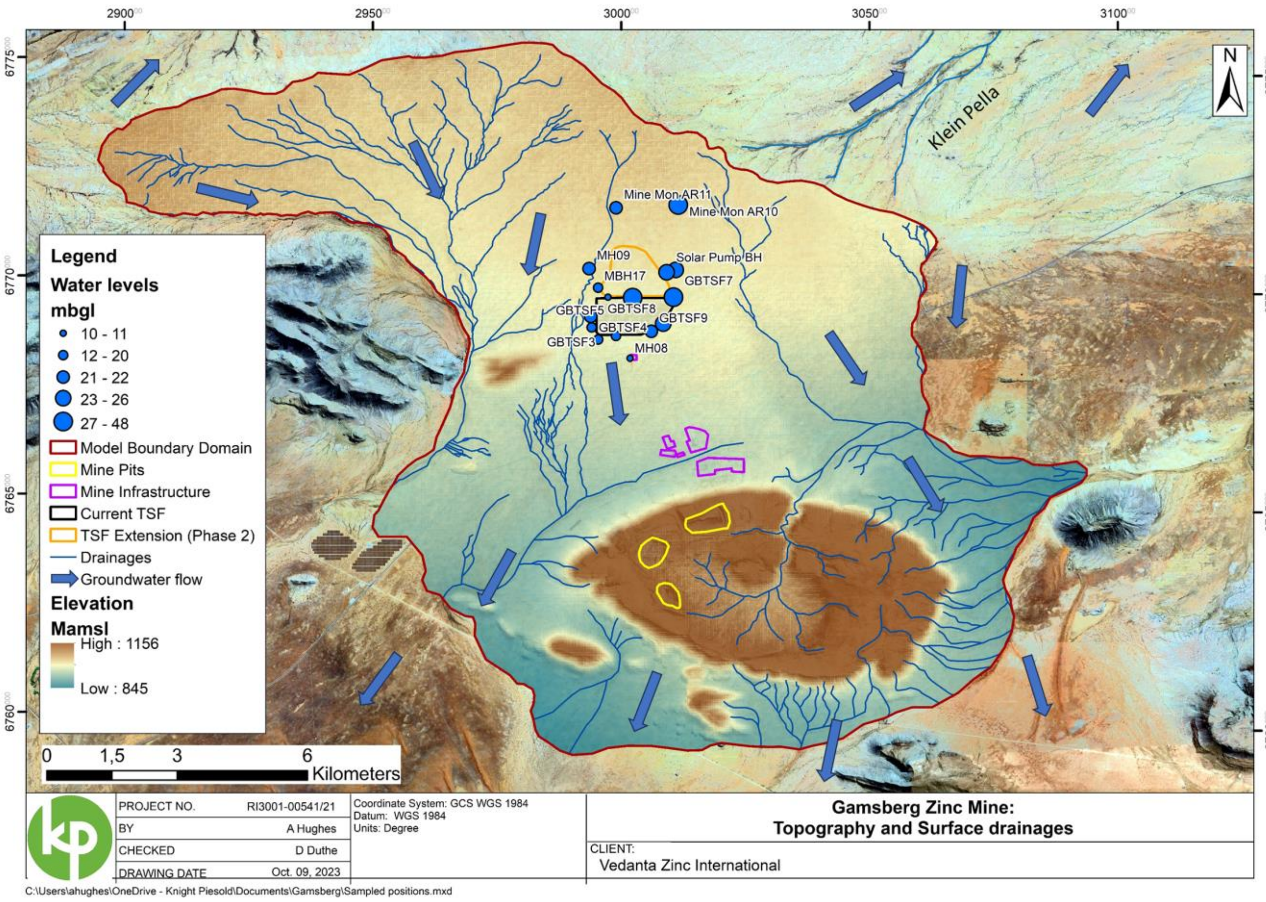

Figure 2-1: Topography and surface drainages around Gamsberg Zinc Mine

2.2 RAINFALL AND RECHARGE

The Gamsberg Mine is located in an arid to semi-arid climate with annual average rainfall of 96 mm (WSP Golder, 2022). Rainfall in this area is sporadic, but the wettest months are February, March and April. The Mean Annual Precipitation (MAP) varies from 74 mm (Pella) to 110 mm (Aggeneys) recorded for the local weather stations in the area. The MAP for the Gamsberg Zinc Mine is 110 mm (Hough & Rudolph, 2022) as shown in Figure 2-2 below. A three-year moving average of annual rainfall indicates decreasing rainfall from an average of ~150 mm/a between 1986 and 2010 to less than 50 mm/a between 2015 and 2018 (SLR, 2020).

The annual pan evaporation is 3115 mm, with greatest evaporation during the hot summer months. There is a constant water deficit as the evaporation exceeds the precipitation (WSP Golder, 2022).

Average summer maximum temperatures are between 30.7° and 35.4°C, with temperatures commonly reaching and exceeding 40°C, and winter maximum temperatures are between 17.8° and 20.8°C with temperatures as low as -2°C experienced overnight (WSP Golder, 2022).

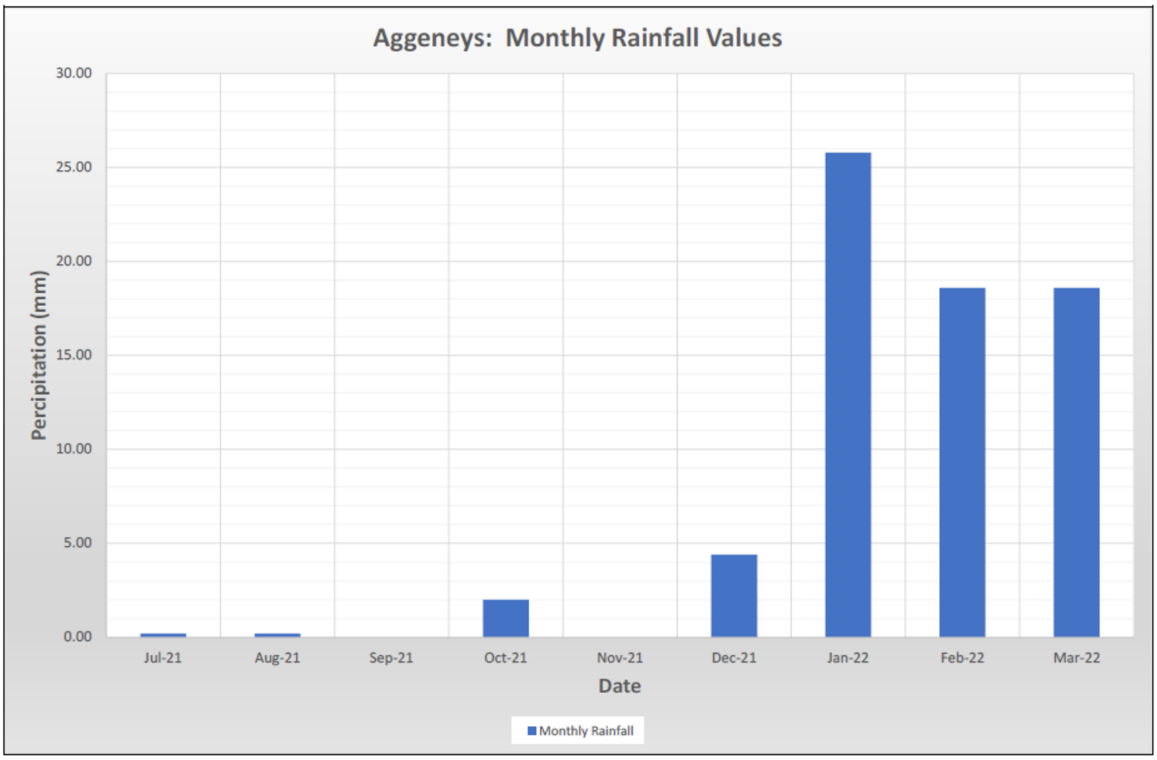

Figure 2-2: Monthly rainfall for the Aggeneys Weather Station (Hough & Rudolph, 2022)

The recharge in this area is expected to be consistent and should range between 2-5% of the MAP (110 mm/a). Previous studies have estimated the recharge to be low, ranging from 0.85 to 10 % of the MAP (SLR, 2020), (Menziwa, 2022) and (Minnaar & Muresan, 2020).

The recharge applied to the model domain, was calculated using the mass chloride method (Wood, 1999), using the equation:

$$R = P\ x\ \frac{Clp}{Clgw}$$

Where: R = recharge rate

P = precipitation,

CLp= Rainfall chloride concentration,

Clgw = Groundwater chloride concentration.

The boreholes located in the various lithological units were used to calculate the recharge values, and the recharge values were estimated at 4-5% of the MAP (110 mm/a). The recharge values used in the model are discussed further below.

2.3 GEOLOGY AND ASSOCIATED AQUIFERS

The Gamsberg Mine lies within the Namaqua Metamorphic Complex, which consists of Precambrian rocks and intrusives, which formed and metamorphosed during the Namaqua Orogeny (ERM, 2013).

The stratigraphic succession for the Project area (Gamsberg Zinc Mine), has been summarised in Figure 2-3 below with the regional geology being shown in Figure 2-4.The regional geology has been delineated from the Council for Geosciences (CGS) geological map 2918 Poffadder ((CGS), 2007). The lithological succession at Gamsberg Zinc Mine comprises of basal quartzo-feldspathic gneiss overlain progressively upwards by siliminite-bearing pelitic schist and metaquartzites of up to 450 m thickness; the Gams Iron Formation (GIF) of 0 to 80 m thickness; and Koeris Formation rocks consisting of quartz-muscovite schist, lenses of conglomerate and amphibolite to a thickness of 400 to 500 m. The latest phase of structural deformation of the local basin resulted in upturning and buckling, to produce a steep-limbed anticlinal structure on the north side of the inselberg (Gamsberg Mountain). There is a shear zone located through the Gamsberg mountain, however it is located further south of the current TSF and not likely to impact any potential plume development from the TSF. The basement rocks are covered by quaternary age reddish windblown sands, scree rubble, sandy soil and alluvium. Calcrete or dorbank is reportedly present within the quaternary sediments (SLR, 2020). The TSF and smelter complex at Gamsberg Zinc Mine are all located on basal gneiss of the Gladkop Group, part of the Haramoep Gneiss formation and no regional scale lineaments are located within the footprint of these facilities.

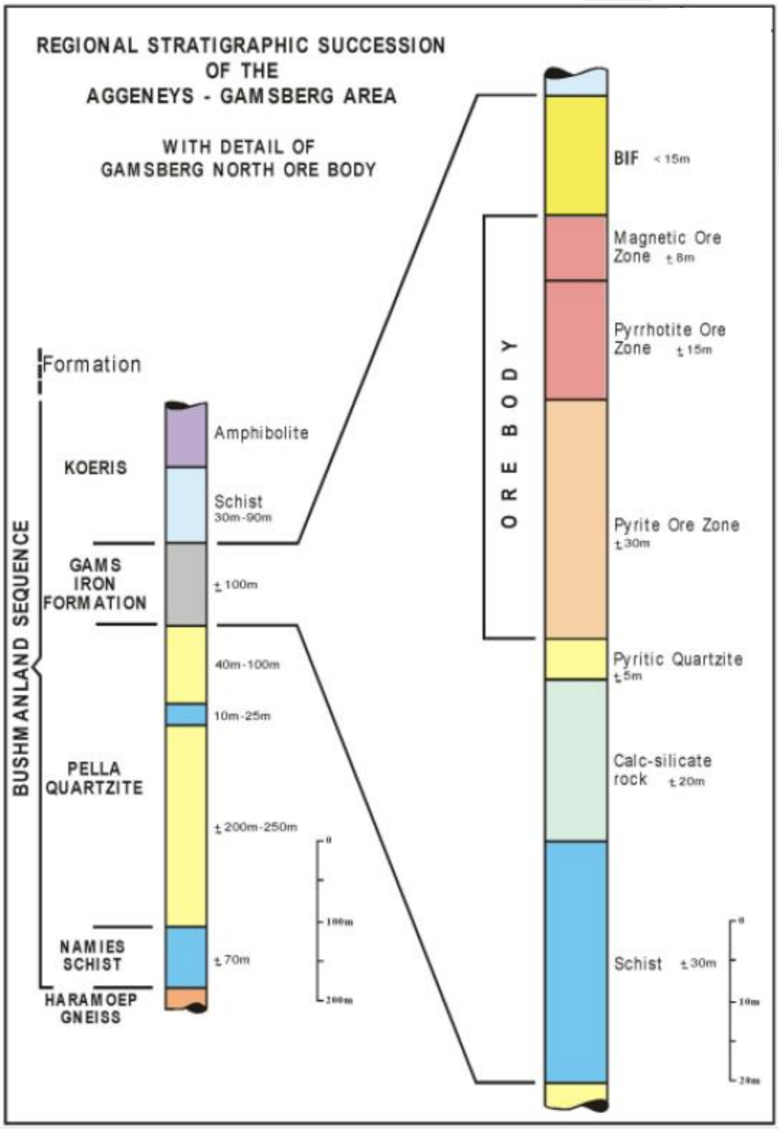

Figure 2-3: Stratigraphic succession for the Gamsberg Area

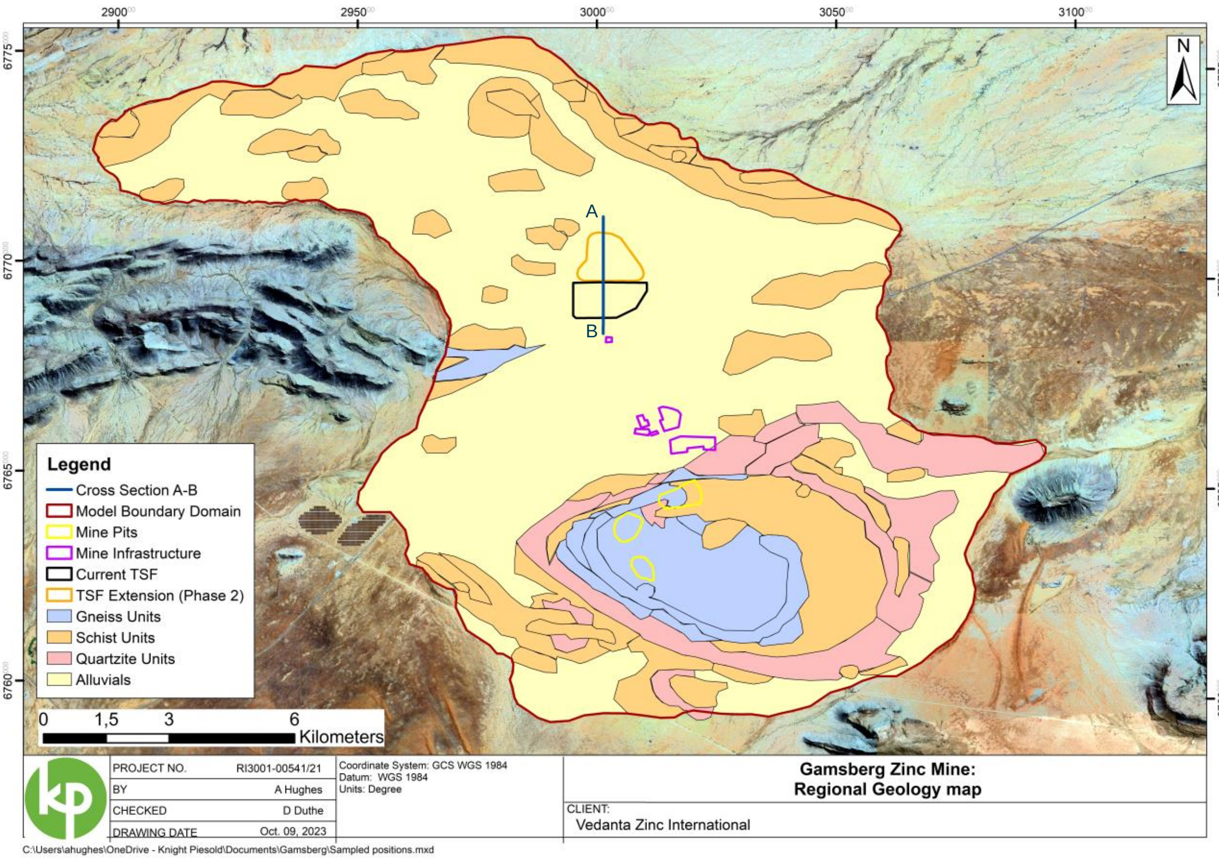

Figure 2-4: Regional Geology of the project area as well as cross section used for CHM

The regional hydrogeology of the area is characterised by secondary fractured-rock aquifers (SLR, 2020). (Hamilton & Heather-Clarck, 2020) states that in the Bushmanland Hydrogeological Region, groundwater occurs in fractured rock below the weathered zone and not at the transition between the weathered zone and fresh rock.

Primary weathered zone aquifers are rare and localised because soils are thinly developed. Previous studies have found that the fractured rock aquifer in this area, had recorded yields ranging from 0.1l/s to 0.49 l/s (van Biljoen, 2023) (Minnaar & Muresan, 2020) (Huisamen & du Toit, 2017).

The local aquifer in the Gamsberg area is located below the weathered zone and in the fresh fractured rock, this zone is, however, thought to be of restricted extent with limited groundwater potential, due to low rainfall and runoff with high evaporation rate resulting in very low and sporadic recharge.

The highly fractured and weathered hard rock terrain of the white quartzite unit, the schist, and the gneiss, are considered to be the water-bearing units. The primary control on permeability is taken as weathering (related to depth from surface) and structures, rather than rock type, appreciating that un-weathered units at depth can also be water bearing, and that fracturing around major faults will increase hydraulic conductivity.

The soil profile in the project area is characterised by distinct units, residual soils to very soft rock gneiss with nodular to hardpan calcrete, with hardpan ferricrete in some places, overlain by aeolian sand. The calcrete layers occur in the upper portion the soil horizon with the hardpan ferricrete normally below the calcrete (Huisamen & du Toit, 2017). The hardpan ferricrete will act locally as an aquitard that could inhibit the recharge to the deeper aquifer, resulting in some variability to the recharge rate. The ferricrete layers form from the seasonal perched aquifer occurring in the wet summer months and receding during the dry winter months. A deeper aquifer is associated with the residual gneiss contact and fractured gneiss, underlying the project area.

2.4 GROUNDWATER LEVELS AND ABSTRACTION

The regional groundwater flow in the northern section is in a north direction towards the Klein Pella tributary, whereas the groundwater flow in the southern sections (surrounding the Mine area) is in a southeasterly direction, as illustrated in Figure 2-1.

The average groundwater levels measured from several hydrocensus investigations is 29.7 mbgl for the Gamsberg Zinc Mine (Schlechter & Allen, 2022). The groundwater levels ranged between artesian conditions and 178.8 mbgl for the boreholes abstracting water (dewatering holes) (Hough & Rudolph, 2022).

The summary of the groundwater levels used for the numerical model (surrounding the TSF) are shown below in Table 2-1, and the complete data set can be found in monitoring report (Hough & Rudolph, 2022).

There are regional groundwater users surrounding the Gamsberg Zinc Mine, privately owned boreholes are located further south and southeast of the mine concession area. However, there is no abstraction data available for the private owned boreholes. The abstraction data was obtained from the environmental department at Gamsberg Zinc Mine, only the dewatering rates for the West pit were available. The current pit depths are at 834 mbgl and a dewatering rate of 2500 l/s or 60 m^3/day is currently used for the West pit area at Gamsberg mine. The current groundwater monitoring programme confirms that the mine is not impacting the regional groundwater levels and quality (Hough & Rudolph, 2022).

Table 2-1: Summary of groundwater levels surrounding the TSF

Borehole Name	East	South	Water Level (mbgl)
Mine Mon AR07 (GBTSF1)	18.93952	-29.19654	17.98
GBTSF2	18.94296	-29.19405	19.51
GBTSF3	18.93817	-29.19405	18.97
GBTSF4	18.93798	-29.19175	21.51
GBTSF5	18.94156	29.1878	10.32
GBTSF6	18.95231	29.18776	34.3
GBTSF7	18.94988	29.19472	48.27
GBTSF8	18.95289	29.19289	25.11
GBTSF9	18.95052	29.19485	22.1
MBH17	18.9395	-29.18583	19.48
MH08	18.94611	-29.20042	11.08
MH09	18.93765	-29.18188	22.32

Borehole Name	East	South	Water Level (mbgl)
Mine Mon AR09	18.95558	-29.18215	25.66
Mine Mon AR10	18.95609	-29.16872	36.76
Mine Mon AR11	18.94323	-29.16931	22.39
Solar Pump BH	18.9537	-29.18263	25.49

The measured hydraulic head (from field data) has been compared to the topographical elevation, as illustrated in Figure 2-5 shows an 87.5% correlation (R=0.8753) implying that this is a dynamic aquifer system, i.e., there is an influence from groundwater users in this region, the pit dewatering and private farm boreholes are impacting the groundwater. However, the influence is highly localised as overall the groundwater (hydraulic head) still mimics the topography of this region.

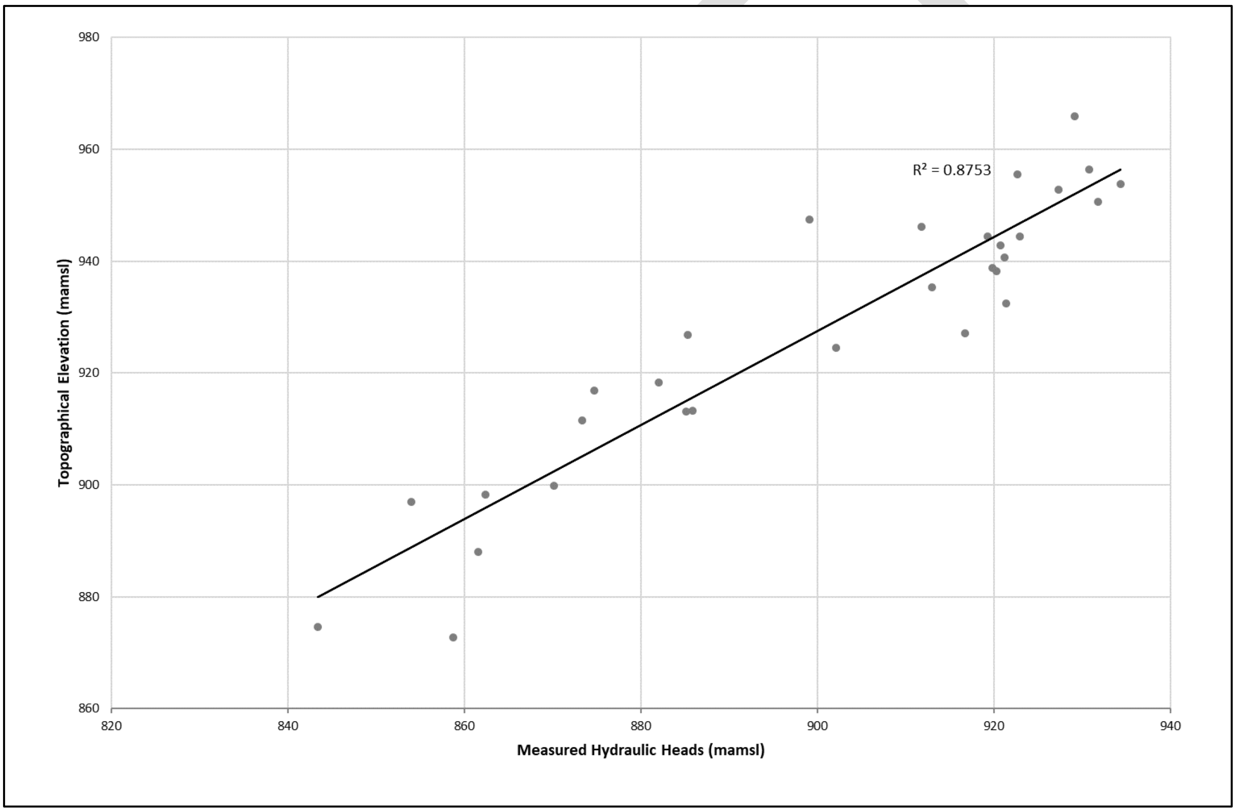

Figure 2-5: Hydraulic Head vs Topographical elevation

2.5 AQUIFER PARAMETERS

The aquifer hydraulic testing results from previous studies indicated that the aquifer units in the Gamsberg area generally have very low to low permeability and increased groundwater occurrence is only associated with secondary structures such as faults and fractures.

Transmissivity (T) ranged between 1.0 E-2 m^2/d and 1.0 E+1 m^2/d for the Gamsberg aquifer units (Huisamen & du Toit, 2017). Pump test information interpreted by (van Biljoen, 2023) indicated similar ranges of hydraulic conductivities in gneiss, schist, and quartzite lithology (1.0 E-4 to 1.0 E-1 m^2/day) and indicated a broadly confined character in the pump test curves.

2.6 WATER QUALITY AND GEOCHEMISTRY

The main sources of potential contamination from the Gamsberg Zinc Mine, are the TSF, RWD and smelter complex. The current hydrochemical data of groundwater from boreholes located north west of the current TSF, show elevated concentrations of dissolved salts particularly SO_4, Cl and Na (Hough & Rudolph, 2022) as shown in Figure 2-6. The available data indicates that there is seepage along the northwestern boundary of the TSF (GBTSF-5, MBH17).However the seepage appears to be localised with a plume remaining within 200 m of the current TSF.

KP performed a geophysical survey around the around the current TSF and further north of the TSF at Gamsberg mine (Van Dyk & Duthe, 2022). The survey concluded that the weathered profile in the north west sections shows that the subsurface has been disturbed creating a weaker platform for the liner and compacted TSF floor. During the construction of the TSF, 2 borrow pits were made north west of the TSF, along with a haul road and it is suggested that the old haul road and borrow pits north west of the TSF have created a preferential flow path for any seepage from the TSF towards the north west.

The existing TSF material and a sample from the pilot test tailings for the expansion was analysed for static geochemical testing by KP in 2023 (Duthe & Hughes, 2023) and a summary of the geochemical report is provided below. Based on the results for the samples (Phase 2 static testing), the following conclusions are noted:

- the leachate from the samples is expected to have an acidic pH due to the presence of high sulphur and sulphate minerals in the tailings.
- There are limited carbonate minerals, only silicate minerals (quartz and chlorite) that will provide limited short term buffering capacity.

The initial ABA analysis and waste classification for the Gamsberg TSF samples showed that all the samples will be acid generating, with some samples classifying as type 0 waste which cannot be disposed of. The leachate of the TSF samples showed elevated heavy metal concentrations particularly for Cd and Pb.

A second round of testing was done in 2023, which included the pilot tailings for the TSF Expansion. Gamsberg Mine intends to include an additional circuit to help remove the high Pb and Cd concentrations, and the 2023 results confirmed this as no samples classified as type 0 waste . However, the leachate generated from the tailings material still classifies as acid generating and will require a liner in order to be disposed. The full report can be found in Appendix A as well as the waste classification of the TSF material.

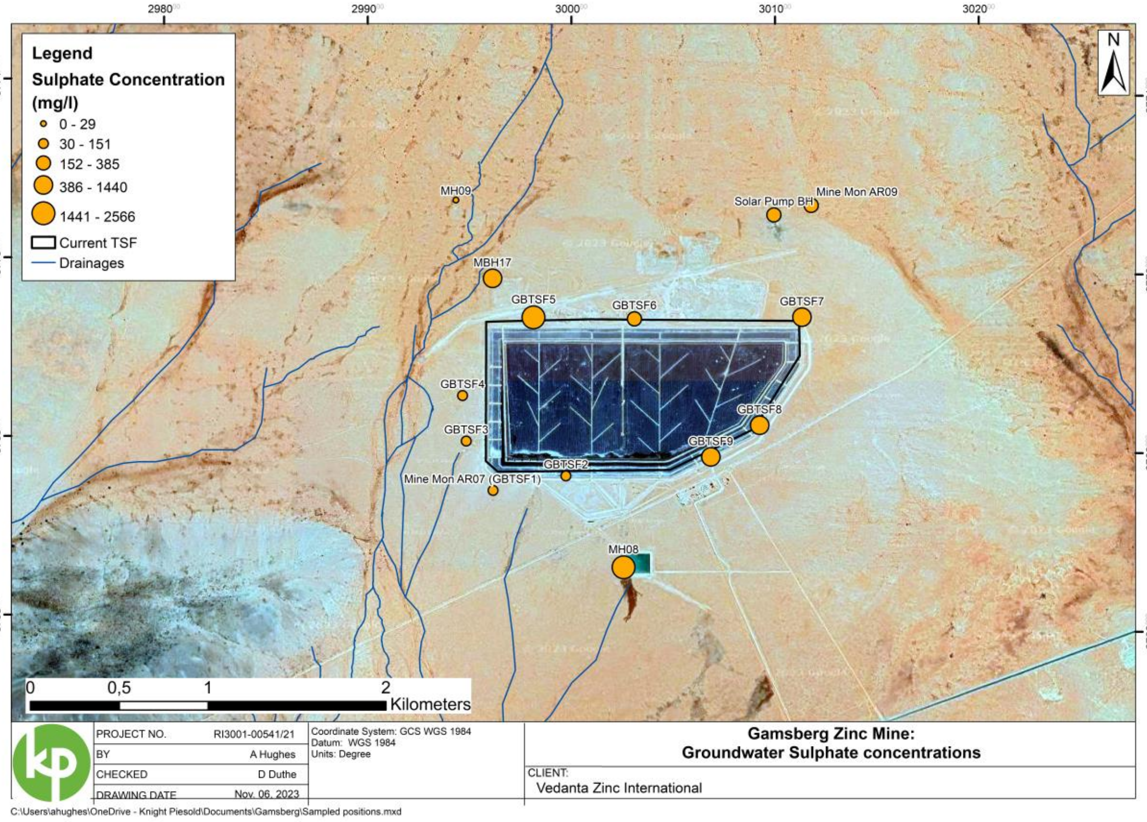

Figure 2-6: Groundwater Sulphate concentrations surrounding the Gamsberg TSF

3.0 HYDROGEOLOGICAL CONCEPTUAL MODEL

The conceptual understanding of the hydrogeological conditions surrounding the TSF area has been based on available information as described in section 2. and identifies any source-path-receptors surrounding the TSF area at the Gamsberg Zinc Mine. The model also shows the extent of the existing solute plume from the TSF as well as any potential future impact from the Phase 2 TSF extension on the groundwater.

The hydrogeological conceptual model was used for the numerical model during the construction, and predictive simulation scenarios. The conceptual model is shown below in Figure 3-1 below and the base image represents a cross section A-B from South to North through the Gamsberg mine concession as shown in Figure 2-4.

The TSF at the Gamsberg Zinc Mine is located on basal gneiss of the Gladkop Group. The highly fractured and weathered hard rock terrain of the gneiss, are considered to be water-bearing units in this area. Other water bearing units such as the fractured schist and quartzite units are located further south of the TSF, around the Gamsberg Inselberg. A shallow aquifer is associated with the alluvium deposits of the drainages, it is likely this is a perched aquifer that only flows intermittently, following rainfall events. While a deeper aquifer is associated with the residual gneiss contact and fractured gneiss, underlying the TSF area at Gamsberg Zinc Mine.

There is one main ephemeral river, with various tributaries, that flows towards the south and along the western boundary of the TSF area and Phase 2 TSF extension. The current drawdown cone of the pit sumps does not impact the TSF area, and the future drawdown cone is not expected to impact the TSF area.

A previous study done by KP, confirms there is seepage along the north western boundary from the existing TSF at Gamsberg Zinc Mine (Van Dyk & Duthe, 2022) due to the ground disturbance from the old haul road and borrow pits north west of the TSF towards the north west. The groundwater levels have been impacted by the TSF where the seepage has increased the water level in the boreholes to the north (GBTSF 5) compared to the south (GBTSF 8).

The conceptual model shows the plume has migrated a maximum of 200m northwest of the current TSF, as inferred from the current groundwater monitoring data for the TSF area. The Phase 2 TSF extension will be developed further north of the current TSF and will overlie the current plume extent. The mass solute plume formed by the integrated TSFs is likely to seep towards the south, following the overall surface topography and groundwater flow direction.

The current groundwater data indicates that there is seepage along the northwest boundary of the TSF, with the current extent of the plume is 250m northwest of the TSF, based on the borehole data (GBTSF 5 and MBH 17). However, there is no evidence of the plume migrating towards the West. BBM plan on expanding the TSF at Gamsberg Zinc Mine, the Phase 2 TSF extension will occur to the North of the current TSF, and the new boundary of the TSF extension will cover the current plume located north west of the TSF. The numerical model will show the direction of the potential plume migration from the Phase 2 TSF extension.

None of the groundwater users (neighboring farms) are located in the in close proximity to the current TSF, all the boreholes abstracting water are located further south and north east of the TSF. The only groundwater users located near the TSF is the Gamsberg Mine (dewatering holes), and the current data shows there is no impact on the TSF groundwater levels from mine dewatering. The main receptor is the shallow aquifer system present in the alluvium deposits of the drainages, and its associated ecosystem. The current TSF poses no contamination threat to any groundwater users in the near vicinity.

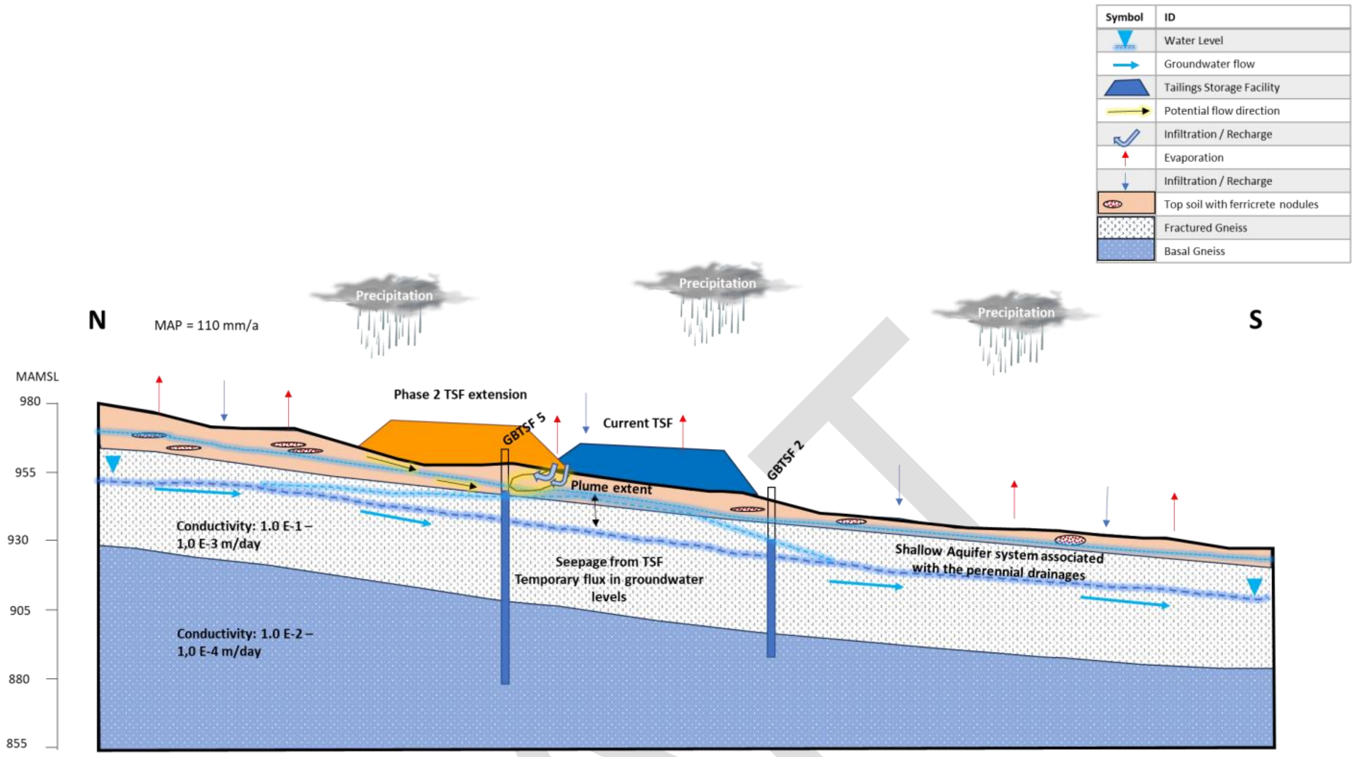

Figure 3-1: Conceptual Hydrogeological Model of the Gamsberg TSF and Phase 2 TSF extension

4.0 NUMERICAL GROUNDWATER MODEL

The numerical model was constructed in FEFLOW according to the topography, geology as well as the main river systems and tributaries. The numerical groundwater model was constructed as a 3-D model using software developed by DHI (FEFLOW 7.4).

The steady state numerical model was calibrated according to the site specific such as the measured groundwater levels, estimated recharge to the different geology groups and the current groundwater quality data.

The calibrated numerical model was then used to simulate two scenarios, in transient state according to the life of operation (13 years) for the Phase 2 TSF extension at Gamsberg Zinc Mine. The second simulation shows a longer-term post operational phase which was simulated over 30 years to evaluate the impacts of the TSF post closure.

4.1 MODEL CONSTRUCTION

A summary of the input data used for the model construction is shown below in Table 4-1. The model domain covers a surface area of 165.62 km^2 with a total volume of 108.16 km^3 and a vertical thickness of 851 m as shown below in Figure 4-1. The modelled area incorporates a small portion of the Quaternary Catchment D82C, the main drainages are non-perennial (ephemeral) rivers that flow during high periods of rainfall. These ephemeral rivers are located in the north east and south western sections of the model domain and flow towards the south. These drainages were used for boundary conditions for the groundwater flow.

The numerical model wireframe was generated based on the finite element approach with elements generated as triangles throughout the model domain and according to the different geology and TSF layout. The delineated drainages (ephemeral river plus tributaries) were also included as part of the wireframe generation. The numerical domain and wireframe is indicated below in Figure 4-1.

The numerical model includes 6 layers and 7 slices that represent a 10 m thick top soil layer, TSF liner depth, open pit depths as well as geological units found within the model domain. Layer one is representative of the surface with the elevation at 923 mamsl while layer 6 is the bottom layer at an elevation of 300 mamsl.

The model wireframe was refined over the TSF area to allow more accurate assignment of model input parameters during the calibration process. The numerical model domain consists of 175,374 elements and 105,224 nodes, that are connected to form the super-mesh for the model domain (Figure 4-1).

Table 4-1: Input data for the Model Construction

Model Data	
Model Input Data	**Data Sources**
DTM data	SRTM database interpolated to 20m spacing
Rainfall data	Rainfall data obtained for Gamsberg Environmental team and monitoring reports (Hough & Rudolph, 2022)
Geology	Obtained from literature and geological maps
Drainages	Delineated from detailed satellite images and elevation profiles

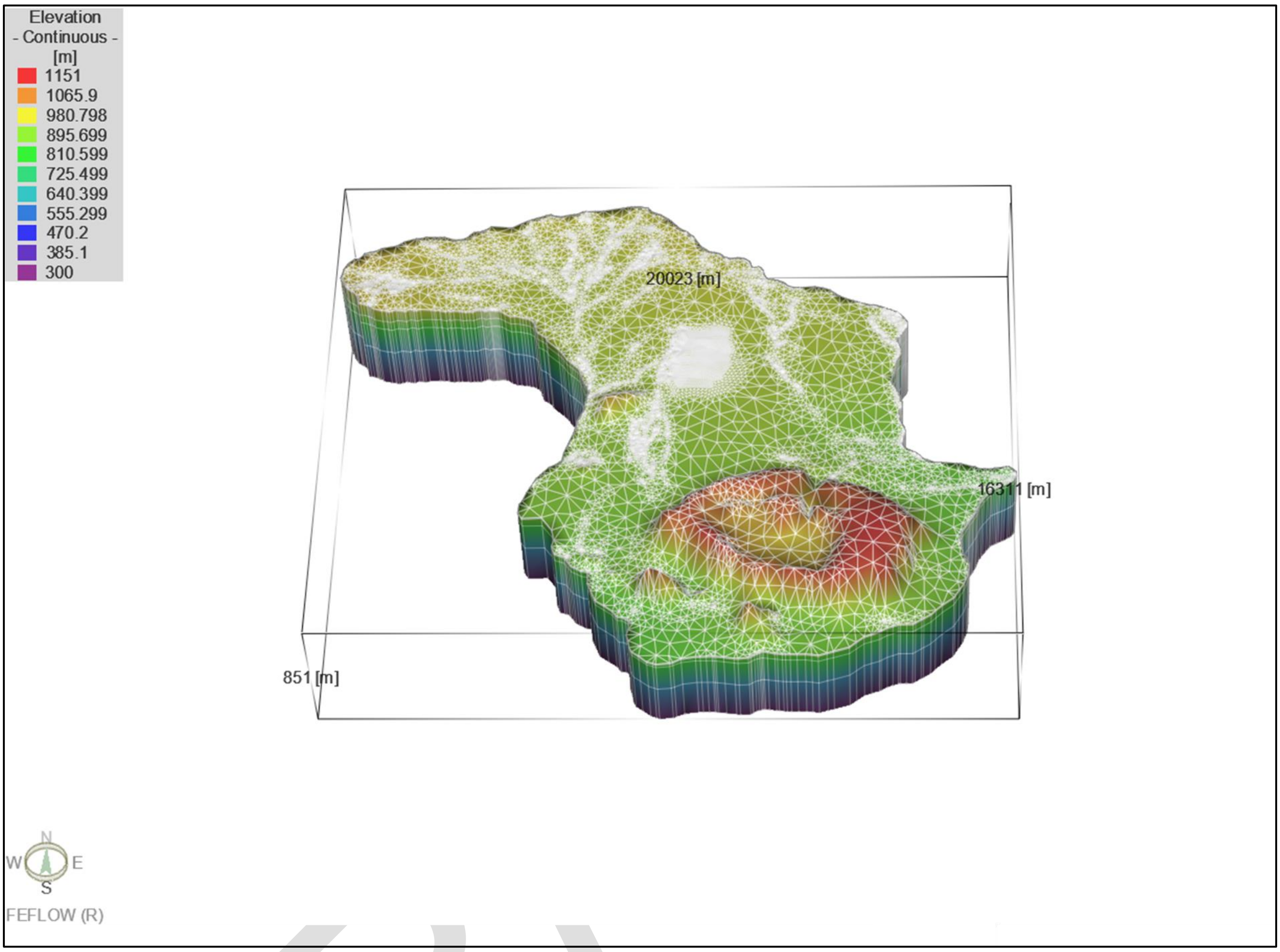

Figure 4-1: Numerical Model Construction and Domain

4.2 MODEL CALIBRATION

The model calibration included two stages to determine initial groundwater conditions prior to the development of any TSF. The steady-state flow calibration was conducted by making minor changes to the model input parameters, mainly the permeability and recharge as well as the storage coefficients to simulate the current groundwater flow conditions. Furthermore, hydraulic head boundary conditions were assigned to the ephemeral rivers (drainages) located within the model boundary to act as drains to the subsurface catchment.

The initial steady-state conditions represent the current groundwater flow conditions in the project area. The sub catchment used to identify the model boundary has excluded groundwater abstraction points from neighbouring farms, so the only groundwater users identified in the model domain is the Gamsberg Mine, there are multiple farms located in the surrounding area however no abstraction data is available for them.

The model hydraulic parameters were taken from literature as no aquifer testing was performed by KP, the selected hydraulic conductivities ranged from 0.001 m/d to 0.9 m/d as stated in literature (van Biljoen, 2023). Higher conductivities were placed on the upper layers representing the top soil and alluvials (0.85 – 1.5 m/day), the alluvials were assigned the highest conductivity (1.5 m/day) to try better represent rapid infiltration into the alluvial deposits. While the conductivities of the granite rock groups were assigned at 0.006 m/day and the Schist and Quartzite rock groups were assigned 0.003 m/day Previous hydrogeological reports for Gamsberg Zinc Mine were also used to confirm the hydraulic conductivity of the various lithological units as well as recharge information of the project area. The hydraulic conductivity values ranged from 0.001 to 0.9 m/d (Huisamen & du Toit, 2017), (Minnaar & Muresan, 2020).

The abstraction data was obtained from the environmental department at Gamsberg Zinc Mine, only the dewatering rates for the West pit were available. A dewatering rate of 2500 l/s or 60 m^3/day is currently used for the West pit area at Gamsberg mine. The current open pit bottom elevation was applied as a hydraulic head boundary condition, to act as a drain at the specific elevation (897 mbgl). The steady state calibration recorded an inflow value of 55 m^3/day which is comparable with the existing dewatering rates.

The recharge input was only applied to the top layer of the model and was calculated based on the CMB method for the geological units as summarised in Table 4-2 below. A recharge value of 10% was applied to the general project area (11.0 mm/a), which represents the quaternary sediments and sediments (alluvial) and overburden. Whereas the Gneiss units had a recharge of 4% while the Quartzite and Schist units had a recharge of 5%. The TSF was assigned a slightly higher recharge of 12% (13 mm/a) to represent the constant deposition of tailings material.

Table 4-2: Calculated Recharge Values of the lithological units

Lithological Unit	Quartzite	Schist	Gneiss
Groundwater Cl (mg/l)	643	559	463
Rainfall Cl (mg/l)	0.25	0.25	0.25
CMB Recharge (%)	4.3	5.1	5.2

The model input parameters for each layer are shown below in Table 4-3 and spatially represented in the 3-D images shown in Figure 4-2. The model results were compared to the CHM and available groundwater data to confirm the groundwater conditions and boundary flow were correct.

Table 4-3: Model Input Parameters

Model Geology	Hydraulic Conductivity (m/d)	Storativity	Recharge (%)	Recharge (m/d)
Layer one (0.5 m)				
Alluvials	1.5	1.00 E-03	15%	4.72 E-05
Quarternary Sediments	0.85	1.00 E-03	10%	3.14 E-05
Granitic Gneiss Formations	0.006	1.00 E-03	4%	1.72 E-05
Quartzite/Schist Formations	0.003	1.00 E-03	5%	1.39 E-05
Layers 2-3 (30 m)				
Quarternary Sediments	0.85	2.00 E-04		
Granitic Gneiss Formations	0.006	2.00 E-04		

Quartzite/Schist Formations	0.003	1.00 E-05		
Layer 4-6 (570 m)				
Diorite Gneiss Formation	0.0075	1.31 E-05		
Grantic Gneiss Formations	0.006	1.05 E-05		
Quartzite/Schist Formations	0.003	5.26 E-06		

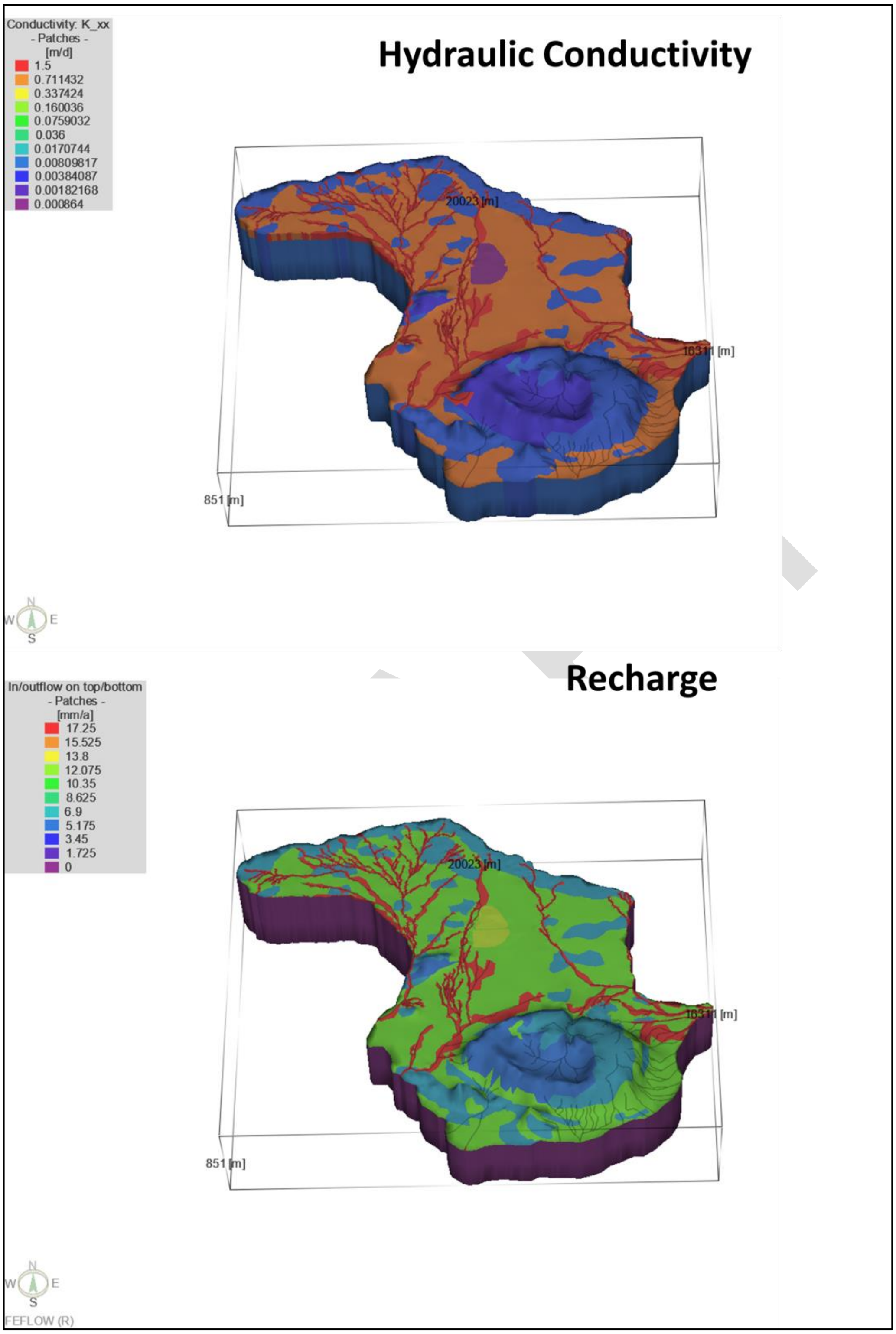

Figure 4-2: Initial State Model Input

The steady-state conditions were satisfactory when the measured hydraulic head and the simulated hydraulic head had a correlation of 87.4% (R=0.874) and a mean error recorded at 9.2 m. This is comparable to the measured hydraulic head (from field data) compared to the topographical elevation (R=0.8751). The calibrated hydraulic head is shown in Figure 4-3 below.

The regional calibrated hydraulic head is below surface elevation and follows the overall topographical gradient for the current steady-state calibration as shown in Figure 4-4 (depth to groundwater level from surface). There are certain areas in the model which show the hydraulic head is above the topography (negative elevation) which can be explained by discrepancies in the DTM (elevation) data.

The man-made features such as tailings storage facilities, constructed dams, and ponding areas may cause further discrepancies as the DTM data does not normally include these features. The Gamsberg mine infrastructure is located within the model boundary. The hydraulic head and groundwater flow follows topography in the TSF area towards the main drainage located south west of the TSF and flows in a southerly direction.

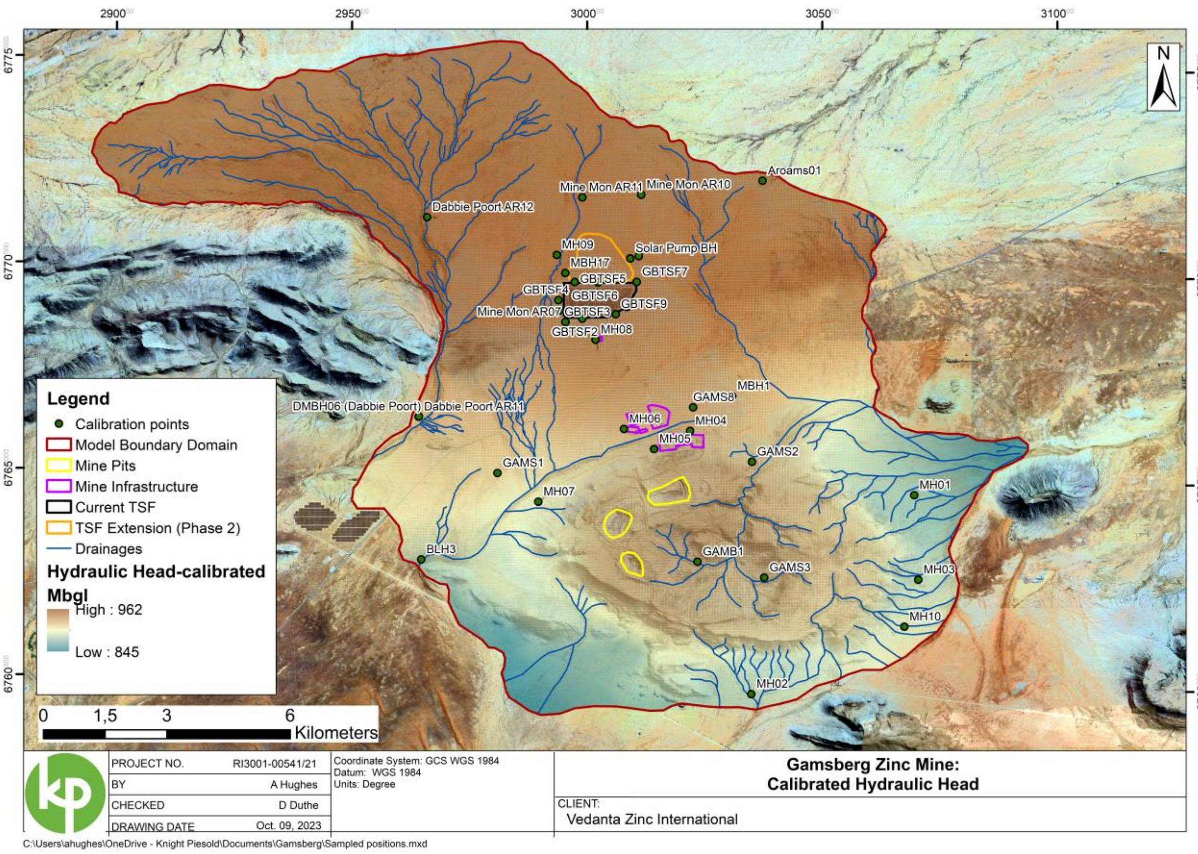

Figure 4-3: Calibrated Hydraulic Head of the Numerical Model

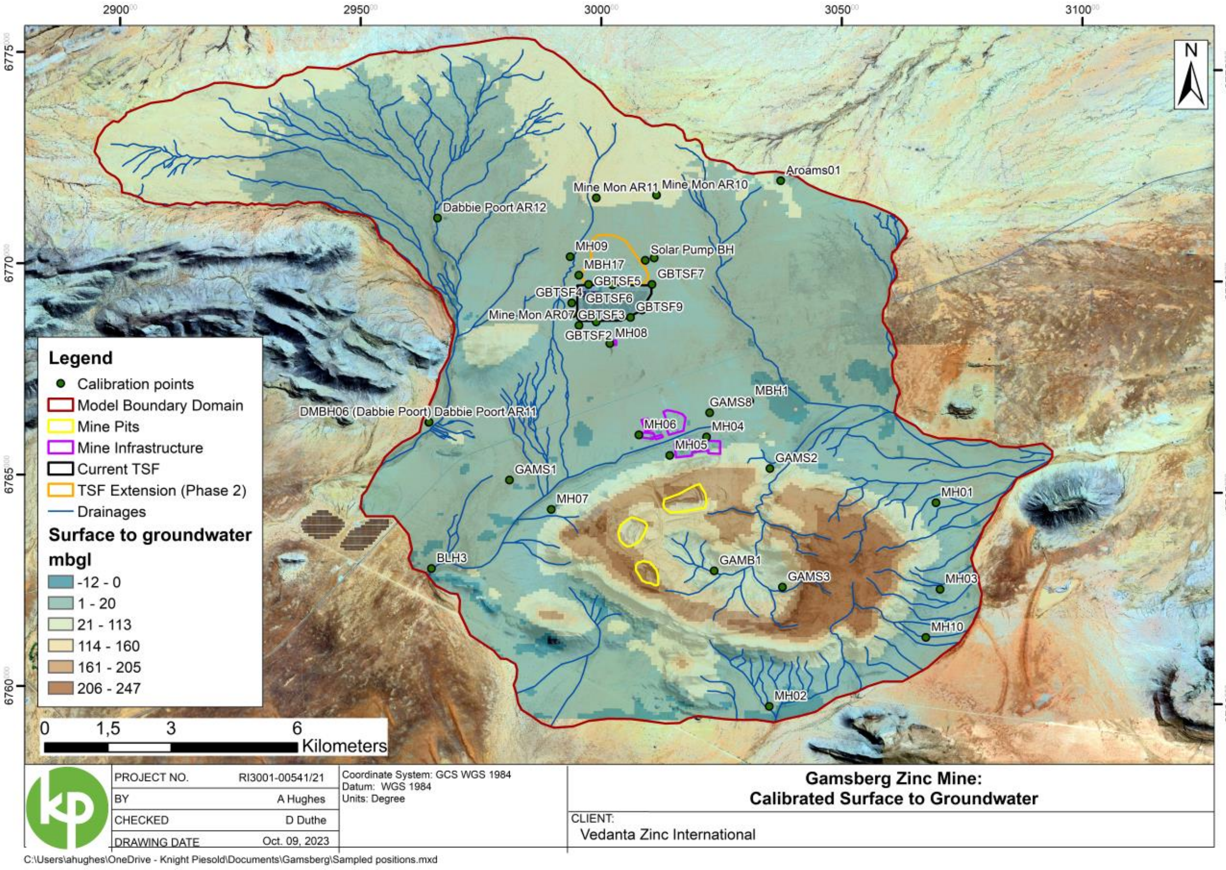

Figure 4-4: Calibrated depth to Groundwater levels from surface for the Numerical Model

4.2.1 CURRENT OPERATIONAL CONDITIONS-TRANSIENT STATE

The steady state calibration was then conducted in transient state to represent the current mining operations and TSF operations that commenced in 2017 up to 2023. Additional model inputs included the TSF liner system, and source concentrations to the existing TSF. SO_4 and Zn were selected as contaminants of concern as the current groundwater concentrations show elevated SO_4 concentrations and previous geochemical testing showed elevated Zn concentrations for the TSF material.

To best represent the liner system for modelling purposes the following was done (Bowser & Spadafora, 2013).

- The current TSF is lined with a HDPE geomembrane and mineral layer, a hydraulic conductivity of $8.6x10^{-4}$ m/d was assigned to best represent any minor or circular defect or tears in the current liner system (Foose, Benson, & Edil, 2001). This also represents a worst-case scenario in which there is a leak from the lined TSF.
- The Phase 2 TSF extension was modelled in the same way.
- In addition, a fluid flux of 0.0003 m/day was assigned to the TSFs (current and extension) to better represent runoff from these facilities.

The background concentrations were based on the hydrochemical data of the upgradient boreholes (SO_4 - 32 mg/l; Zn – 0.04 mg/l), that have not been impacted by the TSF (GHT consultants).

The source concentrations assigned in the numerical model, were selected from the geochemical model as developed by Millswater (Mills, 2023). The geochemical model results show that there are two likely scenarios, the best case where sulphate, zinc and lead concentrations may increase although the pH will remain near-neutral around the TSF. For the worst-case scenario, the pH of groundwater becomes acidic and sulphate and trace element concentrations will increase substantially.

The concentrations assigned to the background and sources are summarised in Table 4-4 below and have been applied to all the model scenarios as constant sources to ensure the worst case :

Table 4-4: Model Source Concentrations (mg/l)

Parameter	Sulphate (mg/l)	Zinc (mg/)
Background Concentration	32	0.04
Source Concentration: Worst case	2500	45
Source Concentration: Best case	1700	15

To better represent the elevated dissolved salts (SO_4, Cl, Na) concentrations north west of the current TSF, source concentrations (best case) were applied to the old borrow pits and haul road located north west of the current TSF.

4.2.2 CURRENT OPERATIONAL CONDITIONS-RESULTS

The results for the steady state simulation can be seen in Figure 4-5 and Figure 4-6 below for SO_4 and Zn. Based on the current operating conditions at Gamsberg Zinc Mine, the following observations are noted:

- Over the six-year period the bulk SO_4 and Zn concentrations of 2500 mg/l and 45 mg/l respectively have remained within the TSF boundary and shows the effectiveness of the current liner system installed. However, along the northwestern boundary of the TSF a clear plume is evident.

- Over the six-year period, two solute migratory patterns for both parameters (SO_4 and Zn) are evident with flow towards the north west and south. The main component of the plume is located towards the south, while a small component of flow is evident towards the north west as well as towards the south west.
- The overall groundwater flow direction around the TSF is towards the south as is the expected migration for any contaminant plumes from the TSF.
- There is migration towards the north west attributed to a preferential flow path from the TSF, created from the old borrow pits and haul road during the construction of the TSF. While the migration to the south west can be attributed to the hydraulic head conditions of the drainages located west of the current TSF.
- The maximum extent of the plume has been defined by the SANS 241:2015 drinking water quality limits for each parameter.
    - For SO_4 the maximum extent of the potential plume (>250 mg/l) is 250m towards the north west from the TSF, however the potential plume has not migrated far from the old borrow pits (<50 m). The maximum extent of the potential plume towards the south is 30 m from the TSF.
    - Unlike sulphate, the potential plume for Zinc has remained highly localised, and remains within the TSF boundary.
- A cross sectional view from north west to south east through the current TSF at Gamsberg is shown below in Figure 4-7. The vertical extent of the plume is shallow (< 15 mbgl), indicating the main impact is on the shallow aquifer/ perched aquifer systems. The main flow direction of the plume is towards the south, which is expected as the hydraulic gradient in this area is towards the south.
- This transient state calibration shows the potential plume could migrate towards the south and south west for both SO_4 and Zn but will remain localised while the plume located north west of the TSF for SO_4 has remained within a 250 m radius of the current TSF.
- Compared with the current groundwater quality data for the boreholes surrounding the TSF, the modelled concentrations show a good correlation, with higher concentrations in the boreholes towards the north west and south of the TSF.

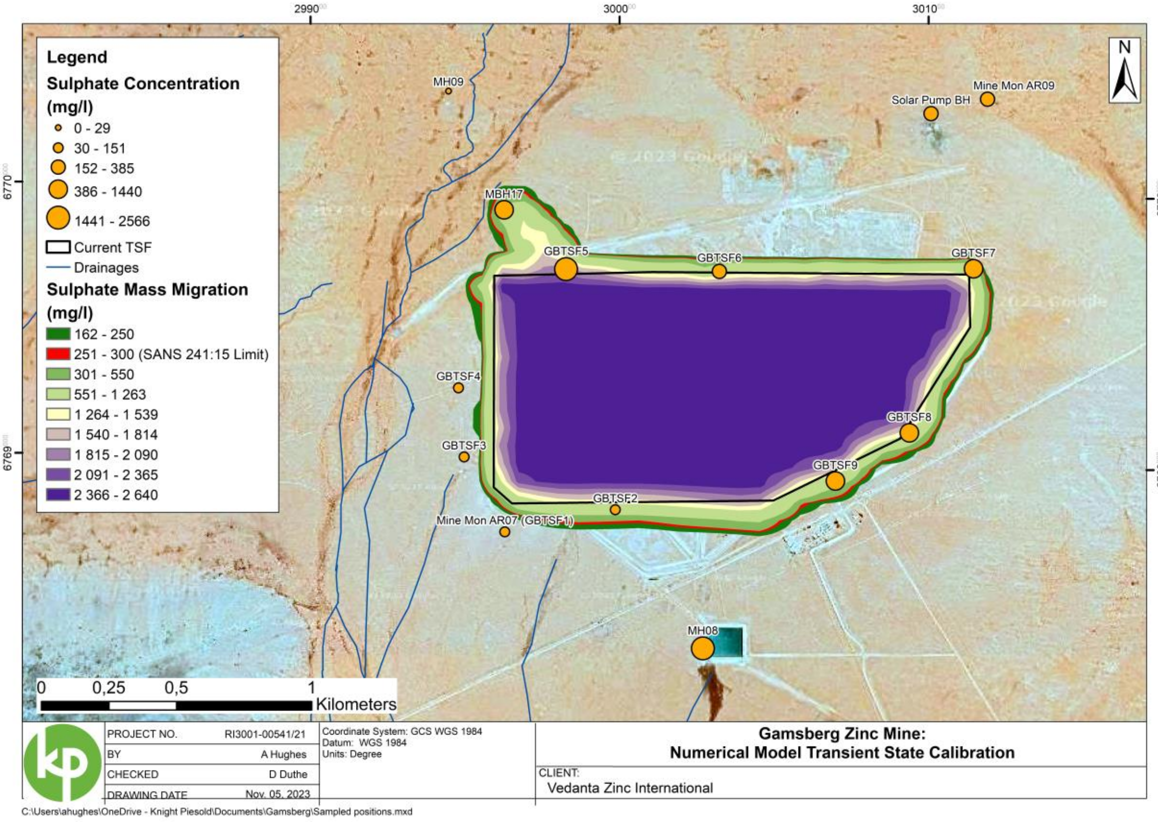

Figure 4-5: Steady State Calibration-Sulphate plume for current TSF operations

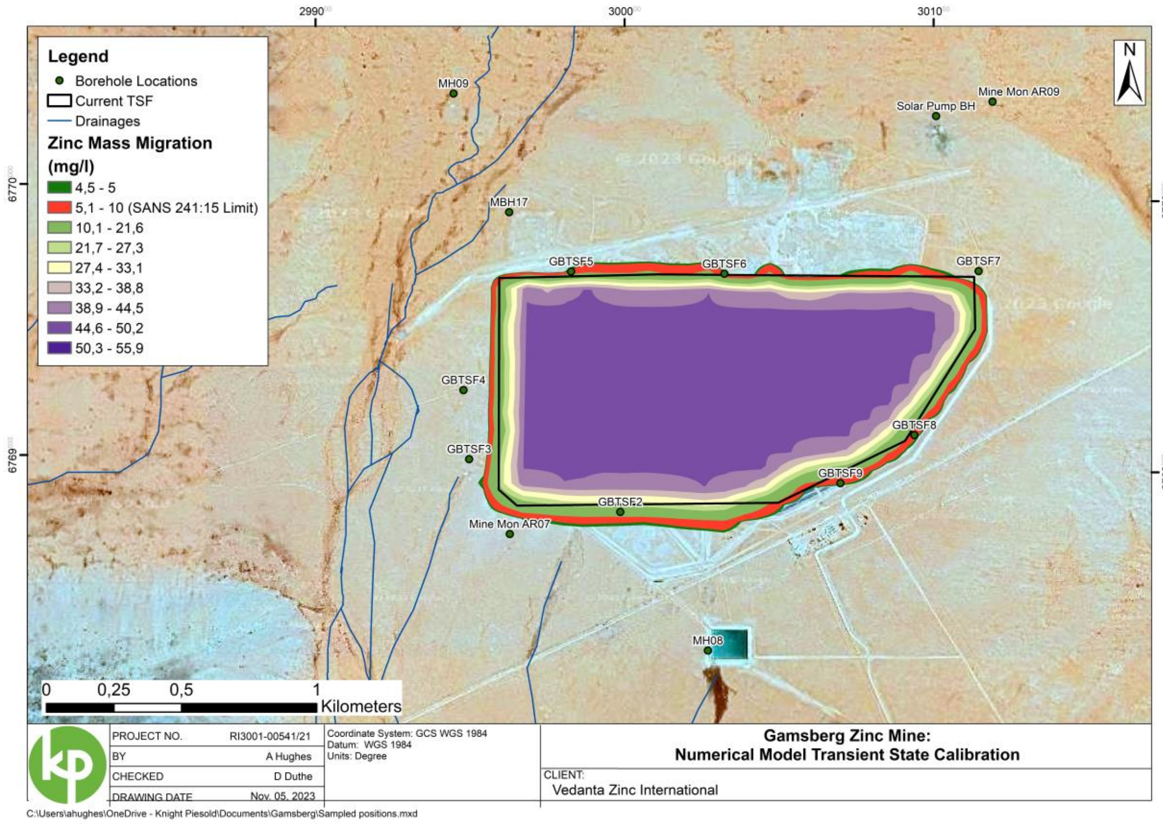

Figure 4-6: Steady State Calibration - Zinc plume for current TSF operations

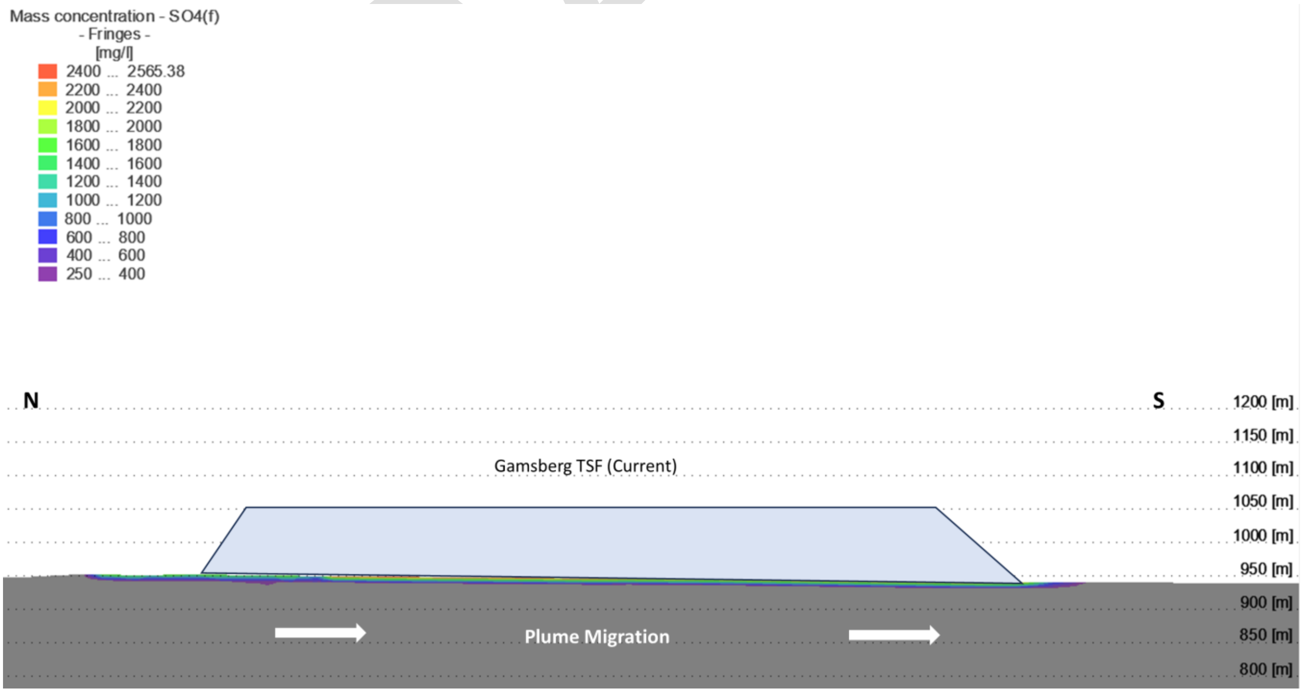

Figure 4-7: Cross section (N-S) through the current TSF sulphate plume for Steady state Calibration

4.3 PREDICTIVE SIMULATIONS-TRANSIENT STATE

As mentioned above, the current monitoring data and calibrated model indicates that seepage from the TSF is occurring along the northwestern boundary. The purpose of the contaminant transport model is to simulate the groundwater flow and associated mass solute migration from the current TSF and TSF Phase 2 extension at Gamsberg Zinc Mine.

The parameters SO_4 and Zn were assigned as a fluid phase that would be subjected to diffusion, dispersion, and advection but no sorption is included. This accounts for the fluid phase degradation as programmed in FEFLOW to ensure the worst case.

The results have been compared to the SANS 241:2015 drinking water limits for the respective parameters of SO_4 and Zn. This allows for any potential contaminant plume and the direction of the plume migration, to be easily identified from the TSF operations.

The predictive modeling simulations included two scenarios namely:

- Scenario 1: Transient simulation of solute transport over a 13-year period for the expected life of design for the TSF extension in operation at Gamsberg Mine
- Scenario 2: Transient simulation of solute transport over a 30-year period for the post mining phase and decommissioning of the TSF operations at Gamsberg mine.

4.3.1 SCENARIO 1: TRANSIENT SIMULATION OF SOLUTE TRANSPORT OVER A 13-YEAR PERIOD FOR THE LIFE OF DESIGN FOR THE TSF EXTENSION

This transient simulation included a 13-year period that represents that expected life of design for the Phase 2 TSF extension at Gamsberg Zinc Mine.

The inputs have remained the same as the calibration input, with additional source concentrations applied to the new TSF extension footprint. The plume has been applied as the 250 mg/l contour for sulphate and 5 mg/l contour for zinc.

The results for this simulation are shown in Figure 4-8 and Figure 4-9 below, based on the Phase 2 TSF life of design at Gamsberg Mine, the following observations are noted;

- After 13 years, the bulk concentrations of SO_4 and Zn within the TSF boundary, indicating the effectiveness of the liner system modelled. The Phase 2 TSF extension (located north of the current TSF) shows no evidence of any plume developing from the TSF, however there is a component of flow towards the south and south west.
- Over the 13-year operational period for the Phase 2 TSF, the main migratory path observed for the modelled parameters (SO_4 and Zn) is towards the south, and south west. The scenario 1 shows that the main component of flow is towards the south while a smaller component of flow is towards the south west and north. It appears that the Phase 2 TSF extension will uptake and to a degree mitigate the plume noted in scenario 1 towards the north west of the current TSF.
- The maximum extent of the potential plume for SO_4 is 185 m towards the south, while the extent towards the south west is 100 m and around 85 m to the north, over the 13 year period. The plume has not migrated much further north west, up to 20m, when compared to the calibrated state. Whereas the potential plume towards the south has migrated up to 80 m. The maximum extent for the Zn plume is 55 m to the north and 125 m to the south, overall the plume for zinc is similar to SO_4 but does not migrate as far.

- Although the hydraulic gradient is towards the S, the results show that any potential plume, for both SO_4 and Zn, will not migrate past the TSF offices, located south of the TSF. And the plume migration towards the north west from the TSF is limited due to the hydraulic gradient. The drainages located west of the TSF are influencing the plume towards the south west from the TSF, however as these are ephemeral rivers the plume does not migrate along the drainages as fast.
- To best show the full extent of the model, a cross section view going from north to south is shown in Figure 4-10. The lateral extent of the plume after 13 years could reach 45 mbgl with the plume flowing in a southerly direction. This simulation shows that the vertical extent of the potential plume could reach the deeper aquifer but will not migrate far (<50 m).
- This simulation shows the potential plume could migrate further towards the south, and towards the south west. However, the potential plume for both SO_4 and Zn has remained localised to the Phase 2 TSF extension, with a low risk to any other groundwater users in the area (private farm boreholes further downgradient).
- The current monitoring network around the TSF should be maintained, this will enable any increase in total dissolved salts to be detected. Based on the second simulation, as the potential plume could migrate further N and SE of the Phase 2 TSF KP recommends that a monitoring borehole be installed north of the TSF, the current boreholes to the east (AR09) can be used as monitoring boreholes once the Phase 2 TSF is constructed.

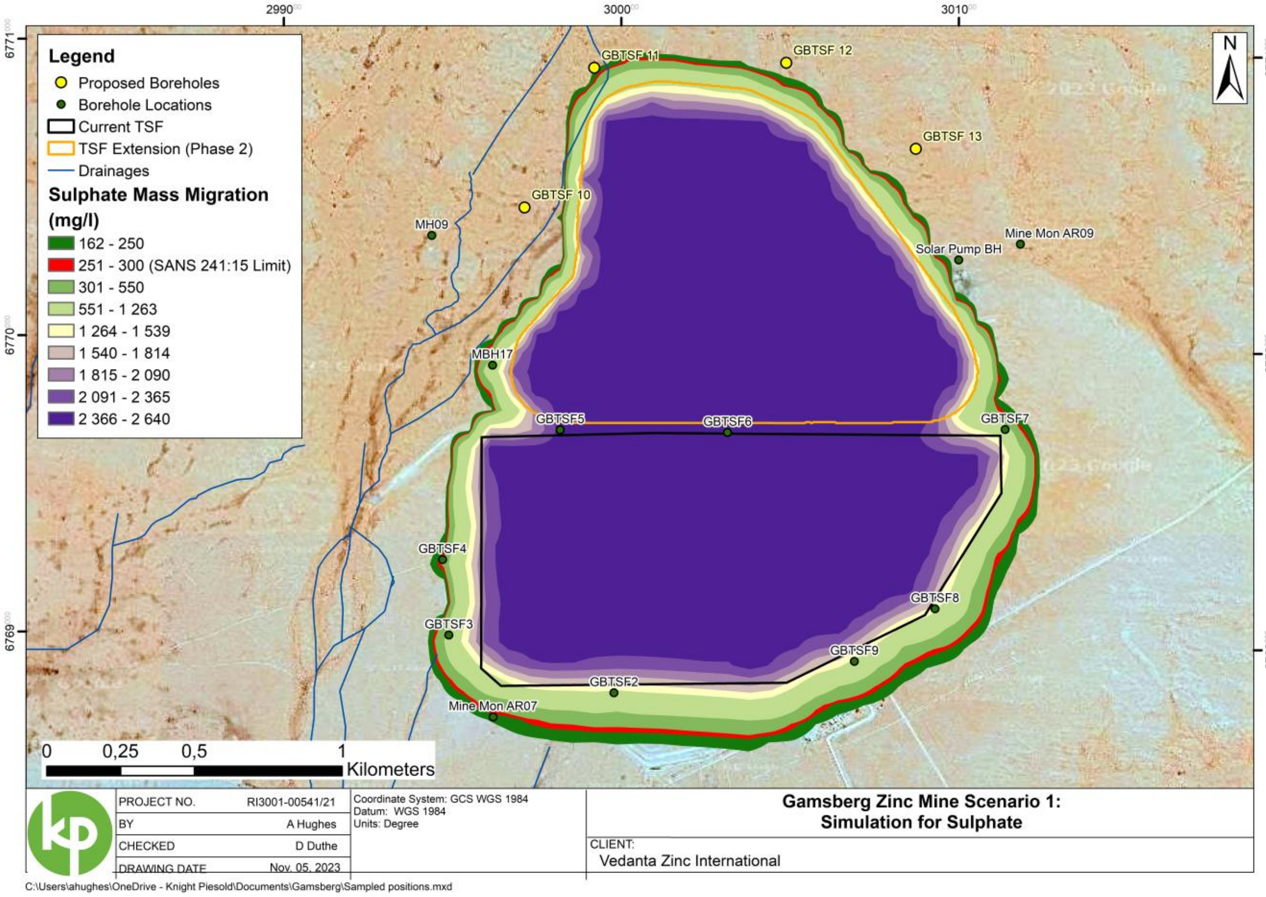

Figure 4-8: Scenario 1-Sulphate plume for TSF Extension Phase 2 operations

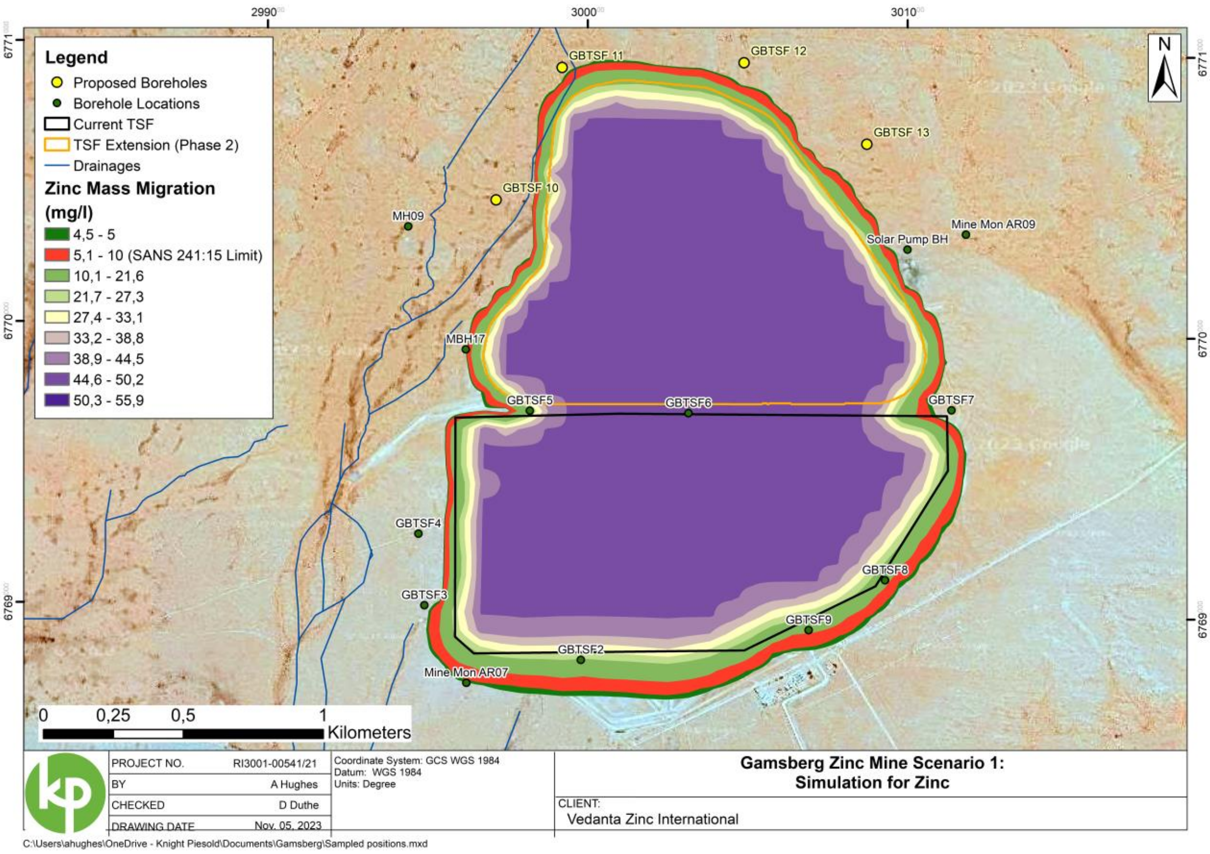

Figure 4-9: Scenario 1-Zinc plume for TSF Extension Phase 2 operations

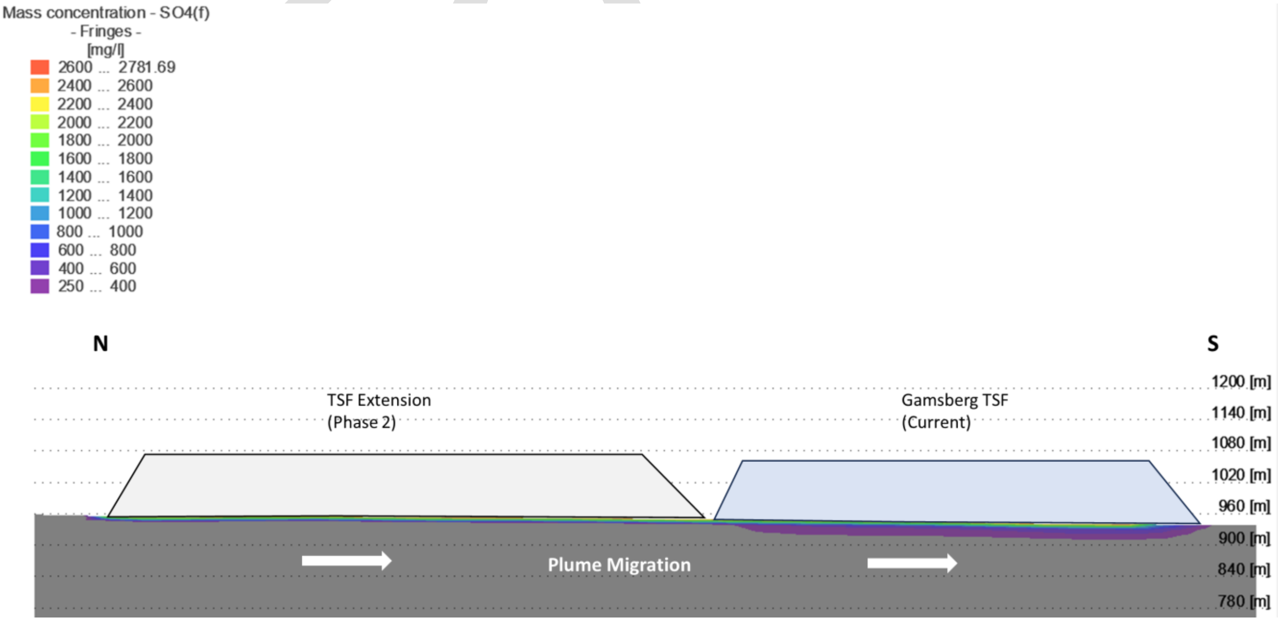

Figure 4-10: Cross section (N-S) through the TSF Extension Phase 2 sulphate plume for Scenario 1

4.3.2 SCENARIO 2: TRANSIENT SIMULATION OF SOLUTE TRANSPORT OVER A 30-YEAR PERIOD FOR THE POST OPERATION PHASE OF THE TSF OPERATIONS

The second transient simulation includes a 30 year period that represents the post operational phase at Gamsberg Zinc Mine. For this scenario the TSFs at Gamsberg Zinc Mine are no longer in operation, with no new deposition occurring.

The model inputs have remained the same as Scenario 1 and 2, with the source concentrations on the Gamsberg TSFs remaining at the worst-case scenario i.e. 2500 mg/l and 45 mg/l for SO_4 and ZN respectively. However, the increased recharge component (flux) has been removed from the TSFs for this simulation as deposition has stopped on the TSFs.

The results are shown in Figure 4-11 and Figure 4-12 below. Based on the post operation phase at Gamsberg Zinc Mine the following observations are noted:

- After 30 years, the bulk concentrations of SO_4 and Zn have remained within the TSF boundary, this has been observed for both Scenario 1 and 2, which indicates the effectiveness of the liner system modelled.
- Similar to Scenario 1, there are 2 migratory flow paths observed for modelled parameters (SO4 and Zn) towards the south and a smaller component towards the south west and north for the Scenario 2.
- The maximum extent of the potential plume for SO_4 and Zn is 55 m towards the north, the plume has not migrated much further north, up to 5m, when compared to the operational phase (scenario 1). While the potential plume towards the south has migrated up to 251 m, and the potential plume towards the south west has migrated up to 195 m. The potential plume towards the south has migrated past the current TSF offices, while the potential plume to the south west has migrated past the borehole GBTSF3. Like scenario 1, the potential plume does not migrate further along the drainages located west of the TSF as they are ephemeral rivers however following a heavy rainfall event the potential plume to the south west could be exacerbated by drainages.
- The results show that the potential plume for SO_4 will migrate past the TSF offices, located to the south over the 30-year period, however the potential plume for Zn will just reach the offices .
- A cross section view going from north to south is shown in Figure 4-13. The lateral extent of the plume after 30 years could reach 55 mbgl with the plume flowing in a southerly direction. This simulation shows that the vertical extent of the potential plume could reach the deeper aquifer. However, the plume does not migrate far away from the TSFs and does not pose any risk to the groundwater users (private farm boreholes) located further downstream.
- This simulation shows the potential plume could migrate further towards the south and south west. However, the potential plume for both SO_4 and Zn has remained localised to the Phase 2 TSF extension (>260 m), with no threat to any other groundwater users in the area (further downgradient).

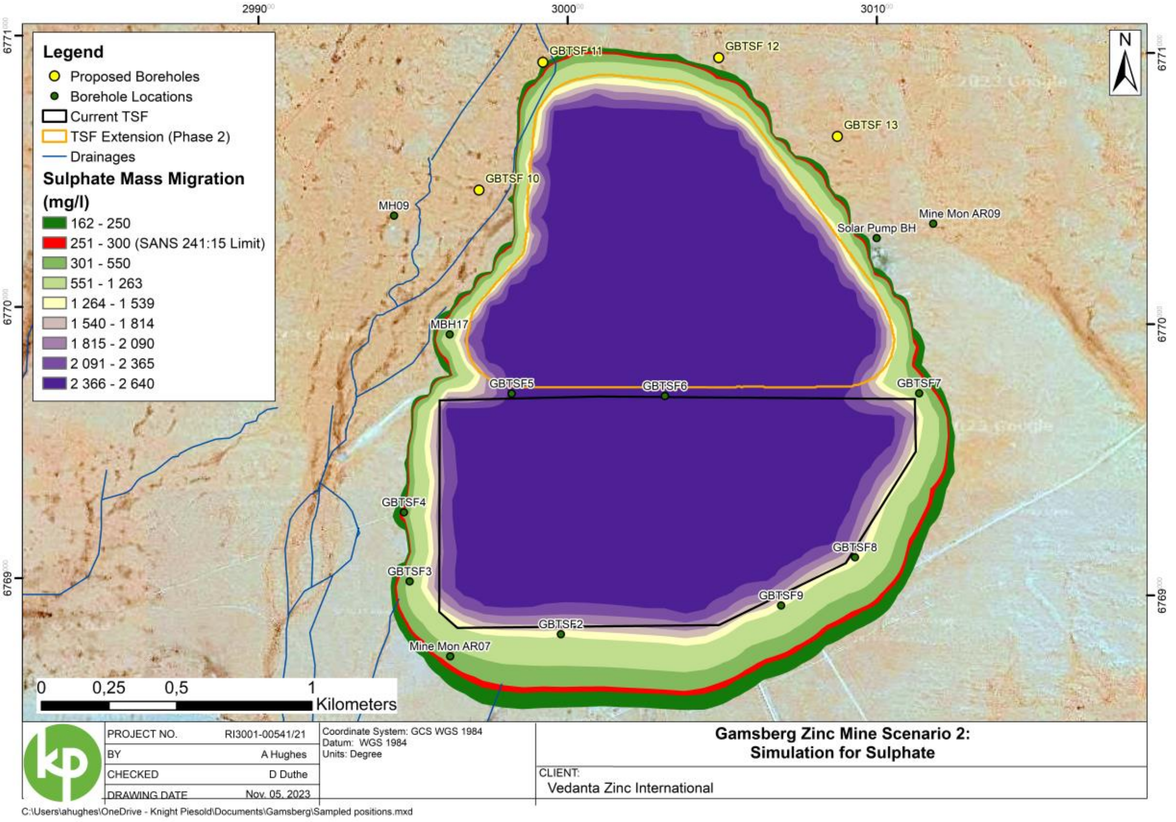

Figure 4-11: Scenario 2-Sulphate plume for TSF Extension Phase 2 post operations

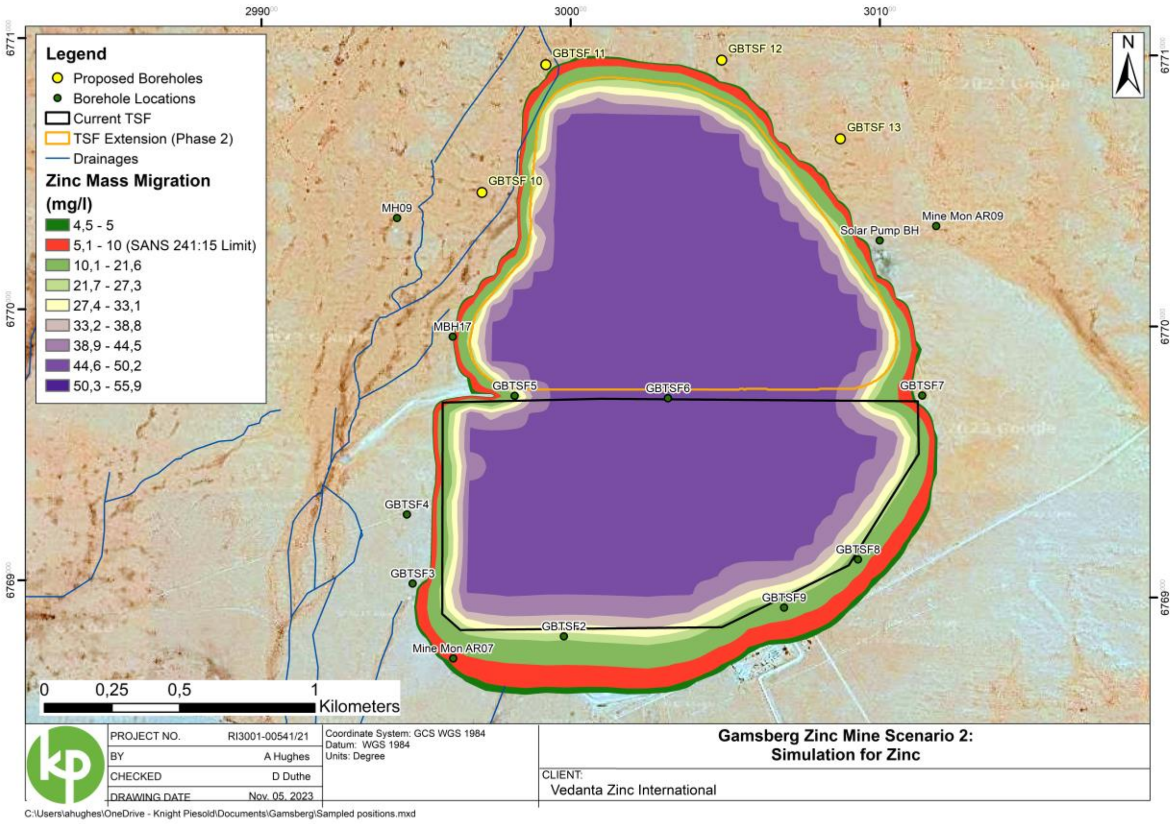

Figure 4-12: Scenario 2-Zinc plume for TSF Extension Phase 2 post operations

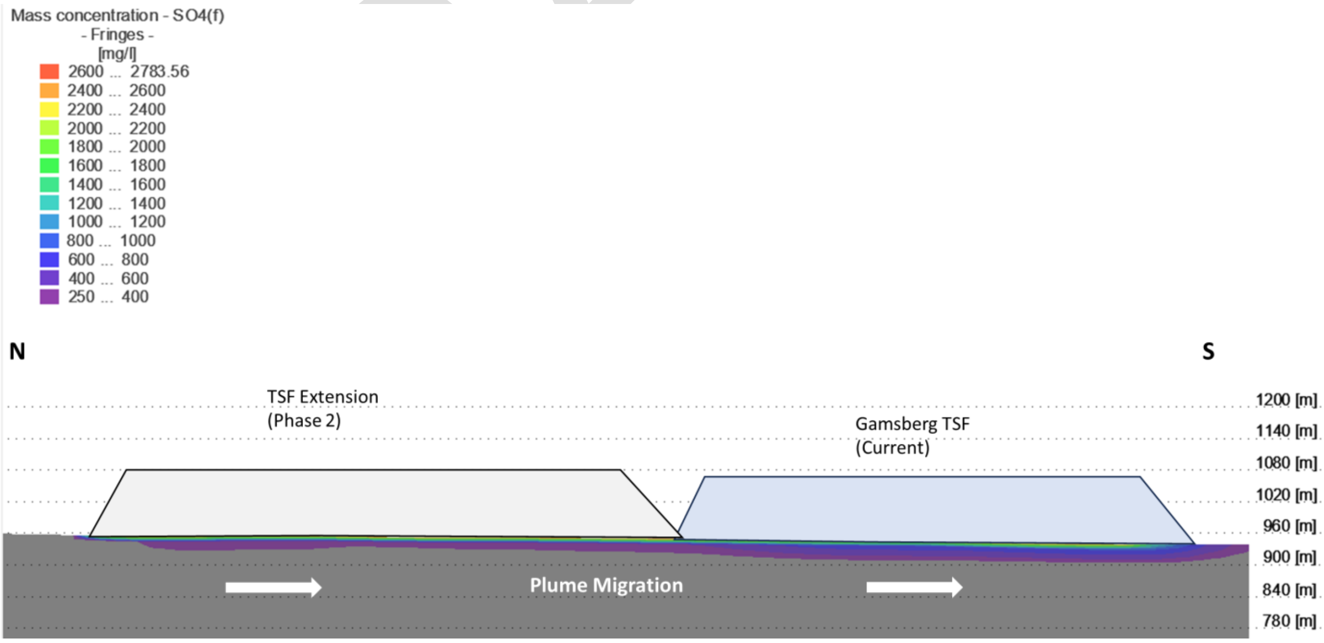

Figure 4-13: Cross section (N-S) through the TSF Extension Phase 2 sulphate plume for Scenario 2

5.0 CONCLUSIONS AND RECOMMENDATIONS

BMM has appointed Knight Piésold (Pty) Ltd (KP) to develop a Contaminant Transport Model (CTM) as part of the hydrogeological study, for the expansion of the Gamsberg TSF (Phase 2). The numerical model and contaminant transport model was developed in 2023.

The conceptual hydrogeological model was developed to illustrate the current groundwater conditions around the TSF and the expected groundwater conditions due to the Phase 2 TSF expansion. The current drawdown cone of the pit sumps does not impact the TSF area, it has remained highly localised to the pits. The non-perennial (ephemeral) river that flows towards the south and along the western boundary of the TSFs at Gamsberg, could act as a preferential flow pathway due to the higher hydraulic conductivities of the shallow aquifer.

Seepage from the current TSF has migrated to the northwest but has remained localised (>200m). The Phase 2 TSF extension will be developed further north of the current TSF and will overlap the current plume extent. The mass solute plume formed by the integrated TSFs is likely to seep towards the south.

Although the future underground development at Gamsberg will increase the dewatering, the future drawdown cone is not expected to impact the TSF area.

The available hydrochemical data from Gamsberg Zinc Mine, shows that the boreholes located north west of the current TSF show elevated concentrations of total dissolved salts particularly SO_4, Na and Cl. A geophysical study conducted by KP around the current TSF suggests that the old haul road may have compromised the liner system. The old road and borrow pits located in the north west during the TSF construction have likely created a preferential flow path for any leakage from the TSF to flow.

A geochemical model was developed by Millswater, to predict the long-term evolution of any TSF seepage quality and reactions with the groundwater. The model outcomes showed a best case and a worst-case scenario for the TSF seepage. The results from both predicted scenarios were incorporated into the numerical contaminant transport model.

A numerical groundwater model of the current TSF at Gamsberg Zinc Mine was constructed to evaluate the potential impacts on the groundwater system and potential receptors surrounding the TSF. The 3-D numerical flow and contaminant transport model was designed using the programme FEFLOW, to determine the possible extent of migration of any potential contaminant plume for the current and Phase 2 TSF extension at Gamsberg Zinc Mine. Two scenarios were included in the contaminant transport model:

- The first scenario is representative of the life of design for the Phase 2 TSF extesnion at Gamsberg Zinc Mine
- The second scenario includes the post operational phase at Gamsberg Zinc Mine

To calibrate the model, input data was obtained from various studies, reports (monitoring, geochemical, geotechnical, and hydrological) on the Gamsberg Zinc Mine. The steady-state flow calibration was conducted by making minor changes to the model input parameters, mainly the permeability and recharge as well as the storage coefficients to simulate the current groundwater flow conditions.

- The current groundwater monitoring data for the boreholes surrounding the TSF were incorporated into the steady state calibration, the groundwater concentrations for SO_4 and Zn were used to ensure that the developed plume is consistent with the actual groundwater concentrations. Although the TSF has been lined with a HDPE geomembrane liner system, as a worst-case scenario, the TSF was modelled with circular defects or tears i.e. represent leakage from the liner. The transient state calibration represents a six-year period for the current operational phase of the TSF at

Gamsberg Zinc Mine. Over the six-year period, two solute migratory patterns for both parameters (SO_4 and Zn) are evident with flow towards the north west and south. The main component of the plume is located towards the south, while a small component of flow is evident towards the north west and south west. The modelled concentrations were consistent with the borehole data, and the initial calibration was finalised.

The first transient simulation included a 13-year period that represents the expected life of design for the Phase 2 TSF extension at Gamsberg Zinc Mine. The inputs have remained the same as the transient state calibration input, with additional source concentrations applied to the new TSF extension footprint.

The second transient simulation includes a 30-year period that represents the post operational phase at Gamsberg Zinc Mine. For this scenario the TSFs at Gamsberg Zinc Mine are no longer in operation, with no new deposition occurring. The model inputs remained the same for this scenario, with highest source concentrations assigned to the TSF facilities, however the increased recharge component on the TSF was removed.

Both the scenarios show that the lined TSF, both current and Phase 2 extension, have kept the high concentrations within their boundaries, showing the effectiveness of the modelled liners.

The modelled simulations (Scenario 1 and 2) show migratory paths of the potential plume from the TSF sources towards the south and south west, as well as towards the north. The hydraulic gradient is towards the south for this area and is the expected direction for any potential plume to migrate.

Overall, the spatial extent of the modelled plumes is within a 260 m radius of the TSF, both the current and Phase 2 extension. The vertical extent of the plume for the TSF could reach a 55 mbgl, indicating the potential to impact the shallow and deep aquifers local to the area. The current simulations show that the risk of the potential contaminant plume from the TSF impacting any groundwater users is low.

Following the development of the numerical model at Gamsberg Zinc Mine, KP recommends the following:

- Continue the quarterly groundwater monitoring at Gamsberg Zinc Mine, this will ensure that any leak and/or contamination will be detected, and the correct mitigation measure can be implemented effectively.
- The current borehole monitoring network infrastructure must be maintained at the Gamsberg Zinc Mine, particularly the boreholes surround the TSF to identify any increasing trends. Particularly north west of the current TSF.
- The numerical flow and transport model should be updated annually with the new monitoring data as a management tool so that any mitigation that may be required can be modelled and planned timeously.
- Several of the boreholes could be used as potential scavenger boreholes to act as seepage capture for future operations if required. Particularly the boreholes located south and south west of the TSFs (GBTSF 3,4,8,9 and AR07).
- Following the construction of the Phase 2 TSF extension, it is recommended that monitoring boreholes are installed north of TSF to ensure that any leak and/or contamination is detected. Four proposed locations are identified in scenario 2, these positions further north of the Phase 2 TSF extension (GBTF 10-13)
- The numerical model should be updated once the remediation plan for the TSFs post closure is finalised. This will allow for a better prediction for any potential plume for the post operation phase at the Gamsberg Zinc Mine.

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7.0 CERTIFICATION

This report was prepared and reviewed by the undersigned.

Prepared:

Aidan Hughes, Pri.Sci.Cand
Hydrogeologist

Reviewed:

Reviewer, P.Eng./R.P.Bio./P.Geo.
Title

Approval that this document adheres to the Knight Piésold Quality System:

APPENDIX A

Gamsberg TSF Waste Assessment

APPENDIX B

Geochemical Model for Gamsberg TSF Extension

(Pages A-1 to A-Xx)