GOLDEN CORE TRADE AND INVEST (PTY) LTD. - MPONENG OPERATIONS

GEOHYDROLOGICAL IMPACT ASSESSMENT FOR THE SAVUKA TAILINGS FACILITY, GAUTENG PROVINCE

FINAL REPORT

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1. INTRODUCTION AND TERMS OF REFERENCE

Golden Core Trade and Invest (Pty) Ltd. - Mponeng Operations (Harmony Gold) own and operate 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 7a & 7b Tailings Storage Facilities (TSFs).

Savuka 7a & 7b TSFs are approaching their final and approved height, and the current planned Life of Mine (LOM) for the West Wits region exceed the available deposition capacity of these TSFs. Accordingly, Harmony is undertaking a feasibility assessment to increase the height of the Savuka 7a & 7b TSFs, by between 5m to 10m.

The TSFs are constructed and operated through a drywall paddock system, however, it is proposed to change the deposition method to cycloning. This will lengthen the deposition timeframe up to current approved height, with cyclone deposition continuing into the height extension. No additional infrastructure is proposed as part of the height extension over and above the conversion to cyclone deposition.

Harmony appointed Environmental Impact Management Services (EIMS) to obtain all the required authorisations for the proposed Savuka TSF height increase. EIMS sub-contracted MVB Consulting to conduct a geohydrological study to assess the potential groundwater impacts associated with the project.

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

The deliverables from the study include the following:

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

2. GEOGRAPHICAL SETTING

2.1 Locality of the Study Area

The Savuka 7a & 7b TSFs are located at 26°26'11.85"S; 27°21'11.38"E, approximately 10km southwest of Carltonville in the Gauteng Province.

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

2.2 Topography and Drainage

The area is part of the Highveld region and has an average elevation of about 1 600 metres above mean sea level (mamsl). The topography changes from 1 740 mamsl on the hill, referred to as the Gatsrant, and slopes towards the Wonderfonteinspruit at 1 465 mamsl (Figure 2.3).

The Savuka TSF falls within quaternary catchment C23E and is drained by an unnamed tributary of the Wonderfonteinspruit (also referred to the Mooirivierloop). The drainage area forms part of the Vaal Water Management Area (WMA No. 5).

The surface water flow from the TSF is to the west and southwest, towards the Wonderfonteinspruit tributary.

Figure 2.1: Project locality

Figure 2.2: **Site layout**

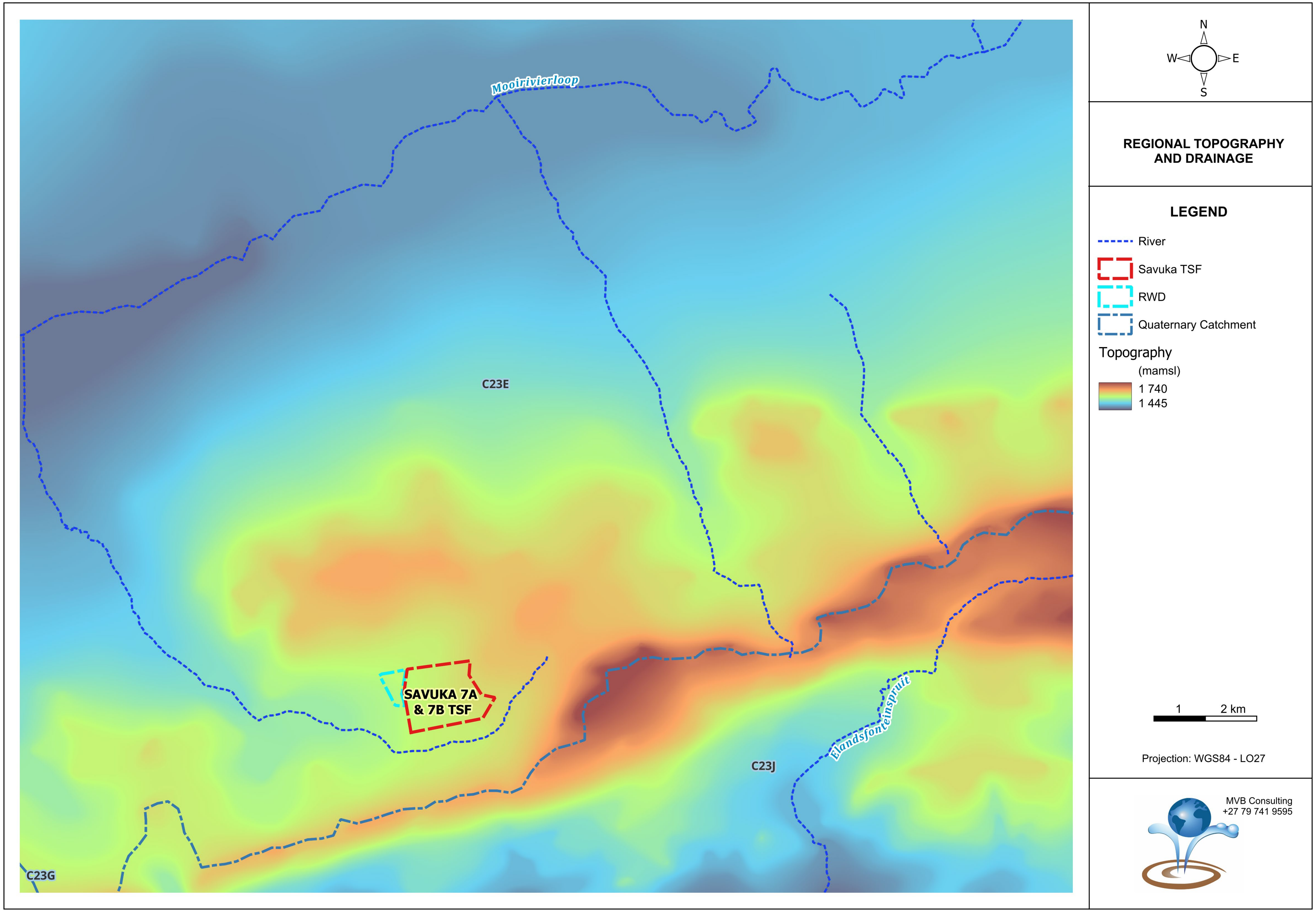

Figure 2.3: **Regional topography and drainage**

2.3 Climate and Rainfall

The area receives most of its rain in the summer months (October-April) (Agreenco, 2023). Figure 2.4 provides a summary of the annual rainfall (from FY2014 to May of FY2023) for the nearby town of Carletonville. The temperature (Figure 2.5) ranges from a mean low of 5°C in the winter months to a mean maximum of 29°C in the summer months (average over ten years) (Agreenco, 2023).

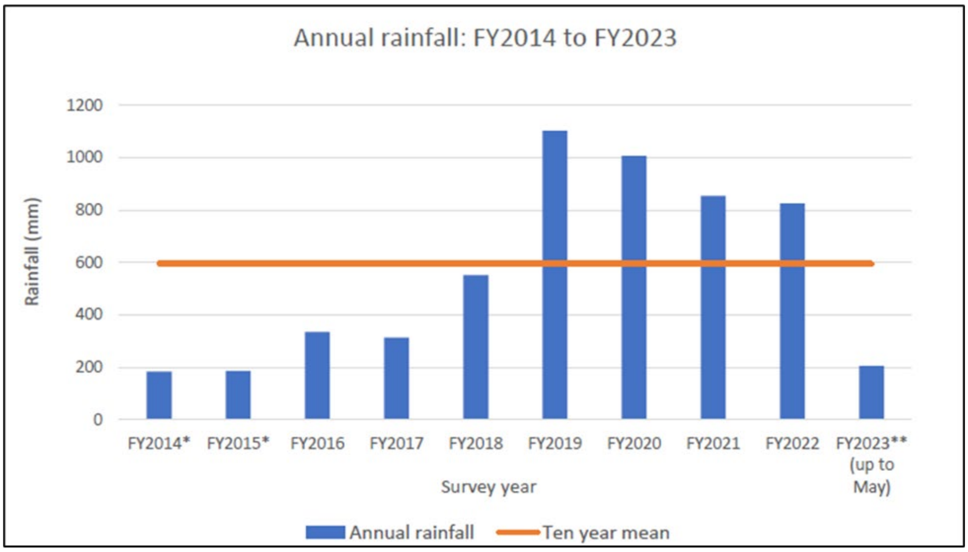

Figure 2.4: Graph showing the annual rainfall for Carletonville (*Drought conditions) (Agreenco, 2023)

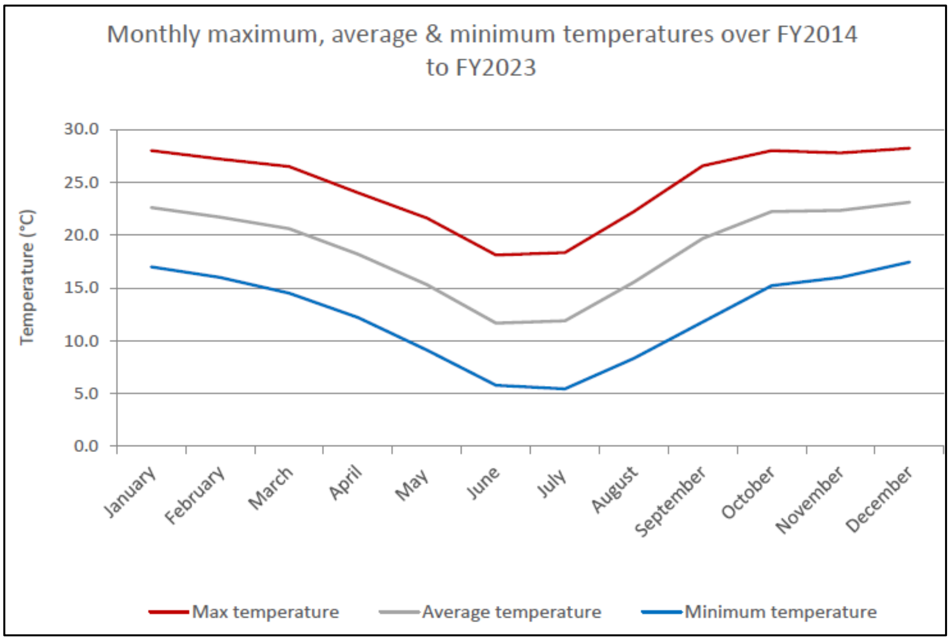

Figure 2.5: Average monthly maximum, Average monthly minimum, and Mean monthly temperatures for Carletonville (Agreenco, 2023)

The average potential mean annual gross evaporation (as measured by Class A-pan) ranges from 1 600 mm in the east to a high of 2 200 mm in the drier western parts. The highest Class A-pan monthly evaporation is in January (ranging from 180 mm to 260 mm), and the lowest evaporation is in June (80 mm to 110 mm) (DWAF, 2004).

3. CONCEPTUAL GEOHYDROLOGICAL MODEL

A description of the conceptual geohydrological 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 geohydrological setting and groundwater occurrence in the mining area.

3.1 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 3.1 and the regional surface geology is presented in Figure 3.2.

3.1.1 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.

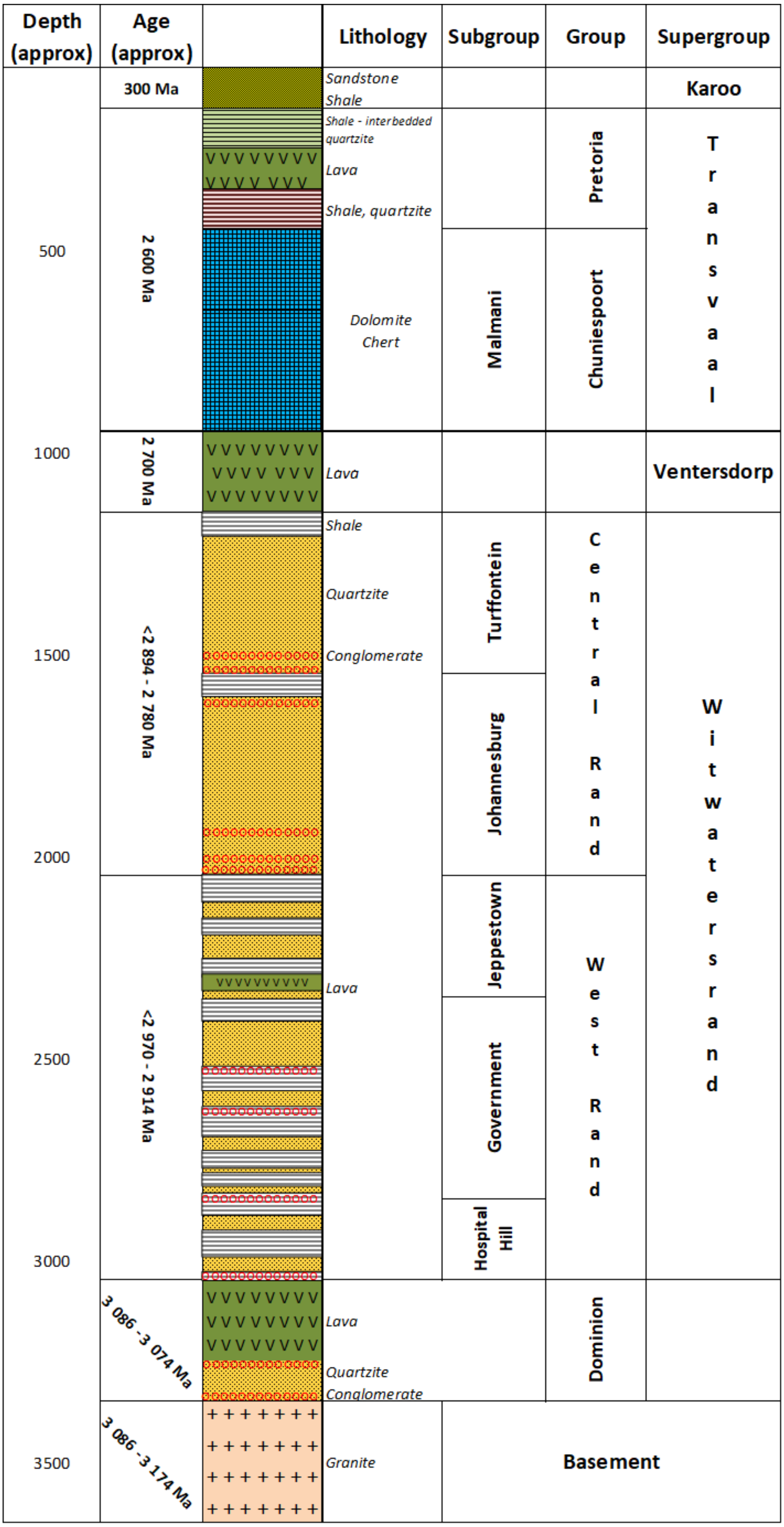

Figure 3.1: Stratigraphy of the study area (after Robb and Robb, 1998)

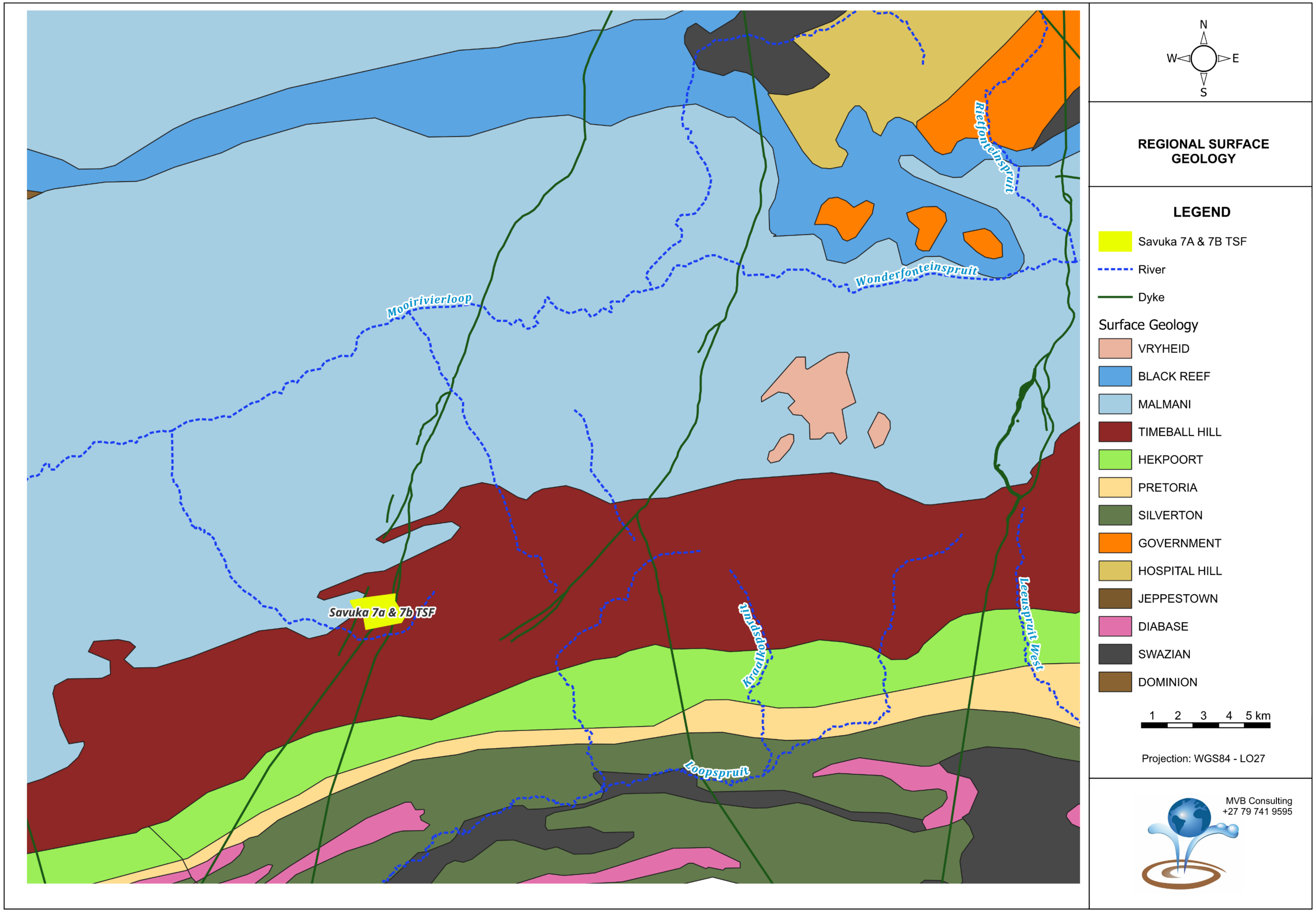

Figure 3.2: **Regional surface geology**

3.1.1 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.

3.1.2 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 dolomite hosts the primary and most significant aquifer in the study area.

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 Leeuspruit tributaries contain grey, silty to clayey soils.

3.1.3 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.

3.2 Geohydrological Setting

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

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

3.2.1 Borehole Information

There are several groundwater monitoring boreholes in the vicinity of the Savuka 7A & 7B TSFs. No private boreholes could be located within a 2km radius of the TSF.

The localities of the available boreholes are shown on Figure 3.3.

3.2.2 Aquifer Type

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

- Weathered and fractured rock aquifer in the Ventersdorp and 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 Savuka TSFs. The Savuka 7A & 7B TSF is located on the shale and sandstone of the Timeball Hill formation. The dolomite is >500m below surface at the Savuka 7A & 7B 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.

3.2.3 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.

Figure 3.3: Available boreholes in the vicinity of the Savuka TSFs

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.

3.2.4 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.

3.2.5 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 3.4 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.

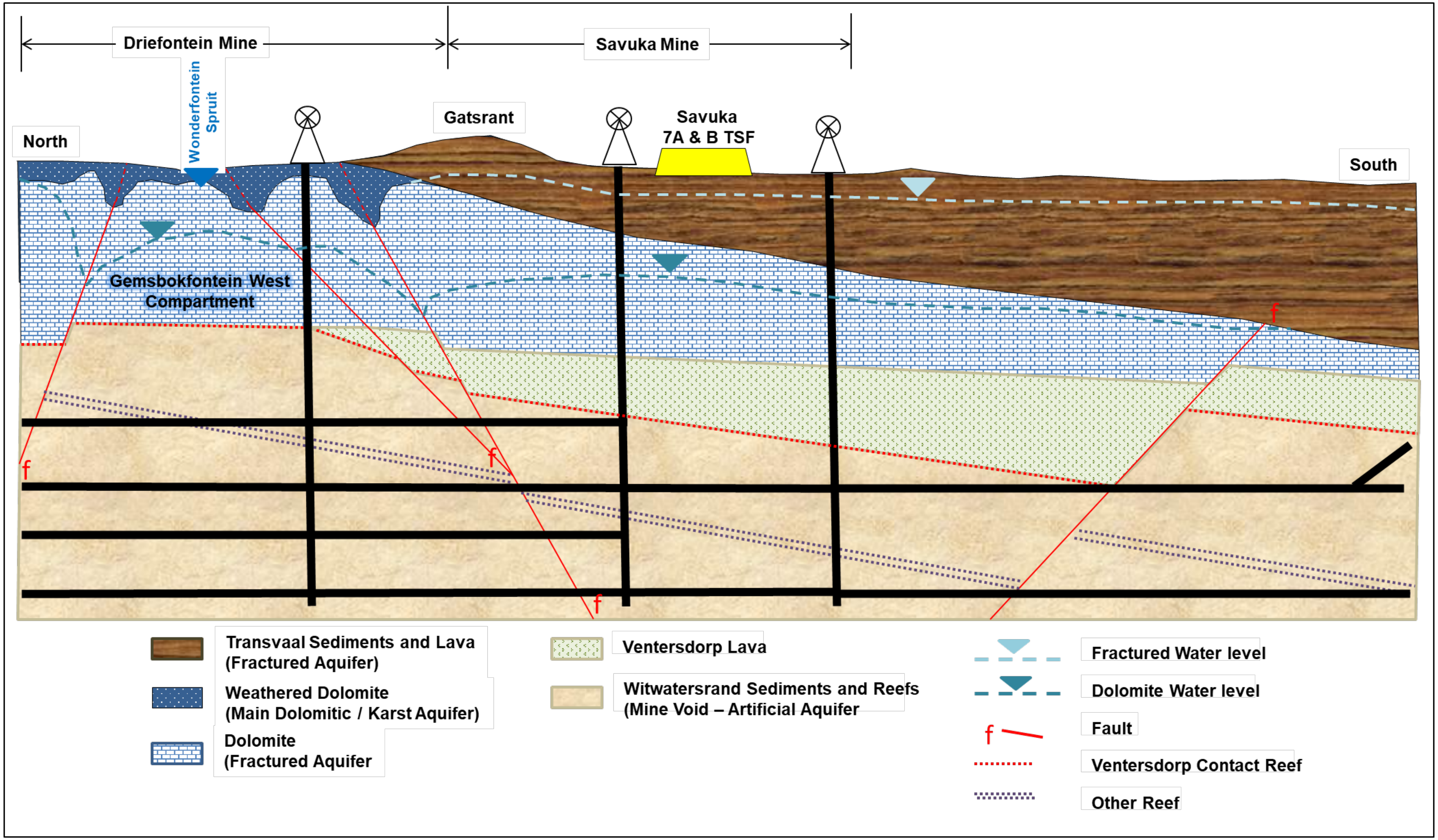

Figure 3.4: **Schematic geological section showing the relationship between the aquifers in the study area (Van Biljon, 2018)**

3.2.6 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 in the region (Van Biljon and Glendinning, 2013) estimated the aquifer parameters in the weathered and fractured aquifer to be as follows (Table 3.1):

Table 3.1: Transmissivity and hydraulic conductivity values in the weathered and fractured aquifers

Borehole	Transmissivity (m^2/d)	Hydraulic conductivity (m/day)	Aquifer
RGC01	0.75	0.02	Dyke contact - Fractured aquifer
RGC02	1.12	0.12	Weathered sandstone, overlying dolerite
RGC02d	0.39	0.02	Fractured dolerite
RGC03	0.42	0.01	Dyke contact - Fractured aquifer
RGC04	0.63	0.06	Weathered sandstone, overlying dolerite
RGC04d	0.43	0.02	Fractured dolerite
BH 0	0.49	0.01	Fractured shale, quartzite
SD1	1.35	0.0604	Weathered shale
SD4	0.65	0.0078	Weathered shale
SD6	0.04	0.0015	Weathered shale
SD7	0.38	0.0216	Weathered shale
SD11	0.1	0.0068	Weathered lava
SD12	3.39	0.2827	Weathered shale
Geometric mean	**0.50**	**0.02**	

3.2.7 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.

3.2.8 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 3.5. This graph indicates a very good correlation (96%) between the topography and the groundwater level, which suggests that groundwater flow will follow the topographical gradient.

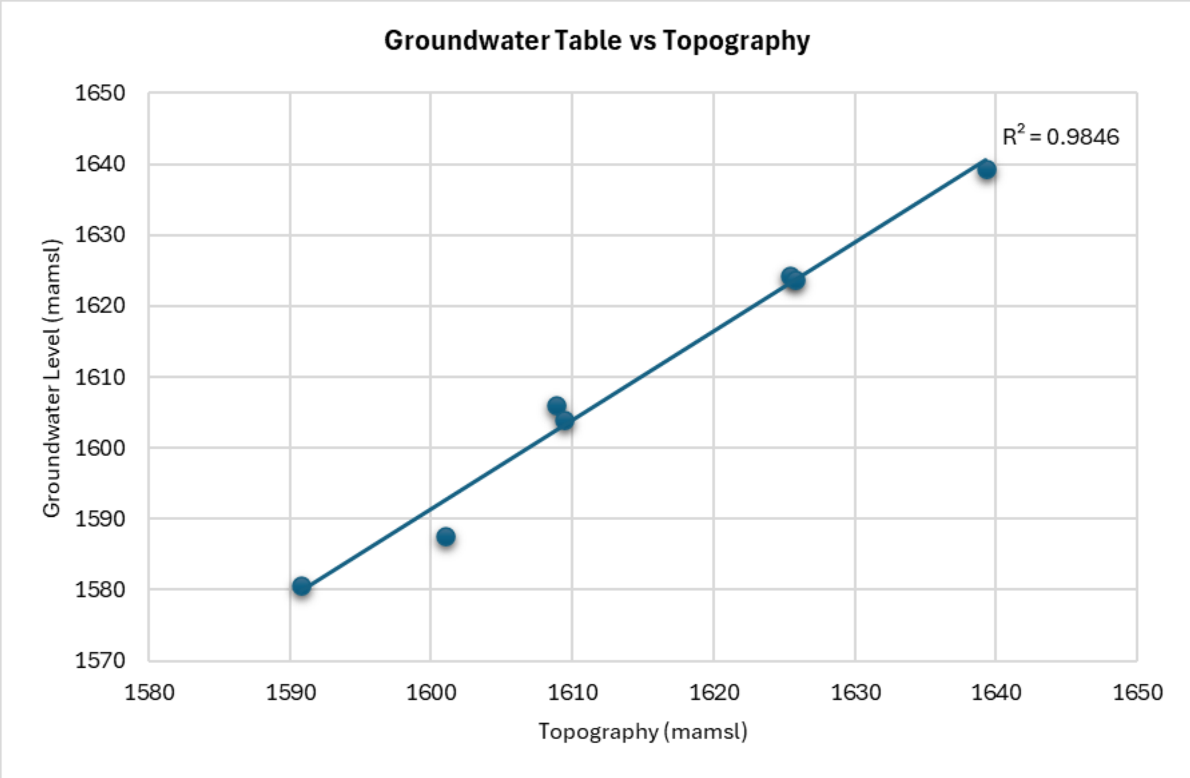

Figure 3.5: Correlation between topography and groundwater level

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 3.6 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-west.

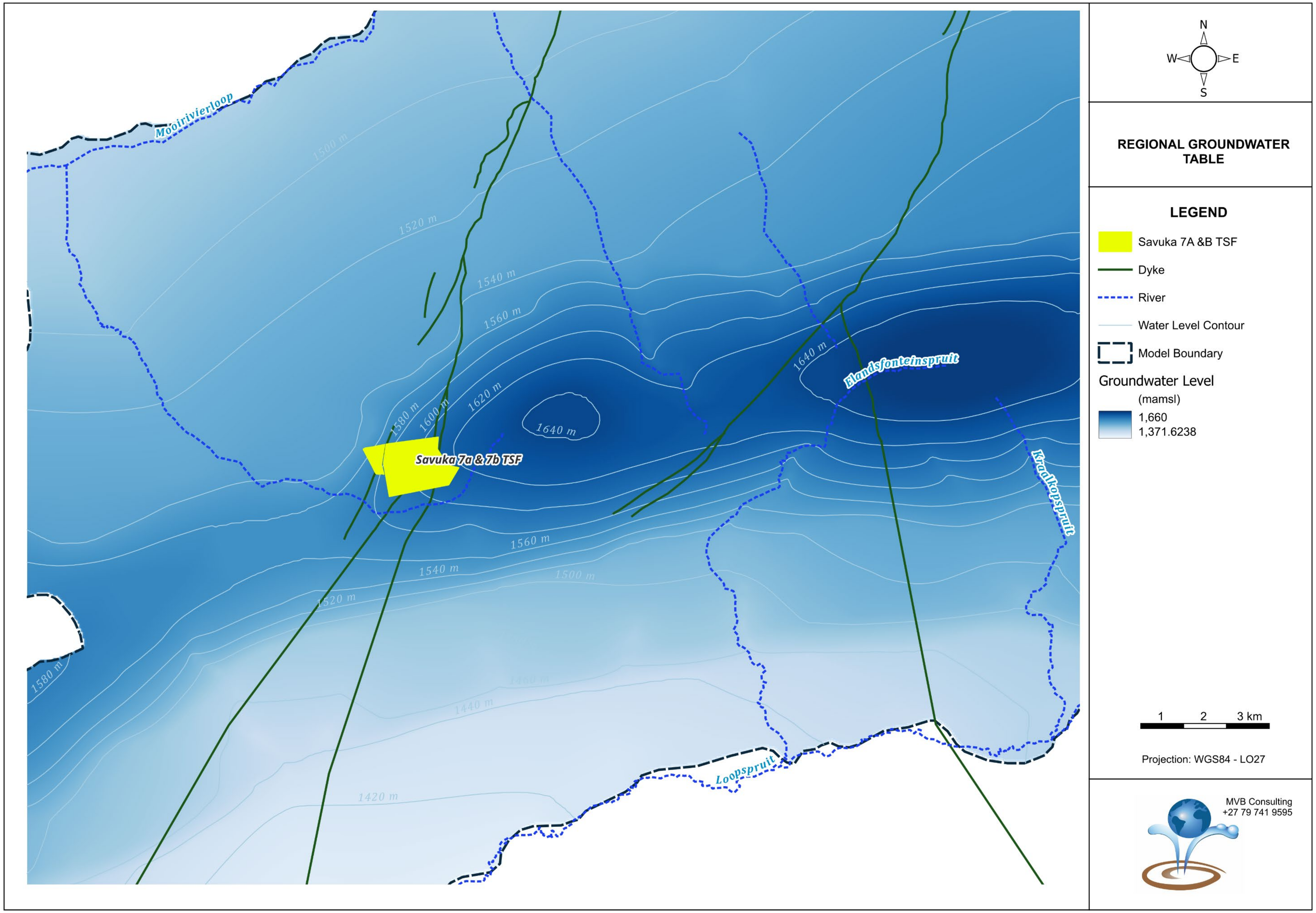

Figure 3.6: Regional groundwater gradient

3.2.9 Groundwater Quality

Since there are no groundwater users downstream from the Savuka TSFs, the groundwater chemistry is compared to the South African Water Quality Guidelines (second edition) Volume 5: Agricultural Use: Livestock Watering (Department of Water Affairs and Forestry, 1996), as well as the SANS 241 (2015). The **SANS 241 Drinking Water Specification** is the definitive reference on acceptable limits for drinking water quality parameters in South Africa and provides guideline levels for a range of water quality characteristics. The SANS 241 (2015) Drinking-Water Specification effectively summarises the suitability of water for drinking water purposes for lifetime consumption.

The guideline for livestock watering represents the target water quality specified in the guidelines. The target water quality guidelines were obtained from the *Department of Water Affairs and Forestry, 1996. South African Water Quality Guidelines (second edition). Volume 5: Agricultural Use: Livestock Watering.* According to the guidelines (DWAF, 1996), the following constituents are of concern for livestock watering (Table 3.2).

Table 3.2: 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		

Selected monitoring boreholes were sampled to assess (in consultation with the mine monitoring data) the current groundwater quality in the vicinity of the TSF. The chemistry of the groundwater is presented in Table 3.3 and the laboratory certificates are attached as Appendix A.

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

With reference to Table 3.3, the following is observed:

- The groundwater in the monitoring boreholes show a mining impact, with high TDS and sulphate concentrations.
- Several heavy metals exceed the SANS 241 and Livestock Watering guidelines.
- Apart from the Savuka 7a & 7b TSF's, there is also a larger impact from neighbouring tailings facilities.
- Borehole MB38 is anomalous and has much better quality than the other monitoring boreholes. This is attributed to this borehole being located within the phyto-remediation area.

The chemical character of the water at the sampling points is best described with the aid of the Piper diagram. The Piper diagram is one of the most commonly used techniques to interpret groundwater chemistry data.

This method proposed the plotting of cations and anions on adjacent trilinear fields with these points then being extrapolated to a central diamond field. Here the chemical character of water, in relation to its environment, could be observed and changes in the quality interpreted. The cation and anion plotting points are derived by computing the percentage equivalents for the main diagnostic cations of Ca, Mg and Na, and anions Cl, SO_4 and HCO_3.

Different waters from different environments always plot in diagnostic areas. The upper half of the diamond normally contains water of static and disordinate regimes, while the middle area normally indicates an area of dissolution and mixing. The lower triangle of this diamond shape indicates an area of dynamic and co-ordinated regimes. Sodium chloride brines normally plot on the right-hand corner of the diamond shape while recently recharge water plots on the left-hand corner of the diamond plot. The top corner normally indicates water contaminated with gypsum (mine impact). In general, the top half of the diamond contains static waters and other unusual waters high in Mg/Ca Cl_2 and Ca/Mg SO_4. The lower half contains those waters normally found in a dynamic basin environment. The values for mixtures of any two waters in any proportion plot along a line joining their respective points in each of these diagrams. Water therefore being invaded by an industrial effluent will plot a vector towards the analysis of the invading fluid.

The Piper diagrams for the Savuka TSF groundwater monitoring boreholes are shown as Figure 3.7.

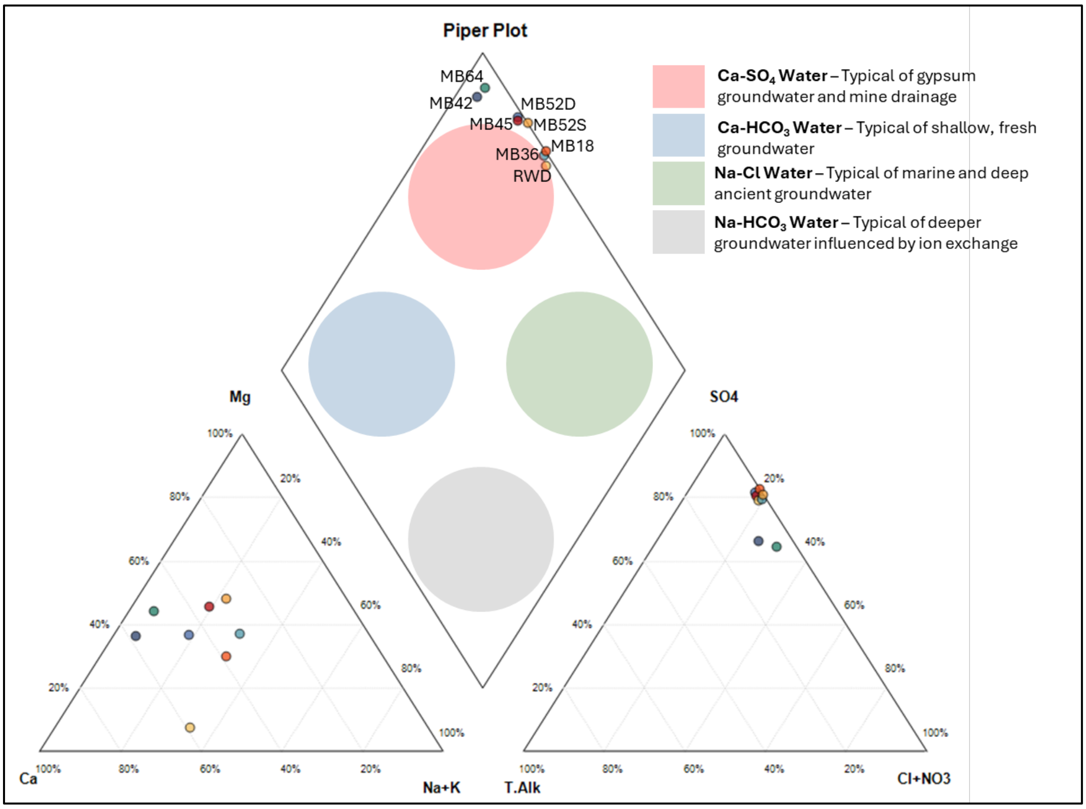

Figure 3.7: Piper diagram for the Savuka region groundwater samples

The mine monitoring boreholes are characterised as $Ca\text{-}SO_4$ (mine drainage) type water.

Table 3.3: Groundwater chemistry

Analyses in mg/ℓ (Unless specified otherwise)	SANS 241	DWAF	MB52D	MB52S	MB18	MB36	MB64	MB45 Artesian	MB42	SD Dam
pH - Value @ 25 ºC	**<5 - >9.7**	**-**	6.0	5.9	5.6	5.7	6.2	5.8	6.5	7.8
Electrical Conductivity in mS/m @ 25°C	**170**	**-**	300	380	422	371	263	349	173	485
Total Dissolved Solids @ 180°C	**1 200**	**1 000**	2 702	3 458	3 796	3 246	2 420	3 296	1 514	4 412
Total Alkalinity as $CaCO_3$	**-**	**-**	36	<5	<5	28	80	52	92	76
Chloride as Cl	**300**	**1500**	209	289	294	277	285	249	157	369
Sulphate as SO_4	**500**	**1 000**	1 390	1 661	1 892	1 529	814	1 548	562	2 096
Fluoride as F	**1.5**	**2**	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2	0.7
Nitrate as N	**11**	**100**	0.7	0.4	2.5	0.4	4.6	0.2	1.8	3.4
Ortho Phosphate as P	**-**	**-**	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
Free and Saline Ammonia as N	**1.5**	**-**	0.1	0.3	0.9	1.8	0.1	0.4	<0.1	7.9
Sodium as Na	**200**	**2000**	168	248	369	338	46	199	25	418
Potassium as K	**-**	**-**	5.9	6.4	9.7	8.3	1	9	2	44
Calcium as Ca	**-**	**1000**	357	297	409	306	330	327	243	685
Magnesium as Mg	**-**	**500**	179	289	191	216	179	255	92	52
Aluminium as Al	**0.3**	**5**	0.213	0.184	0.317	0.189	0.201	0.212	0.108	2.38
Arsenic as As	**0.01**	**1**	0.002	<0.001	0.001	<0.001	<0.001	0.053	<0.001	0.017
Barium as Ba	**0.7**	**-**	0.029	<0.025	0.028	<0.025	<0.025	0.042	<0.025	0.028
Boron as B	**2.4**	**5**	<0.025	<0.025	<0.025	<0.025	<0.025	<0.025	<0.025	<0.025
Total Chromium as Cr	**0.05**	**-**	<0.025	<0.025	<0.025	<0.025	<0.025	<0.025	<0.025	<0.025

Analyses in mg/ℓ (Unless specified otherwise)	SANS 241	DWAF	MB52D	MB52S	MB18	MB36	MB64	MB45 Artesian	MB42	SD Dam
Cobalt as Co	**-**	**1**	0.14	<0.025	1.03	0.288	<0.025	1.18	<0.025	0.594
Copper as Cu	**2**	**0.5**	<0.010	<0.010	<0.010	<0.010	<0.010	<0.010	<0.010	2.7
Iron as Fe	**2**	**10**	0.687	12.00	3.64	6.01	0.116	14.00	0.528	5.57
Lead as Pb	**0.01**	**0.1**	0.013	0.005	0.01	0.004	0.002	0.094	0.002	0.027
Manganese as Mn	**0.4**	**10**	3.84	3.47	16.00	11.00	0.025	5.8	0.048	5.64
Mercury as Hg	**0.006**	**0.001**	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	0.003	0.001
Nickel as Ni	**0.07**	**1**	<0.025	<0.025	0.081	<0.025	<0.025	0.15	<0.025	1.75
Selenium as Se	**0.04**	**0.05**	<0.001	0.001	0.001	0.001	<0.001	<0.001	0.001	0.004
Strontium as Sr	**-**	**-**	0.291	0.196	0.692	0.46	0.875	0.527	0.43	1.89
Uranium as U	**0.03**	**-**	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	0.001	0.382
Zinc as Zn	**5**	**0.02**	<0.025	<0.025	0.058	0.045	<0.025	0.253	<0.025	1.49

3.2.10 Aquifer Classification

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

Other uses could include:

- Defining levels of investigation required for decision making.
- Setting of monitoring requirements.
- 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 3.4). A weighting and rating approach is then used to decide on the appropriate level of groundwater protection (Table 3.5).

Table 3.4: Ratings for the aquifer quality management classification system

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

Table 3.5: 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

4. NUMERICAL GROUNDWATER MODELLING

4.1 Introduction

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

- Contaminant seepage from the Savuka TSFs with the extended height and unlined RWD for periods 50- and 100-years. Deposition on the extension will only be for a period of two years, whereafter the TSF will be dormant.
- Effectiveness of proposed remedial options if the RWD is not lined. This includes the phyto-remediation that is already in place.

The basic steps involved in modelling can be summarised as:

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

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

4.2 Assumptions and Limitations

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

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

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

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

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

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

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

4.3 Model Set-up

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

The network constructed for the site consists of 1 452 117 elements. Figure 4.1 is a representation of the model domain. It must be noted that the network was refined in the vicinity of sources of potential contamination and dewatering.

The model consists of the following layers:

- Layer 1: Weathered formations – 10m thickness.
- Layer 2: Fractured formations – 100m thickness.
- Layer 3: Model base – 100m thickness.

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

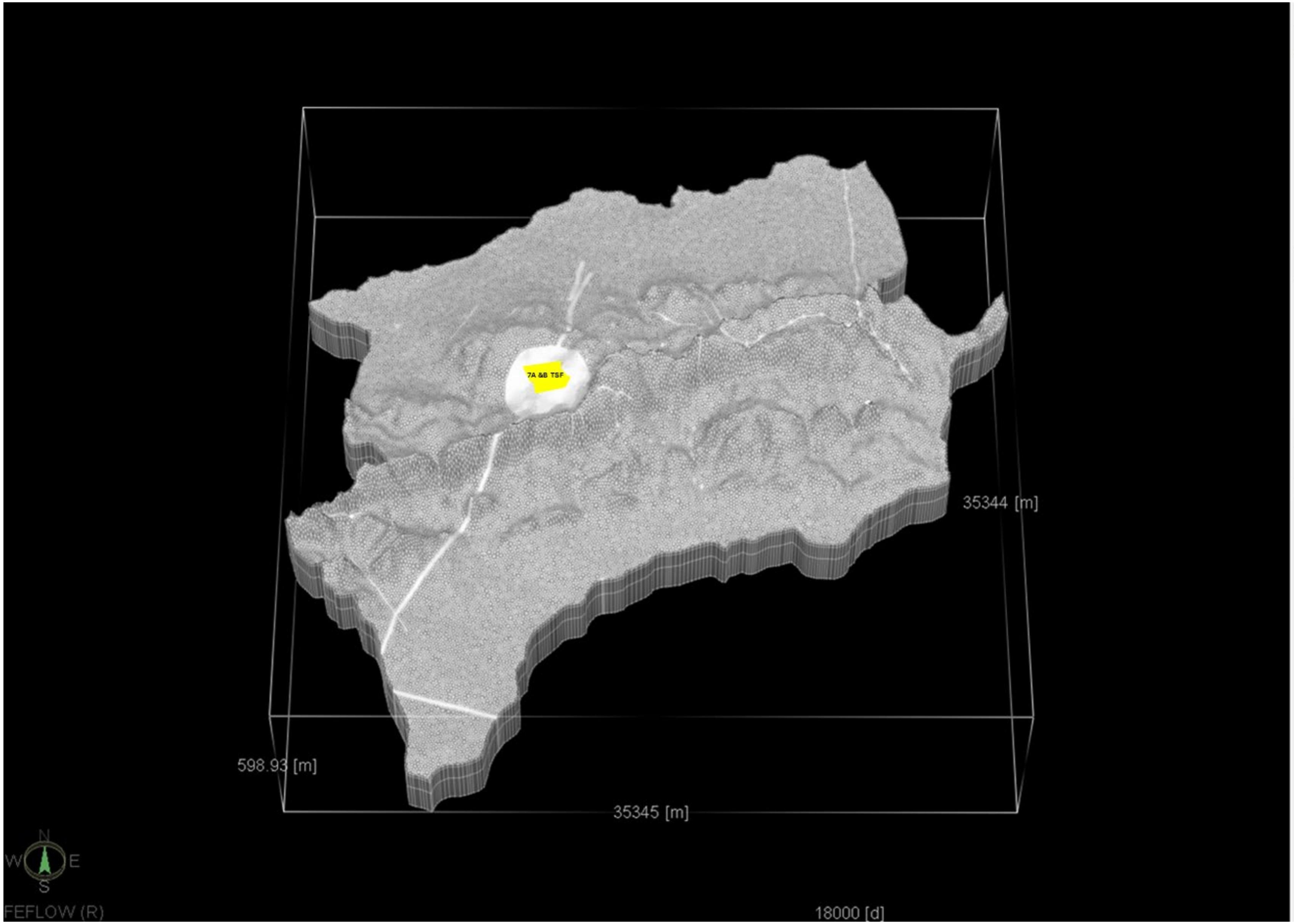

Figure 4.1: Model Domain

4.4 Model Boundary Conditions

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

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

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

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

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

4.5 Initial Conditions

Initial conditions are vital for modelling flow problems. Initial conditions must be specified for the entire area. Generally, the initial water level/head distribution acts as the starting distribution for the numerical calculation. The water levels shown in Figure 3.6 were used as initial conditions for the model.

4.6 Sources and Sinks

Sources and sinks can be defined as recharge and abstraction sources in the aquifer. Sources can be precipitation and inflow from surface water and recharging boreholes. Sinks can be abstraction boreholes, springs, evapotranspiration, and outflow to surface water. Initially only recharge due to precipitation was included in the model. The average mean annual precipitation (MAP) is approximately 646 mm/a. The effective recharge is set at 2-4% of MAP for the weathered aquifer. The modelled aquifer recharge is shown in Figure 4.2.

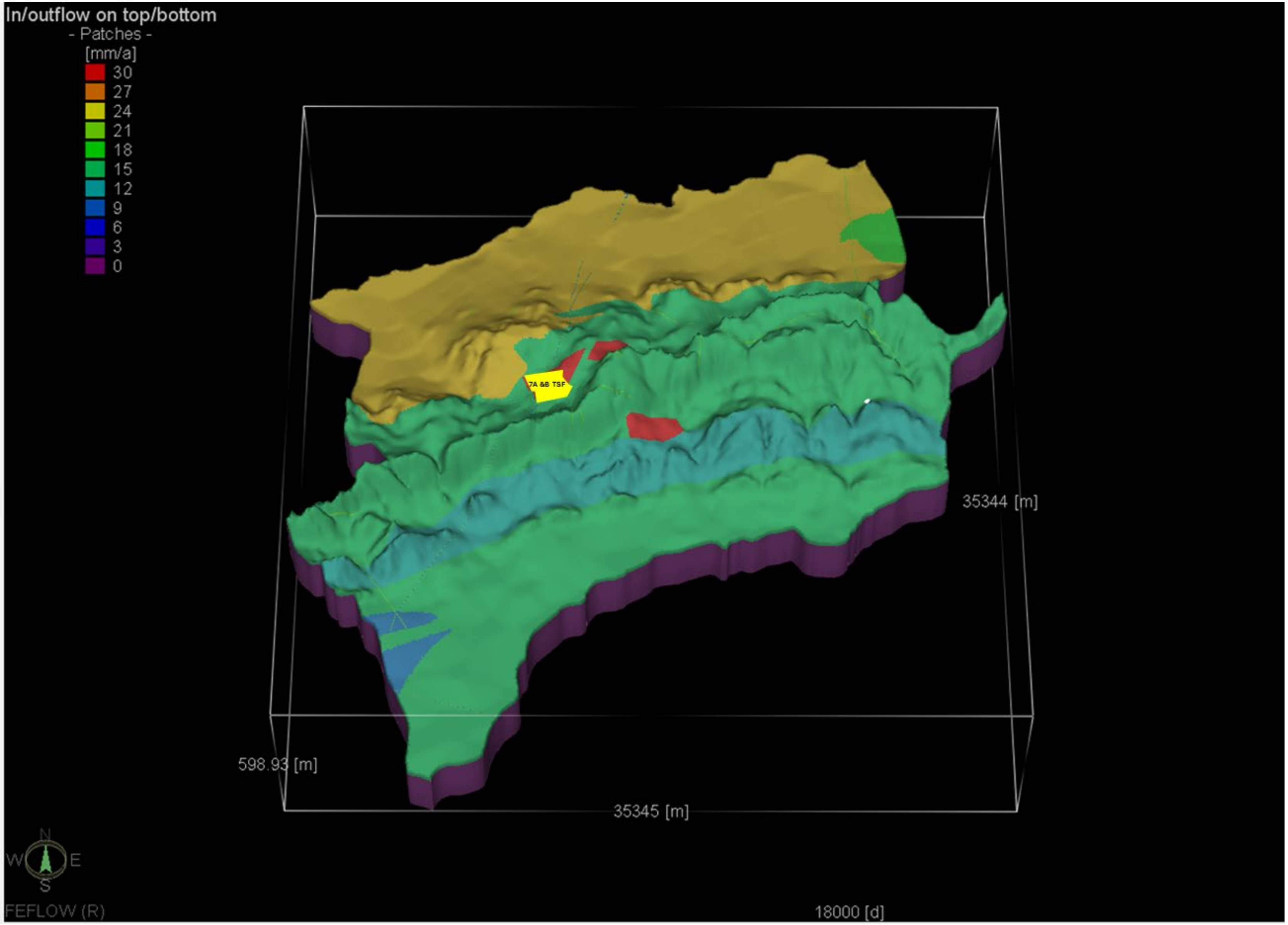

Figure 4.2: Aquifer recharge

4.7 Aquifer Parameters

The aquifer parameters discussed in Section 3.2.6 were initially used in the numerical model. The model is calibrated using the groundwater level elevations which are a function of the product of the saturated aquifer thickness, the hydraulic conductivity and effective aquifer recharge. Should the average aquifer thickness therefore be under/overestimated, this can be compensated for by adjustment of the hydraulic conductivity values during model calibration.

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

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

Table 4.1: Modelled aquifer parameters

Model Layer	Hydrostratigraphic unit	Layer thickness (m)	Hydraulic Conductivity (K)		Recharge (Re)**	Specific storage (Sc)	Porosity (n)
			Kx,y 1:1 (m/d)	Kz 1:10 (m/d)	In/Outflow on top/bottom (mm/a)	Sc (1/m)	%
Layer 1	Malmani Dolomite	10.00	6.00E-01	6.00E-02	25.00	1.00E-02	3.00E-01
	Ecca Group		1.50E-01	1.50E-02	17.50	5.00E-04	1.00E-02
	Pta Group: Siliciclastic rocks		2.50E-02	2.50E-03	15.00	3.00E-03	5.00E-02
	Pta Group: Volcanic rocks		2.00E-01	2.00E-02	12.50	1.00E-03	4.00E-02
	Pta Group: Silverton formation		4.00E-01	4.00E-02	15.00	2.00E-03	3.00E-02
	Dykes		1.00E-02	1.00E-02	10.00	1.00E-05	5.00E-03
	Dykes (weathered perimeter)		7.50E-01	7.50E-01	20.00	1.50E-02	7.50E-02
Layer 2	Malmani Dolomite	100.00	3.00E-01	3.00E-02	0.00	5.00E-03	1.50E-01
	Ecca Group		7.50E-02	7.50E-03		2.50E-04	5.00E-03
	Pta Group: Siliciclastic rocks		1.25E-02	1.25E-03		1.50E-03	2.50E-02
	Pta Group: Volcanic rocks		1.00E-01	1.00E-02		5.00E-04	2.00E-02
	Pta Group: Silverton formation		2.00E-01	2.00E-02		1.00E-03	1.50E-02
	Dykes		5.00E-03	5.00E-04		5.00E-06	2.50E-03
	Dykes (weathered perimeter)		3.75E-01	3.75E-02		7.50E-03	3.75E-02
Layer 3	Malmani Dolomite	100.00	1.50E-01	1.50E-02	0.00	2.50E-03	7.50E-02
	Ecca Group		3.75E-02	3.75E-03		1.25E-04	2.50E-03
	Pta Group: Siliciclastic rocks		6.25E-03	6.25E-04		7.50E-04	1.25E-02
	Pta Group: Volcanic rocks		5.00E-02	5.00E-03		2.50E-04	1.00E-02
	Pta Group: Silverton formation		1.00E-01	1.00E-02		5.00E-04	7.50E-03
	Dykes		2.50E-03	2.50E-04		2.50E-06	1.25E-03
	Dykes (weathered perimeter)		1.88E-01	1.88E-02		3.75E-03	1.88E-02

****Notes: Recharge of 30.00mm assigned to all TSF footprints**

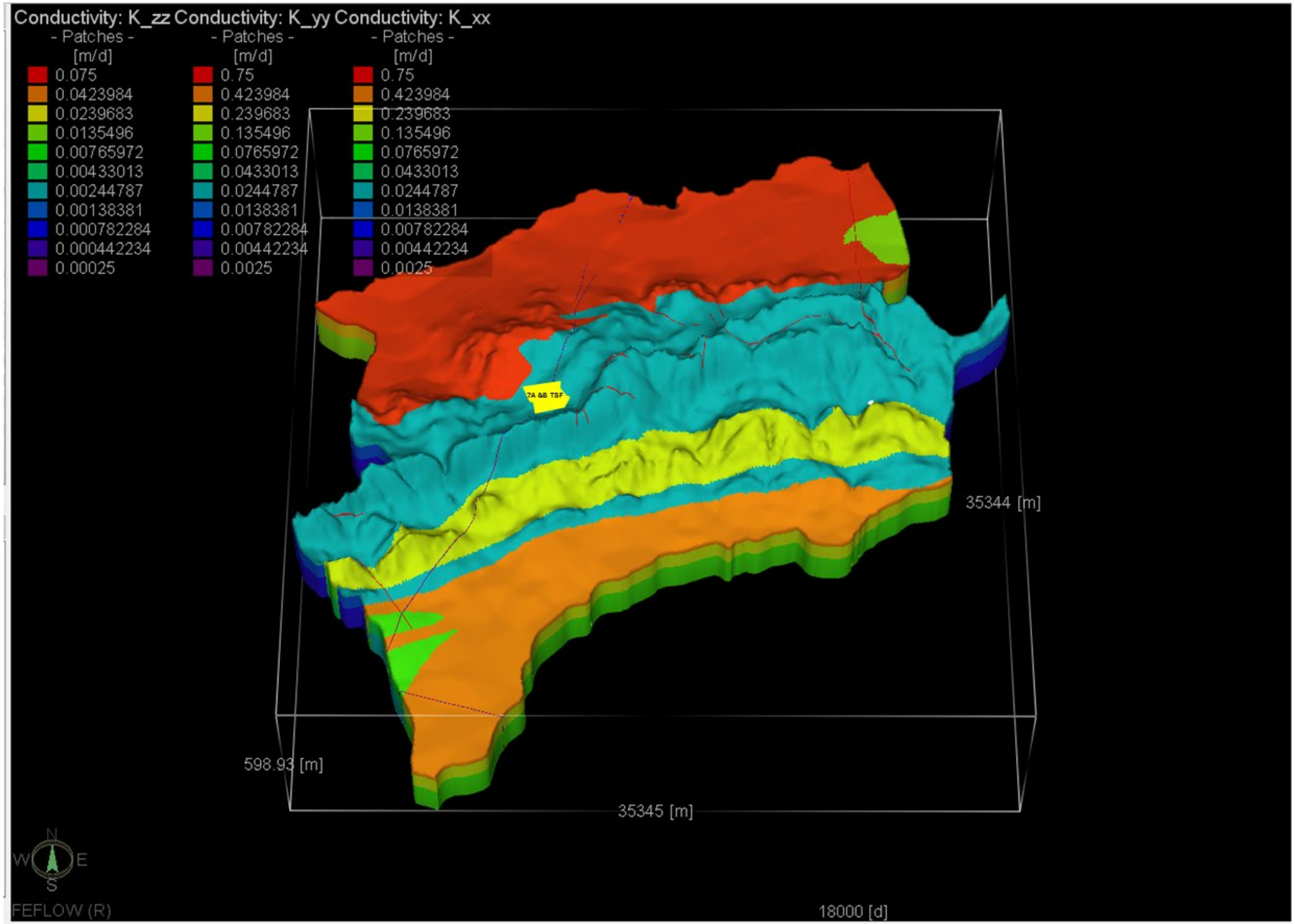

Figure 4.3: **Modelled aquifer parameters**

4.8 Calibration of the Model

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

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

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

Where:

h = hydraulic head [L].

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

S = storage coefficient.

t = time [T].

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

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

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

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

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

The calibration process was done by changing the model parameters for hydraulic conductivity and recharge. The mine monitoring boreholes were used to calibrate groundwater flow model, with these boreholes providing the only available data. The calibration objective was reached when an acceptable correlation was obtained between the observed and simulated piezometric heads (Figure 4.4).

Table 4.2: Flow Calibration Results

Calibration BH	Topographical Elevation (mamsl)	Water Level (mbgl)	Measured head elevation (mamsl)	Simulated head elevation (mamsl)	Mean Error (m)	Mean Absolute Error (m)	Root Mean Square Error (m)
MB18	1613.50	2.91	1610.59	1611.48	-0.89	0.89	0.80
MB36	1604.40	5.51	1598.89	1602.79	-3.90	3.90	15.24
MB42	1599.60	13.32	1586.28	1588.84	-2.56	2.56	6.54
MB45	1641.50	0.00	1641.50	1629.50	12.00	12.00	144.05
MB52	1623.70	1.06	1622.64	1622.71	-0.07	0.07	0.00
MB64	1581.50	10.06	1571.44	1577.93	-6.49	6.49	42.07
Average	**1610.70**	**5.48**	**1605.22**	**1605.54**	**-0.32**	**4.32**	**34.78**
Minimum	**1581.50**	**0.00**	**1571.44**	**1577.93**	**-6.49**	**0.07**	**0.00**
Maximum	**1641.50**	**13.32**	**1641.50**	**1629.50**	**12.00**	**12.00**	**144.05**
Correlation			**0.99**				
∑					**-1.90**	**25.91**	**208.70**
1/n					**-0.32**	**4.32**	**34.78**
Root Mean Square Deviation (RMSD)					**0.56**	**2.08**	**5.90**
Normalised Root Mean Square Deviation (NRMSD) (% of water level range)							**8.42**

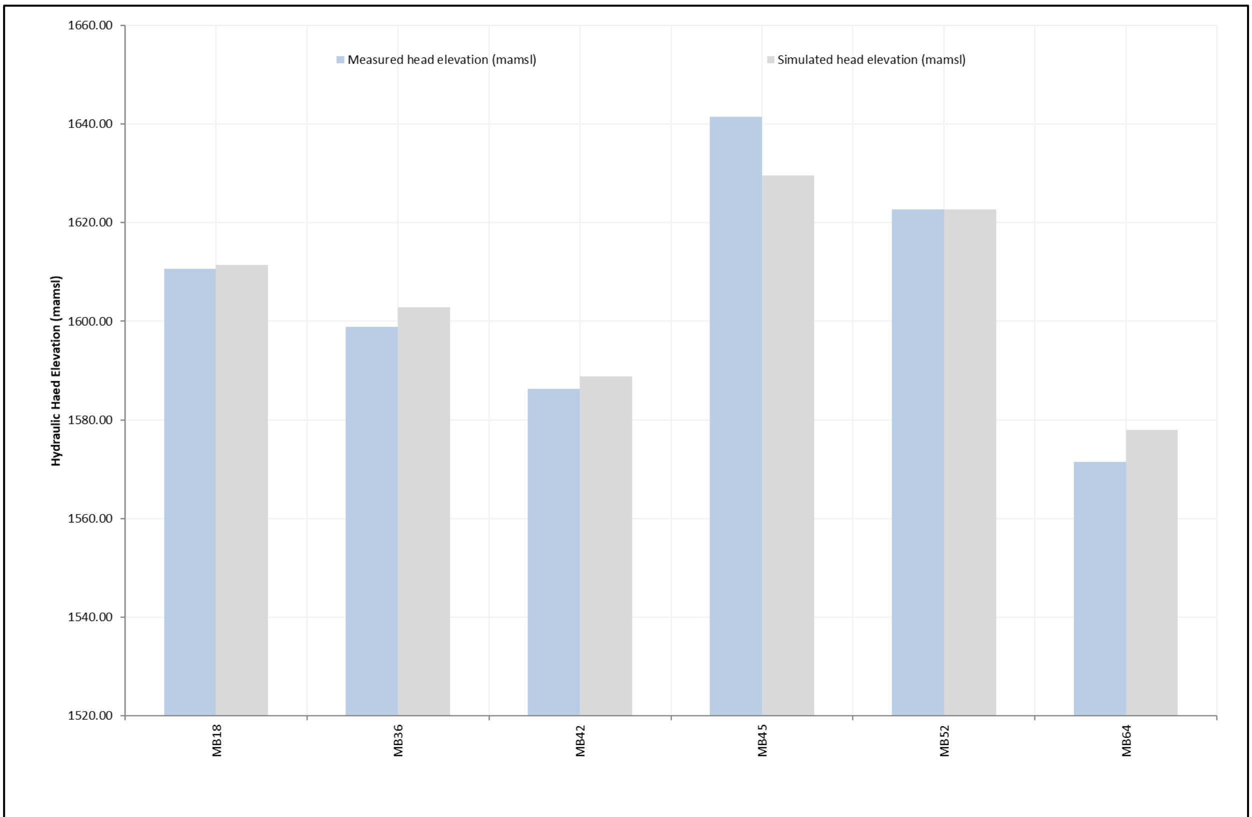

Figure 4.4: Model Calibration - Groundwater Levels

4.9 Numerical Groundwater Mass Transport Model

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

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

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

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

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

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

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

The Sulphate (SO_4) concentrations are elevated in the monitoring boreholes and was selected as representative of the potential impacts from the tailings and return water dam.

The mass transport model was calibrated by assigning a source term concentration of 2 500 mg/L SO_4 to the tailings seepage and the RWD. Figure 4.5 shows the current simulated SO_4 plume compared to the current SO_4 concentrations.

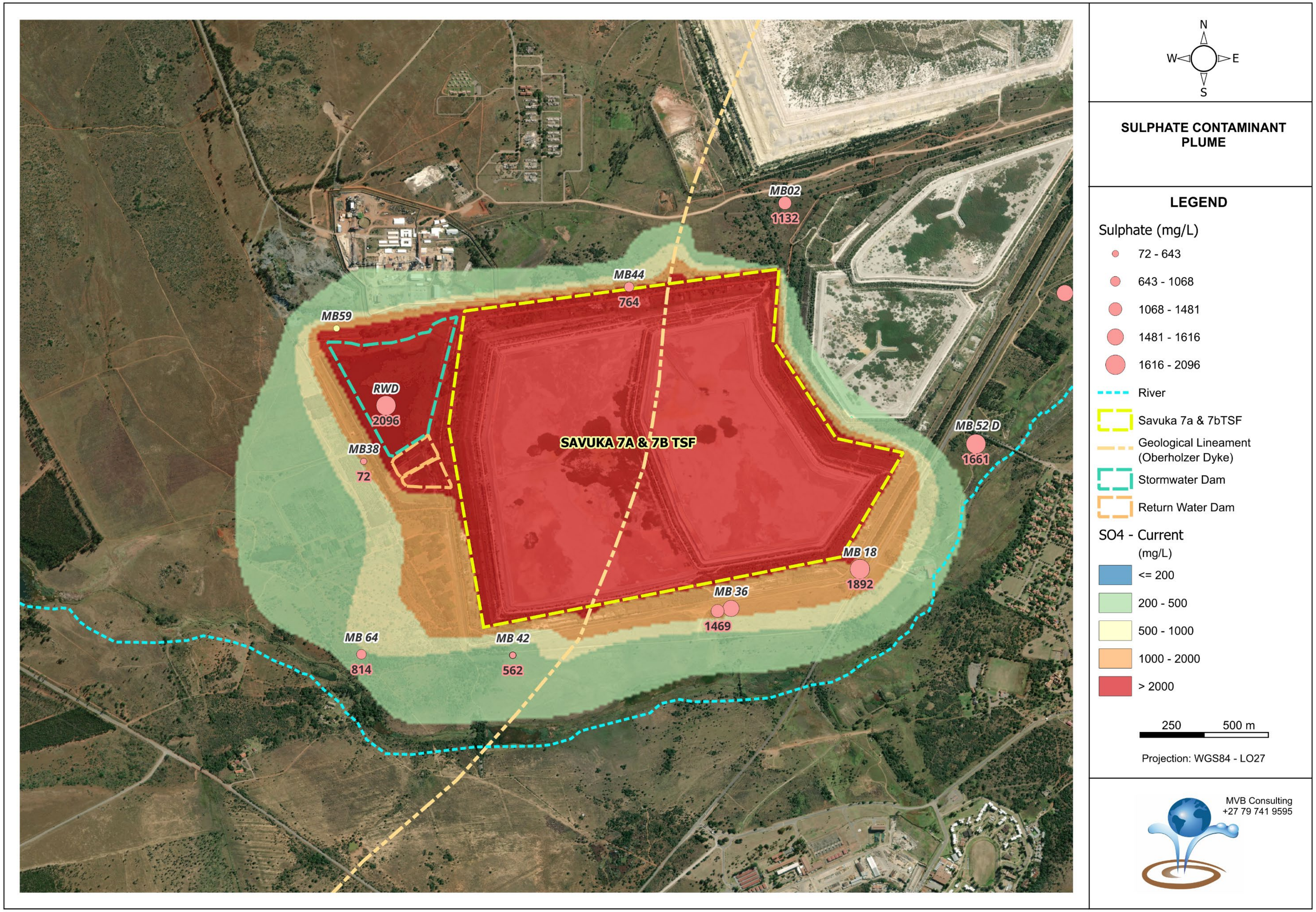

Figure 4.5: **Current simulated plume compared to the measured SO_4 concentrations**

5. GEOHYDROLOGICAL IMPACT ASSESSMENT

5.1 Do – Nothing Scenario

According to records the Savuka TSF was commissioned in 1979 / 1980. The impact from the existing dams were therefore modelled, based on this assumption. The current impact is mainly to the south and west, towards the Wonderfonteinspruit tributary.

Assuming that the existing facility is 44 years old, the average plume migration can be estimated based on Darcy's law. Contaminants are transported in groundwater by advection, that is, the movement of a solute at the speed of the average linear velocity of groundwater (Anderson, *et. al.*, 1992). This is represented by the following formula:

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

where;

v = *velocity in m/day*

K = *Hydraulic Conductivity in m/day*

I = *Gradient as a %*

n = *Porosity as a %*

The hydraulic conductivity for the weathered aquifer is estimated as 0.231 m/day. The groundwater gradient averages 0.64 in the study area. The porosity of the aquifer material is estimated to be between 3 - 7%. Applying the above formula to the study area assuming a porosity of 5% it is calculated that the groundwater velocity averages a rate of 0.030 m/day or 10.79 m per annum. Over the 44-year period the plume migration is estimated at 475m, which is supported by the numerical modelling.

The current impact from the existing Savuka TSF was used as the base case and future impacts over 50-and 100-year periods were simulated as the "do-nothing" scenario. The impacts from adjacent tailings facilities were excluded for this assessment and focus was only on the Savuka TSF and RWD. The TSF and RWD are unlined for the do-nothing scenario. The results from these simulations are presented in Figure 5.1 and Figure 5.2.

Based on the modelling the impact from the TSF has already reached the Wonderfonteinspruit tributary, albeit still at low concentrations (Figure 4.5). The concentrations are expected to increase during the next 50 - 100 years if nothing is done. The tributary acts a groundwater boundary and the plume will not extent beyond the stream. Groundwater contributes to the baseflow of the stream and will therefore impact on the water quality in the stream.

Future impacts from the TSF are compared against the "do-nothing" scenarios.

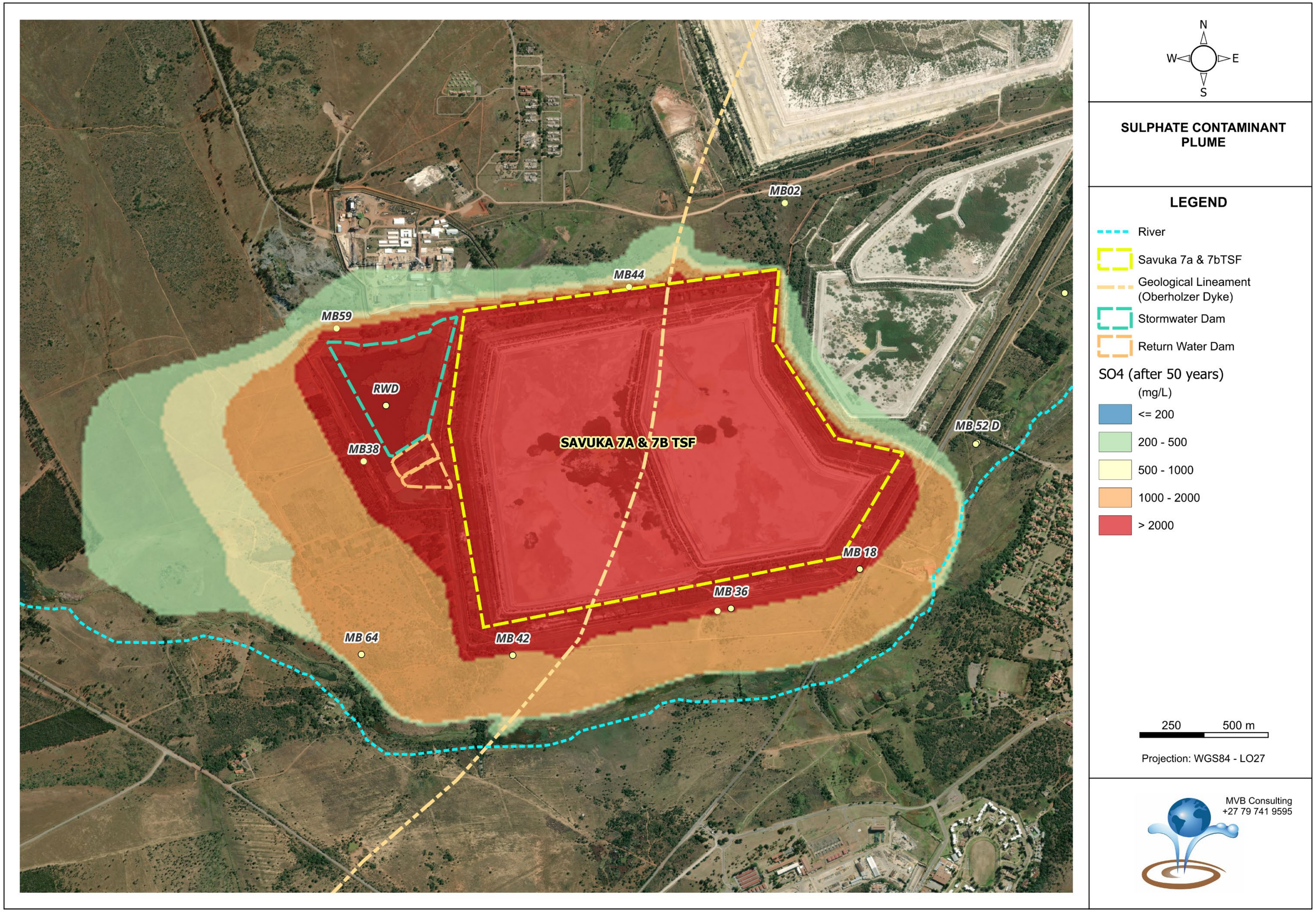

Figure 5.1: **Simulated sulphate plume after 50 years**

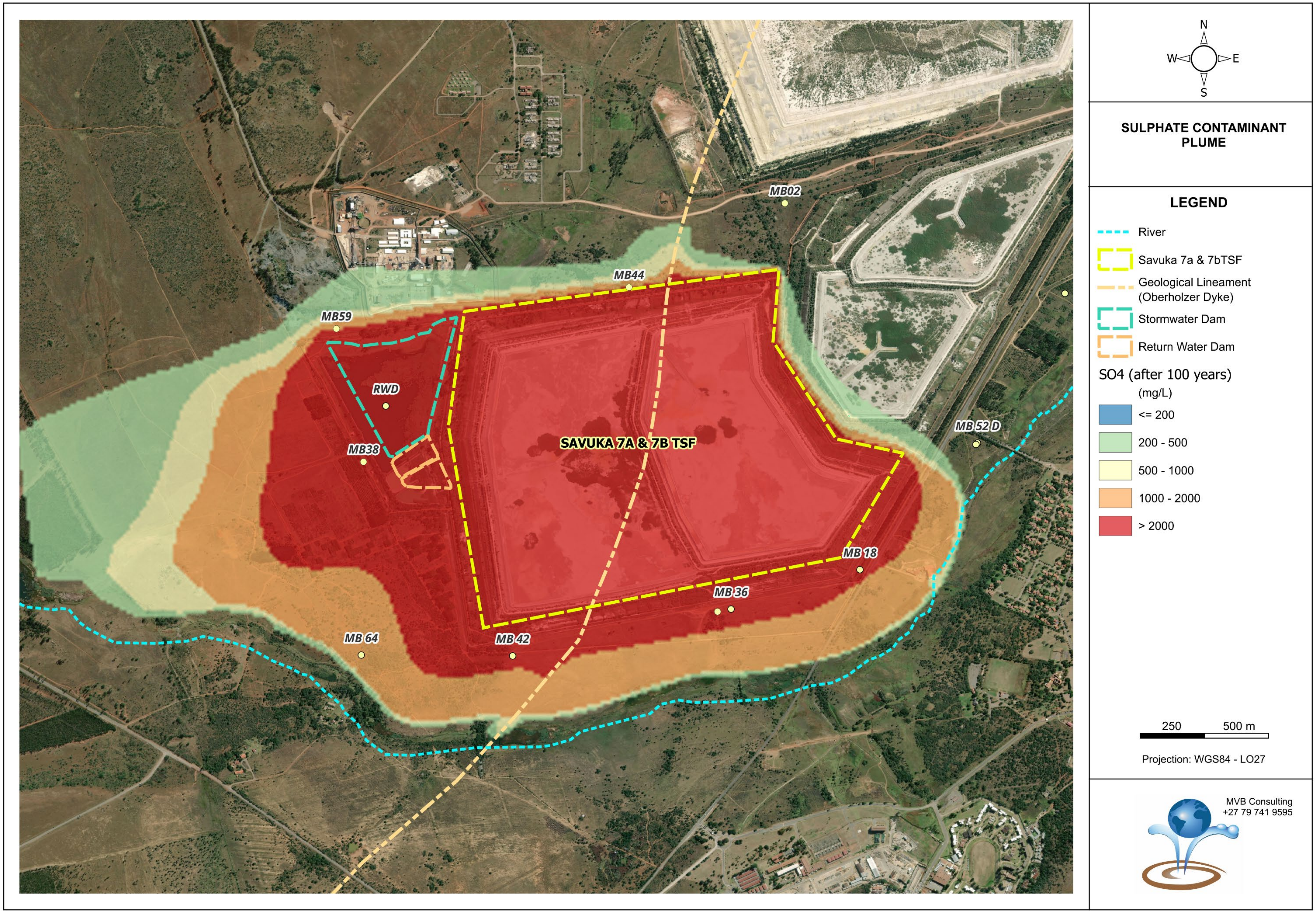

Figure 5.2: Simulated sulphate plume after 100 years

5.2 Effectiveness of Potential Management Options

The “do-nothing” scenario indicated that the contaminant plume from the RWD will migrate in a westerly direction towards the Wonderfonteinspruit tributary.

The figures above do not include the phyto-remediation that is already in place. Based on the sulphate concentration in borehole MB64 (see Figure 4.5) the phyto-remediation is not yet as effective as it is in the vicinity of borehole MB38. As the plants grow it is expected that this remediation method will be very successful.

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

- Lining of the RWD. The TSF will remain unlined.
- Effectiveness of the existing and proposed phyto-remediation over time.
- Implementation of a containment system downgradient from the RWD. This includes interception boreholes, supplementing the existing phyto-remediation.

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. Leakage will continue only during the operational phase. Thereafter the RWD will be rehabilitated.

The effectiveness of lining the RWD is illustrated in Figure 5.3. Plume migration from the TSF continues towards the south, but the westerly migration from the RWD, is contained and the existing impact dissipates over time.

Alternatives to a liner includes the phyto-remediation, with and without supplementary scavenger or interception boreholes. The simulations assumed the following:

- Each tree uses 5 litres / day and there are 1 333 trees / hectare.
- Each scavenger borehole is pumped at 1.5 lit / sec for 24-hours / day.

The effectiveness of the phyto-remediation is remarkable, and it contains the contaminant plume effectively (Figure 5.4). The effectiveness of the phyto-remediation with the lined RWD is illustrated in Figure 5.5. Supplementing the phyto-remediation with scavenger boreholes is illustrated in Figure 5.6. Both options improve the effectiveness of the phyto-remediation, but with very small margins. Considering the costs of a liner and scavenger boreholes, these options are not recommended.

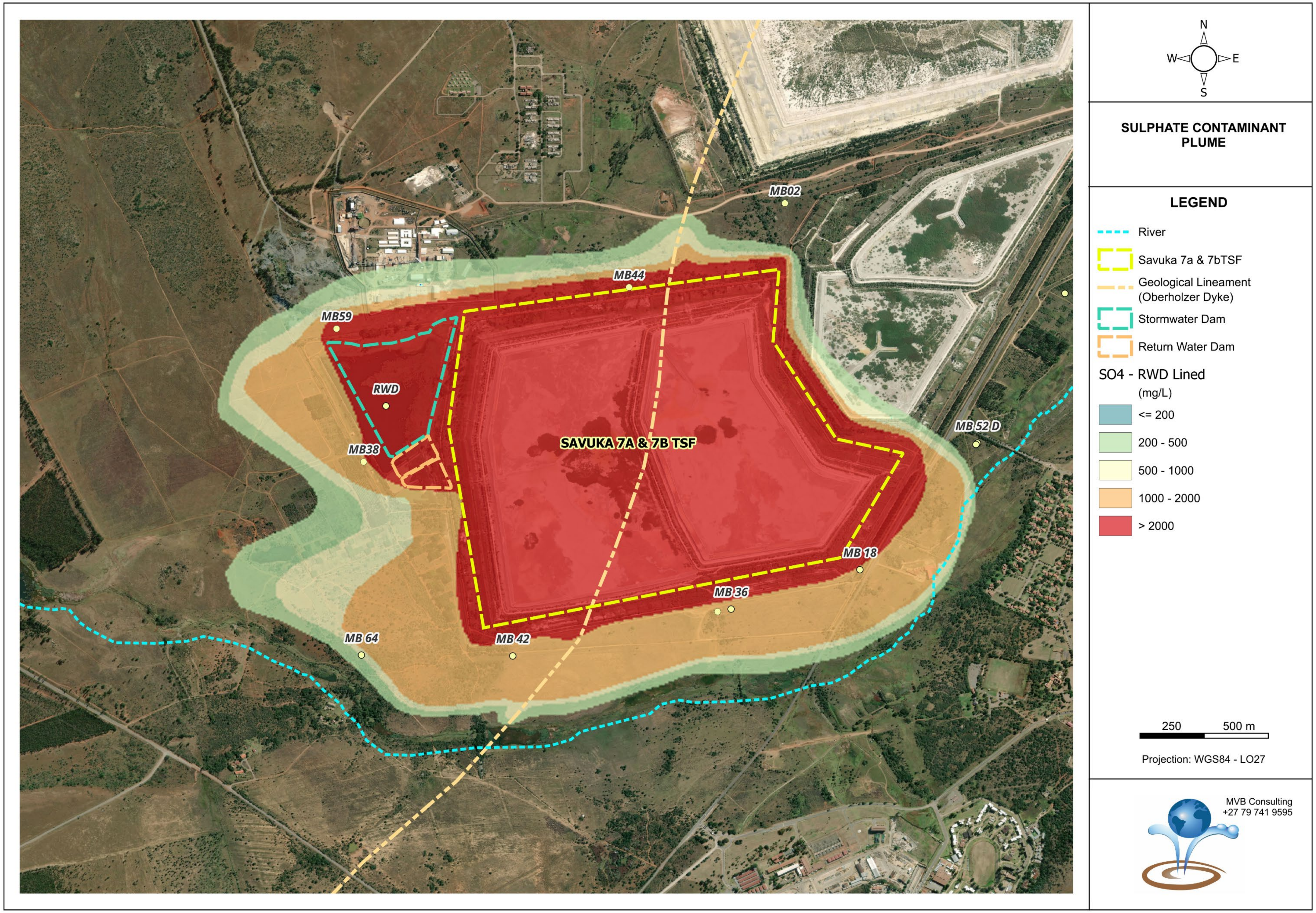

Figure 5.3: **Simulated sulphate plume after 50 years with a liner in the RWD**

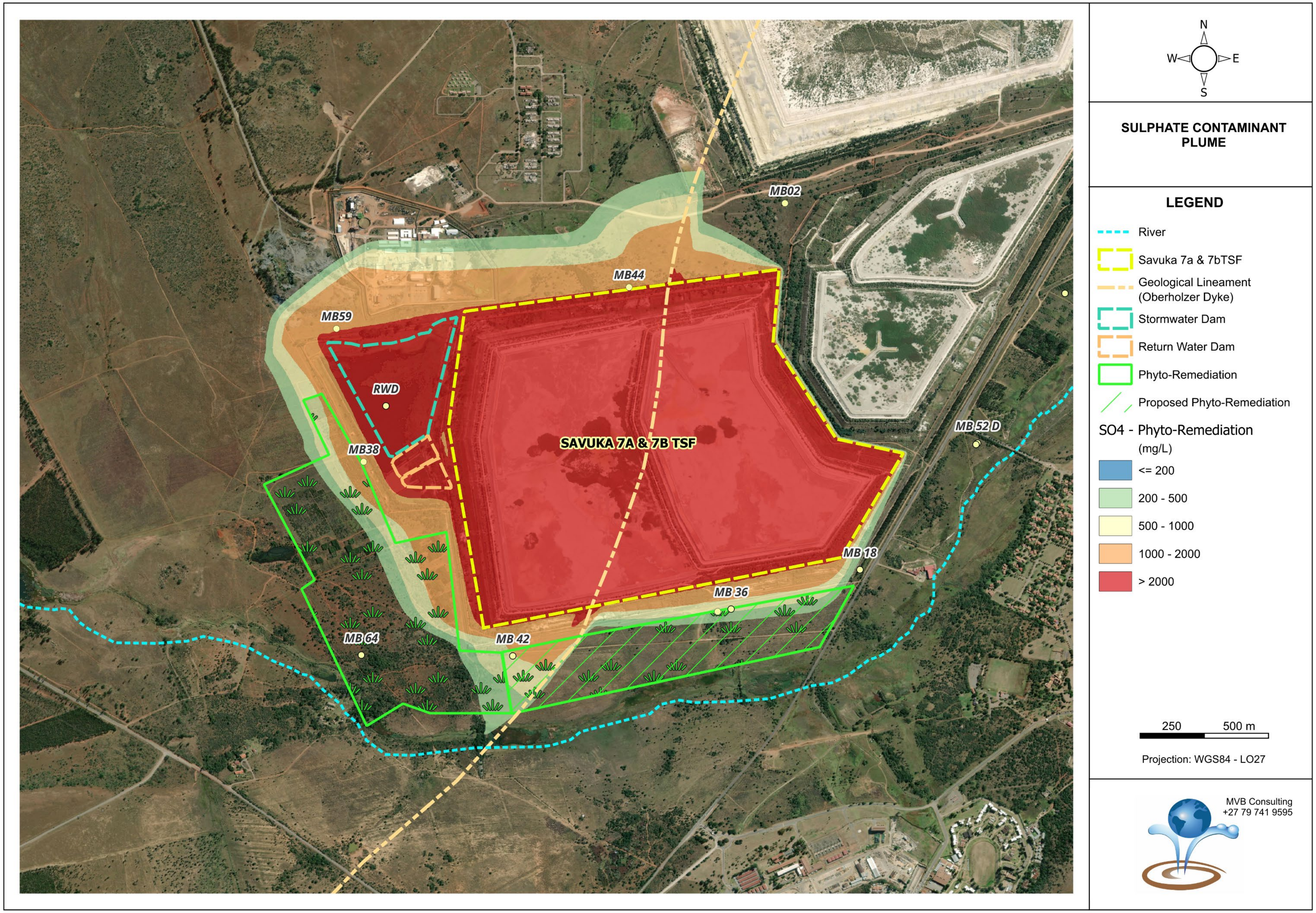

Figure 5.4: Simulated sulphate plume after 50 years with phyto-remediation fully functional

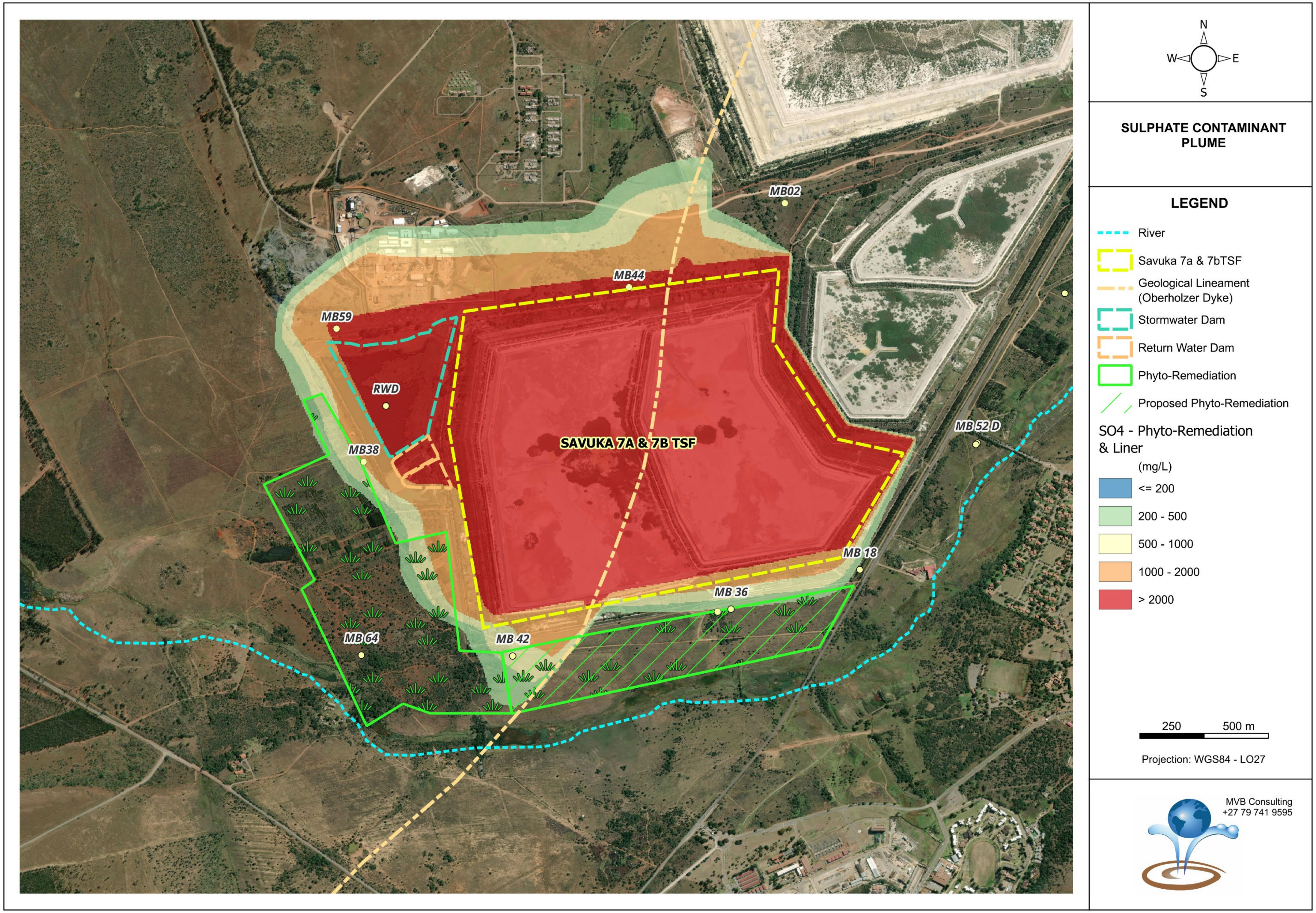

Figure 5.5: Simulated sulphate plume after 50 years with phyto-remediation fully functional and the RWD lined

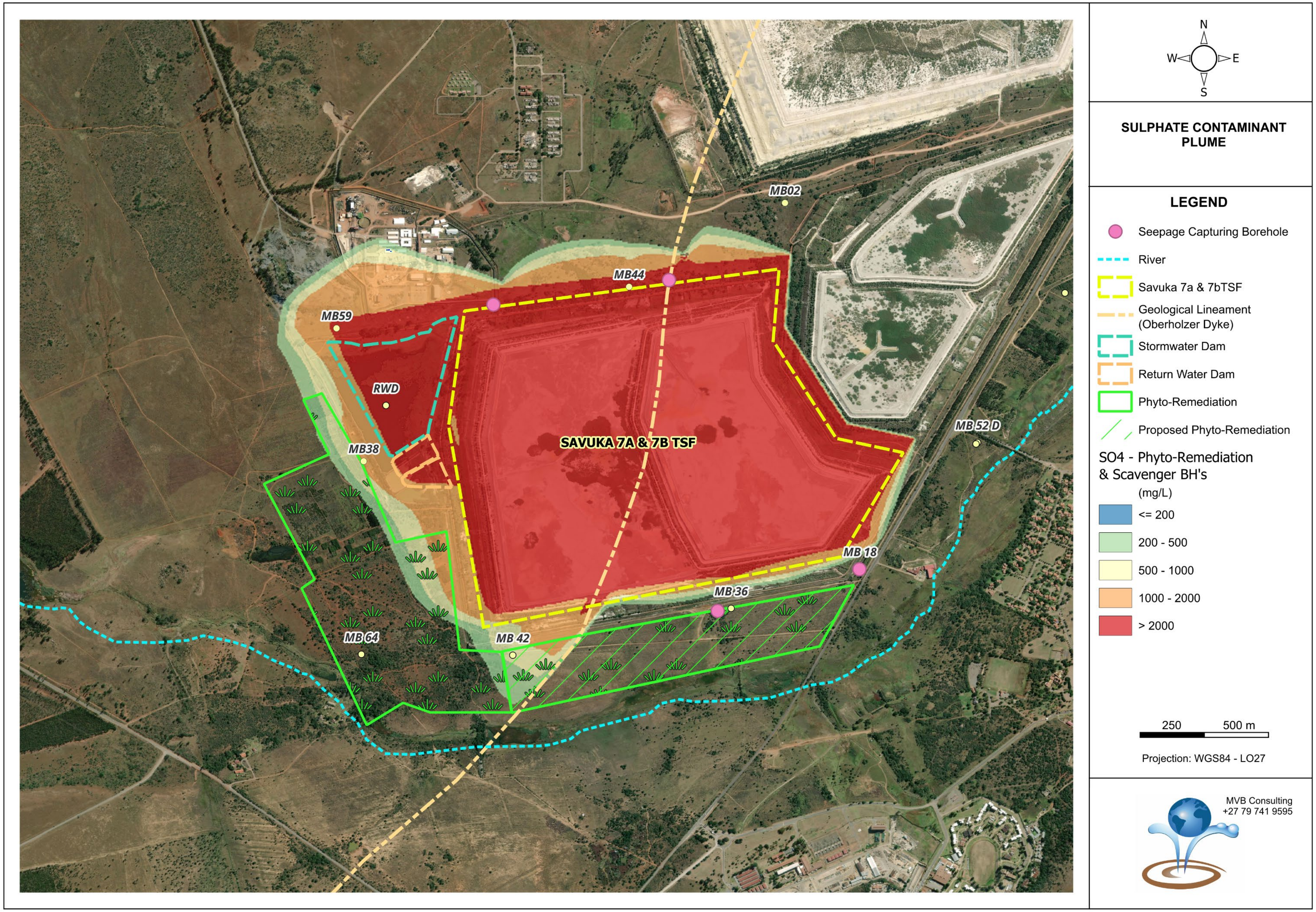

Figure 5.6: **Simulated sulphate plume after 50 years with seepage capturing boreholes supplementing the phyto-remediation**

Figure 5.7 shows the simulated effectiveness of the phyto-remediation, based on the expected sulphate concentration in a conceptual borehole immediately down-gradient from the phyto-remediation.

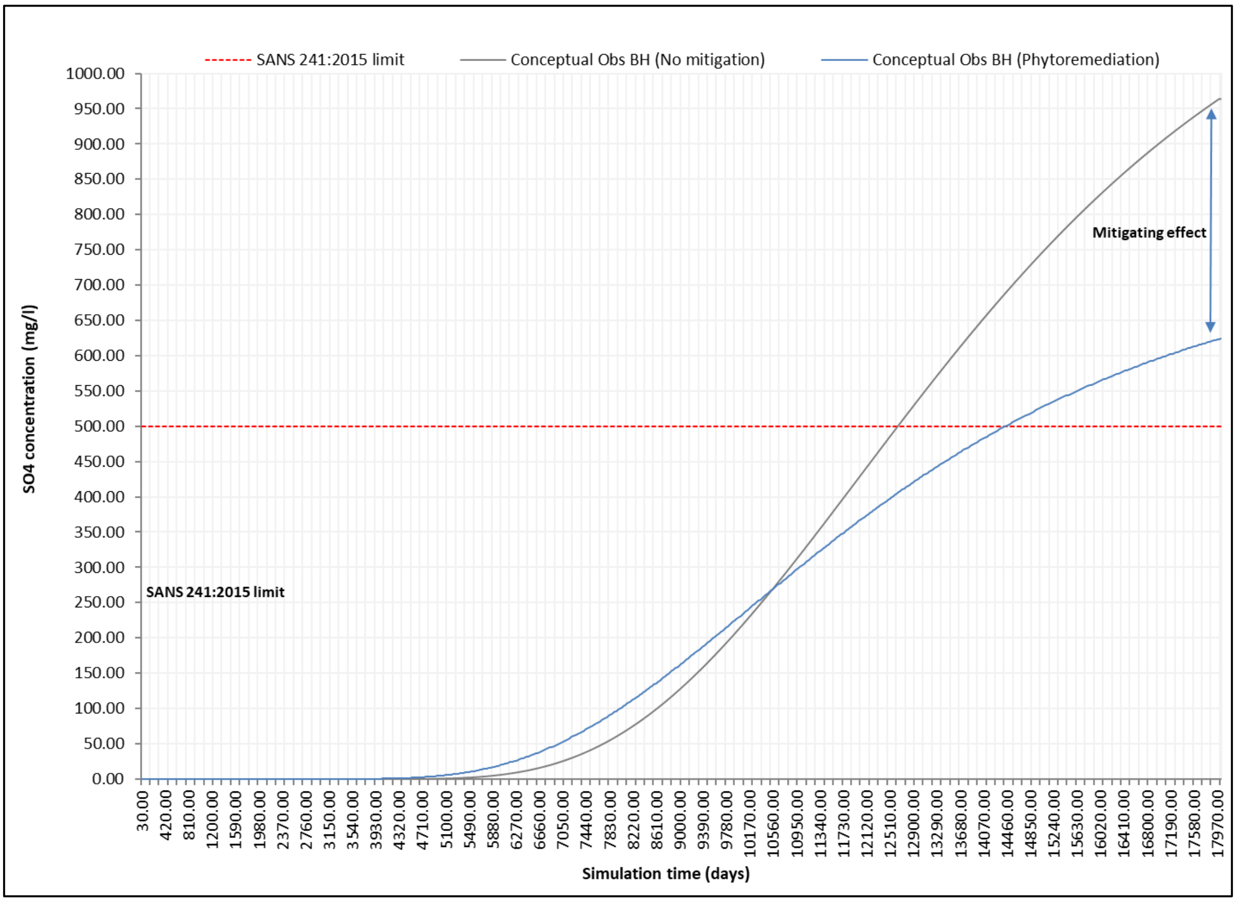

Figure 5.7: Simulated sulphate concentration in an observation borehole over time

It is evident from the graph that the phyto-remediation is very effective in removing contaminants from the groundwater. A summary of the effectiveness of each remedial option is presented in Table 5.1. This is by comparing each option to the Do-Nothing option and based on the 500 mg/L SO_4 impact area.

Table 5.1: Summary of the effectiveness of each remedial option

Remedial Option	500 mg/L SO_4 Impact Area (m_2)	Improvement (Compared to Do-Nothing Option) (m_2)
Current Impact Area	2 857 853	-
Do-Nothing Scenario after 50 Years	4 470 667	-
Lined Return Water Dam	4 123 032	347 635 (7.8%)
Phytoremediation	3 249 323	1 221 344 (27.3%)
Phytoremediation and RWD Lined	3 243 414	1 227 253 (27.5%)
Phytoremediation and Scavenger Boreholes	2 998 986	1 471 681(32.9%)

5.3 Risk Assessment

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

5.3.1 Determination of the Environmental Risk

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

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

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

Each individual aspect in the determination of the consequence is represented by a rating scale as defined in Table 5.2 below.

Table 5.2: 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 5.3.

Table 5.3: 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:

$$ER = C \times P$$

Table 5.4: 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 5.5.

Table 5.5: 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.

5.3.2 Impact Prioritisation

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

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

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

Table 5.6: 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 5. The impact priority is therefore determined as follows:

$$Priority = CI + LR$$

The result is a priority score which ranges from 2 to 6 and a consequent PF ranging from 1 to 2 (refer to Table 5.7).

Table 5.7: 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 5.8: 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.

5.3.3 Impact Assessment Result

The geohydrological impact assessment for the Savuka TSF and RWD is presented in Table 5.8. With reference to Table 5.9 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 (Wonderfonteinspruit tributary).

The following mitigation measures were included in the assessment:

- For the “do-nothing” option (Identifier 1 in the table below) the TSF as well as the RWD remains unlined. The only mitigation is the rehabilitation and decommissioning of the RWD during the closure (decommissioning) phase.
- For Identifier 2 in the table below, the TSF will remain unlined, but a liner in the RWD was considered. This option will change the risk from High Negative to Low Negative during the operational phase. After closure the RWD will be decommissioned and rehabilitated whereafter the risk rating improves marginally.
- For Identifier 3 in the table below, the TSF and RWD will remain unlined, but the existing and proposed phyto-remediation will be fully functional. This option will change the risk from High Negative to Low Negative during the operational phase. After closure the RWD will be decommissioned and rehabilitated whereafter the risk rating improves marginally. This option has the best rating and is the recommended long-term management option.
- For identifier 4 in the table below the phyto-remediation is supplemented with scavenger boreholes. This option will change the risk from High Negative to Low Negative during the operational phase. After closure the RWD will be decommissioned and rehabilitated whereafter the risk rating improves marginally. This option has a slightly lower rating than the previous option, mainly as a result of the higher maintenance costs associated with the borehole maintenance.

Table 5.9: Savuka RWD 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 Savuka RWD (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 Savuka RWD (Lined)	Alternative 2	Operation	-1	4	4	4	4	4	-16	-1	2	3	2	3	2	-5	Medium	2	2	1.25	-6.25
3	Groundwater Contamination from Savuka RWD (Phyto-Remediation)	Alternative 3	Operation	-1	4	4	4	4	4	-16	-1	1	2	1	2	1	-1.5	Medium	1	1	1.00	-1.5
4	Groundwater contamination from Savuka RWD (Phyto-Remediation & Scavenger BH's)	Alternative 4	Operation	-1	4	4	4	4	4	-16	-1	1	2	1	3	2	-3.5	Medium	1	1	1.00	-3.5
1	Groundwater contamination from Savuka RWD (unlined)	Alternative 1	Decommissioning	-1	4	4	4	4	4	-16	-1	4	4	4	3	3	-11.25	Medium	2	2	1.25	-14.0625
2	Groundwater contamination from Savuka RWD (Lined)	Alternative 2	Decommissioning	-1	4	4	4	4	4	-16	-1	2	3	2	2	2	-4.5	Medium	2	2	1.25	-5.625
3	Groundwater Contamination from Savuka RWD (Phyto-Remediation)	Alternative 3	Decommissioning	-1	4	4	4	4	4	-16	-1	1	2	1	2	1	-1.5	Medium	1	1	1.00	-1.5
4	Groundwater contamination from Savuka RWD (Phyto-Remediation & Scavenger BH's)	Alternative 4	Decommissioning	-1	4	4	4	4	4	-16	-1	1	2	1	3	1	-1.75	Medium	1	1	1.00	-1.75

6. GROUNDWATER MONITORING SYSTEM

6.1 Groundwater Monitoring Network

The exiting monitoring network is comprehensive and sufficient to quantify the impact from the RWD and the TSF. The boreholes are generally close to the TSF, referred to as source boreholes. It is important to drill monitoring boreholes further from the contaminant sources to be able to quantify plume migration, as well as close to the property boundary or receptors. These boreholes are referred to as compliance boreholes.

Four additional compliance borehole pairs (one shallow and one deep) are recommended as shown in Figure 6.1. The aim of these boreholes is to monitor the effectiveness of the phyto-remediation. Borehole MB38, which is located inside the phyto-remediation has much better quality than the other monitoring boreholes. Further down-gradient boreholes will confirm that this is because of the phyto-remediation. It is also important to distinguish between the weathered and fractured formations.

The following is recommended in terms of monitoring:

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

6.2 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.

6.3 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).

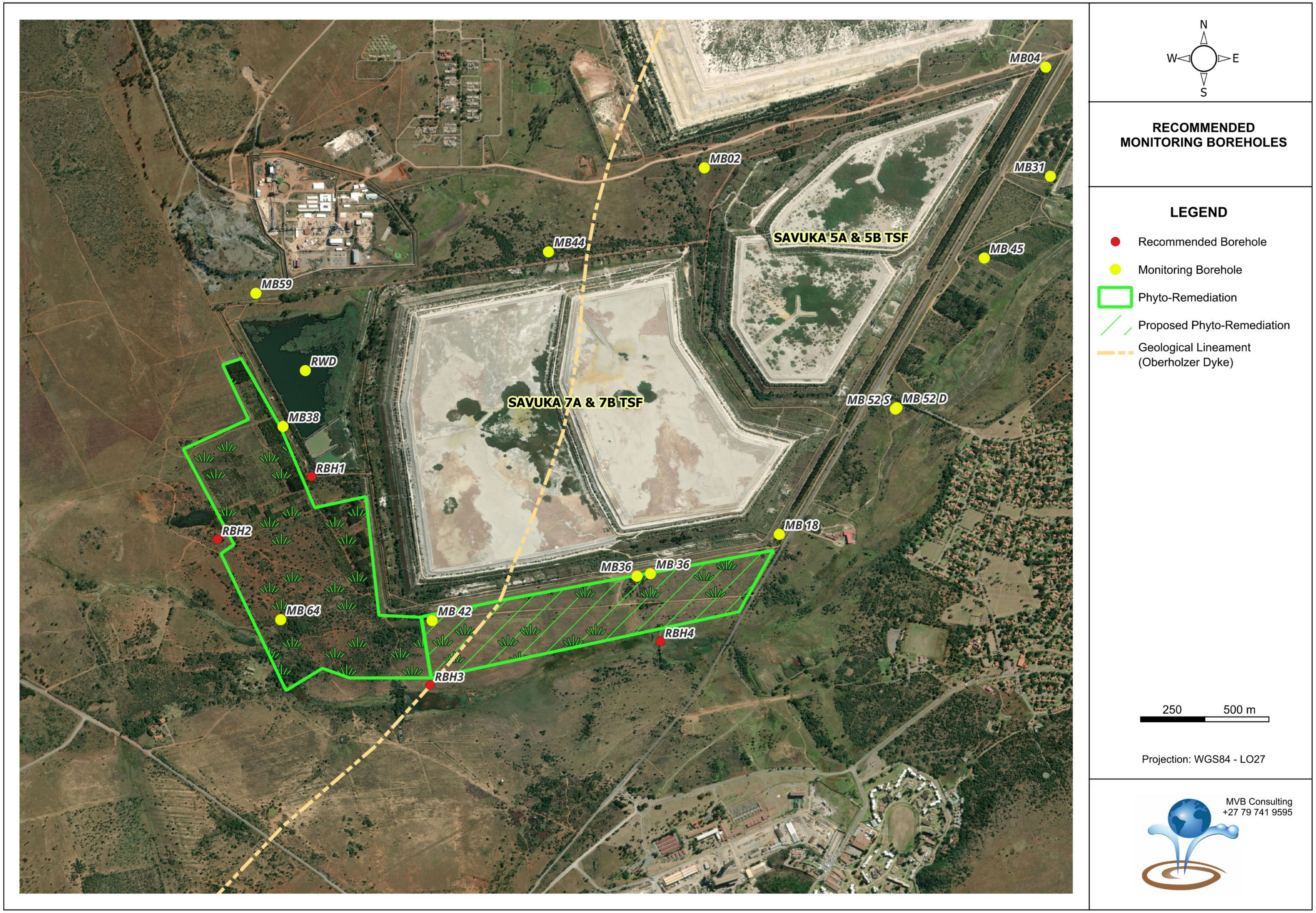

Figure 6.1: Recommended groundwater monitoring network

7. SUMMARY AND CONCLUSIONS

7.1 Study Objectives

Harmony owns and operate 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 7a & 7b TSFs.

Savuka 7a & 7b TSFs are approaching their final and approved height, and the current planned LOM for the West Wits region exceed the available deposition capacity of these TSFs. Accordingly, Harmony is undertaking a feasibility assessment to increase the height of the Savuka 7a & 7b TSFs, by between 5m to 10m.

MVB Consulting was appointed to conduct a geohydrological study to assess the potential groundwater impacts associated with the project.

The purpose of the study is to assess the potential impact from the TSF and Return Water Dam (RWD) on the groundwater regime. A calibrated numerical groundwater flow and mass transport model was developed to simulate the following potential impacts:

- Contaminant seepage from the Savuka TSFs with the extended height and unlined RWD for periods 50- and 100-years.
- Effectiveness of proposed remedial options if the RWD is not lined. This includes the phyto-remediation that is already in place.

7.2 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.

The Savuka 7A & 7B TSF is located on the shale and sandstone of the Timeball Hill formation.

Although the dolomite aquifer is the most prominent aquifer in the region, it does not play any role in the activities at the Savuka TSFs. The dolomite is >500m below surface at the Savuka 7A & 7B 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-west.

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

- The groundwater in the monitoring boreholes show a mining impact, with high TDS and sulphate concentrations.
- Several heavy metals exceed the SANS 241 and Livestock Watering guidelines.
- Apart from the Savuka 7a & 7b TSF's, there is also a larger impact from neighbouring tailings facilities.
- Borehole MB38 is anomalous and has much better quality than the other monitoring boreholes. This is attributed to this borehole being located within the phyto-remediation area.

7.3 Groundwater Modelling and Impact Assessment

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

- Contaminant seepage from the Savuka TSFs with the extended height and unlined RWD for periods 50- and 100-years.
- Effectiveness of proposed remedial options if the RWD is not lined. This includes the phyto-remediation that is already in place.

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

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

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

The model network constructed for the site consists of 1 452 117 elements. The network was refined in the vicinity of sources of potential contamination and dewatering.

The model consists of the following layers:

- Layer 1: Weathered formations – 10m thickness.
- Layer 2: Fractured formations – 100m thickness.
- Layer 3: Model base – 100m thickness.

The sulphate concentrations are elevated in the monitoring boreholes and was selected as representative of the potential impacts from the tailings and return water dam. The mass transport model was calibrated by assigning a source term concentration of 2 500 mg/L SO_4 to the tailings seepage and the RWD.

According to records the Savuka TSF was commissioned in 1979 / 1980. The impact from the existing dams were therefore modelled, based on this assumption. The current impact is mainly to the south and west, towards the unnamed tributary of the Wonderfonteinspruit.

Assuming that the existing facility is 44 years old, the average plume migration can be estimated based on Darcy's law. Applying Darcy's law to the study area it is calculated that the groundwater velocity averages a rate of 0.030 m/day or 10.79 m per annum. Over the 44-year period the plume migration is estimated at 475m, which is supported by the numerical modelling. During this time, it is expected that the impact from the TSF has reached the Wonderfonteinspruit tributary to the south.

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

- Lining of the RWD. The TSF will remain unlined.
- Effectiveness of the existing and proposed phyto-remediation over time.
- Implementation of a containment system downgradient from the RWD. This includes interception boreholes, supplementing the existing phyto-remediation.

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. With the liner in the RWD the plume migration from the

TSF continues towards the south, but the westerly migration from the RWD, is contained and the existing impact dissipates over time.

Alternatives to a liner includes the phyto-remediation, with and without supplementary scavenger or interception boreholes. The simulations assumed the following:

- Each tree uses 5 litres / day and there are 1 333 trees / hectare.
- Each scavenger borehole is pumped at 1.5 lit / sec for 24-hours / day.

The effectiveness of the phyto-remediation is remarkable, and it contains the contaminant plume effectively. Including either a lining in the RWD or scavenger boreholes improve the effectiveness of the phyto-remediation, but with very small margins. Considering the costs of a liner and scavenger boreholes, these options are not recommended.

A summary of the effectiveness of each remedial option is presented below. This is by comparing each option to the Do-Nothing option and based on the 500 mg/L SO_4 impact area.

Remedial Option	500 mg/L SO_4 Impact Area (m_2)	Improvement (Compared to Do-Nothing Option) (m_2)
Current Impact Area	2 857 853	-
Do-Nothing Scenario after 50 Years	4 470 667	-
Lined Return Water Dam	4 123 032	347 635 (7.8%)
Phytoremediation	3 249 323	1 221 344 (27.3%)
Phytoremediation and RWD Lined	3 243 414	1 227 253 (27.5%)
Phytoremediation and Scavenger Boreholes	2 998 986	1 471 681(32.9%)

8. STUDY CONCLUSION AND RECOMMENDATIONS

The following risks are generally associated with this project:

- 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 (Wonderfonteinspruit tributary).

The following mitigation measures were included in the assessment:

- Option 1: For the “do-nothing” option (Identifier 1 in the table below) the TSF as well as the RWD remains unlined. The only mitigation is the rehabilitation and decommissioning of the RWD during the closure (decommissioning) phase.
- Option 2: In this option the TSF will remain unlined, but a liner in the RWD was considered. This option will change the risk from High Negative to Low Negative during the operational phase. After closure the RWD will be decommissioned and rehabilitated whereafter the risk rating improves marginally.
- Option 3: In this option the TSF and RWD will remain unlined, but the existing and proposed phyto-remediation will be fully functional. This option will change the risk from High Negative to Low Negative during the operational phase. After closure the RWD will be decommissioned and rehabilitated whereafter the risk rating improves marginally. This option has the best rating and is the recommended long-term management option.

- Option 4: In this option the phyto-remediation is supplemented with scavenger boreholes. This option will change the risk from High Negative to Low Negative during the operational phase. After closure the RWD will be decommissioned and rehabilitated whereafter the risk rating improves marginally. This option has a slightly lower rating than the previous option, mainly as a result of the higher maintenance costs associated with the borehole maintenance.

It is evident from the assessment that the phyto-remediation is effective, and it is recommended that it be expanded as proposed. 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. The drilling of additional boreholes down-gradient from the phyto-remediation is nevertheless recommended to confirm and quantify the clean-up of the groundwater.

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GEOHYDROLOGICAL IMPACT ASSESSMENT FOR THE SAVUKA TAILINGS FACILITY, GAUTENG PROVINCE

FINAL REPORT

Report: MVB162/25/B048

APPENDIX A

LABORATORY CERTIFICATES

WATERLAB (Pty) Ltd

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T0391

CERTIFICATE OF ANALYSES

GENERAL WATER QUALITY PARAMETERS

Date received: 2024-12-19 **Date completed:** 2025-01-20

Project number: 1000 **Report number:** 139460 **Order number:**

Client name: MVB Consulting **Contact person:** Mr. M. Van Biljon

Address: PO Box 2166, Rant en Dal, 1751 **e-mail:** marius@mvbconsult.co.za

Telephone: 079 741 9595 **Facsimile:** **Mobile:** 079 741 9595

Analyses in mg/ℓ (Unless specified otherwise)		**Method Identification**	Sample Identification: Savuka Project			
			MB52D	MB52S	MB18	MB36
Sample Number			24-31821	24-31822	24-31823	24-31824
Date/Time Sampled			N/A	N/A	N/A	N/A
pH - Value @ 25 ºC	A	WLAB065	6.0	5.9	5.6	5.7
Electrical Conductivity in mS/m @ 25°C	A	WLAB065	300	380	422	371
Total Dissolved Solids @ 180°C	A	WLAB003	2702	3458	3796	3246
Total Alkalinity as $CaCO_3$	A	WLAB007	36	<5	<5	28
Chloride as Cl	A	WLAB046	209	289	294	277
Sulphate as SO_4	A	WLAB046	1390	1661	1892	1529
Fluoride as F	A	WLAB014	<0.2	<0.2	<0.2	<0.2
Nitrate as N	A	WLAB046	0.7	0.4	2.5	0.4
Ortho Phosphate as P	A	WLAB046	<0.1	<0.1	<0.1	<0.1
Free and Saline Ammonia as N	A	WLAB046	0.1	0.3	0.9	1.8
Sodium as Na	A	WLAB015	168	248	369	338
Potassium as K	A	WLAB015	5.9	6.4	9.7	8.3
Calcium as Ca	A	WLAB015	357	297	409	306
Magnesium as Mg	A	WLAB015	179	289	191	216
Aluminium as Al	A	WLAB015	0.213	0.184	0.317	0.189
Arsenic as As	A	WLAB050	0.002	<0.001	0.001	<0.001
Barium as Ba	A	WLAB015	0.029	<0.025	0.028	<0.025
Boron as B	A	WLAB015	<0.025	<0.025	<0.025	<0.025
Total Chromium as Cr	A	WLAB015	<0.025	<0.025	<0.025	<0.025
Cobalt as Co	A	WLAB015	0.140	<0.025	1.03	0.288
Copper as Cu	A	WLAB015	<0.010	<0.010	<0.010	<0.010
Iron as Fe	A	WLAB015	0.687	12	3.64	6.01
Lead as Pb	A	WLAB050	0.013	0.005	0.010	0.004
Manganese as Mn	A	WLAB015	3.84	3.47	16	11
Mercury as Hg	A	WLAB050	<0.001	<0.001	<0.001	<0.001
Nickel as Ni	A	WLAB015	<0.025	<0.025	0.081	<0.025
Selenium as Se	A	WLAB050	<0.001	0.001	0.001	0.001
Strontium as Sr	N	WLAB015	0.291	0.196	0.692	0.460

A. van de Wetering - Chemical Technical Signatory

Start date of analysis: 2024/12/19 Date of Issue: 2025/01/20

Sampled by: Client

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			MB52D	MB52S	MB18	MB36
Sample Number			24-31821	24-31822	24-31823	24-31824
Date/Time Sampled			N/A	N/A	N/A	N/A
Uranium as U	A	WLAB050	<0.001	<0.001	<0.001	<0.001
Zinc as Zn	A	WLAB015	<0.025	<0.025	0.058	0.045
% Anion-Cation Balance	N	---	94.2	92.6	95.4	91.1

A. van de Wetering - Chemical Technical Signatory

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Analyses in mg/ℓ (Unless specified otherwise)		**Method Identification**	Sample Identification: Savuka Project			
			MB64	MB45 Artesian	MB42	SD Dam
Sample Number			24-31825	24-31826	24-31827	24-31828
Date/Time Sampled			N/A	N/A	N/A	N/A
pH - Value @ 25 ºC	A	WLAB065	6.2	5.8	6.5	7.8
Electrical Conductivity in mS/m @ 25°C	A	WLAB065	263	349	173	485
Total Dissolved Solids @ 180°C	A	WLAB003	2420	3296	1514	4412
Total Alkalinity as $CaCO_3$	A	WLAB007	80	52	92	76
Chloride as Cl	A	WLAB046	285	249	157	369
Sulphate as SO_4	A	WLAB046	814	1548	562	2096
Fluoride as F	A	WLAB014	<0.2	<0.2	<0.2	0.7
Nitrate as N	A	WLAB046	4.6	0.2	1.8	3.4
Ortho Phosphate as P	A	WLAB046	<0.1	<0.1	<0.1	<0.1
Free and Saline Ammonia as N	A	WLAB046	0.1	0.4	<0.1	7.9
Sodium as Na	A	WLAB015	46	199	25	418
Potassium as K	A	WLAB015	1.0	9.0	2.0	44
Calcium as Ca	A	WLAB015	330	327	243	685
Magnesium as Mg	A	WLAB015	179	255	92	52
Aluminium as Al	A	WLAB015	0.201	0.212	0.108	2.38
Arsenic as As	A	WLAB050	<0.001	0.053	<0.001	0.017
Barium as Ba	A	WLAB015	<0.025	0.042	<0.025	0.028
Boron as B	A	WLAB015	<0.025	<0.025	<0.025	<0.025
Total Chromium as Cr	A	WLAB015	<0.025	<0.025	<0.025	<0.025
Cobalt as Co	A	WLAB015	<0.025	1.18	<0.025	0.594
Copper as Cu	A	WLAB015	<0.010	<0.010	<0.010	2.70
Iron as Fe	A	WLAB015	0.116	14	0.528	5.57
Lead as Pb	A	WLAB050	0.002	0.094	0.002	0.027
Manganese as Mn	A	WLAB015	0.025	5.80	0.048	5.64
Mercury as Hg	A	WLAB050	<0.001	<0.001	0.003	0.001
Nickel as Ni	A	WLAB015	<0.025	0.150	<0.025	1.75
Selenium as Se	A	WLAB050	<0.001	<0.001	0.001	0.004
Strontium as Sr	N	WLAB015	0.875	0.527	0.430	1.89

A. van de Wetering - Chemical Technical Signatory

Start date of analysis: 2024/12/19 Date of Issue: 2025/01/20

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Results marked "Subcontracted Test" in this report are not included in the SANAS Scope of Accreditation for this Laboratory.

Sample condition acceptable unless specified on the report.
Microbiological standards dictate that zero cannot be reported in cases where no growth is observed. The requirement is to then report as <1cfu/g or ml. A result of <1 implies the absence of the specific test organism and is the lowest reportable result where no growth was detected.

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Analyses in mg/ℓ (Unless specified otherwise)		Method Identification	Sample Identification: Savuka Project			
			MB64	MB45 Artesian	MB42	SD Dam
Sample Number			24-31825	24-31826	24-31827	24-31828
Date/Time Sampled			N/A	N/A	N/A	N/A
Uranium as U	A	WLAB050	<0.001	<0.001	0.001	0.382
Zinc as Zn	A	WLAB015	<0.025	0.253	<0.025	1.49
% Anion-Cation Balance	N	---	89.5	93.2	93.0	97.8

A. van de Wetering - Chemical Technical Signatory

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