ENVIRONMENTAL IMPACT MANAGEMENT SERVICES

HYDROGEOLOGICAL ASSESSMENT FOR THE PROPOSED TAILINGS REDEPOSITION ON THE HARMONY MPONENG LOWER COMPARTMENT TAILINGS STORAGE FACILITY

REVISION 1 REPORT

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1. INTRODUCTION AND TERMS OF REFERENCE

1.1 Site Locality and Project Description

Harmony Gold Mining Limited (Harmony) owns and operates a number of Gold Mines and Plants in the West Wits region in the Gauteng Province. The Savuka Plant currently deposits tailings onto the Savuka 5a, 5b, 7a & 7b Tailings Storage Facilities (TSFs). However, these facilities are approaching their final and approved height, and the current planned Life of Mine (LOM) for the West Wits region exceeds the available deposition capacity of these TSFs. Accordingly, Harmony is undertaking a feasibility assessment to recommence deposition on the Mponeng Lower Compartment Tailings Storage Facility.

Harmony is proposing to recommence deposition on the Mponeng Lower Compartment Tailings Storage Facility (hereafter referred to as Mponeng Lower Compartment TSF). The Mponeng Lower Compartment TSF is located at 26°27'11.18"S; 27°24'43.88"E (Figure 1.1 and Figure 1.2).

Mponeng Lower Compartment TSF is an existing TSF, however, the Mponeng Lower Compartment TSF is no longer in operation and is currently utilised as a Holding Dam, and a portion of it is used as an authorised Landfill Facility. In order to redeposit on the Mponeng TSF, from the Savuka Plant, slurry pipelines will need to be constructed from the Savuka Plant to the TSF. The proposed slurry and return water pipes extend from the south of Savuka Plant at starting point 26°25'24.95"S; 27°23'58.94"E, extending southwards, parallel to each other until reaching the northern extent of Mponeng TSF where they split. Thereafter, the slurry pipeline extends to west before connecting to Mponeng TSF while the return water pipeline extends east then south around the TSF to the return water dam. There is an alternative slurry and return water pipeline route which extends to the east through Western Deep Levels then south along Mponeng Gold Mine before heading to the west where it connects to Mponeng TSF.

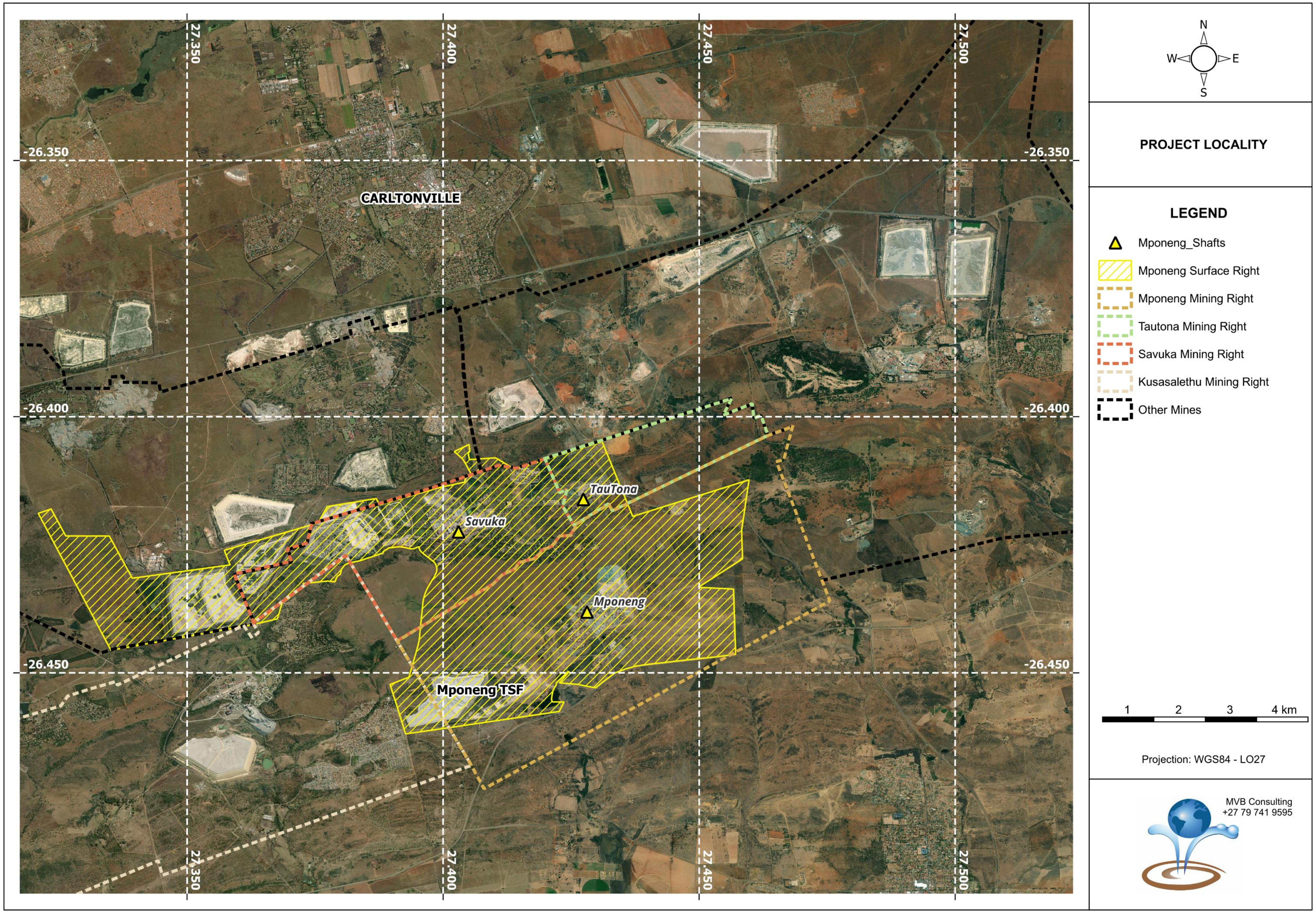

Figure 1.1:Locality of the study area

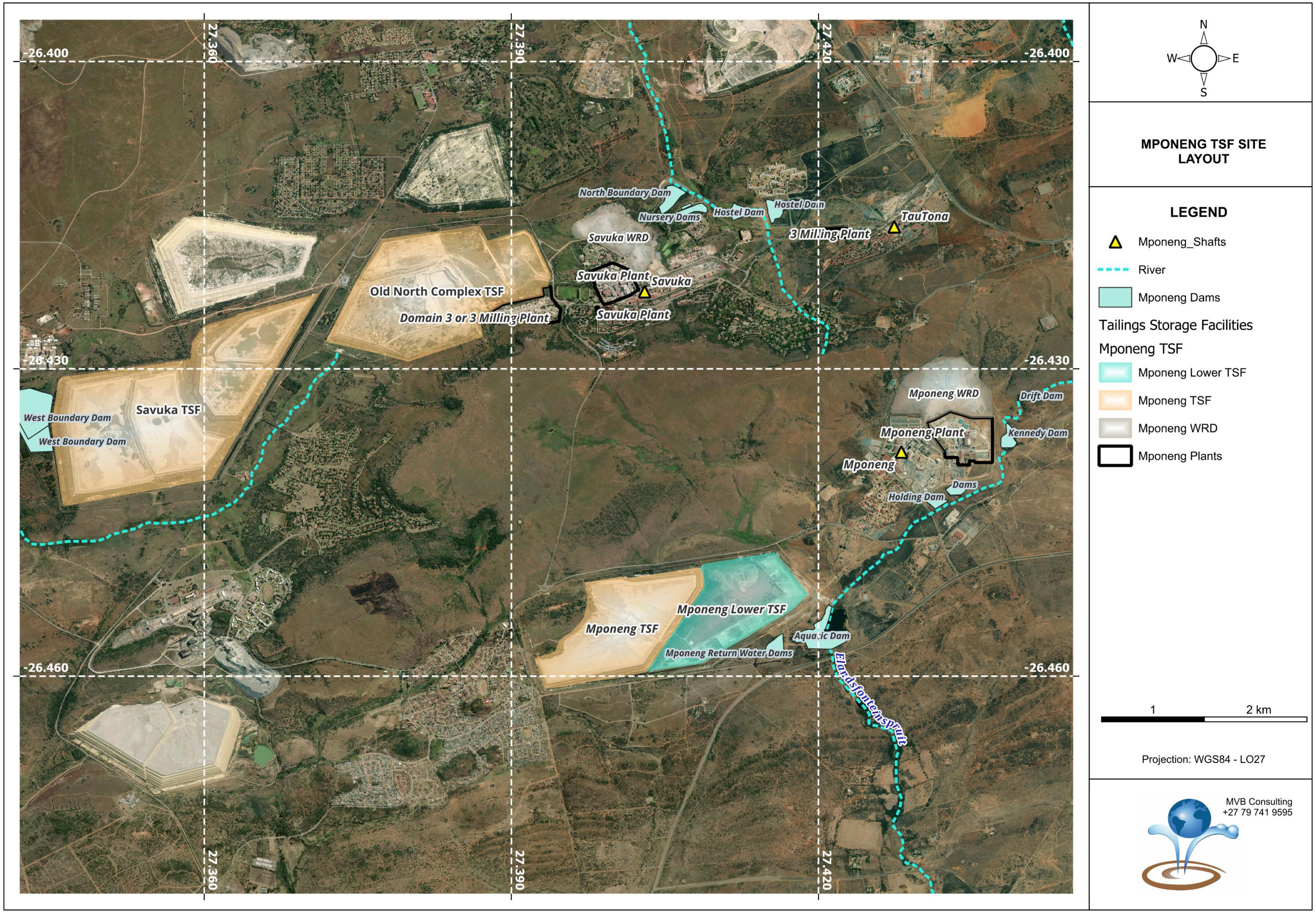

Figure 1.2: Mponeng TSF site layout

2. GEOGRAPHICAL SETTING

2.1 Climate and Rainfall

The climate is a typical Southern African Highveld climate with warm to hot summers and warm sunny winter days with frosty nights. Rainfall occurs predominantly during the summer months because of thunderstorm activity. The mean annual precipitation ranges from 565 mm to 697 mm per annum depending on the location of the weather station. Rainfall data was obtained from several sources, including mine data and data from the South African Weather Service. The rainfall for the region is summarised in Table 2.1.

Table 2.1: Rainfall Summary

Period	1927-2000	1962-2008	1983-2004	1966-2012	1900-2000	1958-2011	Regional Average
Station Name	Fochville	Carltonville	Wes Driefontein	Westonaria	Zuurbekom (RWB)	Randfontein	
Station Number	474899	4746809	04747421	04751744	475528	0475338 9	
Month	Average Monthly Rainfall (mm)						
January	104	118	98	130	113	126	**115**
February	81	86	74	85	98	92	**86**
March	80	77	70	81	78	83	**78**
April	45	52	33	48	46	52	**46**
May	18	14	14	13	17	12	**15**
June	9	7	8	6	6	7	**7**
July	5	3	2	3	5	2	**3**
August	7	7	8	10	7	6	**7**
September	23	19	18	21	19	20	**20**
October	56	70	69	72	68	69	**67**
November	95	87	80	100	100	99	**94**
December	97	111	92	129	111	104	**107**
Total	**620**	**651**	**565**	**697**	**668**	**672**	**646**

2.2 Topography and Drainage

The area north of the Mponeng TSF is characterized by a series of parallel hills that form the Gatsrand and have an elevation of approximately 1 770 metres above mean sea level (mamsl). Drainage from the Mponeng TSF deposits is mainly south (Quaternary catchment C23J and C23E), into the Loop Spruit. The Loop Spruit flows in a westerly direction and joins the Mooi River at Potchefstroom from where it flows to the Vaal River.

The study area forms part of the Lower Vaal Water Management Area. The Vaal Water Management Area (WMA) is the result of the consolidation of the Upper, Middle and Lower Vaal catchments.

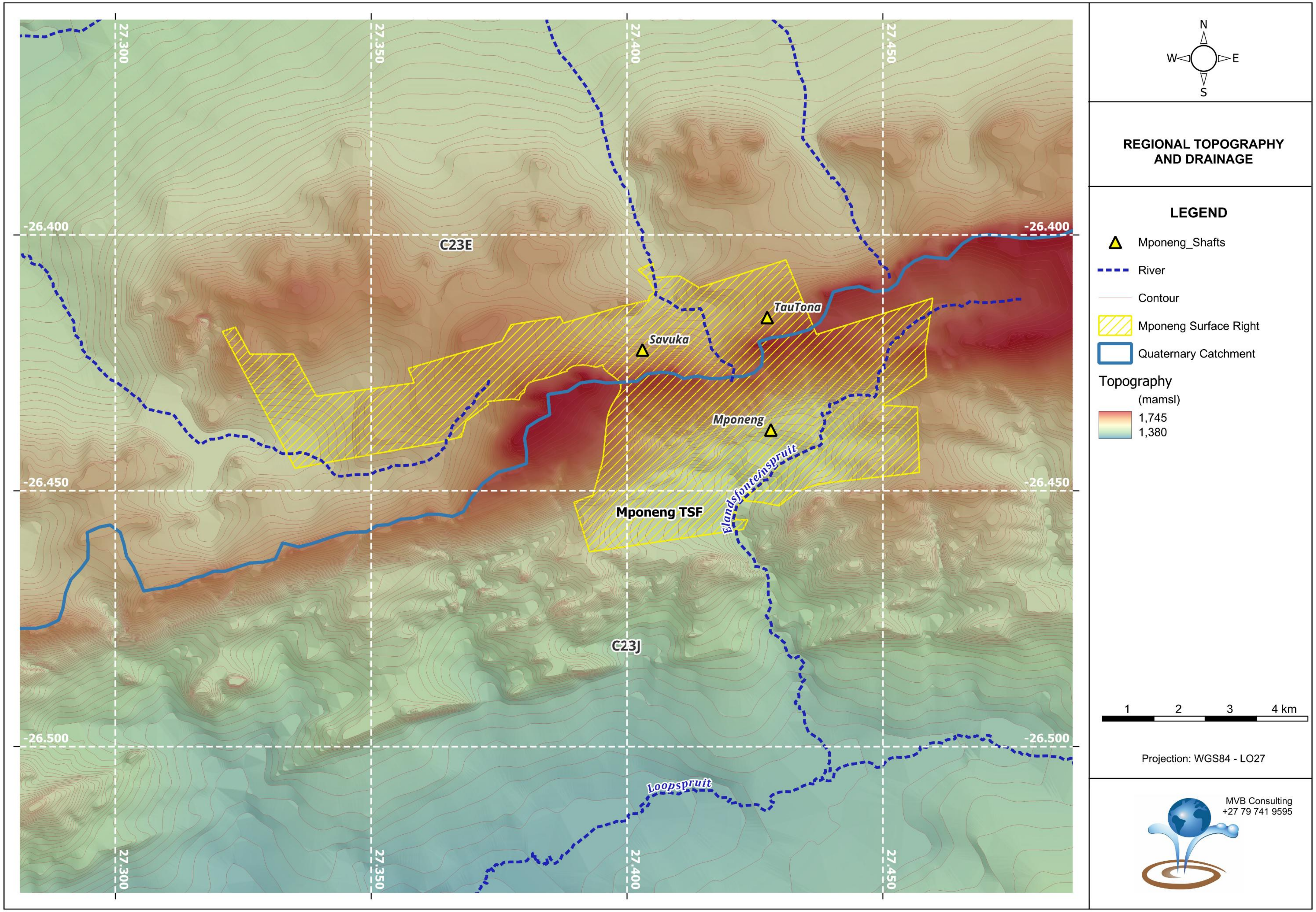

Figure 2.1: Study area topography and drainage

3. SCOPE OF WORK

Harmony has appointed Environmental Impact Management Services (Pty) Ltd (EIMS) as the Environmental Assessment Practitioner (EAP) to undertake the necessary environmental authorisation and associated consultation processes. MVB Consulting was requested to undertake a hydrogeological assessment for the proposed recommencing of tailings deposition on the Mponeng TSF. The hydrogeological study forms part of the environmental authorisation process.

The aim of the hydrogeological study is to assess the following:

- Assessment of the hydrogeological environment in terms of aquifer development, aquifer hydraulics, groundwater flow and groundwater chemistry.
- Assessment of the potential short and long-term impact from the Mponeng TSF on the groundwater environment.
- Recommended management measures to mitigate potential impacts.

The study includes the following:

- Desktop study of existing information.
- Conceptual model of the groundwater system.
- Numerical groundwater flow and mass transport model.
- Risk assessment and reporting.

4. METHODOLOGY

4.1 Desk Study

The datasets and reports listed in Table 4.1 was provided by the client for the study.

Table 4.1: Client datasets

Type	Description
Rainfall	Long-term site-specific data (South African Weather Services)
Monitoring Data	Annual Water Quality Monitoring Report for Harmony Gold Mine – WW & CWC: July 2022 to June 2023 (GCS, 2023)
Hydrogeological Reports	Groundwater Flow & Plume Model Update for the West Wits Operations (GCS, 2024).
	Groundwater Assessment for the Mponeng TSF Complex (GCS, 2019)
	Harmony Mponeng- TSF Spring Hydrogeological Investigation (PHASE 1) (GCS, 2025)

The following additional data sources were also consulted to complete the study:

- Hydrocensus data. Analytical results obtained from groundwater samples collected during August and September 2025.
- 1: 500 000 Hydrogeological Map Series of South Africa.
- 1: 250 000 Geological Map Series of South Africa.

4.2 Hydrocensus and Borehole Information

A hydrocensus was previously conducted that identified seven (7) boreholes to the south of the Mponeng Lower Compartment TSF. A follow-up census was conducted in August 2025 and a further six (6) boreholes were located. Information collected from the hydrocensus include borehole locality, borehole construction details, type of pump, groundwater level and current use.

The hydrocensus information is summarised in Table 4.2 and the localities of the hydrocensus boreholes are shown in Figure 4.1.

4.3 Sampling and Chemical Analysis

The mine routinely monitors the groundwater quality in the vicinity of the Mponeng Lower Compartment TSF. This data was made available and is used to assess the current impacts from the TSF. The hydrocensus boreholes were sampled and the samples submitted to Waterlab (Pty) Ltd, a SANAS accredited laboratory (the laboratory certificates are attached as Appendix A).

The hydrocensus groundwater quality is presented in Table 4.3. The water quality is compared to the SANS 241 (2015) Drinking Water Guidelines since some of the boreholes are used for domestic purposes. The SANS 241 Drinking Water Specification is the definitive reference on acceptable limits for drinking water quality parameters (for a lifetime consumption) in South Africa and provides guideline levels for a range of water quality characteristics.

Concentrations that exceed the SANS 241 limits are highlighted in **red**. The water quality is generally good and only a few parameters exceed the guideline limits. These are:

- Total Chromium (Cr) in borehole WWHC03.
- Iron (Fe) in boreholes MB1, MB2 and MB3.
- Lead (Pb) in borehole MB1.

Although the parameters do not exceed the guideline limits, the borehole to the south of the study area have elevated TDS, chloride (Cl) and sulphate (SO_4) concentrations that may be indicative of an impact from the up-gradient mining area.

4.4 Geophysics and Borehole Drilling

There are a sufficient number of boreholes in the vicinity of the Mponeng Lower Compartment TSF and no additional boreholes were therefore drilled.

There was also no need for further geophysical investigations. Geophysical studies were, however, conducted previously. A geophysical map of the study is presented in Figure 4.2. The geological features identified on this map was incorporated into the numerical groundwater model.

4.5 Aquifer Testing

Aquifer or pump testing that was previously undertaken by GCS (2019) from which the aquifer parameters in the weathered and fractured aquifers were estimated. This is discussed in more detail in Section 5.2.3 of this report.

Table 4.2: Hydrocensus borehole information

ID	Latitude	Longitude	Elevation (mamsl)	Description	Owner	Contact No.	Measured Water Level (mbgl)
MB1	-26.44516	27.43291	1535.00	Borehole is obstructed with rocks. It was previously powered by a mono pump. The borehole was vandalised	Kraalkop Kerneels	078 075 9526	2.86
MB2	-26.44034	27.44059	1555.00	This borehole is also vandalised and filled with rocks			5.96m
MB3	-26.43885	27.44427	1569.00	Borehole not in use			6.85m
MB4	-26.44027	27.45683	1602.00	Borehole not in use			18.67m
MB5	-26.44157	27.48257	1566.00	The shop has a 5000L water storage tank. It takes the borehole 3 hours to fill the tank up from empty. The petrol station has a water monitoring program	Engen N12. Peter	-	14.25m
MB6	-26.41765	27.44654	1690.00	Borehole used for domestic purposes. Reported yield is 2 500 lit/hour	Koos Vaal Maseru	065 811 8454	80m
WWHC1	-26.47573	27.41802	1486.55	Groundwater borehole fitted with a pump. Domestic Use.	Piet Rossouw	082 921 1572	28.18
WWHC2	-26.47344	27.42543	1472.17	Groundwater borehole fitted with a pump. Domestic Use.			49.67
WWHC3	-26.47285	27.41702	1497.28	Groundwater borehole. Not in use.			37.97
WWHC4	-26.47643	27.42859	1462.84	Groundwater borehole fitted with a pump. Water used for washing only.			3.46
WWHC5	-26.47629	27.42934	1465.25	Groundwater borehole. Not in use.	Riaan Eleveld	082 468 7998	7.53
WWHC6	-26.47773	27.42842	1454.92	Elandsfontein Spruit flowing from Mponeng Area.	N/A	N/A	N/A

Table 4.3: Hydrocensus groundwater quality

Analyses in mg/ℓ (Unless specified otherwise)	SANS 241	MB 1	MB 2	MB 3	MB 4	MB 5	MB 6	WW-HC01	WW-HC02	WW-HC03	WW-HC04	WW-HC05	WW-HC06	WW-HC09
pH - Value @ 25 ºC	≥ 5 to ≤ 9.7	7.40	7.90	7.40	7.60	8.10	7.30	7.94	7.63	8.06	7.73	7.61	7.76	6.44
Electrical Conductivity in mS/m @ 25°C	≤170	38	20	5	25	25	8	76	160	56	117	145	110	29
Total Dissolved Solids @ 180°C	≤1200	236	126	32	160	164	50	501	1 161	388	786	1 013	631	179
Total Alkalinity as $CaCO_3$	-	172	88	16	124	100	28	195	184	120	160	145	52	57
Chloride as Cl	≤300	9	5	2	3	8	4	77	295	71	174	243	171	22
Sulphate as SO_4	≤500	18	6	3	6	8	3	74	188	51	176	242	204	34
Fluoride as F	≤1.5	0.3	0.2	<0.2	0.2	0.2	<0.2	-	-	-	-	-	-	-
Nitrate as N	≤11	<0.1	0.1	0.2	0.2	1.1	0.9	2.7	1.3	1.6	<0.1	<0.1	1.4	1.2
Ortho Phosphate as P	-	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	0.09
Free and Saline Ammonia as N	≤1.5	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	-	-	-	-	-	-	-
Sodium as Na	≤200	24	13	3	18	12	3	30.16	33.63	26.53	87.62	61.24	125.63	15.19
Potassium as K	-	0.9	1.8	<0.5	0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	8.36	<0.5
Calcium as Ca	-	48	24	5	32	33	6	82	168	38	83	128	66	19
Magnesium as Mg	-	8	4	1	5	6	4	34	90	33	52	81	20	11
Aluminium as Al	≤0.3	0.153	<0.100	<0.100	<0.100	<0.100	<0.100	-	-	-	-	-	-	-
Arsenic as As	≤0.01	0.083	0.002	<0.001	0.002	0.004	<0.001	-	-	-	-	-	-	-
Barium as Ba	≤0.70	0.06	0.043	0.028	0.061	0.028	0.052	0.02	<0.02	<0.02	0.04	0.06	0.04	0.05
Boron as B	≤2.4	<0.025	<0.025	<0.025	<0.025	<0.025	<0.025	-	-	-	-	-	-	-

Analyses in mg/ℓ (Unless specified otherwise)	SANS 241	MB 1	MB 2	MB 3	MB 4	MB 5	MB 6	WW-HC01	WW-HC02	WW-HC03	WW-HC04	WW-HC05	WW-HC06	WW-HC09
Total Chromium as Cr	**≤0.05**	<0.025	<0.025	<0.025	<0.025	<0.025	<0.025	<0.025	<0.025	0.14	<0.025	<0.025	<0.025	<0.025
Cobalt as Co	**-**	<0.025	<0.025	<0.025	<0.025	<0.025	<0.025	0.01	<0.025	<0.025	<0.025	<0.025	0.02	<0.025
Copper as Cu	**≤2**	<0.010	<0.010	<0.010	<0.010	<0.010	<0.010	<0.010	<0.010	<0.010	<0.010	<0.010	<0.010	0.02
Iron as Fe	**≤2**	3.53	12	3.12	1.35	<0.025	0.049	-	-	-	-	-	-	-
Lead as Pb	**≤0.01**	0.021	0.001	0.005	0.004	<0.001	<0.001	-	-	-	-	-	-	-
Manganese as Mn	**≤0.4**	0.311	0.262	0.304	0.167	0.048	0.361		-	-	-	-	-	-
Mercury as Hg	**≤0.006**	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	0.002	<0.001	<0.001
Nickel as Ni	**≤0.07**	<0.025	<0.025	<0.025	<0.025	<0.025	<0.025		-	-	-	-	-	-
Selenium as Se	**≤0.04**	<0.001	<0.001	<0.001	<0.001	0.002	0.001		-	-	-	-	-	-
Strontium as Sr	**-**	0.306	0.072	<0.025	0.151	0.149	<0.025	0.41	0.37	0.18	0.23	0.31	0.3	0.07
Uranium as U	**≤0.03**	0.005	<0.001	<0.001	0.001	<0.001	<0.001		-	-	-	-	-	-
Zinc as Zn	**≤5**	0.428	<0.025	0.088	0.113	<0.025	<0.025	0.06	0.18	<0.025	0.16	0.02	0.01	0.06

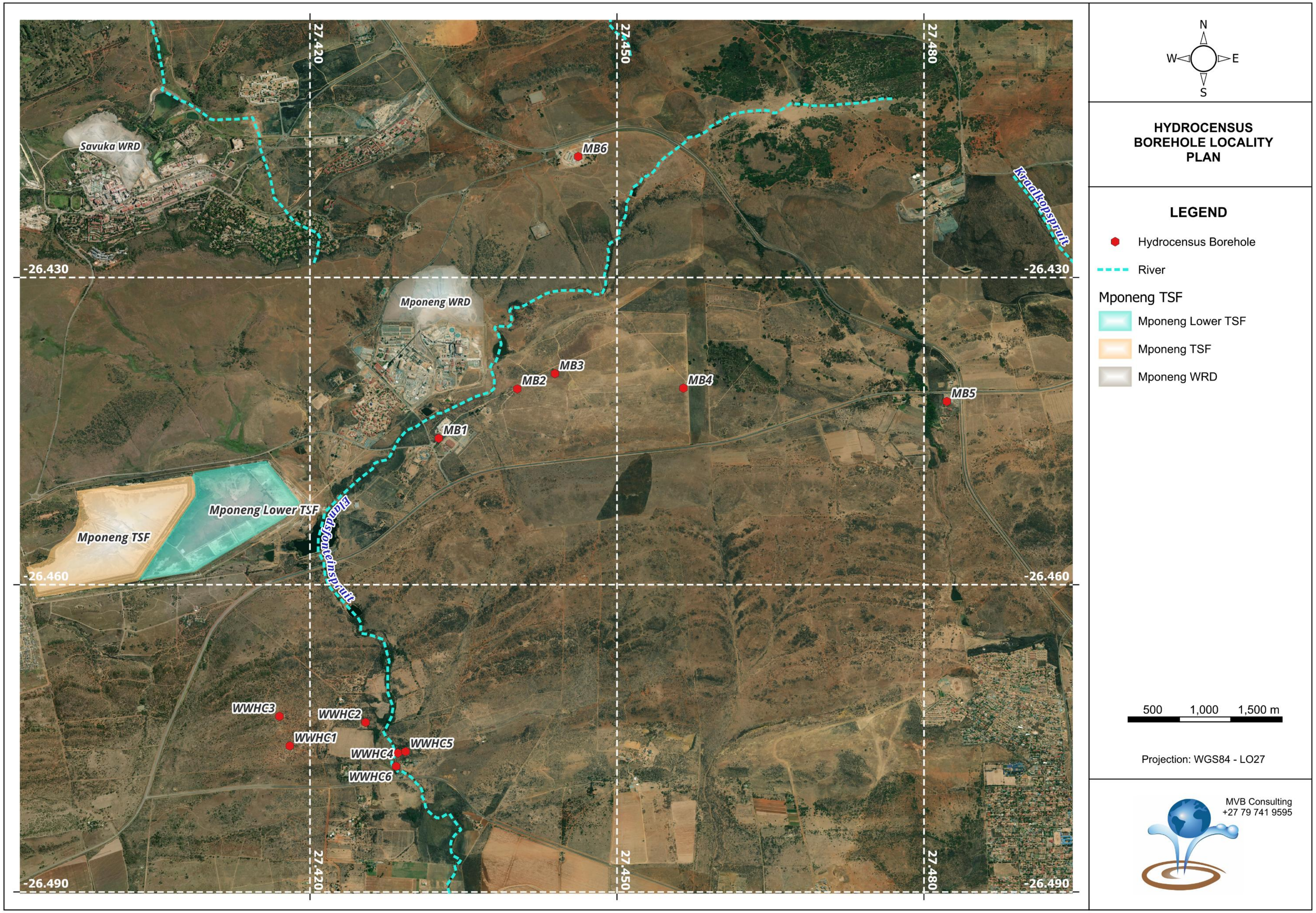

Figure 4.1: Hydrocensus borehole locality plan

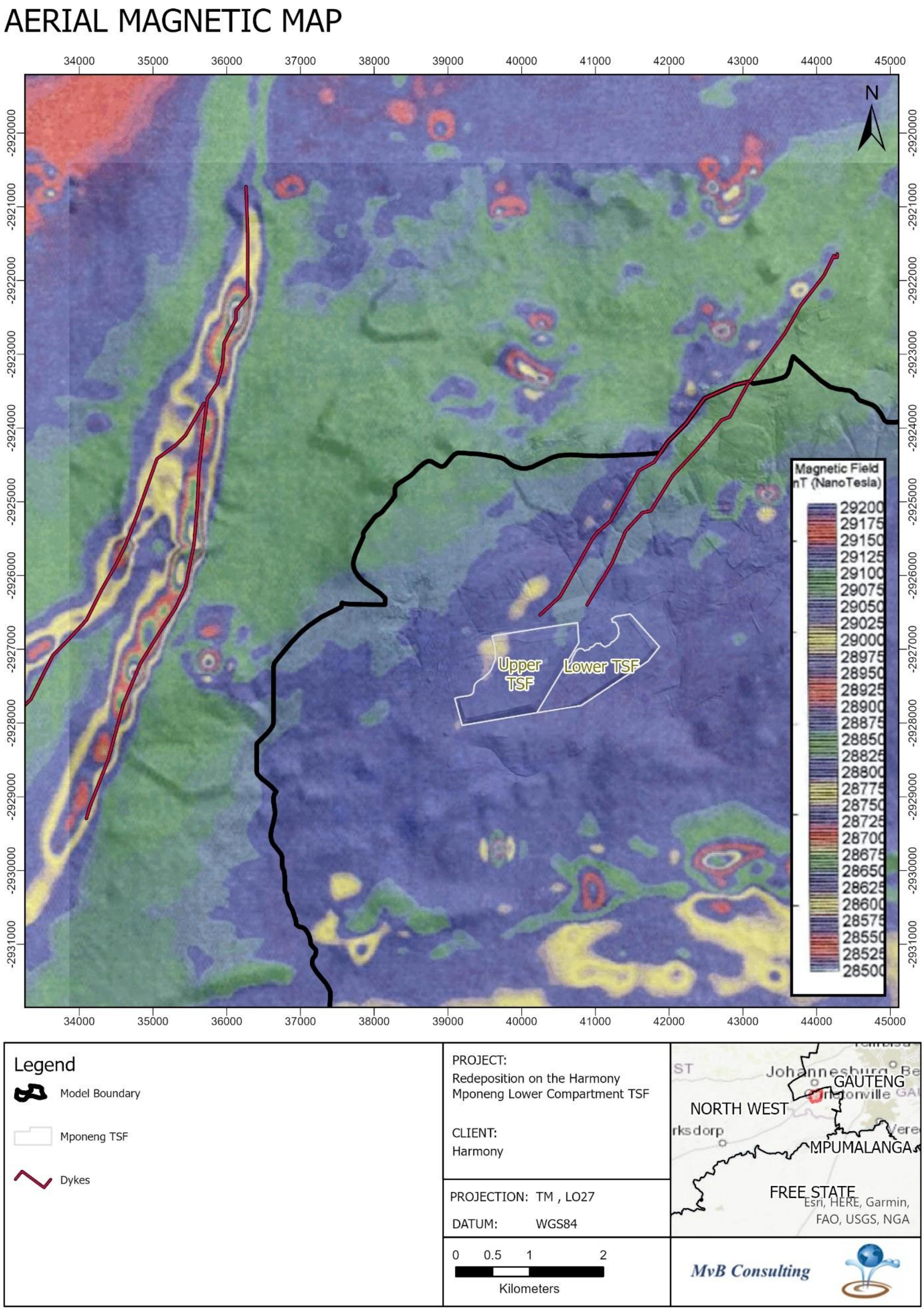

Figure 4.2: Aerial magnetic map of the study area

4.6 Groundwater Recharge Calculations

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. Groundwater recharge (R) for the study area was 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:

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

According to Vegter (1995) the recharge in the fractured aquifer is 31 mm / annum with water occurring in the shallow weathered zone and water bearing fractures only. This is equal to approximately 4% of mean annual precipitation. The average rainfall in the area is approximately 646 mm / annum. The average chloride in rainfall for areas inland is approximately 1.0 mg/L and the harmonic mean of the chloride concentration values in groundwater samples obtained from the mining area is 25.88 mg/L.

$$R = \frac{1}{25.88} \times 100 = 3.9\%$$

This value corresponds with Vegter’s value.

4.7 Groundwater Modelling

A numerical groundwater model was constructed for this project. The modelling objective is to determine the impact of the proposed raising of the Mponeng Lower Compartment TSF. Once the impact is determined the following mitigation scenarios should be considered:

- No mitigation measures.
- A liner between the existing lower compartment and the proposed new tailings deposition.
- Plume containment through scavenger wells.
- Plume containment through tree plantations.

5. PREVAILING GROUNDWATER CONDITIONS

A description of the conceptual hydrogeological model is important to provide an understanding of the regional geology, which is the governing factor in both the aquifer formation and the movement of groundwater, as well as the hydrogeological setting and groundwater occurrence in the mining area.

5.1 Geological Setting

The geology of the study area has been described in detail by several authors and mine geologists. The following section describes the regional and local geology.

The regional surface geology includes, in chronological order:

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

The stratigraphy is shown in Figure 5.1 regional surface geology is presented in Figure 5.2.

5.1.1 Witwatersrand Supergroup

Truswell (1977) describes the geology of the Witwatersrand Basin as follows:

The Witwatersrand Basin is a thick sequence of shale, quartzite and conglomerate. There are two main divisions, a lower predominantly argillaceous unit, known as the West Rand Group and an upper unit, composed almost entirely of quartzite and conglomerates, known as the Central Rand Group.

The West Rand Group is divided into three subgroups namely the Hospital Hill, Government Reef and Jeppestown. These rocks comprise mainly shale, but quartzite, banded ironstones, tillite and intercalated lava flows are also present. The rocks were subjected to low - grade metamorphism causing the shale to become more indurated and slaty. The original sandstone was recrystallised to quartzite.

The Central Rand Group is divided into the Johannesburg and Turffontein Subgroups and is composed largely of quartzite, within which there are numerous conglomerate zones. The conglomerate zones may contain any number of conglomerate bands, with individual bands interbedded with quartzite. The upper conglomerates are usually thicker with coarser fragments. An argillaceous zone known as the Booysens Shale (also known as the Kimberley Shale) separates the Johannesburg and Turffontein Subgroups.

The economic gold placers (reefs) are restricted to the Central Rand Group of the Witwatersrand Supergroup. A primary economic horizon that is mined in all the mines in the region is the Ventersdorp Contact Reef (VCR), at the base of the Ventersdorp lava. The Carbon Leader is also mined extensively in the region. Mponeng exploits the Ventersdorp Contact Reef (VCR) via a twin-shaft system to depths of between 2 800m and 3 400m below surface (AngloGold Ashanti, 2018).

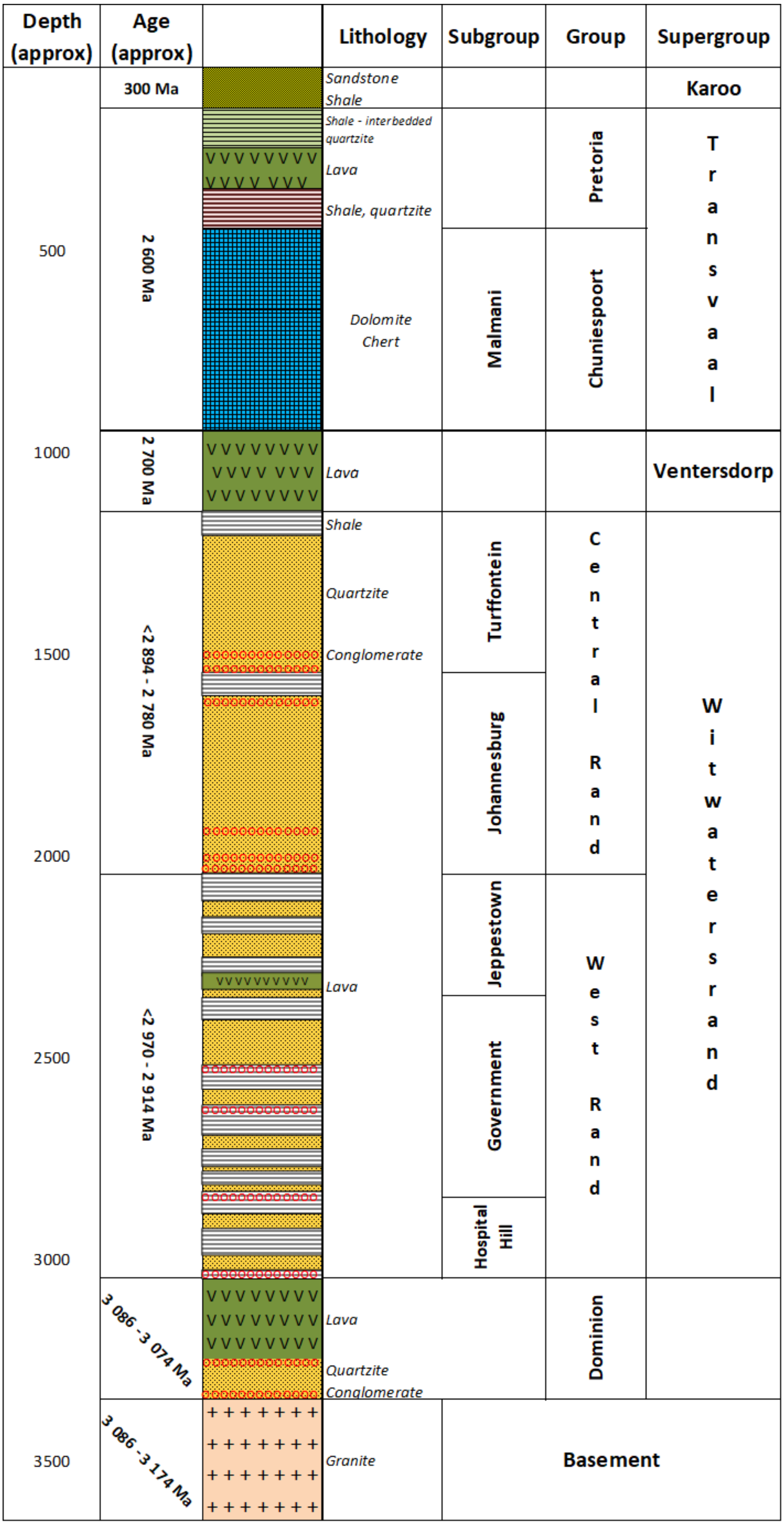

Figure 5.1: Stratigraphy of the study area (after Robb and Robb, 1998)

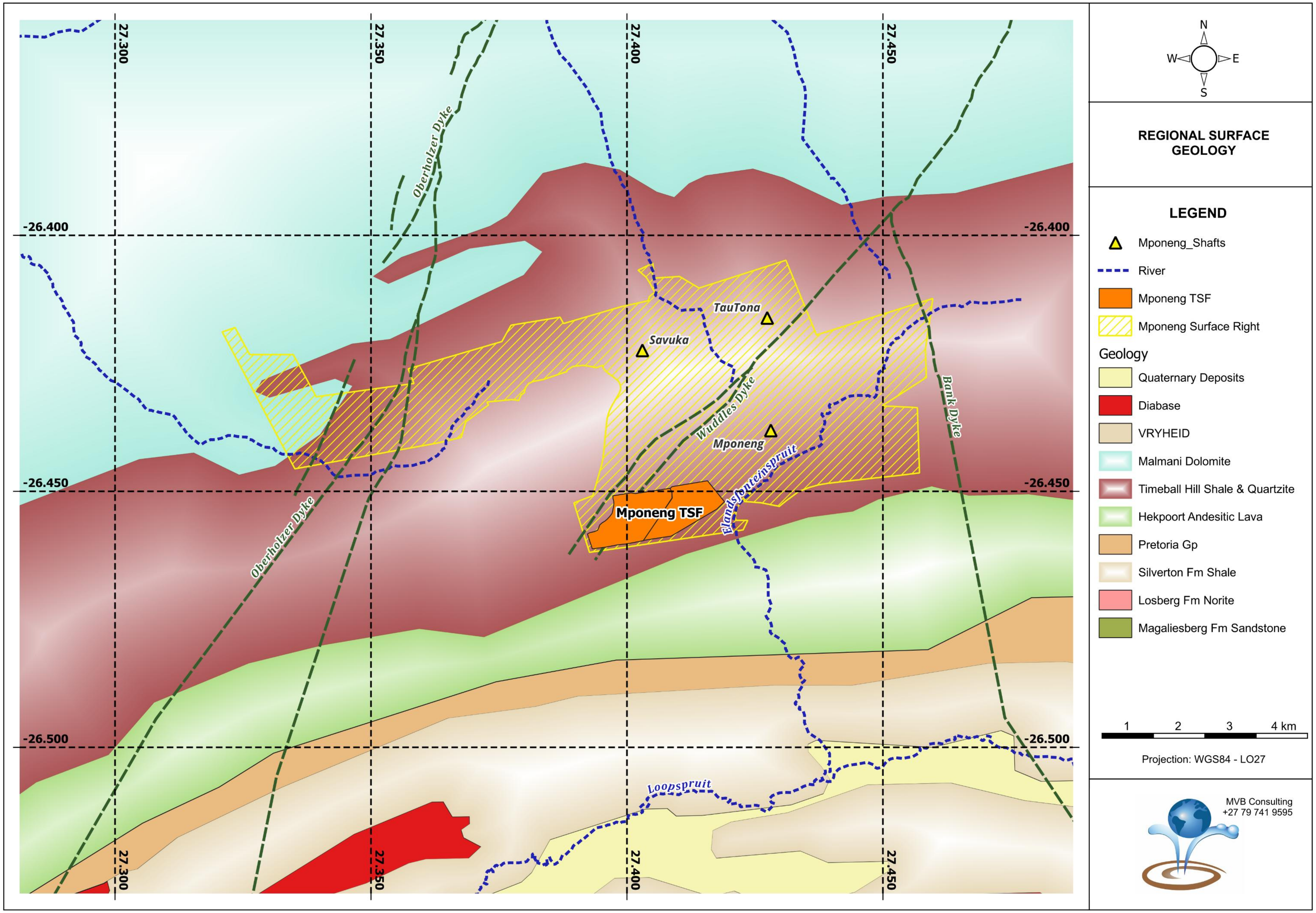

Figure 5.2: **Regional surface geology**

5.1.2 Ventersdorp Supergroup

The younger Ventersdorp Supergroup overlies the Witwatersrand rocks. Although acid lavas and sedimentary intercalations occur, the Ventersdorp is composed largely of andesitic lavas and related pyroclastics. The Ventersdorp Supergroup consists of the Platberg Group and the Klipriviersberg Group. The Klipriviersberg Group consists of the Alberton and Westonaria Formations.

The Ventersdorp lava plays an important role in terms of groundwater ingress into the underground workings. As a rule of thumb, areas that have less than 50 m of lava have a greater risk of water ingress. This is especially the case were mining takes place above the Witwatersrand strata, such as mining of the VCR at the base of the Ventersdorp succession. The lava acts as an impermeable barrier, largely preventing water from the overlying dolomite aquifer entering the mine.

5.1.3 Transvaal Supergroup

Overlying the Ventersdorp Lavas are the Black Reef quartzite and dolomite of the Transvaal Supergroup. The Black Reef quartzite comprises coarse to gritty quartzite with occasional economically exploitable conglomerates (reefs). The entire area was peneplained in post-Ventersdorp time and it was on this surface that the Transvaal Supergroup was deposited, some 2200 million years ago. The deposition commenced with the Kromdraai Member with the Black Reef at its base. The Black Reef has eroded the Witwatersrand outcrop areas and as a result contains zones (reef) in which gold is present. The occurrence of the gold is not as widespread as in the Witwatersrand and mainly restricted to north-south trending channels. The Black Reef is overlain by a dark, siliceous quartzite with occasional grits or small pebble bands. The quartzite grades into black carbonaceous shale. The shale then grades into the overlying dolomite through a transition zone of approximately 10 m thick.

Overlying the Kromdraai Member is the dolomite of the Malmani Subgroup of the Chuniespoort Group. The dolomites vary between 200 m and 1 500 m in thickness. According to Parsons (1991) only the two lower formations of the Malmani Subgroup are present in the study area. The lowermost is the Oaktree Formation, which is succeeded southward by the Monte Christo Formation.

The Oaktree Formation consists of chert-poor homogenous dark-grey dolomite containing interbeds of carbonaceous shale, which decrease in frequency and thickness from the base of the formation upwards. Columnar stromatolytes are numerous within this sequence and the formation follows conformably on the Black Reef Formation with a transitional mixed zone consisting of carbonaceous and calcareous argillaceous and arenaceous sediments (Parsons, 1991).

The Monte Christo Formation follows conformably on the Oaktree Formation. The Monte Christo Formation consists of alternating chert-rich and chert-poor, dark to light-grey dolomite and has an estimated thickness of 700 m (Brink, 1979). A 1.5 m thick chert layer, consisting of 10 cm to 15 cm thick layers of chert separated by manganese-rich bands, is present towards the base of the formation. Layers of crystalline, coarse-grained dark dolomite, laminated calcareous shale, shaley dolomite and fine-grained white dolomite occur in the sequence, parts of which are chert-rich, containing numerous chert layers, 10 cm to 20 cm in thickness (Parsons 1991).

The Pretoria Group rocks overlie the dolomite aquifer and is also the surface geology at Mponeng mine. The Rooihoogte Formation forms the basal member of the Pretoria Group, consisting of the Bevets conglomerate, shale and quartzite. The Bevets conglomerate varies in thickness between 3 m and 60 m (Parsons and Killick, 1985). Overlying the Bevets conglomerate is shale and sporadically developed quartzite, referred to as the Pologround quartzite. Where developed the Pologround quartzite is overlain by 150 m – 200 m of pink to purple shales, forming the basis of the Timeball Hill

Formation. The shale is overlain by quartzite, which forms the linear north-westerly trending ridges in the central portion of the study area.

Further south is the Hekpoort and Strubenkop Formations. These formations consist predominantly of andesite lava (Hekpoort Formation) and ferruginous shale (Strubenskop Formation). The weathering of the shale and the lava results in grey to dark grey silty sand and clay.

The Hekpoort Andesite Formation is visible through a number of scattered lava outcrops, giving it an uneven landscape. The quicker erosion of the softer tuffaceous sediments, interbedded between the amygdaloidal lava flows is believed to be the cause of the topographical features. The weathering of the Hekpoort Andesite results in dark to reddish – brown silty sand. These can contain fragments of lava and quartz ranging between pebble to cobble size.

The Strubenkop Formation achieves a maximum thickness of 130 m and consists predominantly of ferruginous shale. The contact between the Hekpoort and Strubenkop Formations is difficult to identify in the field, especially in view of the fact that localised intrusions of younger dolerite occur.

Most of these rocks, especially in the lower lying areas, are concealed beneath a cover of younger sedimentary rocks, residual soils and alluvium. There is also a significant accumulation of hillwash and transported sediments. The floodplains of the Loopspruit and its tributaries contain grey, silty to clayey soils.

5.1.4 Karoo Supergroup

The Karoo Supergroup was deposited approximately 345 million years ago. It commenced with glacial period during which most of South Africa was covered by a thick sheet of ice. This ice cap slowly moved towards the south, causing extensive erosion as a result of accumulated debris at the base. This debris was eventually deposited as the Dwyka tillite. The Dwyka, which generally form an impermeable barrier to the downward percolation of groundwater, is absent in most parts of the study area. Younger superficial deposits cover the Karoo in places. The Karoo strata filled the extremely rugged paleo-topography of the underlying karst dolomite to form a relatively even topography that is visible today.

5.2 Hydrogeological Setting

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

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

5.2.1 Borehole Information

There are several groundwater monitoring boreholes in the vicinity of the Mponeng Lower Compartment TSF. The localities of the boreholes used during this assessment are shown on Figure 5.3 and summarised in Table 5.1.

Table 5.1: Mine monitoring boreholes (GCS, 2023)

BH ID	Longitude	Latitude	Z	Description	Borehole Depth (m)	Geology
MB10	27.43712	-26.43405	1569.26	SE of Mponeng RD; N of Mponeng GP	29.66	Timeball Hill Shale and Quartzite
MB11	27.42259	-26.45659	1499.16	SE of Mponeng TSF and Below aquatic Dam	30.00	Shales
MB13	27.40448	-26.44829	1560.05	N of Mponeng TSF, N road,	33.50	Timeball Hill Shale and Quartzite
MB20	27.40925	-26.44950	1541.87	Next to eye (fountain).	30.00	Shales (weathered /fractured)
MB21	27.42008	-26.45717	1498.45	SE of Mponeng TSF, SE Mponeng RWD	30.00	Shales
MB22	27.42121	-26.45666	1497.81	SE of Mponeng TSF, SE Mponeng RWD	30.00	Shales and andesite lava
MB25	27.40665	-26.44800	1556.15	N of Mponeng TSF	100.00	Timeball Hill Shale and Quartzite
MB29	27.43672	-26.43869	1555.53	South of anti pollution dams at Mponeng Plant		-
MB32	27.41795	-26.45659	1507.50	S of S Mponeng RWD		-
MB33	27.41029	-26.45851	1524.70	South of South TSF below van Eeden dam		Borehole dry / blocked
MB34	27.40383	-26.45961	1535.43	South of South TSF below partition of 2 dams		Borehole dry / blocked
MB35	27.42000	-26.45030	1512.43	E of S s/dam next to soccer field	30.00	Timeball Hill Shale and Hekpoort andesite
MB39	27.39796	-26.43289	1705.33	On Gatsrand up from Wadela circle to Savuka	114.00	Timeball Hill Shale
MB50	27.43093	-26.43560	1563.83	South-west (down gradient) of Mponeng waste dump	35.00	Timeball Hill Shale and Quartzite
MB58	27.42236	-26.44803	1516.85	Downstream of Mponeng (south) sewage works		Borehole locked
MB62	27.41227	-26.45065	1534.33	Downstream Mponeng Solid Waste Site at TSF Compartment		-

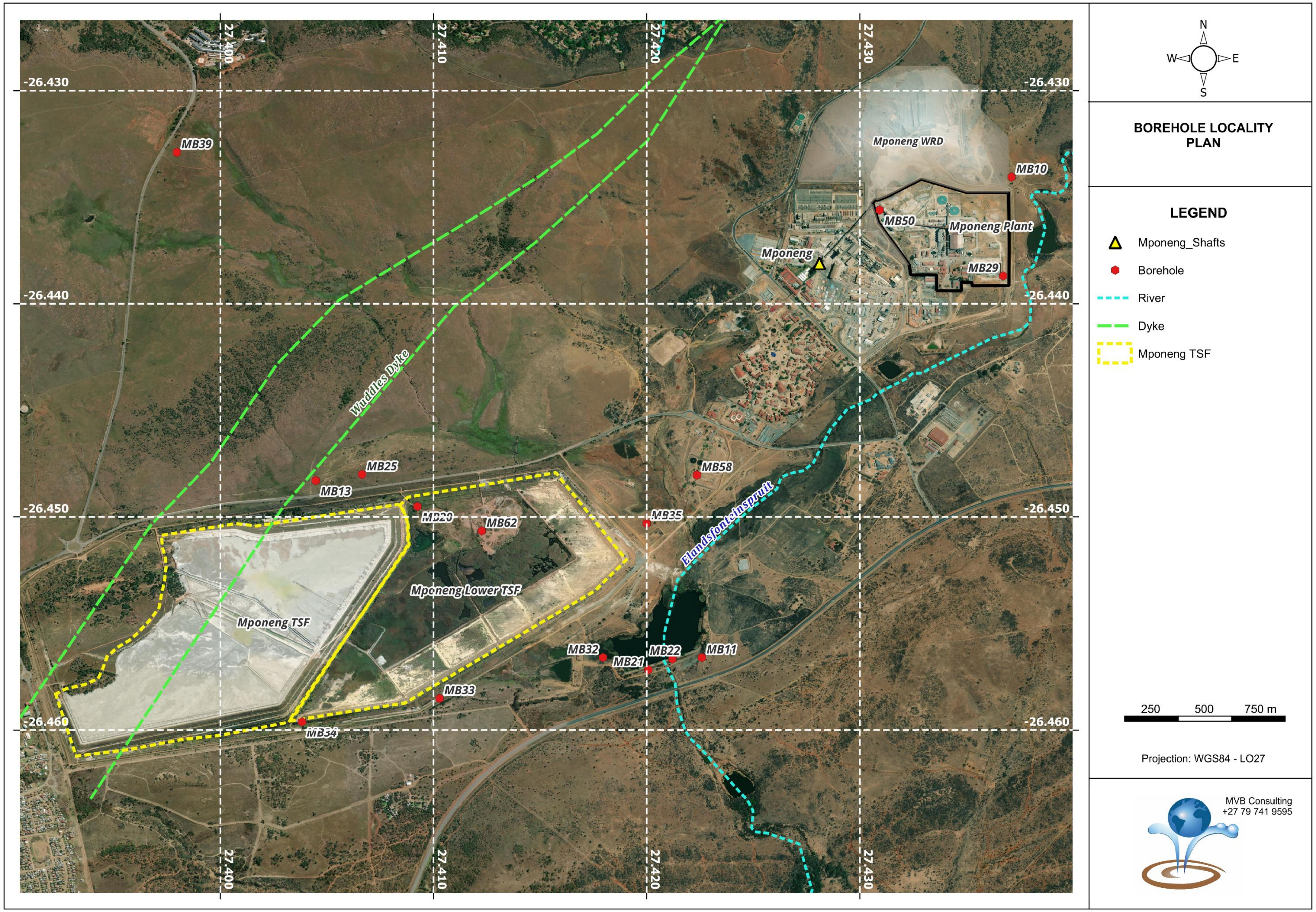

Figure 5.3: Available boreholes in the vicinity of the Mponeng TSF

5.2.2 Aquifer Type

Groundwater occurrences in the study area are predominantly restricted to the following types of terrains.

- Weathered and fractured rock aquifer in the Transvaal Formations.
- Dolomitic and Karst Aquifers.

Although the dolomite aquifer is the most prominent aquifer in the region, it does not play any role in the activities at the Mponeng Lower Compartment TSF. The Mponeng Lower Compartment TSF is predominantly located on the shale of the Timeball Hill formation. The dolomite is ±400m below surface at the Mponeng TSF site. Evidence has shown that there is no connectivity between the weathered / fractured aquifer and the underlying dolomite aquifer. Even in compartments where the dolomite aquifer is dewatered the groundwater levels in the weathered / fractured aquifer remains unaffected.

5.2.2.1. Weathered and Fractured Aquifer

Groundwater occurs in the near-surface geology in the weathered and fractured sedimentary deposits (quartzite and shale) of the Transvaal strata. The lava of the Hekpoort Formation has similar weathering characteristics to that of the shale and is therefore deemed as the same aquifer. These formations are not considered to contain economic and sustainable aquifers, but localised high yielding boreholes may, however, exist where significant fractures are intersected.

Groundwater occurrences are mainly restricted to the weathered formations, although fracturing in the underlying “fresh” bedrock may also contain water. Experience has shown that these open fractures seldom occur deeper than 60m. The base of the aquifer is the impermeable quartzite, shale and lava formations, whereas the top of the aquifer would be the surface topography. The groundwater table is affected by seasonal and atmospheric variations and generally mimics the topography. These aquifers are classified as semi-confined. The two aquifers (weathered and fractured) are mostly hydraulically connected, but confining layers such as clay and shale often separate the two. In the latter instance the fractured aquifer is classified as confined. The aquifer parameters, which includes transmissivity and storativity is generally low and groundwater movement through this aquifer is therefore also slow.

5.2.2.2. Dolomite Aquifer

Dolomite aquifers in the region are known to contain large quantities of groundwater and are commonly associated with sustainable groundwater abstraction. The water that plaques the underground mining is primarily derived from the dolomite aquifer overlying the workings.

The depth to groundwater in the region ranges from 4 m to 41 m below surface in the non-dewatered groundwater compartments (Zuurbekom and Boskop/Turffontein). This is in contrast to the groundwater levels in excess of 200 m in the dewatered compartments (Gemsbokfontein West, Venterspost, Bank and Oberholzer). The unsaturated zone in the dolomite aquifer ranges from weathered wad material and Karoo sediments within deep solution cavities or grykes (deeply weathered paleo-valley within the dolomite) to relatively fresh fractured dolomite between major solution cavities and at depth.

The shallow weathered dolomite aquifer has been formed because of the karstification which has taken place prior to the deposition of the Karoo sediments on top of the dolomites. There is general agreement that this aquifer is the significant source of water within the dolomite. The base of the weathered dolomite (aquifer) is irregular in nature and there are zones of deep weathering (grykes). The maximum depth to the base of this aquifer is in the order of 200 m below surface.

The non-weathered dolomite approximates a traditional fractured rock aquifer at depth where dissolution has been less pronounced. It is extremely unlikely that any significant groundwater flow occurs below these depths except along intersecting structural conduits to the underlying mine workings.

5.2.2.3. Relationship between the Weathered / Fractured Aquifer and the Dolomite Aquifer

Evidence has shown that there is no connectivity between the weathered / fractured aquifer and the underlying dolomite aquifer. Even in compartments where the dolomite aquifer is dewatered the groundwater levels in the weathered / fractured aquifer remains unaffected.

Figure 5.4 illustrates the relationship between the fractured and dolomite aquifers and also shows that the degree of karstification. Based on the exploration borehole information, it appears that the dolomite that that is covered by Transvaal strata is less karstified and the dolomite aquifer is therefore not as well developed. The mines situated south of the “Gatsrant” are generally dry mines with limited groundwater inflow, whereas the mines north of the “Gatsrant” is plagued by high groundwater inflow volumes. This is, in part, attributed to the well-defined karstification in the northern dolomites.

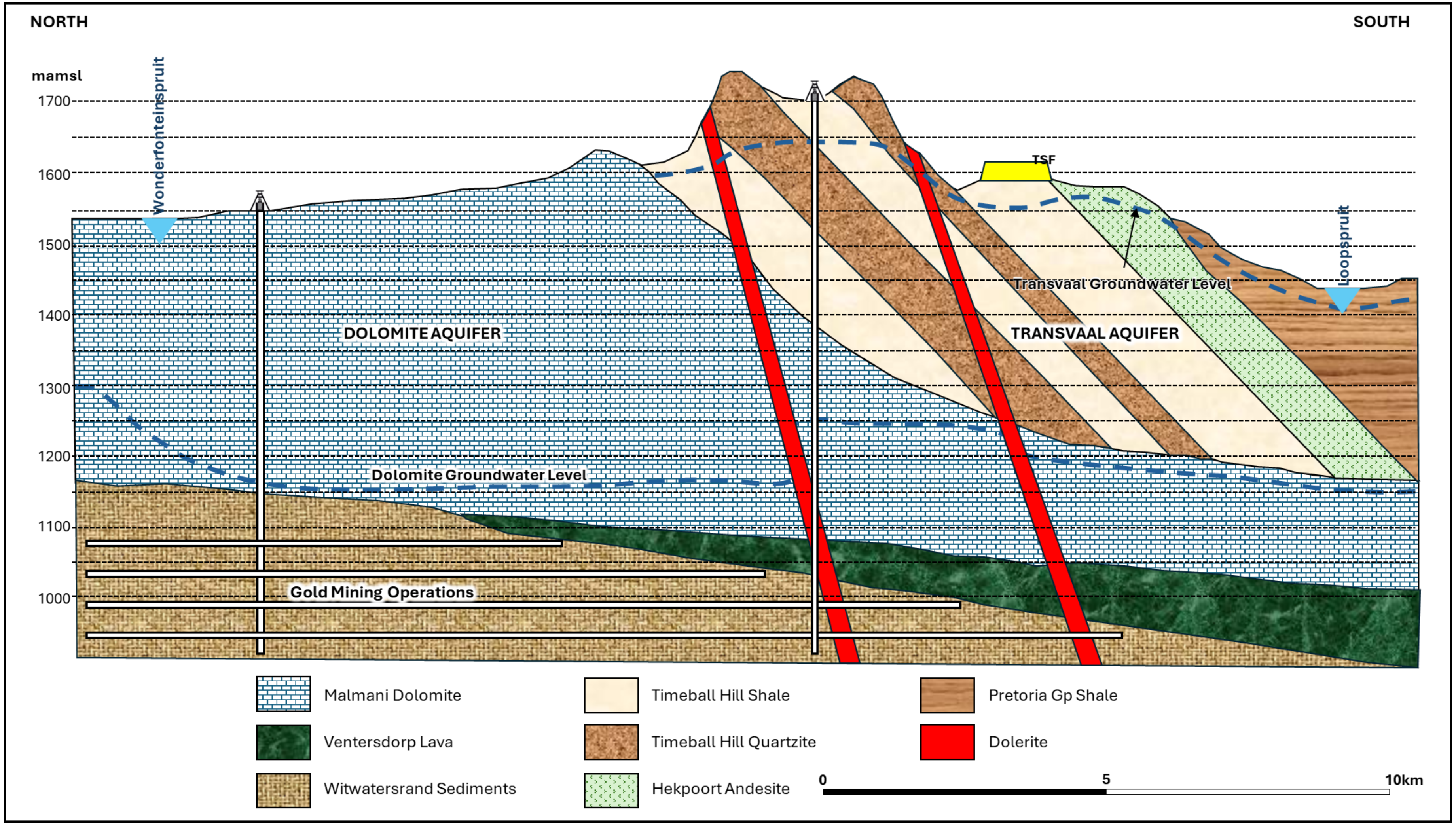

Figure 5.4: **Schematic geological section showing the relationship between the aquifers in the study area (Van Biljon, 2018)**

5.2.3 Aquifer Parameters

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.

Pump testing that was undertaken by GCS (2019) estimated the aquifer parameters in the weathered and fractured aquifer to be as follows (Table 5.2):

Table 5.2: Transmissivity and hydraulic conductivity values in the weathered and fractured aquifers (GCS, 2019)

ID	Blow Yield (litre/hour)	Transmissivity (m^2/day)	Hydraulic conductivity (m/day)		Aquifer
			Constant Discharge Test	Recovery Test	
MB10	23 000	-	12.9	6.08	Timeball Hill Shale and Quartzite
MB11	150	0.07	-	-	Shale
MB12	400	0.01	0.052	0.0303	Shale
MB13	1 190	0.7	0.1194	0.0363	Timeball Hill Shale and Quartzite
MB19	100	-	-	-	Shale
MB20	100 000	337	11.6	14.38	Shale (weathered / fractured)
MB21	1 600	2	-	-	Shale
MB22	3 600	13	0.5573	0.4645	Shale and andesitic lava
MB35	-	-	0.47	1.86	Timeball Hill Shale and Hekpoort Andesite
MB39	-	-	0.04	-	Timeball Hill Shale
MB50	Seepage	-	-	-	Timeball Hill Shale and Quartzite
MB51	Seepage	-	-	-	Timeball Hill Shale and Quartzite
MB58	3 000	-	-	-	Timeball Hill Shale and Quartzite

5.2.4 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. Groundwater recharge (R) for the study area was 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:

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

According to Vegter (1995) the recharge in the fractured aquifer is 31 mm / annum with water occurring in the shallow weathered zone and water bearing fractures only. This is equal to approximately 4% of mean annual precipitation. The average rainfall in the area is approximately 646 mm / annum. The average chloride in rainfall for areas inland is approximately 1.0 mg/L and the harmonic mean of the chloride concentration values in groundwater samples obtained from the mining area is 25.88 mg/L.

$$R = \frac{1}{25.88} \times 100 = 3.9\%$$

This value corresponds with Vegter’s value.

5.2.5 Groundwater Gradients and Flow

The first important aspect when evaluating the geohydrological 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 5.5. This graph indicates a very good correlation (99%) between the topography and the groundwater level, which suggests that groundwater flow will follow the topographical gradient.

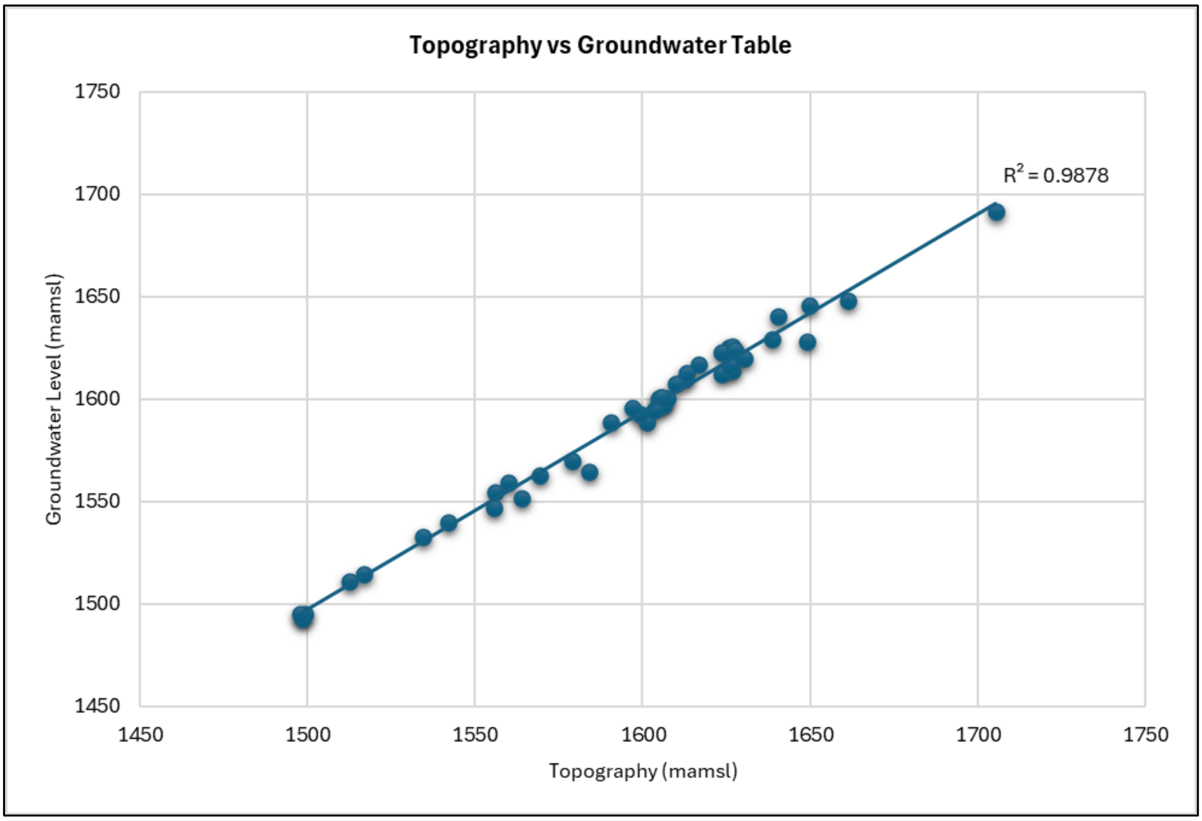

Figure 5.5: Correlation between topography and groundwater level

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 5.6 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-east.

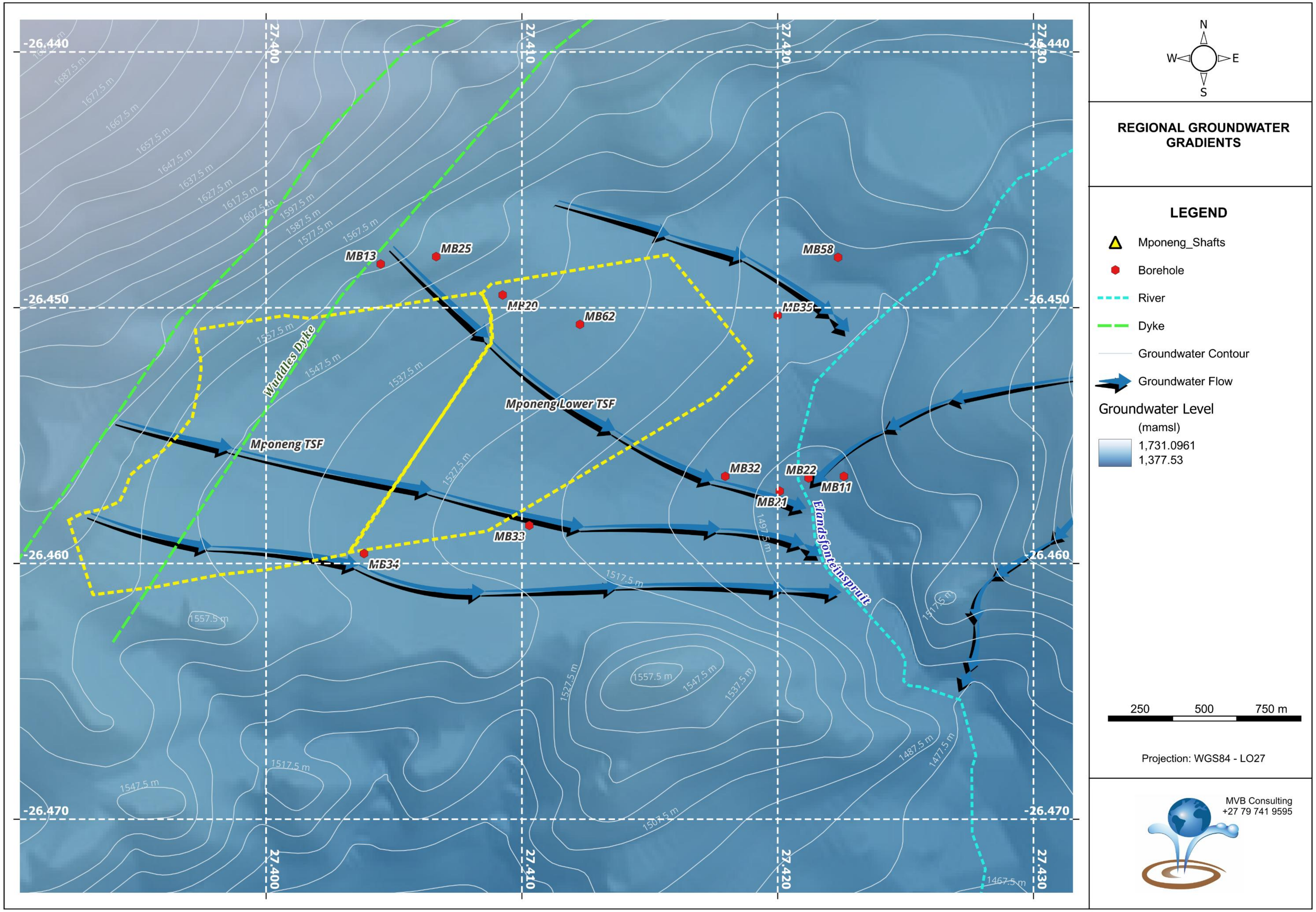

Figure 5.6: Regional groundwater gradient

5.2.6 Groundwater Quality

The mine routinely monitors the groundwater quality in the vicinity of the Mponeng Lower Compartment TSF. This data was made available and is used to assess the current impacts from the TSF.

Since there are no groundwater users within a 1km radius from the Mponeng Lower Compartment TSF, 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 5.3).

Table 5.3: 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
Sulphate	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 5.4. Where either of the guidelines are exceeded, the values are highlighted in pink.

With reference to Table 5.4, the following is observed:

- Monitoring boreholes MB29 and MB50 in the plant area show an impact. This is, however, not applicable to the current investigation.
- Monitoring boreholes MB32 and MB35 show an impact from the up-gradient Mponeng TSF. This is in line with the expected groundwater flow paths.
- The groundwater flow is towards the Return Water Dams (RWD), but borehole BH35 shows that the impacted water passes underneath the RWD. The impact is therefore expected to flow into the Aquatic Dam, or it will form part of the baseflow of the Elandsfonteinspruit. The relatively good water quality in the Aquatic Dam suggests that the impacted groundwater forms part of the baseflow of the stream.

The distribution of the sulphate (SO_4) concentrations provides an aerial view of the impact areas, which is as expected along the eastern and south-eastern boundary of the TSF (Figure 5.7).

Table 5.4: Groundwater chemistry

Analysis in mg/L (unless specified otherwise)	SANS 241	DWAF	MB39	MB10	MB29	MB32	MB50	MB11	MB13	MB62	MB20	MB21	MB22	MB25	MB35
Electrical Conductivity (mS/m)	170	-	2.4	4	219	313	228	118	2.2	7.7	1.5	109	98.5	2.1	435
Hardness Total			7	10	391	837	500	466	7	18	7	399	363	9.5	1434
pH	<5 - >9.7	-	6.5	6.6	5.7	6.6	5.7	7.7	6.3	6.8	6	7.2	6.9	5.8	4.8
Suspended Solids at 105°C	-	-	26	<25	94	<25	257	236	<25	408	358	260	220	1455	59
Total Dissolved Solids at 180°C	1 200	1 000	<100	<100	1 476	2 176	1 499	814	<100	<100	<100	760	682	165	2 971
Alkalinity Total	-	-	<30	<30	<30	57	<30	232	<30	<30	<30	190	156	<30	<30
Ammonia	1.5	-	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5
Calcium	-	1 000	<2.0	2.4	99	201	118	96	<2.0	2.6	<2.0	92	78	2.1	409
Chloride	300	1 500	<5	5	366	571	402	187	<5	12	<5	206	191	<5	814
Fluoride	1.5	2	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5
Magnesium	-	500	<2.0	<2.0	35	80	50	54	<2.0	2.7	<2.0	41	41	<2.0	99.6
Nitrate & Nitrite	11	100	0.8	1.6	11	7.6	54	1.7	1.1	1.7	<0.5	1.2	<0.5	0.9	<0.5
Orthophosphate	-	-	<0.05	<0.05	<0.05	0.1	0.1	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05
Sodium	200	2 000	2.1	3.9	267	351	250	34	2.1	6.8	<2.0	37	32	2.2	396
Sulphate	500	1 000	<5.0	<5.0	468	775	334	94	<5.0	<5.0	<5.0	41	33	<5.0	1 261
Zinc	5	0.02	<0.10	<0.10	0.12	<0.10	0.19	<0.10	<0.10	<0.10	<0.10	<0.10	<0.10	<0.10	1.1
Aluminium	0.3	5	<0.03	<0.03	0.04	<0.03	0.03	<0.03	<0.03	0.07	<0.03	<0.03	<0.03	<0.03	<0.03
Boron	2.4	5	<0.02	<0.02	0.08	0.05	0.04	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02
Cadmium	0.003	0.01	<0.003	<0.003	<0.003	<0.003	<0.003	<0.003	<0.003	<0.003	<0.003	<0.003	<0.003	<0.003	<0.003
Copper	2	0.5	<0.03	<0.03	<0.03	<0.03	<0.03	<0.03	<0.03	<0.03	<0.03	<0.03	<0.03	<0.03	<0.03
Cyanide Dissolved - CFA	0.2	-	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02
Cyanide WAD - CFA	-	-	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02
Iron	2	10	0.05	<0.03	<0.03	0.03	<0.03	0.04	<0.03	0.09	3.5	0.7	4.5	<0.03	4.8
Lead	0.01	0.1	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
Manganese	0.4	10	<0.03	<0.03	1	0.22	0.2	0.23	0.18	0.04	0.26	1.6	2.4	0.091	4.2
Nickel	0.07	1	<0.03	<0.03	0.07	0.05	0.04	<0.03	<0.03	<0.03	<0.03	<0.03	0.05	<0.03	0.14
Uranium	0.03	-	<0.03	<0.03	<0.03	<0.03	<0.03	<0.03	<0.03	<0.03	<0.03	<0.03	<0.03	<0.03	<0.03

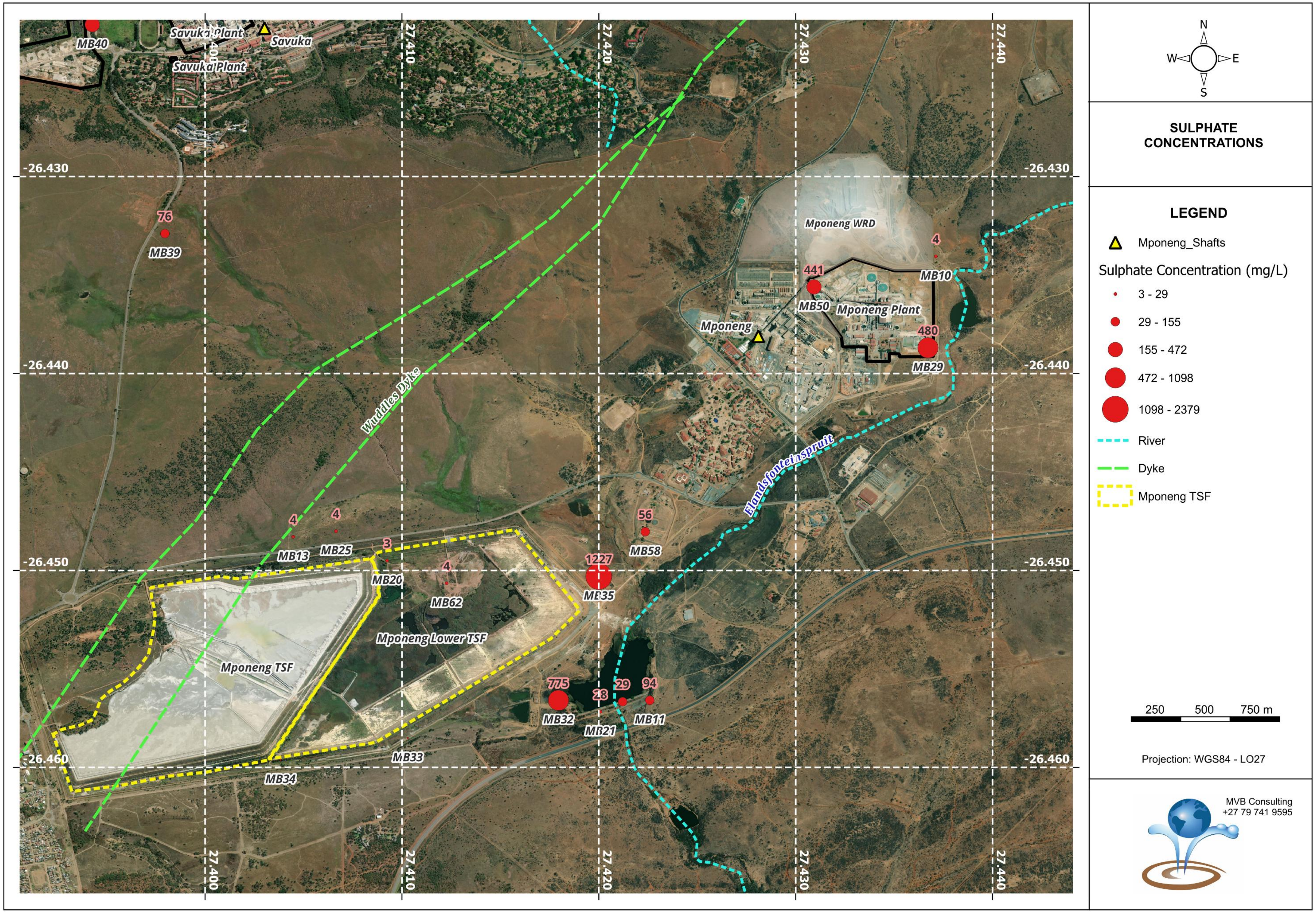

Figure 5.7: **Sulphate concentrations in monitoring boreholes**

5.2.7 Aquifer Vulnerability and Classification

The DRASTIC aquifer vulnerability method makes use of seven (7) factors to calculate the vulnerability index value:

- Depth to groundwater (D) – determines the maximum distance contaminants travel before reaching the aquifer
- Net recharge (R) – the amount of water that is able to travel from ground surface to the water table
- Aquifer (A) – the composition of the aquifer material
- Soil media (S) – the uppermost portion of the unsaturated zone
- Topography (T) – the slope of the ground surface
- Impact of vadose zone (I) – the type of material present between the bottom of the soil zone and water table
- Hydraulic conductivity of the aquifer (C) – indicates the aquifer's ability to allow for the flow of water to occur.

This vulnerability index is used to determine the aquifer's vulnerability to contamination with the index range from 1 to 200, where 200 represents the theoretical maximum aquifer vulnerability. The DRASTIC map for the project area is presented in Figure 5.8. The DRASTIC index ranges from 65 to 130 across the study area, with the lower values being present in the immediate area of the Mponeng TSF. The southern areas adjacent to the Loop Spruit exhibit the highest values. When considering the parameters comprising the vulnerability index, the elevated values likely relate to the simplified geological map used in the calculation.

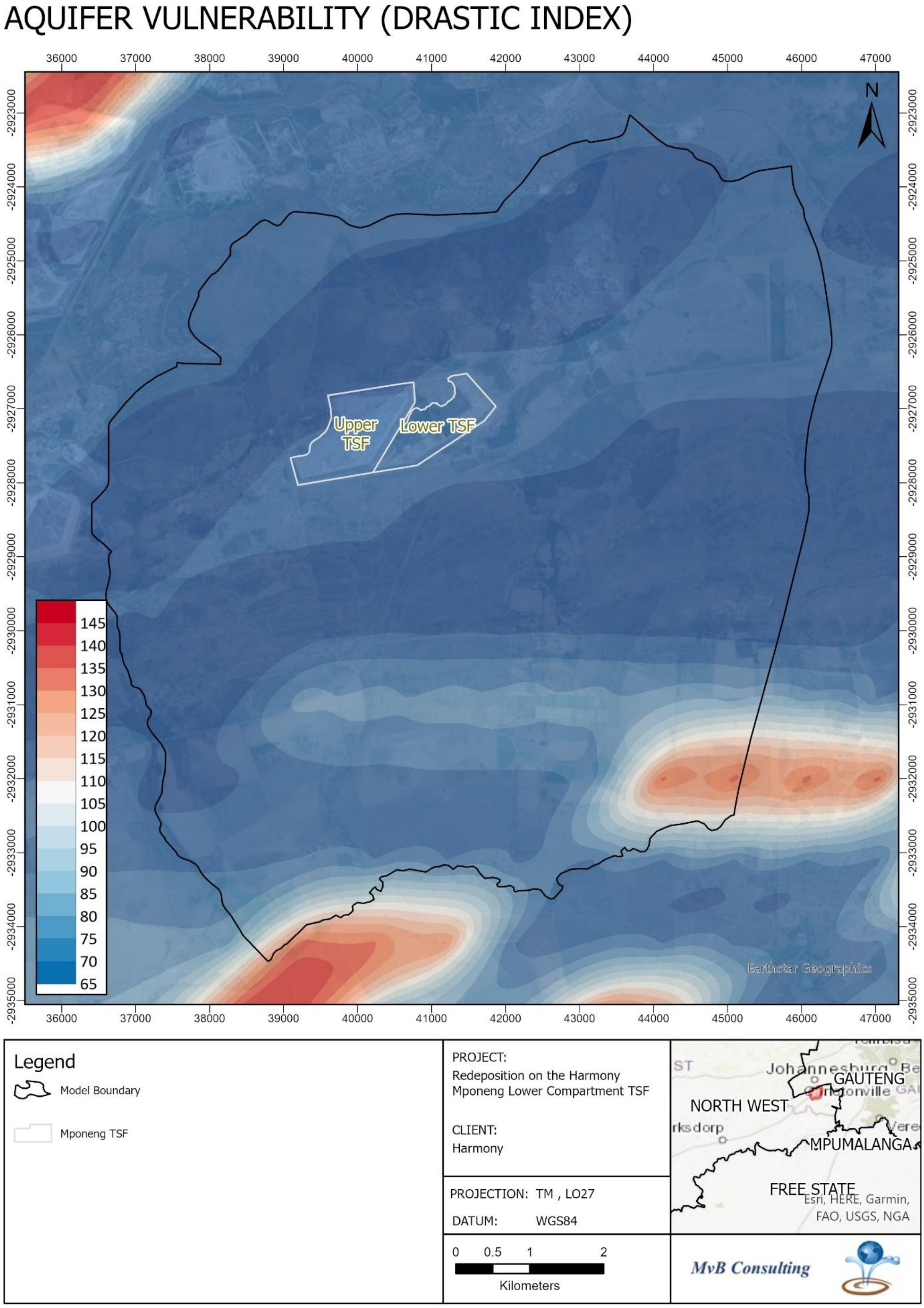

Figure 5.8: Aquifer vulnerability map

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.
- 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.
- 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 5.5). A weighting and rating approach is then used to decide on the appropriate level of groundwater protection (Table 5.6).

Table 5.5: 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 5.6: 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)	1	2	Low
Fractured Aquifer	Minor (2)	1	2	Low

6. NUMERICAL GROUNDWATER MODELLING

6.1 Model Objectives

This section summarises the objectives on how the groundwater model will be used to address the project objectives and the target confidence level.

6.1.1 Objectives

The modelling objective is to determine the impact of the proposed recommencement deposition on the Mponeng TSF lower compartment. Once the impact is determined the following scenarios were considered:

- No mitigation measures.
- A liner between the existing lower compartment and the proposed new tailings deposition.
- Plume containment through scavenger wells.
- Plume containment through tree plantations (phyto-remediation).

6.1.2 Confidence Level

The degree of confidence with which a model's predictions can be used is a critical consideration in the development of any groundwater model. The confidence level classification of a model is often constrained by the available data and the time and budget allocated for the work (Barnett, et al., 2012).

It is necessary to define in non-technical terms a benchmark or yardstick by which the reliability or confidence of the required model predictions can be assessed. The degree of confidence with which a model's predictions will be used is a critical consideration in the development of any groundwater model.

The level of confidence typically depends on (Barnett, et al., 2012):

- **Available data** (and the accuracy of that data) for the conceptualization, design and construction. Consideration should be given to the spatial and temporal coverage of the available datasets and whether or not these are sufficient to fully characterize the aquifer and the historic groundwater behavior that may be useful in model calibration.
- **Calibration procedures** that are undertaken during model development. Factors of importance include the types and quality of data that is incorporated in the calibration, the level of fidelity with which the model is able to reproduce observations, whether it can be demonstrated that the model is able to adequately represent present-day groundwater conditions. This is important if the model predictions are to be run from the present day forward.
- **Consistency between the calibration and predictive analysis**. Models should be used in prediction in a manner that is consistent with their calibration. For example, a model that is calibrated in steady state only will likely produce transient predictions of low confidence. Conversely, when a transient calibration is undertaken, the model may be expected to have a high level of confidence when the time frame of the predictive model is of less or similar to that of the calibration model.
- L**evel of stresses** applied in predictive models. When a predictive model includes stresses that are well outside the range of stresses included in calibration, the reliability of the predictions will be low and the model confidence level classification will also be low.

Predefined criteria exist for classing model confidence where a Class 1 model, for example, has relatively low confidence associated with any predictions and is therefore best suited for managing low value resources (i.e. few groundwater users with few or low-value groundwater dependent ecosystems) for assessing impacts of low-risk developments or when the modelling objectives are relatively modest. The Class 1 model may also be appropriate for providing insight into processes of importance in particular settings and conditions. Class 2 and 3 models are suitable for assessing higher risk developments in higher-value aquifers. In some circumstances Class 1 or Class 2 confidence-level classification will provide sufficient rigor and accuracy for a particular modelling objective, irrespective of the available data and level of calibration. (Barnett, et al., 2012).

Considering all factors that include available data and time frame a model of Class 2 confidence is likely to be achieved and the criteria for a Class 2 model is presented in Table 6.1 (Barnett, et al., 2012). It is not expected that any individual model will have all the defining characteristics of a specific class. The characteristics described are features that may have a bearing on the confidence with which the model can be used.

Table 6.1: Class 2 model confidence criteria

Data	Calibration	Prediction	Key Indicator
• Groundwater head observations and borehole logs are available but may not provide adequate coverage throughout the model domain. • Metered groundwater extraction data may be available but spatial and temporal coverage may not be extensive. • Streamflow data and baseflow estimates available at a few points. • Reliable irrigation application data available in part of the area of for part of the model duration.	• Validation is either not undertaken or is not demonstrated for the full model domain. • Calibration statistics are generally reasonable but may suggest significant errors in part of the model domain. • Long-term trends do not replicate in all parts of the model domain. • Transient calibration to historic data but not extending to present day. • Seasonal fluctuations not adequately replicated in all parts of the model domain. • Observations of the key modelling outcome data set are not used in calibration.	• Transient calibration over a short time frame compared to that of prediction. • Temporal discretization used in the predictive model is different from that used in transient calibration. • Level and type of stresses included in the predictive model are outside the range of those used in the transient calibration. • Validation suggests relatively poor match to observations when calibration data is extended in time and/or space.	• Key calibration statistics suggest poor calibration in part of the model domain. • Model predictive time frame is between 3 and 10 times the duration of transient calibration. • Stresses are between 2 and 5 times greater than those included in calibration. • Temporal discretisation in predictive model is not the same as that used in calibration. • Mass balance closure error is less than 1% of total. • Not all model parameters consistent with conceptualisation. • Spatial refinement too coarse in key parts of the model domain. • The model has been reviewed and deemed fit for purpose by an independent hydrogeologist.

6.2 Conceptualisation

6.2.1 Overview

This section describes the current level of understanding of the aquifer system and how this is translated into a conceptual hydrogeological model to address the model objectives. It is important that an appropriate scale for the conceptual model is selected for the placement of a boundary for the data collection and interpretation activities. Since the model is intended to determine the impact on the aquifer due to the additional deposition of tailings on an existing TSF, an appropriate catchment was selected and all available data within and at the edges were used to contract the conceptual hydrogeological model.

6.2.2 Conceptual Boundaries

The conceptualisation process establishes where the boundaries to the groundwater flow system exists based on an understanding of groundwater flow processes. The conceptualisation should also consider the boundaries to the groundwater flow system in the light of future stresses being imposed (Barnett, et al., 2012).

The model boundary is chosen wider than the immediate TSF footprint so that the model boundary conditions do not interfere with the system response in the vicinity of the TSF. The chosen model boundary together with the TSF footprint is presented in Figure 6.1. The criteria for the model boundary selection are summarised as follows:

- The northern boundary co-inside with the quaternary (C23J) boundary and also with the geology (Figure 6.2 and Table 6.2).
- The eastern boundary is aligned with the surface geology (Figure 6.2 and Table 6.2) which is a Syentite feature.
- The southern boundary aligns with the Loop Spruit.
- The western boundary is represented by a regional drainage line.

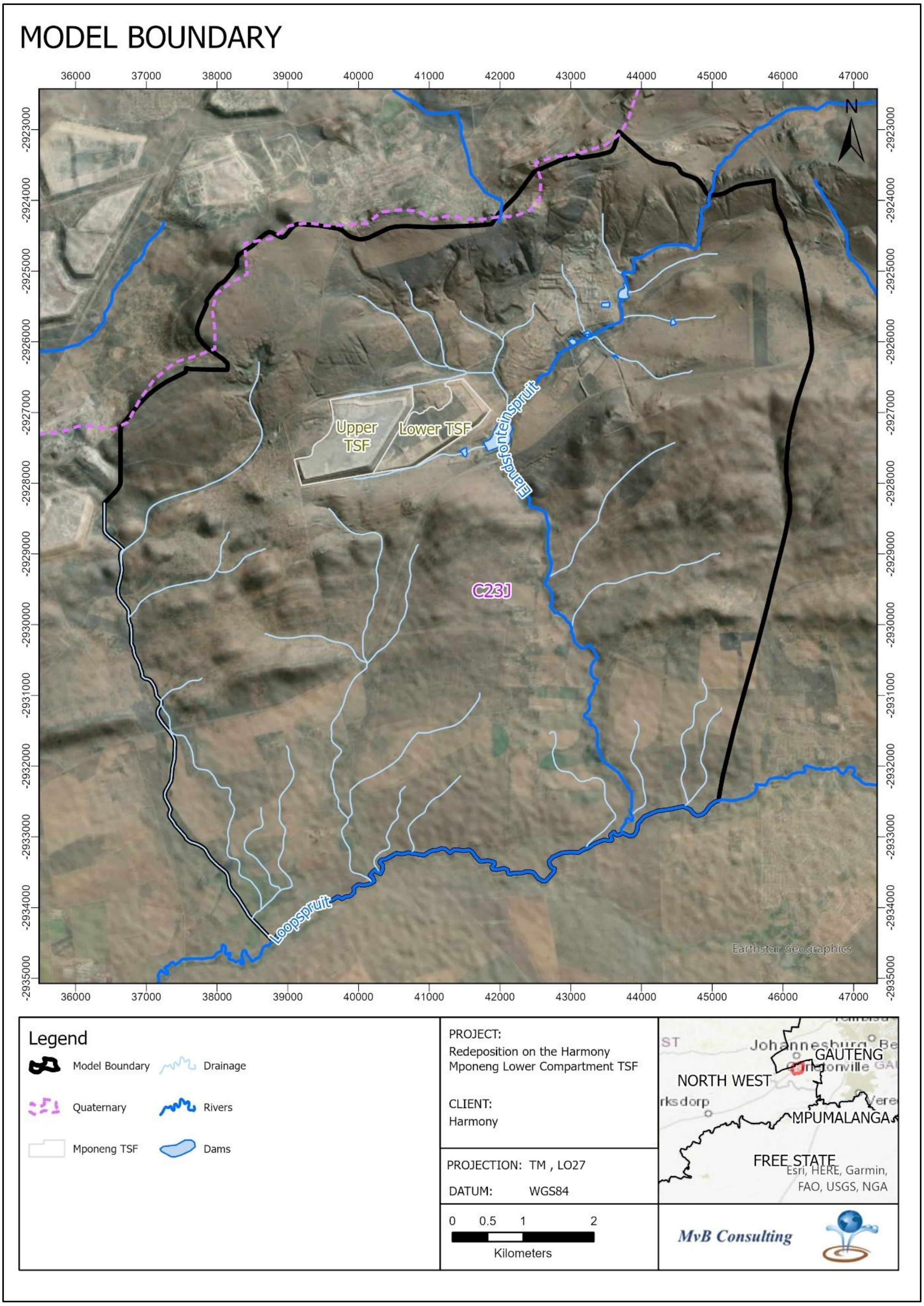

Figure 6.1:Model boundary selection

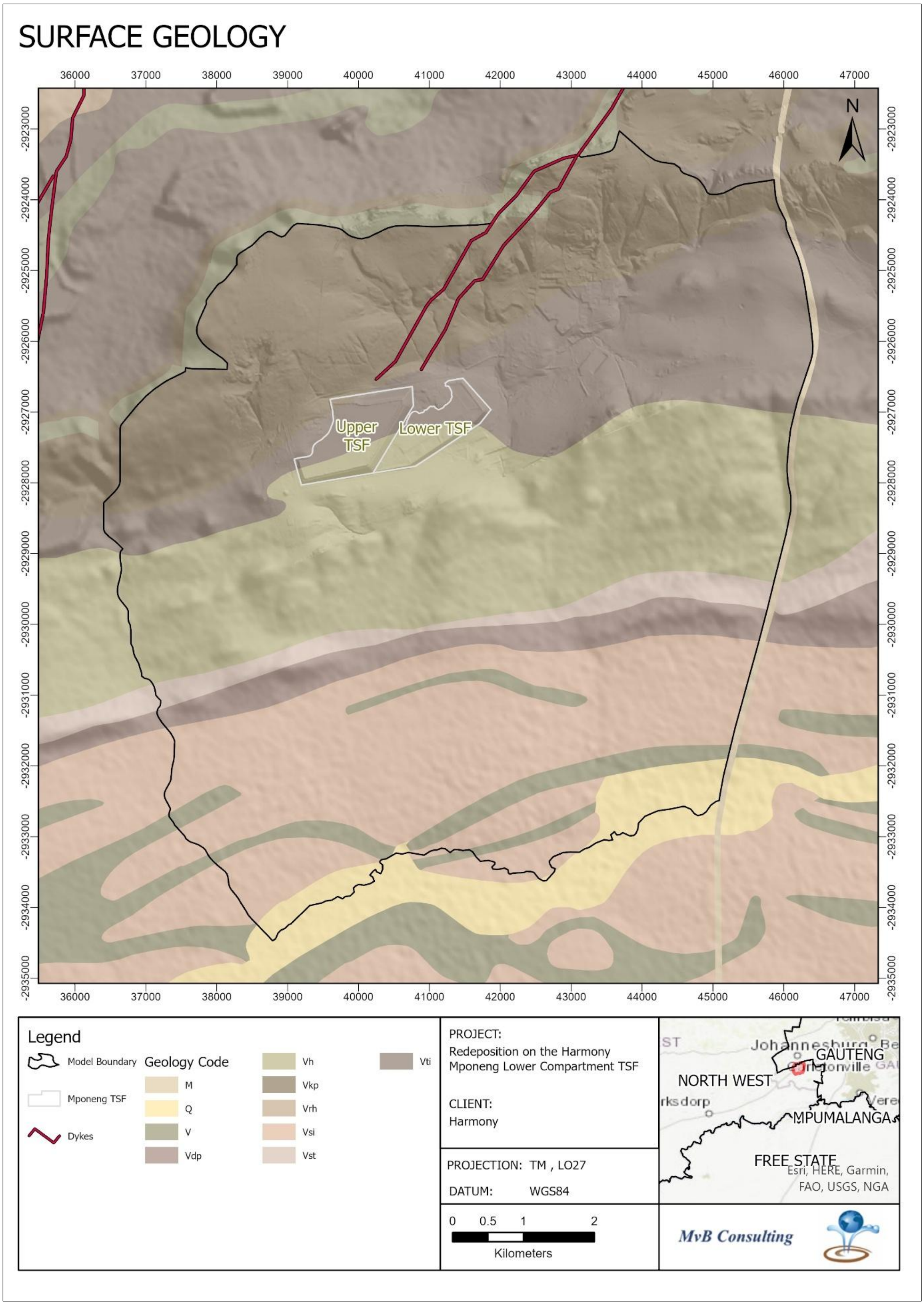

Figure 6.2: Model boundary alignment with surface geology

Table 6.2: Geological map codes

Code	Lithostratigraphy / Chronostratigraphic	Description
M	MOKOLIAN	Syenite
Q	QUATERNARY	Alluvium
V	VAALIAN	Diabase
Vbo	BOSHOEK	Arkosic quartzite, subgreywacke, siltstone, shale,
Vdp	DASPOORT	Quartzite with minor shale and siltstone
Vh	HEKPOORT	Andesitic lava, subordinate pyroclastic rocks, minor quartzite, shale and conglomerate
Vkp	KLAPPERKOP QUARTZITE	Quartzite (ferruginous in places), wacke, siltstone, shale, magnetic ironstone
Vma	MALMANI	Dolomite, subordinate chert, minor carbonaceous shale, limestone and quartzite
Vrh	ROOIHOOGTE	Quartzite
Vrh	ROOIHOOGTE	Shale
Vsi	SILVERTON	Shale, minor limestone/dolomite, minor limestone/dolomite, basalt and tuff
Vst	STRUBENKOP	Shale, subordinate siltstone, minor quartzite
Vti	TIMEBALL HILL	Mudrock, quartzite, minor diamictite, conglomerate (in places)

6.2.3 Hydrogeological Domain

The definition of the hydrogeological domain (or the conceptual domain) provides the architecture of the conceptual model and aquifer properties, which leads to consideration of the physical processes operating within the domain.

A conceptual cross-section of the larger study area is presented in Figure 5.4, which is used to inform the construction of the regional conceptual model.

Based on available borehole information (GCS, Groundwater Assessment for the Mponeng TSF, 2019) a regional model comprising of two layer were decided on with the first layer representing a wreathed aquifer ranging in thickness from 25 m to 30 m. A second layer representing a fractured aquifer of thickness 150 m is underlying the first layer. Previous reports (GCS, Groundwater Flow and Plume Model Update for the West Wits Operations, 2023) indicate more model layers used, but considering the available information a regional two later model is selected. The weathered aquifer comprise of multiple zones of hydraulic conductivity whereas the bottom layer is selected a homogenous layer which will be represented by an effective hydraulic conductivity eliminating the need for further model complexity. Finally a TSF layer will exist above the first layer on the TSF footprint and dykes are allowed to traverse the regional aquifer layers. The conceptual layering is shown in Table 6.3.

Table 6.3: Conceptual model layers

<table>
<tr><th colspan="5">Description</th><th>Thickness (m)</th></tr>
<tr><td></td><td>TSF</td><td colspan="3"></td><td>~ 60</td></tr>
<tr><td>Zone 1</td><td>Zone 2</td><td>Zone 3</td><td rowspan="2">dyke</td><td>Zone 4</td><td>25 – 30</td></tr>
<tr><td colspan="3">Fractured Aquifer</td><td>Fractured Aquifer</td><td>150</td></tr>
</table>

The TSF layer is defined by the final elevation of the lower compartment as shown in Figure 6.3 which also shows a cross section through the TSF. Finally, the 3D conceptual model showing the layering is presented in Figure 6.4.

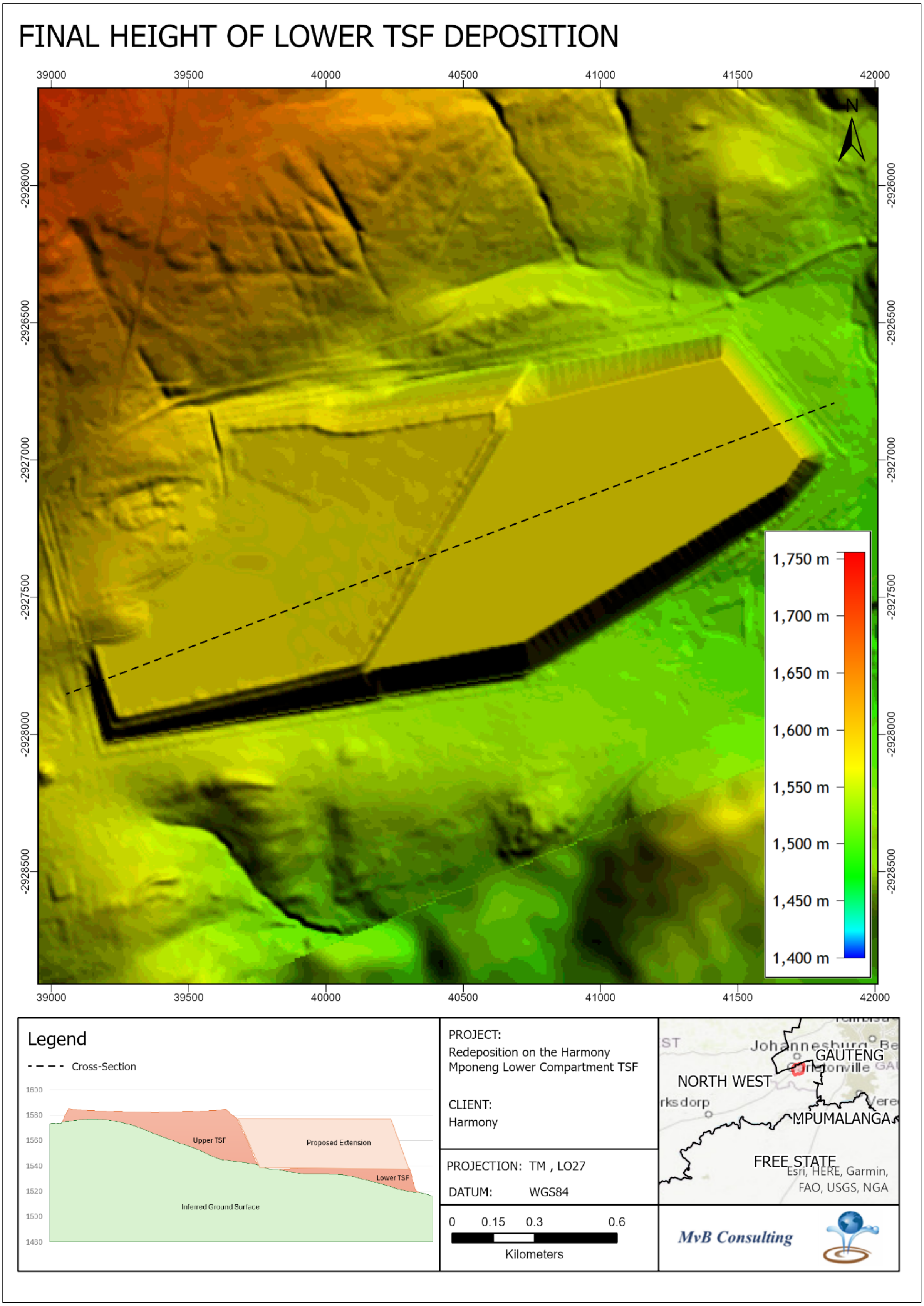

Figure 6.3:Final TSF elevation

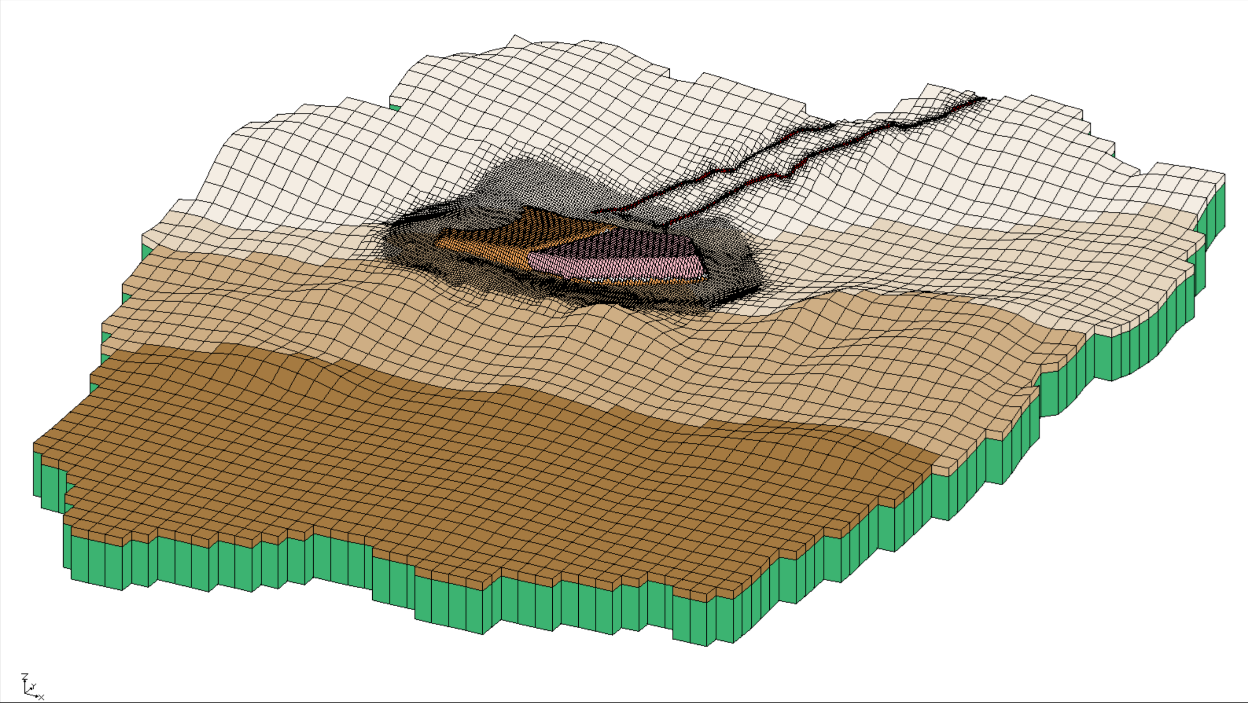

Figure 6.4: 3D conceptual model

6.2.4 Aquifer Properties

The aquifer properties control water flow and storage, through the hydrogeological domain. Quantified aquifer properties are critical to the success of the model calibration. It is also well understood that aquifer properties vary spatially and are almost unknowable at the detailed scale (Barnett, et al., 2012). As such, quantification of aquifer properties is one area where simplification is often applied. Hydraulic properties that should be characterised include hydraulic transmissivity (or hydraulic conductivity) and the storage coefficient.

The aquifer parameters were obtained from existing reports (GCS, Groundwater Assessment for the Mponeng TSF, 2019) (Barnard, 2013) and selected parameters are presented in Table 5.2.

6.2.5 Recharge

The quaternary recharge data for the area are presented in Table 6.4, alongside recharge values derived from the chloride mass balance method. Water balance methods were not employed for recharge estimates due to the need for site-specific rainfall data. The chloride value corresponds well to the recharge figure presented in Section 4.6.

Table 6.4: Summary of recharge values (GCS, 2023)

Quat		MAP (mm/a)		Recharge (mm/a)			Recharge (%)		
		GRA2	*WR2012*	*GRA2*	*Chloride*	*Average*	*GRA2*	*Chloride*	*Average*
C23J		620	620	39.6	18.6	29.1	6.4	3.0	4.7

When comparing GRA2 values with those from the chloride mass balance method, the GRA2 values appear to be approximately twice as high. The chloride mass balance method utilizes the harmonic mean to determine a representative groundwater chloride concentration:

$$Cl_{gw} = N \left(\sum_{i=1}^{N} \frac{1}{Cl_{igw}} \right)^{-1}$$

The harmonic mean offers the benefit of reducing the influence of high chloride concentrations unrelated to natural groundwater chloride levels in areas affected by pollution. The percentage recharge is calculated as the ratio of chloride concentrations in rainfall to those in groundwater. When rainfall chloride data are unavailable, it is common practice in South Africa to assume a rainfall chloride concentration of 1 mg/L.

Possible reasons for the discrepancy between the recharge values are as follows:

- The assumption of the concentration of the rainfall chloride concentration could be wrong and the ratio calculation is sensitive to this.
- The GRA2 values are representative of the quaternary values and since the study area only forms a small part of the quaternary and is situated near a topographical high where it is expected to have less recharge than compared to lower-lying areas.

6.2.6 Groundwater Levels

Static groundwater levels are representative of the natural aquifer conditions when no pumping takes place. Groundwater level data exist for the period between 2019 and 2023. The groundwater level response during this period is presented in Figure 6.5 where the majority of the boreholes exhibit small water level fluctuations that is associated with seasonality with the exception of MB10, MB39 and MB50 which shows a recovery trend during this period, although the variability of the recorded water levels are high compared to the others as shown in Figure 6.6.

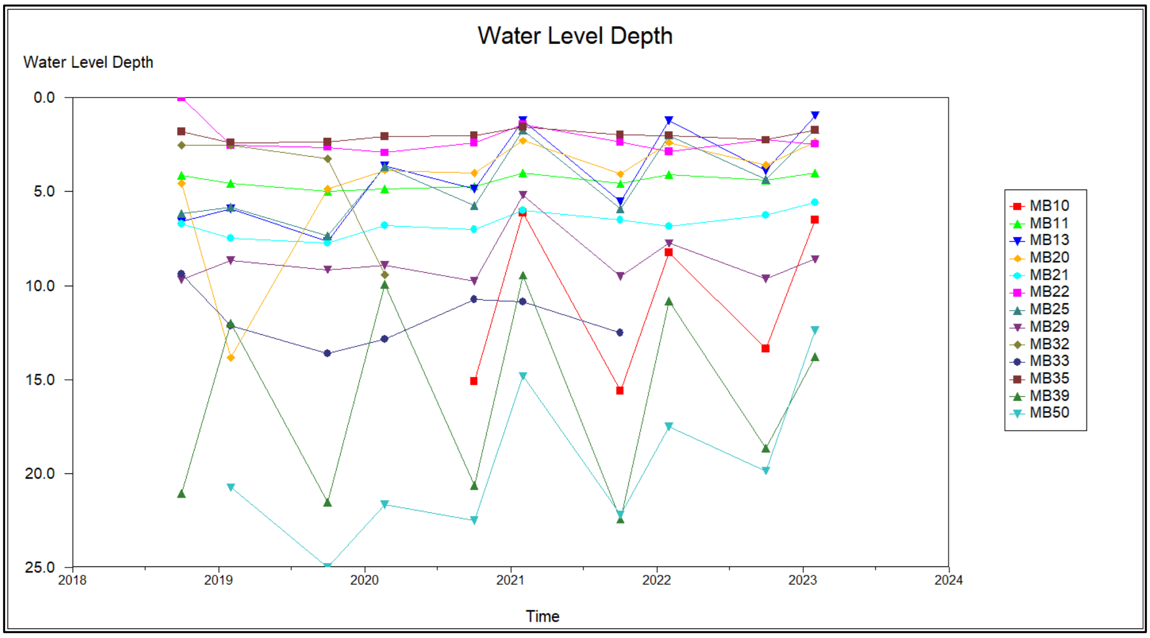

Figure 6.5:Time series water levels

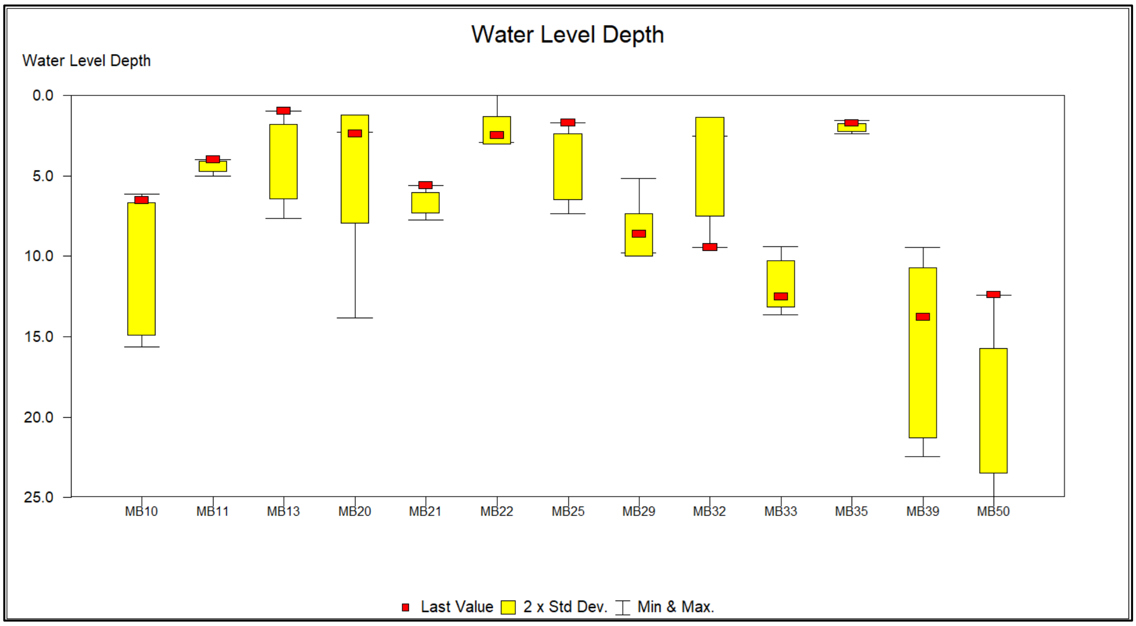

Figure 6.6: Water level variability

Making use of the average water level response recorded a high correlation between surface elevation and groundwater levels as presented in Figure 6.7.

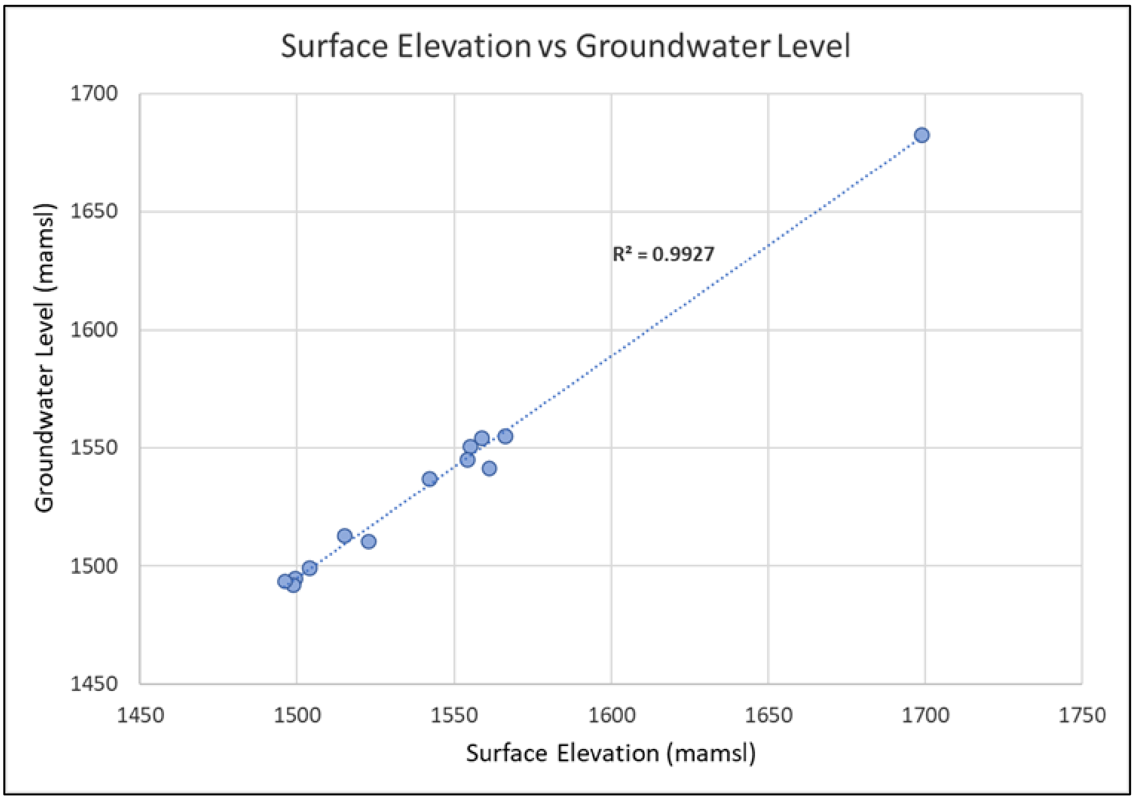

Figure 6.7: Groundwater water levels versus surface elevation

Due to the high correlation between surface topography and groundwater level, the Bayesian interpolation method can be used to generate a groundwater level map of the model domain. The Bayesian interpolation method makes use of the statistical relationship between the water level and surface topography and then predict water levels at specified elevation coordinates which makes this an ideal method to extrapolate water levels over a domain where data is sparse. The resulting groundwater level map with groundwater flow directions is presented in Figure 6.8 which also indicate the spatial distribution of the monitoring boreholes.

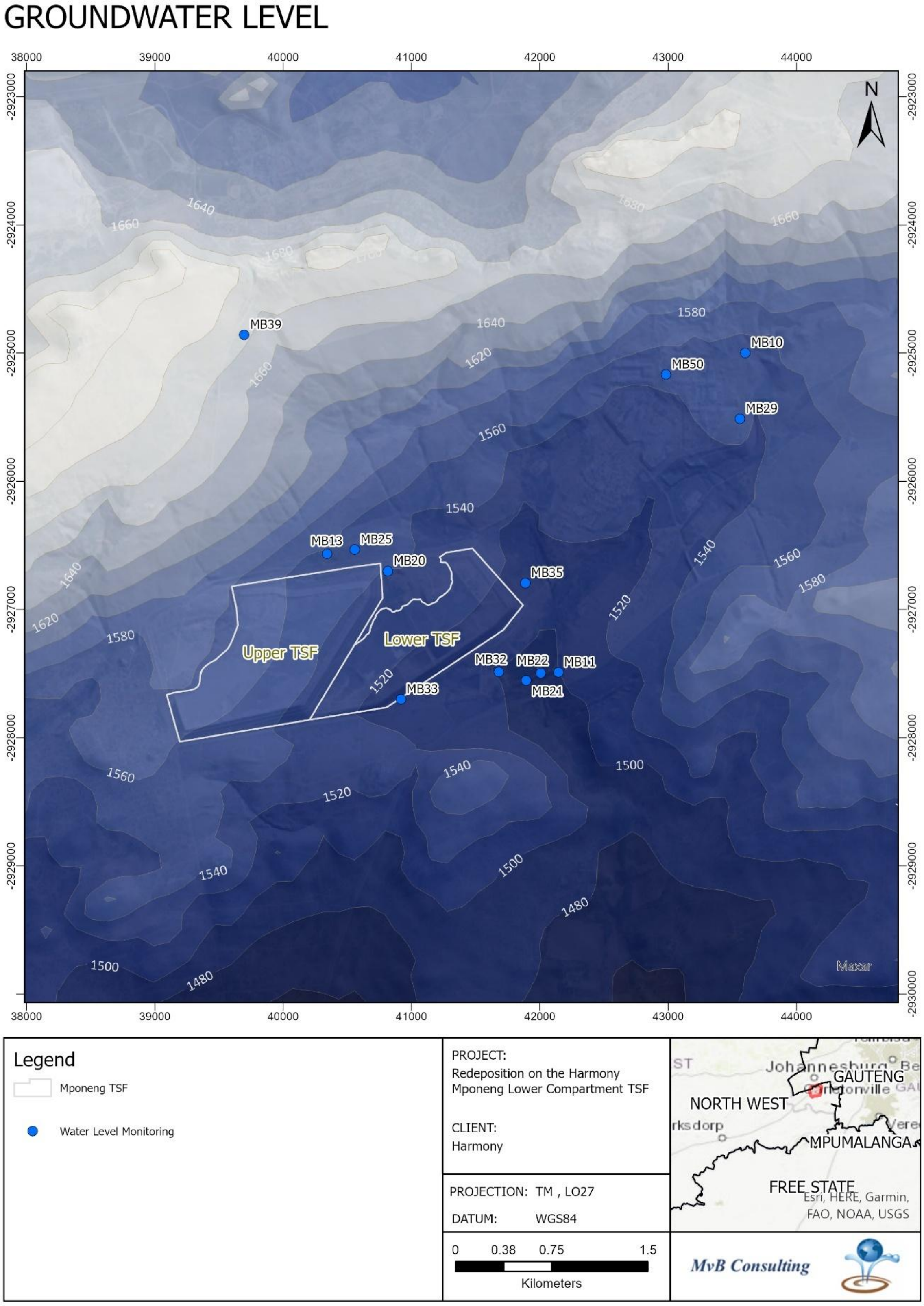

Figure 6.8:Groundwater water level map

6.3 Model Design

The model design section specifies the model confidence level and the technical details of the groundwater model such as spatial and temporal discretisation, parameter distributions, implementation of stresses and boundary conditions, and model code and software.

6.3.1 Numerical Method

To investigate the behaviour of aquifer systems in time and space, it is necessary to employ a mathematical model. MODFLOW, a modular three-dimensional finite difference groundwater flow model was chosen as the model code to be used. It is an internationally accepted modelling package, which calculates the solution of the groundwater flow equation using the finite difference approach.

The simulation model used in this modelling study is based on three-dimensional groundwater flow as described by the following equation:

$$\frac{\partial}{\partial x}\left(K_x \frac{\partial h}{\partial x}\right) + \frac{\partial}{\partial y}\left(K_y \frac{\partial h}{\partial y}\right) + \frac{\partial}{\partial z}\left(K_z \frac{\partial h}{\partial z}\right) \pm W = S_s \frac{\partial h}{\partial t}$$

where,

h	=	*Hydraulic head*
K_x, K_y, K_z	=	*Hydraulic conductivity in differen directions*
S	=	*Specific Storage*
t	=	*Time*
W	=	*Source (recharge) or sink (pumping) pe unit area*
x, y z	=	*Coordinate into model*

For steady-state conditions the groundwater flow equation reduces to the following:

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

With the release of MODFLOW 6, a generalized control-volume finite-difference (CVFD) approach is supported in which a cell can be hydraulically connected to any number of surrounding cells. The following equation specify the general form of the CVFD balance equation for cell n:

$$\sum_{m \in \mu_n} C_{nm}(h_n - h_m) + HCOF_n(h_n) = RHS_n$$

where,

C_{nm}	=	*Inter-cell conductance between cells n and m*
h_n, h_m	=	*Hydraulic heads at cells n and m*
$HCOF_n$	=	*Sum of all terms that are coefficients of h_n*
RHS_n	=	*Right-hand-side value of the balance equation*
μ_n	=	*Set of cells that are connected to cell n*

The CVFD functionality support the creation of an unstructured grid (USG) that allow refinement of specified features.

6.3.2 Software

The modelling software used is summarised in Table 6.5. GMS is the GUI used and offer the advantage of setting up a conceptual model making use of GIS files and then projecting the data on a specified model grid. This functionality allows for quick updates to the model configuration.

Table 6.5: Modelling Software

Component	Description
Graphical User Interface (GUI)	GMS from Aquaveo
Model Flow Engine	MODFLOW USG with SMS (Sparse Matrix Solver) and PCGU linear matri solver.

Although MODFLOW is a porous flow model, fractured rock aquifers are commonly modelled as equivalent porous media and this assumption is usually valid for large-scale groundwater flow models. MODFLOW supports 3D models in both steady and transient state which is a requirement for this project.

6.3.3 Model Domain

6.3.3.1. Model Dimension

A 3D model is used for this project where flows occur in all directions. 3D groundwater flow models are needed to simulate groundwater movement in both the horizontal and vertical planes and are required when there are several overlying hydrogeological units where horizontal flow in individual units and flow between adjoining units are important (Barnett, et al., 2012).

6.3.3.2. Extent

The model extent covers an area of 80.5 km^2 with a maximum elevation difference of 350 m across the model boundary.

6.3.3.3. Spatial Discretisation

Numerical models require the model domain to be subdivided (discretised) into a grid (or mesh) that defines the locations of the points (commonly referred to as nodes) at which heads or solute concentrations are calculated and the geometry of the cells (or elements) that controls the calculation of the volumetric or mass flow rates of water and solutes. The appropriate level of spatial discretisation depends on the size of the model domain, the modelling objectives and the desired level of accuracy (Barnett, et al., 2012).

6.3.3.4. Model Domain

The model domain is defined by a primary grid of 200 m x 200 m cross the study area and a refined grid of 25 m x 25 m across the immediate vicinity of the TSF footprint and an additional grid refinement of 15 m x 15m for the dykes as shown in Figure 6.9.

The purpose of the grid refinement is to provide a high resolution in the area of interest while the remainder of the model domain can be represented by a coarse grid to reduce computational time and complexity. Large models with fine grids will generate large model input and output files that become difficult to process. As file sizes increase the time taken to manipulate and use the files also increases. In some cases model files become too large to open in some software packages.

A zoomed version of the model grid is presented in Figure 6.10 to highlight the grid refinement across the TSF footprint. The grid refinement is carried throughout all model layers.

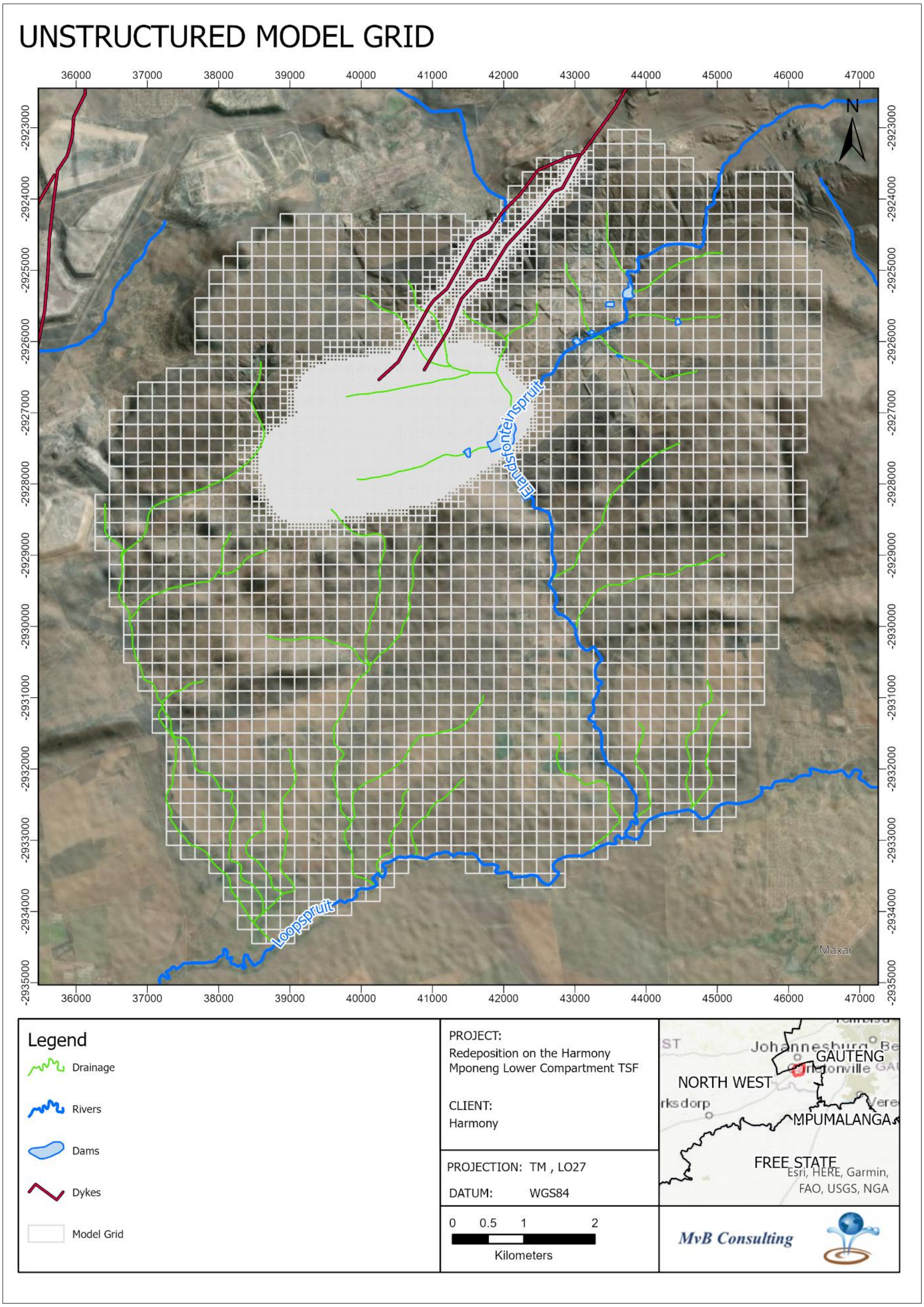

Figure 6.9: Model unstructured grid

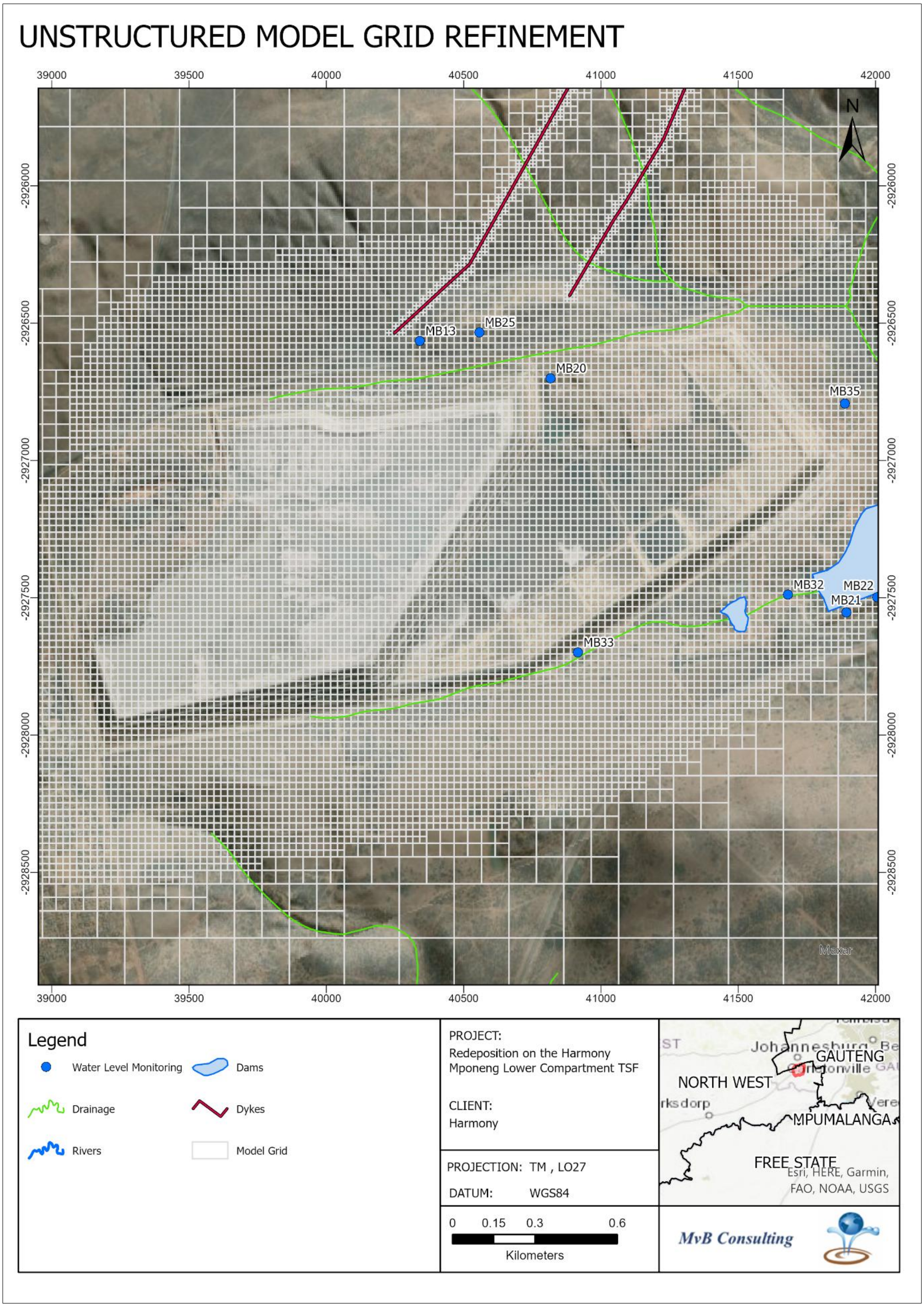

Figure 6.10: Model grid refinement

6.3.4 Boundary Conditions

Groundwater flow models require information about the head and/or head gradient at the boundaries of the model domain. There are three types of boundary conditions (Barnett, et al., 2012):

- **Type 1**, Dirichlet or specified head boundary condition: The head of a boundary cell or node is specified. When the head is specified along a section of the model boundary, the flow across this model boundary section is calculated.
- **Type 2**, Neumann or specified head-gradient boundary condition: The gradient of the hydraulic head is specified at the boundary, which implies that the flow rate across the boundary is specified.
- **Type 3**, Cauchy or specified head and gradient boundary condition: Both the head and the head gradient are specified. In flow models this type of boundary condition is implemented in an indirect manner by specifying a head and a hydraulic conductance or resistance.

For this particular model, the boundary conditions around the model domain are specified as follows:

- The northern and eastern boundaries are considered no-flow boundaries
- The southern boundary that aligns with the Loop Spruit is considered a specified head boundary (Type 1).
- The western boundary is a drainage boundary. The drainage lines are modelled with a drain for which a drain elevation and conductance value is specified for each cell. The drain is inactive while the head value is below the specified drain elevation. When the head value exceeds the specified drain elevation, water will be released from the model at the affected cells and the gradient between simulated water level and specified level together with the conductance determines the amount of water released per time step (Type 3).

Surface water dams are modelled as general head boundaries (Type 3) and the water level at these cells will vary according to the gradient between the dam level and that of the groundwater controlled by a conductance factor.

Recharge areas are modelled as flux boundaries (Type 2) where the recharge rate is specified. For steady state conditions this recharge rate is constant, but during transient state modelling the recharge rate varies from one time step to the next as the rainfall rate changes.

6.4 Initial Conditions

Initial conditions define the groundwater conditions present at the start of the model run. The choice of initial conditions for a steady state model does not influence the model outcome, but the steady state solution is obtained more rapidly when initial conditions are defined that are reasonably close to the final solution.

The water levels generated in Figure 6.7 is used as initial water levels for the steady state model calibration and the calibrated water levels in turn are used as the initial water levels for the transient model.

6.5 Model Calibration

6.5.1 Overview

Calibration is required to account for unmeasured, unknown, or unrepresented conditions or processes and uncertainty in measured input data. The model calibration phase includes the following steps:

- Defining the model calibration criteria based on model confidence requirements and objectives and the availability of calibration data.
- Simulating natural background conditions and comparison of these predictions with any available observations.
- Modifying the model assumptions and/or uncertainties within reasonable bounds to converge on a realistic simulation. Specification of the model input data in ranges of values, noting the accuracy of these data so that changes made during the calibration procedure concentrate on the most uncertain data while remaining within realistic bounds.

6.5.2 Model Calibration Criteria

In the model objectives it was stated that the confidence level aimed to be achieved is a Class 2 model. Class 2 models are founded on sufficient hydrogeological data (i.e. water level data and aquifer hydraulic parameters) and can be used to predict the future behavior of a groundwater aquifer system.

The targeted model calibration criteria for this project are summarised in Table 6.6.

Table 6.6: Model calibration criteria

No.	Simulation Requirements	Acceptability Criteria
1	Convergent	Head change criteria within 0.001 m (This is the maximum absolute value of the head change for the iteration for each cell).
		Residual criterion is within 0.001 m^3 (This is the maximum absolute value of the difference between inflows and outflows for each cell).
2	Well balanced	Water flow mass balance (inputs vs outputs) has an error of < 0.5%
3	Any 'dry' model cells don't hinder vertical flow.	No dry model cells existing in intermediary layers with wet cells on top and below. Dry cells in the top layer should correlate approximately with areas of likely unsaturation.
4	Long-term groundwater flow directions correlate with the conceptual model.	Qualitative check that the groundwater flow directions correlate with the conceptual model flow directions.
5	Long-term measured water levels correlate well to observed data.	Modelled water levels must correlate to observed data within a residual root mean square (RMSE) error of <15m and scaled RMSE of <5% as per internationally accepted modelling practices (Barnett, et al., 2012).
6	Model water mass balance correlates to conceptual model.	Mass balance inputs and outputs must correlate to the conceptual model e.g., flows across model boundaries, recharge, etc.

6.5.3 Initial Estimates of Model Parameters

Initial model aquifer parameters are based on the aquifer test data. These parameters are then altered during the calibration process to minimize the error between observed and simulated water levels.

6.5.3.1. Hydraulic Conductivity

The average hydraulic conductivity derived from the transmissivity values were used as the initial values. Table 6.7 lists the initial values used for each zone and dykes were assigned a hydraulic conductivity of 2 m/d. The delineation of the hydraulic conductivity zones related to the geology is shown in Figure 6.11.

Table 6.7: Horizonal hydraulic conductivities

Description					K_h (m/d)
	TSF				0.0008
Zone 1	Zone 2	Zone 3	dyke	Zone 4	0.03, 0.20, 0.10, 0.07
Fractured Aquifer				Fractured Aquifer	0.001

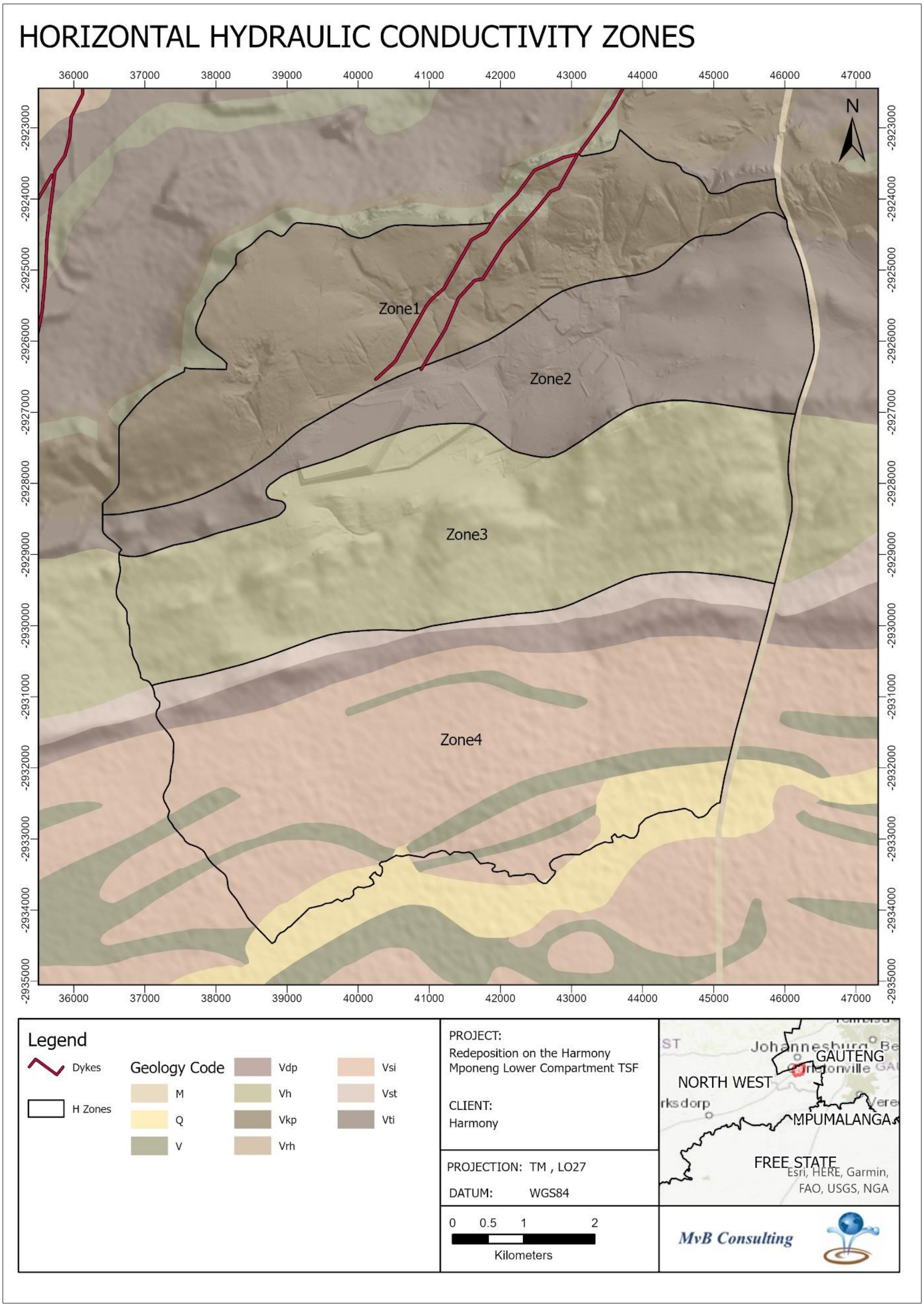

Figure 6.11:Hydraulic conductivity zones

6.5.4 Recharge Rates

The average recharge rate (25.88 mm/a) derived from the available recharge values were used as the initial regional value, including the recharge on the TSF.

6.5.5 Parameter Challenges

During model calibration several challenges exist which are outlined in the sections that follow. The available data in the context of the model domain results in an under-determined model and the conceptualisation explicitly attempted to keep the complexity of the model low.

6.5.5.1. Identifiability and non-uniqueness

One challenge in model calibration is commonly described as the non-uniqueness problem; the possibility that multiple combinations of parameters may be equally good at fitting historical measurements. Model parameters can be non-identifiable or non-unique if the mathematical equations that describe a situation of interest depend on parameters in combination, rather than individually, in such a way that the product or ratio of parameters may be identifiable, but not the individual parameters themselves (Barnett, et al., 2012).

6.5.5.2. Over-determined and under-determined systems

Another challenge relates to the number of available measurements and the number of parameters to be estimated, or more precisely, the amount of information contained in measurements and the effective number of parameters to be estimated. Groundwater flow models, however, are often under-determined, for example, when hydraulic conductivity and other hydrogeological properties vary from point to point, at very small spatial scales, leading to a very large number of unknown model parameters relative to the likely number of measurements (Barnett, et al., 2012).

6.5.5.3. Parsimony versus highly parameterised models

The modeller should find a balance between simplicity (parsimony) and complexity (highly parameterised spatial distribution of some properties). Non-uniqueness should be managed by reducing the number of parameters or by regularisation, which is a way of ensuring that parameter estimates do not move far from initial estimates that are considered to be reasonable (Barnett, et al., 2012).

6.5.6 Calibration Results

6.5.6.1. Steady State

The steady state water level calibration result is shown in Figure 6.12 with the calibration metrics. The calibration is deemed sufficient to comply with a Class 2 confidence model considering the simplicity and extent of the model. To reduce the minimum and maximum residuals, the conceptual model would have to be refined which in turn would require more data.

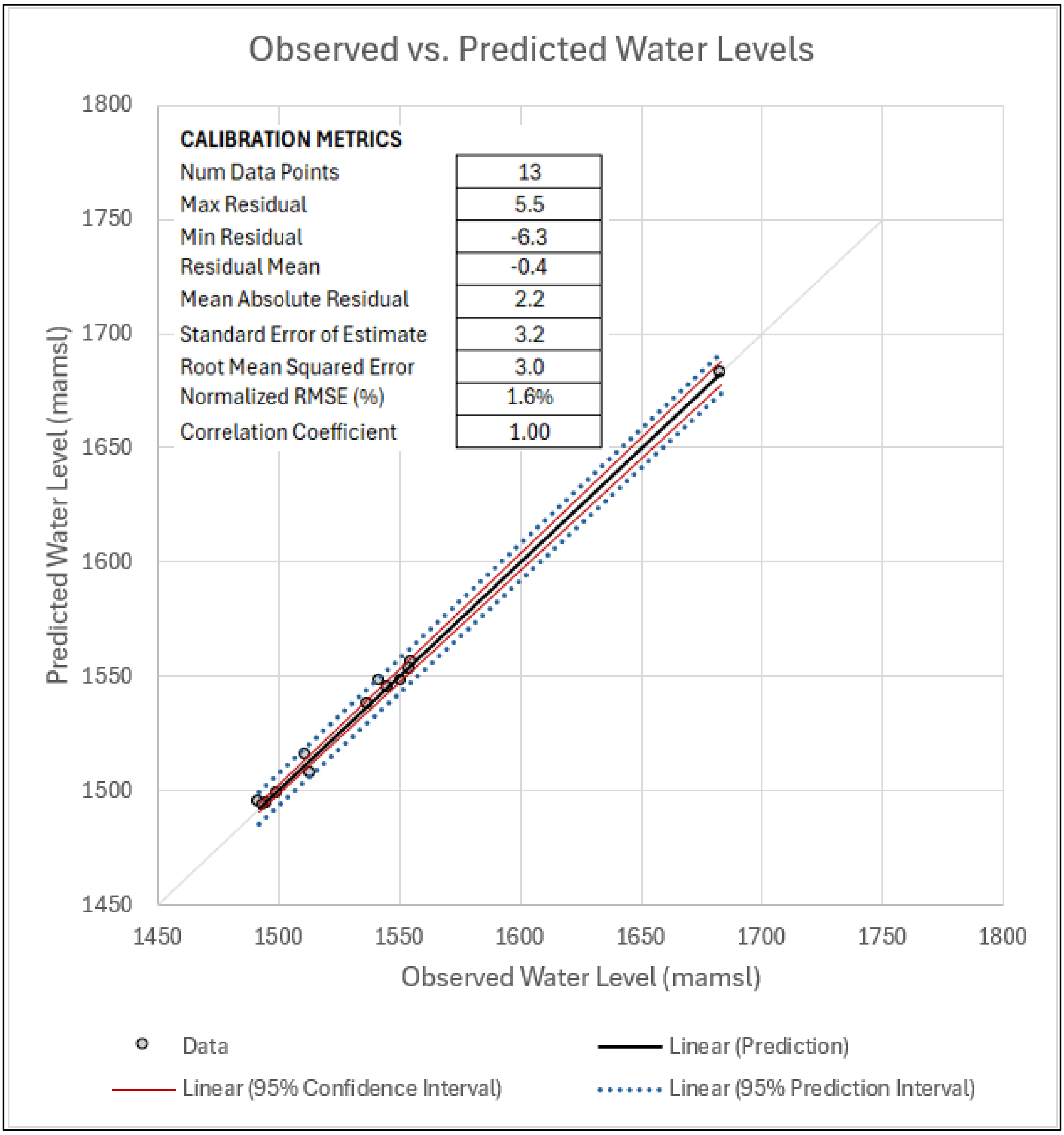

Figure 6.12: Steady state calibration

A summary of the steady state calibration parameters are presented in Table 6.8 and Table 6.9. It should be noted that the hydraulic conductivities presented in Table 6.8 represent the horizontal hydraulic conductivities. It is assumed that the vertical anisotropy (K_h/K_v) with respect to the hydraulic conductivity is equal to 10. Calibration was done on a fixed drainage conductance of 12 m^2/d.

Table 6.8: Calibrated hydraulic conductivity

Description					K_h (m/d)
	TSF				0.000864
Zone 1	Zone 2	Zone 3	dyke	Zone 4	0.036, 0.21, 0.19, 0.07
Fractured Aquifer				Fractured Aquifer	0.0012

Table 6.9: Calibrated recharge rates

Recharge Zone	Rate (m/d)
Regional	0.0000655
Upper TSF	0.0000527
Lower TSF	0.0000305

The regional water balance of the calibration is presented in Table 6.10 and with a total error of -0.127% which is also well within the acceptance criteria.

Table 6.10: Steady state mass balance

Feature	Inflows *(m^3/d)*	Outflows *(m^3/d)*
Recharge	5 397	0
Constant Head	34	-189
Head Dependant Boundary	0.2	0
Drains	0	-5 248
Total	5 431	-5 438
Percent Error (Difference)	-0.127%	

6.5.6.2. Transient State

The transient state of the model is running in annual time steps to simulate the evolution of the TSF over the LOM (1989 – 2060) and the only water level observation data used in the calibration is from 2019 to 2023 (Figure 6.5). The water level calibration is presented in Figure 6.13 and the associated storage coefficients are summarized in Table 6.11.

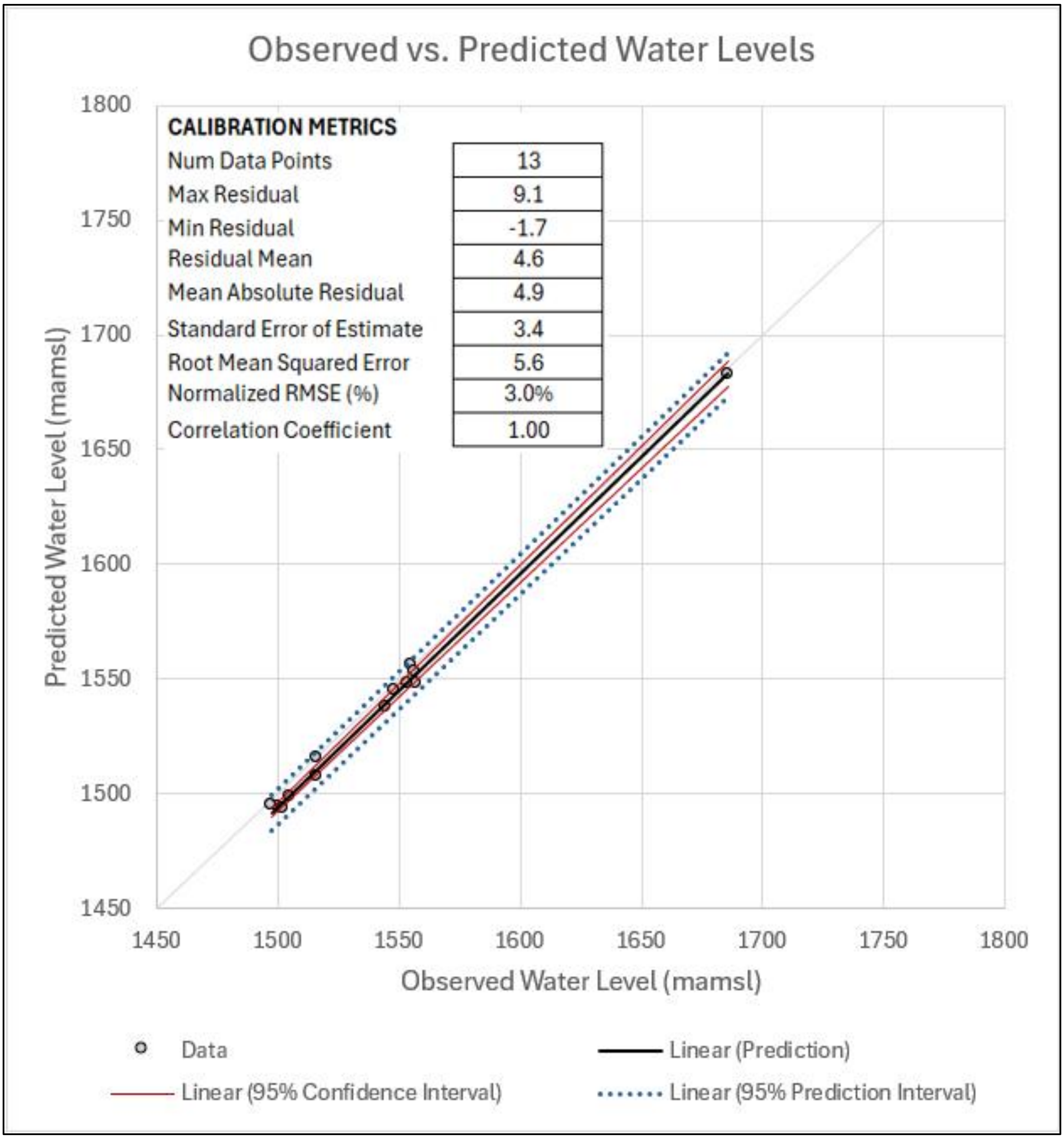

Figure 6.13: Transient state water level calibration

Table 6.11: Storage coefficients

Description					S_s (1/m)	Sy
	TSF				1.0e-006	0.2
Zone 1	Zone 2	Zone 3	dyke	Zone 4	1.0e-7 to 1.0e-6	-
Fractured Aquifer			dyke	Fractured Aquifer	1.0e-6	-

The calibration of the sulphate values focused on the most recent data due to the variability in the monitored concentrations in certain boreholes as shown in Figure 6.14.

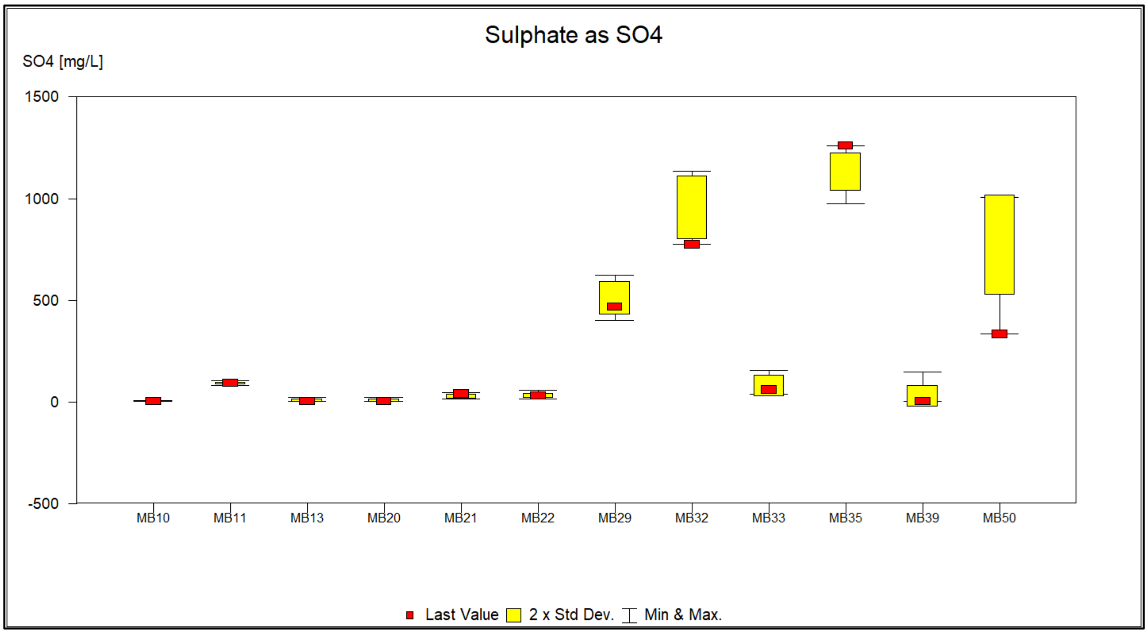

Figure 6.14: Variability in SO_4 concentrations

The calibration result of all available sulphate concentrations is presented in Figure 6.15 and only the recent data calibration is shown in Figure 6.16. To achieve better calibration more site-specific details would be required to inform the model. The purpose of this model is to establish a baseline for the status quo and see how the additional disposal will alter the baseline, and the presented concentration calibration is deemed sufficient for this purpose

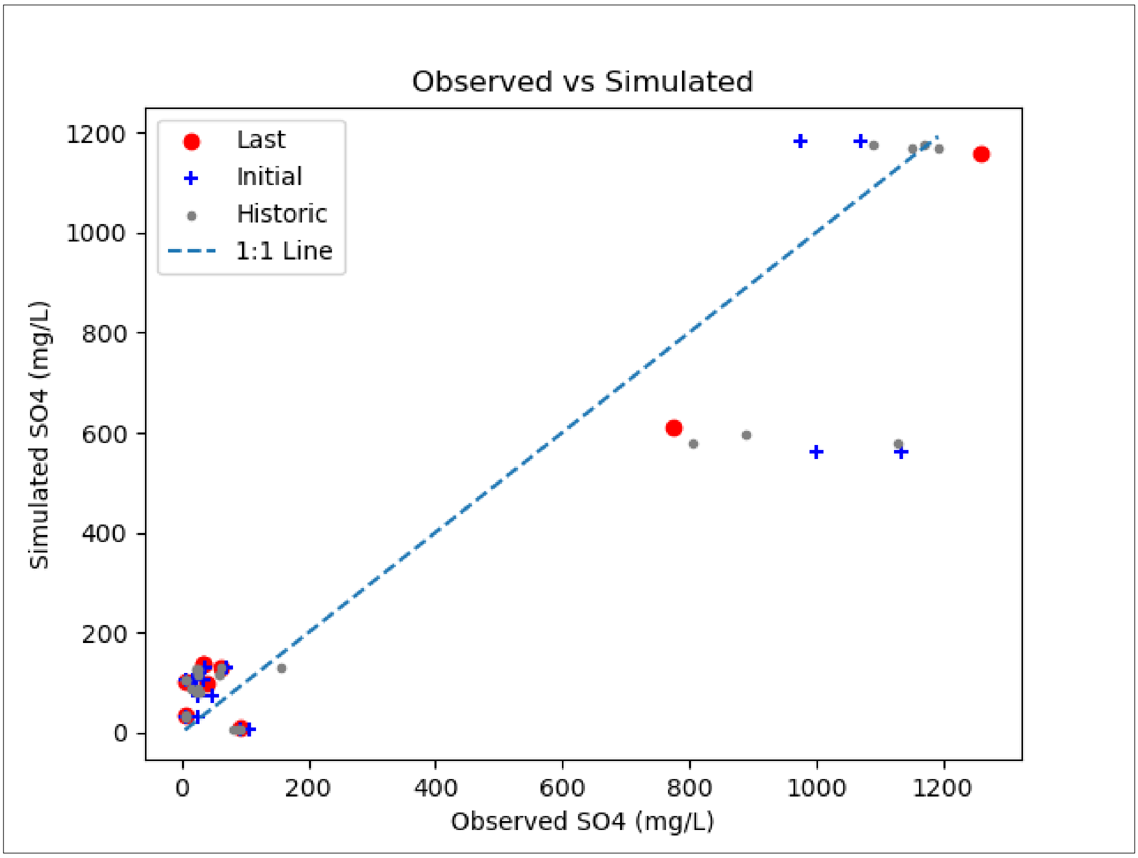

Figure 6.15:SO_4 calibration (all data)

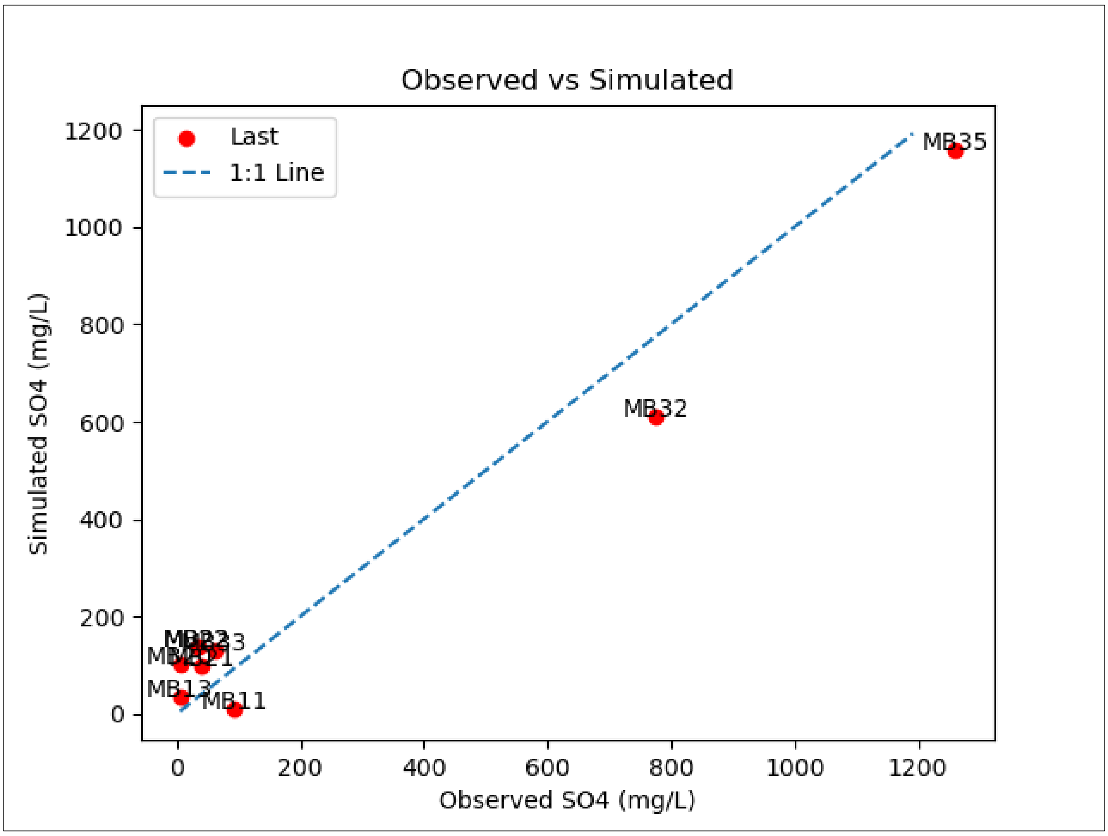

Figure 6.16: SO_4 calibration (latest data)

As part of the calibration process the maximum SO4 source term concentration was modified until the best fit was obtained. The SO_4 source term used is shown in Figure 6.17.

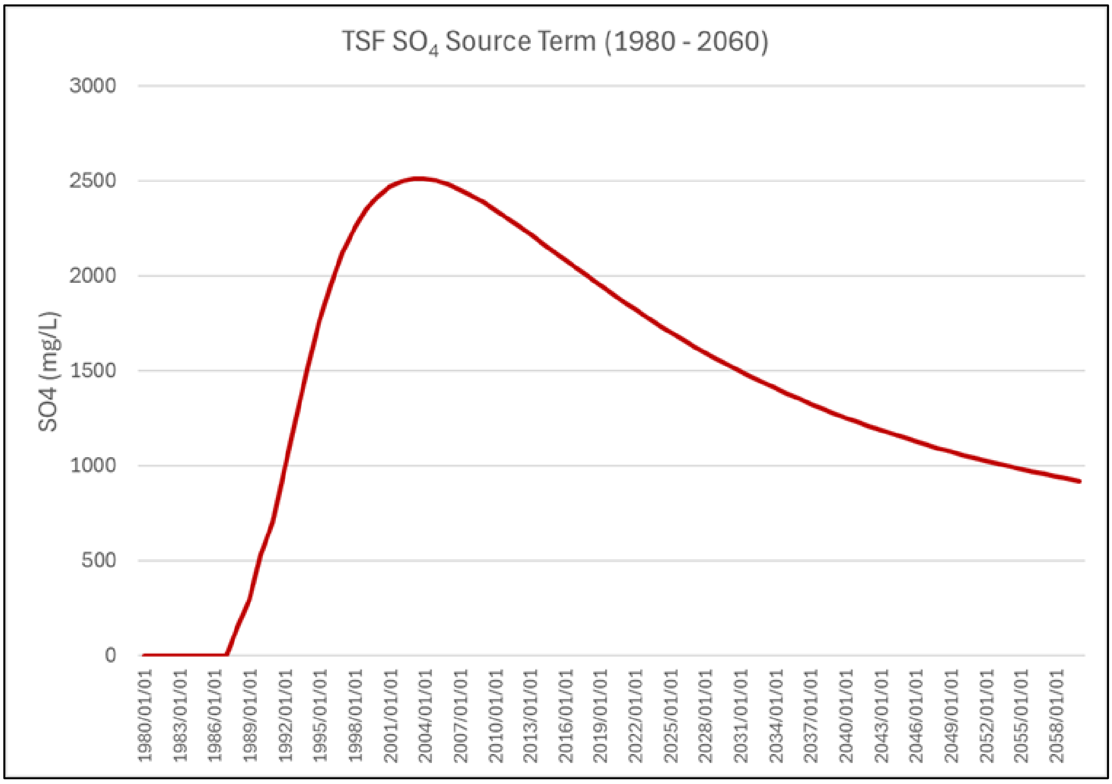

Figure 6.17:SO_4 source term

The seepage rates presented in Table 6.12 for the upper and lower TSF was used as part of the source term modelling and data was adopted from the 2019 TSF study (GCS, Groundwater Assessment for the Mponeng TSF, 2019).

Table 6.12: TSF seepage rates over LOM

TSF Seepage Rates (mm/a)			
Date	Upper TSF	Proposed Lower TSF	Status Quo Lower TSF
1980-01-01	23.9	23.9	23.9
1989-01-01	19.2	11.3	11.3
2010-01-01	19.2	11.3	11.3
2025-01-01	19.2	11.3	11.3
2030-01-01	20.5	15.4	11.3
2035-01-01	22.3	18.8	11.3
2040-01-01	24.2	22.2	11.3
2045-01-01	26.0	25.6	11.3
2050-01-01	27.9	29.1	11.3
2055-01-01	29.7	32.5	11.3
2060-01-01	32.1	35.3	11.3

The plume calibration for 2023 is presented in Figure 6.18: SO_4 plume calibration (2023).

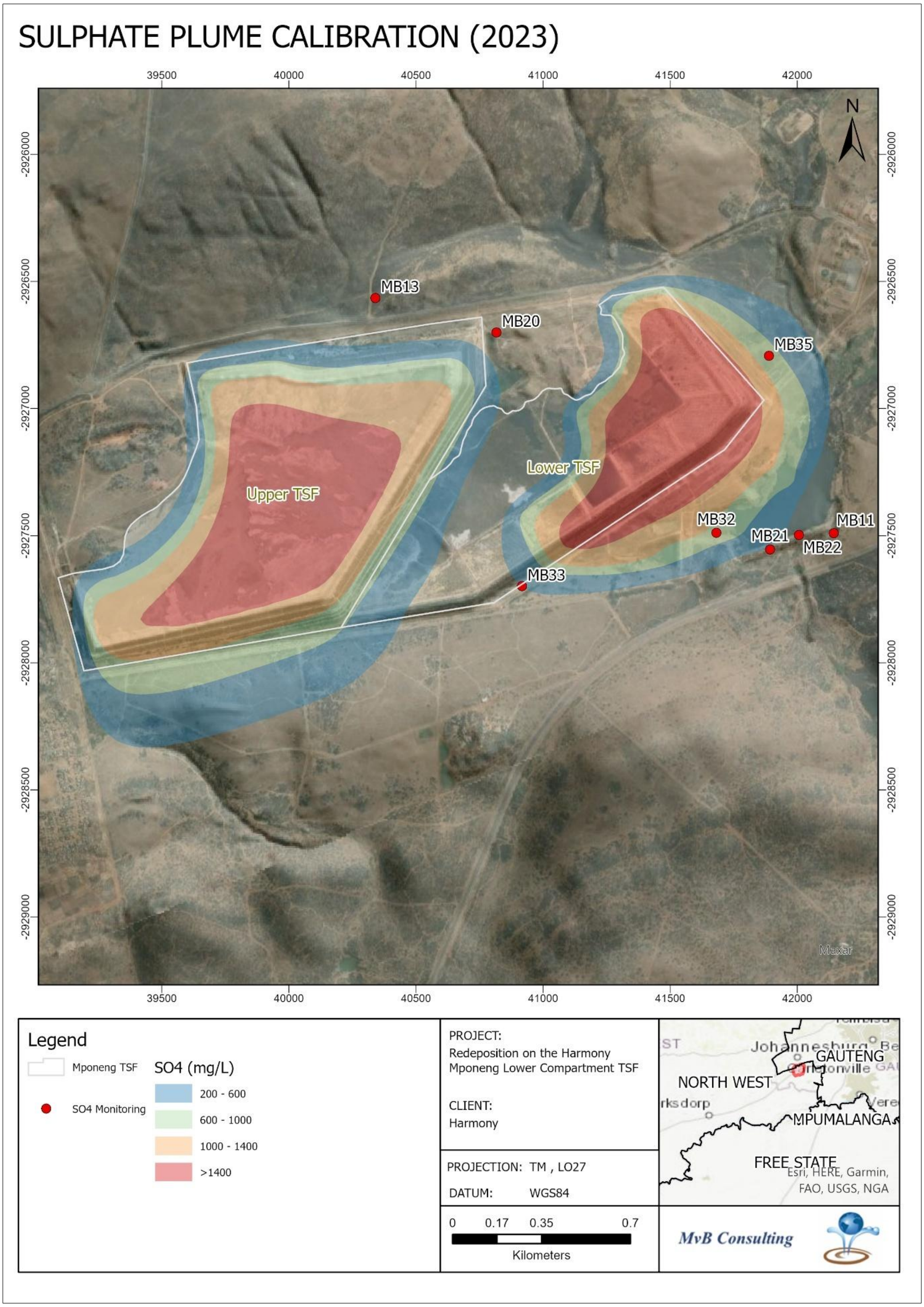

Figure 6.18:SO_4 plume calibration (2023)

6.5.7 Sensitivity Analysis

Sensitivity analysis should be performed to compare model outputs with different sets of reasonable parameter estimates. In strict mathematical terms, a sensitivity measures how fast one quantity changes when another changes. A sensitivity is the derivative, or slope, of a function.

Model sensitivity is a function of groundwater response to changes in model inputs, such as groundwater recharge and aquifer hydraulic properties. The results of the sensitivity analysis are presented in Figure 6.19.

The Timeball Hill Quartzites (Zone 1) hydraulic conductivity is the most sensitive with the Timeball Hill Shales (Zone 2) and the Hekpoort Andesite (Zone 3) very similar in sensitivity. Regional recharge is the most sensitive parameter of all the recharge zones.

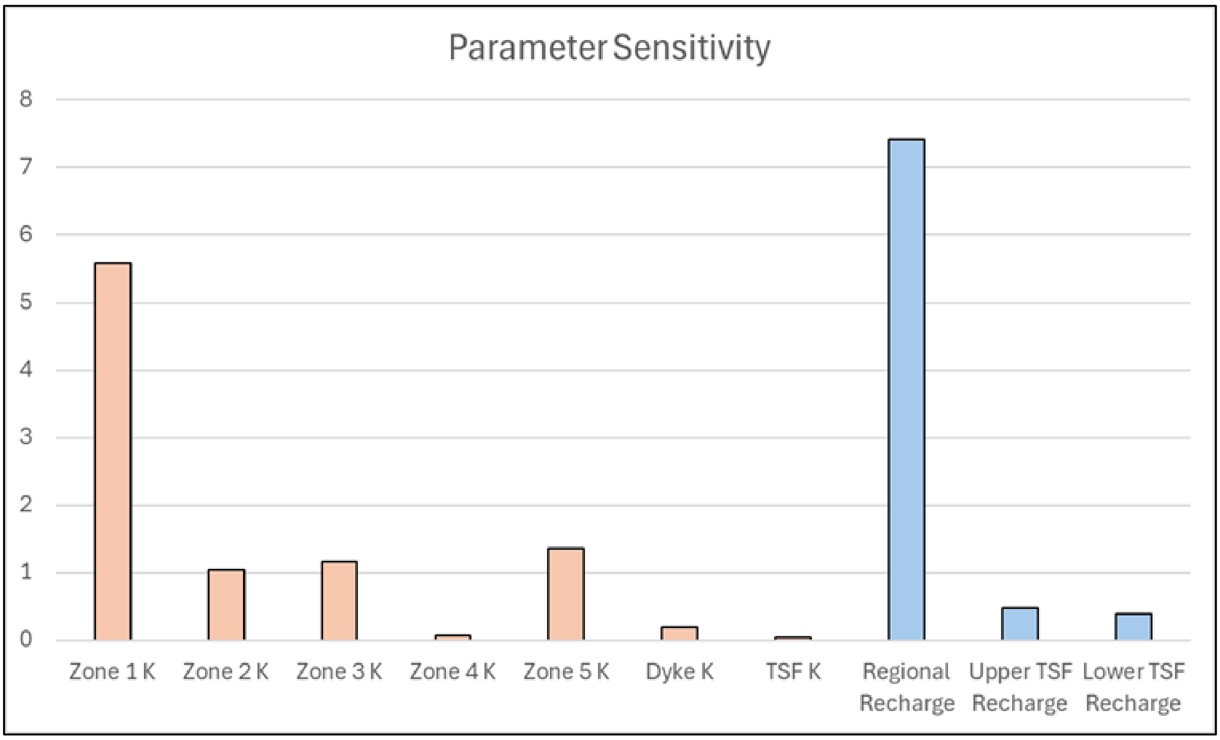

Figure 6.19: Parameter sensitivity

When refining input parameter estimates, it is important to focus on the parameters with higher sensitivities as they will have a larger impact on the groundwater response.

7. HYDROGEOLOGICAL IMPACT ASSESSMENT

This report considers four scenarios as outlined in the model objectives:

1. No mitigation measures.
2. A liner between the existing lower compartment and the proposed new tailings deposition.
3. Plume containment through scavenger wells.
4. Plume containment through tree plantations.

It is assumed that all mitigation measures start at the end of 2025 and is 100% effective on commencement.

7.1 Scenario 1 – No mitigation

In this scenario, the lower compartment TSF will be raised to a total of 60m, and no mitigation measures are implemented. The 2060 result is presented in Figure 7.1 and plume movement is in a south easterly direction towards the Elandsfontein Spruit.

7.2 Scenario 2 – TSF Liner

Gold tailings are generally classified as Type 3 waste under the NEMWA Regulations 2013, necessitating a Class C containment barrier. This single composite barrier system includes underdrainage, a base preparation layer, a 300mm thick compacted clay liner (CCL), a 1.5mm thick geomembrane, a dual-purpose ballast and protection layer at least 100mm thick, and an above-liner drainage system. The barrier's effectiveness depends significantly on design specifications and Construction Quality Assurance (CQA). The presence and extent of wrinkles affect containment performance, with an anticipated seepage rate of approximately 140 litres per hectare per day.

The 140 litres per hectare per day translate to approximately 5 mm/a which is significantly lower than the seepage rates specified for the TSF source term (Table 6.12). The Class C containment barrier can reduce the contaminant with 95% when installed correctly. The scenario result is presented in Figure 7.2 and it is clear that a significant attenuation of the high concentration SO_4 is achieved. Having said that, the plume footprint in 2060 does not differ much from the no liner scenario.

7.3 Scenario 3 – No TSF liner with scavenger wells

The results for the scenario where no liner is installed, but scavenger wells are introduced as a mitigation measure is presented in Figure 7.3. This scenario features 9 scavenger wells positioned along the southern and eastern side of the TSF to intercept the plume. All nine wells are operating at 2 L/s and are continuously running.

This option is successful in containing the contamination, but the footprint area is not much smaller than the no-liner option.

7.4 Scenario 4 – No TSF liner with tree plantations

In this scenario 44 hectares is planted with trees and each hectare has roughly 1300 trees with an optimal water use of 5 l/d per tree. It was further assumed that the maximum root depth is 8m, so when the water level drops below the root depth, evapotranspiration is terminated. The result of this scenario is presented in Figure 7.4.

The plume is somewhat reduced on the eastern side, when compared to the no liner scenario which is considered the baseline for comparison. A significant reduction in the plume extent is visible in the southwest corner of the TSF.

A comparison between the different scenarios, showing its effectiveness, is presented in Table 7.1.

Table 7.1: Comparison of the effectiveness of each remedial option (2060)

Remedial Option	600 mg/L SO_4 Impact Area (m_2)	Improvement (Compared to Do-Nothing Option) (m_2)
Current Impact Area	2 049 823	-
Do-Nothing Scenario after 35 Years	2 843 514	-
Lower Compartment TSF (Lined)	1 720 106	1 123 408 (39.5%)
Scavenger Boreholes	2 638 597	204 917 (7.2 %)
Evapo-Transpiration (Phytoremediation)	1 767 158	1 076 356 (37.9%)

It is evident that lining the Mponeng Lower Compartment TSF is the best option. The benefit is, however, minimal when comparing it to the phytoremediation option, which is a much more cost-effective option. This option is therefore recommended as a suitable management option.

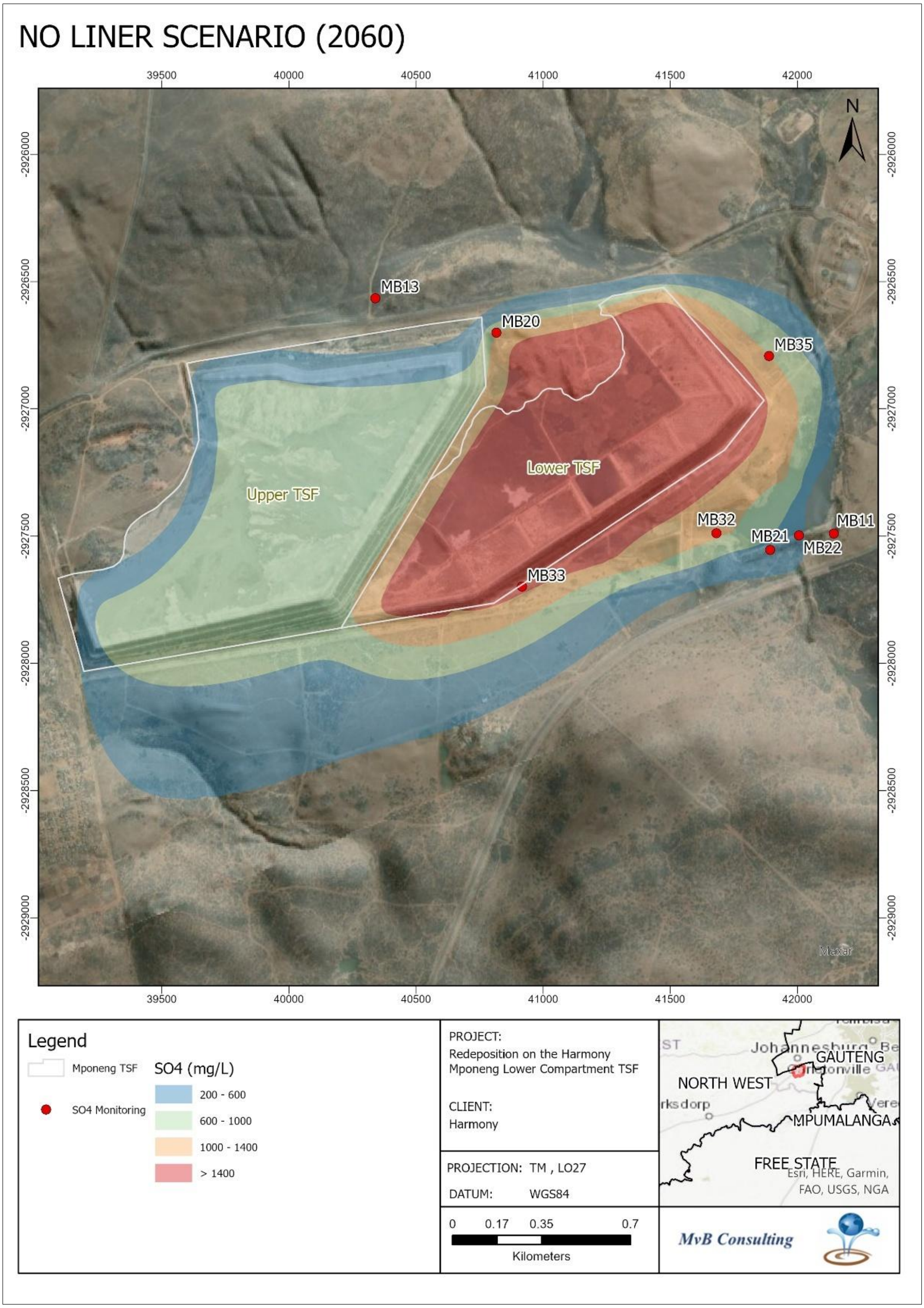

Figure 7.1:Scenario 1 - No mitigation (2060)

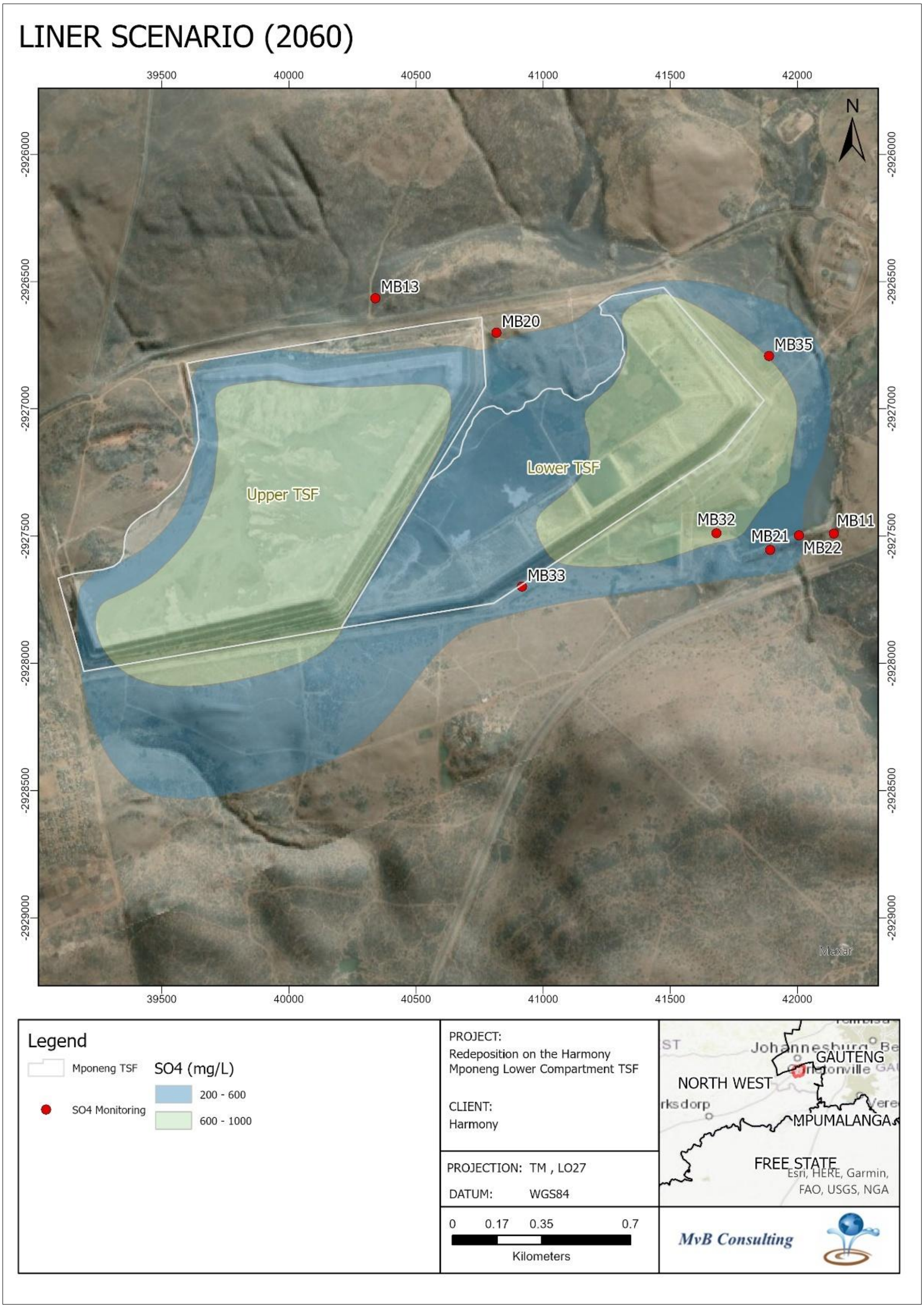

Figure 7.2:Scenario 2 – Liner installed (2060)

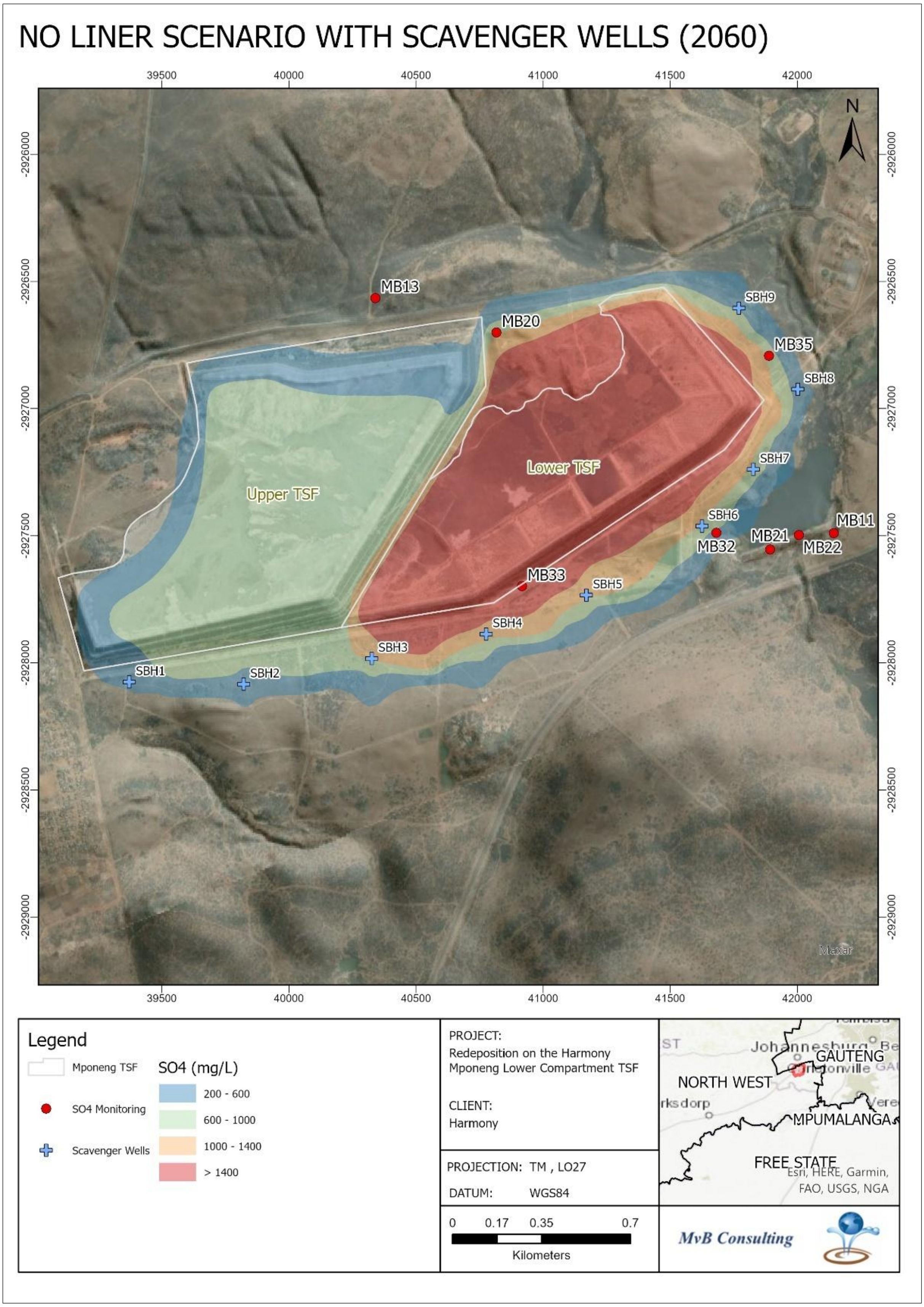

Figure 7.3:Scenario 3 – No Liner with scavenger wells (2060)

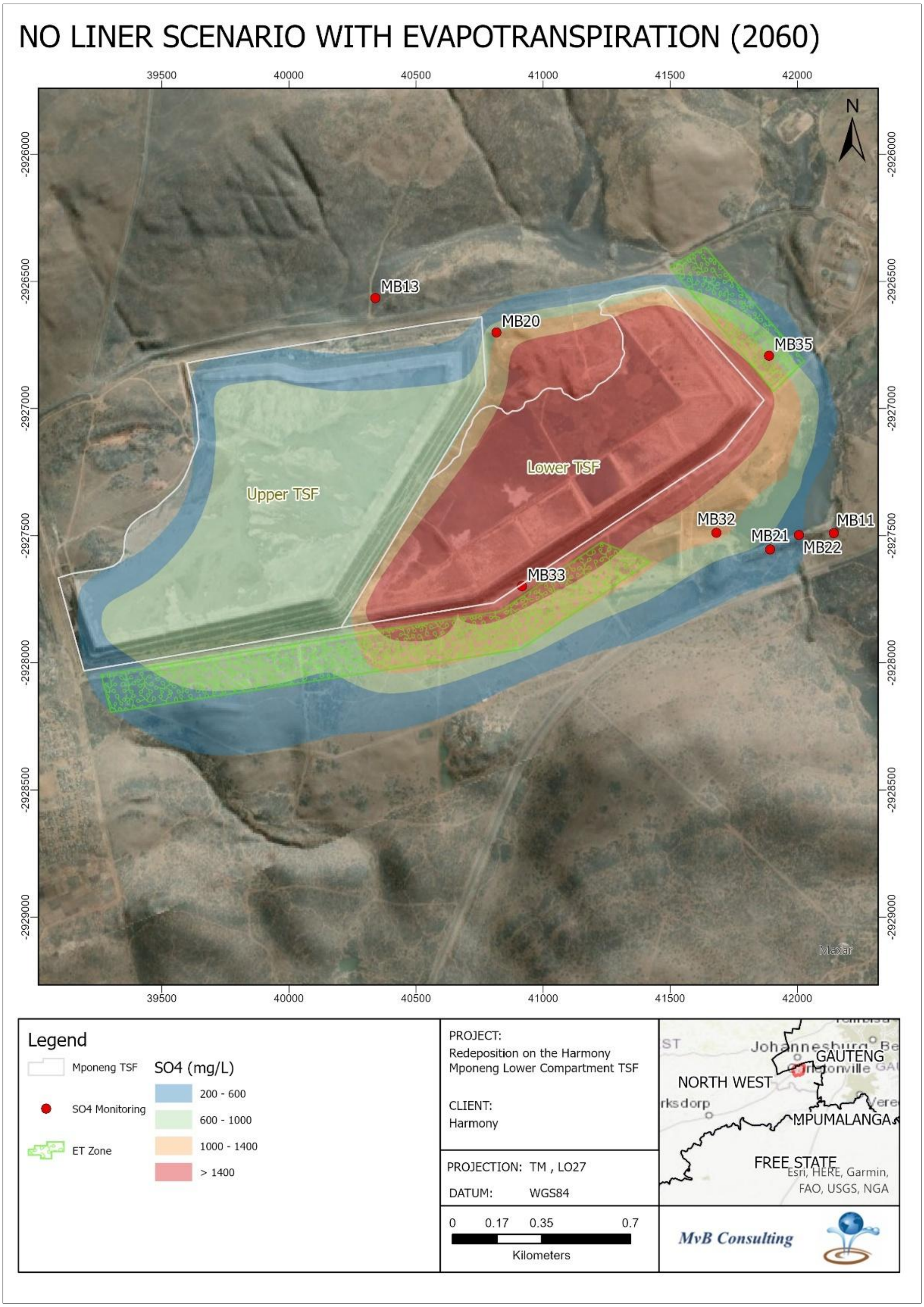

Figure 7.4: Scenario 4 – No liner installed with evapotranspiration measures (2060)

7.5 Model Limitations

The numerical groundwater model is based on the layered conceptual model presented, which was derived from the review of the information provided.

For the model setup, the following typically needs to be described:

- Geological and hydrogeological features.
- Boundary conditions of the study area (based on the geology and hydrogeology).
- Initial water 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/hydrogeological information was used to describe the different aquifers.
- The available information on the geology and field measurements is considered as correct.
- Due to the lack long term monitoring data only a period of a five years was used to describe the initial conditions of the steady state model.
- The general water level trend in the project area is assumed to be correct.
- The pumping tests are representative of the specific geological formation they target and these results can be considered representative of the whole formation.

In order to develop a model of the aquifer system, certain assumptions had to be made. These include:

- The system is initially in equilibrium and therefore in steady state, even though natural conditions could have been disturbed.
- It is assumed no pumping was taking place during the steady state calibration.
- The boundary conditions assigned to the model are considered correct.
- The impacts of other activities (e.g. agriculture) have not been taken into account.
- Although MODFLOW is a porous flow model, the fractured rock aquifers can be modelled as equivalent porous media for the scale considered in the model.
- 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.

7.6 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.

7.6.1 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 7.2 below.

Table 7.2: 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 7.3.

Table 7.3: 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:

$$ER = C \ x \ P$$

Table 7.4: 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 7.5.

Table 7.5: 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.

7.6.2 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 7.6: 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 7.7. The impact priority is therefore determined as follows:

$$\boldsymbol{Priority = CI + LR}$$

The result is a priority score which ranges from 2 to 6 and a consequent PF ranging from 1 to 2 (refer to Table 7.7).

Table 7.7: 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 7.8: 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.

7.6.3 Impact Assessment Result

The geohydrological impact assessment for the Mponeng Lower Compartment TSF is presented in Table 7.9. With reference to Table 7.9 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 (Elandsfontein Spruit).

The following mitigation measures were included in the assessment:

- For the “do-nothing” option (Identifier 1 in the table below) the Mponeng Lower Compartment TSF remains unlined. The only mitigation is the rehabilitation and decommissioning of the TSF during the closure (decommissioning) phase.
- For Identifier 2 in the table below, the Mponeng Lower Compartment TSF will be lined. This option will change the risk from High Negative to Low Negative during the operational and closure phases. This option has the best rating.
- For identifier 3 in the table below the drilling of scavenger boreholes were considered. This option will change the risk from High Negative to Low Negative during the operational and closure phases. This option has the lowest rating due to the maintenance requirements for scavenger boreholes.
- For Identifier 4 in the table below, the Mponeng Lower Compartment TSF will remain unlined, but the proposed phyto-remediation will be fully functional. This option will change the risk from High Negative to Low Negative during the operational and closure phases. This option has lower rating than a liner, but a better rating than the scavenger boreholes and is the recommended long-term management option.

Table 7.9: Mponeng Lower Compartment 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 MLC TSF (Unlined)	Alternative 1	Operation	-1	4	4	4	4	4	-16	-1	4	4	4	4	4	-16	Medium	2	2	1.25	-20
2	Groundwater contamination from MLC TSF (Lined)	Alternative 1	Operation	-1	4	4	4	4	4	-16	-1	1	3	2	2	3	-6	Medium	2	2	1.25	-7.5
3	Groundwater contamination from MLC TSF (Scavenger BH's)	Alternative 1	Operation	-1	4	4	4	4	4	-16	-1	3	3	2	2	3	-7.5	Medium	2	2	1.25	-9.375
4	Groundwater contamination from MLC TSF (Phyto-Remediation)	Alternative 1	Operation	-1	4	4	4	4	4	-16	-1	2	3	2	2	3	-6.75	Medium	1	1	1.00	-6.75
1	Groundwater contamination from MLC TSF (Unlined)	Alternative 1	Decommissioning	-1	4	4	4	4	4	-16	-1	4	4	4	4	4	-16	Medium	2	2	1.25	-20
2	Groundwater contamination from MLC TSF (Lined)	Alternative 1	Decommissioning	-1	4	4	4	4	4	-16	-1	1	3	2	2	3	-6	Medium	2	2	1.25	-7.5
3	Groundwater contamination from MLC TSF (Scavenger BH's)	Alternative 1	Decommissioning	-1	4	4	4	4	4	-16	-1	3	3	2	2	3	-7.5	Medium	2	2	1.25	-9.375
4	Groundwater contamination from MLC TSF (Phyto-Remediation)	Alternative 1	Decommissioning	-1	4	4	4	4	4	-16	-1	2	3	2	2	3	-6.75	Medium	2	2	1.25	-8.4375

8. GROUNDWATER MONITORING SYSTEM

8.1 Groundwater Monitoring Network

The exiting monitoring network is comprehensive and sufficient to quantify the impact from the Mponeng Lower Compartment TSF. No further drilling is recommended at this stage.

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.

8.2 Monitoring frequency

- 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.

8.3 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).

9. SUMMARY AND CONCLUSIONS

9.1 Study Objectives

Harmony Gold Mining Limited (Harmony) owns and operates a number of Gold Mines and Plants in the West Wits region in the Gauteng Province. The Savuka Plant currently deposits tailings onto the Savuka 5a, 5b, 7a & 7b TSFs. However, these facilities are approaching their final and approved height, and the current planned Life of Mine (LOM) for the West Wits region exceeds the available deposition capacity of these TSFs. Accordingly, Harmony is undertaking a feasibility assessment to recommence deposition on the Mponeng Lower Compartment TSF.

Mponeng Lower Compartment TSF is an existing TSF, however, the Mponeng Lower Compartment TSF is no longer in operation and is currently utilised as a Holding Dam, and a portion of it is used as an authorised Landfill Facility.

The purpose of the study is to assess the potential impact from the Mponeng Lower Compartment TSF 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 Mponeng Lower Compartment TSF with the additional deposition.
- Effectiveness of proposed remedial options.

9.2 Geohydrological Conceptual Setting

Groundwater occurrences in the study area are predominantly restricted to the following types of terrains:

- Weathered and fractured rock aquifer in the Ventersdorp and Transvaal Formations.
- Dolomitic and Karst Aquifers.

Groundwater occurrences in the study area are predominantly restricted to the following types of terrains.

- Weathered and fractured rock aquifer in the Transvaal Formations.
- Dolomitic and Karst Aquifers.

Although the dolomite aquifer is the most prominent aquifer in the region, it does not play any role in the activities at the Mponeng Lower Compartment TSF. The Mponeng Lower Compartment TSF is predominantly located on the shale of the Timeball Hill formation. The dolomite is ±400m below surface at the Mponeng TSF site. Evidence has shown that there is no connectivity between the weathered / fractured aquifer and the underlying dolomite aquifer. Even in compartments where the dolomite aquifer is dewatered the groundwater levels in the weathered / fractured aquifer remains unaffected.

- ***Weathered and Fractured Aquifer:*** Groundwater occurs in the near-surface geology in the weathered and fractured sedimentary deposits (quartzite and shale) of the Transvaal strata. The lava of the Hekpoort Formation has similar weathering characteristics to that of the shale and is therefore deemed as the same aquifer. These formations are not considered to contain economic and sustainable aquifers, but localised high yielding boreholes may, however, exist where significant fractures are intersected. Groundwater occurrences are mainly restricted to the weathered formations, although fracturing in the underlying "fresh" bedrock may also contain water. The groundwater table is affected by seasonal and atmospheric variations and generally mimics the topography. These aquifers are classified as semi-confined. The two aquifers (weathered and fractured) are mostly hydraulically connected, but confining layers such as clay and shale often separate the two. The aquifer parameters, which includes transmissivity and storativity is generally low and groundwater movement through this aquifer is therefore also slow.

- ***Dolomite Aquifer:*** Dolomite aquifers in the region are known to contain large quantities of groundwater. The unsaturated zone in the dolomite aquifer ranges from weathered wad material and Karoo sediments within deep solution cavities or grykes (deeply weathered paleo-valley within the dolomite) to relatively fresh fractured dolomite between major solution cavities and at depth. The shallow weathered dolomite aquifer has been formed because of the karstification which has taken place prior to the deposition of the Karoo sediments on top of the dolomites. There is general agreement that this aquifer is the significant source of water within the dolomite. The base of the weathered dolomite (aquifer) is irregular in nature and there are zones of deep weathering (grykes). The maximum depth to the base of this aquifer is in the order of 200 m below surface. The non-weathered dolomite approximates a traditional fractured rock aquifer at depth where dissolution has been less pronounced. It is extremely unlikely that any significant groundwater flow occurs below these depths except along intersecting structural conduits to the underlying mine workings.

Rainfall in the region is approximately 646 mm/annum and recharge to the aquifer is estimated at 3.9% of the annual rainfall.

The groundwater mimics the topography and the groundwater flow in the study area is perpendicular to the groundwater contours and flows predominantly towards the south-east.

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

- Monitoring boreholes MB29 and MB50 in the plant area show an impact. This is, however, not applicable to the current investigation.
- Monitoring boreholes MB32 and MB35 show an impact from the up-gradient Mponeng TSF. This is in line with the expected groundwater flow paths.
- The groundwater flow is towards the Return Water Dams (RWD), but borehole BH35 shows that the impacted water passes underneath the RWD. The impact is therefore expected to flow into the Aquatic Dam, or it will form part of the baseflow of the Elandsfonteinspruit. The relatively good water quality in the Aquatic Dam suggests that the impacted groundwater forms part of the baseflow of the stream.

9.3 Groundwater Modelling and Impact Assessment

The conceptual geohydrological model 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:

- Plume migration without any mitigation measures.
- Placement of a liner between the existing lower compartment and the proposed new tailings deposition.

- Plume containment through scavenger wells.
- Plume containment through tree plantations (phyto-remediation).

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

- The top of the aquifer is represented by the generated groundwater heads
- The available geological/hydrogeological information was used to describe the different aquifers.
- The available information on the geology and field measurements is considered as correct.
- Due to the lack long term monitoring data only a period of a five years was used to describe the initial conditions of the steady state model.
- The general water level trend in the project area is assumed to be correct.
- The pumping tests are representative of the specific geological formation they target and these results can be considered representative of the whole formation.

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.

To investigate the behaviour of aquifer systems in time and space, it is necessary to employ a mathematical model. MODFLOW, a modular three-dimensional finite difference groundwater flow model was chosen as the model code to be used. It is an internationally accepted modelling package, which calculates the solution of the groundwater flow equation using the finite difference approach.

The numerical model was used to simulate the effectiveness of the following management options:

- **Lining of the Mponeng Lower Compartment TSF**. The gold tailings are typically 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 ”inverted 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).

  The expected leakage rates through the “inverted barrier system” were included in the model and the impact simulated.

- **Implementation of interception (scavenger) boreholes on the down-gradient side of the TSF**. This scenario features 9 scavenger wells positioned along the southern and eastern side of the TSF to intercept the plume. All nine wells are operating at 2 L/s and are continuously running.

- **Implementation of phyto-remediation on the down-gradient side of the TSF**. In this scenario 44 hectares is planted with trees and each hectare has roughly 1300 trees with an optimal water use of 5 l/d per tree. It was further assumed that the maximum root depth is 8m.

A comparison between the different scenarios, showing its effectiveness, is presented below.

Remedial Option	600 mg/L SO_4 Impact Area (m_2)	Improvement (Compared to Do-Nothing Option) (m_2)
Current Impact Area	2 049 823	-
Do-Nothing Scenario after 35 Years	2 843 514	-
Lower Compartment TSF (Lined)	1 720 106	1 123 408 (39.5%)
Scavenger Boreholes	2 638 597	204 917 (7.2 %)
Evapo-Transpiration (Phytoremediation)	1 767 158	1 076 356 (37.9%)

It is evident that lining the Mponeng Lower Compartment TSF is the best option. The benefit is, however, minimal when comparing it to the phytoremediation option, which is a much more cost-effective option. This option is therefore recommended as a suitable management option.

10. STUDY CONCLUSION AND RECOMMENDATIONS

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 (Elandsfontein Spruit).

The following mitigation measures were included in the assessment:

- For the "do-nothing" option (Identifier 1 in the table below) the Mponeng Lower Compartment TSF remains unlined. The only mitigation is the rehabilitation and decommissioning of the TSF during the closure (decommissioning) phase.
- For Identifier 2 in the table below, the Mponeng Lower Compartment TSF will be lined. This option will change the risk from High Negative to Low Negative during the operational and closure phases. This option has the best rating.
- For identifier 3 in the table below the drilling of scavenger boreholes were considered. This option will change the risk from High Negative to Low Negative during the operational and closure phases. This option has the lowest rating due to the maintenance requirements for scavenger boreholes.
- For Identifier 4 in the table below, the Mponeng Lower Compartment TSF will remain unlined, but the proposed phyto-remediation will be fully functional. This option will change the risk from High Negative to Low Negative during the operational and closure phases. This option has lower rating than a liner, but a better rating than the scavenger boreholes and is the recommended long-term management option.

It is evident from the assessment that the phyto-remediation is effective, and it is recommended that this option be considered. The installation of a liner and / or scavenger boreholes may improve the rehabilitation of the groundwater, but it is considered unnecessary as the phyto-remediation is effective on its own.

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APPENDIX A

LABORATORY CERTIFICATES