HARMONY GOLD MINING COMPANY LIMITED

GEOHYDROLOGICAL IMPACT ASSESSMENT FOR THE PROPOSED VALLEY TAILINGS FACILITY, FREE STATE PROVINCE

FINAL REPORT

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1. INTRODUCTION AND TERMS OF REFERENCE

Harmony Gold Mining Company Limited (Harmony) own and operate a number of Gold Mines and Plants in the Welkom region in the Free State Province. Harmony's One Plant is located south of the town Welkom. The plant is currently depositing half of its residue onto the Free State South (FSS) 2 Tailings Storage Facility (TSF) and the other half onto the recommissioned St. Helena 4 TSF. These two facilities have deposition capacity until the end of June 2024 at which time another deposition site will be required to accept the residue from One Plant.

A new deposition site will be required for Harmony One Plant to replace the FSS2 and St. Helena 4 TSFs by July 2024. Several alternative sites were identified and assessed as possible suitable deposition sites for the tailings from Harmony One Plant after June 2024 but was found not feasible. Following a review of other possibilities for One Plant's future tailings deposition, an option to utilise the space between the Free State North 1 (FSN) and Free State North 2 (FSN) TSFs and portion of the footprint of the FSN4 TSF has been identified as possible deposition site, referred to as the Valley TSF.

Geotheta (Pty) Ltd (Geotheta) was appointed by Harmony Gold Mining Company Ltd (Harmony) to redesign the Valley TSF decant, solution trench and return water dam (RWD) at the Free State Operations. Geotheta previously did a design for the Valley TSF and its two return water dams in March 2024. The previous design included a new lined 'Valley Return Water Dam' to the north in the location of the existing FSN2 RWD and the unlined FSN1 RWD.

The previous design of the Valley TSF was subsequently altered to only utilise and line the FSN1 RWD, which would then be known as the new Valley Return Water Dam. The construction of the new Valley RWD will involve managing stormwater effluent from the dormant FSN1 TSF in the existing FSN1 RWD while the new Valley RWD is under construction. This will be done by creating two compartments within the existing FSN1 RWD by utilizing the existing divisional wall. Each compartment will be isolated by extending the divisional wall to the perimeter embankments and the dam constructed sequentially on one compartment while the other will be used to collect stormwater from the FSN1 TSF (Geothea, 2025).

Harmony appointed Environmental Impact Management Services (EIMS) to obtain all the required authorisations for the proposed Valley TSF. EIMS sub-contracted MVB Consulting to conduct a geohydrological study to assess the potential groundwater impacts associated with the proposed deposition of gold tailings.

The purpose of the study is to assess the potential impact from the proposed TSF on the groundwater regime. A calibrated numerical groundwater flow and mass transport model was developed to simulate the potential impacts.

The deliverables from the study include the following:

- Conceptual model.
- Baseline groundwater quality interpretation.
- Numerical groundwater flow and mass transport model to the potential impacts over time.
- Proposed mitigation measures to minimise impacts on the groundwater system during operational and post-closure phase.
- Design of a structured groundwater monitoring programme, incorporating the available boreholes as well as recommended new boreholes, if necessary.

2. GEOGRAPHICAL SETTING

2.1 Locality of the Study Area

The proposed Valley TSF is located approximately 8km northwest of Welkom in the Free State Province.

Figure 2.1 shows the regional locality and Figure 2.2 shows the proposed tailings layout.

2.2 Topography and Drainage

The area is part of the Highveld region and has an average elevation of about 1340 metres above mean sea level (mamsl). The study area is flat with a gentle decrease in elevation to the west and southwest at a gradient of 0.3% and 0.5% respectively (Figure 2.3). There are no prominent topographical landmarks in the area although pans are a feature of the area (Avgold Target Division EMP).

The proposed TSF falls within quaternary catchment C43B although a very small portion falls within sub-catchment C25B. The area is drained by the Mahemspruit (C43B) and the Sandspruit (C25B). The drainage area forms part of the Middle Vaal Water Management Area.

2.3 Climate and Rainfall

The area is termed as the ‘Northern Steppe’ and is characterised by a dry climate where the potential evaporation is usually 4 times the mean annual precipitation; water shortages are common (Avgold Target Division EMP).

The climate is of a typical Highveld type with high temperature differences between winter and summer. The average daily temperature fluctuates from a mean maximum of 30°C in mid-summer to 17°C in mid-winter, with highs of 39°C and lows of up to -7°C (Avgold Target Division EMP).

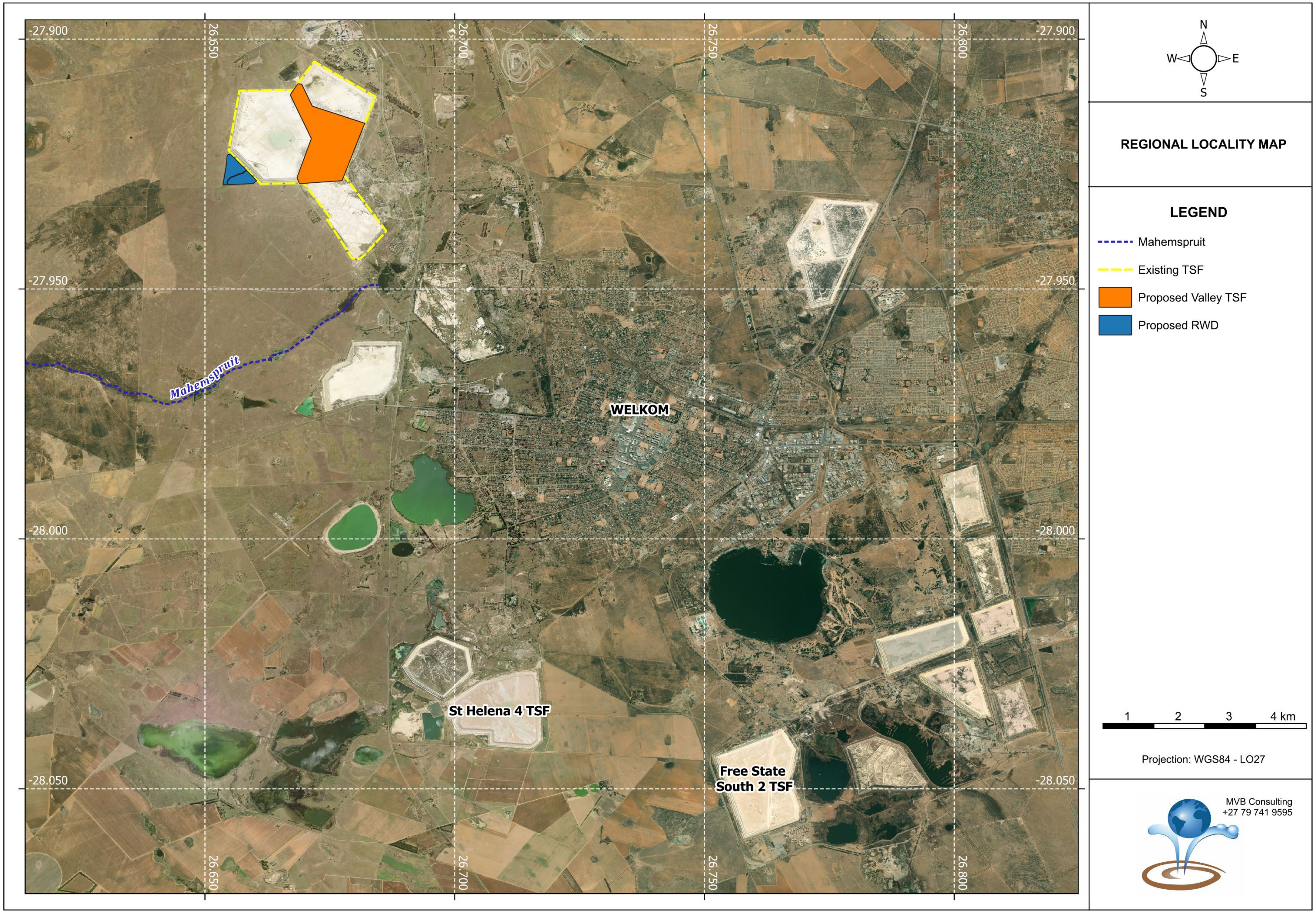

Figure 2.1: Regional locality map

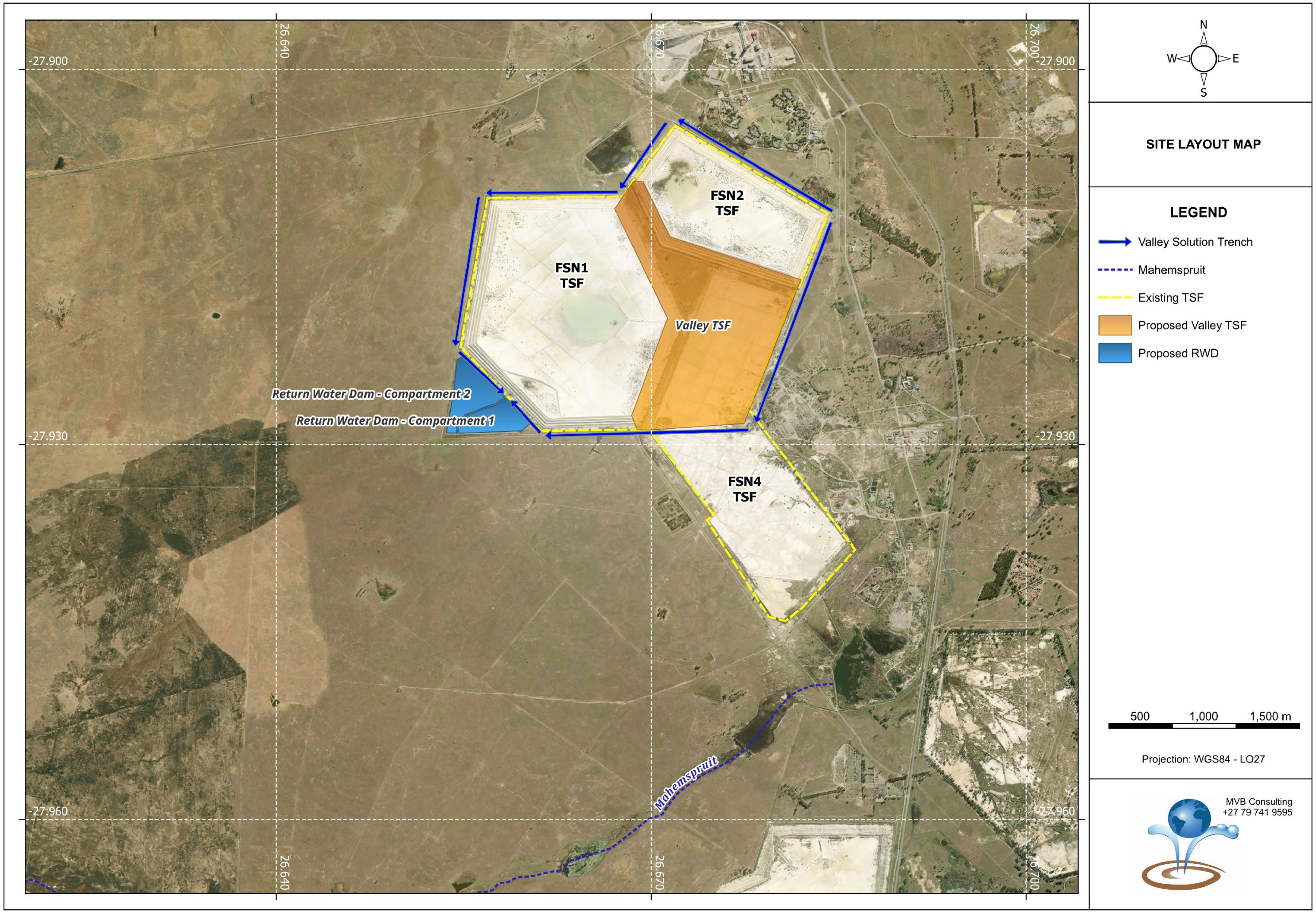

Figure 2.2: Site layout

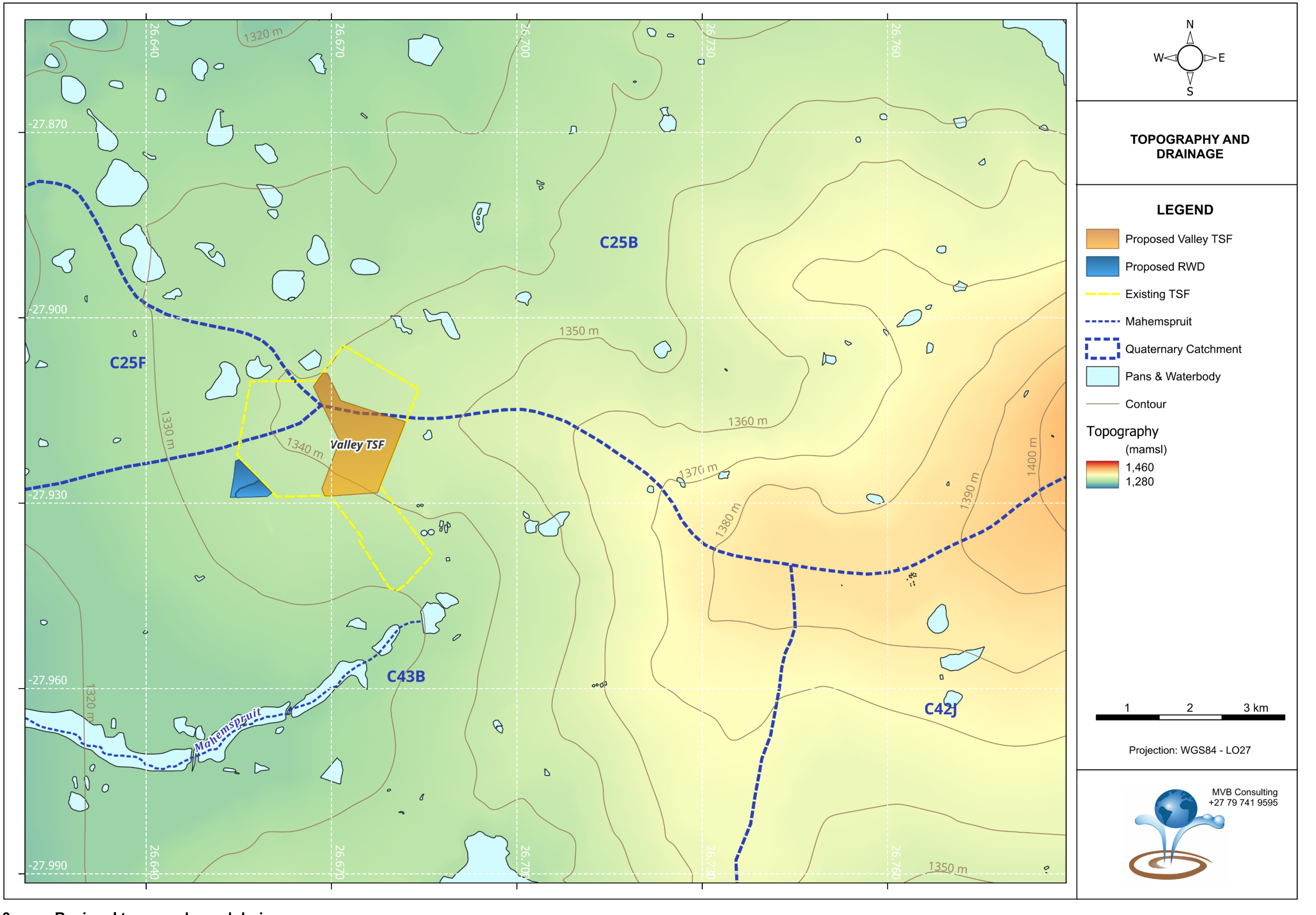

Figure 2.3: **Regional topography and drainage**

Precipitation is important to groundwater studies since it provides the mechanism that may lead to subsurface infiltration (groundwater recharge). The average monthly rainfall figures for the region, as per the IWWMP (2015), are presented in Table 2.1 and Figure 2.4.

Table 2.1: Average monthly rainfall

Month	Average Rainfall (mm)
Jan	69
Feb	84
Mar	67
Apr	50
May	14
Jun	7
Jul	6
Aug	10
Sep	22
Oct	57
Nov	80
Dec	72
Total	**538**

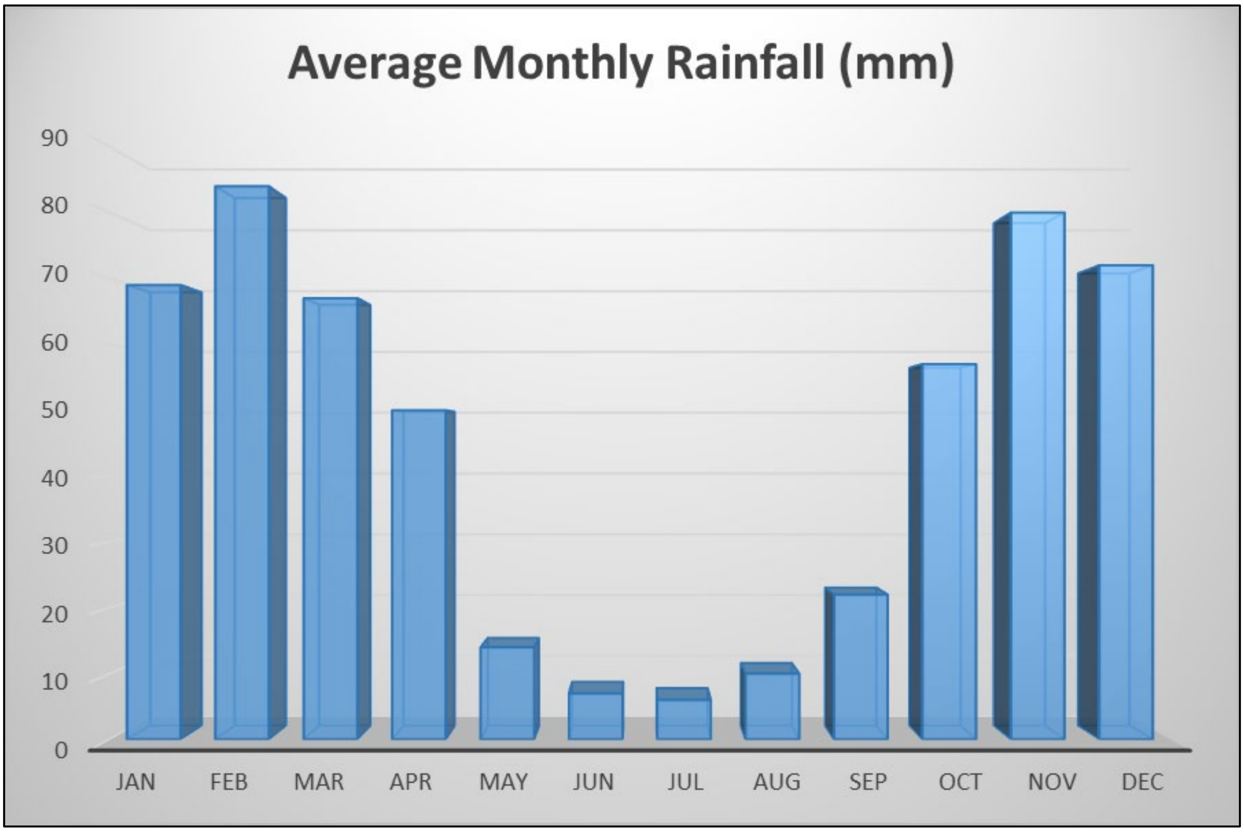

Figure 2.4: Average monthly rainfall

Rainfall occurs predominantly in the summer months, typically from October to April. The average annual total amounts to 538 mm/annum.

3. CONCEPTUAL GEOHYDROLOGICAL MODEL

3.1 Geological Setting

The Free State Goldfield, which forms as triangle between Allanridge, Welkom and Virginia, produces gold from auriferous bearing reefs situated within sediments of the Central Rand Group of the Witwatersrand Supergroup. A detailed description of the geology of the Welkom Goldfields is provided by in Minter et. al; (1986). The mine geology, from shallow to deep, consist of the following (Figure 3.1):

- Karoo Supergroup.
- Ventersdorp Supergroup.
- Witwatersrand Supergroup.

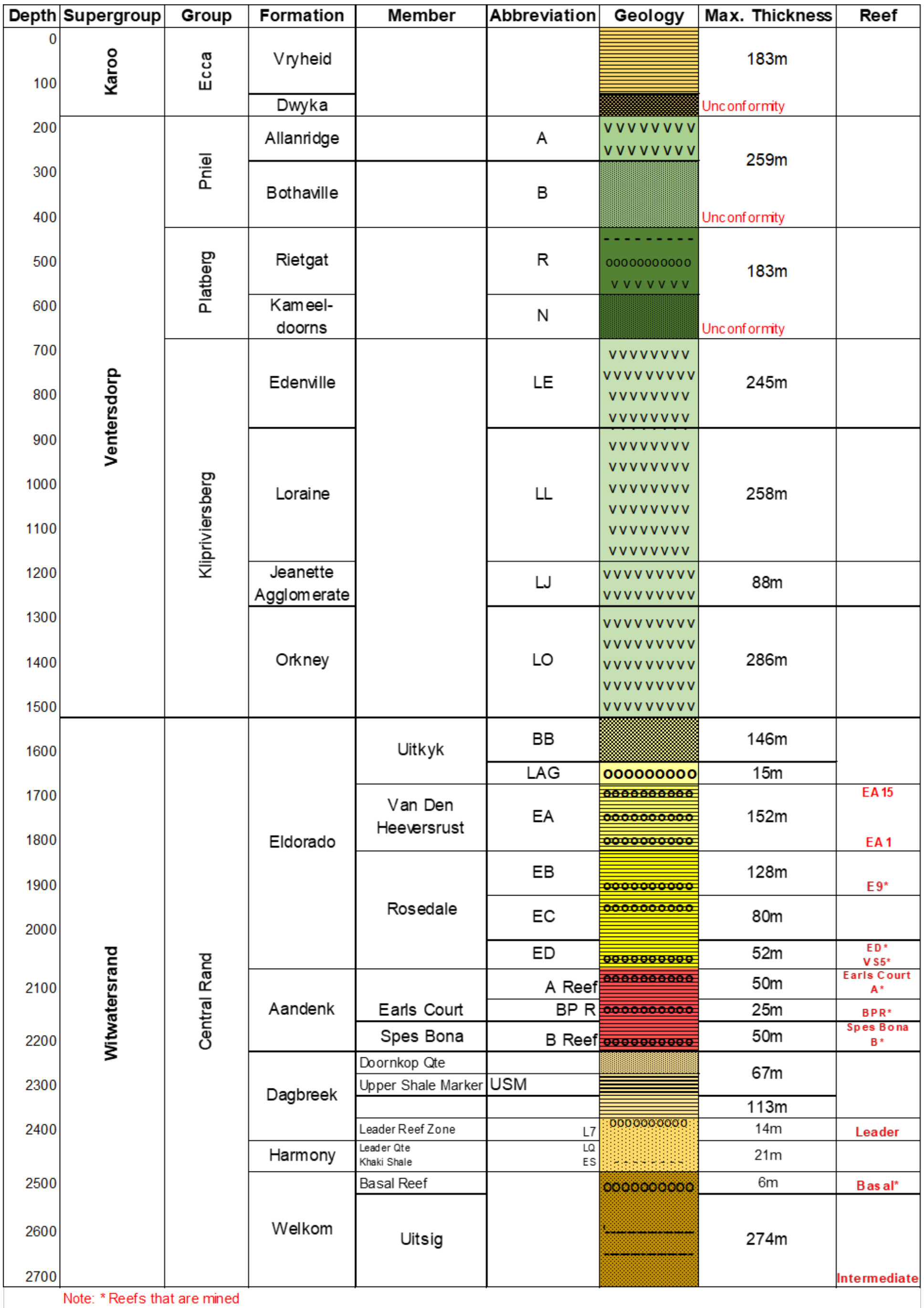

Figure 3.1: Stratigraphy of the Free State Golffields

3.1.1 Karoo Supergroup

Sediments of the Vryheid Formation of the Ecca Group underlie the study area (Figure 3.2). The Vryheid Formation (Ecca Group) mainly comprises mudstone, siltstone and fine- to coarse-grained sandstone (pebbly in places).

According to Tankard et. al. (1982) the Ecca Group (Vryheid Formation) overlies the Dwyka Formation gradationally and comprises predominantly clastic sediments deposited in an extensive landlocked basin experiencing only rare marine incursion. Steyn and Beukes (1977) described the lower Vryheid Formation as upwards-coarsening shale and sandstone cycles, which represent prograding deltaic environments. This in turn is overlain by upwards-fining sandstone and shale cycles, which are of a fluvial origin. The coal beds, which were deposited in the back swamps of meandering river systems, cap the Lower Vryheid lithologies. The depositional environment is believed to be a dendritic channel system that resulted in the deposition of more arenaceous material in the active channels and mud and coal deposited on their floodplains.

Channel closure led to the filling of channels by mud, the establishment of swamps and the deposition of coal beds within them. Similar deltaic and fluvial processes characterise the sediments overlying the coal seams, consisting mainly of alternating sequences of shale and sandstone. The more competent sandstone formations can result in localised hilly terrains. The surface and near surface lithologies comprise topsoil, weathered sandstone and dolerite. The latter is important as it generally forms an impermeable layer, affecting groundwater flow.

Although not exposed on surface the Dwyka Formation underlies the Ecca Group. The Dwyka sediments were deposited during late Carboniferous to early Permian times by glacial processes. The group consists mainly of diamictite (tillite), which is generally massive with little jointing, but it may be stratified in places. The Dwyka diamictite consists of angular to rounded clasts of basement rock embedded in a clay and silt matrix. Individual clasts measure up to 3m in diameter. Subordinate rock types are conglomerate, sandstone, rhythmite and mudstone (both with and without dropstones).

From a groundwater perspective, the Dwyka is considered a very low permeable horizon and classified as an aquiclude. This unit forms a barrier between the upper Karoo aquifer and the lower Witwatersrand aquifer. A review of the geological exploration boreholes confirmed the presence of the Dwyka, which varies in thickness between 7m – 28m (borehole VDH6, farm Van den Heeversrust 419).

Dolerite intrusions are common in this type of geological terrain and represent the roots of the volcanic system and are presumed to be of the same age as the extrusive lavas (Fitch and Miller, 1984). The level of erosion that affected the Main Karoo basin has revealed the deep portions of the intrusive system, which displays a high degree of tectonic complexity. The Karoo dolerite, which includes a wide range of petrological facies, consists of an interconnected network of dykes and sills and it is nearly impossible to single out any particular intrusive or tectonic event. It would, however, appear that a very large number of fractures were intruded simultaneously by magma and that the dolerite intrusive network acted as a shallow stockwork-like reservoir.

Based on the exploration drilling the Karoo Supergroup has an average thickness of 183m in the study area.

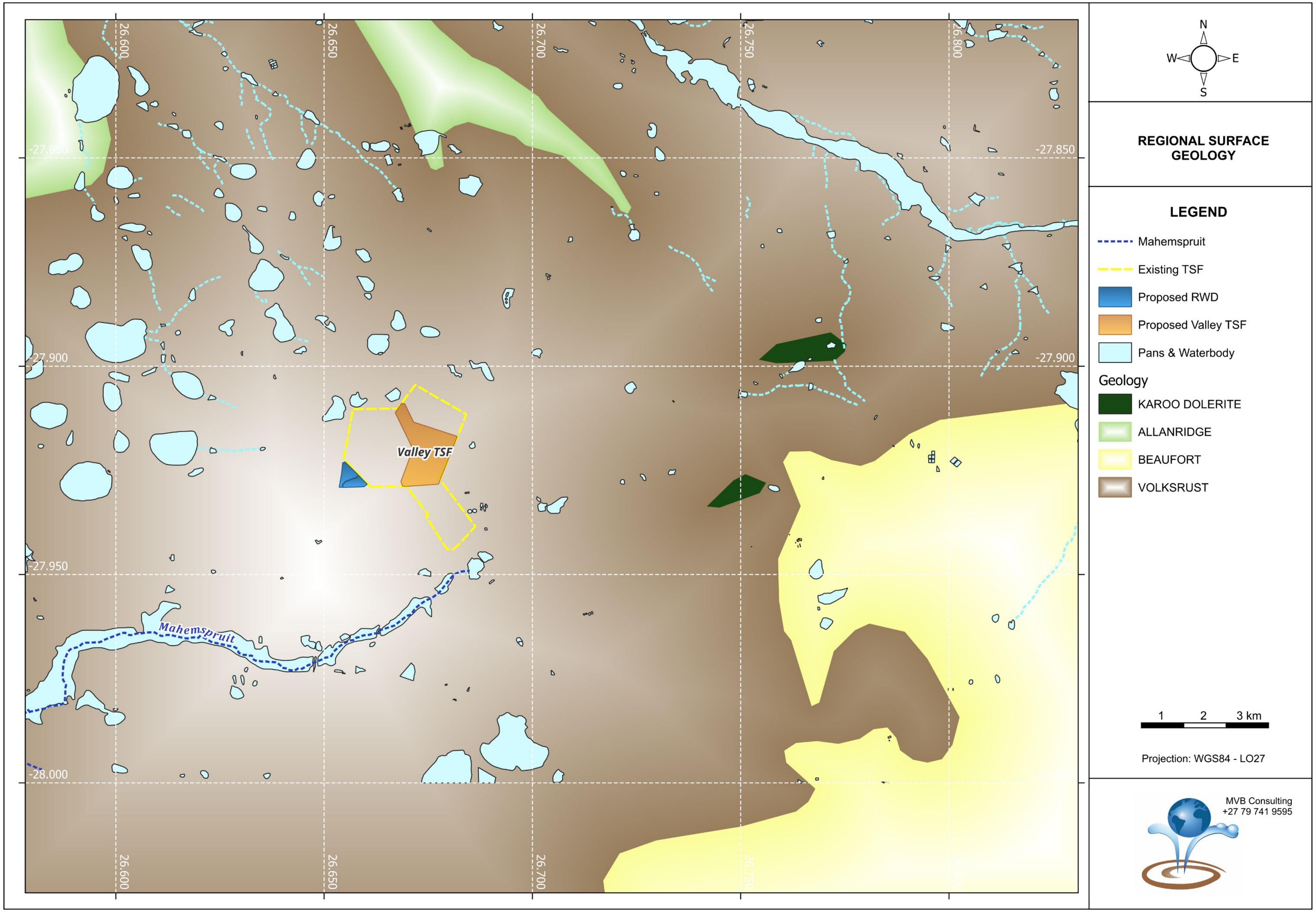

Figure 3.2: Regional surface geology

3.1.2 Ventersdorp Supergroup

The Witwatersrand Supergroup is unconformably overlain by the volcanic and sedimentary rock of the Ventersdorp Supergroup.

Within the Free State Goldfield, the Ventersdorp Supergroup can be divided into the Pniel sequence, the Platberg Group and the basal Kliprivierberg Group consisting of alternating sediments, amygdaloidal and non-amygdaloidal andesitic lavas, tuffs and agglomerates (Minter et.al; 1986).

Based on the exploration drilling the Ventersdorp Supergroup has an average thickness of 1 319m in the study area.

3.1.3 Witwatersrand Supergroup

Within the Free State Goldfield, the Witwatersrand Supergroup, comprising a thick succession of clastic sediments with minor intercalated lava flows, rests on the granites and schist of the Archean Basement. The Central Rand Group of the Witwatersrand Supergroup contains the economic reef horizons mined throughout the basin. The Central Rand Group is dominated by quartzite with minor shale and conglomerate. Several unconformities in the succession are overlain by the economic auriferous paleoplacers (reefs).

The Central Rand Group has been divided into an upper Turffontein Subgroup comprising the Eldorado and Aandenk Formation and a lower Johannesburg Subgroup comprising the Dagbreek, Harmony, Welkom, St Helena and Virginia Formations (see Figure 3.1).

3.2 Geohydrological Setting

The geohydrological setting and conceptual model of the study area is described according to the following criteria:

- Borehole information.
- Aquifer type.
- Groundwater use.
- Aquifer parameters.
- Aquifer recharge.
- Groundwater gradients and flow.
- Groundwater quality.
- Aquifer classification.

3.2.1 Borehole Information

During a study conducted by Golder Associates in 2009 eighteen new boreholes were drilled to assess the groundwater regime underlying the Valley TSF. Information from these boreholes was used to conduct the geohydrological assessment. The localities of the boreholes are shown on Figure 3.3. The borehole information is summarised in Table 3.1.

Table 3.1: Borehole Information (Golder Associates, 2009)

ID	X	Y	Z	Depth (mbc)	Water Level (mbc)
BH1	26.65620	-27.92963	1335	90	5.50
BH2	26.65627	-27.92970	1331	36	6.41
BH3	26.65732	-27.94308	1334	73	54.03
BH4	26.65735	-27.94312	1336	24	Artesian
BH5	26.64065	-27.93760	1327	73	Dry
BH6	26.64062	-27.93755	1330	23	17.99
BH7	26.64061	-27.93019	1336	73	72.38
BH8	26.64057	-27.93023	1336	26	20.87
BH9	26.67978	-27.94499	1330	73	4.12
BH10	26.67975	-27.94496	1329	23	6.47
BH11	26.67250	-27.90450	1350	68	Artesian
BH12	26.67256	-27.90454	1348	27	Artesian
BH13	26.68095	-27.90938	1354	73	52.48
BH14	26.68097	-27.90936	1349	29	2.02
BH15	26.68849	-27.91220	1353	73	52.13
BH16	26.68845	-27.91220	1352	30	Dry
BH17	26.67954	-27.92358	1345	73	40.06
BH18	26.67952	-27.92365	1345	29	4.03

Note: *mbc = metres below casing*

Subsequent to the Golder study new boreholes were drilled, which are currently used for groundwater monitoring. There is no information available on the new borehole and it appears if the Golder boreholes no longer exist. The current monitoring network is presented in Figure 3.4.

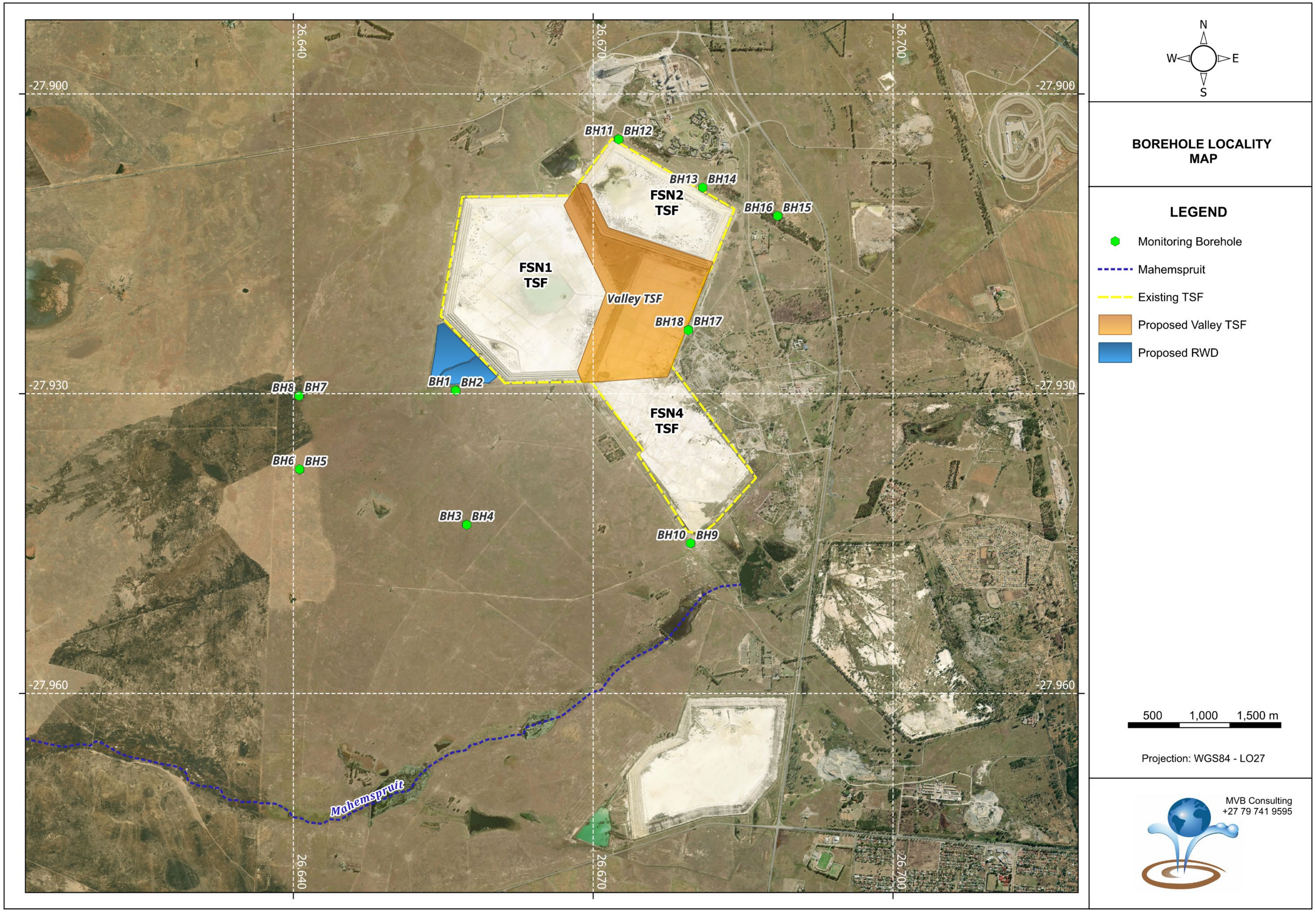

Figure 3.3: **Valley TSF boreholes (Golder Associates, 2009)**

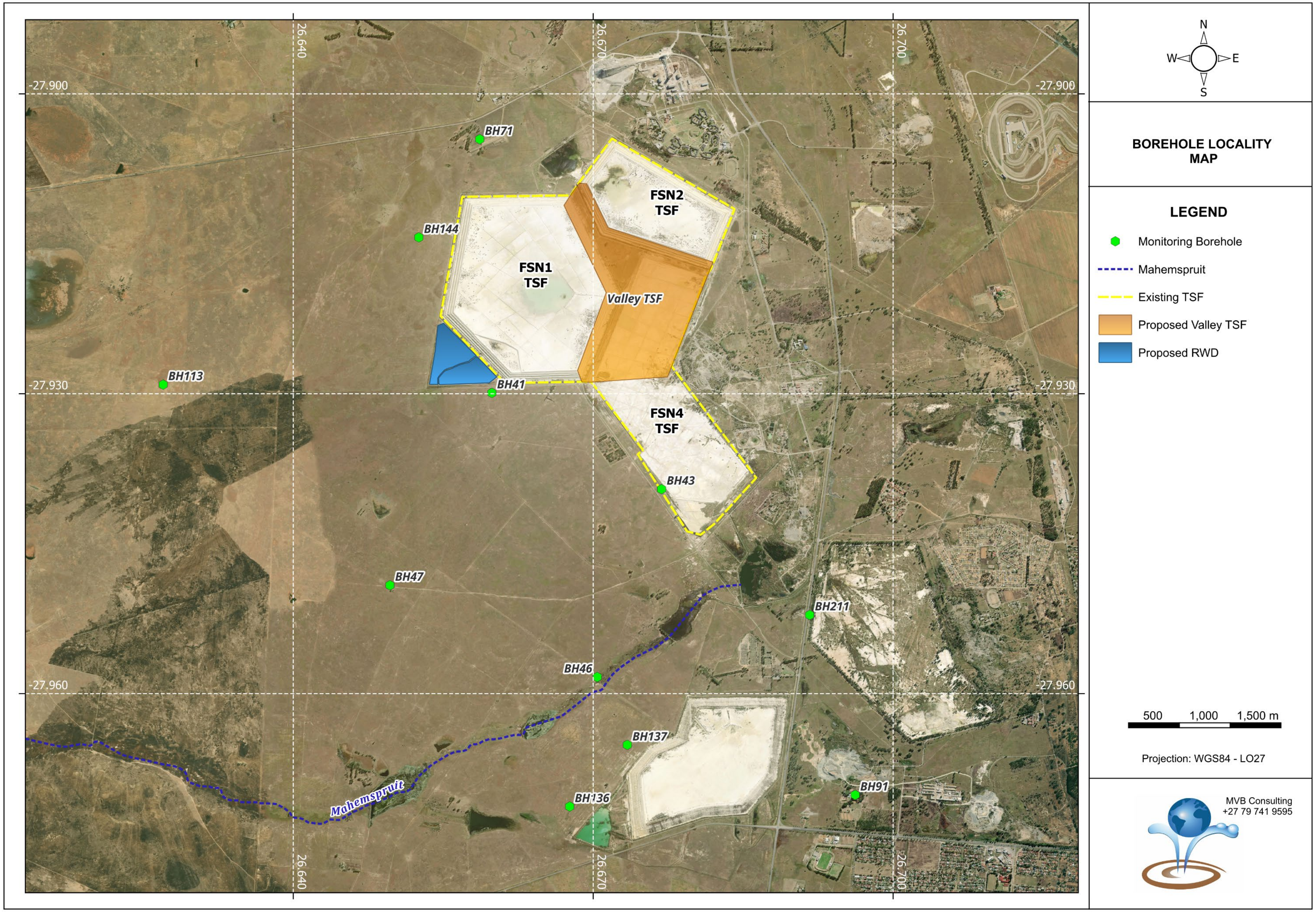

Figure 3.4: Valley TSF boreholes – Current monitoring network

3.2.2 Aquifer Type

The mine infrastructure is situated on interbedded siltstone/sandstone and shale of the Vryheid Formation. Even though the shale and sandstone are not known to contain economic aquifers, groundwater contributes to stream flow and in some instances, high yielding boreholes have been recorded. The following three aquifers underlie the site:

- ***Weathered Aquifer (Karoo Formations):*** A shallow, weathered aquifer exists in the weathered shale and sandstone at an average depth of 10m – 20m below ground level. The most consistent water strike is located at the fresh bedrock / weathering interface. The hydraulic conductivity of the weathered aquifer is typically in the order of 0.1 m/day. The vertical permeability is in the order of 0.001 m/day to 0.00010 m/day, which is sufficiently low to confine the groundwater in the underlying fractured rock aquifer.
- ***Fractured Aquifer (Karoo Formations):*** The primary porosity of the Vryheid Formation is very low. Any water bearing capacity is therefore associated with secondary joints, bedding planes and faults. The contact zones of dolerite intrusions are characterised by cooling joints and fractures, which are considered the primary source of groundwater flow within the deeper formations. The hydraulic conductivity of the fractured rock aquifer is typically in the order of 0.001 m/day to 0.1 m/day. The depth to groundwater in this aquifer can be variable due to confining layers in parts of the study area.

  The two aquifers may or may not be hydraulically connected, dependent on the local geology.
- ***Witwatersrand / Ventersdorp Aquifer:*** The deep brine Witwatersrand aquifer is situated approximately 300m below surface. Mining prospecting boreholes indicated this level to be between 170m to 270m (EMP, 2009). This aquifer is thought to be connate (i.e. original formation water) or extremely old (fossil) water and is usually concentrated on geological structures such as fault zones or igneous intrusions (e.g. dykes).

  The time gap between the end of the Central Rand Group and the start of the Karoo deposition was in the order of 2.3Ga. There is also a significant time gap between the Central Rand Group and the Ventersdorp Supergroup. During these intervening periods, the older rocks were uplifted and exposed to erosion and the near surface rocks to pressure release. This resulted in the forming of fractures in approximately the upper 150m of the rock succession. Subsequent land surface changes and inundation by a shallow sea allowed marine water to percolate into the network of fractures in the Witwatersrand and Ventersdorp rocks (Young, 1990).

  The major fractures that that formed during the Ventersdorp tectonic events were filled with water to a depth of several kilometres. The impermeable nature of the overlying Karoo sediments, particularly the Dwyka Formation at the base of the Karoo, effectively sealed of the aquifer (Van Biljon, 1995). Post-Karoo movement and intrusions provided conduits for leakage from the Karoo aquifers to the deep Witwatersrand aquifer. However, the deep aquifer recharge from surface is regarded as negligible and at best localised (Van Biljon, 1995).

  The Witwatersrand aquifer has been largely dewatered during the past 40 years of mining and the water levels in the aquifer dropped significantly. In spite of the dewatering of the Witwatersrand aquifer, there is no evidence of dewatering of the Karoo aquifers.

It is therefore concluded that:

- There is no or very limited hydraulic connectivity between the Karoo aquifers and the deeper Witwatersrand aquifer.
- Recharge to the Witwatersrand aquifer is negligible.
- Once the Witwatersrand aquifer is dewatered (or the water level lowered) it will not recover. The estimated post-mining water level in the Witwatersrand aquifer will therefore be deeper than the pre-mining water level of ~200m below surface.

A graphical illustration of the aquifers is presented in Figure 3.5.

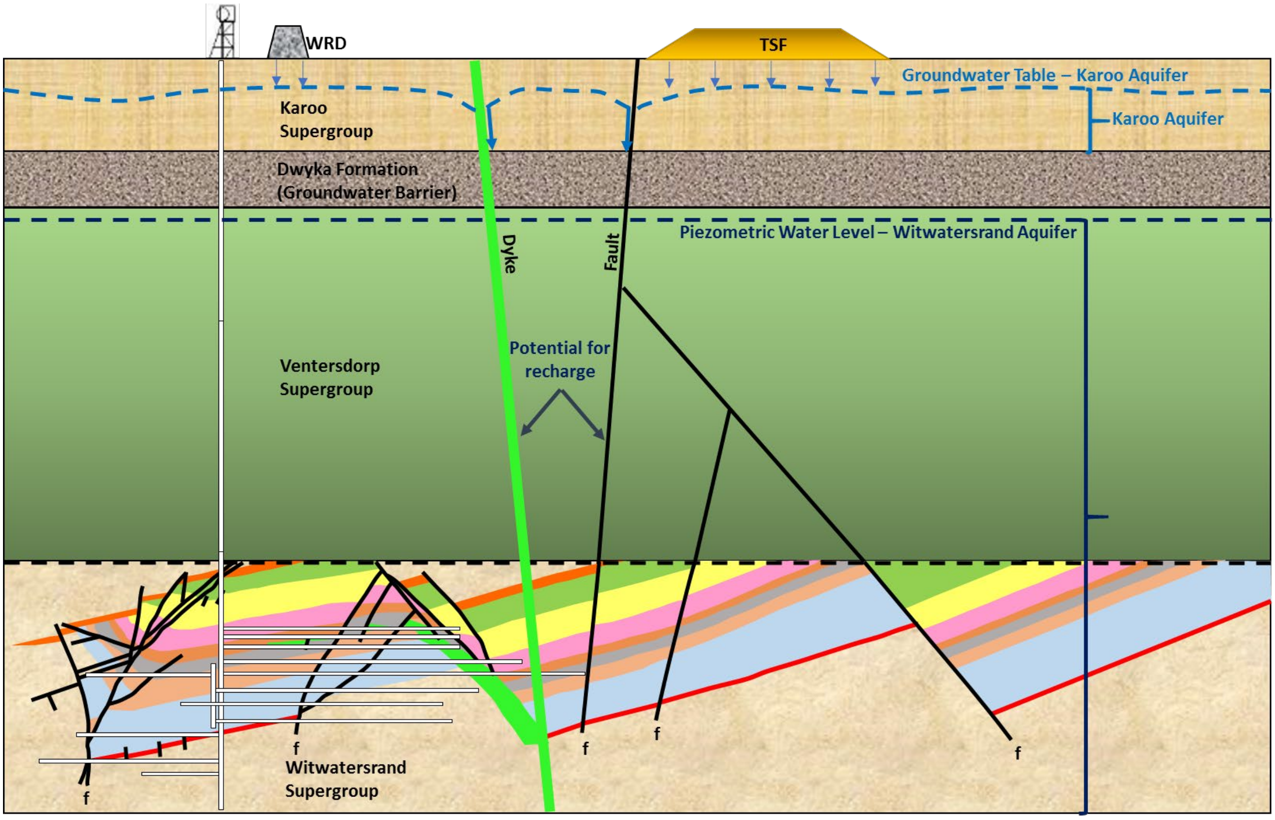

Figure 3.5: Graphical illustration of the aquifers in the study area

3.2.3 Groundwater Use

There are no large-scale groundwater supply boreholes within the study area. Farmers are, however, reliant on boreholes for domestic use and stock watering. Windmills have traditionally been utilised in the area. There are no springs recorded.

Percussion boreholes drilled through the Karoo established the following information (EMP, 2009):

- Number of Boreholes: 43
- Average Thickness of Karoo: 117m
- Percentage of boreholes intersecting dolerite in Karoo: 33%
- Average depth of dolerite from surface: 74m

The drilling indicated that groundwater occurrence is predominantly on the contact zones with dolerite intrusions and on the contact between the Karoo sediments and the Ventersdorp lavas. Measured yields vary from 0.10 litre per second (ℓ/sec) to 22 ℓ/sec.

3.2.4 Aquifer Parameters

The newly drilled boreholes were pump tested by Golder Associates (2009). Important parameters that can be obtained from borehole or test pumping include Hydraulic Conductivity (K), Transmissivity (T) and Storativity (S). These parameters are defined as follows (Krusemann and De Ridder, 1991):

- *Hydraulic Conductivity (K):* This is the volume of water that will move through a porous medium in unit time under a unit hydraulic gradient through a unit area measured at right angles to the direction of flow. It is normally expressed in metres per day (m/day).
- *Transmissivity (T):* This is the rate of flow under a unit hydraulic gradient through a cross-section of unit width over the full, saturated thickness of the aquifer. Transmissivity is the product of the average hydraulic conductivity and the saturated thickness of the aquifer. Transmissivity is expressed in metres squared per day (m^2/day).
- *Storativity (S):* The storativity of a saturated confined aquifer is the volume of water released from storage per unit surface area of the aquifer per unit decline in the component of hydraulic head normal to that surface. Storativity is a dimensionless quantity.

The test pumping information is summarized in Table 3.2. Based on this information the average transmissivity of the shallow aquifer is estimated at 2.3 m^2/day, while that of the deep aquifer is estimated at 0.9 m^2/day.

3.2.5 Aquifer Recharge

Recharge is defined as the process by which water is added from outside to the zone of saturation of an aquifer, either directly into a formation, or indirectly by way of another formation. According to the Groundwater Assessment Phase II (GRAII) the recharge is approximately 4% of mean annual precipitation.

Groundwater recharge (*R*) for the area is also calculated using the chloride method (Bredenkamp *et al.*, 1995) and is expressed as a percentage of the Mean Annual Precipitation (MAP). The method is based on the following equation:

$$R = \frac{\text{Chloride concentration in rainfall}}{\text{Chloride concentration in ground water}} \times 100$$

The average rainfall in the area is approximately 540 mm/a. The average chloride in rainfall for areas inland is approximately 1 mg/l therefore according to the equation:

$$R = \frac{1.5}{94} \times 100 = 1.6\%$$

where 94 mg/l is the chloride concentration in borehole BH113, which is furthest from the mining area. This implies that approximately 8.64 mm/a of precipitation recharges the groundwater system which is lower than the GRAII values.

Table 3.2: Aquifer parameters (Golder Associates, 2009)

ID	X	Y	Z	Depth (m)	Water Level (m)	Abstraction Rate (lit/sec)	Drawdown (m)	Recovery (%)	Transmissivity (m²/day)			Hydraulic Conductivity (m/day)
									Constant Rate Test	Recovery Test	Average	
BH1	26.65620	-27.92963	1335	90	5.50	0.55	60.22	92	0.10	0.10	**0.10**	0.001
BH2	26.65627	-27.92970	1331	36	6.41	0.45	20.63	94	0.40	0.50	**0.45**	0.015
BH3	26.65732	-27.94308	1334	73	54.03	0.44	8.88	87	0.70	2.50	**1.60**	0.084
BH4	26.65735	-27.94312	1336	24	0.00	0.51	19.66	100	0.40	0.40	**0.40**	0.017
BH5	26.64065	-27.93760	1327	73	Dry							
BH6	26.64062	-27.93755	1330	23	17.99	0.60	2.37	91	3.80	10.20	**7.00**	1.400
BH7	26.64061	-27.93019	1336	73	72.38	Not enough water						
BH8	26.64057	-27.93023	1336	26	20.87	5.00	1.93	100	2.60	15.60	**9.10**	1.800
BH9	26.67978	-27.94499	1330	73	4.12	0.73	19.07	92	2.30	1.50	**1.90**	0.028
BH10	26.67975	-27.94496	1329	23	6.47	0.14	19.37	70	0.10	0.20	**0.15**	0.009
BH11	26.67250	-27.90450	1350	68	0.00	2.02	29.30	100	0.50	0.70	**0.60**	0.009
BH12	26.67256	-27.90454	1348	27	0.00	0.51	25.42	100	0.20	0.30	**0.25**	0.009
BH13	26.68095	-27.90938	1354	73	52.48	0.43	22.97	41	0.20	1.90	**1.05**	0.051
BH14	26.68097	-27.90936	1349	29	2.02	0.50	24.93	92	0.30	0.90	**0.60**	0.022
BH15	26.68849	-27.91220	1353	73	52.13	0.37	17.98	54	0.30	0.50	**0.40**	0.043
BH16	26.68845	-27.91220	1352	30	Dry							
BH17	26.67954	-27.92358	1345	73	40.06	0.45	46.82	47	0.10	0.30	**0.20**	0.006
BH18	26.67952	-27.92365	1345	29	4.03	0.49	23.26	94	0.30	0.40	0.35	0.014

3.2.6 Groundwater Gradients and Flow

The first important aspect when evaluating the hydrogeological regime and groundwater flow mechanisms is the groundwater gradients. Groundwater gradients, taking into consideration fluid pressure, are used to determine the hydraulic head which is the driving force behind groundwater flow. The flow governs the migration of contaminants and a detailed assessment of the flow was required to determine sub-surface flow directions from the TSF or any other potential contaminant source.

In most geological terrains, the groundwater mimics the topography and to test if this is the case within the study area the available groundwater levels were plotted against the topography (represented by the borehole collar elevations). The result of this assessment is presented in Figure 3.6. This graph indicates a very good correlation (96%) between the topography and the groundwater level, which suggests that groundwater flow will follow the topographical gradient.

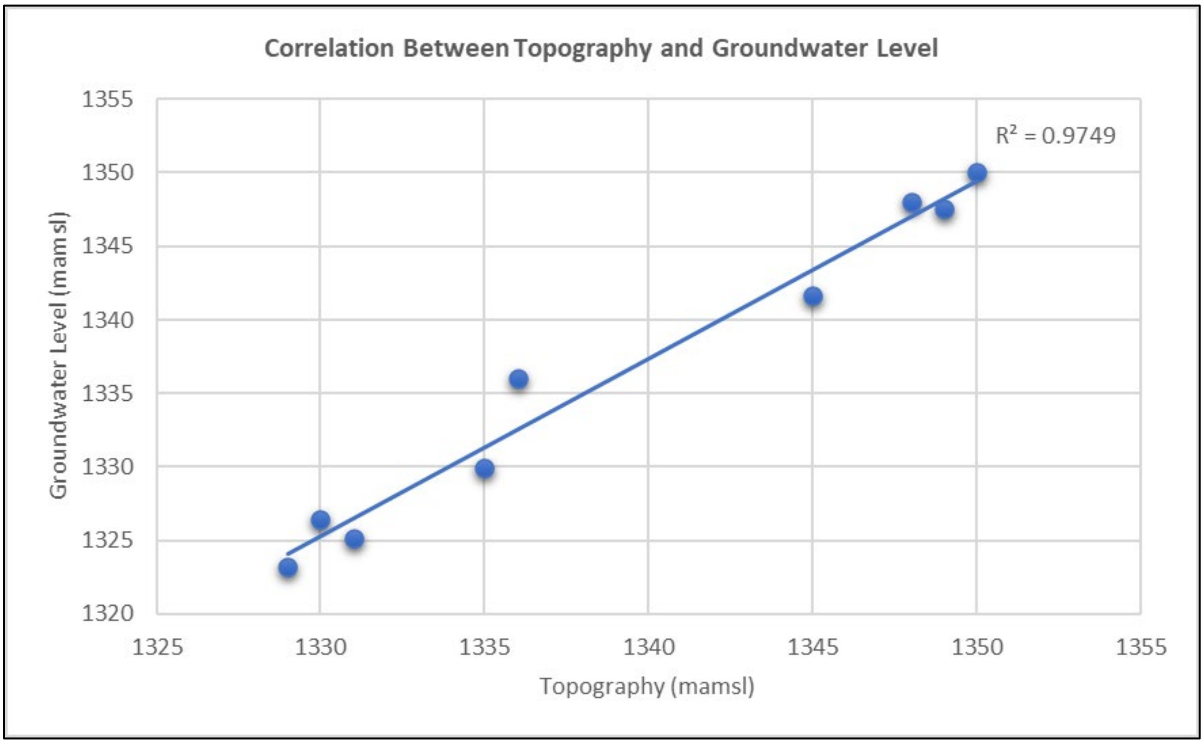

Figure 3.6: Correlation between topography and groundwater level

This relationship is known as the Bayesian relationship, and where this exists, the regional topography can be used to interpolate (Bayesian interpolation) a regional groundwater gradient map. Figure 3.7 depicts the groundwater level elevations, which as expected mimic the surface contours. Groundwater flow is perpendicular to the groundwater contours and flows predominantly towards the south-west.

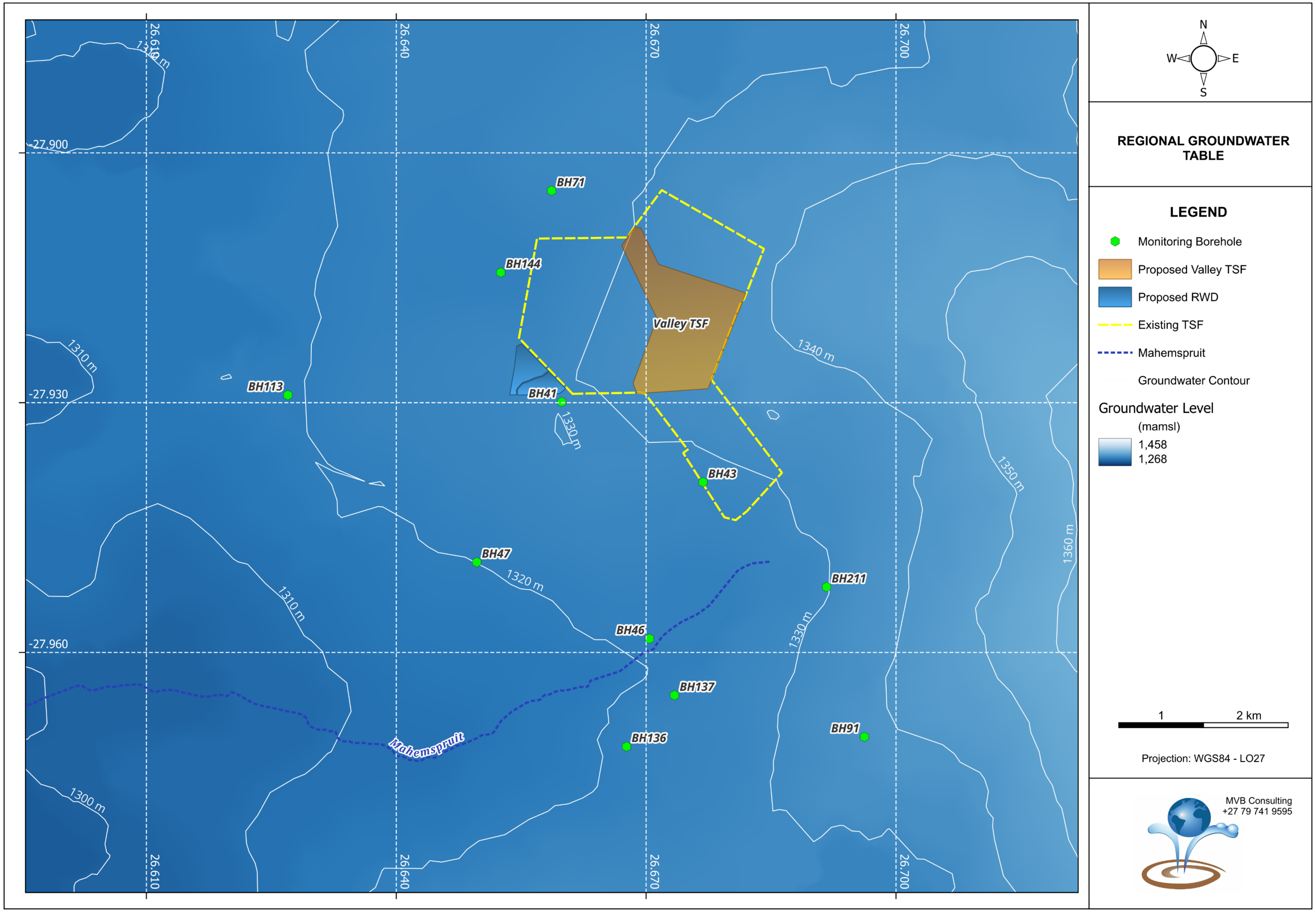

Figure 3.7: Regional groundwater gradient

3.2.7 Groundwater Quality

The groundwater chemistry is compared to the South African Water Quality Guidelines (second edition) Volume 5: Agricultural Use: Livestock Watering (Department of Water Affairs and Forestry, 1996), as well as the SANS 241 (2015). The **SANS 241 Drinking Water Specification** is the definitive reference on acceptable limits for drinking water quality parameters in South Africa and provides guideline levels for a range of water quality characteristics. The SANS 241 (2015) Drinking-Water Specification effectively summarises the suitability of water for drinking water purposes for lifetime consumption.

The guideline for livestock watering represents the target water quality specified in the guidelines. The target water quality guidelines were obtained from the *Department of Water Affairs and Forestry, 1996. South African Water Quality Guidelines (second edition). Volume 5: Agricultural Use: Livestock Watering.* According to the guidelines (DWAF, 1996), the following constituents are of concern for livestock watering (Table 3.3).

Table 3.3: Livestock watering – chemicals of concern (DWAF, 1996)

Category A			
Water quality constituents that are potentially hazardous, with a high incidence of occurrence			
Constituent	**Target water quality (TWQR)**	**Constituent**	**Target water quality (TWQR)**
Salinity (TDS)	1000 mg/l	Calcium	1000 mg/l
Chloride	3000 mg/l	Fluoride	2 mg/l
Sulfate	1000 mg/l	Molybdenum	0.01 mg/l
Arsenic	1 mg/l	Magnesium	500 mg/l
Copper	5 mg/l	Nitrate and Nitrite	100 mg/l NO_3
Sodium	2000 mg/l	Toxic algae	-
Category B			
Water quality constituents that are potentially hazardous, with a low incidence of occurrence			
Constituent	**Target water quality (TWQR)**	**Constituent**	**Target water quality (TWQR)**
Cadmium	0.01 mg/l	Cobalt	1 mg/l
Chromium	-	Iron	10 mg/l
Mercury	1 µg/l	Nickel	5 mg/l
Lead	0.5 mg/l	Vanadium	1 mg/l
Zinc	20 mg/l	Manganese	10 mg/l
Selenium	50 µg/l	Pesticides	-
Boron	5 mg/l	Pathogens	200 counts/100ml Faecal Coliform
Aluminium	5 mg/l		

The chemistry of the groundwater is presented in Table 3.4.

The chemical concentrations are compared to the Guidelines for Livestock Watering. Where these guidelines are exceeded, the values are highlighted in red. In the absence of limits for livestock watering the chemical concentrations are compared to the SANS 241 (2015) Guidelines for Drinking Water.

With reference to Table 3.4, the following is observed:

- The groundwater in the Free State is generally saline and most of the boreholes have EC and TDS concentrations that exceed the guideline limits. Very high TDS concentrations are recorded in borehole BH46. This borehole is situated very close to a stream indicating that spillage is occurring or has occurred into this stream. The high concentrations are not attributed to natural plume migration.
- The high salt (concentrations are primarily attributed to chloride, sulphate and sodium.
- The existing tailings facilities have impacted on the surrounding groundwater environment. The extent of this impact is best illustrated through the sulphate (SO_4) concentrations in the monitoring boreholes (Figure 3.8). The most impacted areas appear to be associated with the return water dams, and / or spillage into a surface stream and not necessarily the TSF itself.

Table 3.4: Groundwater chemistry

Parameter	SANS 241	DWAF	BH71	BH144	BH41	BH47	BH43	BH46	BH211	BH137	BH136	BH91	BH113
pH	<5 - >9.7	NG	8.29	7.61	7.89	8.63	2.63	7.80	8.19	8.87	7.66	7.83	8.06
EC mS/m	170	NG	615	1 641	906	146	1 355	4 980	142	141	2 234	302	74
TDS mg/L	1 200	1 000	3 860	11 124	6 110	1 029	8 997	39 137	852	863	14 881	2 381	472
Total Alk mg/L	NG	NG	244	513	501	190	6	551	238	518	472	405	194
Cl mg/L	300	1 500	1 373	4 466	2 229	246	5 106	16 284	171	105	6 854	562	94
SO_4 mg/L	500	1 000	939	2 660	1 583	107	1 121	8 622	233	115	2 723	834	84
NO_3-N mg/L	11	100	38.77	<0.46	0.50	51.43	1.63	<0.46	<0.46	0.59	1.55	<0.46	0.81
Ca mg/L	NG	1 000	284	478	182	31	823	738	90	13	528	241	13
Mg mg/L	NG	500	172	279	214	24	671	1 979	33	4	487	121	10
Na mg/L	200	2 000	746	2 902	1 576	268	1 254	11 146	171	306	3 975	348	138
K mg/L	NG	NG	26	24	18	8	15	29	8	2	19	26	11
Fe mg/L	2	10	0.009	<0.009	0.090	<0.009	<0.009	<0.009	<0.009	<0.009	<0.009	0.016	<0.009
Mn mg/L	0.4	10	0.001	<0.001	2.142	<0.001	12.288	<0.001	<0.001	<0.001	<0.001	<0.001	0.011

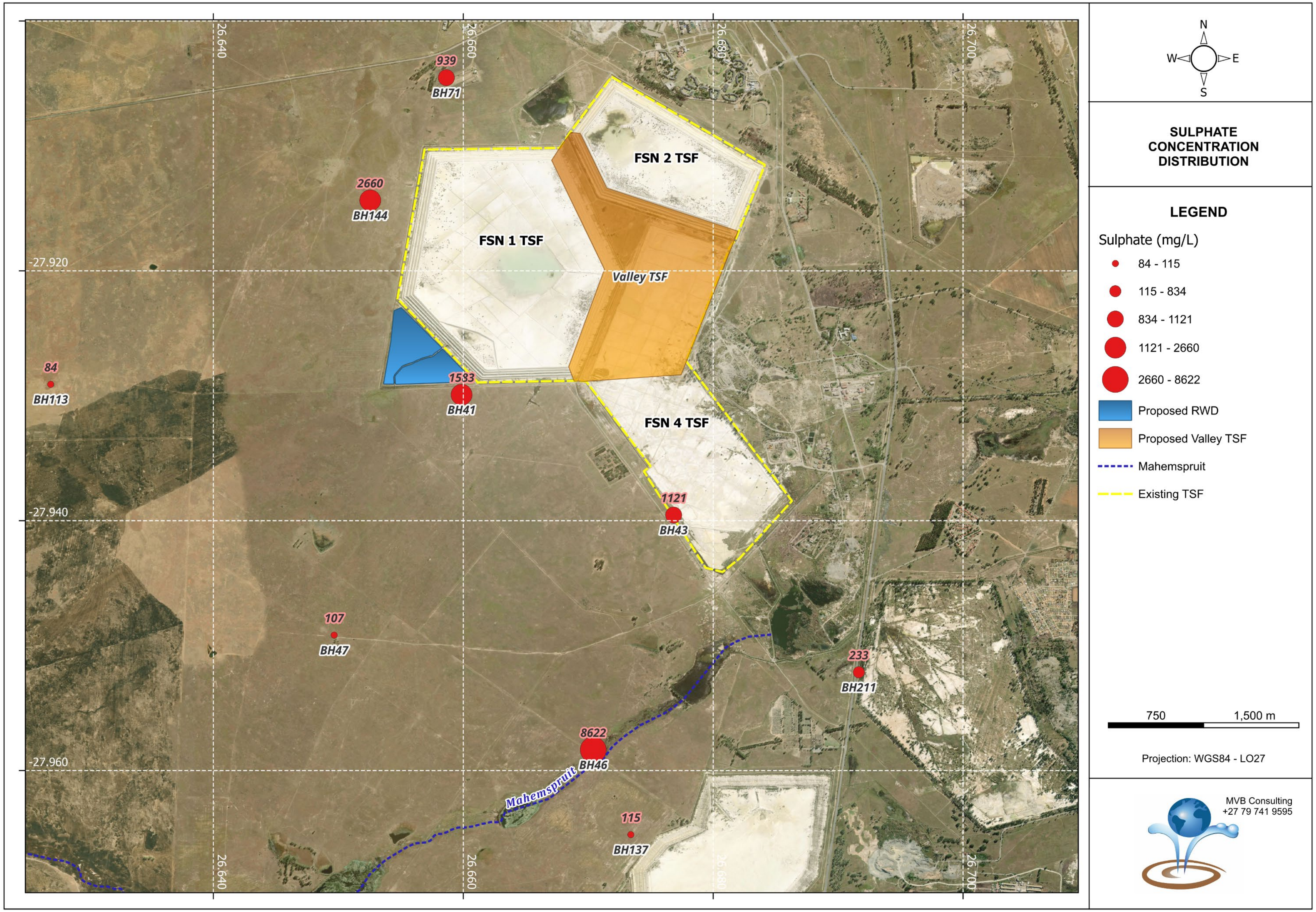

Figure 3.8: **Sulphate concentration distribution in the groundwater monitoring boreholes**

3.2.8 Aquifer Classification

An aquifer classification system provides a framework and objective basis for identifying and setting appropriate levels of groundwater resource protection. This would facilitate the adoption of a policy of differentiated groundwater protection.

Other uses could include:

- Defining levels of investigation required for decision making;
- Setting of monitoring requirements; and
- Allocation of manpower resources for contamination control functions.

The aquifer classification system used to classify the aquifers is the proposed National Aquifer Classification System of Parsons (1995). This system has a certain amount of flexibility and can be linked to second classifications such as a vulnerability or usage classification. Parsons suggests that aquifer classification forms a very useful planning tool that can be used to guide the management of groundwater issues. He also suggests that some level of flexibility should be incorporated when using such a classification system.

The South African Aquifer System Management Classification is presented by five major classes:

- Sole Source Aquifer System;
- Major Aquifer System;
- Minor Aquifer System;
- Non-Aquifer System; and
- Special Aquifer System.

The following definitions apply to the aquifer classification system:

- Sole source aquifer system: “An aquifer that is used to supply 50 % or more of domestic water for a given area, and for which there are no reasonable alternative sources should the aquifer become depleted or impacted upon. Aquifer yields and natural water quality are immaterial”.
- Major aquifer system: “Highly permeable formations, usually with a known or probable presence of significant fracturing. They may be highly productive and able to support large abstractions for public supply and other purposes. Water quality is generally very good”.
- Minor aquifer system: “These can be fractured or potentially fractured rocks that do not have a high primary permeability, or other formations of variable permeability. Aquifer extent may be limited and water quality variable. Although this aquifer seldom produces large quantities of water, they are both important for local supplies and in supplying base flow for rivers”.
- Non-aquifer system: “These are formations with negligible permeability that are generally regarded as not containing groundwater in exploitable quantities. Water quality may also be such that it renders the aquifer unusable. However, groundwater flow through such rocks does occur, although imperceptible, and needs to be considered when assessing risk associated with persistent pollutants”.
- Special aquifer system: “An aquifer designated as such by the Minister of Water Affairs, after due process”.

A second variable classification is needed for sound decision making, as the ability of an aquifer to yield water to a particular user is not adequately stated. In this case it was decided to use the vulnerability of the aquifer to contamination as a second parameter (Table 3.5). A weighting and rating approach is then used to decide on the appropriate level of groundwater protection (Table 3.6).

Table 3.5: Ratings for the aquifer quality management classification system

Class	Points	Class	Points
Sole Source Aquifer System	6	**High**	3
Major Aquifer System	4	**Medium**	2
Minor Aquifer System	2	**Low**	1
Non-Aquifer System	0		
Special Aquifer System	0-6		

Table 3.6: Appropriate level of groundwater protection required

GQM Index	Level of Protection
<1	Limited Protection
1 – 3	Low Level Protection
3 – 6	Medium Level Protection
6 – 10	High Level Protection
>10	Strictly Non-degradation

After rating the aquifer system management and the aquifer vulnerability, the points are multiplied to obtain a Groundwater Quality Management (GQM) index.

Based on the above, the aquifers in the study area are classified as follows:

Description	Aquifer	Vulnerability	Rating	Protection
Weathered Aquifer	Minor (2)	2	4	Medium
Fractured Aquifer	Minor (2)	1	2	Low

4. NUMERICAL GROUNDWATER MODELLING

4.1 Introduction

The conceptual geohydrological model described in the previous section was translated to a calibrated numerical groundwater flow and mass transport model. The purpose of the model is mainly to use as a tool to simulate the following:

- Contaminant seepage from the proposed Valley TSF and RWD without any liner for periods 50- and 100-years.
- Contaminant seepage from the proposed Valley TSF and RWD with a liner for a period of 100-years.
- Cumulative impact from the larger tailings facility for periods 50- and 100-years.

The basic steps involved in modelling can be summarised as:

- *Collecting and interpreting field data:* Field data are essential to understand the natural system and to specify the investigated groundwater problem. The numerical model develops into a site-specific groundwater model when real field parameters are assigned. The quality of the simulations depends largely on the quality of the input data.
- *Calibration & validation:* Model calibration and validation are required to overcome the lack of input data, but they also accommodate the simplification of the natural system in the model. In model calibration, simulated values like potentiometric surface or concentrations are compared with field measurements. The model input data are altered within ranges, until the simulated and observed values are fitted within a chosen tolerance. Input data and comparison of simulated and measured values can be altered either manually or automatically.
- Model validation is required to demonstrate that the model can be reliably used to make predictions. A common practice in validation is the comparison of the model with a data set not used in model calibration. Calibration and validation are accomplished if all known and available groundwater scenarios are reproduced by the model without varying the material properties or aquifer characteristics supplied to the model.

  Modelling scenarios: Alternative scenarios for a given area may be assessed efficiently. When applying numerical models in a predictive sense, limits exist in model application. Predictions of a relative nature are often more useful than those of an absolute nature.

4.2 Assumptions and Limitations

The following conditions typically need to be described in a model:

- Geological and geohydrological features.
- Boundary conditions of the study area (based on the geology and geohydrology).
- Initial groundwater levels of the study area.
- The processes governing groundwater flow.
- Assumptions for the selection of the most appropriate numerical code.

Field data is essential in solving the conditions listed above and developing the numerical model into a site-specific groundwater model. Specific assumptions related to the available field data include:

- The top of the aquifer is represented by the generated groundwater heads.
- The available geological / geohydrological information was used to describe the different aquifers. The available information on the geology and field tests is considered as correct.
- Many aquifer parameters have not been determined in the field and therefore have to be estimated.

In order to develop a model of an aquifer system, certain assumptions have to be made. The following assumptions were made:

- No abstraction boreholes were included in the initial model.
- The boundary conditions assigned to the model are considered correct.
- The impacts of other activities (e.g. agriculture) have not been considered.

It is important to note that a numerical groundwater model is a representation of the real system. It is therefore at most an approximation, and the level of accuracy depends on the quality of the data that is available. This implies that there are always errors associated with groundwater models due to uncertainty in the data and the capability of numerical methods to describe natural physical processes.

4.3 Model Set-up

In order to investigate the behaviour of aquifer systems in time and space, it is necessary to employ a mathematical model. FEFLOW, a modular three-dimensional finite element groundwater flow model was the software used during this investigation. It is an internationally accepted modelling package, which calculates the solution of the groundwater flow equation using the finite element approach.

The network constructed for the site consists of 1 033 948 elements. Figure 4.1 is a representation of the model domain. It must be noted that the network was refined in the vicinity of sources of potential contamination and dewatering.

The model consists of the following layers:

- Layer 1: Weathered formations – 30m thickness.
- Layer 2: Fractured formations – 150m thickness.

See Table 4.1 for the modelled aquifer parameters associated with each model layer.

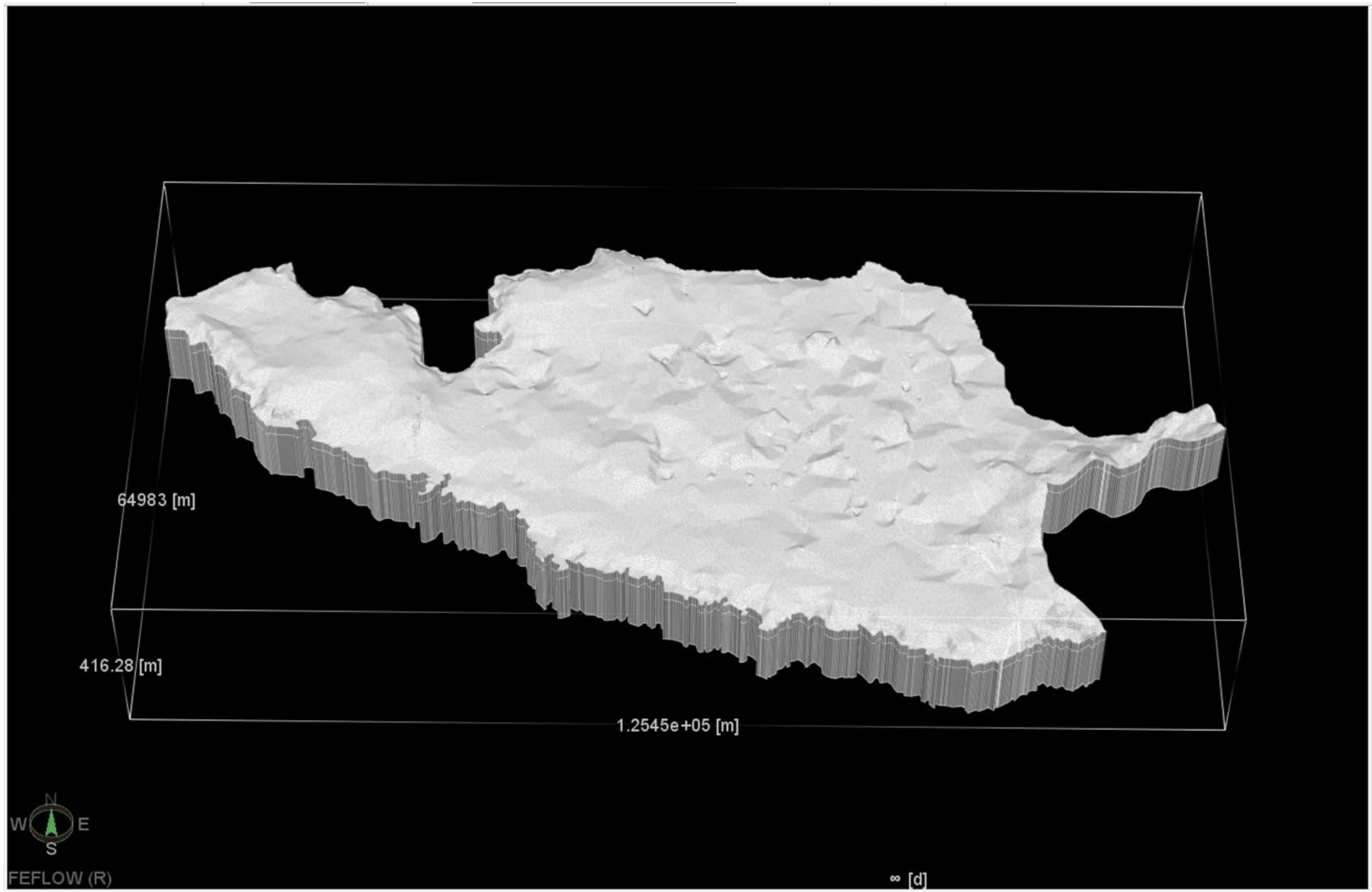

Figure 4.1: Model Domain

4.4 Model Boundary Conditions

One of the first and most demanding tasks in groundwater modelling is that of identifying the model area and its boundaries. Consequently, a model boundary is the interface between the model area and the surrounding environment. Conditions on the boundaries, however, have to be specified. Boundaries occur at the edges of the model area and at locations in the model area where external influences are represented, such as rivers, boreholes, and leaky impoundments.

Criteria for selecting hydraulic boundary conditions are primarily topography, hydrology and geology. The topography, geology, or both, may yield boundaries such as impermeable strata or potentiometric surface controlled by surface water, or recharge/discharge areas such as inflow boundaries along mountain ranges. The flow system allows the specification of boundaries in situations where natural boundaries are a great distance away.

Boundary conditions must be specified for the entire boundary and may vary with time. At a given boundary section just one type of boundary condition can be assigned. As a simple example, it is not possible to specify groundwater flux and groundwater head at an identical boundary section. Boundaries in groundwater models can be specified as:

- Dirichlet (also known as constant head or constant concentration) boundary conditions.
- Neuman (or specified flux) boundary conditions.
- Cauchy (or a combination of Dirichlet and Neuman) boundary conditions.

Natural water divides were set as no flow boundaries to the model domain.

4.5 Initial Conditions

Initial conditions are vital for modelling flow problems. Initial conditions must be specified for the entire area. Generally, the initial water level/head distribution acts as the starting distribution for the numerical calculation. The water levels shown in Figure 3.7 were used as initial conditions for the model.

4.6 Sources and Sinks

Sources and sinks can be defined as recharge and abstraction sources in the aquifer. Sources can be precipitation and inflow from surface water and recharging boreholes. Sinks can be abstraction boreholes, springs, evapotranspiration, and outflow to surface water. Initially only recharge due to precipitation was included in the model. The average mean annual precipitation (MAP) is approximately 347 mm/a. The effective recharge is set at 2-4% of MAP for the weathered aquifer. The modelled aquifer recharge is shown in Figure 4.2.

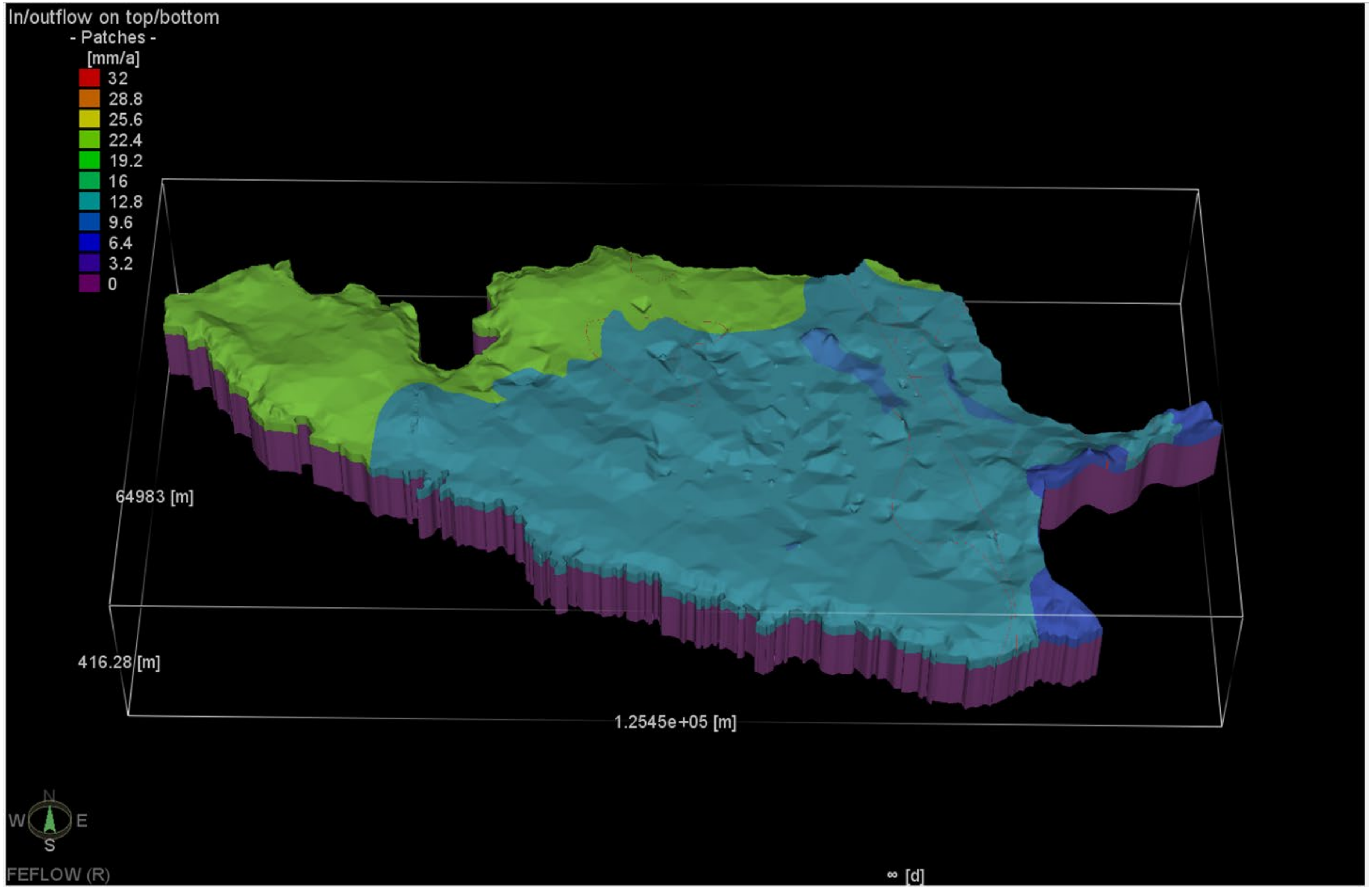

Figure 4.2: Aquifer recharge

4.7 Aquifer Parameters

The aquifer parameters discussed in Section 3.2.4 were initially used in the numerical model. The model is calibrated using the groundwater level elevations which are a function of the product of the saturated aquifer thickness, the hydraulic conductivity and effective aquifer recharge. Should the average aquifer thickness therefore be under/overestimated, this can be compensated for by adjustment of the hydraulic conductivity values during model calibration.

The simulated groundwater level distribution is compared to the measured head distribution and the hydraulic conductivity or recharge values can be altered until an acceptable correlation between measured and simulated heads is obtained. The calibration process was done by adjusting the model parameters for hydraulic conductivity (K) and recharge within a narrow range compatible with the historic data and hydrogeological situation.

The calibrated hydraulic conductivities of the study area are summarised in Table 4.1 and regionally illustrated in Figure 4.3.

Table 4.1: Modelled aquifer parameters

Model Layer	Hydrostratigraphic unit	Layer thickness (m)	Hydraulic Conductivity (K)		Recharge (Re)	Specific storage (Sc)	Porosity (n)
			Kx,y 1:1 (m/d)	Kz 1:10 (m/d)	In/Outflow on top/bottom (mm/a)	Sc (1/m)	
Layer 01	Alluvial deposits	30.00	3.000	3.000	12.00	5.00E-02	5.00E-02
	Beaufort Group		0.030	0.003	8.00	1.00E-03	5.00E-03
	Platberg Group		0.015	0.002	10.00	1.00E-03	1.00E-03
	Volksrust Formation		0.400	0.040	12.00	1.00E-04	7.50E-03
	Ecca Formation		0.250	0.025	22.00	1.00E-03	1.00E-02
	Geological Lineaments		0.750	0.075	32.00	5.00E-02	3.00E-02
Layer 02	Beaufort Group	150.00	0.015	0.002	0.0	5.00E-04	2.50E-03
	Platberg Group		0.008	0.001		1.00E-03	3.00E-02
	Volksrust Formation		0.200	0.020		1.00E-03	3.00E-02
	Ecca Formation		0.125	0.013		1.00E-03	3.00E-02
	Geological Lineaments		0.375	0.038		5.00E-04	5.00E-04

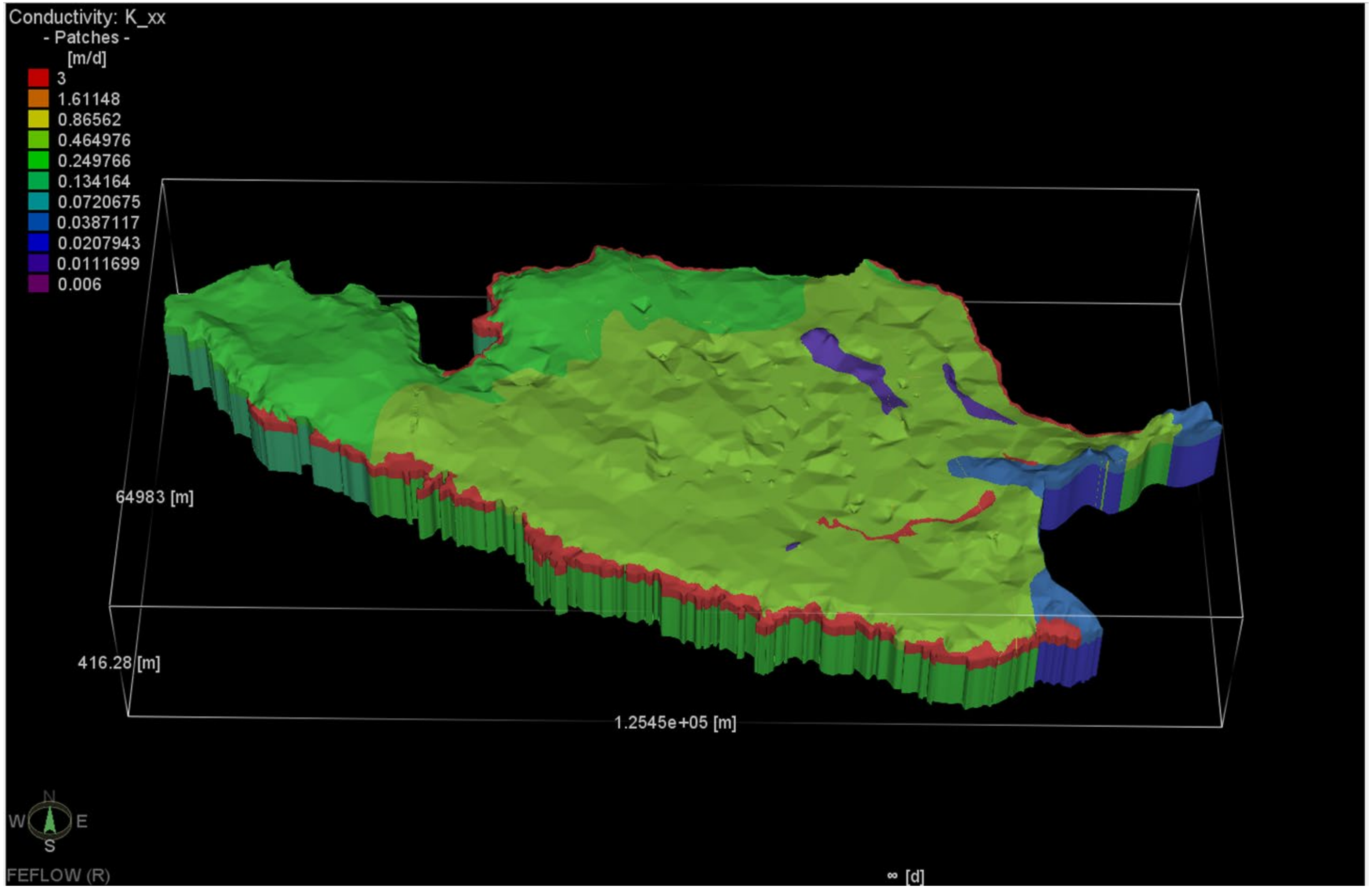

Figure 4.3: Modelled aquifer parameters

4.8 Calibration of the Model

A groundwater flow model for the study area was constructed to simulate disturbed groundwater flow conditions. The calibrated conditions serve as starting heads for the transient simulations of groundwater flow.

The simulation model (FEFLOW) used in this modelling study is based on three-dimensional groundwater flow and may be described by the following equation:

$$\frac{\partial}{\partial x}(K_x\frac{\partial h}{\partial x})+\frac{\partial}{\partial y}(K_y\frac{\partial h}{\partial y})+\frac{\partial}{\partial z}(K_z\frac{\partial h}{\partial z})\pm W=S\frac{\partial h}{\partial t} \qquad (1)$$

Where:

h = hydraulic head [L].

K_x, K_y, K_z = Hydraulic Conductivity [L/T].

S = storage coefficient.

t = time [T].

W = source (recharge) or sink (pumping) per unit area [L/T].

x, y, z = spatial co-ordinates [L].

For steady state conditions the groundwater flow Equation (1) reduces to the following equation:

$$\frac{\partial}{\partial x}(K_x\frac{\partial h}{\partial x})+\frac{\partial}{\partial y}(K_y\frac{\partial h}{\partial y})+\frac{\partial}{\partial z}(K_z\frac{\partial h}{\partial z})\pm W=0 \qquad (2)$$

The head distribution is dependent upon the recharge, hydraulic conductivity, sources, sinks and boundary conditions specified. For a given recharge component and set of boundary conditions, the head distribution across the aquifer can be obtained for a specific hydraulic conductivity value. The simulated head distribution can then be compared to the measured head distribution and the hydraulic conductivity or recharge values can be altered until an acceptable correspondence between measured and simulated heads is obtained.

The calibration process was done by changing the model parameters for hydraulic conductivity and recharge. Hydro-census boreholes were used to calibrate groundwater flow model, with these boreholes providing the only available data. Many of the measured levels are pumped levels, providing only a basic insight into the groundwater level behaviour in the aquifer. The calibration objective was reached when an acceptable correlation was obtained between the observed and simulated piezometric heads (Figure 4.4).

Table 4.2: Flow Calibration Results

Calibration BH	Topographical Elevation (mamsl)	Water Level (mbgl)	Measured head elevation (mamsl)	Simulated head elevation (mamsl)	Mean Error (m)	Mean Absolute Error (m)	Root Mean Square Error (m)
BH1	1334.68	5.50	1329.18	1328.60	0.58	0.58	0.33
BH2	1334.71	6.41	1328.30	1328.60	-0.30	0.30	0.09
BH9	1331.86	4.12	1327.74	1329.32	-1.58	1.58	2.50
BH10	1331.87	6.47	1325.40	1329.32	-3.92	3.92	15.38
BH11	1350.00	0.00	1350.00	1348.81	1.19	1.19	1.43
BH12	1348.00	0.00	1348.00	1348.83	-0.83	0.83	0.69
BH14	1349.00	2.02	1346.98	1351.60	-4.62	4.62	21.35
BH18	1345.00	4.03	1340.97	1338.70	2.27	2.27	5.15
Average	**1340.64**	**3.57**	**1337.07**	**1337.97**	**-0.90**	**1.91**	**5.87**
Minimum	**1331.86**	**0.00**	**1325.40**	**1328.60**	**-4.62**	**0.30**	**0.09**
Maximum	**1350.00**	**6.47**	**1350.00**	**1351.60**	**2.27**	**4.62**	**21.35**
Correlation			**0.97**				
∑					**-7.22**	**15.30**	**46.93**
1/n					**-0.90**	**1.91**	**5.87**
Root Mean Square Deviation (RMSD)					**0.95**	**1.38**	**2.42**
Normalised Root Mean Square Deviation (NRMSD) (% of water level range)							**9.85**

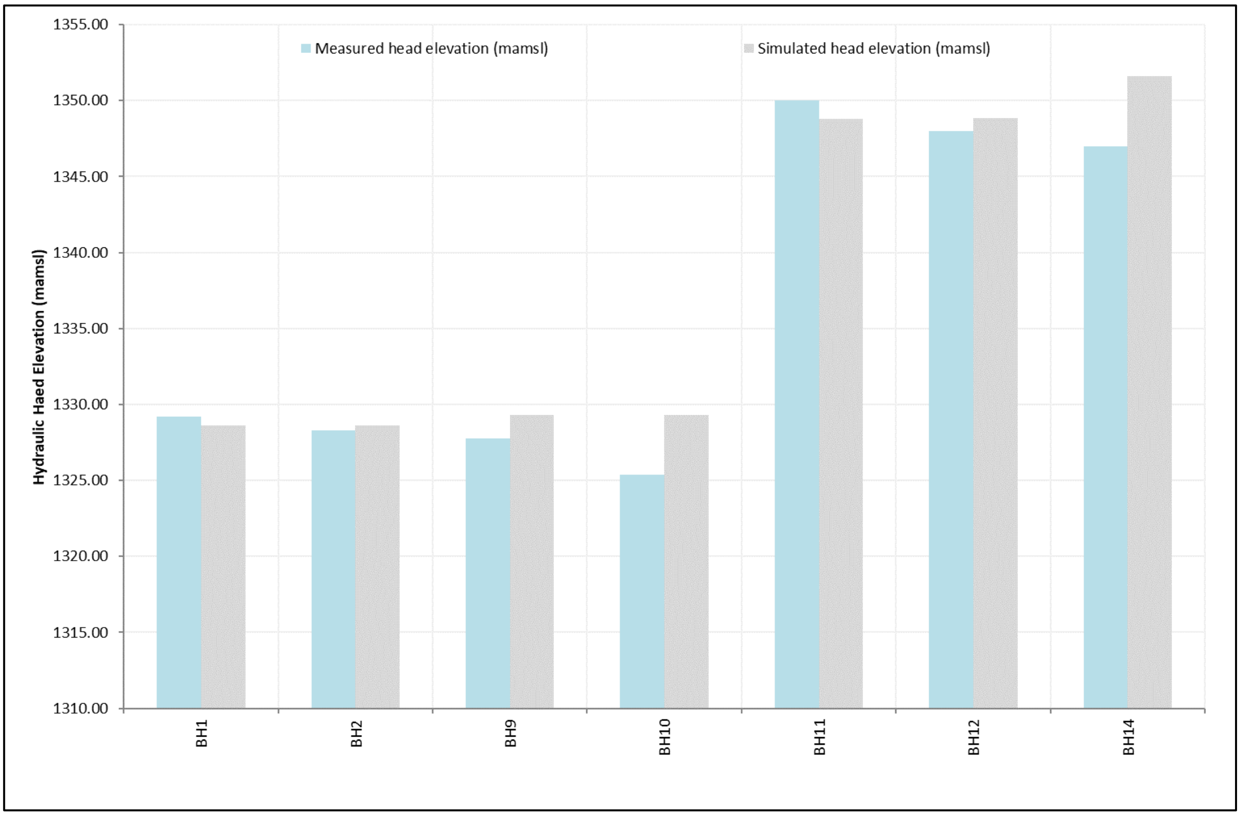

Figure 4.4: Model Calibration - Groundwater Levels

4.9 Numerical Groundwater Mass Transport Model

Mass transport modelling in this situation refers to the simulation of water contamination or pollution due to deteriorating water quality in response to man's disturbance of the natural environment (for example residue deposits). Transport through a medium is mainly controlled by the following two processes:

- Advection is the component of contaminant movement described by Darcy's Law. If uniform flow at a velocity V takes place in the aquifer, Darcy's law calculates the distance (x) over which a labelled water particle migrates over a time period t as x = Vt.
- Hydrodynamic dispersion comprises two processes:
  - Mechanical dispersion is the process whereby the initially close group of labelled particles are spread in a longitudinal as well as in a transverse direction because of the velocity distribution (as a result of varying microscopic streamlines) that develops at the microscopic level of flow around the grain particles of the porous medium. Although this spreading is both in the longitudinal and transversal direction of flow, it is primarily in the former direction. Very little spreading can be caused in the transversal direction by velocity variations alone.
  - Molecular diffusion mainly causes transversal spreading, by the random movement of the molecules in the fluid from higher contaminant concentrations to lower ones. It is thus clear that if V = 0, the contaminant is transported by molecular diffusion, only or in other words the higher the velocity of the groundwater, the less the relative effect of molecular diffusion on the transportation of a labelled particle.

In addition to advection, mechanical dispersion and molecular diffusion, several other phenomena may affect the concentration distribution of a contaminant as it moves through a medium. The contaminant may interact with the solid surface of the porous matrix in the form of adsorption of contaminant particles on the solid surface, deposition, solution of the solid matrix and ion exchange. All these phenomena cause changes in the concentration of a contaminant in a flowing fluid.

The FEFLOW software was used to provide numerical solutions for the concentration values in the aquifer in time and space. The required input into the model includes:

- Input concentrations of contaminants.
- Hydraulic conductivity values.
- Porosity values.
- Longitudinal dispersivities.
- Transversal dispersivities.
- Hydraulic heads/water levels in the aquifer over time.

Hydraulic conductivities for the aquifer were specified according to the values obtained during the scenario of the groundwater level calibration.

A longitudinal dispersivity value of 100 m was selected for the simulations (see Table D.3 – Field-Scale Dispersivities in Spitz and Moreno, 1996). Bear and Verruijt (1992) estimated the average transversal dispersivity to be 10 to 20 times smaller than the longitudinal dispersivity. An average value of 10 m was selected for this parameter during the simulations. Input concentrations in the model were specified at nodes over the areas where contamination is expected.

Sulphate was selected as representative of the potential impacts from the tailings dam. Based on the waste assessment conducted by Jones & Wagener Engineering and Environmental Consultants (2022), a source concentration of 2 000 mg/L was included in the model (Table 4.3).

Table 4.3: Distilled 1:2 water leach results (Jones & Wagener, 2022)

Chemical Parameter(1)	Dry Residue Sample	Wet Residue Sample	SANS 241 (2015)	Risk
pH	4.6	8.4	≥ 5.0 – ≤ 9.7	Operational
TDS	4 466	364	≤ 1 200	Aesthetic
Nitrate as N	2.6	2.7	≤ 11.0	Acute health
Cyanide as CN	<0.07	<0.07	≤ 0.200	Acute health
Fluoride	<0.200	0.200	≤ 1.50	Chronic health
Al	75	0.058	≤ 0.300	Operational
As	0.038	0.664	≤ 0.010	Chronic health
B	0.240	0.075	≤ 2.400	Chronic health
Ba	<0.025	<0.025	≤ 0.700	Chronic health
Ca	441	55	No standard	
Cd	0.022	<0.003	≤ 0.003	Chronic health
Co	6.07	0.059	No standard	
Cr (total)	0.122	<0.025	≤ 0.050	Chronic health
Cr (VI)	<0.010	<0.010	No standard	
Cu	1.63	<0.025	≤ 2.000	Chronic health
Fe	10	0.038	≤ 2.000	Chronic health
Hg	<0.001	<0.001	≤ 0.003	Chronic health
K	17.0	7.4	No standard	
Mg	184	<1.000	No standard	
Mn	35	<0.025	≤ 0.400	Chronic health
Mo	<0.025	<0.025	No standard	
Na	423	56	≤ 200	Aesthetic
Ni	11	<0.025	≤ 0.070	Chronic health
Pb	0.126	<0.010	≤ 0.010	Chronic health
Sb	0.003	0.016	≤ 0.020	Chronic health
Se	<0.001	0.003	≤ 0.010(2)	Health
U			≤ 0.030	Chronic health
V	<0.025	<0.025	No standard	
Zn	9.66	<0.025	≤ 5.000	Aesthetic
Sulfate as SO_4^{2-}	2 193	100	≤ 500	Acute health
Note 1	All concentrations in mg/ℓ except pH			
Note 2	Guidelines for Canadian Drinking Water Quality			
(highlighted)	Concentration exceeds drinking water standard			

5. GEOHYDROLOGICAL IMPACT ASSESSMENT

The proposed Valley TSF will be built between existing tailings facilities. The date of construction of these facilities is unclear but it was assumed that the dams were established during the 1970's. The impact from the existing dams were therefore modelled, based on this assumption, and the current modelled impact from these dams are shown in Figure 5.1 to Figure 5.3. The current impact is mainly towards the southwest and the Mahemspruit.

Assuming that the existing facility is 50 years old, the average plume migration can be estimated based on Darcy's law. Contaminants are transported in groundwater by advection, that is, the movement of a solute at the speed of the average linear velocity of groundwater (Anderson, *et. al.*, 1992). This is represented by the following formula:

$$v = \frac{K \times I}{n}$$

where;

v = *velocity in m/day*

K = *Hydraulic Conductivity in m/day*

I = *Gradient as a %*

n = *Porosity as a %*

The hydraulic conductivity for the weathered aquifer is estimated as 0.289 m/day. The groundwater gradient averages 0.6% in the study area. The porosity of the aquifer material is estimated to be between 3 - 7% (AquiSim Consulting, 2012). Applying the above formula to the study area assuming a porosity of 5% it is calculated that the groundwater velocity averages a rate of 0.035 m/day or 12.66 m per annum. Over the 50-year period the plume migration is estimated at 633m, which is supported by the numerical modelling.

To address the objectives of this study, the potential of impacted seepage from surface infrastructure (tailings dam) affecting downgradient receptors was evaluated. The first part of the assessment looks at the potential future impact from the proposed Valley tailings facility only and the second part of the assessment looks at the cumulative impact from the existing infrastructure and the proposed infrastructure.

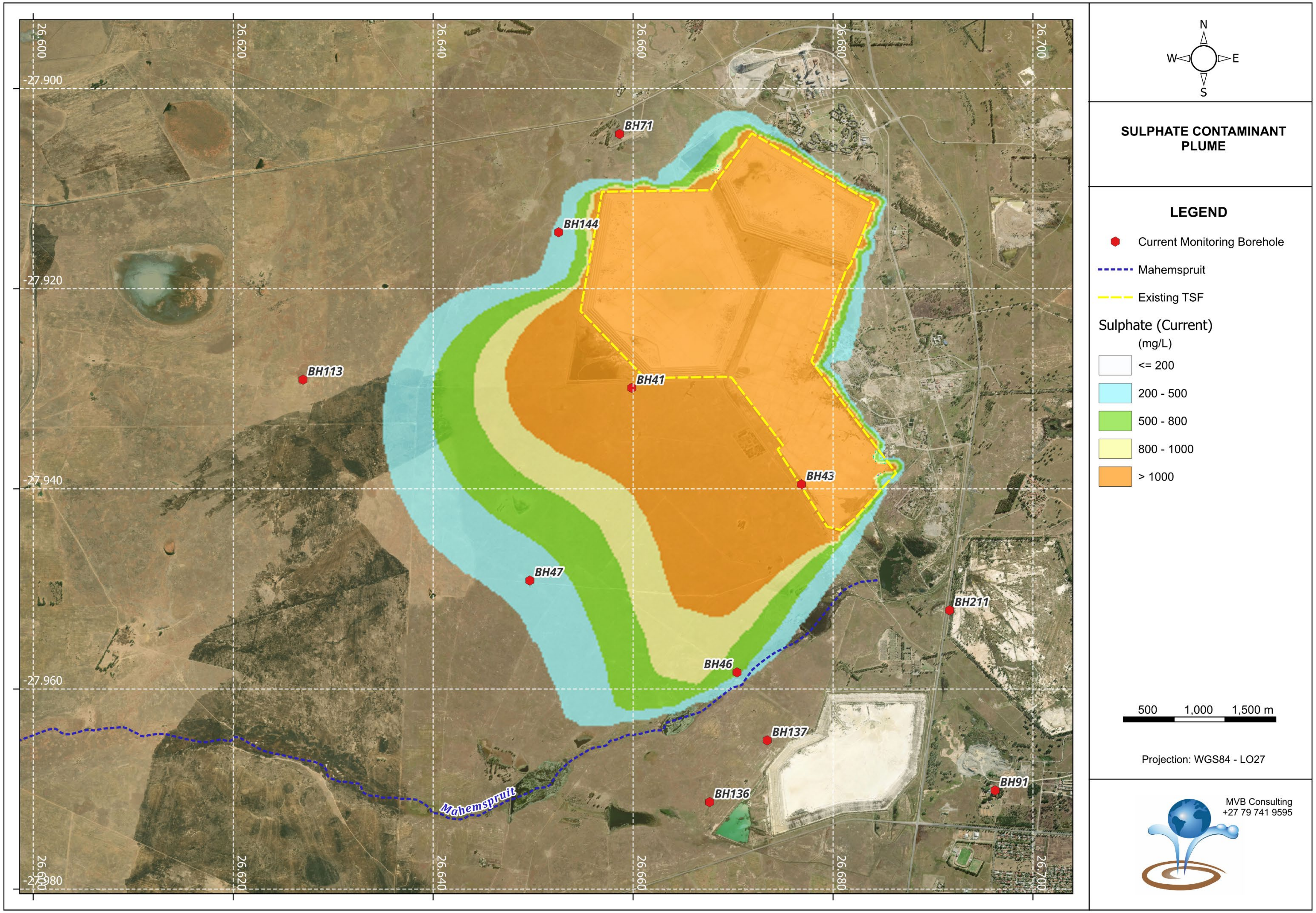

Figure 5.1: Simulated current sulphate plume from existing tailings facilities

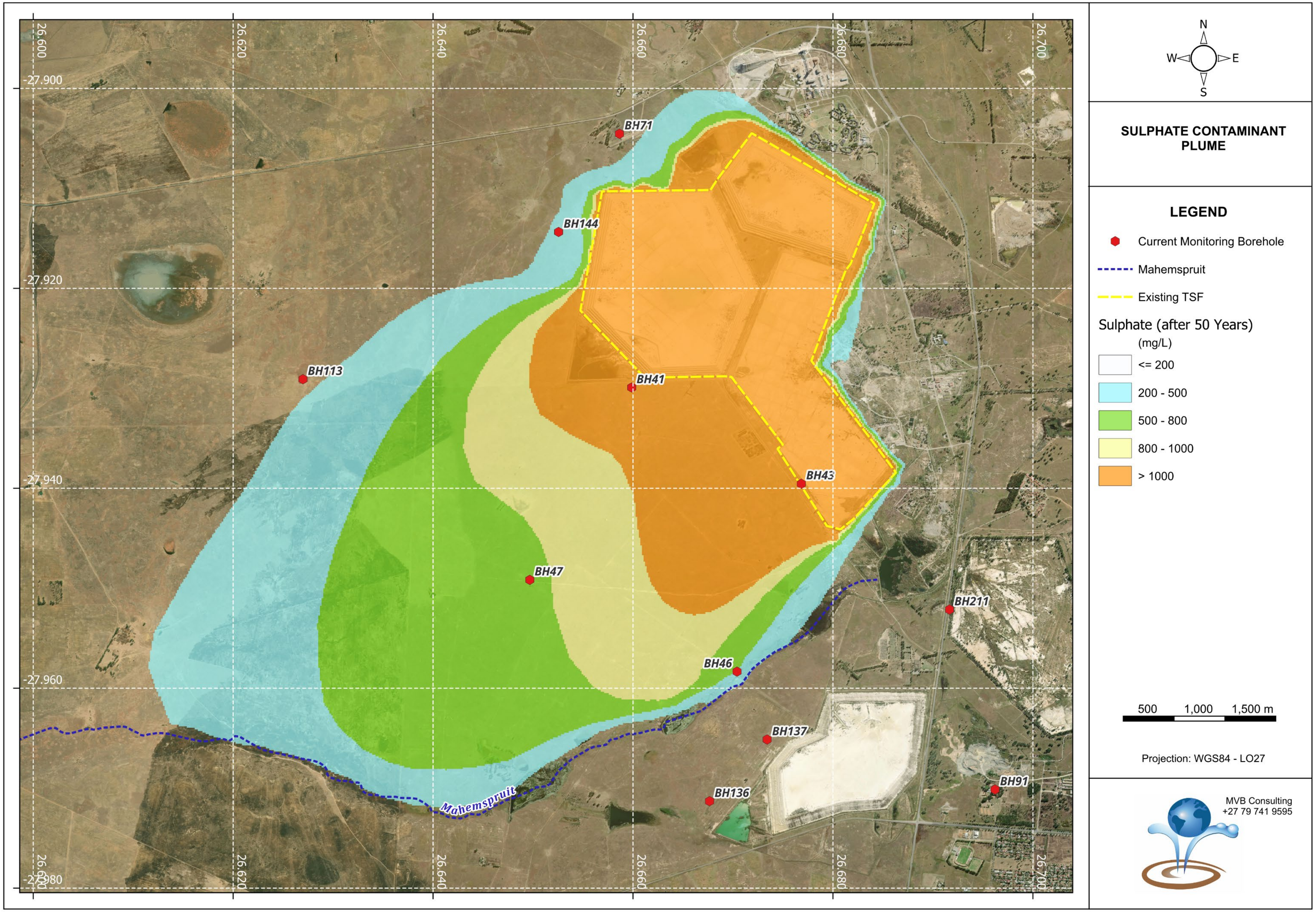

Figure 5.2: Simulated current sulphate plume from existing tailings facilities after 50 years

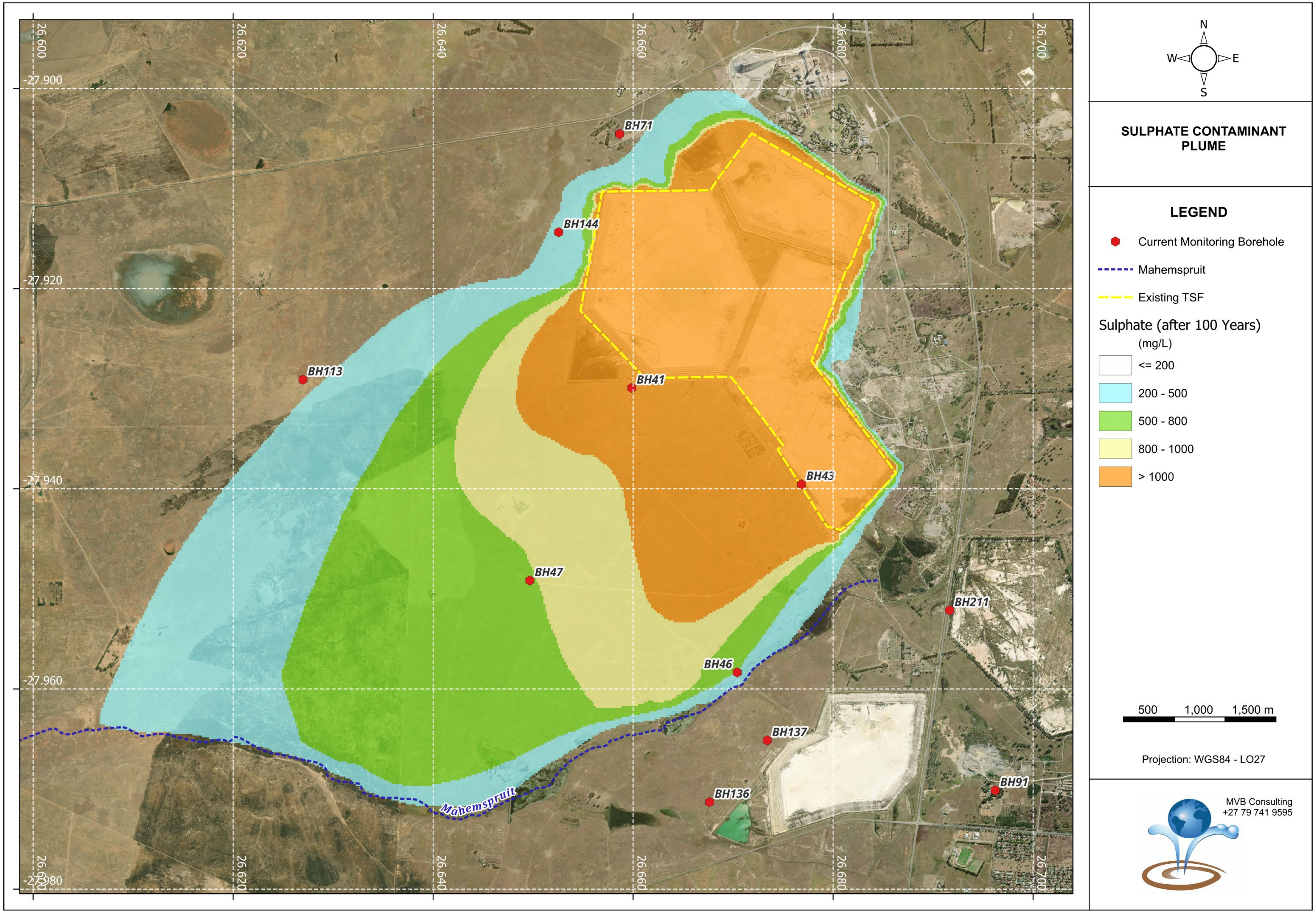

Figure 5.3: Simulated current sulphate plume from existing tailings facilities after 100 years

5.1 Assessment of Potential Impacts from the Valley TSF

The numerical model was used to simulate the following scenarios:

- Contaminant seepage from the proposed TSF and RWD without any liner for periods 10-, 50- and 100-years.
- Contaminant seepage from the proposed TSF and RWD with an engineered liner for a period of 100-years.

5.1.1 Contaminant Seepage from the Tailings Dam Without Liner

The Tailings Dam was modelled as a constant source (worst-case scenario) as it is assumed that the facility will continue to release impacted seepage to the environment. The impacts after 10 years, 50 years and 100 years were simulated and the results presented in Figure 5.5 to Figure 5.7.

The simulated sulphate concentration increase in down-gradient model observation borehole is illustrated Figure 5.4. It shows that after 48 years the sulphate concentration will exceed the SANS 241 limits.

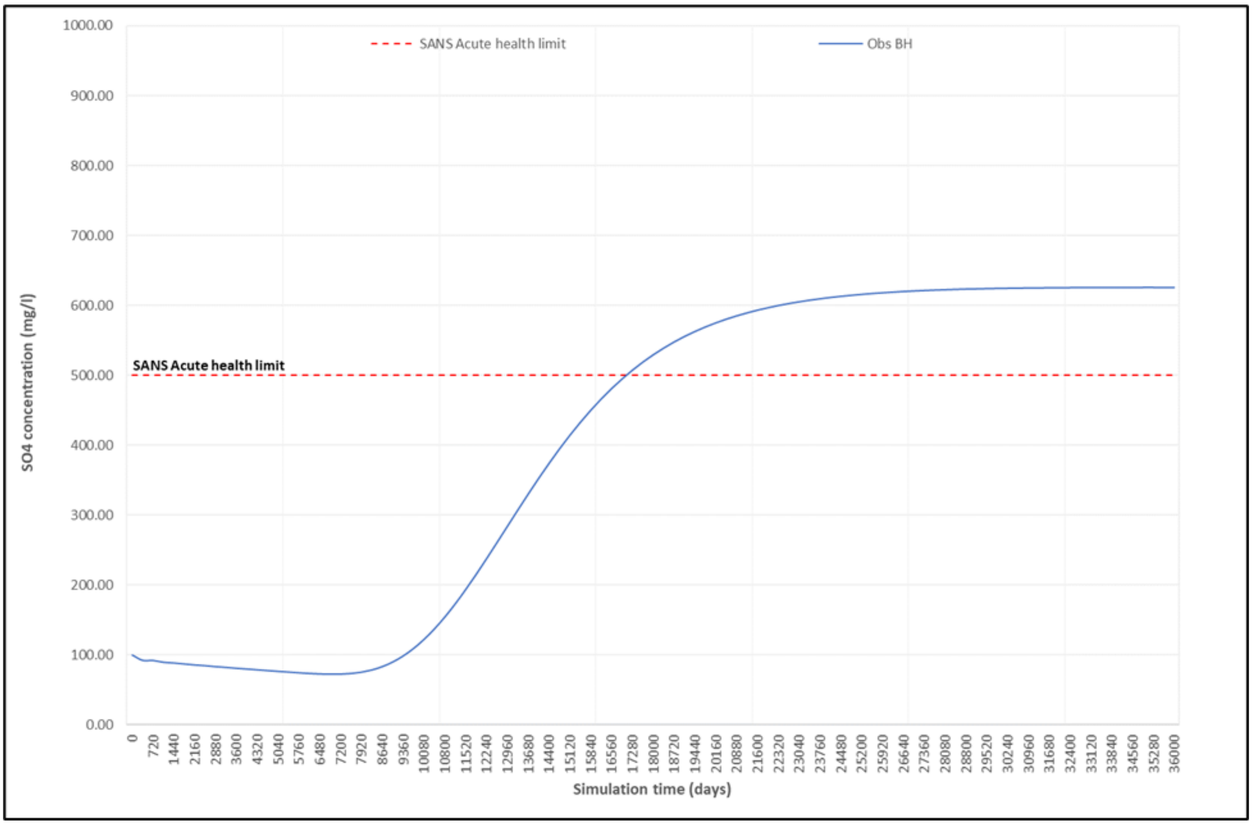

Figure 5.4: Simulated sulphate concentration in an observation borehole over time

Seepage from the proposed TSF migrates to the southwest, towards the Mahemspruit. Slightly elevated concentrations, between 200 – 500 mg/L reaches the stream after approximately 100 years.

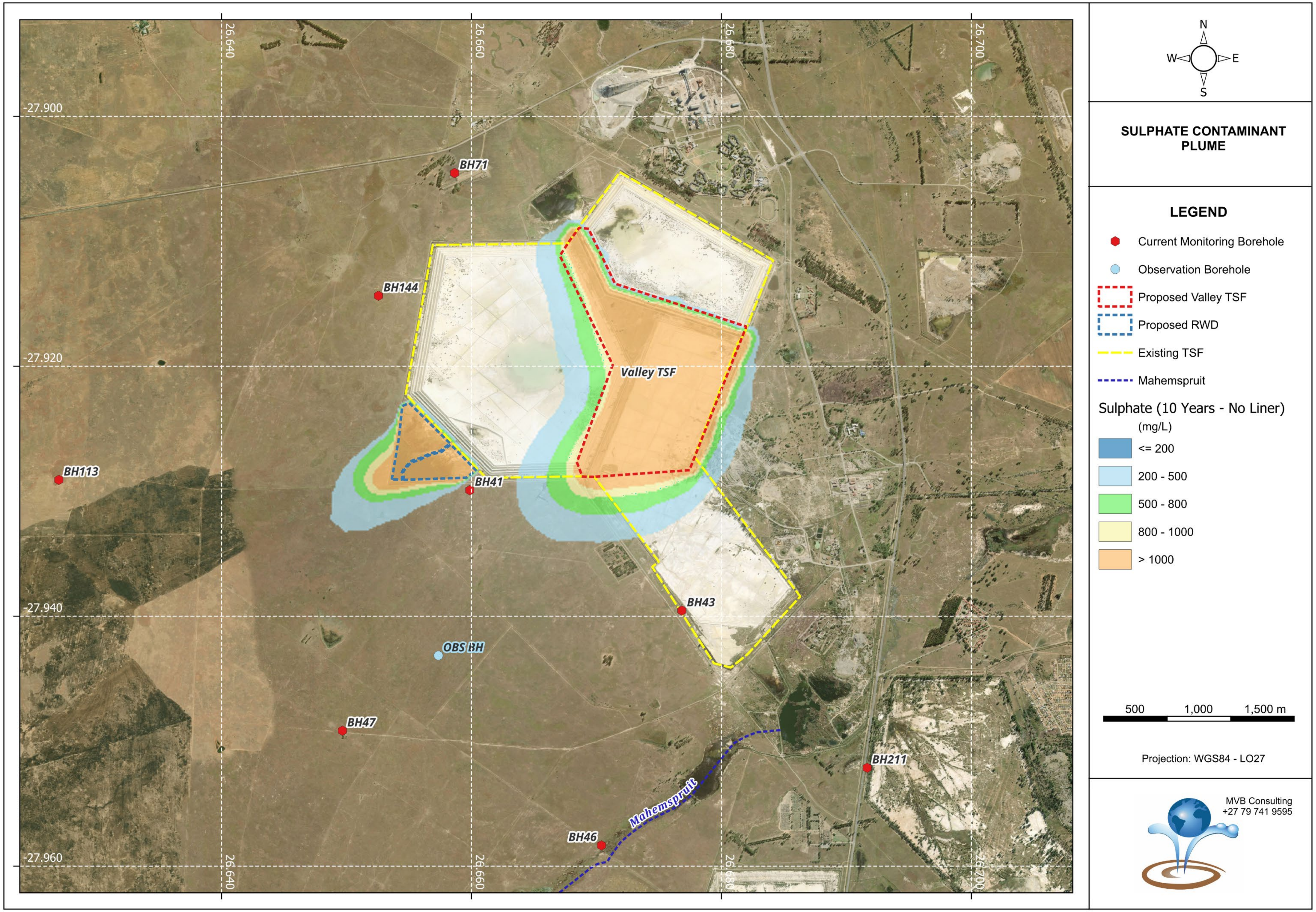

Figure 5.5: **Simulated sulphate plume after 10 years without a liner**

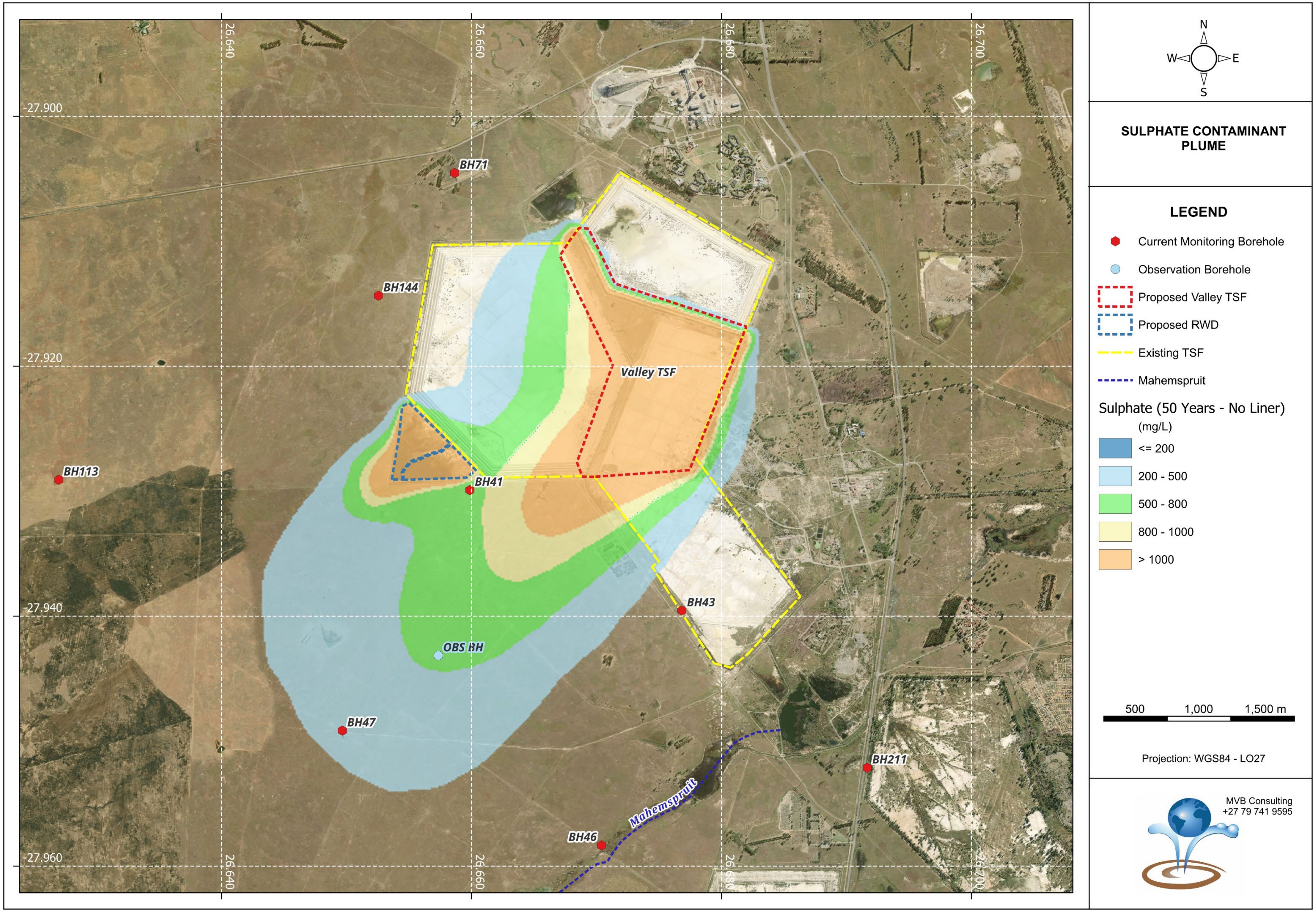

Figure 5.6: Simulated sulphate plume after 50 years without a liner

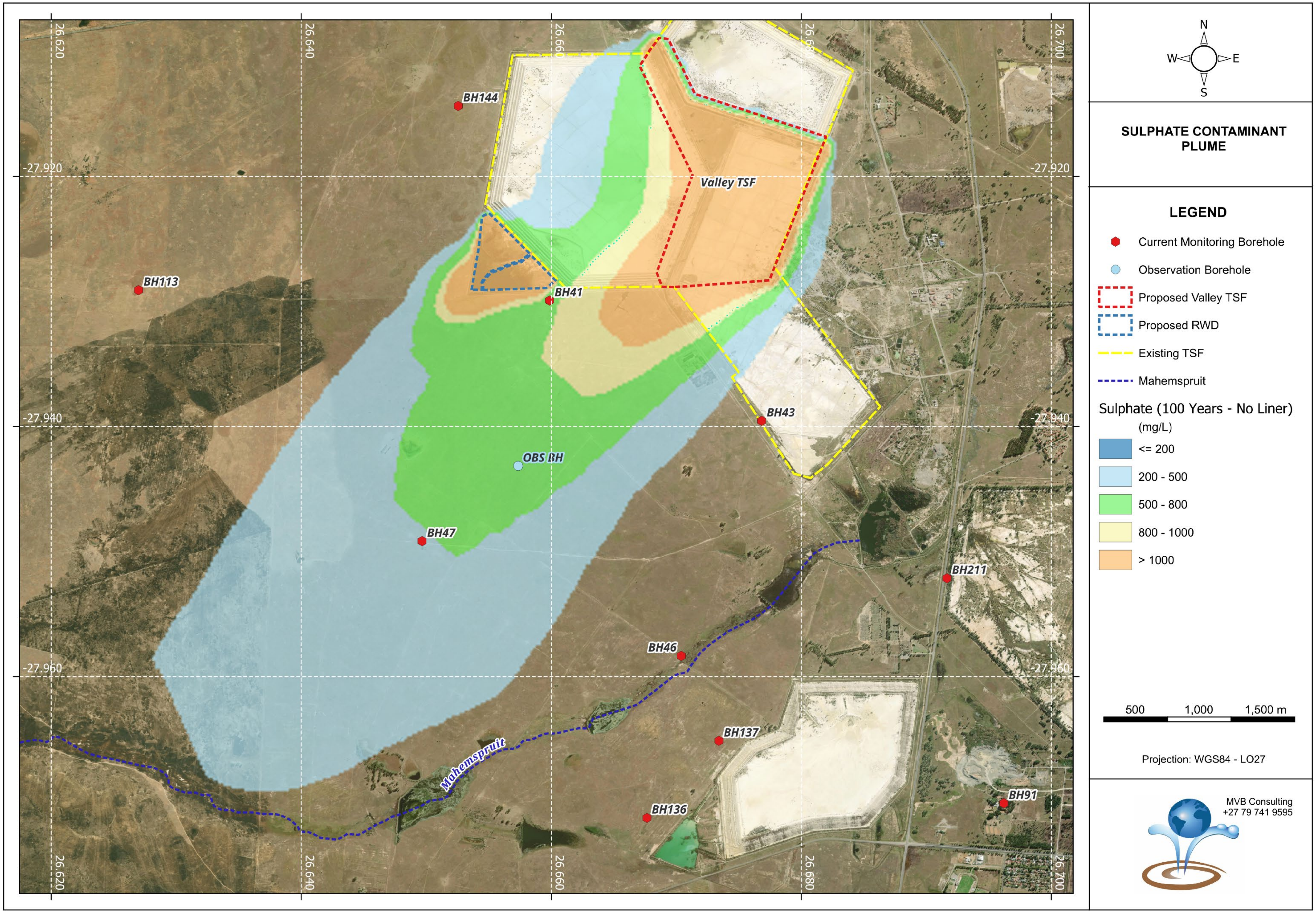

Figure 5.7: **Simulated sulphate plume after 100 years without a liner**

5.1.2 Contaminant Seepage from the Tailings Dam with a Liner

The gold tailings that will be deposited on the Valley TSF are classified as a Type 3 waste in terms of the NEMWA Regulations 2013 requiring a Class C containment barrier performance. The Class C single composite barrier system comprises of underdrainage; a base preparation layer; a 300mm thick compacted clay liner (CCL); a 1,5mm thick geomembrane; a dual-purpose ballast and protection layer of at least 100mm thickness, and above liner drainage system. The performance of such a barrier is largely influenced by the design specifications and associated Construction Quality Assurance (CQA). The nature and extent of wrinkles influences the containment performance, with an expected seepage rate to be in the order of 140 litres / hectare / day (Legge, 2024).

By making use of an ”ïnverted barrier system” comprising of underdrainage and a base preparation layer; a 1.5mm thick geomembrane ; and covered tailings the barrier system performance is improved by (a) seepage losses are reduced from about 140 l/ha/day to about 3 l/ha/day due to the change from Bernoulli flow at discontinuities to D’Arcian flow controlled by the tailings permeability at these points (Legge, 2024).

These leakage rates were included in the model and the impact simulated. The result from the 100-year simulation is presented in Figure 5.8 and shows that any contamination from the site will be contained. The small volume of seepage that may flow through the liner system is diluted to the extent that contamination is not detected.

5.2 Assessment of Cumulative Impacts from the Existing and Proposed TSF’s

The new Valley TSF will therefore not contribute to the groundwater quality deterioration, but the existing tailings facilities will continue to impact on the groundwater environment.

The following scenarios were modelled to illustrate this continued impact:

- The impacts from the existing tailings facility as well as the proposed, lined Valley TSF, after 50 years.
- The impacts from the existing tailings facility as well as the proposed, lined Valley TSF, after 100 years.

The results from the above simulations are shown in Figure 5.9 to Figure 5.10.

It is evident from this assessment that the area is already impacted by the historical activities. Plume migration is, however, slow and although the simulated plume has reached the Mahemspruit, the concentrations are <1 000 mg/L. The Mahemspruit is, however, impacted not only by this tailings facility, but also by other contaminant sources in the region.

The expected contribution of the impact from the Valley TSF is low and contained within the current impacted footprint.

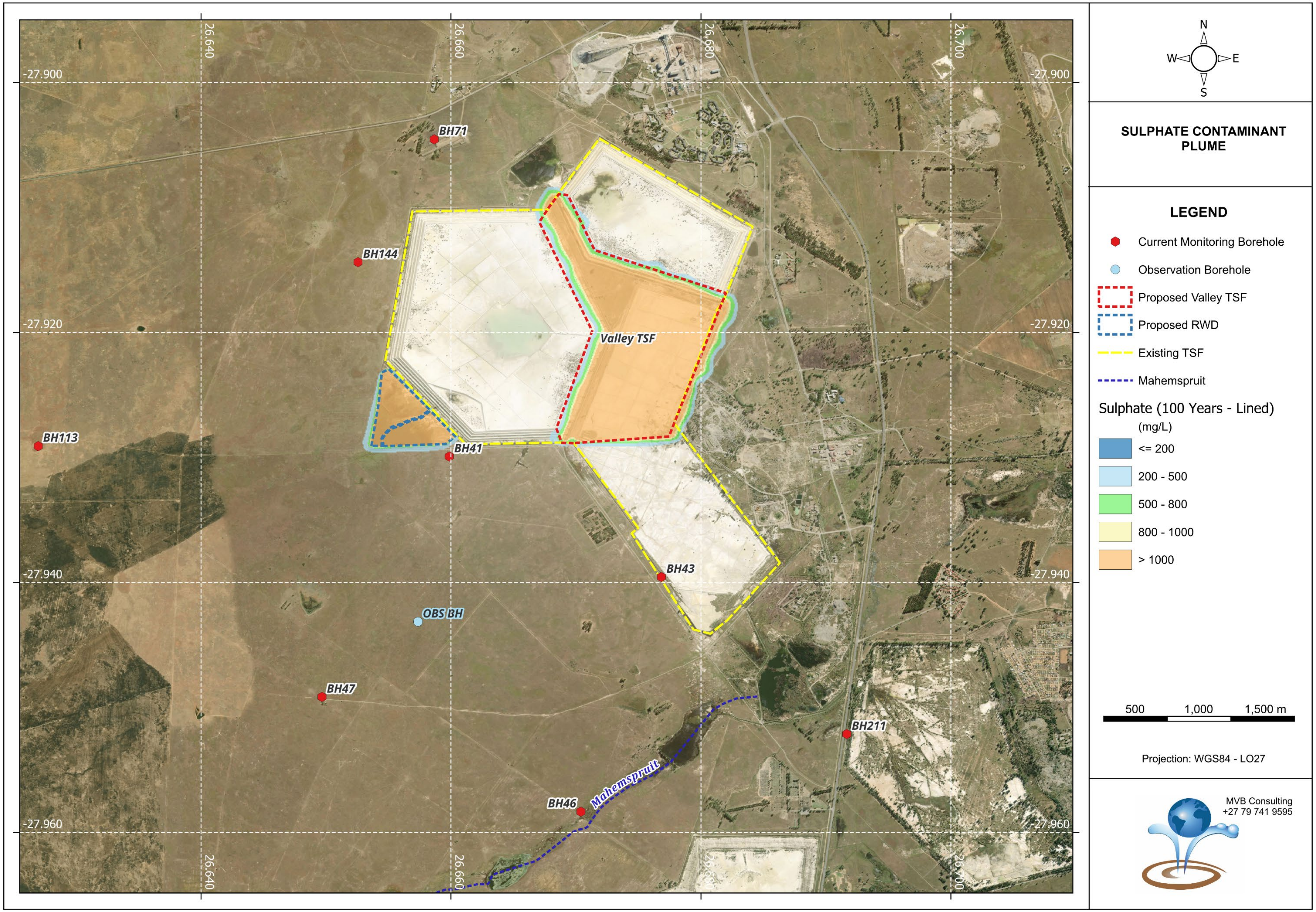

Figure 5.8: Simulated sulphate plume after 100 years with a liner

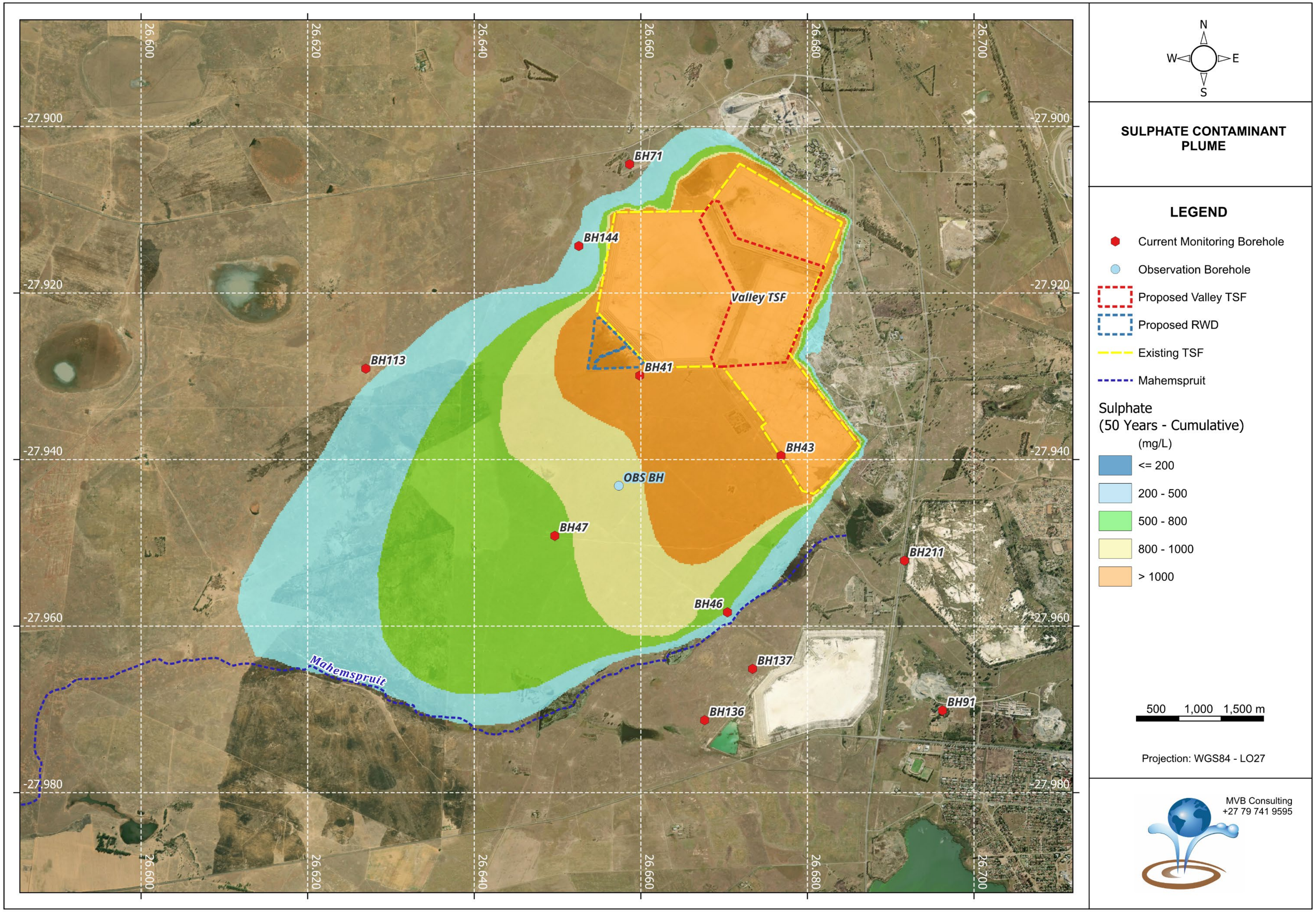

Figure 5.9: **Cumulative impact from the existing and Valley TSF after 50 years**

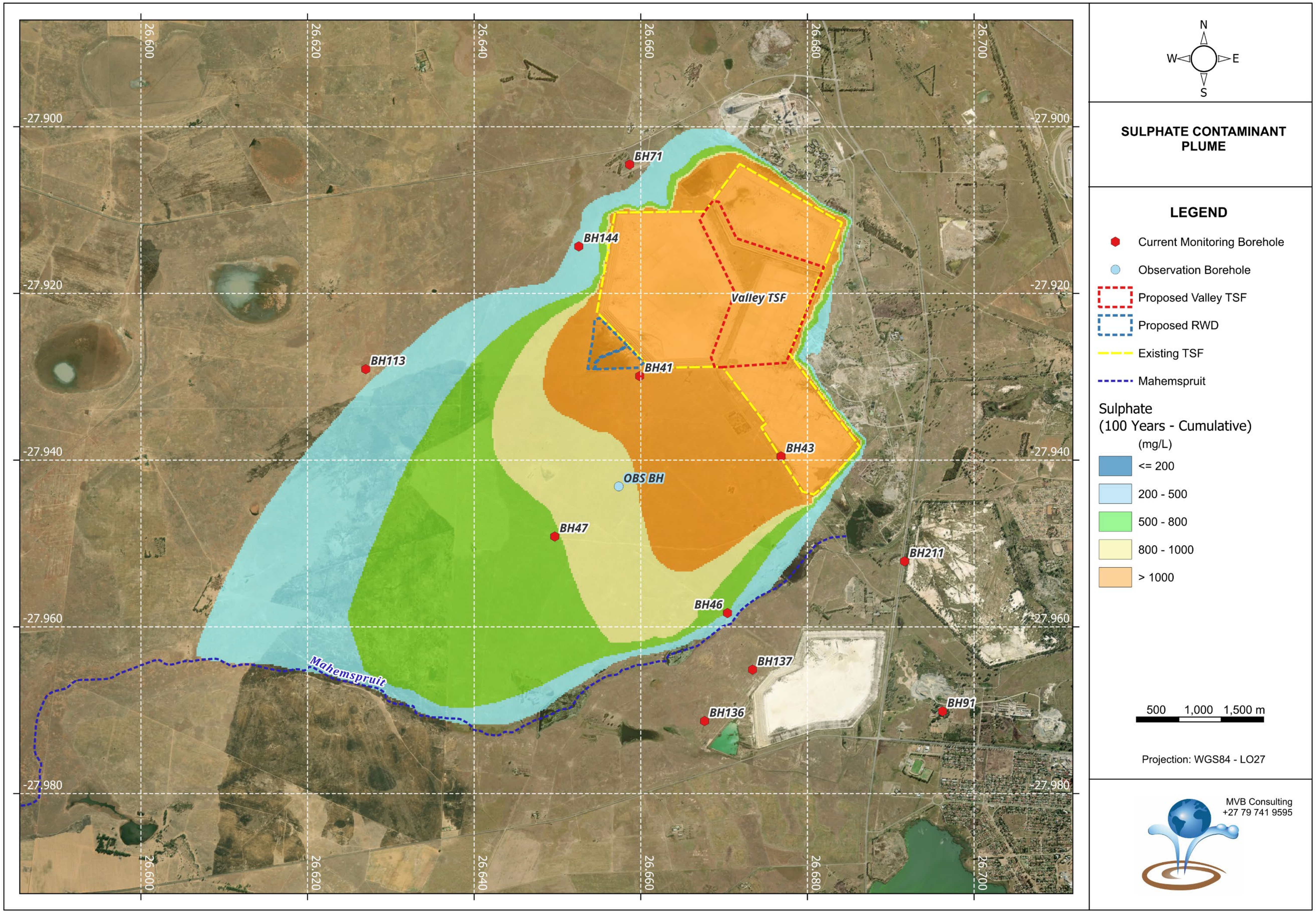

Figure 5.10: Cumulative impact from the existing and Valley TSF after 100 years

With reference to the above figures, it appears that the lining of the proposed Valley TSF will have little positive impact on the down-gradient groundwater quality. It is, however noted that although the positive impact is not visible on the extent of the plume, there is nevertheless a reduction in the contaminant concentration over time. Figure 5.11 shows the reduction in the sulphate concentration down-gradient from the facility with a liner installed.

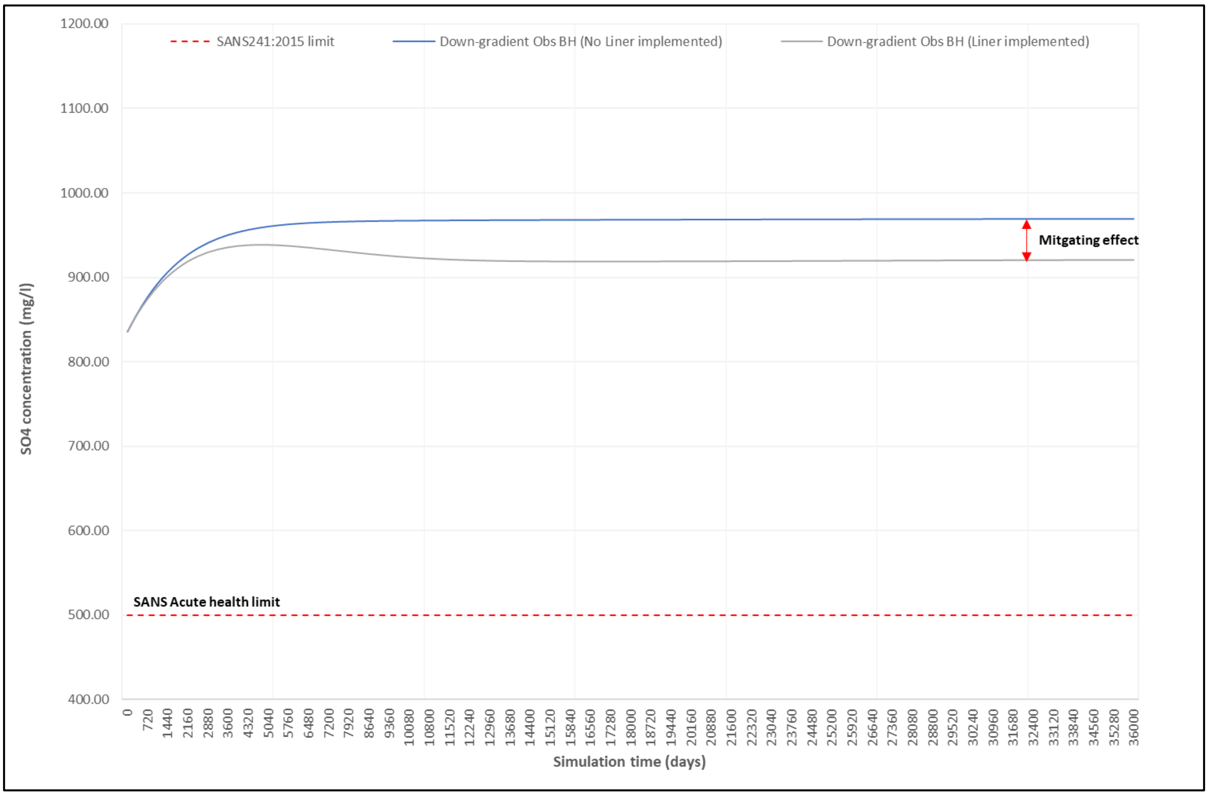

Figure 5.11: Simulated sulphate concentration in an observation borehole over time, with and without a liner

5.3 Risk Assessment

The impact significance rating methodology, as presented herein and utilised for all EIMS Impact Assessment Projects, is guided by the requirements of the NEMA EIA Regulations 2014 (as amended). The broad approach to the significance rating methodology is to determine the environmental risk (ER) by considering the consequence (C) of each impact (comprising Nature, Extent, Duration, Magnitude, and Reversibility) and relate this to the probability/ likelihood (P) of the impact occurring. The ER is determined for the pre- and post-mitigation scenario. In addition, other factors, including cumulative impacts and potential for irreplaceable loss of resources, are used to determine a prioritisation factor (PF) which is applied to the ER to determine the overall significance (S). The impact assessment will be applied to all identified alternatives.

5.3.1 Determination of the Environmental Risk

The significance (S) of an impact is determined by applying a prioritisation factor (PF) to the environmental risk (ER). The environmental risk is dependent on the consequence (C) of the particular impact and the probability (P) of the impact occurring. Consequence is determined through the consideration of the Nature (N), Extent (E), Duration (D), Magnitude (M), and Reversibility (R) applicable to the specific impact.

For the purpose of this methodology the consequence of the impact is represented by:

$$\boldsymbol{C} = \frac{(\boldsymbol{E}+\boldsymbol{D}+\boldsymbol{M}+\boldsymbol{R})*\boldsymbol{N}}{\boldsymbol{4}}$$

Each individual aspect in the determination of the consequence is represented by a rating scale as defined in Table 5.1 below.

Table 5.1: Criteria for determining Impact Consequence

Nature	-1	Likely to result in a negative/ detrimental impact
	+1	Likely to result in a positive/ beneficial impact
Extent	1	Activity (i.e. limited to the area applicable to the specific activity)
	2	Site (i.e. within the development property boundary)
	3	Local (i.e. the area within 5 km of the site)
	4	Regional (i.e. extends between 5 and 50 km from the site)
	5	Provincial / National (i.e. extends beyond 50 km from the site)
Duration	1	Immediate (<1 year)
	2	Short term (1-5 years)
	3	Medium term (6-15 years)
	4	Long term (15-65 years, the impact will cease after the operational life span of the project)
	5	Permanent (>65 years, no mitigation measure of natural process will reduce the impact after construction)
Intensity	1	Minor (where the impact affects the environment in such a way that natural, cultural and social functions and processes are not affected)
	2	Low (where the impact affects the environment in such a way that natural, cultural and social functions and processes are slightly affected)
	3	Moderate (where the affected environment is altered but natural, cultural and social functions and processes continue albeit in a modified way, moderate improvement for positive impacts)
	4	High (where natural, cultural or social functions or processes are altered to the extent that it will temporarily cease, high improvement for positive impacts)
	5	Very high / don't know (where natural, cultural or social functions or processes are altered to the extent that it will permanently cease, substantial improvement for positive impacts)
Reversibility	1	Impact is reversible without any time and cost.
	2	Impact is reversible without incurring significant time and cost.
	3	Impact is reversible only by incurring significant time and cost.
	4	Impact is reversible only by incurring prohibitively high time and cost.
	5	Irreversible Impact.

Once the C has been determined, the ER is determined in accordance with the standard risk assessment relationship by multiplying the C and the P. Probability is rated/ scored as per Table 5.2.

Table 5.2: Probability scoring

Probability	1	Improbable (the possibility of the impact materialising is very low as a result of design, historic experience, or implementation of adequate corrective actions; <25%),
	2	Low probability (there is a possibility that the impact will occur; >25% and <50%),
	3	Medium probability (the impact may occur; >50% and <75%),
	4	High probability (it is most likely that the impact will occur- > 75% probability), or
	5	Definite (the impact will occur),

The result is a qualitative representation of relative ER associated with the impact. ER is therefore calculated as follows:

$$ER = C \times P$$

Table 5.3: Determination of Environmental Risk

Consequence	5	5	10	15	20	25
	4	4	8	12	16	20
	3	3	6	9	12	15
	2	2	4	6	8	10
	1	1	2	3	4	5
		1	2	3	4	5
	Probability					

The outcome of the environmental risk assessment will result in a range of scores, ranging from 1 through to 25. These ER scores are then grouped into respective classes as described in Table 5.4.

Table 5.4: Environmental Risk Scores

ER Score	Description
<9	Low (i.e. where this impact is unlikely to be a significant environmental risk/ reward).
≥9 ≤17	Medium (i.e. where the impact could have a significant environmental risk/ reward),
>17	High (i.e. where the impact will have a significant environmental risk/ reward).

The impact ER will be determined for each impact without relevant management and mitigation measures (pre-mitigation), as well as post implementation of relevant management and mitigation measures (post-mitigation). This allows for a prediction in the degree to which the impact can be managed/mitigated.

5.3.2 Impact Prioritisation

Further to the assessment criteria presented in the section above, it is necessary to assess each potentially significant impact in terms of:

- Cumulative impacts; and
- The degree to which the impact may cause irreplaceable loss of resources.

To ensure that these factors are considered, an impact prioritisation factor (PF) will be applied to each impact ER (post-mitigation). This prioritisation factor does not aim to detract from the risk ratings but rather to focus the attention of the decision-making authority on the higher priority/significance issues and impacts. The PF will be applied to the ER score based on the assumption that relevant suggested management/mitigation impacts are implemented.

Table 5.5: Criteria for Determining Prioritisation

Cumulative Impact (CI)	Low (1)	Considering the potential incremental, interactive, sequential, and synergistic cumulative impacts, it is unlikely that the impact will result in spatial and temporal cumulative change.
	Medium (2)	Considering the potential incremental, interactive, sequential, and synergistic cumulative impacts, it is probable that the impact will result in spatial and temporal cumulative change.
	High (3)	Considering the potential incremental, interactive, sequential, and synergistic cumulative impacts, it is highly probable/ definite that the impact will result in spatial and temporal cumulative change.
Irreplaceable Loss of Resources (LR)	Low (1)	Where the impact is unlikely to result in irreplaceable loss of resources.
	Medium (2)	Where the impact may result in the irreplaceable loss (cannot be replaced or substituted) of resources but the value (services and/or functions) of these resources is limited.
	High (3)	Where the impact may result in the irreplaceable loss of resources of high value (services and/or functions).

The value for the final impact priority is represented as a single consolidated priority, determined as the sum of each individual criteria represented in Table 5. The impact priority is therefore determined as follows:

$$Priority = CI + LR$$

The result is a priority score which ranges from 2 to 6 and a consequent PF ranging from 1 to 2 (refer to Table 5.6).

Table 5.6: Determination of Prioritisation Factor

Priority	Prioritisation Factor
2	1
3	1.125
4	1.25
5	1.375
6	1.5

In order to determine the final impact significance, the PF is multiplied by the ER of the post mitigation scoring. The ultimate aim of the PF is an attempt to increase the post mitigation environmental risk rating by a factor of 0.5, if all the priority attributes are high (i.e. if an impact comes out with a high medium environmental risk after the conventional impact rating, but there is significant cumulative impact potential and significant potential for irreplaceable loss of resources, then the net result would be to upscale the impact to a high significance).

Table 5.7: Final Environmental Significance Rating

Significance Rating	Description
<-17	High negative (i.e. where the impact must have an influence on the decision process to develop in the area).
≥-17, ≤-9	Medium negative (i.e. where the impact could influence the decision to develop in the area).
>-9, < 0	Low negative (i.e. where this impact would not have a direct influence on the decision to develop in the area).
0	No impact
>0, <9	Low positive (i.e. where this impact would not have a direct influence on the decision to develop in the area).
≥9, ≤17	Medium positive (i.e. where the impact could influence the decision to develop in the area).
>17	High positive (i.e. where the impact must have an influence on the decision process to develop in the area).

The significance ratings and additional considerations applied to each impact provide a quantitative comparative assessment of the alternatives being considered.

5.3.3 Impact Assessment Result

The geohydrological impact assessment for the proposed Valley TSF is presented in Table 5.8. With reference to Table 5.8 the following is concluded:

- The primary risk that this proposed project poses is the seepage of contaminants into the aquifer, and the migration of these contaminants into down-gradient receptors.

Table 5.8: Valley TSF groundwater impact assessment table

IMPACT DESCRIPTION				Pre-Mitigation							Post Mitigation								Priority Factor Criteria			
Identifier	Impact	Alternative	Phase	Nature	Extent	Duration	Magnitude	Reversibility	Probability	Pre-mitigation ER	Nature	Extent	Duration	Magnitude	Reversibility	Probability	Post-mitigation ER	Confidence	Cumulative Impact	Irreplaceable loss	Priority Factor	Final score
1	Groundwater contamination from Valley TSF-Unlined	Alternative 1	Operation	-1	2	3	2	3	3	-7.5	-1	1	2	2	3	2	-4	Medium	2	2	1.25	-5
2	Cumulative groundwater contamination-Valley TSF Unlined	Alternative 1	Operation	-1	3	4	3	3	4	-13	-1	2	3	3	3	4	-11	Medium	2	2	1.25	-13.75
1	Groundwater contamination from Valley TSF-Lined	Alternative 2	Operation	-1	1	2	1	2	2	-3	-1	1	2	2	3	1	-2	Medium	2	2	1.25	-2.5
2	Cumulative groundwater contamination-Valley TSF Lined	Alternative 2	Operation	-1	3	4	3	3	4	-13	-1	2	3	3	3	4	-11	Medium	2	2	1.25	-13.75
1	Groundwater contamination from Valley TSF-Unlined	Alternative 1	Decommissioning	-1	2	3	2	3	3	-7.5	-1	1	2	2	3	2	-4	Medium	2	2	1.25	-5
2	Cumulative groundwater contamination-Valley TSF Unlined	Alternative 1	Decommissioning	-1	3	4	3	3	4	-13	-1	2	3	3	3	4	-11	Medium	2	2	1.25	-13.75
1	Groundwater contamination from Valley TSF-Lined	Alternative 2	Decommissioning	-1	1	2	1	2	2	-3	-1	1	2	2	3	1	-2	Medium	2	2	1.25	-2.5
2	Cumulative groundwater contamination-Valley TSF Lined	Alternative 2	Decommissioning	-1	3	4	3	3	4	-13	-1	2	3	3	3	4	-11	Medium	2	2	1.25	-13.75

6. GROUNDWATER MONITORING SYSTEM

6.1 Introduction

A long-term monitoring programme should be developed based on the guideline documented in Best Practice Guideline G3 Water Monitoring Systems (2007) available from the Department of Water and Sanitation (DWS). These guidelines are summarised and implemented in the proposed monitoring plan.

A monitoring plan is necessary because (DWS, 2007):

- Accurate and reliable data forms a key component of many environmental management actions.
- Water monitoring is a legal requirement.
- The most common environmental management actions require data and thus the objectives of water monitoring include the following:
  - Development of environmental and water management plans based on impact and incident monitoring (facilitate in decision-making, serve as early warning to indicate remedial measures or that actions are required in certain areas) for the mine and region.
  - Generation of baseline/background data before project implementation.
  - Identification of sources of pollution and extent of pollution (legal implications or liabilities associated with the risks of contamination moving off site).
  - Monitoring of water usage by different users (control of cost and maximising of water reuse).
  - Calibration and verification of various prediction and assessment models (planning for decommissioning and closure).
  - Evaluation and auditing of the success of implemented management actions (ISO 14000, compliance monitoring).
  - Assessment of compliance with set standards and legislation (EMPs, water use licenses).
  - Assessment of impact on receiving water environment.

Monitoring within a project area consists of various components as illustrated by the overall monitoring process (Figure 6.1) It should be recognised and understood that the successful development and implementation of an appropriate, accurate and reliable monitoring programme requires that a defined structured procedure be followed. A monitoring programme should include the location of all monitoring points (indicated on a map), the type of data to be collected, as well as the data collection (protocol / procedure / methodology, frequency of monitoring and parameters determined, quality control and assurance), management (database and assessment) and reporting procedures. This programme should then be implemented. The results from the monitoring programme should be representative of the actual situation. To ensure that the monitoring programme functions properly, an operating and maintenance programme should be developed and implemented. A data management system is necessary to ensure that data is stored / used optimally and is accessible to all the relevant users. The monitoring programme should include quality control measures. It is important to note that this programme is dynamic and should change as the mine and water management needs change.

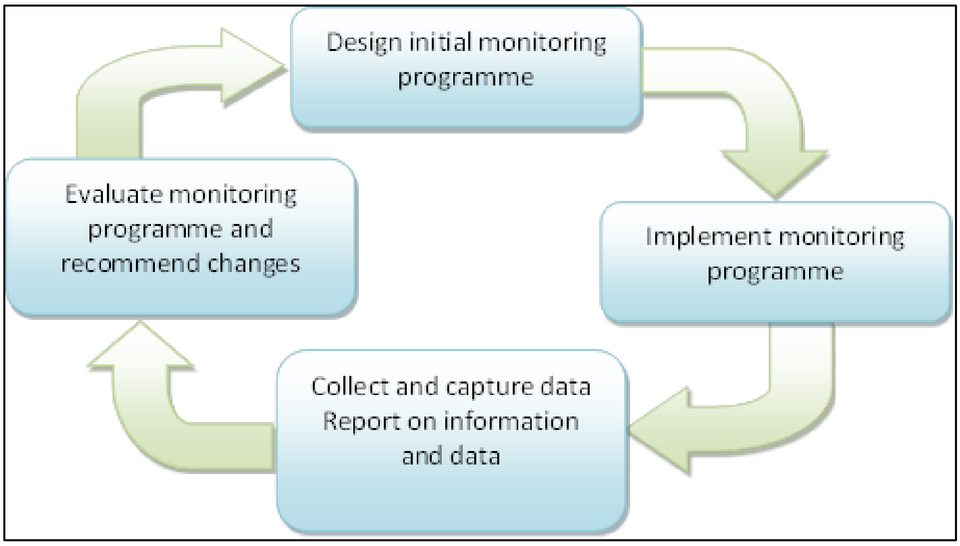

Figure 6.1: Monitoring process (DWA, 2007)

Effective groundwater monitoring systems consist of the following components:

- Groundwater quality monitoring system.
- Groundwater flow monitoring system.
- Data and information management system.

When designing the monitoring system, the following issues should also be taken into consideration:

- Potential or actual water use.
- Aquifer or catchment vulnerability.
- Toxicity of chemicals.
- Potential for seepage or releases.
- Quantities and frequency of release to the environment (point and non-point).
- Management measures in place to minimise risk.

Groundwater sampling should be done in accordance with industry standards. The sampling procedures are discussed in detail in:

- Weaver, J.M.C. 1992a. Groundwater sampling: A comprehensive guide for sampling methods (WRC Report No. TT 54/92). Pretoria: Water Research Commission.
- Weaver, J.M.C. 1992b. Groundwater sampling: An abbreviated field guide for sampling methods (WRC Report No. TT 56/92). Pretoria: Water Research Commission.

These sampling procedures should be adhered to.

6.2 Groundwater Monitoring Network

Three additional borehole pairs (one shallow and one deep) are recommended as shown in Figure 6.2. The impact from the lined Valley TSF will not extend beyond the dam itself, and the monitoring is therefore aimed at the entire footprint, not only the Valley TSF.

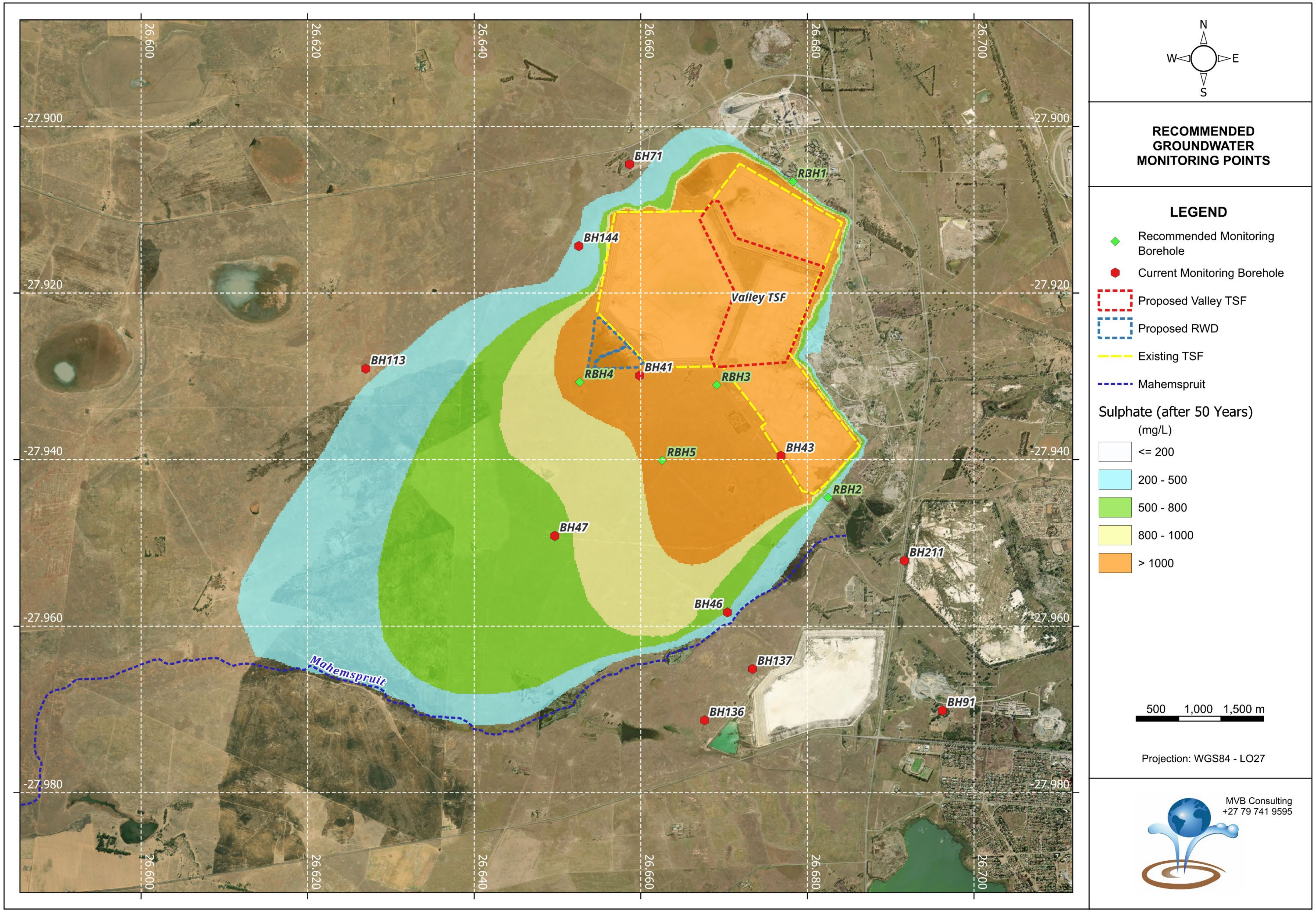

Figure 6.2: **Recommended groundwater monitoring network**

The following is recommended in terms of monitoring:

- Groundwater levels.
- Groundwater quality.
- Data should be stored electronically in an acceptable database.
- On the completion of every sampling run a monitoring report should be written. Any changes in the groundwater levels and quality should be flagged and explained in the report.
- A compliance report can be submitted to DWS once a year, if required.

6.3 Monitoring frequency

- A comprehensive quarterly analysis of the dedicated monitoring boreholes.
- Groundwater levels should be monitored monthly in the dedicated groundwater monitoring boreholes.
- Rainfall should be monitored daily.

6.4 Monitoring Parameters

Samples should be submitted to a SANAS accredited laboratory. The following recommended parameters to be analysed for include:

- pH.
- Electrical Conductivity.
- Total Dissolved Solids.
- Total Alkalinity.
- Anions and Cations (Ca, Mg, Na, K, NO_3, NH_4, Cl, SO_4, F, Fe, Mn, Al, Cr).

7. SUMMARY AND CONCLUSIONS

7.1 Study Objectives

A new deposition site will be required for Harmony One Plant to deposit gold tailings, by July 2024. Following a review of other possibilities for One Plant's future tailings deposition, an option to utilise the space between the Free State North 1 and Free State North 2 TSFs and portion of the footprint of the FSN4 TSF has been identified as possible deposition site, referred to as the Valley TSF. The previous design of the Valley TSF was altered to utilise and line the FSN1 RWD, which would then be known as the new Valley Return Water Dam.

The purpose of the study was to assess the potential impact from the proposed Valley TSF and RWD on the groundwater regime. A calibrated numerical groundwater flow and mass transport model was developed to simulate the following potential impacts:

- Contaminant seepage from the proposed Valley TSF and RWD without any liner for periods 50- and 100-years.
- Contaminant seepage from the proposed Valley TSF and RWD with a liner for a period of 100-years.
- Cumulative impact from the larger tailings facility for periods 50- and 100-years.

7.2 Geohydrological Conceptual Setting

Sediments of the Vryheid Formation of the Ecca Group underlie the study area. The Vryheid Formation (Ecca Group) mainly comprises mudstone, siltstone and fine- to coarse-grained sandstone (pebbly in places).

Dolerite intrusions are common in this type of geological terrain and governs groundwater flow in the deeper un-weathered formations. Based on the exploration drilling the Karoo Supergroup has an average thickness of 183m in the study area.

Even though the shale and sandstone are not known to contain economic aquifers, groundwater contributes to stream flow and in some instances, high yielding boreholes have been recorded. The following three aquifers underlie the site:

- ***Weathered Aquifer (Karoo Formations):*** A shallow, weathered aquifer exists in the weathered shale and sandstone at an average depth of 10m – 20m below ground level. The most consistent water strike is located at the fresh bedrock / weathering interface. The hydraulic conductivity of the weathered aquifer is typically in the order of 0.1 m/day. The vertical permeability is in the order of 0.001 m/day to 0.00010 m/day, which is sufficiently low to confine the groundwater in the underlying fractured rock aquifer.
- ***Fractured Aquifer (Karoo Formations):*** The primary porosity of the Vryheid Formation is very low. Any water bearing capacity is therefore associated with secondary joints, bedding planes and faults. The contact zones of dolerite intrusions are characterised by cooling joints and fractures, which are considered the primary source of groundwater flow within the deeper formations. The hydraulic conductivity of the fractured rock aquifer is typically in the order of 0.001 m/day to 0.1 m/day. The depth to groundwater in this aquifer can be variable due to confining layers in parts of the study area.

  The two aquifers may or may not be hydraulically connected, dependent on the local geology.
- ***Witwatersrand / Ventersdorp Aquifer:*** The deep brine Witwatersrand aquifer is situated approximately 300m below surface. This aquifer is thought to be connate

(i.e. original formation water) or extremely old (fossil) water and is usually concentrated on geological structures such as fault zones or igneous intrusions (e.g. dykes).

The Witwatersrand aquifer has been largely dewatered during the past 40 years of mining and the water levels in the aquifer dropped significantly. In spite of the dewatering of the Witwatersrand aquifer, there is no evidence of dewatering of the shallow Karoo aquifers.

Rainfall in the region is approximately 540 mm/annum and recharge to the aquifer is estimated at 2-4% of the annual rainfall.

The groundwater mimics the topography and the groundwater flow in the study area is generally to the southwest, towards the Mahemspruit.

Routine groundwater sampling is conducted on the site and the following is observed in terms of the groundwater quality:

- The groundwater in the Free State is generally saline and most of the boreholes have EC and TDS concentrations that exceed the guideline limits. Very high TDS concentrations are recorded in borehole BH46. This borehole is situated very close to a stream indicating that spillage is occurring or has occurred into this stream. The high concentrations are not attributed to natural plume migration.
- The high salt (concentrations are primarily attributed to chloride, sulphate and sodium.
- The existing tailings facilities have impacted on the surrounding groundwater environment. The most impacted areas appear to be associated with the return water dams, and / or spillage into a surface stream and not necessarily the TSF itself.

7.3 Groundwater Modelling and Impact Assessment

The conceptual geohydrological model described in the previous section was translated to a calibrated numerical groundwater flow and mass transport model. The purpose of the model is mainly to use as a tool to simulate the following:

- Contaminant seepage from the proposed Valley TSF and RWD without any liner for periods 50- and 100-years.
- Contaminant seepage from the proposed Valley TSF and RWD with a liner for a period of 100-years.
- Cumulative impact from the larger tailings facility for periods 50- and 100-years.

In order to develop a model of an aquifer system, certain assumptions have to be made. The following assumptions were made:

- No abstraction boreholes were included in the initial model.
- The boundary conditions assigned to the model are considered correct.
- The impacts of other activities (e.g. agriculture) have not been considered.

It is important to note that a numerical groundwater model is a representation of the real system. It is therefore at most an approximation, and the level of accuracy depends on the quality of the data that is available. This implies that there are always errors associated with groundwater models due to uncertainty in the data and the capability of numerical methods to describe natural physical processes.

The model network constructed for the site consists of 1 033 948 elements. The model consists of the following layers:

- Layer 1: Weathered formations – 30m thickness.
- Layer 2: Fractured formations – 150m thickness.

Sulphate was selected as representative of the potential impacts from the tailings dam. Based on the waste assessment conducted by Jones & Wagener (2022), a source concentration of 2 000 mg/L was included in the model to assess how contamination from the proposed Valley TSF and RWD will migrate.

The mass transport and flow modelling results can be summarised as follows:

- **Contaminant Seepage from the Tailings Dam Without Liner**

  The TSF was modelled as a constant source (worst-case scenario) as it is assumed that the facility will continue to release impacted seepage to the environment. The impacts after 10 years, 50 years and 100 years were simulated.

  Seepage from the proposed Valley TSF and RWD migrates to the southwest, towards the Mahemspruit. Slightly elevated concentrations, between 200 – 500 mg/L reaches the stream after approximately 100 years. The simulated sulphate concentration increase, at an observation point some 2 000m down-gradient from the TSF, shows that after 48 years the sulphate concentration will exceed the SANS 241 limits.

- ***Contaminant Seepage from the Tailings Dam with an Engineered Liner***

  The gold tailings that will be deposited on the Valley TSF are classified as a Type 3 waste in terms of the NEMWA Regulations 2013 requiring a Class C containment barrier performance. The Class C single composite barrier system has an expected seepage rate in the order of 140 litres / hectare / day (Legge, 2024).

  By making use of an ”ïnverted barrier system” comprising of underdrainage and a base preparation layer; a 1.5mm thick geomembrane ; and covered tailings the barrier system performance is improved by (a) seepage losses are reduced from about 140 l/ha/day to about 3 l/ha/day due to the change from Bernoulli flow at discontinuities to D’Arcian flow controlled by the tailings permeability at these points (Legge, 2024).

  These leakage rates were included in the model and the impact simulated. The result from the 100-year simulation shows that any contamination from the site will be contained. The small volume of seepage that may flow through the liner system is diluted to the extent that contamination is not detected.

7.4 Study Conclusion

The following risks are generally associated with this project:

- Impact on the regional groundwater quality because of seepage of contaminants from the TSF and / or RWD.

It is evident from this assessment that the area is already impacted by the historical activities. Plume migration is, however, slow and although the simulated current plume has reached the Mahemspruit, the concentrations are <500 mg/L. The Mahemspruit is, however, impacted not only by this tailings facility, but also by other contaminant sources in the region.

The expected contribution of the impact from the Valley TSF is low and contained within the current impacted footprint.

The unmitigated impact shows that a contaminant plume will migrate from the proposed TSF towards the only down-gradient receptor, the Mahemspruit. This contaminant flow is very slow and small impacts (<500 mg/L SO_4) will only reach the stream after approximately 100 years.

With reference to the modelled plumes, it appears that the lining of the proposed Valley TSF will have little positive impact on the down-gradient groundwater quality. It is, however noted that although the positive impact is not visible on the extent of the plume, there is nevertheless a reduction in the contaminant concentration over time. The reduction in the sulphate concentration down-gradient from the facility, with a liner installed, is approximately 50mg/L after 30 years.

This is a small improvement and it is therefore recommended that a rehabilitation plan be developed to address the groundwater deterioration from the existing TSF, in conjunction with the lining of the Valley TSF.

8. RECOMMENDATIONS

At this stage only monitoring is recommended to verify the findings of the numerical modelling and three additional groundwater monitoring borehole pairs are recommended (see Figure 6.2 for the localities of the recommended boreholes). The impact from the lined Valley TSF will not extend beyond the dam itself, and the monitoring is therefore aimed at the entire footprint, not only the Valley TSF.

The following is recommended in terms of monitoring:

- A comprehensive bi-annual analysis of the dedicated monitoring boreholes.
- Groundwater levels should be monitored monthly in the dedicated groundwater monitoring boreholes.
- Rainfall should be monitored daily.

Samples should be submitted to a SANAS accredited laboratory. The following recommended parameters to be analysed for include:

- pH.
- Electrical Conductivity.
- Total Dissolved Solids.
- Total Alkalinity.
- Anions and Cations (Ca, Mg, Na, K, NO_3, NH_4, Cl, SO_4, F, Fe, Mn, Al, Cr).

In addition it is also recommended that the possibility of phyto-remediation is considered and implemented as soon as possible.

Phytoremediation (‘phyto’ means plant) is a generic term for the group of technologies that use plants for remediating soils, sludges, sediments and water contaminated with organic and inorganic contaminants. Phytoremediation can be defined as “the efficient use of plants to remove, detoxify or immobilise environmental contaminants in a growth matrix (soil, water or sediments) through the natural biological, chemical or physical activities and processes of the plants” (https://bohatala.com/application-and-techniques-for-phytoremediation/).

Phytoremediation is a bioremediation process that uses various types of plants to remove, transfer, stabilise, and/or destroy contaminants in the soil and groundwater. There are several different types of phytoremediation mechanisms. These are:

- Rhizosphere biodegradation. In this process, the plant releases natural substances through its roots, supplying nutrients to microorganisms in the soil. The microorganisms enhance biological degradation.

- Phyto-stabilization. In this process, chemical compounds produced by the plant immobilize contaminants, rather than degrade them.
- Phyto-accumulation (also called phyto-extraction). In this process, plant roots sorb the contaminants along with other nutrients and water. The contaminant mass is not destroyed but ends up in the plant shoots and leaves. This method is used primarily for wastes containing metals. At one demonstration site, water-soluble metals are taken up by plant species selected for their ability to take up large quantities of lead (Pb). The metals are stored in the plants aerial shoots, which are harvested and either smelted for potential metal recycling/recovery or are disposed of as a hazardous waste. As a general rule, readily bio available metals for plant uptake include cadmium, nickel, zinc, arsenic, selenium, and copper. Moderately bio-available metals are cobalt, manganese, and iron. Lead, chromium, and uranium are not very bio-available.
- Hydroponic Systems for Treating Water Streams (Rhizofiltration). Rhizofiltration is similar to phyto-accumulation, but the plants used for clean-up are raised in greenhouses with their roots in water. This system can be used for ex-situ groundwater treatment. That is, groundwater is pumped to the surface to irrigate these plants. Typically, hydroponic systems utilize an artificial soil medium, such as sand mixed with perlite or vermiculite. As the roots become saturated with contaminants, they are harvested and disposed of.
- Phyto-volatilization. In this process, plants take up water containing organic contaminants and release the contaminants into the air through their leaves.
- Phytoextraction – uptake and concentration of substances from the environment into the plant biomass.
- Phyto-degradation. In this process, plants metabolise and destroy contaminants within plant tissues.
- Hydraulic Control. In this process, trees indirectly remediate by controlling groundwater. Trees act as natural pumps when their roots reach down towards the water table and establish a dense root mass that takes up large quantities of water.

For the Valley TSF application it is recommended that Phyto-accumulation and Hydraulic Control be further investigated. The main aim of such a study will be to find the most suitable tree species to absorb the chemicals of concern and to obtain the necessary permits from the authorities.

It will take time for the tress to grow to a point where they are fully functional. It is therefore recommended that if this option is selected it be implemented as soon as possible.

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