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TETRA 4 GAS PRODUCTION CLUSTER 2 EIA HYDROGEOLOGICAL BASELINE INVESTIGATION AND GROUNDWATER IMPACT ASSESSMENT

October 2022

Conducted on behalf of:
Environmental Impact Management Services (Pty) Ltd

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- I act as the independent specialist in this application.
- I will perform the work relating to the application in an objective manner, even if this results in views and findings that are not favourable to the applicant.
- I declare that there are no circumstances that may compromise my objectivity in performing such work.
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- All the particulars furnished by me in this form are true and correct.

JFW Mostert (Hydrogeologist)

M.Sc. Hydrogeology, Pr.Sci.Nat.

Executive summary

Gradient Consulting (Pty) Ltd was appointed by Environmental Impact Management Services (Pty) Ltd to conduct a hydrogeological baseline investigation and groundwater impact assessment to be conducted to support an Environmental Impact Assessment (EIA) and Water Use Licence Application (WULA) authorisation process to be followed. The project entails expansion of the existing Tetra 4 natural gas production development and will include a combined helium and liquid natural gas (LNG) plant, gas wells and the associated pipelines and compressor infrastructure.

The objective of this investigation is to determine the status quo of the regional groundwater system and aim to quantify and qualify potential impacts of the proposed expansion project on sensitive environmental and groundwater receptors.

The gas production right and greater study area covers a total area of ~187 000ha and falls within the Free State Province of South Africa.

The topography of the greater study area is generally flat and can be classified as a central interior plain or plateau. The lowest topographical elevation on-site is recorded as ~1280.0mamsl which is situated towards the western and eastern borders where the Sandrivier enters and exists the gas production right boundary and form part of the on-site drainage system. The highest topographical point recorded on site is approximately 1405.0mamsl and form part of the quaternary catchment boundary and groundwater/ surface water divide to the southern and south-western portion of the study area.

The greater study is situated in primary catchment (C) of the Vaal River drainage system which falls under the Vaal Water Management Area. The project area is situated within quaternary catchments C42K and C42L.

The hydrology of the region is characterised by predominately perennial watercourses with the regional drainage occurring in a general west to north-western direction via the Sandrivier and Doringrivier both of which are traversing the study area from east to west (Sandrivier) and southeast to northwest (Doringrivier). A non-perennial drainage, Bosluisspruit, also traverse the study area and generally drain the catchment in a northern direction.

The study area's rainfall is strongly seasonal, and the weather pattern reflects a typical summer rainfall region, with > 80.0% of precipitation occurring as convective thunderstorms from October to March. The calculated mean annual precipitation (MAP) for this rainfall zone is 521.0mm/a, with the 5th percentile of the data set (roughly equivalent to a 1:20 year drought period) calculated at 343.38mm/a while the 95th percentile (representing a 1:20 flood period) is calculated at 752.43mm/a. The mean annual evaporation (s-pan) ranging between 1600mm/a to 1680mm/a, more than threefold the annual precipitation.

The project area's surficial geology comprises mostly aeolian sands, quaternary deposits and isolated outcrops of the Karoo Supergroup i.e., dolerite and sandstone/ shales, while the greater study area is generally also underlain by rocks of the Witwatersrand Supergroup as well as the Ventersdorp Supergroup. Isolated patches within the study area are also covered by alluvial sand deposits which is mainly associated with the Sand and Doringriver floodplains and constrained by drainage patterns and riparian zones. The primary source of gas originates from the Witwatersrand Supergroup as well as the shallower Karoo sediments.

According to the DWS Hydrogeological map the site is predominantly underlain by an intergranular and fractured aquifer system (d2) with the aquifer media consisting mainly of fractured and weathered compact argillaceous strata. According to Vegter's groundwater regions delineated (2000) the study area can be classified as falling under the North-eastern Pan Belt region.

For the purposes of this investigation, four main hydrostratigraphic units/aquifer systems can be inferred in the saturated zone:

i. **A shallow quaternary and recent types of sediments** (unconfined) are characteristically a primary porosity aquifer associated with alluvium material deposited in flood plains of the main rivers traversing the study area. These aquifers cover a large portion of the study area and are limited to a zone of variable width and depth. The alluvial aquifer is specifically vulnerable to contamination as it there is a direct connectivity with rivers and streams and associated high permeability.

ii. **A shallow, intergranular aquifer** (unconfined to semi-confined) occurring in the transitional soil and weathered bedrock formations of the Karoo Supergroup rocks underlain by more consolidated bedrock. Groundwater flow patterns usually follow the topography, discharging as natural springs at topographic low-lying areas. Usually, this aquifer can be classified as a secondary porosity aquifer and is generally unconfined with phreatic water levels. Due to higher effective porosity (*n)* this aquifer is most susceptible to impacts from contaminant sources.

iii. **An intermediate, fractured aquifer** (semi-confined to confined) where pores are well-cemented and do not allow any significant flow of water. Groundwater flow is dictated by transmissive secondary porosity structures such as bedding plane fractures, faults, contact zones as well as fracture zones that occur in the relatively competent Karoo Supergroup host rock. Fractured sandstones, mudstones and shales sequences are considered as fractured rock aquifers holding water in storage in both pore spaces and fractures. This aquifer system usually displays semi-confined or confined characteristics with piezometric heads often significantly higher than the water-bearing fracture position. Although generally low yielding, this aquifer is important to local groundwater users as it form the sole source of water supply in the region (Lea, 2017).

iv. **A deeper, fractured aquifer** (semi-confined to confined) where pores are well-cemented and do not allow any significant flow of water. Groundwater flow is dictated by transmissive secondary porosity structures such as bedding plane fractures, faults and contact zones fracture zones that occur in the relatively competent Ventersdorp and Witwatersrand Supergroups host rock. Volcanic formations of the Ventersdorp lavas can also act as aquicludes, restricting the vertical movement of groundwater. Fractured quartzites of the Witwatersrand Supergroup are considered as fractured rock aquifers holding water in storage in both pore spaces and fractures. Groundwater yields, although more heterogeneous, can be expected to be higher than the weathered zone aquifer. This aquifer system usually displays semi-confined or confined characteristics with piezometric heads often significantly higher than the water-bearing fracture position.

The water in the deep aquifers is naturally saline due to their marine depositional history. It should be noted that the shallow potable Karoo aquifers are separated from deep aquifer systems associated with the Ventersdorp and Witwatersrand Supergroup formations by the 30.0m thick dolerite sill (which may act as an aquitard) that extends across the study area and by the 65.0m thick Dwyka Tillite sedimentary deposit acting as an aquiclude. It should furthermore be noted that, under natural conditions, there is very limited hydraulic connectivity between the deep, fractured and shallow, intergranular aquifers.

The hydraulic conductivity of sedimentary formations such as evident on site can range from $10E^{-6}$ – $10E^{-2}$ m/d. Historical aquifer tests results confirm that the permeability of the shales is very low ($9E^{-4}$m/d). The hydraulic conductivity of fractured igneous rocks (i.e., dolerite) varies between $10E^{-6}$ – $10E^{-1}$ m/d, while conductivity values for un-fractured igneous rocks (i.e., fresh dolerite sill) ranges between $10E^{-9}$ – $10E^{-6}$ m/d. The hydraulic conductivity of quaternary deposits and alluvial pockets associated with the drainage system i.e., riverbed aquifers can be orders higher and can vary between $10E^{-2}$ – $10E^{1}$ m/d.

An approximation of recharge for the study area is estimated at ~4.0% of MAP i.e., ~21.69mm/a.

A total of 78 groundwater receptors i.e., boreholes, artesian wells, wind pumps as well as surface water features were visited as part of the hydrocensus user survey which are largely applied for livestock watering and domestic water supply purposes. Of the boreholes recorded, the majority are in use (>78.0%) while ~17.0% are not currently being utilized.

The unsaturated zone within the study area is in the order of 0 (fully saturated to surface) to >26.0m with a mean thickness of approximately ~9.0m. It should be noted that due to the argillaceous nature of the host aquifer(s) the shallow water levels observed at some of the borehole localities can be attributed to clay/silt lenses and be indicative of perched aquifer conditions and not necessarily represent the vadose zone.

Artesian conditions were observed at three of the boreholes visited namely HBH31, 21B as well as 8B which can be indicative of semi-confined to confined aquifer conditions present or perched aquifer conditions. The minimum water level was recorded at 0.0mbgl, while the deepest water level was measured at borehole locality Mon-HDR1 (26.71mbgl).

It is noted that most water levels suggest a decrease in water levels and recovering trend. The latter can be attributed the onset of the wet cycle and above average rainfall events experienced with rainfall recharge replenishing aquifer storage. It can be observed that there is a definite a relatively quick response to rainfall, suggesting that recharge of the shallow, intergranular aquifer takes place without a prolonged lag effect. Statistical analyses of the water level trends furthermore suggest that the local groundwater system is in quasi-steady state conditions.

Analysed data indicate that the surveyed water levels correlate very well to the topographical elevation (R^2 <0.98). Accordingly, it can be assumed that the regional groundwater flow direction is dictated by topography. Bayesian interpolation was used to interpolate the groundwater levels throughout the study area.

The inferred groundwater flow direction will be towards the lower laying drainage system(s) traversing the project area from where groundwater will discharge as baseflow. The groundwater flow direction within the southern catchment of the Sandrivier and Doringrivier, also in the vicinity of the proposed plant expansion footprint, will be in a general northern direction, whereas the groundwater flow direction within the northern catchment of the study area will be mostly in a south to southwestern direction.

The average groundwater gradient (i) of the shallow, weathered aquifer in the vicinity of the proposed plant expansion footprint is relatively flat and calculated at a mean of 0.002, with a maximum of 0.003 in a south to north orientation and a minimum of 0.001 in a general southeast to northwest orientation.

The expected seepage rate from contamination originating at the proposed plant expansion footprint as well as associated infrastructure is estimated at an average of approximately 1.26m/a, with a maximum distance of ~2.20m/a in a southern to northern direction.

Under natural conditions this area exhibits certain regions where there is pronounced interaction between surface and groundwater and regional drainages can be generally classified as influent or gaining stream systems. The alluvial associated with the floodplains of the Sand - and Doringrivier forms a primary aquifer and is directly connected with surface water resources, especially during high flow conditions.

The hydrochemical results of the hydrocensus boreholes water samples analysed suggest the overall ambient groundwater quality is good with most macro and micro determinants falling within or below the SANS 241:2015 limits. Groundwater can be described as neutral, saline to very saline and hard to very hard. The groundwater quality is impacted by the geological formations, which were deposited in shallow marine environments and are therefore naturally saline.

It is observed that most of the boreholes indicate elevated Nitrate (NO_3) concentrations. The latter may be attributed to the agricultural land-use activities dominating the greater study area with elevated NO_3 concentrations potentially derived from leachate of fertilizer to the local aquifer. It is noted that borehole localities with elevated NO_3 concentrations are situated within or directly down-gradient of planted crop areas as well as near surface water features.

Surface water quality can be classified as moderate to good with Aluminum (Al) and Iron (Fe) being slightly elevated. It should be noted that there is not a significant change in the downstream water quality compared to the upstream quality with an increase in Aluminum (Al), however all surface water samples analysed suggest elevated heavy metal concentrations i.e., Al and Fe.

Three distinct categories can be observed, Category A: Calcium-Bi-carbonate dominance which suggest a recently recharged and unimpacted groundwater environment (majority of samples), Category B: Calcium-Magnesium-Chloride dominance which indicate a static and disordinate environment as well as Category C: Sodium-Potassium-Bi-carbonate dominance which indicate an area of dynamic groundwater environments.

The surface water samples analysed can be categorized as having Calcium-Magnesium-Chloride dominance which indicate a static and disordinate environment, one would except a more Calcium-Bi-carbonate signature from an unpolluted surface water source, however baseflow discharge present from the saline groundwater resource will have an impact on the salinity of the surface water resources as is evident.

Comparison of different hydrochemical signatures observed suggest on-site boreholes to target a shallow, inter-granular aquifer unit as well as a deeper (possibly intermediate, fractured aquifer unit) being more saline.

The Sodium-Potassium-Chloride dominance of the deep, fractured aquifer groundwater suggests extremely saline conditions as expected.

According to the aquifer classification map of South Africa the project area is underlain by a “Minor aquifer”. It should however be noted that the shallow, intergranular aquifer is important to local groundwater users as it forms the sole source of water supply in the region. Furthermore, the primary riparian zone aquifer is classified as a major aquifer system due to its highly permeable nature as well as good water quality.

A GQM Index = 4 was calculated for the local aquifer system and according to this estimate, a “Medium” level groundwater protection is required for this aquifer system. According to the DRASTIC index methodology applied, the existing/proposed activities and associated infrastructure’s risk to groundwater pollution of the shallow, intergranular aquifer is rated as “Moderate”, Di = 109.

A numerical groundwater flow and mass transport migration model was developed and calibrated in steady state based on gathered site characterisation information which was applied as initial hydrogeological conditions for transient simulations.

A scenario was simulated representing point source pollution plume migration of saline groundwater emanating from leaking boreholes targeting the deep, fractured aquifer for the operational phase (20-year period). The TDS pollution plume extend covers a total area of approximately 414.06ha in the Karoo formations, reaching a maximum distance of ~80.0m in a radial pattern from the gas production borehole(s), and approximately 251.60ha in the alluvial deposits, reaching a maximum distance of ~200.0m in a radial pattern from the gas production borehole(s) after a simulation period of 20-years. The simulation indicates that the following neighbouring boreholes will potentially be intercepted by the simulated pollution plume HBH08, HBH41, HBH42, HBH43, HBH63, HBH72, HBH73 and HBH74.

It can be noted that the pollution plume migration in the denser Karoo formations is sluggish while movement in the unconsolidated alluvial deposits of the riparian zone suggest a larger flux.

It is evident that source term mass load contribution to existing neighbouring borehole situated near the gas production borehole(s) does not exceed ~800.0mg/l and ranges between 600mg/l to 700.0mg/l.

A scenario was simulated representing point source pollution plume migration of stray methane (CH_4) gas emanating from leaking boreholes targeting the deep, fractured aquifer for the operational phase (20-year period). The CH_4 pollution plume extend covers a total area of approximately 162.74ha in the Karoo formations, reaching a maximum distance of ~50.0m in a radial pattern from the gas production borehole(s), and approximately 62.83ha in the alluvial deposits, reaching a maximum distance of ~100.0m in a radial pattern from the gas production borehole(s) after a simulation period of 20-years. The simulation indicates that the following neighbouring boreholes will potentially be intercepted by the simulated pollution plume HBH08, HBH41, HBH42, HBH43, HBH63, HBH72, HBH73 and Tetra4 monitoring borehole 11A.

It is noted that the source term mass load contribution to existing neighbouring borehole situated near the gas production borehole(s) remains below the EPA safety threshold (2011) of 10.0mg/l and ranges between 0.01mg/l to 1.50mg/l.

A scenario was simulated with a pollution plume migration from the plant footprint areas for the operational phase. The TDS pollution plume extend covers a total area of approximately 48.80ha reaching a maximum distance of ~110.0m in a general north-northwest direction towards the lower laying drainage system(s) after a simulation period of 20-years. The simulation indicates that no neighbouring boreholes or local drainages are expected to be impacted on during the operational phase.

It is evident that the TDS mass load contribution to down-gradient receptors increase to a concentration of between 200.0 – 800.0 mg/l, however, remains below the SANS 241:2015 limit of 1200.0mg/l for the duration of the simulation period.

It can be noted that the mass transport of the pollution plume is mostly limited to the shallow, intergranular aquifer.

A scenario was simulated representing point source pollution plume migration of saline groundwater emanating from leaking boreholes targeting the deep, fractured aquifer for the post-closure phase. The TDS pollution plume extend covers a total area of approximately 643.70ha in the Karoo formations, reaching a maximum distance of ~100.0m in a radial pattern from the gas production borehole(s), and approximately 392.70ha in the alluvial deposits, reaching a maximum distance of ~250.0m in a radial pattern from the gas production borehole(s) after a simulation period of 50-years. The TDS pollution plume extend covers a total area of approximately 1 456.42ha in the Karoo formations, reaching a maximum distance of ~150.0m in a radial pattern from the gas production borehole(s), and approximately 769.70ha in the alluvial deposits, reaching a maximum distance of ~350.0m in a radial pattern from the gas production borehole(s) after a simulation period of 100-years. The simulation indicates that the following neighbouring boreholes will potentially be intercepted by the simulated pollution plume HBH08, HBH41, HBH42, HBH43, HBH48, HBH50, HBH63, HBH72, HBH73, HBH74 as well as Tetra4 monitoring boreholes Mon 2057 and 11A.

It is noted that source term mass load contribution to existing neighbouring and monitoring boreholes situated near the gas production boreholes ranges between 650.0mg/l to >1200.0mg/l. Furthermore, it is observed that the SANS241:2015 limit is exceeded at borehole localities HBH63 and Mon 2057.

A scenario was simulated representing point source pollution plume migration of stray methane (CH_4) gas emanating from leaking boreholes targeting the deep, fractured aquifer for the post-closure phase. The CH_4 pollution plume extend covers a total area of approximately 414.06ha in the Karoo formations, reaching a maximum distance of ~80.0m in a radial pattern from the gas production borehole(s), and approximately 141.37ha in the alluvial deposits, reaching a maximum distance of ~150.0m in a radial pattern from the gas production borehole(s) after a simulation period of 50-years. The CH_4 pollution plume extend covers a total area of approximately 643.70ha in the Karoo formations, reaching a maximum distance of ~100.0m in a radial pattern from the gas production borehole(s,) and approximately 392.70ha in the alluvial deposits, reaching a maximum distance of ~250.0m in a radial pattern from the gas production borehole(s) after a simulation period of

100-years. The simulation indicates that the following neighbouring boreholes will potentially be intercepted by the simulated pollution plume HBH08, HBH41, HBH42, HBH43, HBH48, HBH49, HBH63, HBH72, HBH73 as well as Tetra4 monitoring boreholes Mon 2057 and 11A.

It is evident that source term mass load contribution to existing neighbouring and monitoring boreholes situated near the gas production boreholes ranges between 0.50mg/l to ~2.0mg/l, however, remains below the EPA safety threshold (2011) of 10.0mg/l.

A scenario was simulated with a pollution plume migration from the plant footprint areas for the post-closure phase. The TDS pollution plume extend covers a total area of approximately 54.8ha reaching a maximum distance of ~170.0m in a general north-northwest direction towards the lower laying drainage system(s) after a simulation period of 50-years and covers a total area of approximately 71.20ha reaching a maximum distance of ~300.0m in a general north-northwest direction towards the lower laying drainage system(s) after a simulation period of 100-years. It is evident that the pollution plume potentially reaches the local drainages system down-gradient of the plant footprint during the post-closure phase.

It is observed that the TDS mass load contribution to down-gradient receptors increase to a concentration above the SANS 241:2015 limit of 1200.0mg/l for the post-closure simulation period. It is noted that the TDS mass load contribution increases to a percentage of ~10.0% to the Sandrivier where the mass load contribution to the Doringrivier increase to a percentage of ~2.0% for the duration of the post-closure simulation period.

It should be noted that vast areas within the study area have been subjected to historical mining activities and, as such, reflect modified to highly modified present ecological status. A total number of >15 000 historical exploration wells have been drilled throughout the study area, some of which remain uncased and unsealed. The latter may act as preferential pathways and conduits for groundwater flow and contaminant transport mechanisms. As mentioned earlier an impact can be defined as any change in the physical-chemical, biological, cultural and/or socio-economic environmental system that can be attributed to human and/or other related activities. Accordingly, this already highly modified zones should form part of the impact significance rating and risk approach. During the construction phase the environmental significance rating of groundwater quality impacts on down-gradient receptors are rated as **medium negative** without implementation of remedial measures and **low negative** with implementation of proposed mitigation measures. The main impacts associated with the construction phase activities include the following:

- Groundwater deterioration and siltation due to contaminated stormwater run-off from the construction area.
- Poor quality leachate may emanate from the construction camp which may have a negative impact on groundwater quality.
- Mobilisation and maintenance of heavy vehicles and machinery on-site may cause hydrocarbon contamination of groundwater resources.
- Poor storage and management of hazardous chemical substances on-site may cause groundwater pollution.

During the operational phase the environmental significance rating of groundwater quality impacts on down-gradient receptors are rated as **medium** to **high negative** without implementation of remedial measures and **low** to **medium negative** with implementation of proposed mitigation measures. The main impacts associated with the operational phase activities include the following:

- Migration of saline groundwater from the deep, fractured aquifer to the overlying, potable aquifer(s) during the gas production phase.
- Migration of stray methane (CH_4) gas from the deep, fractured aquifer to the overlying, potable aquifer(s) during the gas production phase.
- Groundwater pollution because of wastewater spills and seepage from the evaporation dams.
- Poor quality leachate may emanate from the plant footprint area which may have a negative impact on groundwater quality.
- Mobilisation and maintenance of heavy vehicle and machinery on-site may cause hydrocarbon contamination of groundwater resources.
- Poor storage and management of hazardous chemical substances on-site may cause groundwater pollution.
- Leakage of harmful substances from tanks, pipelines or other equipment may cause groundwater pollution.
- Leachate of contaminants used in the drilling mud sump(s) to the intergranular, potable aquifer(s) during the operational phase.

During the decommissioning and post-closure phase the environmental significance rating of groundwater quality impacts on down-gradient receptors are rated as **medium negative** without implementation of remedial measures and **low** to **medium negative** with implementation of proposed mitigation measures. The main impacts associated with the post-closure and decommissioning phase activities include the following:

- Migration of saline groundwater from the deep, fractured aquifer to the overlying, potable aquifer(s) during the borehole closure and decommissioning phase.
- Migration of stray methane (CH_4) gas from the deep, fractured aquifer to the overlying, potable aquifer(s) borehole closure and decommissioning phase.
- Groundwater pollution because of wastewater spills and seepage from the evaporation dams.
- Poor quality leachate may emanate from the plant footprint area which may have a negative impact on groundwater quality.
- De-mobilisation of heavy vehicle and machinery as part of the decommissioning phase on-site may cause hydrocarbon contamination of groundwater resources.

The most significant impact of the project on the regional groundwater regime is deterioration of the potable Karoo aquifer water quality as well as modification of the riparian zone primary porosity aquifer associated with alluvium material deposited in flood plains. Groundwater is the sole water resource to the landowners and rural communities within the study area and can thus be classified as a sole source aquifer. It can be concluded that, should the prescribed mitigation and management measures, as stipulated in the groundwater management plan, be implemented and honoured, the impacts associated with the project phases can be minimised. It is important that an integrated groundwater monitoring program be developed and applied serving as an early warning and detection mechanism to implement mitigation measures. The calibrated groundwater flow model should be applied as groundwater management tool for future scenario predictions.

The following recommendations are proposed following this investigation:

i. Mitigation and management measures as set out in the groundwater management plan should be implemented as far as practically possible. It should be noted that the mitigation and management measures recommended in this report should be incorporated into the existing EMPr groundwater management plan and do not substitute the existing mitigation measures, but rather supplement them.

ii. Any development and/or drilling which takes place within the primary porosity aquifer associated with alluvium material deposited in flood plains must be avoided where possible and restricted if it cannot be avoided.

iii. The identified hydrogeological sensitive areas and buffer zones delineated as part of this assessment must be adhered to during the construction and operational phase activities. It is recommended that a localised hydrocensus user survey be performed within a 500.0m radius of each proposed gas production borehole situated within the riparian zone(s) and 350.0m radius of each proposed gas production borehole situated within the Karoo formations in order to identify the presence of other sensitive groundwater receptors and/or private boreholes. Accordingly, the gas production well design must take the results of the hydrocensus into consideration, specifically with regard to the planning and placement of boreholes as part of future drilling programmes.

iv. Additional monitoring boreholes should be established down-gradient of the existing and proposed plant expansion footprints to evaluate the mass load contribution to sensitive environmental and groundwater receptors. Drilling localities should be determined by means of a geophysical survey to target lineaments and weathered zones acting as preferred groundwater flow pathways and contaminant transport mechanisms.

v. It is recommended that the revised monitoring program as set out in this report should be implemented and adhered to. It is imperative that monitoring be conducted to serve as an early warning and detection system. Monitoring results should be evaluated on a bi-annual basis by a suitably qualified person for interpretation and trend analysis and submitted to the Regional Head: Department of Water and Sanitation.

vi. The numerical groundwater flow modelling assumptions should be verified and confirmed. The calibrated groundwater flow model should be updated on a biennial basis as newly gathered monitoring results become available to be applied as groundwater management tool for future scenario predictions.

vii. All preferred groundwater flow pathways which are in direct connection with surface topography such as decommissioned gas production boreholes as well as historical mining exploration boreholes should be sealed off and rehabilitated according to best practise guidelines.

List of Abbreviations

ASTM	**American Society for Testing Materials**
Avg	**Average**
BH	**Borehole**
CMB	**Chloride Mass Balance**
CNG	**Compressed Natural Gas**
CV	**Coefficient of Variation**
b	**Saturated Thickness**
DMR	**Department of Environmental Affairs**
DEM	**Digital Elevation Model**
DRASTIC	**DI Index**
DWS	**Department of Water Affairs and Sanitation**
EC	**Electrical Conductivity (mS/m)**
EA	**Environmental Authorisation**
EIA	**Environmental Impact Assessment**
EMPr	**Environmental Management Programme**
E.N.	**Electro Neutrality**
EPA	**United States Environmental Protection Agency**
ha	**Hectares**
GIS	**Geographic Information Systems**
GN	**Government Notice**
GQM	**Groundwater Quality Management**
i	**Hydraulic gradient (dimensionless)**
I& AP	**Interested and Affected Party**
ICP-OES	**Inductively coupled plasma optical emission spectrometer**
ICP-MS	**Inductively coupled plasma mass spectrometry**
IWULA	**Integrated Water Use License Application**
ISP	**Internal Strategic Perspective**
K	**Hydraulic Conductivity (m/d)**
l/s	**Litre per second**
LNG	**Liquid Natural Gas**
m^3/d	**Cubic meters per day**
MAE	**Mean Annual Evaporation OR Mean Absolute Error**
mamsl	**Metres Above Mean Sea Level**
MAP	**Mean Annual Precipitation**
MAR	**Mean Annual Runoff**
mbgl	**Metres Below Ground Level**
mcm	**Million Cubic Metres**
ME	**Mean Error**
meq/L	**Mili-equivalents per litre**
mg/l	**Milligrams per litre**
mm/a	**Millimetre per annum**
n	**Porosity**
NAWL	**No Access to Water Level**
NGA	**National Groundwater Archive**
NGDB	**National Groundwater Database**

NRMSD	**Normalised Root Mean Square Deviation**
NWA	**National Water Act (Act 36 of 1998)**
REV	**Representative Elementary Value**
RMSE	**Root Mean Square Error**
S	**Storage coefficient**
Sc	**Specific Storage**
SoW	**Scope of Work**
SANAS	**South African National Accreditation System**
SANS	**South African National Standards**
T	**Transmissivity (m^2/d)**
TDS	**Total Dissolved Solids**
UNESCO	**The United Nations Educational, Scientific and Cultural Organisation**
USGS	**United States Geological Survey**
WGS	**World Geodetic System**
WM	**With Mitigation**
WOM	**Without Mitigation**
WULA	**Water Use Licence Application**

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1. INTRODUCTION

1.1. Project background

Gradient Consulting (Pty) Ltd was appointed by Environmental Impact Management Services (Pty) Ltd (hereafter referred to as EIMS) to conduct a hydrogeological baseline investigation and groundwater impact assessment to be conducted to support an Environmental Impact Assessment (EIA) and Water Use Licence Application (WULA) authorisation process to be followed.

The project entails the Tetra 4 natural gas production development which operates under an existing production right (PASA Ref. 12/4/1/07/2/2) as well as environmental authorisation and associated water use licence for their current gas production activities (referred to as Cluster 1). The Tetra 4 Cluster 2 natural gas production project entails the expansion of the existing natural gas production and will include a combined helium and liquid natural gas (LNG) plant, gas wells and the associated pipelines and compressor infrastructure.

This report focuses on the status quo of the regional groundwater system and aims to quantify and qualify potential impacts of the proposed expansion project on sensitive environmental and groundwater receptors.

1.2. Objectives

The objective of this investigation is to:

i. Establish site baseline and background conditions and identify sensitive environmental receptors.

ii. Determine the current status quo of the regional groundwater system including aquifer classification, aquifer unit delineation and vulnerability.

iii. Development of a conceptual groundwater flow model.

iv. Development of a numerical groundwater flow and mass transport model to quantify and qualify the potential impact of the gas extraction as well as simulate potential saline water migration towards the shallow aquifer.

v. Hydrogeological impact assessment and risk matrix.

vi. Recommendations on best practise mitigation and management measures to be implemented.

vii. Compilation of an integrated groundwater monitoring network and protocol.

1.3. Terms of reference

The investigation is based on the terms of reference and scope of work (SoW) as detailed in proposal ref.no. HG-P-21-055-V1, submitted in September 2021. This project plan and scope of work was compiled based on the following guidelines and regulations:

i. Government Notice NO. R. 267: Regulations regarding the procedural requirements for water use licence applications.

ii. Government Gazette No. 40713, dated 24 March 2017 and Government Gazette No. 40772 dated 07 April 2017 in terms of the National Environmental Management Act, 1998 (Act No. 107 of 1998)

(NEMA).

iii. Best Practice Guidelines (BPG4 – Impact Prediction) as published by the former Department of Water Affairs and Sanitation (DWS, 2008).

1.3.1. Phase A: Desk study and gap analysis

Phase A will entail the following activities:

i. Information gathering and data acquisition.

ii. Desk study and review of historical groundwater baseline information, existing specialist reports as well as DWS supported groundwater databases i.e., national groundwater archive (NGA).

iii. Fatal flaw and gap analysis.

1.3.2. Phase B: Hydrogeological baseline assessment - hydrocensus user survey, hydrochemical analysis and aquifer classification

Phase B will entail the following activities:

will entail the following activities:

i. Hydrocensus user survey to evaluate and verify existing surface and groundwater uses, local and neighbouring borehole locations and depths, spring localities and seepage zones, regional water levels, abstraction volumes, groundwater application as well as environmental receptors in the vicinity of the proposed gas exploration area.

ii. Sampling of existing boreholes and surface water bodies according to best practise guidelines and analyses of water samples to determine the macro and micro inorganic chemistry and hydraulic connections based on hydrochemistry (analyses at SANAS accredited laboratory).

iii. Assess the structural geology and geometry of the aquifer systems with respect to hydraulic interactions and compartmentalisation.

iv. Data interpretation aiding in aquifer classification, delineation and vulnerability ratings. Development of a scientifically defendable hydrogeological baseline.

v. Compilation of geological, hydrogeological and hydrochemical thematic maps summarising the aquifer system(s), indicating aquifer delineation, groundwater piezometric map, depth to groundwater, groundwater flow directions as well as regional geology.

1.3.3. Phase C: Numerical groundwater flow and contamination transport model update

Phase C will entail the following activities:

i. Development of a conceptual hydrogeological model in conjunction with interpreted geology data and gathered site characterisation information.

ii. Development of a regional numerical groundwater flow model by applying the Finite Element Flow

(FEFLOW) modelling software. Model domain to include proposed infrastructure and gas exploration footprint as well as associated activities.

iii. Calibration of groundwater flow model using site specific data including hydrocensus geosites information.

iv. Development of a numerical mass transport model utilizing the calibrated groundwater flow model as basis.

v. The calibrated model will be used to simulate management scenario's as follows:

   a. Steady state groundwater flow directions, hydraulic gradient and flow velocities.

   b. Seepage potential from waste facilities and mass transport plume migration with time.

   c. Hydrochemical migration of deeper, saline water towards the shallow aquifer and plume propagation with time.

   d. Migration of dissolved gas within the aquifer units and plume migration with time.

   e. Post-closure scenarios.

   f. Water management alternatives and best practice mitigation measures.

1.3.4. Phase D: Hydrogeological impact assessment update and reporting

Phase D will entail the following activities:

i. Compilation of a detailed hydrogeological specialist investigation update report with conclusions and recommendations on the following aspects:

   a. Fatal flaw and gap analyses.

   b. Site baseline characterisation.

   c. Field work summary and interpretation.

   d. Aquifer classification and vulnerability.

   e. Numerical groundwater flow and mass transport model development, calibration and simulations.

   f. Formulation of an impact assessment and risk matrix of proposed activities.

   g. Recommendation on best practise mitigation and management measures to be implemented.

ii. Development of an integrated surface water and groundwater monitoring program for implementation.

1.4. Details and expertise of the author

Ferdinand Mostert is a consulting hydrogeologist and specializes in providing hydrogeological advisory and supporting services. He holds a M.Sc. in Hydrogeological from the Institute of Groundwater Studies (IGS) at the

University of the Free State and is a registered Professional Scientist in the Water Resource Sciences field. His experience of 13$^+$ years include environmental impact and risk assessments, hydrogeological baseline assessments, aquifer sustainability studies contamination risk assessments, numerical groundwater flow and mass transport modeling, mine dewatering designs, groundwater due diligence studies, groundwater resource development, integrated groundwater and surface water management as well as practical implementation and decision-making approaches. He also has thorough knowledge and understanding of the National Water Act (Act 36 of 1998) and has in excess of 10 years' experience in compliance auditing focusing mainly on external water use licence audits. He has worked in all provinces throughout South Africa as well as sub-Saharan Africa countries, and his experience includes commodities such as iron ore, gold, coal and platinum. The details of the author(s) who prepared this report are summarised in Table 1-1 below.

Table 1-1 Details of the authors.

Author	Ferdinand Mostert
Highest qualification	M.Sc. Hydrogeology
Years' experience	13$^+$
Professional registration	SACNASP Member (Reg. No 40057/14 – Water Resource Science). Member of the Groundwater Division of the Geological Society of South Africa (MGSSA).

1.5. Available information

The following information was available and used in this investigation:

i. Aquiworx software. 2016. Version 2.5.2.0. Centre for Water Sciences and Management at the North-West University.
ii. Barnard, H. C., 2000. An explanation of the 1:500 000 general Hydrogeological Map. Kroonstad 2726.
iii. Chief Directorate. Surveys and Mapping. 2003. Cape Town, 2826BA, 2826BB, 2826BC, 2826BD [Map]. Edition 9. Scale 1:50,000. Mowbray, South Africa: Chief Directorate of Surveys and Mapping.
iv. Council of Geoscience geological map sheet 2826: Winburg (1:250 000).
v. Department of Water Affairs: Directorate Hydrological Services, 2012. Aquifer classification of South Africa.
vi. Department of Water Affairs: Directorate Hydrological Services, 2012. Aquifer susceptibility of South Africa.
vii. Department of Water Affairs: Directorate Hydrological Services, 2012. Aquifer vulnerability of South Africa.
viii. Department of Water Affairs and Forestry, South Africa. 2004. Internal Strategic Perspective: Middle Vaal Water Management Area. Prepared by PDNA, WMB and WRP on behalf of the Directorate National Water Resources Planning. Report no. 09/000/00/0304.
ix. ESRI basemaps, 2022.
x. Google Earth, 2022. 6.0.12032 Beta.
xi. i.lEH. 2017. *Tetra 4 Cluster 1 Production Right EIA Hydrogeological Specialist Report.* Report No iLEH-EIMS MOL-1 05-15.
xii. Lynch, S.D., Reynders, A.G. and Schulze, R.E., 1994: A DRASTIC approach to groundwater vulnerability mapping in South Africa. SA Jour. Sci., Vol. 93, pp 56 - 60.

i. JR Vegter, DWS and WRC, 1995. Groundwater Resources of the Republic of South Africa.
ii. Parsons, R, 1995. A South African Aquifer System Management Classification, Water Research Commission, WRC Report No KV 77/95.
iii. Tetra 4. 2021/2022. Monthly Groundwater Monitoring Data.
iv. van Tonder and Xu, 2000. Program to estimate groundwater recharge and the Groundwater Reserve.
v. Water Research Commission (WRC), 2012. Water Resources of South Africa.

1.6. Project assumptions and limitations

Data limitations were addressed by following a conservative approach and assumptions include the following:

i. The scale of the investigation was set at 1:50 000 resolutions in terms of topographic and spatial data, a lower resolution of 1:250 000 scale for geological data and a 1: 500 000 scale resolution for hydrogeological information.
ii. The Digital Elevation Model (DEM) data was interpolated with a USGS grid spacing of 25.0m intervals.
iii. Rainfall data and other climatic data was sourced from the WR2012 database.
iv. Water management and catchment-based information was sourced from the GRDM and Aquiworx databases.
v. The concept of representative elementary volumes (REV) has been applied i.e., a scale has been assumed so that heterogeneity within a system becomes negligible and thus can then be treated as a homogeneous system. The accuracy and scale of the assessment will result in deviations at point e.g. individual boreholes.
vi. The investigation relied on data collected as a snapshot of field surveys and existing monitoring data. Further trends should be verified by continued monitoring as set out in the monitoring program.
vii. Stratigraphical units, as delineated from surface geology within the model domain, are assumed to occur throughout the entire thickness of the model and were incorporated as such.
viii. The geological structures (fault zones and dyke contact zones) were modelled as permeable linear zones.
ix. The model basement i.e., competent Karoo basement or Dwyka tillite/diamictite is assumed to generally be impermeable and serves to isolate the fractured Karoo aquifer from the fractured pre-Karoo aquifer units.
x. Model calibration was achieved by assigning a ratio of 1:1 for Hydraulic Conductivity (K) in x and y directions, with a ratio of 1:10 in the z direction i.e., anisotropic aquifer (except for alluvial deposits which were assigned at a 1:1 ratio).
xi. Perennial rivers within the model domain have been treated as gaining type streams. As such groundwater is lost from the system via baseflow to local drainages.
xii. Groundwater divides have been assumed to align with surface water divides and it is assumed that groundwater cannot flow across this type of boundaries.
xiii. The numerical groundwater flow model was developed considering site specific information. It should be stated that influences from neighbouring mining developments were not taken into consideration

as part of this investigation.

xiv. Prior to development, the system is in equilibrium and therefore in steady state.

xv. Where data was absent or insufficient, values were assumed based on literature studies and referenced accordingly[1]

2. METHODOLOGY

The groundwater impact assessment was undertaken by applying the methodologies as summarised below.

2.1. Desk study and review

This task entails the review of available geological and hydrogeological information including DWS supported groundwater databases (NGA/ Aquiworx), existing specialist reports, development plans as well as climatic and other relevant groundwater data. Data collected was used to delineate various aquifer and hydrostratigraphic units, establish the vulnerability of local aquifers, aquifer classification as well as aquifer susceptibility.

2.2. Evaluation of potential environmental receptors

A hydrocensus user survey was conducted in February 2022 in which high-risk environmental receptors have been identified. The hydrocensus user survey will evaluate and verify existing surface and groundwater uses, local and neighbouring borehole locations and depths, spring localities and seepage zones, regional water levels, abstraction volumes, groundwater application as well as environmental receptors in the vicinity of the existing gas production operations.

2.3. Hydrochemical analysis

Water samples collected were submitted at a SANAS accredited laboratory to determine the macro and micro inorganic chemistry and potential hydraulic connections present. SANS 241:2015 Drinking Water Standards was applied and used a guideline for all water quality analysis.

2.4. Hydrogeological baseline description

Based on the gathered groundwater and site characterisation data a baseline description of the current status quo of the regional groundwater system including aquifer classification, aquifer unit delineation and vulnerability is formulated.

2.5. Development of a conceptual hydrogeological model

The hydrogeological conceptual model consists of a set of assumptions, which will aid in reducing the problem statement to a simplified and acceptable version. Data gathered during the desk study and site investigation has been incorporated to develop a conceptual understanding of the regional hydrogeological system.

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[1] Where model assumptions were made or reference values used, a conservative approach was followed. Data gaps identified should be addressed as part of the model update.

2.6. Numerical groundwater flow and mass transport model development

A numerical groundwater flow and mass transport model was developed based on the defined groundwater conceptual model. The latter will serve as a tool to evaluate various water management options and different scenarios will be applied to quantify and qualify potential groundwater impacts.

2.7. Groundwater impact assessment

Identification of preliminary and potential impacts and ratings related to new developments and/or listed activities are defined based on outcomes of the investigation. An impact can be defined as any change in the physical-chemical, biological, cultural and/or socio-economic environmental system that can be attributed to human and/or other related activities. Risk assessment involves the calculation of the magnitude of potential consequences (levels of impacts) and the likelihood (levels of probability) of these consequences to occur. Mitigation measures were recommended to render the significance of impacts identified.

3. LEGAL FRAMEWORK AND REGULATORY REQUIREMENTS

The following water management legislation should be adhered to:

3.1. The National Water Act (Act 36 of 1998) as amended

The purpose of the National Water Act, 36 of 1998 (“NWA”) as set out in Section 2, is to ensure that the country’s water resources are protected, used, developed, conserved, managed, and controlled, in a way which inter alia considers the reduction, prevention and degradation of water resources. The NWA states in Section 3 that the National Government is the public trustee of the Nation’s water resources. The National Government must ensure that water is protected, used, developed, conserved, managed and controlled in a sustainable and equitable manner for the benefit of all persons and in accordance with its constitutional mandate. Section 22 of the NWA states that a person may only use water without a license if such water use is: permissible under Schedule 1, if that water use constitutes as a continuation of an existing lawful water use, or if that water use is permissible in terms of a general authorization issued under Section 39. Permissible water use furthermore includes water use authorised by a license issued in terms of the NWA or alternatively without a license if the responsible authority dispensed with a license requirement under subsection 3. Section 21 of the National Water Act indicates that water use includes the following:

a. taking water from a water resource (section 21(a));
b. storing water (section 21(b));
c. impeding or diverting the flow of water in a water course (section 21(c));
d. engaging in a stream flow reduction activity contemplated in section 3649 (section 21(d));
e. engaging in a controlled activity which has either been declared as such or is identified in section 37(1)50 (section 21(e));
f. discharging waste or water containing waste into a water resource through a pipe, canal, sewer, sea outfall or other conduit (section 21(f));
g. disposing of waste in a manner which may detrimentally impact on a water resource (section 21(g);

h. disposing in any manner of water which contains waste from, or which has heated in, any industrial or power generation process (section 21 (h));
i. altering the bed, banks, course or characteristics of a water course (section 21(i));
j. removing, discharging or disposing of water found underground if it is necessary for the efficient continuation of an activity or for the safety of people (section 21(j)); and
k. using water for recreational purposes (section 21(k)).

3.2. National Environmental Management Act (Act 107 of 1998) as amended

The National Environmental Management Act 107 of 1998 intends:

i. to provide for co-operative, environmental governance by establishing principles for decision-making on matters affecting the environment, institutions that will promote co-operative governance and procedures for co-ordinating environmental functions exercised by organs of state; and
ii. to provide for matters connected therewith.

3.3. Mineral and Petroleum Resources Development Act (Act 28 of 2002) as amended

The Mineral and Petroleum Resources Development Act 28 of 2002 intends to

i. to make provision for equitable access to and sustainable development of the nation's mineral and petroleum resources; and
ii. to provide for matters connected therewith.

4. STUDY AREA AND LISTED ACTIVITIES

4.1. Regional setting and site locality

The project area is situated on the farm Mond van Doornrivier 38 which is located between Welkom (16.7km SSW), Virginia (14.4km SWW), and Theunissen (30.0km N). The gas production right and greater study area covers a total area of ~187 000ha and falls within the Free State Province of South Africa. The site is accessible via the R30 secondary route from the north as well as the southeast. General site coordinates are listed in Table 4-1 and a map indicating an aerial extent of the greater study area is indicated in Figure 4-1 with the project boundary and topo-cadastral map depicted in Figure 4-2.

Table 4-1 General site coordinates (Coordinate System: Geographic, Datum: WGS84).

Latitude	-28.129°
Longitude	26.718°

4.2. Project description and proposed infrastructure

The Tetra 4 Gas Production Project entails a natural gas production facility within an existing Production Right (PASA Ref. 12/4/1/07/2/2). The extracted gas is compressed and reticulated via pipelines to further infield compressors. From here the gas is piped to a combined helium and liquid natural gas (LNG) plant for processing. The final products (helium and LNG) will be stored temporarily in tankers on site and then trucked away for sale to the end users (EIMS, 2016a). The current development includes a combined helium and LNG plant, gas wells as well as associated pipelines and compressor infrastructure. Refer to Figure 4-3 for an infrastructure and layout map indicating the proposed drilling priorities as well expansion footprints. The planned expansions will include the following:

i. Expansions to the current liquid natural gas (LNG) and Helium production plant located on the Farm Mond van Doorn River. The planned expansions will be to increase the helium and LNG production capacities significantly (~30fold increase) and increase the footprint of the existing approved plant by approximately 10ha.

ii. The drilling of new gas wells ~300 wells spread over a total study area (referred to as Cluster 2) of approximately 27 500ha.

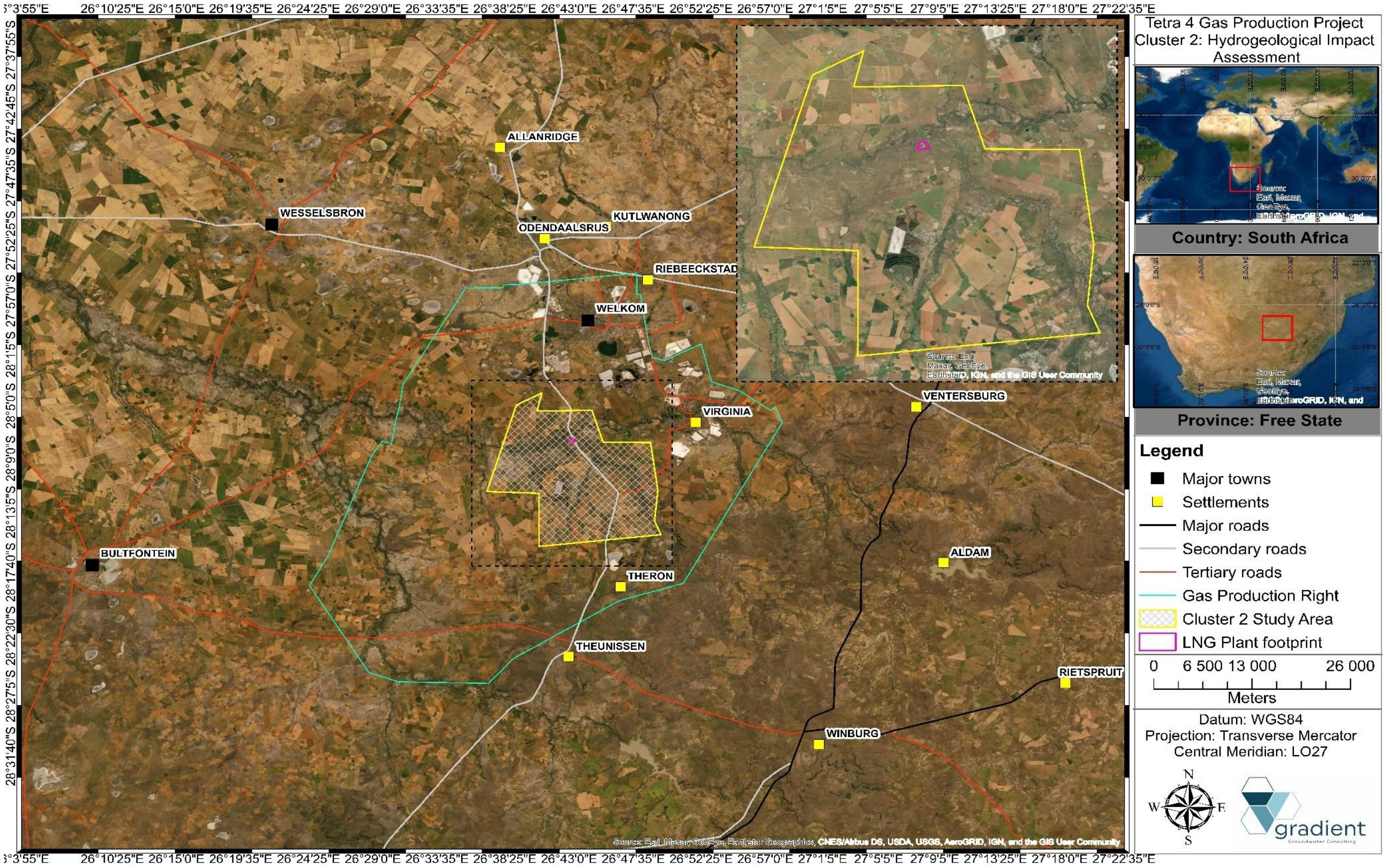

Figure 4-1 **Aerial extent and greater study area.**

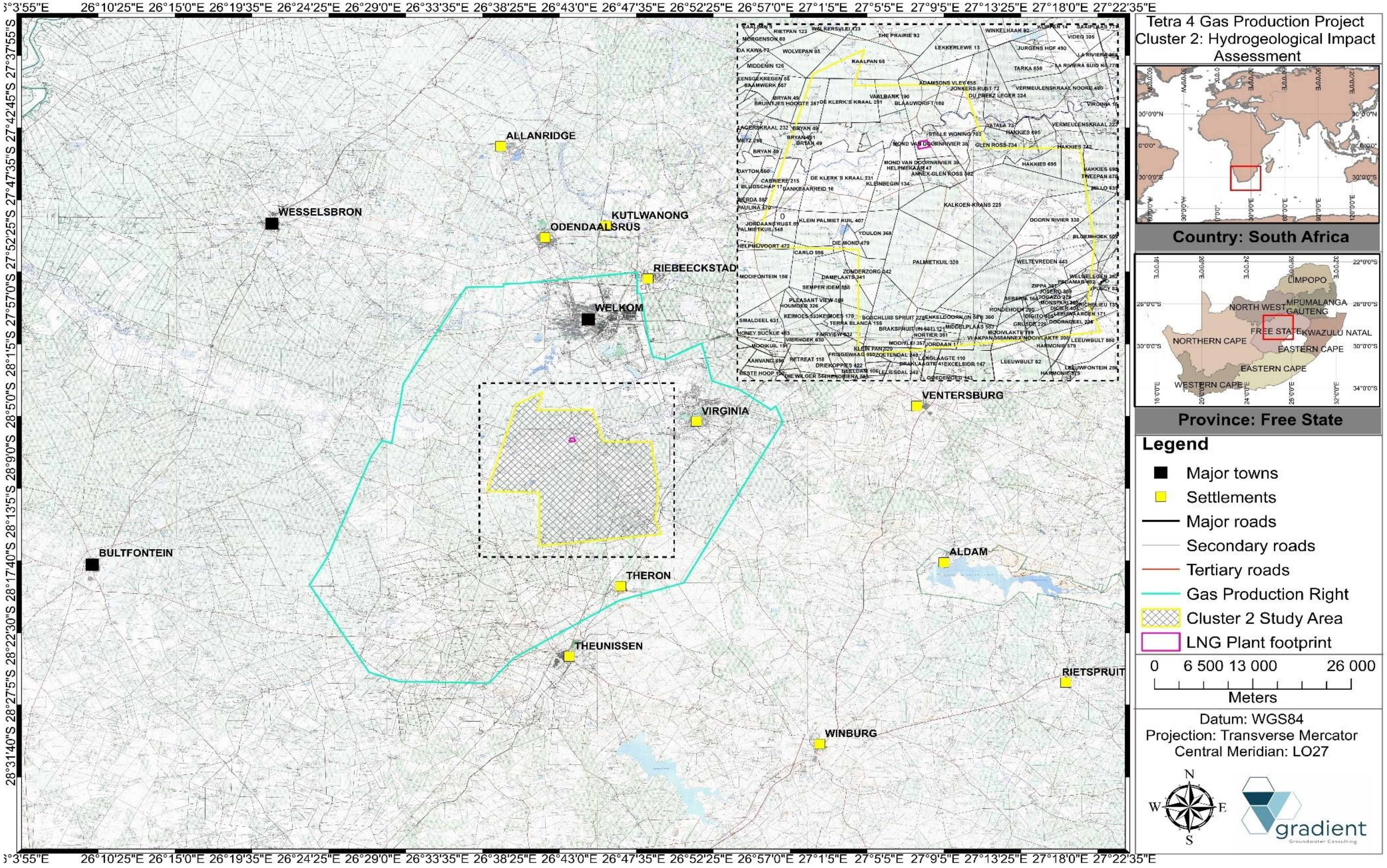

Figure 4-2 **Greater study area (1:50 000 topographical mapsheet 2826BA).**

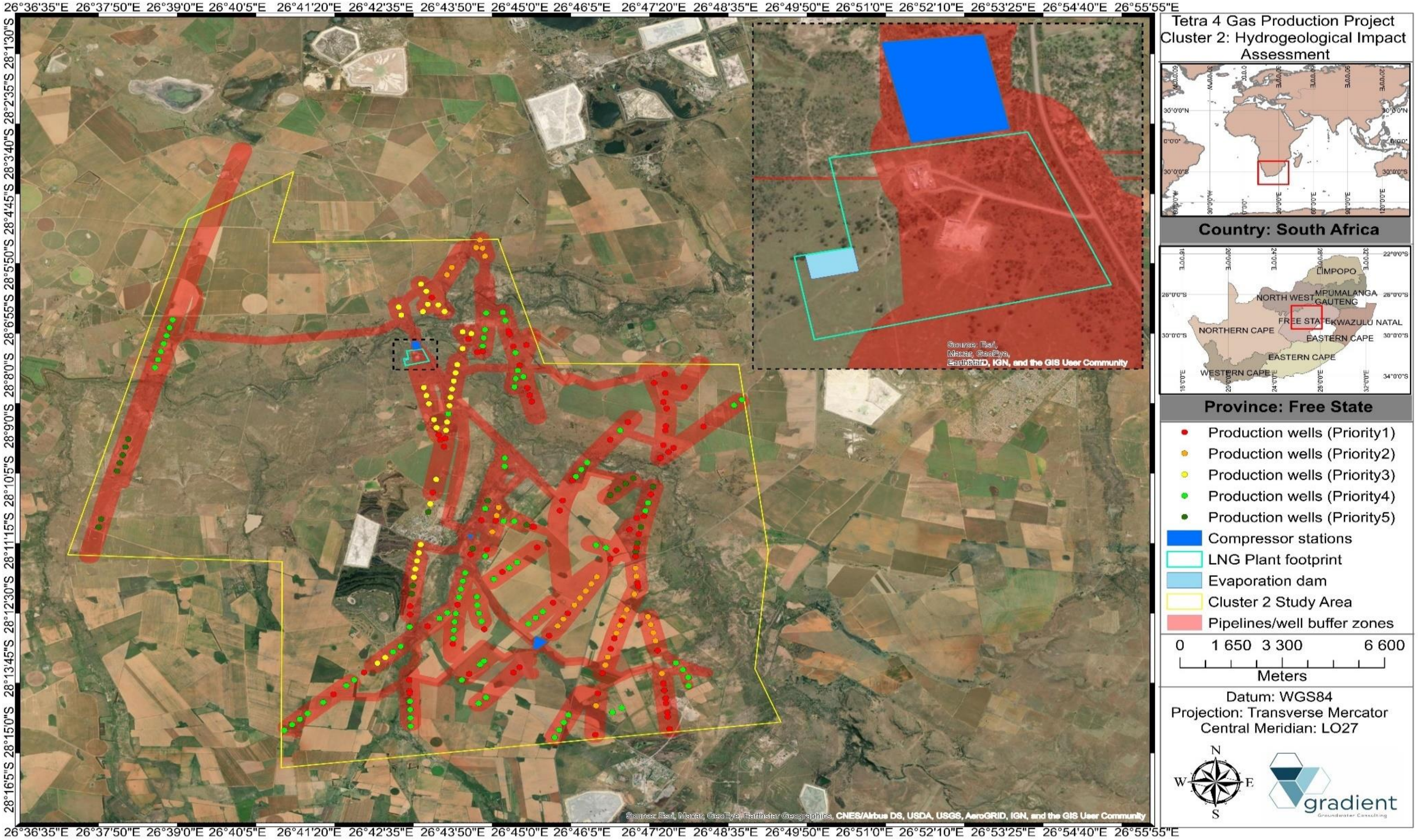

Figure 4-3 **Layout and infrastructrure map.**[2]

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[2] It should be note that the indicated production borehole localities is based on a high level of uncertainty and is subject to change. Borehole positions will however not fall outside of the proposed buffer zone(s).

5. PHYSIOGRAPHY

The following sub-sections evaluate the physiography of the study area.

5.1. Topography

The topography of the greater study area is generally flat and can be classified as a central interior plain or plateau. Large dolerite intrusions are observed throughout the study area and because of its relative resistance to erosion, the Karoo dolerite sheets generally give rise to very prominent high-standing topographic features (DWAF, 2004). The relief of the area varies between 0 – 130.0m. The landscape gradually flattens out towards the lower laying drainage system in the north-west (approximate elevation low of 1250.0mamsl), while the southern and south-eastern perimeters are shaped by scattered outcrops with a regional topographical high point recorded as 1540.0mamsl.

The lowest topographical elevation on-site is recorded as ~1280.0mamsl which is situated towards the western and eastern borders where the Sandrivier enters and exists the gas production right boundary and form part of the on-site drainage system. The highest topographical point recorded on site is approximately 1405.0mamsl and form part of the quaternary catchment boundary and groundwater/ surface water divide to the southern and south-western portion of the study area. On-site gradients are variable, but generally gentle with the average slope calculated at ~0.80% and an elevation loss of 130.0 m over a lateral distance of 16.0km in a north-south orientation whereas an average slope of ~0.40% and elevation loss of 70.0m over a lateral distance of 17.50km is calculated in an east- west orientation. Figure 5-1 depicts a topographical cross-section (south-western aspect) of the greater study area while Figure 5-2 shows the regional topographical contours and setting.

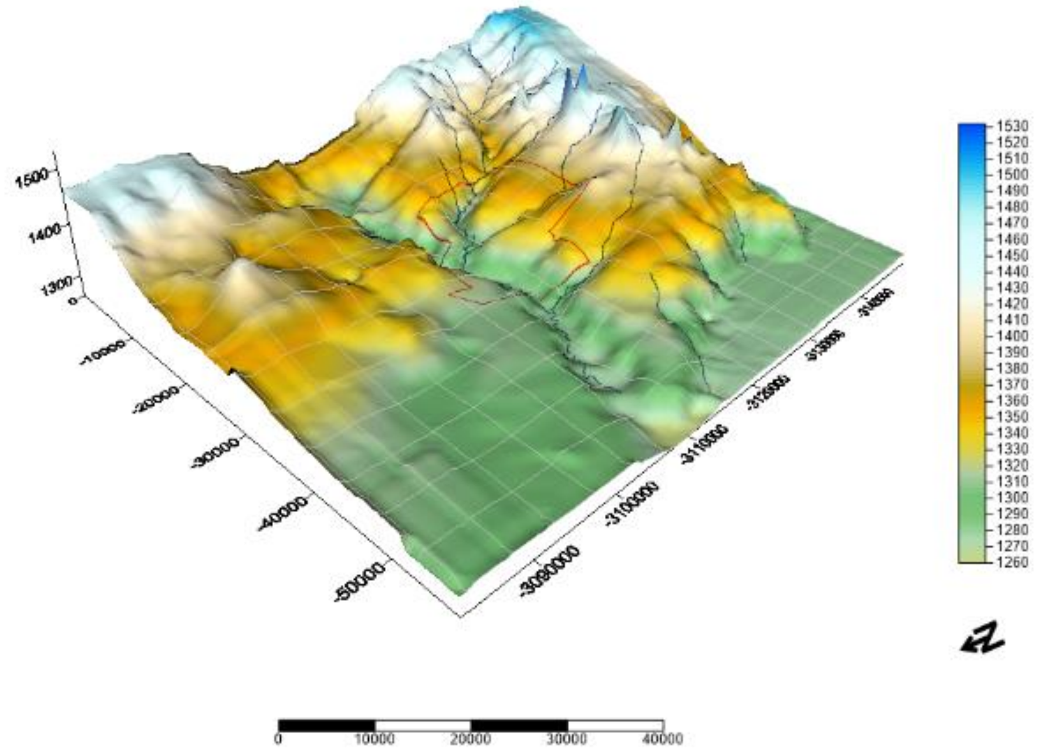

Figure 5-1 **Topographical cross-sections of the greater project area.**

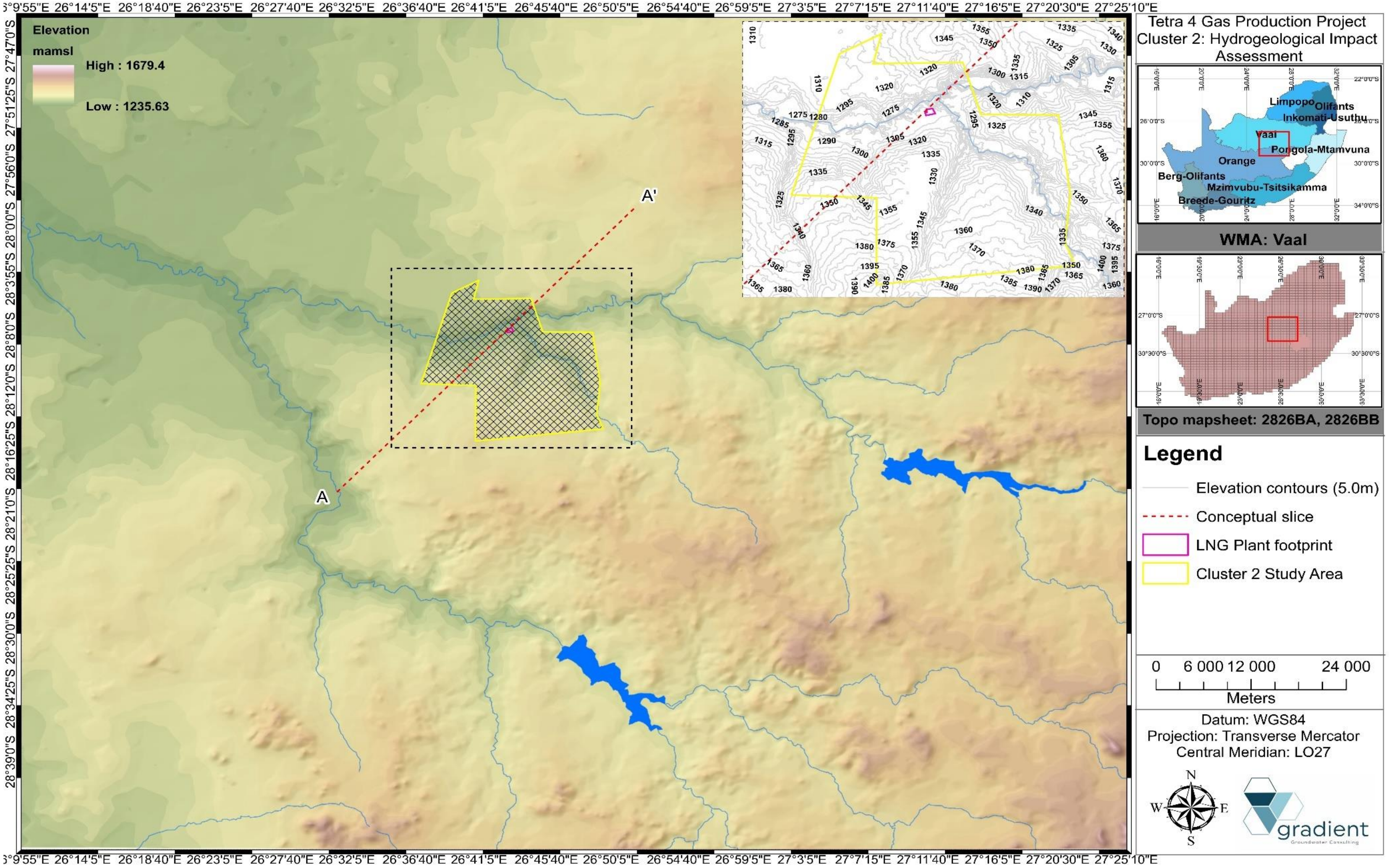

Figure 5-2 Regional topography and conceptual slice (Refer to Figure 11-2).

5.2. Drainage and catchment

The greater study is situated in primary catchment (C) of the Vaal River drainage system which covers a total area of approximately 246 674.5km^2. The resource management falls under the Vaal Water Management Area (WMA5) which spans portions of the North West Province, northern Free State as well northern sections of the Northern Cape.

The project area is situated within quaternary catchments C42K (nett surface area of 668.0km^2) and C42L (nett surface area of 510.8km^2), falls within hydrological zone E and has an estimated mean annual runoff (MAR) of between 10.0 to 13.0mcm (million cubic metres) (WR 2012).

The hydrology of the region is characterised by predominately perennial watercourses with the regional drainage occurring in a general west to north-western direction via the Sandrivier and Doringrivier both of which are traversing the study area from east to west (Sandrivier) and southeast to northwest (Doringrivier). A non-perennial drainage, Bosluisspruit, also traverse the study area and generally drain the catchment in a northern direction. The Doringrivier convergences with the Sandrivier approximately 1.30km to the northeast of the study area from where it flows in a general westerly direction before joining the Vetrivier roughly ~ 30.0km downstream of the project area. Major surface water features being fed by the drainage system(s) of this quaternary catchment include the Bloemhof Dam situated <100.0 km to the northwest. Table 5-1 provides a summary of relevant climatological and hydrogeological information for the relevant quaternary catchments.

Table 5-1 **Quaternary catchment information.**

Attribute	**C42K**	**C42L**
Water Management Area (WMA)	Vaal	Vaal
Primary catchment	C	C
Secondary catchment	C4	C4
Tertiary catchment	C42	C42
Quaternary catchment	C42K	C42L
Major rivers	Sandrivier, Vetrivier and Doringrivier	Sandrivier, Vetrivier and Doringrivier
Hydro-zone	E	E
Rainfall zone	C4C	C4D
Area (km^2)	668.0	510.8
Mean annual rainfall (mm)	521.2	505.9
Mean annual evaporation (mm)	1600.0	1680.0
Mean annual runoff (mm)	23.8	22.7
Baseflow	2.9	2.5
Total groundwater use (l/s)	27.9	22.7
Present Eco Status Category	Category C	Category C
Recharge (mm)	15 - 25	15 - 25
Average water level (mbgl)	39.3	23.0
Soil type	SaClLm-SaCl	SaClLm-SaCl
Groundwater General Authorization	75m^3/ha/a	75m^3/ha/a

Note: Catchment based information sourced from Aquiworx 2014

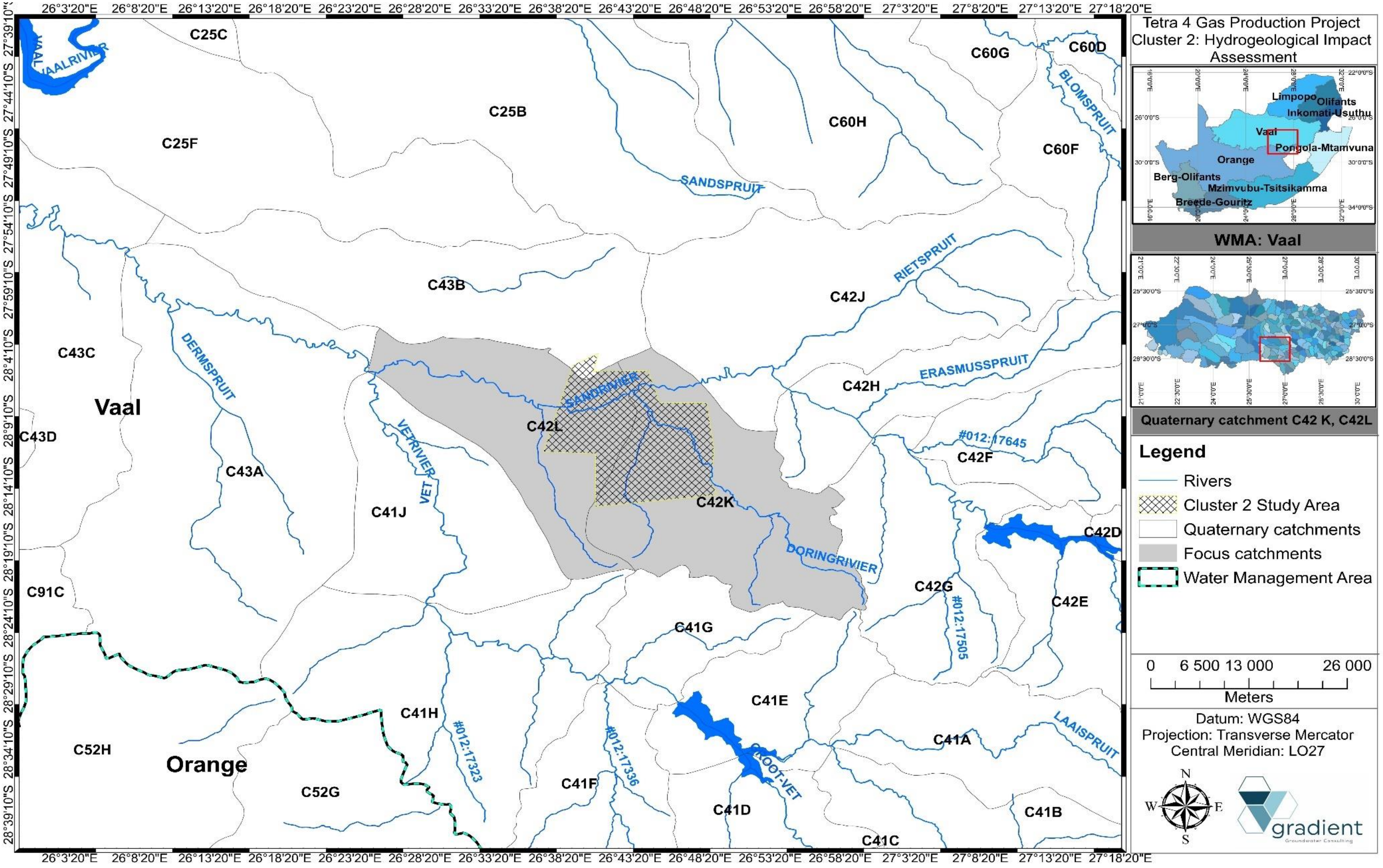

Figure 5-3 **Quaternary catchments and water management area.**

5.3. Climate

The study area’s rainfall is strongly seasonal, and the weather pattern reflects a typical summer rainfall region, with > 80.0% of precipitation occurring as convective thunderstorms from October to March. Patched rainfall and evaporation data were sourced from the WR2012 database (Rainfall zone 4C4) and span a period of some 90 years (1920 – 2009). Refer to Appendix A for time-series rainfall data tables.

The calculated mean annual precipitation (MAP) for this rainfall zone is 521.0mm/a, with the 5th percentile of the data set (roughly equivalent to a 1:20 year drought period) calculated at 343.38mm/a while the 95th percentile (representing a 1:20 flood period) is calculated at 752.43mm/a. The highest MAP for the 90 years of rainfall data was recorded as 860.30mm (1942) while the lowest MAP of 264.0mm was recorded during 2006.

Both catchment areas are categorised under evaporation zone 19C which have a mean annual evaporation (s-pan) ranging between 1600.0mm/a to 1680.0mm/a. The highest evaporation is usually experienced in December (215.0mm) while the lowest evaporation is in June (61.0mm). Figure 5-4 depicts a bar chart of the yearly rainfall distributions with Figure 5-5indicating monthly rainfall patterns. It is evident that the peak rainfall months are December and January. Figure 5-6 compares monthly precipitation volumes with monthly evaporation volumes. It is noted that the annual evaporation volumes are more than threefold the annual precipitation.

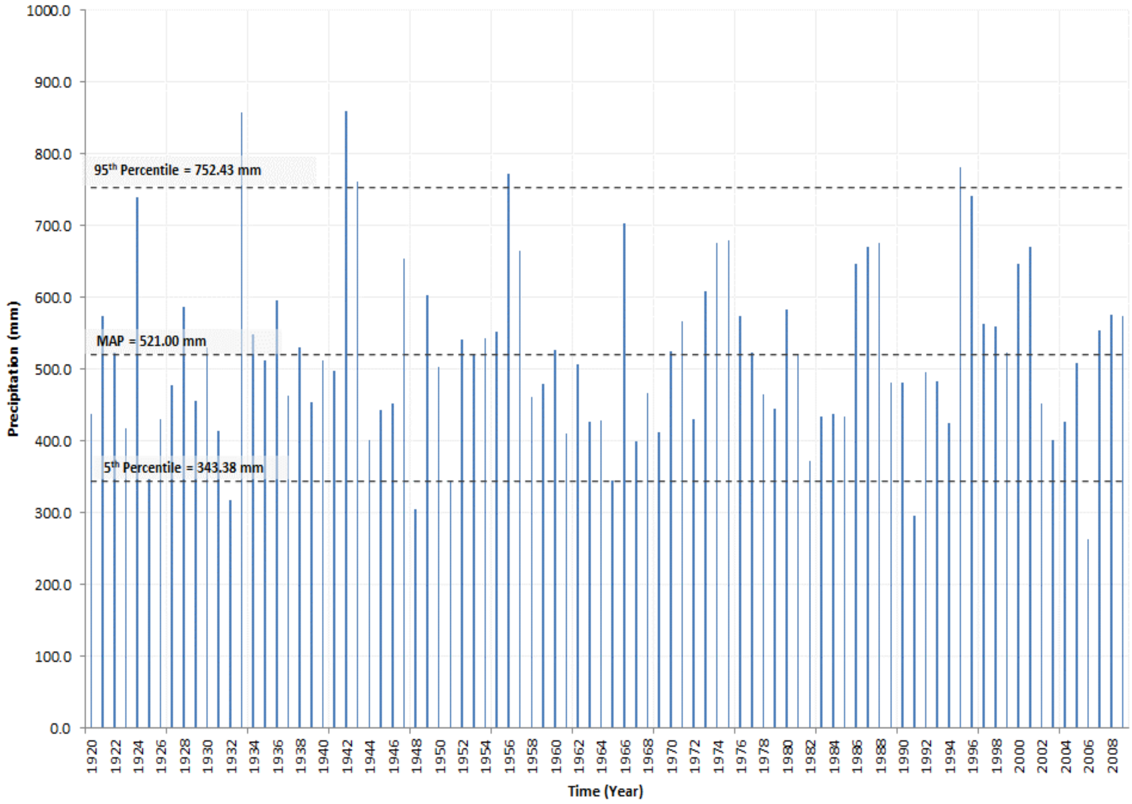

Figure 5-4 **Bar chart indicating yearly rainfall distribution for rainfall zone V3B (WR2012).**

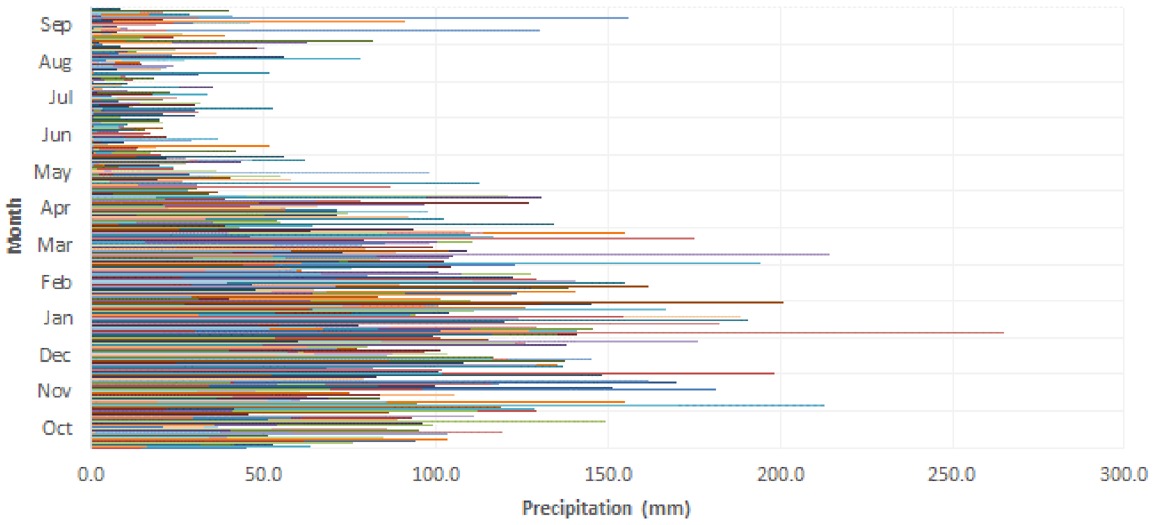

Figure 5-5 **Bar chart indicating monthly rainfall distribution for rainfall zone 4C4 (WR2012).**

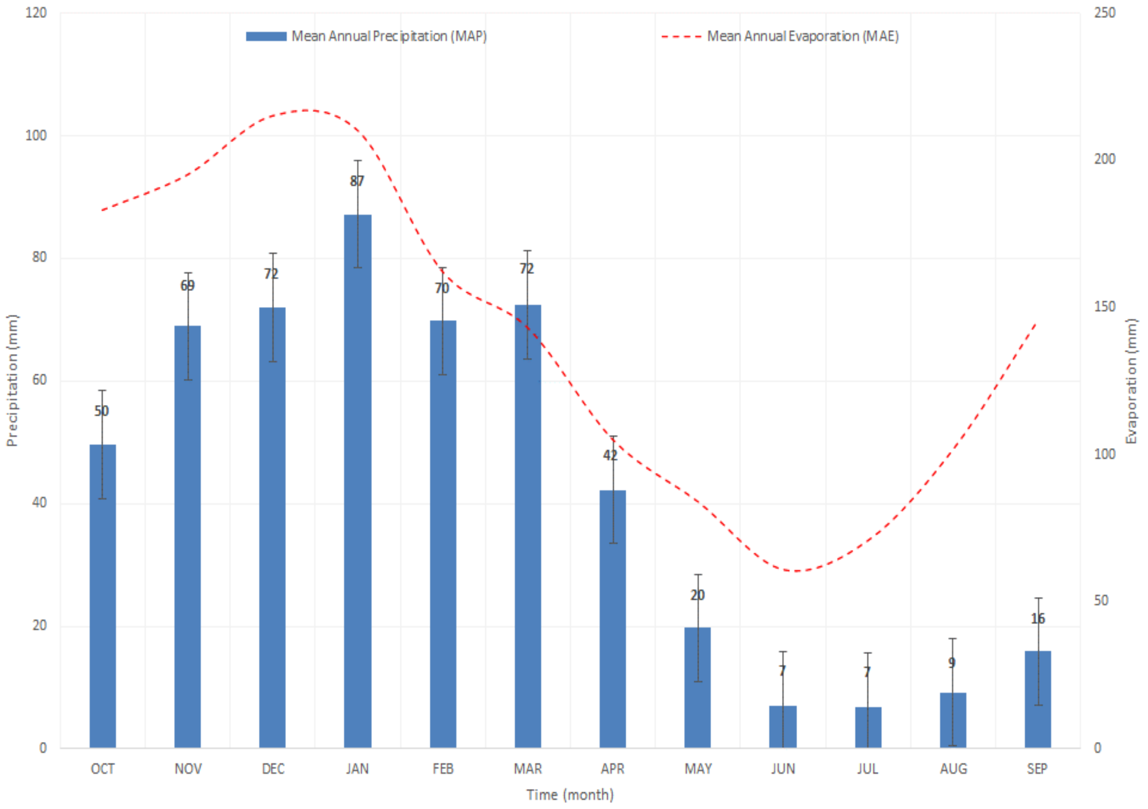

Figure 5-6 **Bar chart and curve comparing monthly rainfall and evaporation distribution for rainfall zone 4C4 (WR2012).**

5.4. Geological setting

The following sections summarises the regional and local geology.

5.4.1. Regional geology

Although the project area's surficial geology comprises mostly aeolian sands, quaternary deposits and isolated outcrops of the Karoo Supergroup i.e., dolerite and sandstone/ shales, the greater study area is generally also underlain by rocks of the Witwatersrand Supergroup as well as the Ventersdorp Supergroup. The primary source of gas originates from the Witwatersrand Supergroup as well as the shallower Karoo sediments (Lea, 2017). Figure 5-7 represents a regional geological cross section (Shango, 2016). It can be inferred from exploration borehole geological logs that the estimated depth of the unconsolidated material on-site is approximately 11.0m (Lea, 2017).

The Witwatersrand Supergroup is a sedimentary deposition across the stable granite-gniess basement which commenced around 3 billion years ago. In stratigraphic terms the Witwatersrand sequence is divided into two divisions, the lower dominantly marine, slate rich West Rand Group and the upper dominantly alluvial sandstone rich Central Rand Group (Johnson, 2006). The Witwatersrand Supergroup depth within the study area was inferred from exploration borehole geological logs and is estimated at an average depth of >1600.0mbgl (Lea, 2017).

The Ventersdorp Supergroup uncomformably overlies the Witwatersrand Supergroup. This Group is very thick, more than 4500.0m. The lower Kliprivierberg Group is mafic lava and tuff while the upper Platberg Group is conglomerates and breccia on top of Kliprivierberg, with intermediate and felsic lava higher, with quartzite, shale and siltstone layers in between (Johnson, MR. Anhauser, CR., Thomas, RJ., 2006). The Ventersdorp Supergroup depth within the study area was inferred from exploration borehole geological logs and is estimated at an average depth of >1120.0mbgl. Gas will be extracted from deep-seated fracture zones associated with the Ventersdorp lavas and Witwatersrand quartzites (Lea, 2017).

The Karoo Super Group is the largest stratigraphic unit in Southern Africa covering almost two thirds of the land surface. The supergroup consists of a sequence of units, mostly of nonmarine origin, deposited between the Late Carboniferous and Early Jurassic, a period of about 120 million years. The Karoo Supergroup consist of argillaceous rocks of the Beaufort Group i.e. lower Adelaide Subgroup (Late Permian) and an upper Tarkastad Subgroup, the Permian Ecca Group which consist largely of shales and sandstones as well as the Dwyka Group (Late Carboniferous to Early Permian) which consists mainly of diamictite (tillite). The Ecca Group underlies the Beaufort Group in all known outcrops and exposures and follows conformably after the Dwyka Group in certain sections, however in some localities overlies unconformably over older basement rocks (Schlüter and Thomas, 2008). The Karoo Supergroup (which include the Beaufort as well as Ecca Groups) depth within the study area was inferred from exploration borehole geological logs and is estimated at an average depth of 300.0mbgl.

5.4.2. Local geology

According to the 1:250 000 geological maps (2826: Winburg), a large portion of the study area's surficial geology comprises aeolian sands and quaternary deposits. Isolated patches within the study area are also covered by alluvial sand deposits which is mainly associated with the Sand and Doringriver floodplains and constrained by drainage patterns and riparian zones. The site is underlain by the Adelaide Subgroup (Vpa) consisting of alternating layers of bluish-grey, greenish-grey or greyish-red mudrock and grey, very fine to medium-grained, lithofeldspathic sandstone, the Vryheid Formation (Pv) which consists mainly of fine grained mudstone, carbonaceous shale with alternating and coarse grained, bioturbated immature sandstones respectively as well as the Volksrust Formation (PVo) which consists of grey to black, silty shale with thin, usually bioturbated, siltstone or sandstone lenses and beds, particularly towards its upper and lower boundaries. The Dwyka Group consists mainly of diamictite (tillite) which is generally massive with little jointing, but it may be stratified in places.

5.4.3. Structural geology

Large dolerite intrusions in the form of dykes and sills are observed throughout the study area. The Karoo sediments in this portion of the WMA are much intruded by sub accordant sheets, and to a lesser extent by near-vertical dykes of Karoo dolerite (DWAF, 2004). The Karoo Basin is characterised by a vast network of post-Karoo intrusive dolerite (Jd) sills and dykes that rapidly intruded at 183.0 to 182.3Ma (Svensen et al., 2012). The intrusive Karoo dolerite suite represents a shallow feeder system which occurs as an interconnected network of dykes, sills as well as sheets which typically form resistant caps of hills compromising softer sedimentary strata (Chevallier and Woodford, 1999). Exploration data evaluated suggest dykes are relatively thin, usually not wider than 5.0m while sills may be as thick as 100.0m. On a regional scale various dykes can be observed which may have an impact on the local hydrogeological regime as it can serve as potential preferred pathways for groundwater flow and contaminant transport. Deep fault zones that will be targeted for gas production are associated with the Central Rand Group and Ventersdorp lavas.

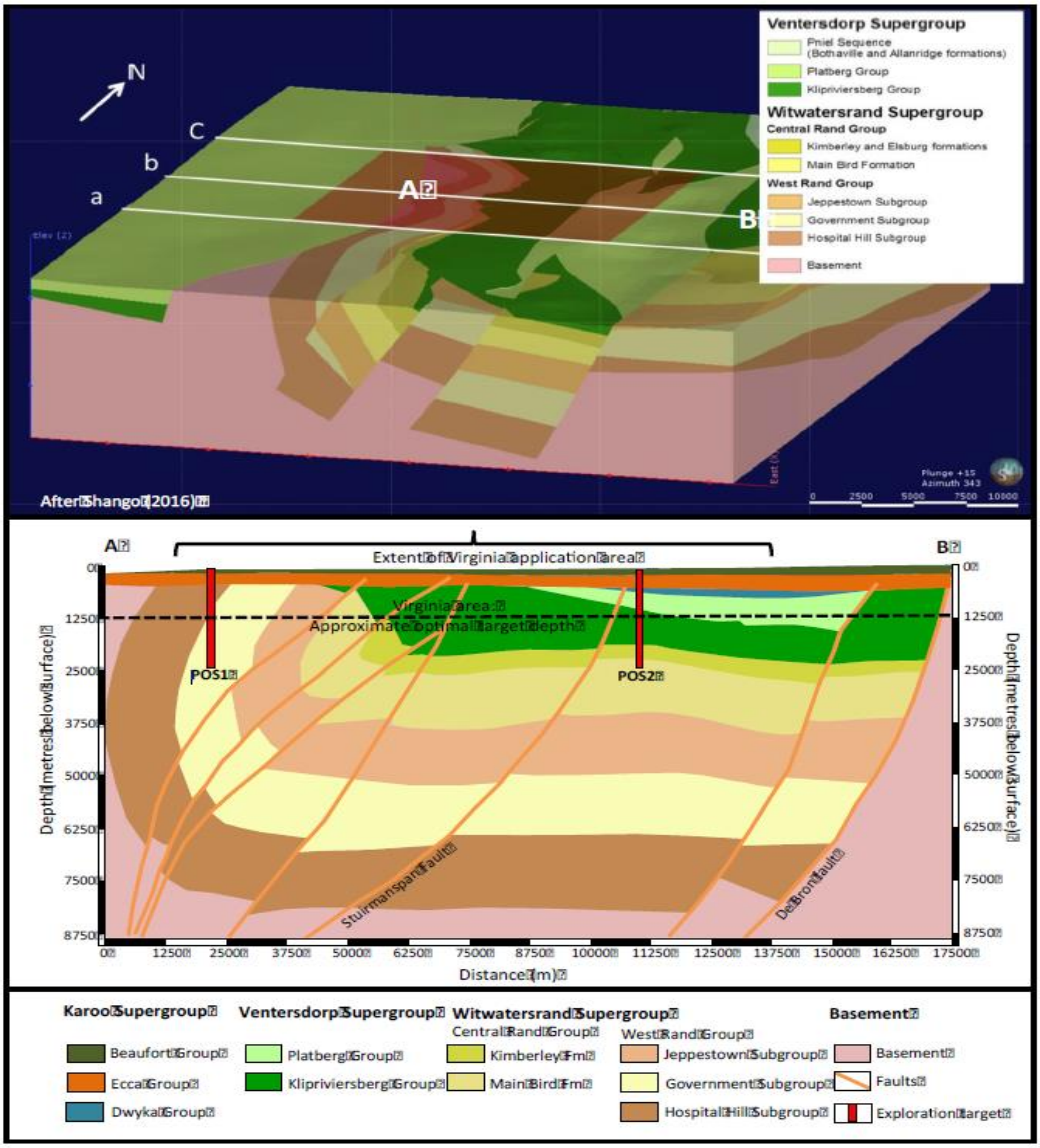

Figure 5-7 Cross section of the regional geology (after Shango, 2016).

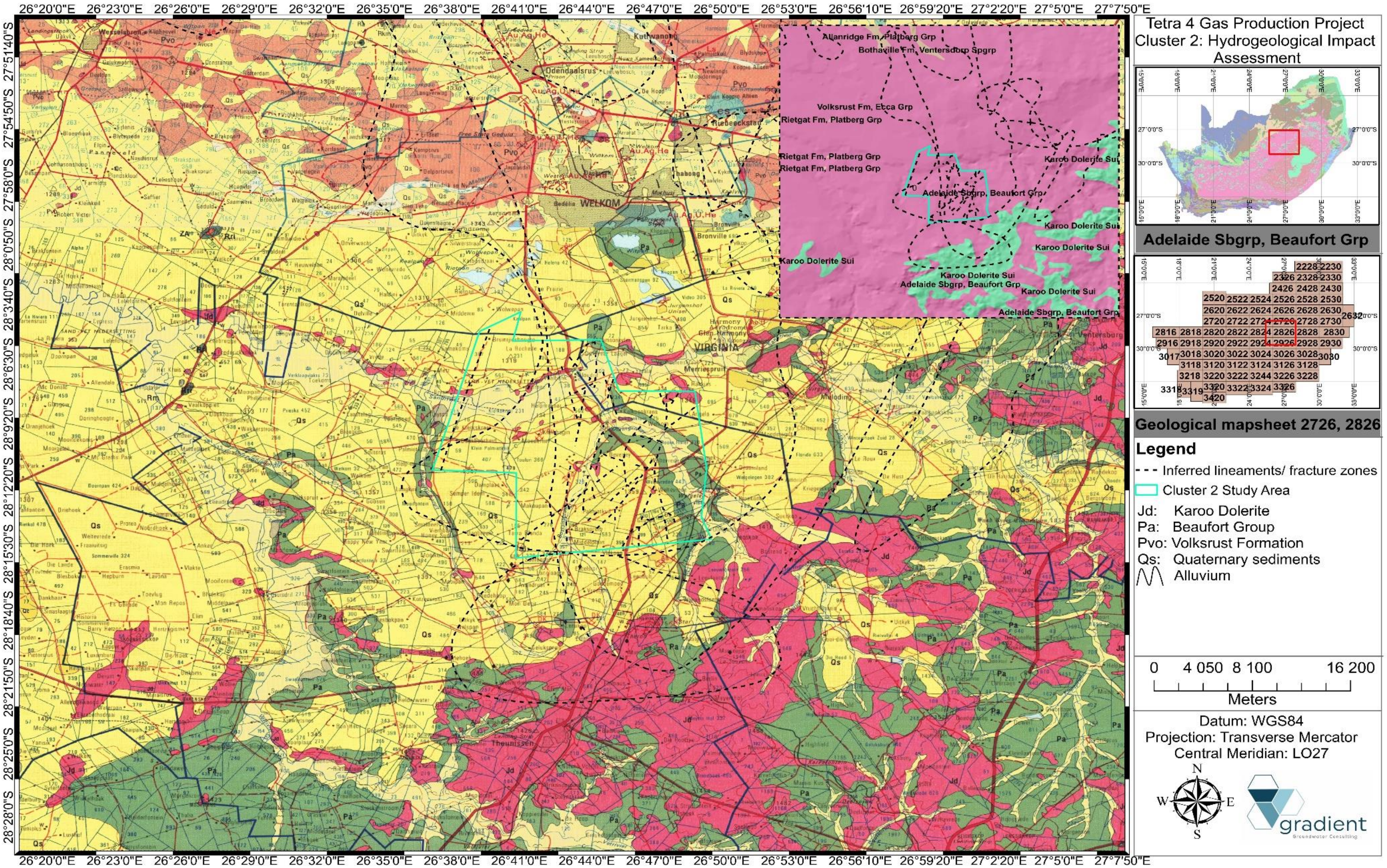

Figure 5-8 **Regional geology and stratigraphy (Geological map sheet 2826: Winburg).**

6. HYDROGEOLOGICAL BASELINE ASSESSMENT

The following sections summarises the regional and site-specific hydrogeology.

6.1. Regional hydrogeology

The Department have characterised South African aquifers based on host-rock formations in which it occurs together with its capacity to transmit water to boreholes drilled into relative formations. The water bearing properties of respective formations can be classified into four aquifer classes defined below. Each of these classes is further subdivided into groups relating to the capacity of an aquifer to transmit water to boreholes, typically measured in l/s. The groups therefore represent various ranges of borehole yields:

a. **Class A:** Intergranular Aquifers associated either with loose and unconsolidated formations such as sands and gravels or with rock that has weathered to only partially consolidated material.
b. **Class B:** Fractured Aquifers associated with hard and compact rock formations in which fractures, fissures and/or joints occur that are capable of both storing and transmitting water in useful quantities.
c. **Class C:** Karst Aquifers associated with carbonate rocks such as limestone and dolomite in which groundwater is predominantly stored in and transmitted through cavities that can develop in these rocks.
d. **Class D:** Intergranular and fractured Aquifers that represent a combination of Class A and B aquifer types. This is a common characteristic of South African aquifers. Substantial quantities of water are stored in the intergranular voids of weathered rock but can only be tapped via fractures penetrated by boreholes drilled into it.

According to the DWS Hydrogeological map (DWS Hydrogeological map series 2726 Kroonstad) the site is predominantly underlain by an intergranular and fractured aquifer system (d2) (refer to Figure 6-1) with the aquifer media consisting mainly of fractured and weathered compact argillaceous strata (refer to Figure 6-2). According to Vegter's groundwater regions delineated (2000) the study area can be classified as falling under the North-eastern Pan Belt region. Most hard-rock aquifers are secondary in nature with groundwater associated with fracturing, fault zones as well as contact zones of the dolerite intrusions.

The geometry of argillaceous rock aquifers is complicated by the lateral migration of meandering streams over a floodplain. Aquifers in the Beaufort Group will thus not only be multi-layered, but also multi-porous with variable thicknesses. The contact plane between two different sedimentary layers will cause a discontinuity in the hydraulic properties of the composite aquifer. The Ecca Group aquifers consists mainly of shales and sandstones that are very dense with permeability usually very low due to poorly sorted matrices. The aquifer has a low development potential (Botha *et al.*, 1998) with borehole yields ranging from 0.1 – 0.5l/s, however higher yielding boreholes (>5.0l/s) may occur along intruding dyke contact zones and other structural features i.e., fault zones etc. (Barnard, 2000).

The maximum aquifer thickness (i.e., shallow, intergranular aquifer system) is 20m with water stored mainly in decomposed/partly decomposed rock and water bearing fractures principally restricted to a shallow zone below the static groundwater level.

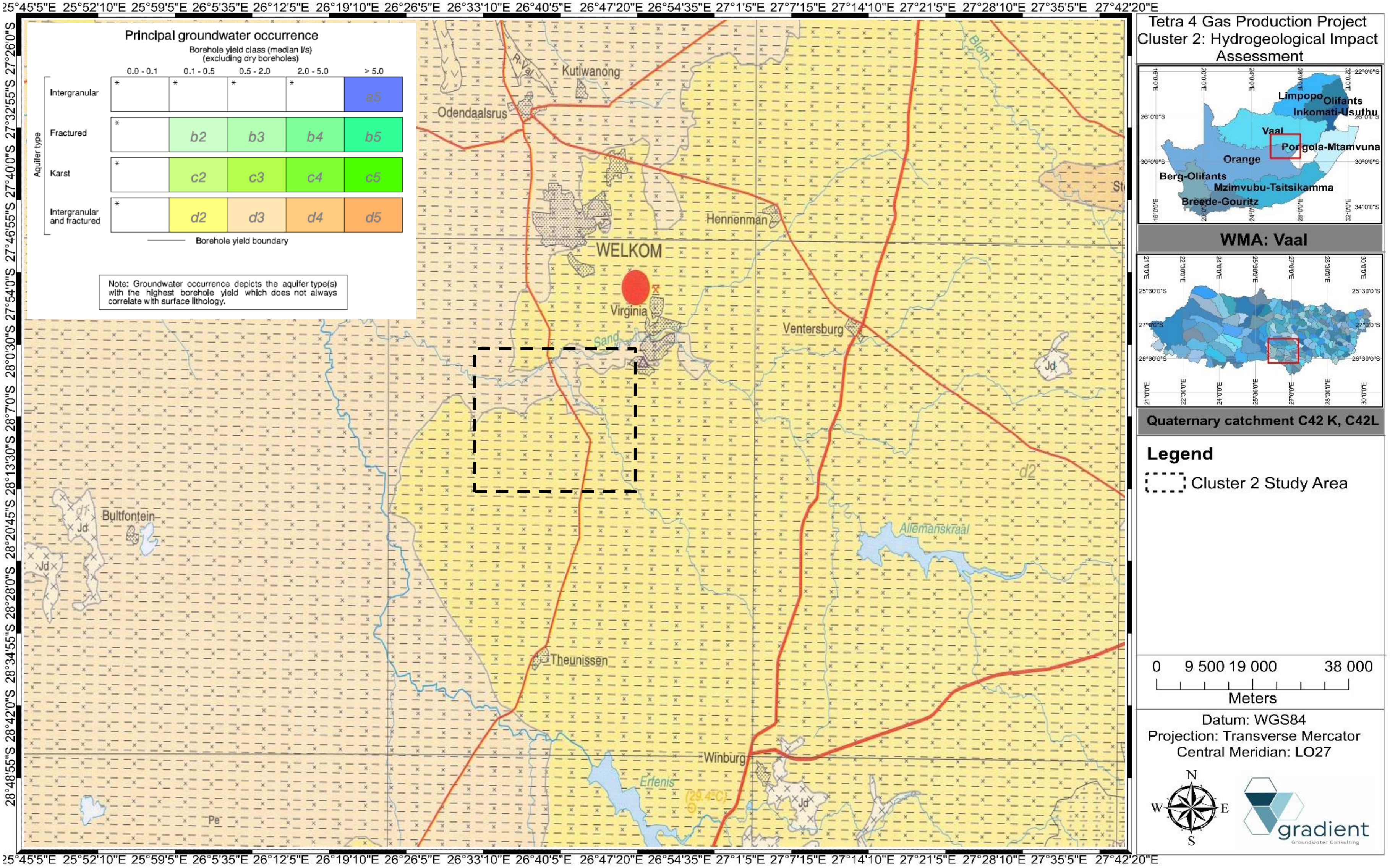

Figure 6-1 Hydrogeological map illustrating the typical groundwater occurrence for the study area (2726 Kroonstad).

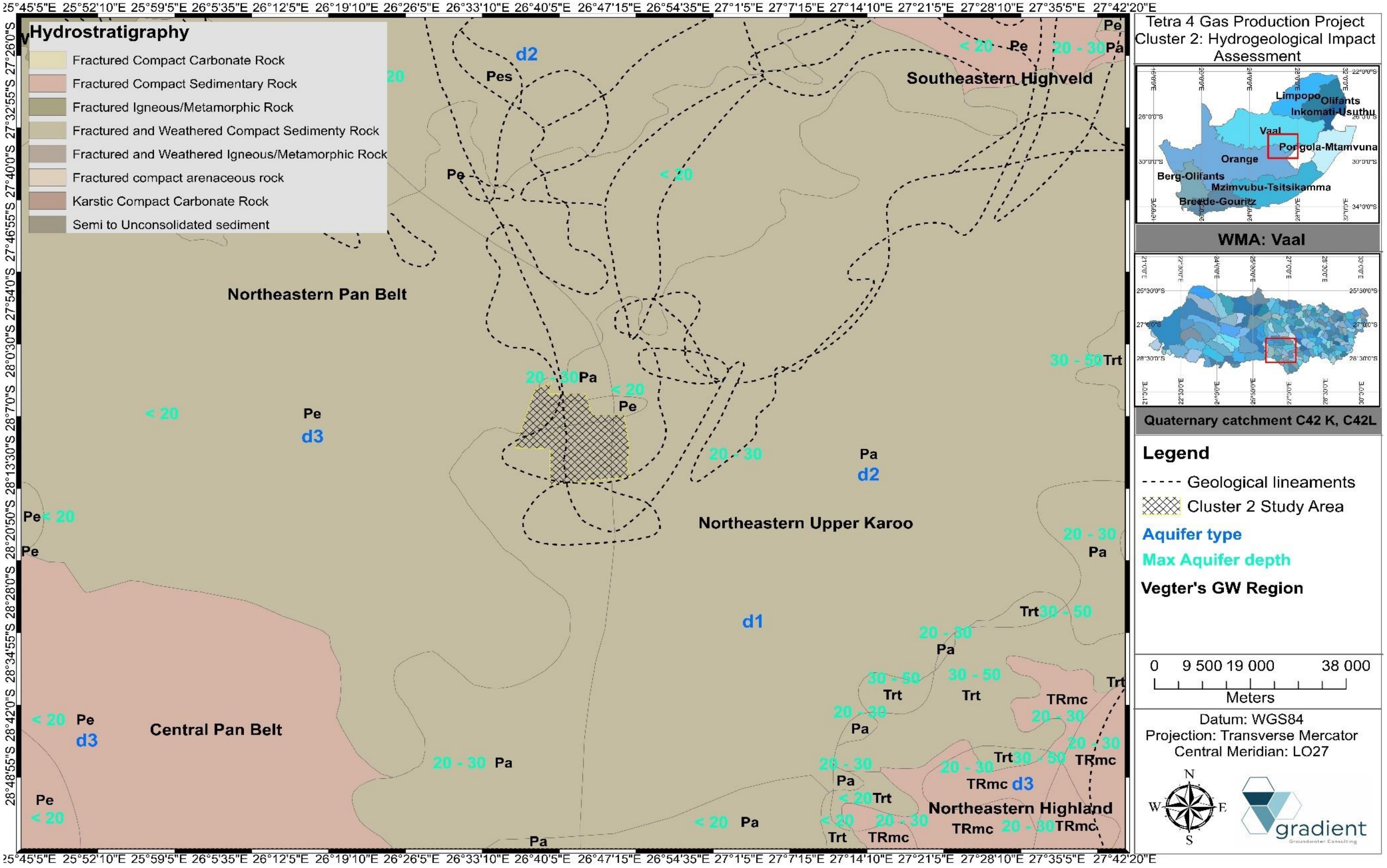

Figure 6-2 Hydrogeological map illustrating the typical groundwater occurrence for the study region (2726 Kroonstad).

6.2. Local hydrostratigraphic units

For the purposes of this investigation, four main hydrostratigraphic units/aquifer systems can be inferred in the saturated zone:

i. **A shallow quaternary and recent types of sediments** (unconfined) are characteristically a primary porosity aquifer associated with alluvium material deposited in flood plains of the main rivers traversing the study area. These aquifers cover a large portion of the study area and are limited to a zone of variable width and depth. The alluvial aquifer is specifically vulnerable to contamination as it there is a direct connectivity with rivers and streams and associated high permeability.

ii. **A shallow, intergranular aquifer** (unconfined to semi-confined) occurring in the transitional soil and weathered bedrock formations of the Karoo Supergroup rocks underlain by more consolidated bedrock. Groundwater flow patterns usually follow the topography, discharging as natural springs at topographic low-lying areas. Usually, this aquifer can be classified as a secondary porosity aquifer and is generally unconfined with phreatic water levels. Due to higher effective porosity (*n)* this aquifer is most susceptible to impacts from contaminant sources.

iii. **An intermediate, fractured aquifer** (semi-confined to confined) where pores are well-cemented and do not allow any significant flow of water. Groundwater flow is dictated by transmissive secondary porosity structures such as bedding plane fractures, faults, contact zones as well as fracture zones that occur in the relatively competent Karoo Supergroup host rock. Fractured sandstones, mudstones and shales sequences are considered as fractured rock aquifers holding water in storage in both pore spaces and fractures. This aquifer system usually displays semi-confined or confined characteristics with piezometric heads often significantly higher than the water-bearing fracture position. Although generally low yielding, this aquifer is important to local groundwater users as it forms the sole source of water supply in the region (Lea, 2017).

iv. **A deeper, fractured aquifer** (semi-confined to confined) where pores are well-cemented and do not allow any significant flow of water. Groundwater flow is dictated by transmissive secondary porosity structures such as bedding plane fractures, faults and contact zones fracture zones that occur in the relatively competent Ventersdorp and Witwatersrand Supergroups host rock. Volcanic formations of the Ventersdorp lavas can also act as aquicludes, restricting the vertical movement of groundwater. Fractured quartzites of the Witwatersrand Supergroup are considered as fractured rock aquifers holding water in storage in both pore spaces and fractures. Groundwater yields, although more heterogeneous, can be expected to be higher than the weathered zone aquifer. This aquifer system usually displays semi-confined or confined characteristics with piezometric heads often significantly higher than the water-bearing fracture position. The water in the deep aquifers is naturally saline due to their marine depositional history. Below a depth of 300.0m, groundwater quality deteriorates, and the permeability of the water-bearing formations decreases by orders of magnitude and consequently these aquifers are not used for water supply or private water use (Steyl et al, 2012). It should be noted that the shallow potable Karoo aquifers are separated from deep aquifer systems associated with the Ventersdorp and Witwatersrand Supergroup formations by the 30.0m thick dolerite sill (which may act as an aquitard) that extends across the study area and by the 65.0m thick Dwyka Tillite sedimentary deposit acting as an aquiclude (Lea, 2017). It should furthermore be noted that, under natural conditions, there is very limited hydraulic connectivity between the deep, fractured and shallow, intergranular aquifers (Steyl et al, 2012).

6.3. Hydraulic parameters

To follow is a brief overview of aquifer hydraulic parameters based on published literature for similar hydrogeological conditions as well as historical reports.

6.3.1. Hydraulic conductivity and Transmissivity

Hydraulic conductivity is the constant of proportionality in Darcy's Law which states that the rate of flow through a porous medium is proportional to the loss of head, and inversely proportional to the length of the flow path as indicated in the following equation:

Equation 6-1 Hydraulic Conductivity (Darcy's Law).

$$\boldsymbol{K} = \frac{\boldsymbol{Q}}{\boldsymbol{A}\left(\frac{\boldsymbol{dh}}{\boldsymbol{dl}}\right)}$$

where:

K = Hydraulic Conductivity (m/d).

Q = Flow of water per unit of time (m^3/d).

dh/dl = Hydraulic gradient.

A = is the cross-sectional area, at a right angle to the flow direction, through which the flow occurs (m^2)

The hydraulic conductivity of sedimentary formations such as evident on site can range from $10E^{-6}$ – $10E^{-2}$ m/d. Historical aquifer tests results confirm that the permeability of the shales is very low ($9E^{-4}$m/d). The hydraulic conductivity of fractured igneous rocks (i.e. dolerite) varies between $10E^{-6}$ – $10E^{-1}$ m/d, while conductivity values for un-fractured igneous rocks (i.e. fresh dolerite sill) ranges between $10E^{-9}$ – $10E^{-6}$ m/d. The hydraulic conductivity of quaternary deposits and alluvial pockets associated with the drainage system i.e., riverbed aquifers can be orders higher and can vary between $10E^{-2}$ – $10E^{1}$ m/d as depicted in Figure 6-3 (Freeze and Cherry, 1979).

Transmissivity can be expressed as the product of the average hydraulic conductivity (K) and thickness (b) of the saturated portion of an aquifer and expressed by:

Equation 6-2 Transmissivity.

$$T = Kb$$

where:

T = Transmissivity (m^2/d).

K = Hydraulic Conductivity (m/d).

b = Saturated aquifer thickness.

From historical aquifer tests conducted it is calculated that the average transmissivity for the shallow, weathered aquifer ranges between 0.12 m/d^2 to 0.6m^2/d depending on the saturated thickness of the aquifer targeted[3].

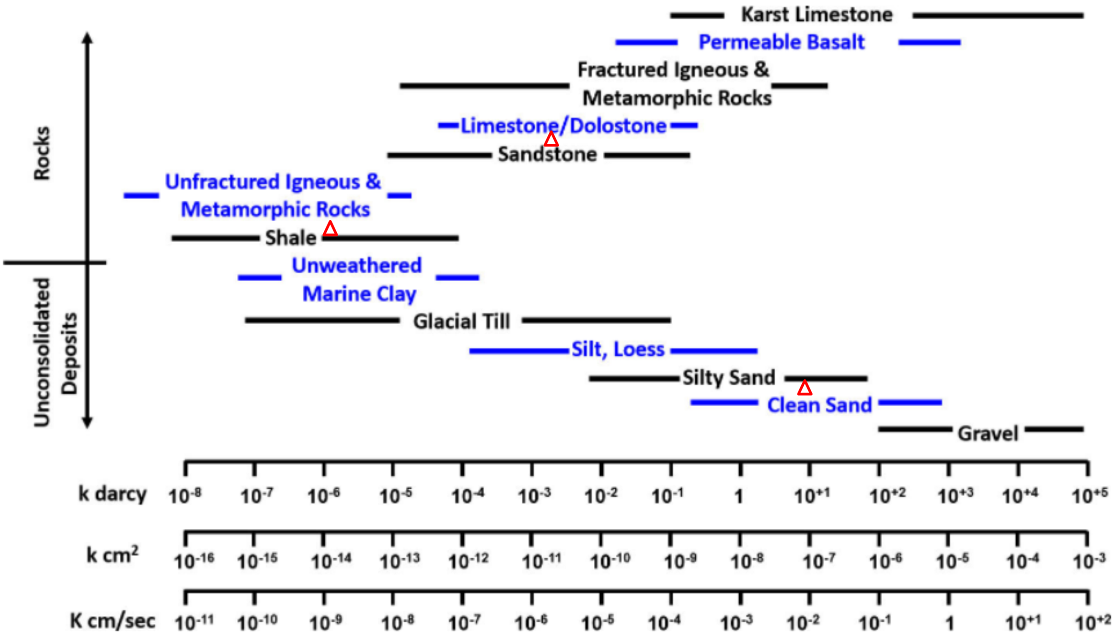

Figure 6-3 **Typical hydraulic conductivity values for on-site hydrostratigraphical units.**

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[3] It should be noted that no additional aquifer tests were conducted as part of this investigation.

6.3.2. Storativity

Storativity refers to the volume of water per volume of aquifer released as a result of a change in head. For a confined aquifer, the storage coefficient is equal to the product of the specific storage and aquifer thickness. Typical storativity values for fractured rock systems is in the order of $10E^{-5}$ – $10E^{-3}$ (Freeze and Cherry, 1979). Storativity values of the shallow, weathered aquifer will be slightly higher i.e., $10E^{-2}$.

6.3.3. Porosity

Porosity is an intrinsic value of seepage velocity and hence contamination migration. Porosity is an intrinsic value of seepage velocity and hence contamination migration. The porosity of fractured sedimentary formations ranges between 3% – 10%, while porosity of weathered formations can range between 10% to 15% depending on the nature and state of weathering. The intrinsic porosity of primary aquifers i.e., alluvial deposits can be as high as 20% depending on the nature of sorting (Freeze and Cherry, 1979).

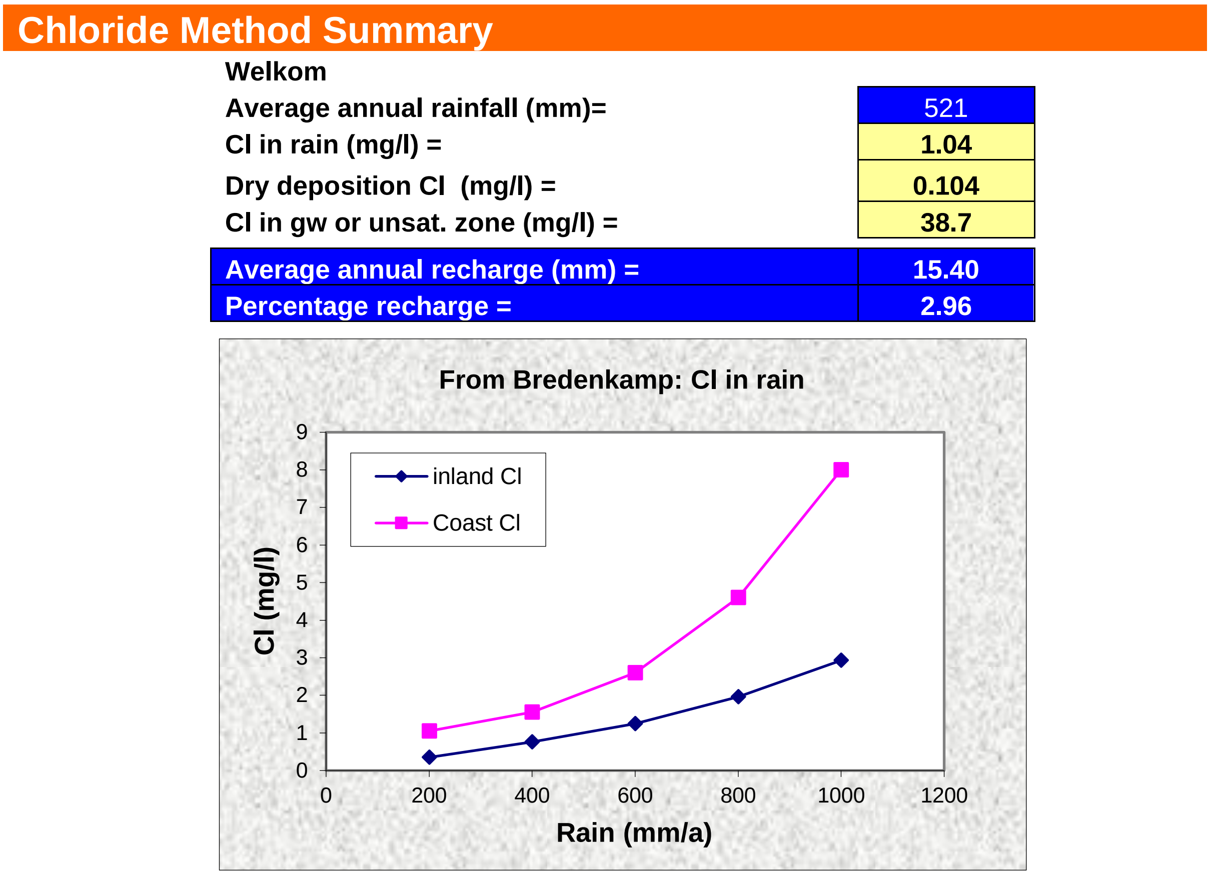
6.3.4. Recharge

An approximation of recharge for the study area is estimated at ~4.0% of MAP i.e., ~21.69 mm/a as summarised in Table 6-1. Groundwater recharge was calculated using the RECHARGE Program1 (van Tonder and Xu, 2000), which includes using qualified guesses as guided by various schematic maps. The following methods/sources were used to estimate the recharge: (i) Chloride (Cl) method (Figure 6-4) (ii) Geology (iii) Vegter Groundwater Recharge Map (Figure 6-5) (iv) Harvest Potential (Figure 6-6) (v) Baseflow as a minimum of recharge (vi) Qualified opinion and, (vii) Literature review.

Table 6-1 Recharge estimation (after van Tonder and Xu, 2000).

Recharge method/ Reference	Recharge (mm/a)	Recharge (% of MAP)	Weighted Average (High = 5; Low = 1)
Chloride	15.40	2.96	4.00
Geology	21.60	4.15	2.00
Vegter	32.00	6.14	3.00
Harvest Potential	25.00	4.80	2.00
Baseflow	25.00	4.80	2.00
Qualified Opinion	18.24	3.50	4.00
Literature	14.58	2.80	3.00
Weighted average	**21.69**	**4.01**	**20.00**

Notes: Recharge per annum were calculated using a MAP of 521.0 mm/a.



Chloride Method Summary

Welkom

Average annual rainfall (mm)=	521
Cl in rain (mg/l) =	**1.04**
Dry deposition Cl (mg/l) =	**0.104**
Cl in gw or unsat. zone (mg/l) =	**38.7**
Average annual recharge (mm) =	**15.40**
Percentage recharge =	**2.96**

Figure 6-4 **Chloride method summary.**

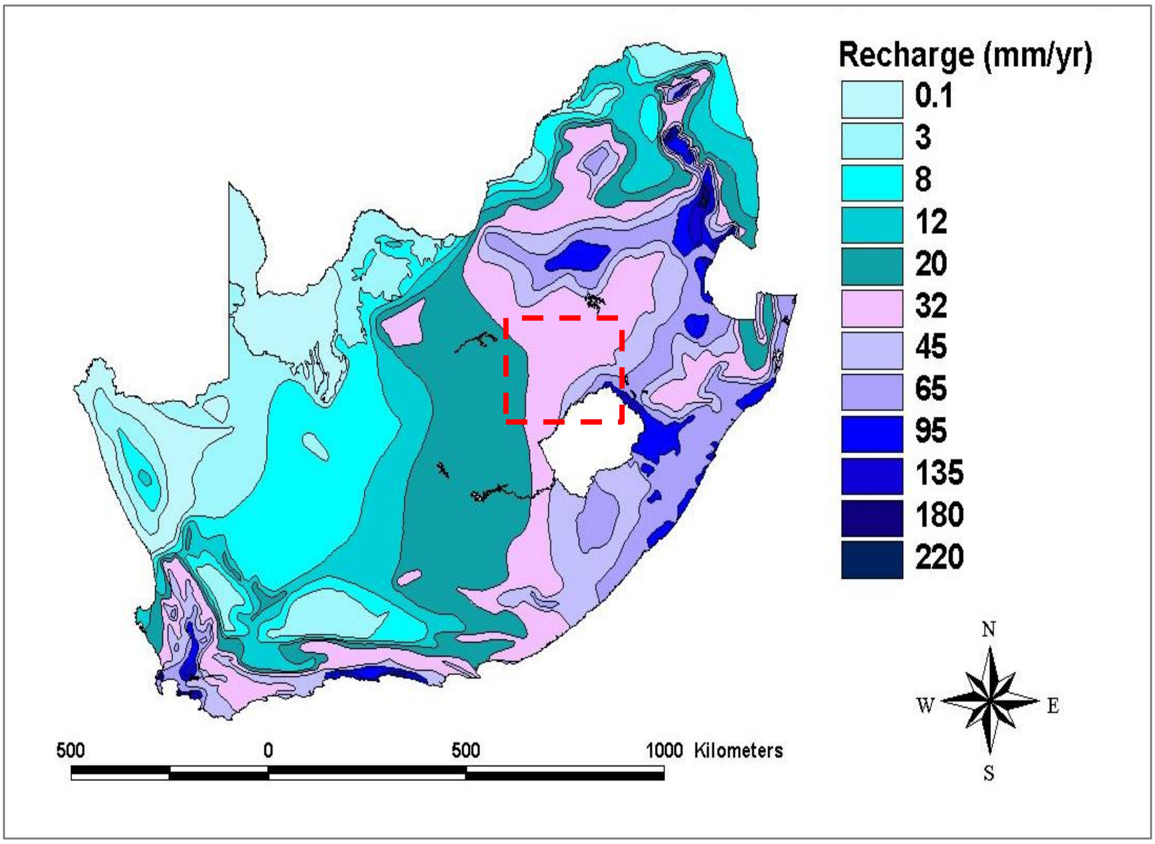


Figure 6-5 Groundwater recharge distribution in South Africa (After Vegter, 1995).

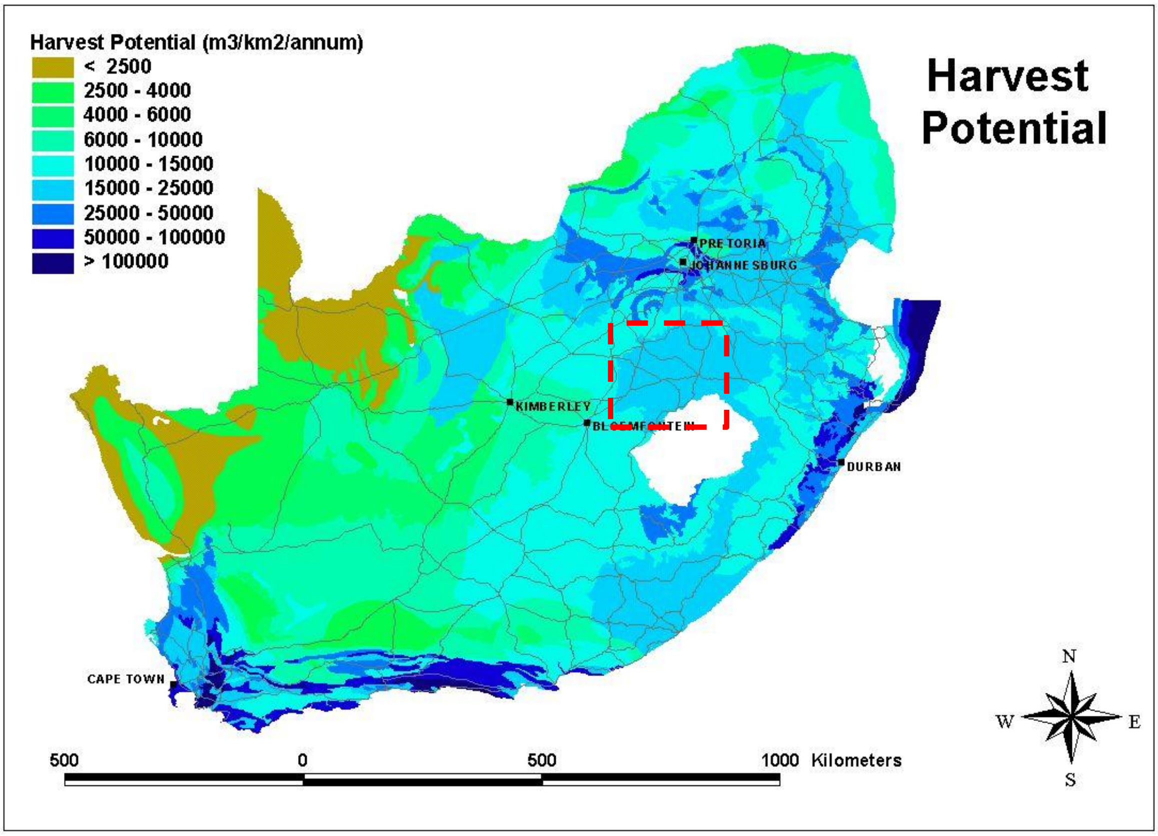


Figure 6-6 Harvest potential distribution in South Africa (DWS, 2013).

7. SITE INVESTIGATION

7.1. Hydrocensus user survey

A hydrocensus user survey within the greater study area was conducted during February and March 2022[4] where relevant hydrogeological baseline information was gathered. The aim of the hydrocensus survey is to determine the ambient and background groundwater conditions and applications and to identify potential sensitive environmental receptors i.e., groundwater users in the direct vicinity of the gas production operations. A total of 78 groundwater receptors i.e., boreholes, artesian wells, wind pumps as well as surface water features were visited as part of the hydrocensus user survey which are largely applied for livestock watering and domestic water supply purposes. Relevant hydrocensus information is summarised in Table 7-1 while a spatial distribution map is shown in Figure 7-5.

7.1.1. Groundwater status

Of the boreholes recorded, the majority are in use (>78.0%) while ~17.0% are not currently being utilized. Approximately 4.0% of boreholes allocated could not be visited due to access challenges. Refer to Figure 7-2 for a summary of the groundwater status quo.

7.1.2. Groundwater application

Most boreholes recorded are being applied for livestock watering and domestic water supply purposes (~45.0%) while domestic and household purposes which is combined with either irrigation or livestock purposes account for >18.0%. A small number of boreholes are also being applied for either monitoring or industrial purposes (~5.0%) while ~17.0% of boreholes do not have an application and are not currently being utilized. Refer to Figure 7-3 for a summary of groundwater applications. According to the Middle Vaal ISP (DWAF, 2004), most boreholes are being applied for irrigation and small-town water supply.

7.1.3. Borehole equipment

Most boreholes visited are equipped with submersible pumps and account to 57.0%, while 15.0% of boreholes were fitted either with a wind pump, mono pump (4.0%), handpump (1.0%) or solar pump (1.0%). An average of 18.0% of boreholes are not equipped as indicated in Figure 7-4.

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[4] It should be noted that relevant site information gathered will be representative of wet season contribution.

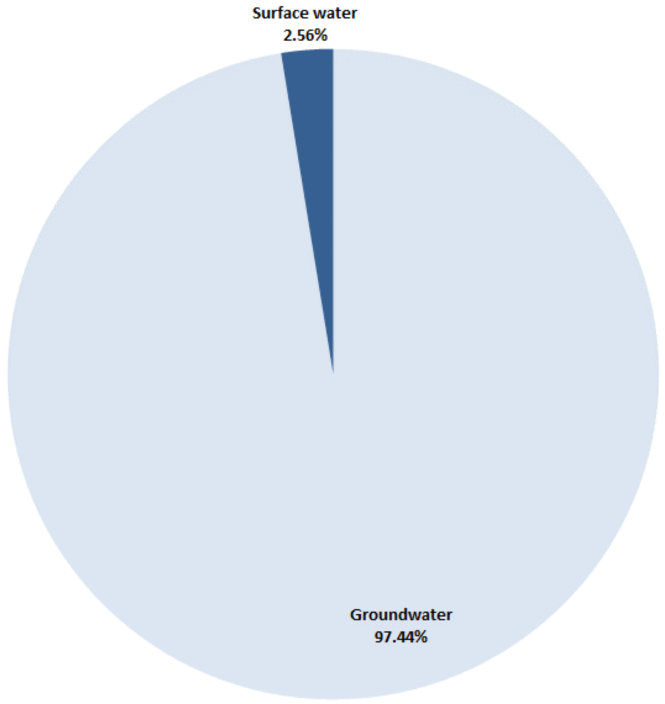

Figure 7-1 Hydrocensus user survey: Geosite type.

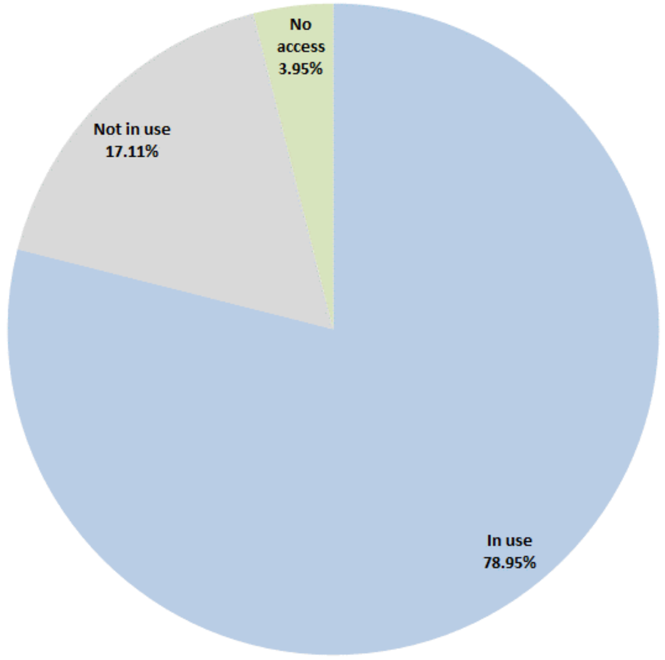

Figure 7-2 Hydrocensus user survey: Groundwater status.

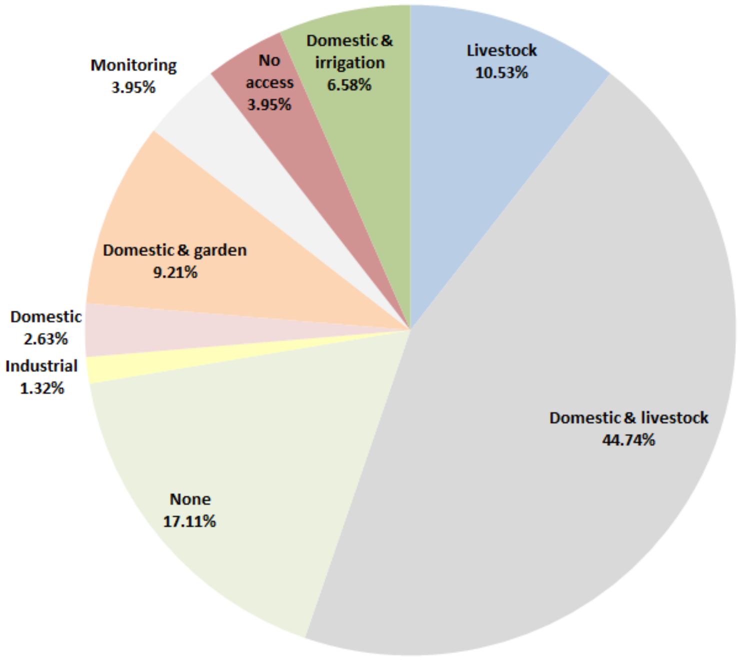

Figure 7-3 Hydrocensus user survey: Groundwater application.

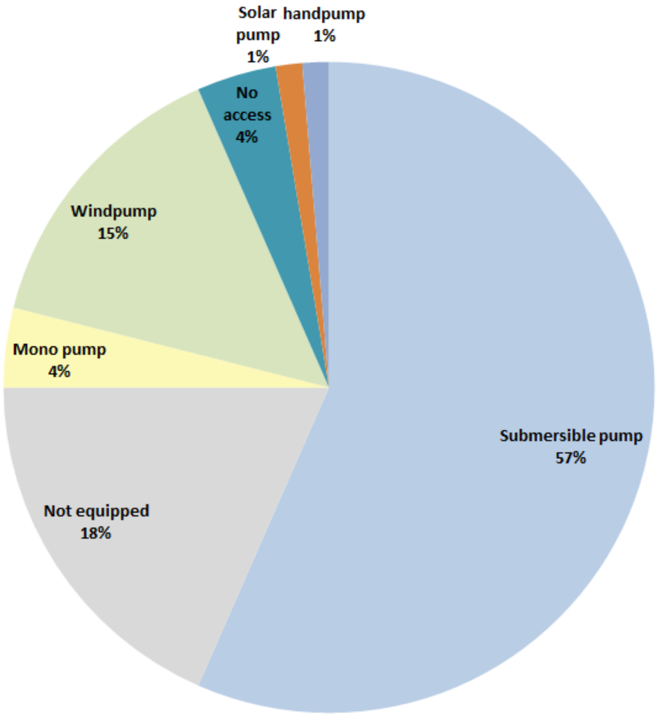

Figure 7-4 Hydrocensus user survey: Equipment type.

Table 7-1 **Hydrocensus user survey: relevant geosite information.**

Site ID	Latitude	Longitude	Water level (mbgl)	Borehole depth (mbgl)	Site type	Site status	Equipment	Water application	Field notes
HBH1	-28.14362	26.80863	NAWL		Borehole	In use	Submersible pump	Livestock	Flooded Area
HBH2	-28.12872	26.80516	NAWL		Borehole	In use	Windpump	Domestic & livestock	
HBH3	-28.12768	26.80522	NAWL		Borehole	In use	Submersible pump	Domestic & livestock	ROCLA
HBH4	-28.12407	26.80630	NAWL		Borehole	In use	Submersible pump	Domestic & livestock	ROCLA
HBH5	-28.11982	26.80036	NAWL		Borehole	In use	Submersible pump	Domestic & livestock	ROCLA
HBH6	-28.12005	26.79521	1.52	30	Borehole	In use	Submersible pump	Domestic & garden	
HBH7	-28.12940	26.77388	NAWL		Borehole	Not in use	No access	None	Blocked
HBH8	-28.15651	26.79403	NAWL		Borehole	In use	Submersible pump	Livestock	
HBH9	-28.15477	26.78428	10.87	30	Borehole	In use	Submersible pump	Livestock	
HBH10	-28.11906	26.81375	NAWL		Borehole	In use	Submersible pump	Industrial	ROCLA
HBH11	-28.11540	26.81199	NAWL		Borehole	In use	Submersible pump	Domestic	
HBH12	-28.13337	26.76153	13.65	30	Borehole	In use	Submersible pump	Domestic & livestock	
HBH13	-28.13200	26.76094	12.35	70	Borehole	In use	Submersible pump	Domestic & livestock	
HBH14	-28.12823	26.75381	16.65		Borehole	In use	Submersible pump	Domestic & livestock	
HBH15	-28.12852	26.75373	17.74		Borehole	In use	Submersible pump	Domestic & livestock	
HBH16	-28.13105	26.75641	25.40	45	Borehole	In use	Submersible pump	Domestic & livestock	
HBH17	-28.12700	26.75455	11.55	40	Borehole	In use	Submersible pump	Domestic & livestock	
HBH18	-28.13405	26.75741	16.47	40	Borehole	Not in use	Not equipped	None	Open
HBH19	-28.13356	26.75760	NAWL		Borehole	In use	Submersible pump	Domestic & livestock	
HBH20	-28.08584	26.75406	1.10	70	Borehole	In use	Submersible pump	Domestic & livestock	
HBH21	-28.09424	26.73133	2.67		Borehole	Not in use	Not equipped	None	Open
HBH22	-28.11837	26.71244	NAWL		Borehole	Not in use	Not equipped	None	Closed
HBH23	-28.10725	26.70513	3.16	18	Borehole	Not in use	Not equipped	None	Open
HBH24	-28.11683	26.70197	8.50		Borehole	In use	Submersible pump	Domestic & livestock	
HBH25	-28.11792	26.68013	24.20		Borehole	In use	Submersible pump	Domestic & livestock	
HBH26	-28.12714	26.65699	NAWL		Borehole	Not in use	Not equipped	None	Closed
HBH27	-28.12845	26.65437	1.40		Borehole	In use	Submersible pump	Domestic & livestock	
HBH28	-28.06977	26.66653	5.02	40	Borehole	In use	Submersible pump	Domestic	
HBH29	-28.07050	26.66551	NAWL		Borehole	In use	Mono pump	Livestock	
HBH30	-28.07475	26.67059	NAWL		Borehole	In use	Submersible pump	Livestock	
HBH31	-28.10189	26.64343	0.00		Borehole	In use	Not equipped	Domestic & garden	Artesian
HBH32	-28.09055	26.65710	NAWL		Borehole	In use	Mono pump	Domestic & garden	
HBH33	-28.11279	26.63522	15.70		Borehole	In use	Submersible pump	Domestic & garden	

Site ID	Latitude	Longitude	Water level (mbgl)	Borehole depth (mbgl)	Site type	Site status	Equipment	Water application	Field notes
HBH34	-28.12682	26.69912	26.04	60	Borehole	In use	Submersible pump	Domestic & livestock	
HBH35	-28.11991	26.69965	3.70	20	Borehole	In use	Submersible pump	Domestic & garden	
HBH36	-28.06441	26.66184	2.66	18	Borehole	In use	Submersible pump	Domestic & garden	
HBH37	-28.06606	26.66227	3.18	20	Borehole	In use	Submersible pump	Domestic & garden	
HBH38	-28.18060	26.64045	2.94	50	Borehole	In use	Submersible pump	Livestock	
HBH39	-28.16963	26.63504	8.26	40	Borehole	In use	Submersible pump	Domestic & livestock	
HBH40	-28.16964	26.63456	8.75	16	Borehole	Not in use	Not equipped	None	Open
HBH41	-28.14747	26.72413	NAWL	80	Borehole	In use	Submersible pump	Domestic & irrigation	
HBH42	-28.14750	26.72416	NAWL	80	Borehole	In use	Submersible pump	Domestic & irrigation	
HBH43	-28.15102	26.72540	NAWL		Borehole	Not in use	Not equipped	None	No access
HBH44	-28.15038	26.72384	8.46	50	Borehole	In use	Submersible pump	Domestic & livestock	
HBH45	-28.15055	26.72382	8.40	50	Borehole	In use	Submersible pump	Domestic & livestock	
HBH46	-28.14817	26.72182	14.50		Borehole	In use	Submersible pump	Domestic & livestock	
HBH47	-28.14472	26.73037	NAWL		Borehole	In use	Solar pump	Domestic & livestock	
HBH48	-28.17827	26.74558	11.03		Borehole	In use	Submersible pump	Domestic & livestock	
HBH49	-28.17886	26.74621	7.12		Borehole	In use	Submersible pump	Domestic & livestock	
HBH50	-28.18372	26.74679	NAWL		Borehole	In use	No access	Domestic & livestock	No access
HBH51	-28.19216	26.72884	NAWL		Borehole	In use	No access	Monitoring	No access
HBH52	-28.18767	26.73012	1.08	10	Borehole	In use	Not equipped	Monitoring	Open
HBH53	-28.18655	26.73110	2.80	5	Borehole	In use	Not equipped	Monitoring	Open
HBH54	-28.24539	26.71029	7.98		Borehole	In use	Submersible pump	Domestic & livestock	
HBH55	-28.24598	26.71291	NAWL		Borehole	In use	Submersible pump	Domestic & livestock	
HBH56	-28.21266	26.69929	1.79	30	Borehole	Not in use	Not equipped	None	Open
HBH57	-28.25142	26.74366	NAWL		Borehole	Not in use	Not equipped	None	Blocked
HBH58	-28.25125	26.74377	7.95		Borehole	In use	Submersible pump	Domestic & livestock	
HBH59	-28.25111	26.74382	8.35		Borehole	In use	Submersible pump	Domestic & irrigation	
HBH60	-28.24983	26.74353	12.90		Borehole	In use	Submersible pump	Domestic & irrigation	
HBH61	-28.24970	26.74315	12.55		Borehole	In use	Submersible pump	Domestic & irrigation	
HBH62	-28.22459	26.80767	12.70	30	Borehole	In use	Windpump	Livestock	
HBH63	-28.20166	26.78398	NAWL		Borehole	In use	Windpump	Livestock	
HBH64	-28.21076	26.78479	NAWL		Borehole	No access	Windpump	No access	
HBH65	-28.21203	26.79141	NAWL		Borehole	No access	Windpump	No access	
HBH66	-28.21220	26.78951	NAWL		Borehole	No access	Windpump	No access	
HBH67	-28.21859	26.75478	NAWL		Borehole	Not in use	Not equipped	None	Open. Bees.
HBH68	-28.22435	26.75422	NAWL		Borehole	In use	Windpump	Domestic & livestock	

Site ID	Latitude	Longitude	Water level (mbgl)	Borehole depth (mbgl)	Site type	Site status	Equipment	Water application	Field notes
HBH69	-28.22273	26.75010	1.67		Borehole	In use	Submersible pump	Domestic & livestock	
HBH70	-28.22878	26.74097	3.10		Borehole	In use	Windpump	Domestic & livestock	
HBH71	-28.19508	26.74163	NAWL		Borehole	In use	Windpump	Domestic & livestock	
HBH72	-28.19312	26.73970	1.75		Borehole	Not in use	Not equipped	None	Open
HBH73	-28.19301	26.73964	1.63		Borehole	In use	Mono pump	Domestic & livestock	
HBH74	-28.22959	26.80025	NAWL		Borehole	In use	Windpump	Domestic & livestock	
HBH75	-28.23077	26.80533	NAWL		Borehole	In use	Windpump	Domestic & livestock	
HBH76	-28.09771	26.73687	NAWL		Borehole	Not in use	Handpump	None	
SRD	-28.12263	26.70925	N/A		Surface water	N/A	N/A	N/A	Sand River downstream point
SRU	-28.10651	26.73623	N/A		Surface water	N/A	N/A	N/A	Sand River upstream point

N/A: Not applicable

NAWL: No access to water level

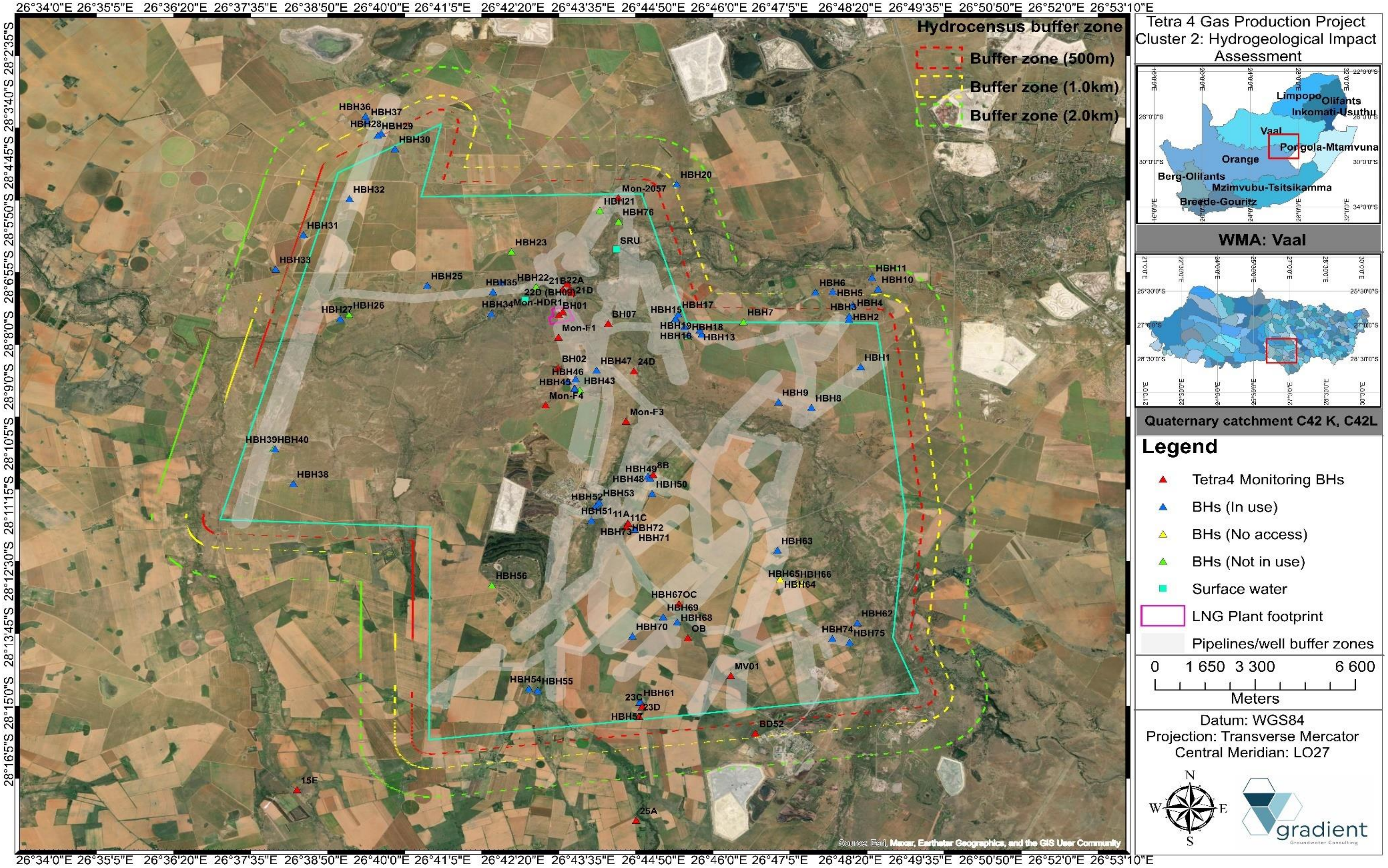

Figure 7-5 **Spatial distribution of hydrocensus user survey geosites.**

8. GROUNDWATER FLOW EVALUATION

The following sub-sections outline the groundwater flow dynamics of the study area.

8.1. Unsaturated zone

The thickness of the unsaturated or vadose zone was determined by subtracting the undisturbed static water level elevation from corresponding surface topography. The latter will govern the infiltration rate, as well as effective recharge of rainfall to the aquifer. Furthermore, the nature of the formation(s) forming the unsaturated zone will significantly influence the mass transport of surface contamination to the underlying aquifer(s). The unsaturated zone within the study area is in the order of 0 (fully saturated to surface) to >26.0m with a mean thickness of approximately ~9.0m. It should be noted that due to the argillaceous nature of the host aquifer(s) the shallow water levels observed at some of the borehole localities can be attributed to clay/silt lenses and be indicative of perched aquifer conditions and not necessarily represent the vadose zone.

8.2. Depth to groundwater

A distribution of borehole water levels recorded as part of the hydrocensus user survey conducted as well as monitoring borehole water levels measured were considered and used to interpolate local groundwater elevation and hydraulic head contours as summarised in Table 8-1 and depicted in Figure 8-1. Artesian conditions were observed at three of the boreholes visited namely HBH31, 21B as well as 8B which can be indicative of semi-confined to confined aquifer conditions present or perched aquifer conditions. The minimum water level was recorded at 0.0mbgl, while the deepest water level was measured at borehole locality Mon-HDR1 (26.71mbgl)[5]. The average water level is calculated at 8.91mbgl which is much shallower than the regional average water level of ~23.0mbgl (Aquiworx, 2014).

Figure 8-2 summarises time-series water levels within the existing Tetra 4 monitoring boreholes by comparing water levels representative of the dry-cycle contribution vs water levels representative of the wet cycle contribution. It is noted that most water levels suggest a decrease in water levels and recovering trend. The latter can be attributed the onset of the wet cycle and above average rainfall events experienced with rainfall recharge replenishing aquifer storage. It can be observed that there is a definite a relatively quick response to rainfall, suggesting that recharge of the shallow, intergranular aquifer takes place without a prolonged lag effect. The average change in most water levels is <5.0%, which accounts to less than 0.5m, while the relatively low Coefficient of Variation (CV) values derived from statistical analyses suggest that the local groundwater system is in quasi-steady state conditions.

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[5] It should be noted that due to this borehole currently being applied for supply purposes, it can be assumed that this water level represents a dynamic water level.

Table 8-1 **Regional water level summary.**

Site ID	Topographical Elevation (mamsl)	Water level (mbgl)	Groundwater Elevation (mamsl)
HBH6	1308.35	1.52	1306.83
HBH9	1314.33	10.87	1303.46
HBH12	1317.12	13.65	1303.47
HBH13	1317.12	12.35	1304.77
HBH14	1306.16	16.65	1289.51
HBH15	1306.16	17.74	1288.42
HBH16	1311.92	25.40	1286.52
HBH17	1306.16	11.55	1294.61
HBH18	1312.93	16.47	1296.46
HBH20	1341.47	1.10	1340.37
HBH21	1316.68	2.67	1314.01
HBH23	1313.61	3.16	1310.45
HBH24	1296.78	8.50	1288.28
HBH25	1306.46	24.20	1282.26
HBH27	1300.84	1.40	1299.44
HBH28	1312.85	5.02	1307.83
HBH31	1308.76	0.00	1308.76
HBH33	1303.06	15.70	1287.36
HBH34	1282.46	26.04	1256.42
HBH35	1293.51	3.70	1289.81
HBH36	1311.04	2.66	1308.38
HBH37	1311.33	3.18	1308.15
HBH38	1338.24	2.94	1335.30
HBH39	1312.52	8.26	1304.26
HBH40	1312.52	8.75	1303.77
HBH44	1318.93	8.46	1310.47
HBH45	1318.93	8.40	1310.53
HBH46	1314.70	14.50	1300.20
HBH48	1325.03	11.03	1314.00
HBH49	1325.03	7.12	1317.91
HBH52	1323.97	1.08	1322.89
HBH53	1323.97	2.80	1321.17
HBH54	1363.06	7.98	1355.08
HBH56	1358.94	1.79	1357.15
HBH58	1373.57	7.95	1365.62
HBH59	1373.57	8.35	1365.22
HBH60	1371.99	12.90	1359.09
HBH61	1371.99	12.55	1359.44
HBH62	1337.84	12.70	1325.14
HBH69	1358.14	1.67	1356.47
HBH70	1360.24	3.10	1357.14
HBH72	1332.90	1.75	1331.15
HBH73	1332.90	1.63	1331.27
15E	1380.01	2.20	1377.81
21A (BH05)	1281.21	12.48	1268.74
21B	1281.21	0.00	1281.21
21D	1280.00	16.09	1263.91
22A	1282.95	10.64	1272.31
22D (BH09)	1281.21	8.33	1272.89
23C	1373.57	5.42	1368.16
25B	1404.66	9.39	1395.27
8B	1325.03	0.00	1325.03
BD52	1381.39	0.73	1380.66
BH01	1283.95	23.33	1260.63

Site ID	Topographical Elevation (mamsl)	Water level (mbgl)	Groundwater Elevation (mamsl)
BH02	1308.60	10.07	1298.53
BH07	1281.69	16.97	1264.73
Mon-2057	1320.23	3.09	1317.14
Mon-F1	1290.60	21.46	1269.14
Mon-F3	1304.74	7.74	1297.00
Mon-F4	1319.62	7.69	1311.93
Mon-HDR1	1283.95	26.71	1257.24
OB	1364.24	0.70	1363.54
Geometric Mean	**1321.87**	**8.91**	**1312.88**
Minimum	**1280.00**	**0.00**	**1256.42**
Maximum	**1404.66**	**26.71**	**1395.27**
Standard deviation	**30.02**	**7.17**	**33.46**
Correlation		**0.98**	

Notes: Boreholes highlighted in red represent the current Tetra 4 monitoring localities.

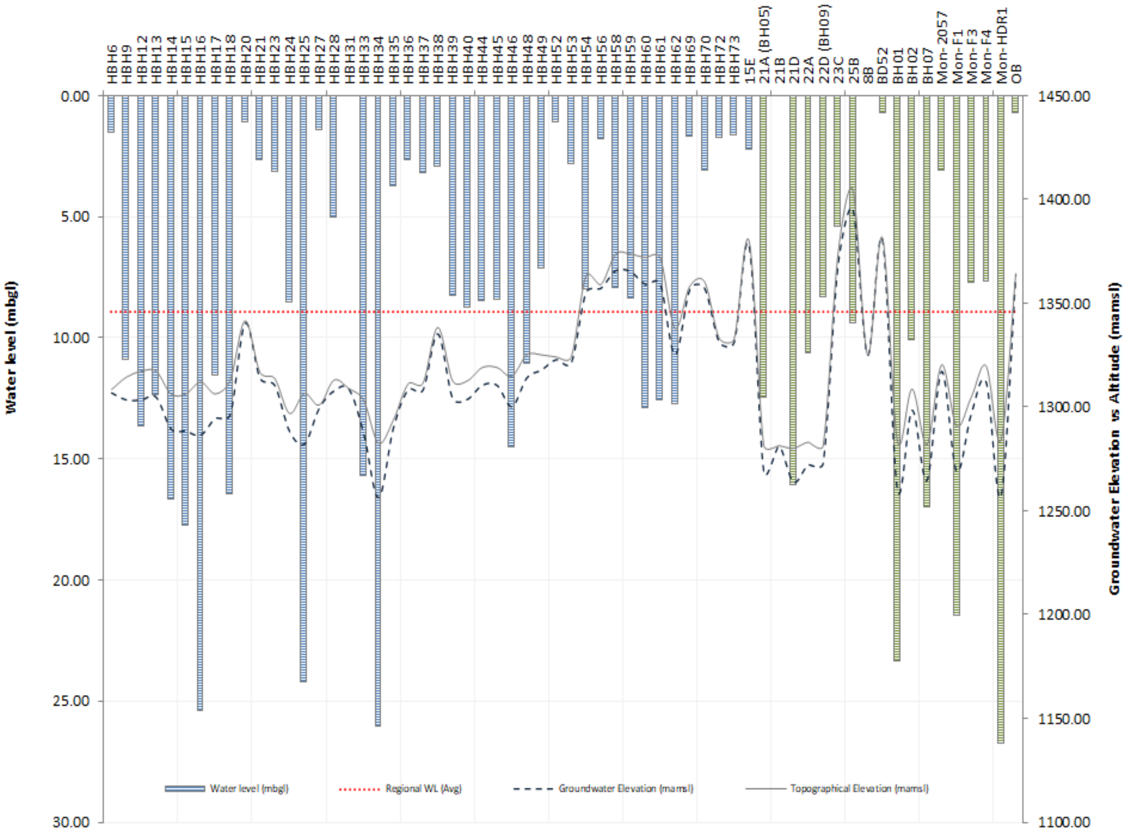

Figure 8-1 **Bar chart indicating regional water level summary.**

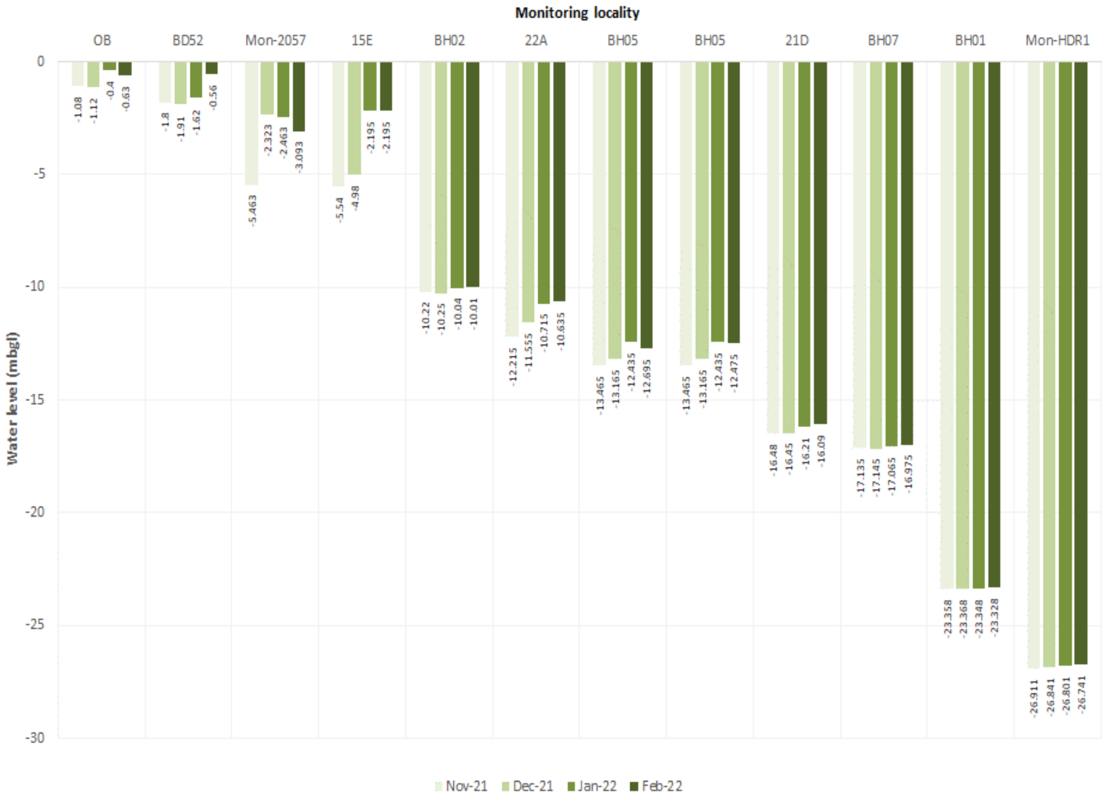

Figure 8-2 **Bar chart indicating time-series water level comparison of the Tetra 4 monitoring boreholes.**

8.3. Groundwater flow direction and hydraulic gradients

Analysed data indicate that the surveyed water levels correlate very well to the topographical elevation (R^2 <0.98) (Figure 8-3). Accordingly, it can be assumed that the regional groundwater flow direction is dictated by topography. Bayesian interpolation was used to interpolate the groundwater levels throughout the study area. The inferred groundwater flow direction will be towards the lower laying drainage system(s) traversing the project area from where groundwater will discharge as baseflow. The groundwater flow direction within the southern catchment of the Sandrivier and Doringrivier, also in the vicinity of the proposed plant expansion footprint, will be in a general northern direction, whereas the groundwater flow direction within the northern catchment of the study area will be mostly in a south to southwestern direction as depicted in Figure 8-4.

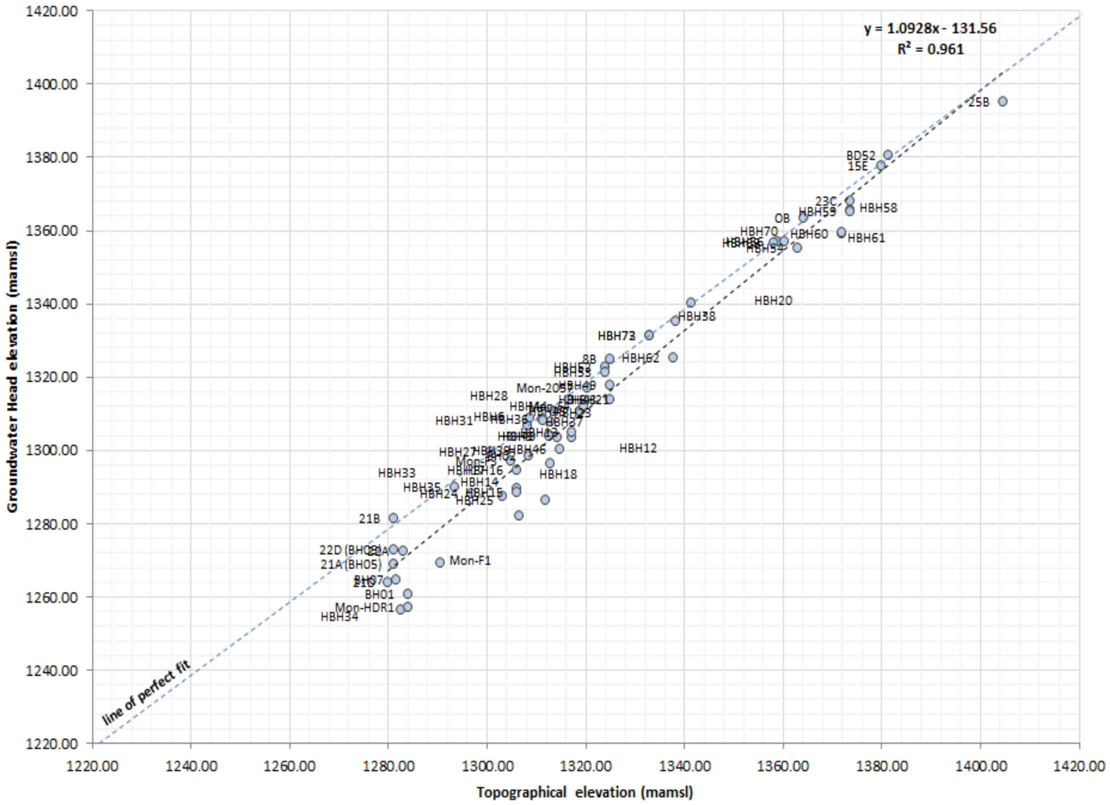

Figure 8-3 **Topographical elevation vs. groundwater elevation correlation graph.**

Groundwater flow path lines are lines perpendicular to groundwater contours, flow generally occurs faster where contours are closer together and gradients are thus steeper. The groundwater or hydraulic gradient is the change in the hydraulic head over a certain distance, mathematically it is the difference in hydraulic head over a distance along the flow path between two points. The latter provides an indication of the direction of groundwater flow. The following equation can be applied:

Equation 8-1 **Hydraulic gradient.**

$$i = \frac{dh}{dl}$$

where:

i = Hydraulic gradient (dimensionless).

dh = Is the head loss between two observation wells.

dL = Horizontal distance between two observation points...

The average groundwater gradient (i) of the shallow, weathered aquifer in the vicinity of the proposed plant expansion footprint is relatively flat and calculated at a mean of 0.002, with a maximum of 0.003 in a south to north orientation and a minimum of 0.001 in a general southeast to northwest orientation as summarised in Table 8-2 below.

Table 8-2 Inferred groundwater gradient and seepage direction.

Inferred seepage direction	Hydraulic gradient (i)
S to N	0.003
E to W	0.001
SW to NE	0.001
SE to NW	0.002
Minimum	**0.001**
Maximum	**0.003**
Standard deviation	**0.001**
Geometric Mean	**0.002**

8.4. Darcy flux and groundwater flow velocity

The Darcy flux (or velocity) is a function of the hydraulic conductivity (K) and the hydraulic gradient as suggested by Equation 8-2 whereas the seepage velocity can be defined as the Darcy flux divided by the effective porosity[6] (Equation 8-3). This is also referred to as the average linear velocity and can be calculated by applying the following equations (Fetter 1994).

Equation 8-2 Darcy flux.

$$v = Ki$$

Equation 8-3 Seepage velocity.

$$v = \frac{Ki}{\emptyset}$$

where:

v = flow velocity (m/d).

K = hydraulic conductivity (m/d).

i = hydraulic gradient (dimensionless).

ø = effective porosity.

The expected seepage rate from contamination originating at the proposed plant expansion footprint as well as associated infrastructure is estimated at an average of approximately 1.26m/a, with a maximum distance of ~2.20m/a in a southern to northern direction as summarised in Table 8-3 below.

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[6] It should be noted that effective porosity percentages have been assumed and in situ tests have not been conducted to confirm these ratios.

Table 8-3 **Darcy flux and seepage rates[7].**

Shallow, intergranular aquifer	Hydraulic gradient (i)	Hydraulic conductivity (K)	Darcy flux (m/d)	Effective porosity	Seepage velocity (m/d)	Seepage velocity (m/a)
S to N	0.003	0.188	0.00060	0.100	0.006	2.202
E to W	0.001	0.188	0.00023	0.100	0.002	0.825
SW to NE	0.001	0.188	0.00025	0.100	0.002	0.908
SE to NW	0.002	0.188	0.00035	0.100	0.003	1.264
Minimum	**0.001**	**0.188**	**0.0002**	**0.100**	**0.002**	**0.825**
Maximum	**0.003**	**0.188**	**0.0006**	**0.100**	**0.006**	**2.202**
Standard deviation	**0.001**	**0.000**	**0.0001**	**0.000**	**0.001**	**0.546**
Geometric Mean	**0.002**	**0.188**	**0.0003**	**0.100**	**0.003**	**1.202**

8.5. Groundwater-surface water interaction

Groundwater and surface water interaction is an essential component of the hydrological cycle. The hyporheic zone (stream bed) is the zone of most interaction (Adams et. al.,2012). According to records documented by Van Tonder and Dennis (2003), under natural conditions this area exhibits certain regions where there is pronounced interaction between surface and groundwater. The two regimes are therefore well-linked and should be integrated to manage any water related issues in these catchments. Regional drainages can be generally classified as influent or gaining stream systems as the groundwater head elevation of the water table in the vicinity of the stream is higher than the altitude of the stream bed and, accordingly, there definitely exists groundwater discharge as baseflow to local drainages. The alluvial associated with the floodplains of the Sand - and Doringrivier forms a primary aquifer and is directly connected with surface water resources, especially during high flow conditions (Lea, 2017).

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[7] This estimate does however not take into account all known or suspected zones in the aquifer like preferential flow paths formed by faults and fracture zones or igneous contact zones like the intrusive dykes that have higher transmissivities than the general aquifer matrix. Such structures may cause flow velocities to increase several meters or even tens of meters per year under steady state conditions. Under stressed conditions such as at groundwater abstraction areas the seepage velocities could increase another order of magnitude.

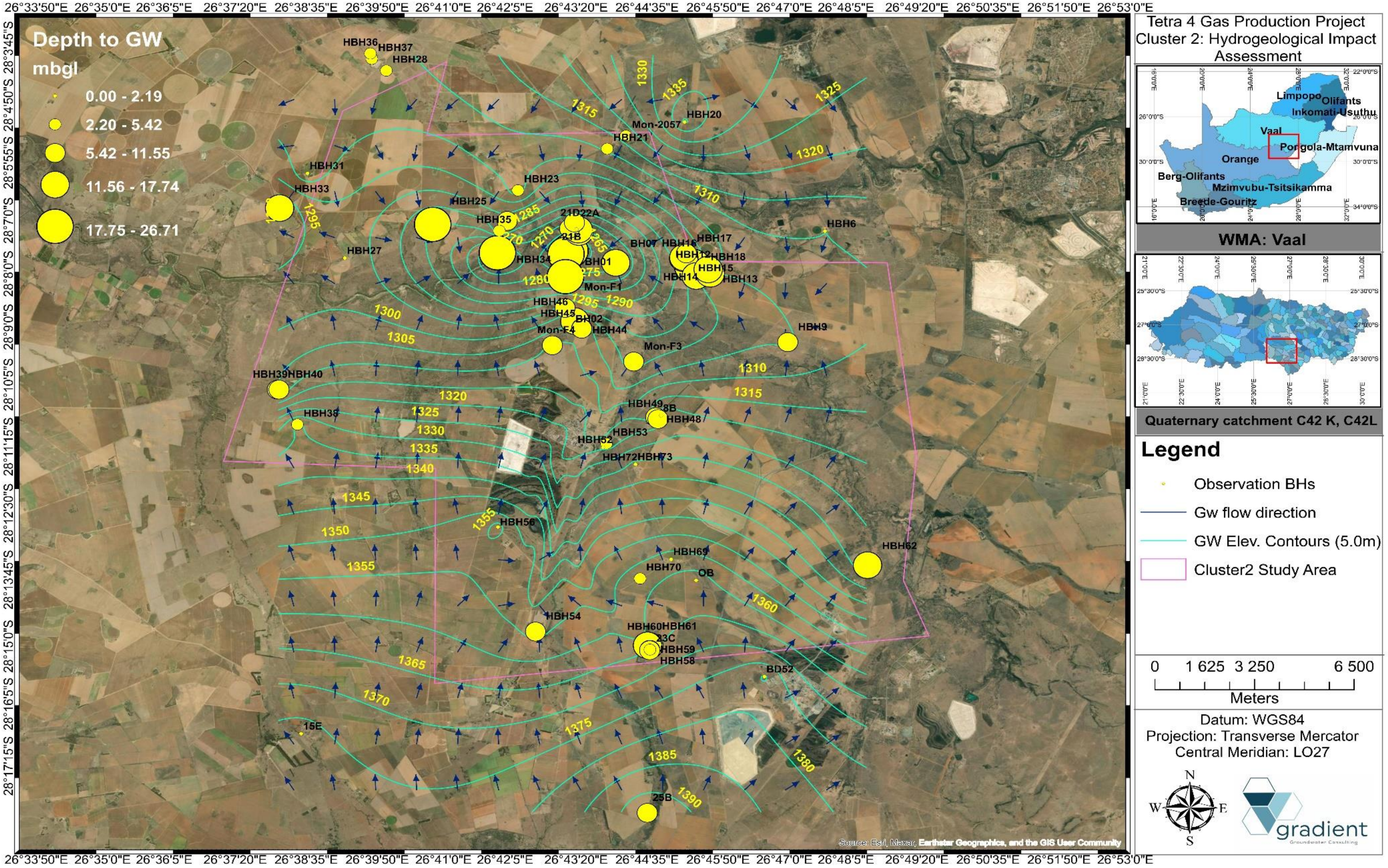


Figure 8-4 Regional groundwater flow direction and depth to groundwater.

9. HYDROCHEMISTRY

To assess future impacts of the proposed gas production activities on the groundwater regime, it is necessary to develop a baseline/background to be applied as benchmark prior to onset. The following section serves to characterise ambient groundwater quality and develop a relevant baseline for future reference.

9.1. Water quality analysis

The South African National Standards (SANS 241: 2015) have been applied to assess the water quality within the project area. The standards specify a maximum limit based on associated risks for constituents (Refer to Table 9-1). Water samples were submitted for analysis at a SANAS accredited laboratory for inorganic analysis. Parameters exceeding the stipulated SANS 241:2015 thresholds are highlighted in red (acute health), elemental concentrations above this range are classed as unsuitable for domestic consumption without treatment whereas yellow highlighted cells indicate parameters above aesthetic limits. These standards were selected for use as the current and future water uses in the area are primarily domestic application and/or livestock watering.

Table 9-1 SANS 241:2015 risks associated with constituents occurring in water.

Risk	Effect
Aesthetic	Determinant that taints water with respect to taste, odour and colour and that does not pose an unacceptable health risk if present at concentration values exceeding the numerical limits specified.
Operational	Determinant that is essential for assessing the efficient operation of treatment systems and risks to infrastructure.
Acute Health – 1	Routinely quantifiable determinant that poses an immediate health risk if consumed with water at concentration values exceeding the numerical limits specified.
Acute Health – 2	Determinant that is presently not easily quantifiable and lacks information pertaining to viability and human infectivity which, however, does pose immediate unacceptable health risks if consumed with water at concentration values exceeding the numerical limits specified.
Chronic Health	Determinant that poses an unacceptable health risk if ingested over an extended period if present at concentration values exceeding the numerical limits specified.

Table 9-2 SANS 241:2015 physical aesthetic, operational and chemical parameters.

Parameter	Risk	Unit	Standard limits [a]
Physical and aesthetic determinants			
Electrical conductivity (EC)	Aesthetic	mS/m	≤170
Total Dissolved Solids (TDS)	Aesthetic	mg/l	≤1200
Turbidity [b]	Operational	NTU	≤1
	Aesthetic	NTU	≤5
pH [c]	Operational	pH units	≥5 to ≤9,7
Chemical determinants – macro			
Nitrate as N[d]	Acute health	mg/l	≤11
Sulphate as SO_4^{-2}	Acute health	mg/l	≤500
	Aesthetic	mg/l	≤250
Fluoride as F	Chronic health	mg/l	≤1.5
Ammonia as N	Aesthetic	mg/l	≤1.5
Chloride as Cl^-	Aesthetic	mg/l	≤300
Sodium as Na	Aesthetic	mg/l	≤200
Zinc as Zn	Aesthetic	mg/l	≤5
Chemical determinants – micro			
Antimony as Sb	Chronic health	mg/l	≤0.02
Arsenic as As	Chronic health	mg/l	≤0.010
Cadmium as Cd	Chronic health	mg/l	≤0.003
Total chromium as Cr	Chronic health	mg/l	≤0.050
Copper as Cu	Chronic health	mg/l	≤2.0
Iron as Fe	Chronic health	mg/l	≤2.0
	Aesthetic	mg/l	≤0.30
Lead as Pb	Chronic health	mg/l	≤0.010
Manganese as Mn	Chronic health	mg/l	≤0.50
	Aesthetic	mg/l	≤0.10
Mercury as Hg	Chronic health	mg/l	≤0.006
Nickel as Ni	Chronic health	mg/l	≤0.07
Selenium as Se	Chronic health	mg/l	≤0.010
Uranium as U	Chronic health	mg/l	≤0.015
Vanadium as V	Chronic health	mg/l	≤0.2
Aluminium as Al	Operational	mg/l	≤0.3

a The health-related standards are based on the consumption of 2 L of water per day by a person of a mass of 60 kg over a period of 70 years.

b Values in excess of those given in column 4 may negatively impact disinfection.

c Low pH values can result in structural problems in the distribution system.

d This is equivalent to nitrate at 50 mg/l NO_3^-.

9.2. Data validation

The laboratory precision was validated by employing the plausibility of the chemical analysis, electro neutrality (E.N.) which is determined according to Equation 10-1, below. An error of less than 5.0% is an indication that the analysis results are of suitable precision for further evaluation. All water samples analysed indicate a good plausibility (<5.0%) and data can be considered as accurate and correct (Table 9-3).

Equation 9-1 Electro-neutrality.

$$\boldsymbol{E.N.} = \frac{\sum cations\left[\frac{meq}{L}\right]+\sum anions\left[\frac{meq}{L}\right]}{\sum cations\left[\frac{meq}{L}\right]-\sum anions\left[\frac{meq}{L}\right]}\mathbf{.100\% < 5.0\%}$$

Table 9-3 Laboratory precision and data validity.

Sample Localities	Σ Major cations (meq/l)	Σ Major anions (meq/l)	Electro-Neutrality [E.N.] %
HBH 2	10.059	10.210	-0.75%
HBH 9	7.701	8.017	-2.01%
HBH 12	9.023	9.401	-2.05%
HBH 15	7.072	7.356	-1.97%
HBH 16	9.304	9.647	-1.81%
HBH 19	11.087	11.471	-1.70%
HBH 21	12.503	12.595	-0.37%
HBH 23	3.118	3.238	-1.89%
HBH 24	8.057	8.363	-1.86%
HBH 25	13.868	13.865	0.01%
HBH 27	12.578	12.225	1.42%
HBH 31	6.659	6.955	-2.18%
HBH 32	8.917	9.245	-1.81%
HBH 34	11.112	11.473	-1.60%
HBH 35	9.681	9.871	-0.97%
HBH 38	6.811	7.078	-1.93%
HBH 42	8.578	8.858	-1.61%
HBH 44	15.226	15.754	-1.70%
HBH 46	10.424	10.775	-1.66%
HBH 48	26.369	26.526	-0.30%
HBH 49	13.933	14.434	-1.77%
HBH 55	7.981	8.271	-1.79%
HBH 56	5.985	6.212	-1.86%
HBH 63	9.392	9.699	-1.61%
HBH 68	9.863	9.480	1.98%
HBH 69	12.426	12.921	-1.95%
HBH 70	11.028	11.473	-1.98%
HBH 73	11.682	12.043	-1.52%
HBH 74	19.709	20.530	-2.04%
HBH 75	21.617	22.267	-1.48%
HBH 76	16.525	17.199	-2.00%
SRD	8.764	9.039	-1.55%
SRU	10.504	10.822	-1.49%

Note: E.N. < 5.0% generally reflect an accurate laboratory analysis.

Table 9-4, Table 9-5 as well as Table 9-6 below classify water quality according to pH, salinity as well as hardness.

Table 9-4 **Hydrochemical classification according to pH-values.**

pH Values used to indicate alkalinity or acidity of water	
pH: > 8.5	Alkaline/Basic
pH: 6.0- 8.5	Neutral
pH: < 6	Acidic

Table 9-5 **Hydrochemical classification according to salinity.**

TDS Concentrations to indicate the salinity of water	
TDS < 450 mg/l	Non-saline
TDS 450 - 1 000 mg/l	Saline
TDS 1 000 - 2 400 mg/l	Very saline
TDS 2 400 - 3 400 mg/l	Extremely saline

Table 9-6 **Hydrochemical classification according to hardness.**

Hardness concentrations to indicate softness or hardness of water	
Hardness < 50 mg/l	Soft
Hardness 50 – 100 mg/l	Moderately soft
Hardness 100 – 150 mg/l	Slightly hard
Hardness 150 – 200 mg/l	Moderately hard
Hardness 200 – 300 mg/l	Hard
Hardness 300 – 600 mg/l	Very hard
Hardness > 600mg/l	Extremely hard

9.3. Water quality

The hydrochemical results of the hydrocensus boreholes water samples analysed suggest the overall ambient groundwater quality is good with most macro and micro determinants falling within or below the SANS 241:2015 limits. Groundwater can be described as neutral, saline to very saline and hard to very hard. The groundwater quality is impacted by the geological formations, which were deposited in shallow marine environments and are therefore naturally saline (Lea, 2017).

It is observed that most of the boreholes indicate elevated Nitrate (NO_3) concentrations. The latter may be attributed to the agricultural land-use activities dominating the greater study area with elevated NO_3 concentrations potentially derived from leachate of fertilizer to the local aquifer. It should be noted that elevated nitrate concentrations were also recorded in most of the hydrocensus boreholes identified during the initial groundwater study of 2017. It is noted that the TDS concentration increases towards the northern section of the study area as well as near the drainages present. This can most likely be attributed to the geology within these sections, however, should be confirmed. Refer to Figure 9-4 for a spatial distribution map of nitrate concentrations per borehole locality analysed. It is noted that borehole localities with elevated NO_3 concentrations are generally situated within or directly down-gradient of planted crop areas as well as near surface water features.

Isolated sampling localities also suggest elevated Calcium (Ca)/Magnesium (Mg)/Sodium (Na)-Chloride (Cl) concentrations which may be indicative of the intermediate, fractured aquifer unit being targeted by the respective borehole(s), sourcing more stagnant groundwater. The latter may also be indicative of over-abstraction of the respective boreholes which result in more saline matrix water being sourced due to turbulent flow conditions instead of water being sourced from fractures via laminar flow conditions.

Surface water samples include an upstream (SRU) and down-stream (SRD) water sample which were collected from the Sandrivier passing down-gradient of the existing and proposed plant expansion footprint area. The surface water quality can be classified as moderate to good with Aluminum (Al) and Iron (Fe) being slightly elevated. It should be noted that there is not a significant change in the downstream water quality compared to the upstream quality with an increase in Aluminum (Al), however all surface water samples analysed suggest elevated heavy metal concentrations i.e., Al and Fe.

The hydrochemical results of the monitoring boreholes water samples analysed suggest the overall ambient groundwater quality to be moderate with a higher salt load being observed. Groundwater can be described as neutral, saline to very saline and hard to very hard. Most samples analysed suggest elevated Calcium/Magnesium-Chloride concentrations with isolated boreholes (BH04 and BH05) indicating elevated concentrations of Manganese (Mn).

Table 9-7, Table 9-8 and Table 9-9 summarises water quality analysis for the hydrocensus samples analysed whereas Table 9-10 tabulates the monitoring borehole water samples analysed. Figure 9-1 (hydrocensus boreholes) and Figure 9-2 (monitoring boreholes) depicts a bar-chart of the major anion and cation composition while Figure 9-3 indicate a spatial distribution map of hydrochemical composition per sampling locality. It is evident that borehole localities HBH44, HBH48, HBH74, HBH75, BH01, BH04, BH05 and BH08 indicate a higher salt load compared to the other sampling localities which may be indicative of a different, potentially deeper, aquifer unit being targeted, however this should be confirmed be evaluation of borehole drilling logs and construction. Below is a short summary of water quality per sampling locality.

9.3.1. Borehole locality HBH2

Water quality can be described as neutral, saline and hard:

- pH of 7.60.
- TDS of 537.38mg/l.
- Total Hardness ($CaCO_3$/l) of 375.86mg/l.

9.3.2. Borehole locality HBH9

Water quality can be described as neutral, non-saline and hard:

- pH of 7.51.
- TDS of 449.27mg/l.
- Total Hardness ($CaCO_3$/l) of 236.78mg/l.

The following chemical variable concentrations exceeded SANS 241-1: 2015:

- NO_3 of 16.03mg/l.

9.3.3. Borehole locality HBH12

Water quality can be described as neutral, saline and very hard:

- pH of 7.33.
- TDS of 511.56mg/l.
- Total Hardness ($CaCO_3$/l) of 361.56mg/l.

The following chemical variable concentrations exceeded SANS 241-1: 2015:

- NO_3 of 12.80 mg/l.

9.3.4. Borehole locality HBH15

Water quality can be described as neutral, non-saline and hard:

- pH of 7.55.
- TDS of 420.78mg/l.
- Total Hardness ($CaCO_3$/l) of 219.26mg/l.

The following chemical variable concentrations exceeded SANS 241-1: 2015:

- NO_3 of 18.80mg/l.

9.3.5. Borehole locality HBH16

Water quality can be described as neutral, saline and very hard:

- pH of 7.48.
- TDS of 539.41mg/l.
- Total Hardness ($CaCO_3$/l) of 323.10mg/l.

The following chemical variable concentrations exceeded SANS 241-1: 2015:

- NO_3 of 16.90mg/l.

9.3.6. Borehole locality HBH19

Water quality can be described as neutral, saline and very hard:

- pH of 7.44.
- TDS of 646.73mg/l.
- Total Hardness ($CaCO_3$/l) of 417.83mg/l.

The following chemical variable concentrations exceeded SANS 241-1: 2015:

- NO_3 of 21.70mg/l.

9.3.7. Borehole locality HBH21

Water quality can be described as neutral, saline and very hard:

- pH of 7.24.
- TDS of 686.31mg/l.
- Total Hardness ($CaCO_3$/l) of 430.64mg/l.

9.3.8. Borehole locality HBH23

Water quality can be described as neutral, non-saline and moderately soft:

- pH of 8.32.
- TDS of 174.51mg/l.
- Total Hardness ($CaCO_3$/l) of 70.0mg/l.

9.3.9. Borehole locality HBH24

Water quality can be described as neutral, non-saline and hard:

- pH of 7.52.
- TDS of 462.11mg/l.
- Total Hardness ($CaCO_3$/l) of 258.30mg/l.

The following chemical variable concentrations exceeded SANS 241-1: 2015:

- NO_3 of 14.30mg/l.

9.3.10. Borehole locality HBH25

Water quality can be described as neutral, saline and very hard:

- pH of 7.40.
- TDS of 747.67mg/l.
- Total Hardness ($CaCO_3$/l) of 360.76mg/l.

The following chemical variable concentrations exceeded SANS 241-1: 2015:

- NH_3 of 3.89mg/l.

9.3.11. Borehole locality HBH27

Water quality can be described as neutral, saline and very hard:

- pH of 7.47.
- TDS of 671.76mg/l.
- Total Hardness ($CaCO_3$/l) of 390.20mg/l.

9.3.12. Borehole locality HBH31

Water quality can be described as neutral, non-saline and moderately hard:

- pH of 7.47.
- TDS of 410.94mg/l.
- Total Hardness ($CaCO_3$/l) of 189.05mg/l.

The following chemical variable concentrations exceeded SANS 241-1: 2015:

- NO_3 of 26.20mg/l.

9.3.13. Borehole locality HBH32

Water quality can be described as neutral, saline and hard:

- pH of 7.52.
- TDS of 528.42mg/l.
- Total Hardness ($CaCO_3$/l) of 249.77mg/l.

The following chemical variable concentrations exceeded SANS 241-1: 2015:

- NO_3 of 24.60mg/l.

9.3.14. Borehole locality HBH34

Water quality can be described as neutral, saline and soft:

- pH of 8.17.
- TDS of 635.87mg/l.
- Total Hardness ($CaCO_3$/l) of 7.48mg/l.

9.3.15. Borehole locality HBH35

Water quality can be described as neutral, saline and hard:

- pH of 7.37.
- TDS of 546.79mg/l.
- Total Hardness ($CaCO_3$/l) of 281.13mg/l.

The following chemical variable concentrations exceeded SANS 241-1: 2015:

- NO_3 of 14.50mg/l.

9.3.16. Borehole locality HBH38

Water quality can be described as neutral, non-saline and hard:

- pH of 7.12.
- TDS of 417.21mg/l.
- Total Hardness ($CaCO_3$/l) of 205.38mg/l.

9.3.17. Borehole locality HBH42

Water quality can be described as neutral, saline and hard:

- pH of 7.23.
- TDS of 478.99mg/l.
- Total Hardness ($CaCO_3$/l) of 291.82mg/l.

9.3.18. Borehole locality HBH44

Water quality can be described as neutral, saline and very hard:

- pH of 7.40.
- TDS of 848.64mg/l.
- Total Hardness ($CaCO_3$/l) of 491.49mg/l.

9.3.19. Borehole locality HBH46

Water quality can be described as neutral, saline and very hard:

- pH of 7.62.
- TDS of 613.93mg/l.
- Total Hardness ($CaCO_3$/l) of 333.20mg/l.

The following chemical variable concentrations exceeded SANS 241-1: 2015:

- NO_3 of 21.10mg/l.

9.3.20. Borehole locality HBH48

Water quality can be described as neutral, saline and extremely hard:

- pH of 7.05.
- TDS of 1558.04mg/l.
- Total Hardness ($CaCO_3$/l) of 946.03mg/l.

The following chemical variable concentrations exceeded SANS 241-1: 2015:

- TDS of 1558.04mg/l.
- Electrical Conductivity 255.0mS/m.
- Cl of 523.0mg/l.
- NO_3 of 53.5mg/l.
- Ca of 272.0mg/l.

9.3.21. Borehole locality HBH49

Water quality can be described as neutral, saline and very hard:

- pH of 7.72.
- TDS of 806.77mg/l.
- Total Hardness ($CaCO_3$/l) of 444.52mg/l.

The following chemical variable concentrations exceeded SANS 241-1: 2015:

- NO_3 of 19.70mg/l.

9.3.22. Borehole locality HBH55

Water quality can be described as neutral, saline and moderately hard:

- pH of 7.91.
- TDS of 462.33mg/l.
- Total Hardness ($CaCO_3$/l) of 178.29mg/l.

The following chemical variable concentrations exceeded SANS 241-1: 2015:

- NO_3 of 12.80mg/l.

9.3.23. Borehole locality HBH56

Water quality can be described as neutral, non-saline and hard:

- pH of 8.47.
- TDS of 354.36mg/l.
- Total Hardness ($CaCO_3$/l) of 208.12mg/l.

The following chemical variable concentrations exceeded SANS 241-1: 2015:

- NO_3 of 14.80mg/l.

9.3.24. Borehole locality HBH63

Water quality can be described as neutral, saline and hard:

- pH of 7.78.
- TDS of 530.94mg/l.
- Total Hardness ($CaCO_3$/l) of 288.56mg/l.

The following chemical variable concentrations exceeded SANS 241-1: 2015:

- NO_3 of 13.0mg/l.

9.3.25. Borehole locality HBH68

Water quality can be described as neutral, saline and very hard:

- pH of 7.58.
- TDS of 527.78mg/l.
- Total Hardness ($CaCO_3$/l) of 310.88mg/l.

The following chemical variable concentrations exceeded SANS 241-1: 2015:

- NO_3 of 13.80mg/l.

9.3.26. Borehole locality HBH69

Water quality can be described as neutral, saline and very hard:

- pH of 7.40.
- TDS of 698.14mg/l.
- Total Hardness ($CaCO_3$/l) of 387.80mg/l.

The following chemical variable concentrations exceeded SANS 241-1: 2015:

- NO_3 of 15.70mg/l.

9.3.27. Borehole locality HBH70

Water quality can be described as neutral, saline and very hard:

- pH of 8.17.
- TDS of 630.74mg/l.
- Total Hardness ($CaCO_3$/l) of 323.66mg/l.

The following chemical variable concentrations exceeded SANS 241-1: 2015:

- NO_3 of 19.90mg/l.

9.3.28. Borehole locality HBH73

Water quality can be described as neutral, saline and very hard:

- pH of 7.83.
- TDS of 664.41mg/l.
- Total Hardness ($CaCO_3$/l) of 351.60mg/l.

The following chemical variable concentrations exceeded SANS 241-1: 2015:

- NO_3 of 14.90mg/l.

9.3.29. Borehole locality HBH74

Water quality can be described as neutral, very saline and extremely hard:

- pH of 7.56.
- TDS of 1132.04mg/l.
- Total Hardness ($CaCO_3$/l) of 782.31mg/l.

The following chemical variable concentrations exceeded SANS 241-1: 2015:

- Electrical Conductivity 189.0mS/m.
- Cl of 477.0mg/l.
- NO_3 of 26.30mg/l.
- Ca of 216.0mg/l.

9.3.30. Borehole locality HBH75

Water quality can be described as neutral, very saline and very hard:

- pH of 7.83.
- TDS of 1230.35mg/l.
- Total Hardness ($CaCO_3$/l) of 479.80mg/l.

The following chemical variable concentrations exceeded SANS 241-1: 2015:

- Electrical Conductivity 208.0mS/m.
- TDS of 1230.35mg/l.
- Cl of 598.0mg/l.

9.3.31. Borehole locality HBH76

Water quality can be described as neutral, saline and extremely hard:

- pH of 7.49.
- TDS of 942.94mg/l.
- Total Hardness ($CaCO_3$/l) of 669.22mg/l.

The following chemical variable concentrations exceeded SANS 241-1: 2015:

- NO_3 of 30.20mg/l.

9.3.32. Surface water locality SRU

Water quality can be described as neutral, saline and hard:

- pH of 7.38.
- TDS of 613.94mg/l.
- Total Hardness ($CaCO_3$/l) of 290.92mg/l.

The following chemical variable concentrations exceeded SANS 241-1: 2015:

- Fe of 1.05mg/l.

9.3.33. Surface water locality SRD

Water quality can be described as neutral, saline and hard:

- pH of 7.42.
- TDS of 506.36mg/l.
- Total Hardness ($CaCO_3$/l) of 235.90mg/l.

The following chemical variable concentrations exceeded SANS 241-1: 2015:

- Al of 1.18mg/l.
- Fe of 0.94mg/l.

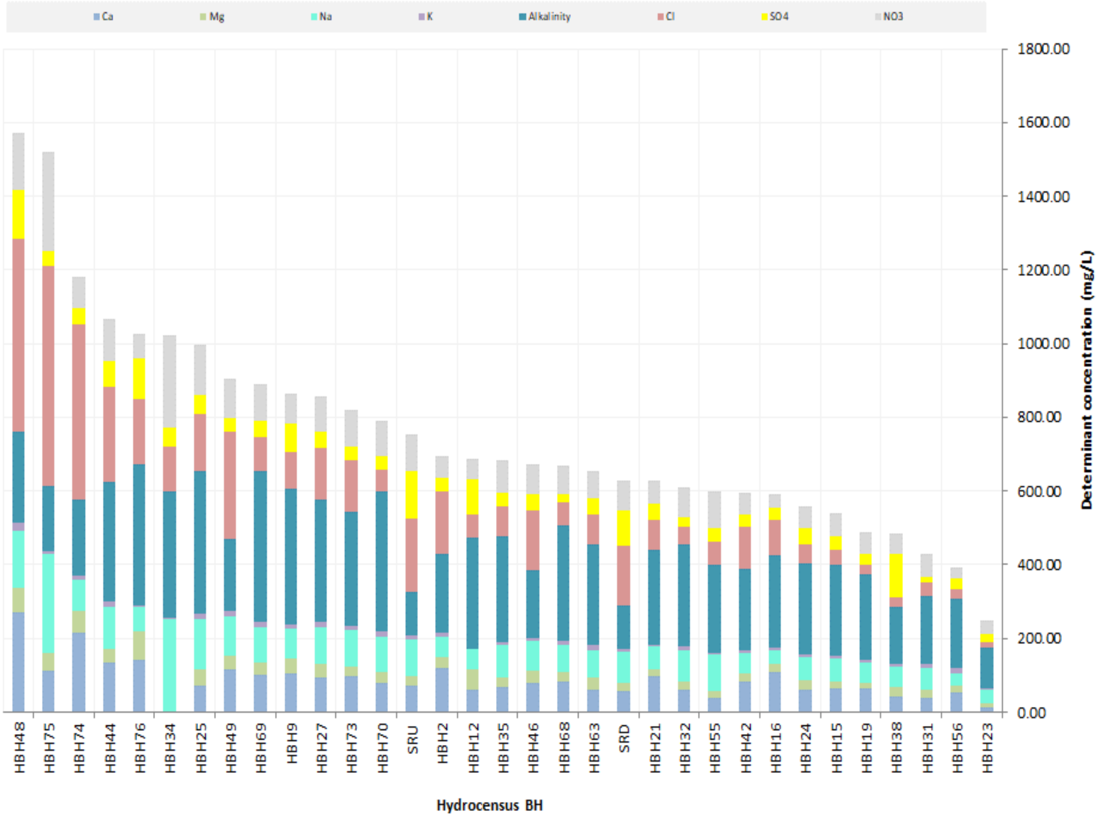


Figure 9-1 Hydrochemistry: Composite bar-chart indicating groundwater major anion cation composition of hydrocensus samples analysed.

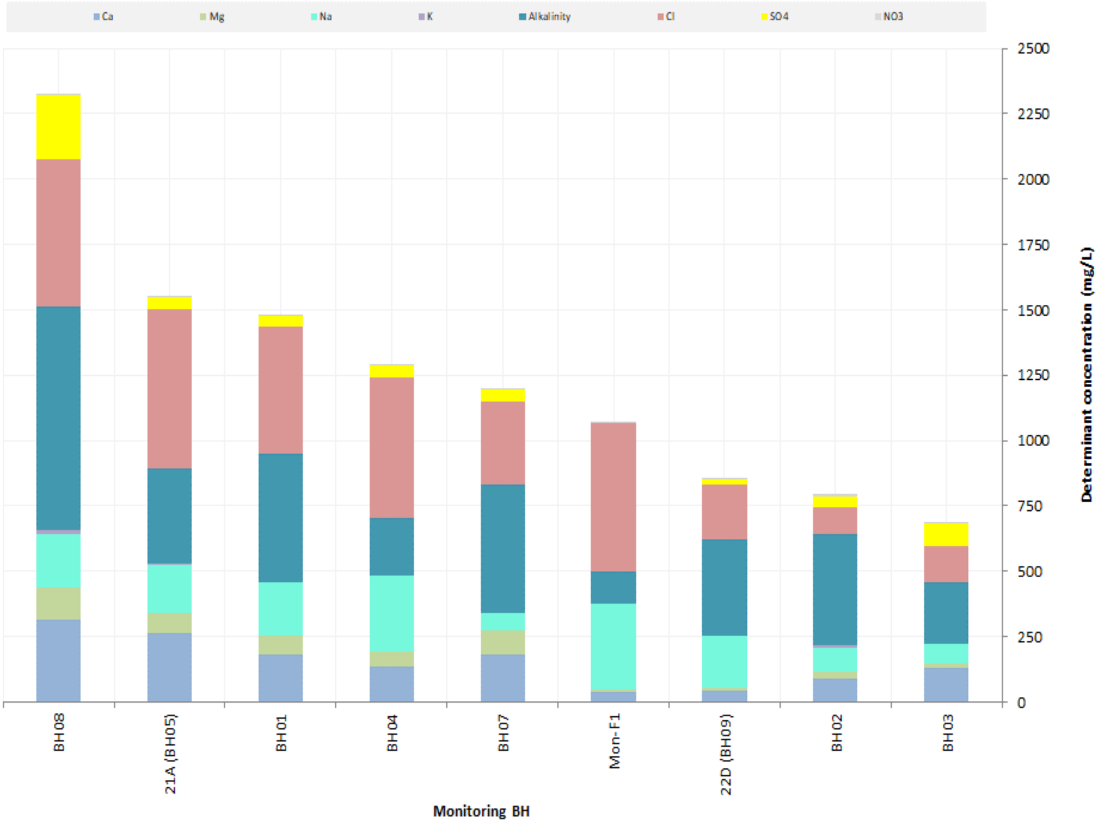


Figure 9-2 Hydrochemistry: Composite bar-chart indicating groundwater major anion cation composition of monitoring borehole samples analysed.

Table 9-7 **Hydrochemistry: Groundwater quality evaluation of hydrocensus samples analysed.**

Determinant	Unit	Risk	SANS 241:2015 limits	HBH 2	HBH 9	HBH 12	HBH 15	HBH 16	HBH 19	HBH 21	HBH 23	HBH 24	HBH 25	HBH 27
Physical determinants														
Colour	-	-	-	Clear	Clear	Clear	Clear	Clear	Clear	Clear	Clear	Clear	Clear	Clear
Temperature	°C	-	-	21.00	21.00	21.00	21.00	21.00	21.00	21.00	21.00	21.00	21.00	21.00
General parameters														
pH	-	**Operational**	**≥5.0 ≤ 9.5**	7.60	7.51	7.33	7.55	7.48	7.44	7.24	8.32	7.52	7.40	7.47
EC	mS/m	**Aesthetic**	**≤170.0**	92.80	75.20	88.30	67.80	89.30	126.00	116.00	32.80	74.70	136.00	120.00
TDS		**Aesthetic**	**≤ 1 200.0**	537.38	449.27	511.56	420.78	539.41	646.73	686.31	174.51	462.11	747.67	671.76
Total Alkalinity	CaCO3/l	-	-	301.00	246.00	250.00	232.00	256.00	216.00	367.00	112.00	248.00	389.00	330.00
Total Hardness	mg/l	-	-	375.86	236.78	361.56	219.26	323.10	417.83	430.64	70.00	258.30	360.76	390.20
Anions														
Cl	mg/l	**Aesthetic**	**≤300.0**	61.10	40.70	97.70	25.10	84.00	167.00	98.50	13.80	52.50	152.00	141.00
SO_4	mg/l	**Acute health**	**≤500.0**	95.70	36.40	33.20	31.30	43.50	39.60	77.80	22.80	42.10	53.90	42.40
F	mg/l	**Acute health**	**≤1.50**	0.13	0.14	<0.09	<0.09	<0.09	<0.09	<0.09	0.25	<0.09	<0.09	<0.09
NO_3< N	mg/l	**Acute health**	**≤12.0**	6.16	**16.30**	**12.80**	**18.80**	**16.90**	**21.70**	11.40	1.59	**14.30**	8.06	9.92
PO_4	mg/l	**Acute health**	**≤5.0**	<0.03	<0.03	<0.03	<0.03	0.11	<0.03	<0.03	<0.03	<0.03	0.39	<0.03
NH_3	mg/l	**Acute health**	**≤1.5**	<0.45	<0.45	<0.45	<0.45	<0.45	<0.45	<0.45	<0.45	<0.45	**3.89**	<0.45
Cations and metals														
Na	mg/l	**Aesthetic**	**≤200.0**	55.20	63.20	36.50	57.10	61.20	55.90	80.10	36.70	60.80	135.00	98.60
K	mg/l	**Aesthetic**	**≤50.0**	2.88	6.69	6.20	5.95	4.92	9.60	12.60	4.10	7.86	15.90	15.90
Ca	mg/l	**Aesthetic**	**≤150.0**	58.50	62.50	110.00	63.40	97.40	120.00	106.00	13.90	60.40	70.10	93.60
Mg	mg/l	**Operational**	**70.0**	55.80	19.60	21.10	14.80	19.40	28.70	40.30	8.57	26.10	45.10	38.00
Al	mg/l	**Operational**	**0.3**	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
Fe	mg/l	**Acute health**	**2.0**	<0.01	<0.01	<0.01	<0.01	<0.01	0.01	0.01	0.06	<0.01	<0.01	0.03
Mn	mg/l	**Operational**	**0.4**	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
As	mg/l	**Acute health**	**0.01**	<0.009	<0.009	<0.009	<0.009	<0.009	<0.009	<0.009	<0.009	<0.009	<0.009	<0.009
CN	mg/l	**Acute health**	**0.2**	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
Zn	mg/l	**Acute health**	**5.0**	<0.01	<0.01	<0.01	0.44	0.01	<0.01	<0.01	<0.01	0.02	0.01	0.04

Note: "- " indicate that no limits have been provided by the SANS 2015:241 guidelines.
"<" below detection limit
Shaded cells exceed SANS 241:2015 drinking water guidelines.

Table 9-8 Hydrochemistry: Groundwater quality evaluation of hydrocensus samples analysed (Cont.).

Determinant	Unit	Risk	SANS 241:2015 limits	HBH 31	HBH 32	HBH 34	HBH 35	HBH 38	HBH 42	HBH 44	HBH 46	HBH 48	HBH 49	HBH 55
Physical determinants														
Colour	-	-	-	Clear	Clear	Clear	Clear	Clear	Clear	Clear	Clear	Clear	Clear	Clear
Temperature	°C	-	-	21.00	21.00	21.00	21.00	21.00	21.00	21.00	21.00	21.00	21.00	21.00
General parameters														
pH	-	Operational	≥5.0 ≤ 9.5	7.47	7.52	8.17	7.37	7.12	7.23	7.40	7.62	7.05	7.72	7.91
EC	mS/m	Aesthetic	≤170.0	65.30	85.20	119.00	95.00	67.60	87.50	149.00	103.00	255.00	133.00	75.70
TDS		Aesthetic	≤ 1 200.0	410.94	528.42	635.87	546.79	417.21	478.99	848.64	613.93	1558.04	806.77	462.33
Total Alkalinity	CaCO3/l	-	-	184.00	276.00	345.00	284.00	153.00	219.00	324.00	182.00	246.00	195.00	238.00
Total Hardness	mg/l	-	-	189.05	249.77	7.48	281.13	205.38	291.82	491.49	333.20	946.03	444.52	178.29
Anions														
Cl	mg/l	Aesthetic	≤300.0	35.80	50.30	120.00	81.20	25.20	114.00	259.00	162.00	523.00	292.00	61.10
SO_4	mg/l	Acute health	≤500.0	17.80	25.20	52.80	39.40	119.00	35.90	70.40	46.60	135.00	36.70	39.60
F	mg/l	Acute health	≤1.50	<0.09	<0.09	0.49	<0.09	0.42	<0.09	<0.09	<0.09	<0.09	<0.09	0.11
NO_3< N	mg/l	Acute health	≤12.0	26.20	24.60	<0.35	14.50	11.10	6.58	5.19	21.10	53.50	19.70	12.80
PO_4	mg/l	Acute health	≤5.0	0.06	<0.03	<0.03	0.10	<0.03	<0.03	0.35	0.26	0.21	0.16	0.15
NH_3	mg/l	Acute health	≤1.5	<0.45	<0.45	<0.45	<0.45	<0.45	<0.45	<0.45	<0.45	<0.45	<0.45	<0.45
Cations and metals														
Na	mg/l	Aesthetic	≤200.0	59.80	81.70	251.00	86.50	56.50	57.60	113.00	78.90	154.00	107.00	96.70
K	mg/l	Aesthetic	≤50.0	9.34	12.60	1.19	9.72	8.14	7.48	15.50	10.20	23.60	12.10	6.67
Ca	mg/l	Aesthetic	≤150.0	39.10	58.80	1.61	67.40	43.00	82.40	134.00	80.50	272.00	117.00	37.10
Mg	mg/l	Operational	70.0	22.20	25.00	0.84	27.40	23.80	20.90	38.10	32.10	64.80	37.00	20.80
Al	mg/l	Operational	0.3	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
Fe	mg/l	Acute health	2.0	0.08	0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
Mn	mg/l	Operational	0.4	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	0.01	<0.01	<0.01
As	mg/l	Acute health	0.01	<0.009	<0.009	<0.009	<0.009	<0.009	<0.009	<0.009	<0.009	<0.009	<0.009	<0.009
CN	mg/l	Acute health	0.2	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
Zn	mg/l	Acute health	5.0	<0.01	<0.01	<0.01	<0.01	<0.01	0.01	<0.01	<0.01	<0.01	<0.01	<0.01

Note: "- " indicate that no limits have been provided by the SANS 2015:241 guidelines.
"<" below detection limit
Shaded cells exceed SANS 241:2015 drinking water guidelines.

Table 9-9 Hydrochemistry: Groundwater quality evaluation of hydrocensus samples analysed (Cont.).

Determinant	Unit	Risk	SANS 241:2015 limits	HBH 56	HBH 63	HBH 68	HBH 69	HBH 70	HBH 73	HBH 74	HBH 75	HBH 76	SRD	SRU
Physical determinants														
Colour	-	-	-	Clear	Brownish	Clear	Clear	Clear	Clear	Clear	Clear	Clear	Brownish	Clear
Temperature	°C	-	-	21.00	21.00	21.00	21.00	21.00	21.00	21.00	21.00	21.00	21.00	21.00
General parameters														
pH	-	**Operational**	**≥5.0 ≤ 9.5**	8.47	7.78	7.58	7.40	8.17	7.83	7.56	7.83	7.49	7.42	7.38
EC	**mS/m**	**Aesthetic**	**≤170.0**	54.50	89.90	93.90	114.00	97.50	108.00	**189.00**	**208.00**	143.00	85.50	105.00
TDS		**Aesthetic**	**≤ 1 200.0**	354.36	530.94	527.78	698.14	630.74	664.41	1132.04	**1230.35**	942.94	506.36	613.94
Total Alkalinity	**CaCO3/l**	-	-	189.00	273.00	312.00	409.00	379.00	308.00	204.00	174.00	384.00	116.00	119.00
Total Hardness	**mg/l**	-	-	208.12	288.56	310.88	387.80	323.66	351.60	782.31	479.80	669.22	235.90	290.92
Anions														
Cl	**mg/l**	**Aesthetic**	**≤300.0**	23.90	82.00	61.50	94.20	58.50	140.00	**477.00**	**598.00**	175.00	162.00	196.00
SO_4	**mg/l**	**Acute health**	**≤500.0**	29.10	46.20	23.60	44.30	38.10	39.10	44.90	42.70	112.00	96.10	131.00
F	**mg/l**	**Acute health**	**≤1.50**	<0.09	<0.09	<0.09	<0.09	<0.09	<0.09	<0.09	1.20	0.38	0.13	0.10
NO_3< N	**mg/l**	**Acute health**	**≤12.0**	**14.80**	**13.00**	**13.80**	**15.70**	**19.90**	**14.90**	**26.30**	10.30	**30.20**	0.92	1.22
PO_4	**mg/l**	**Acute health**	**≤5.0**	0.84	<0.03	<0.03	<0.03	<0.03	<0.03	0.04	<0.03	0.03	0.09	0.13
NH_3	**mg/l**	**Acute health**	**≤1.5**	<0.45	0.60	<0.45	<0.45	<0.45	<0.45	<0.45	<0.45	<0.45	<0.45	<0.45
Cations and metals														
Na	**mg/l**	**Aesthetic**	**≤200.0**	31.60	74.00	76.00	97.50	95.10	98.90	82.30	268.00	65.00	82.30	98.60
K	**mg/l**	**Aesthetic**	**≤50.0**	16.30	11.90	10.70	13.60	13.90	11.60	13.60	9.13	4.76	9.58	11.40
Ca	**mg/l**	**Aesthetic**	**≤150.0**	53.86	61.80	80.80	99.40	78.00	97.60	**216.00**	112.00	143.00	57.20	70.00
Mg	**mg/l**	**Operational**	**70.0**	17.88	32.60	26.50	33.90	31.30	26.20	59.00	48.60	**75.80**	22.60	28.20
Al	**mg/l**	**Operational**	**0.3**	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	**1.18**	<0.01
Fe	**mg/l**	**Acute health**	**2.0**	0.02	<0.01	0.06	<0.01	<0.01	<0.01	0.02	<0.01	<0.01	**0.94**	**1.05**
Mn	**mg/l**	**Operational**	**0.4**	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	0.06	0.03	0.04
As	**mg/l**	**Acute health**	**0.01**	<0.009	<0.009	<0.009	<0.009	<0.009	<0.009	<0.009	<0.009	<0.009	<0.009	<0.009
CN	**mg/l**	**Acute health**	**0.2**	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
Zn	**mg/l**	**Acute health**	**5.0**	<0.01	0.03	0.04	0.02	<0.01	<0.01	<0.01	<0.01	2.43	<0.01	<0.01

Note: "- " indicate that no limits have been provided by the SANS 2015:241 guidelines.
"<" below detection limit
Shaded cells exceed SANS 241:2015 drinking water guidelines.

Table 9-10 Hydrochemistry: Groundwater quality evaluation of monitoring samples analysed.

Determinant	Unit	Risk	SANS 241:2015 limits	BH01	BH02	BH04	21A (BH05)	BH07	BH08	22D (BH09)	Mon-F1
General parameters											
pH	**-**	**Operational**	**≥5.0 ≤ 9.5**	7.14	7.22	7.50	7.05	6.97	7.05	7.88	8.26
EC	**mS/m**	**Aesthetic**	**≤170.0**	**328.00**	117.10	**325.00**	**398.00**	**286.10**	**505.00**	126.20	**214.90**
TDS		**Aesthetic**	**≤ 1 200.0**	**1653.00**	676.00	**1662.00**	**2140.00**	**1511.00**	**2559.00**	697.00	1098.00
Total Alkalinity	**CaCO3/l**	**-**	**-**	488.00	427.00	216.60	366.00	488.00	854.00	366.00	122.00
Total Hardness	**mg/l**	**-**	**-**	739.00	328.00	571.00	983.00	826.00	1280.00	147.00	127.00
Anions											
Cl	**mg/l**	**Aesthetic**	**≤300.0**	**488.00**	101.00	**540.00**	**609.00**	**318.00**	**566.00**	210.00	**568.00**
SO_4	**mg/l**	**Acute health**	**≤500.0**	39.00	43.00	43.00	44.00	48.00	246.00	23.00	0.29
F	**mg/l**	**Acute health**	**≤1.50**	0.06	0.04	0.11	0.07	0.04	0.04	0.88	0.12
NO_3< N	**mg/l**	**Acute health**	**≤12.0**	3.80	6.40	0.02	0.02	0.02	6.60	0.02	0.02
NH_3	**mg/l**	**Acute health**	**≤1.5**	0.01	0.04	1.20	1.10	0.07	0.01	0.17	0.52
Cations and metals											
Na	**mg/l**	**Aesthetic**	**≤200.0**	**205.00**	93.00	**288.00**	183.00	67.00	**208.00**	200.00	**327.00**
K	**mg/l**	**Aesthetic**	**≤50.0**	3.00	9.00	4.20	3.90	2.90	12.00	1.90	2.70
Ca	**mg/l**	**Aesthetic**	**≤150.0**	**183.00**	87.00	137.00	**262.00**	**181.00**	**315.00**	43.00	40.00
Mg	**mg/l**	**Operational**	**70.0**	69.00	27.00	56.00	**80.00**	**91.00**	**121.00**	9.70	6.80
Al	**mg/l**	**Operational**	**0.3**	0.002	0.002	0.002	0.002	0.002	0.002	0.002	0.002
Fe	**mg/l**	**Acute health**	**2.0**	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04
Mn	**mg/l**	**Operational**	**0.4**	0.01	0.10	**1.20**	**5.10**	0.11	0.02	0.05	0.09
As	**mg/l**	**Acute health**	**0.01**	0.0004	0.0004	0.0004	0.0004	0.0004	0.0004	0.0004	0.0004
Zn	**mg/l**	**Acute health**	**5.0**	0.54	0.04	0.01	0.04	0.04	0.18	0.04	0.04

Note: "- " indicate that no limits have been provided by the SANS 2015:241 guidelines.
"<" below detection limit
Shaded cells exceed SANS 241:2015 drinking water guidelines.

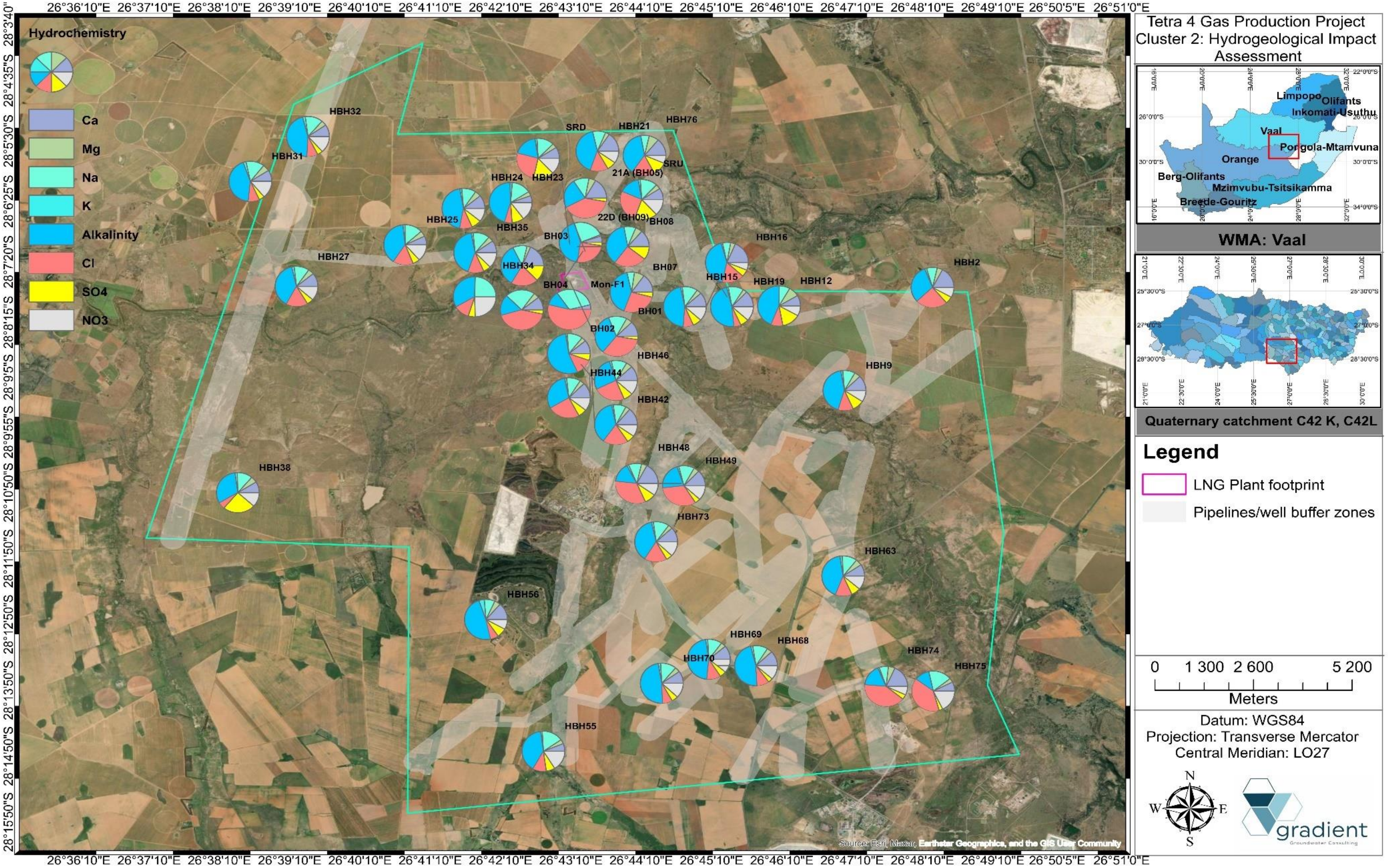


Figure 9-3 **Hydrochemical analysis spatial distribution (mg/l).**

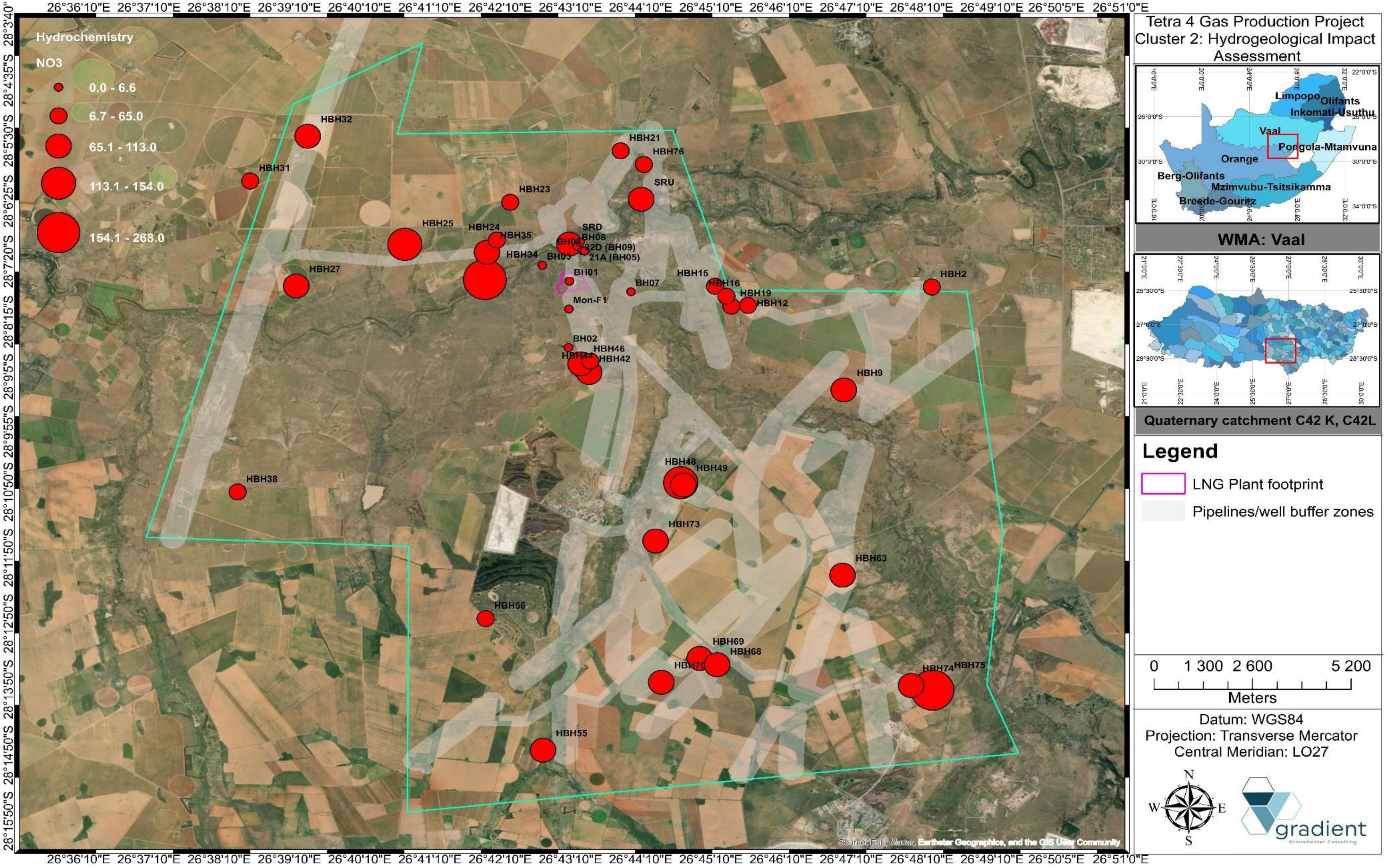


Figure 9-4 Nitrate (NO_3) spatial distribution (mg/l).

9.4. Hydrochemical signature

The hydrochemical signature of the samples analysed were evaluated by means of diagnostic plots. The latter aids to get an understanding of various environments and sources from where groundwater and surface water originates. Three types of diagnostic plots were used to characterise analysed water samples based on hydrochemistry.

9.4.1. Piper diagrams

A piper diagram is a diagnostic representation of major anions and cations as separate ternary plots as summarised in Figure 9-5. Different water types derived from different environments plot in diagnostic areas. The upper half of the diamond normally contains water of static and disordinate regimes, while the middle area generally indicates an area of dissolution and mixing. The lower triangle of this diamond shape indicates an area of dynamic and coordinated regimes. Figure 9-6 depicts a piper diagram developed from the water quality analysis results. Most water samples analysed suggest no cation dominance while the dominant anion is either chloride (sodium or chloride enrichment) or carbonate/bicarbonate (recently recharged water). Accordingly, three distinct categories can be observed, Category A: Calcium-Bi-carbonate dominance which suggest a recently recharged and unimpacted groundwater environment (majority of samples), Category B: Calcium-Magnesium-Chloride dominance which indicate a static and disordinate environment (HBH48, HBH49, HBH74 and HBH75) as well as Category C: Sodium-Potassium-Bi-carbonate dominance which indicate an area of dynamic groundwater environments (HBH34 and BH09).

The surface water samples analysed can be categorized as having Calcium-Magnesium-Chloride dominance which indicate a static and disordinate environment, one would except a more Calcium-Bi-carbonate signature from an unpolluted surface water source, however baseflow discharge present from the saline groundwater resource will have an impact on the salinity of the surface water resources as is evident. Figure 9-7 indicate a piper diagram comparison of major anions and cations of the deep vs shallow aquifer(s) and the Sodium-Potassium-Chloride dominance of the deep, fractured aquifer groundwater suggest extremely saline conditions as expected.

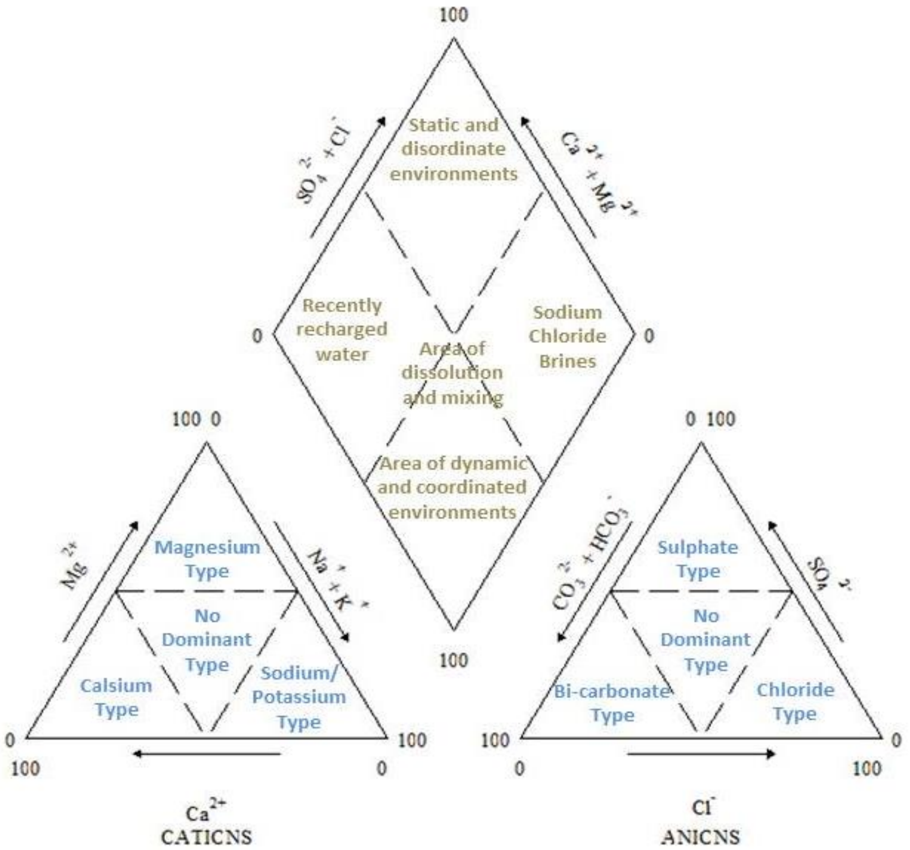


Figure 9-5 Piper diagram indicating classification for anion and cation facies in terms of ion percentages

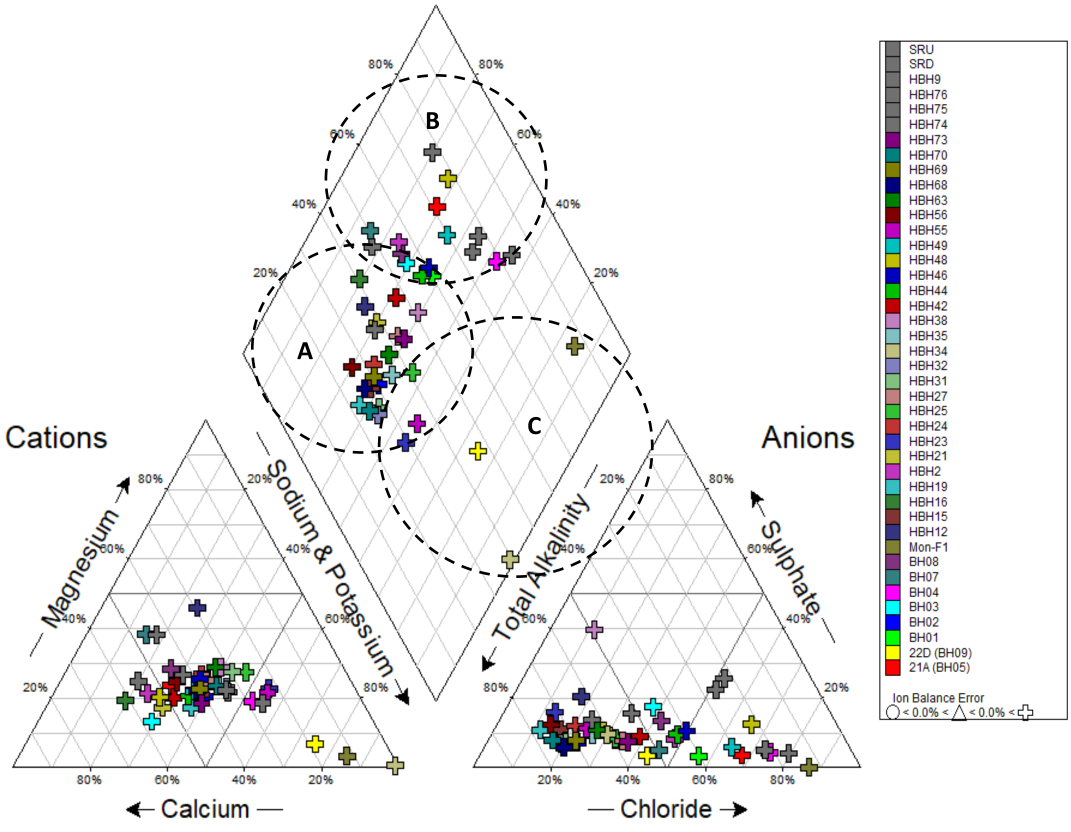


Figure 9-6 Piper diagram indicating major anions and cations of water samples analysed.

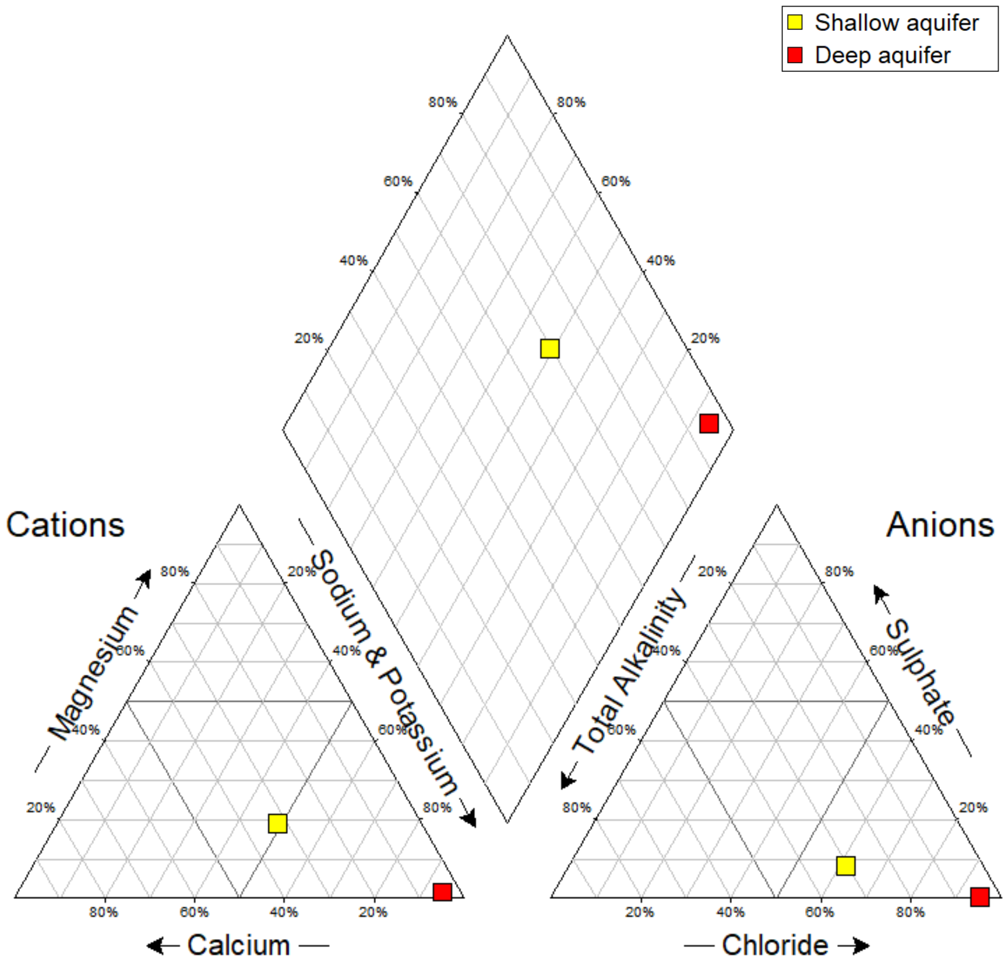


Figure 9-7 **Piper diagram indicating a comparison of major anions and cations of the deep vs shallow aquifer(s).**

9.4.2. Stiff diagrams

A Stiff diagram, or Stiff pattern, is a graphical representation of chemical analyses and major anions and cations, first developed by H.A. Stiff in 1951. STIFF diagrams plot the equivalent concentrations of major anions and cations on a horizontal scale on opposite sides of a vertical axis. The plot point of each parameter is linked to the adjacent point creating a polygon around the vertical axis. Water with similar major ion ratios will show similar geometries. Figure 9-8 and Figure 9-9 depicts Stiff diagrams compiled from the hydrocensus groundwater sampling analysis while Figure 9-10 indicate Stiff diagrams compiled from the monitoring water quality data evaluated. It is evident that borehole localities HBH48, HBH49, HBH74 and HBH75indicate a different ion composition and geometry compared the other groundwater sampling localities and suggest two different aquifer or hydrostratigraphical units being targeted, possibly a deeper, more stagnant water source. Monitoring localities BH04, BH05, BH09 also suggests a higher salt load with sodium-chloride enrichment and may also represent a deeper aquifer unit being targeted. Figure 9-11 indicate a Stiff diagram comparison of major anions and cations of the deep vs shallow aquifer(s) and the Sodium-Potassium-Chloride dominance of the deep, fractured aquifer groundwater show extremely saline conditions.

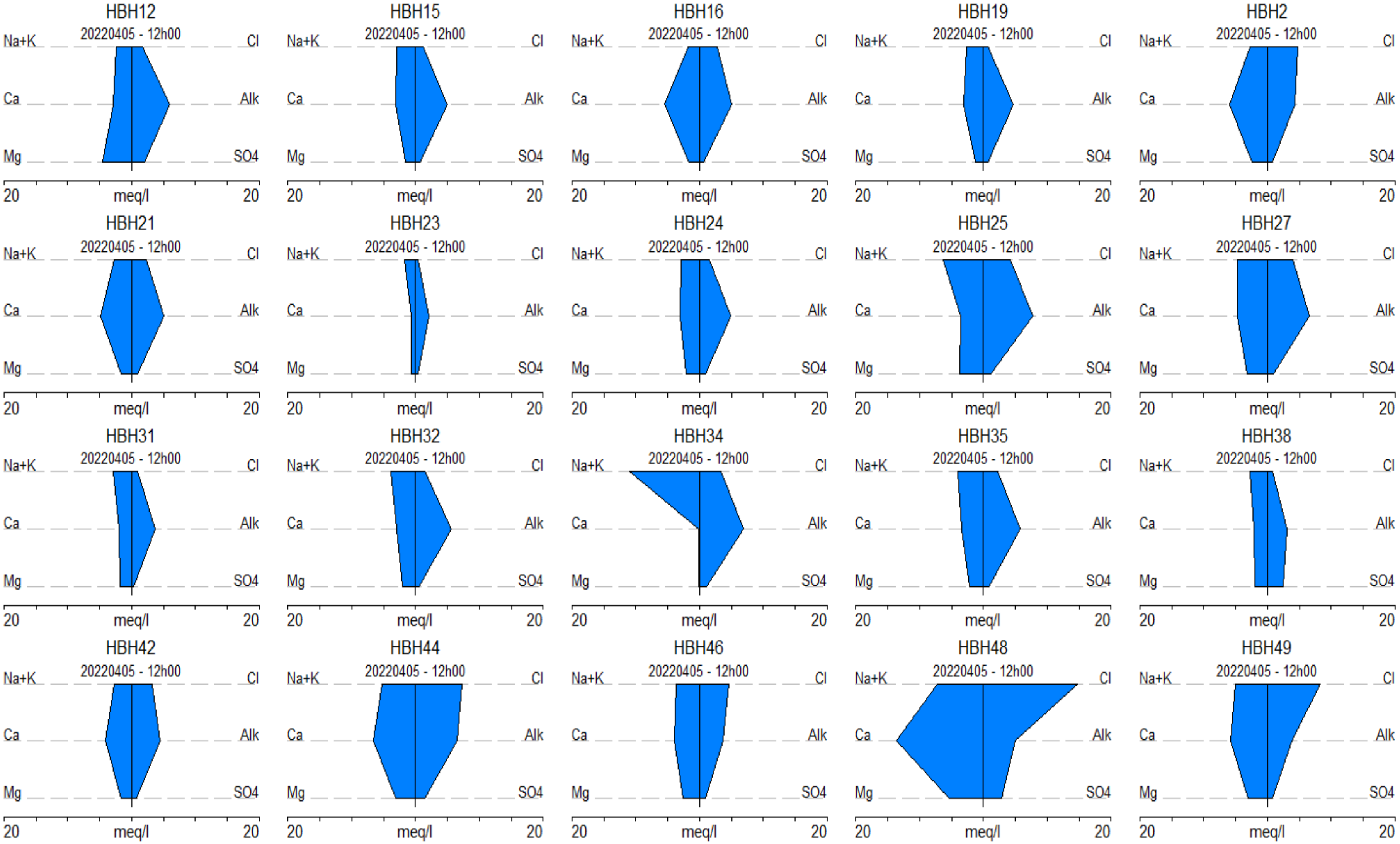


Figure 9-8 **Stiff diagrams representing the hydrocensus groundwater sampling localities analysed.**

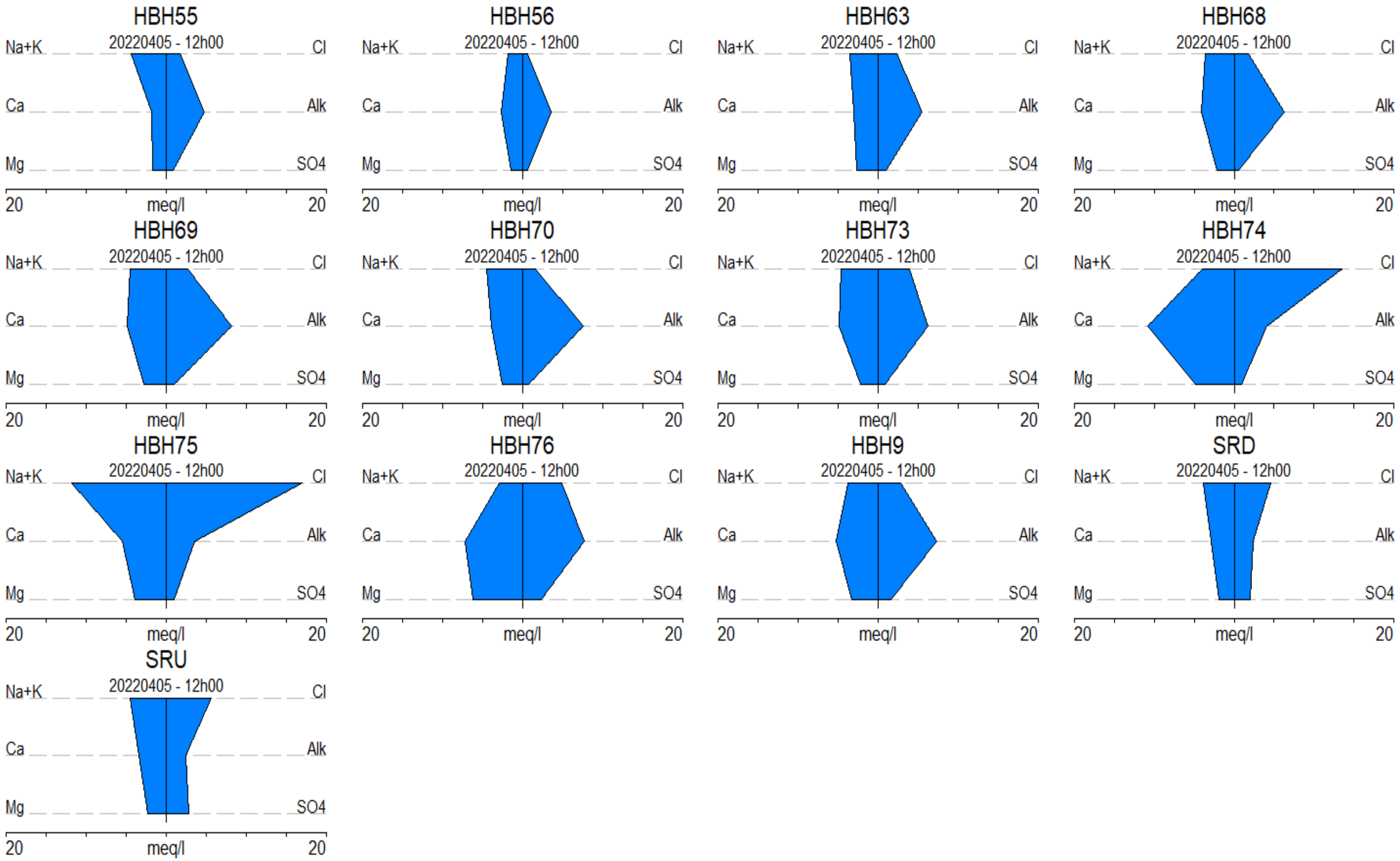


Figure 9-9 **Stiff diagrams representing the hydrocensus groundwater sampling localities analysed.**

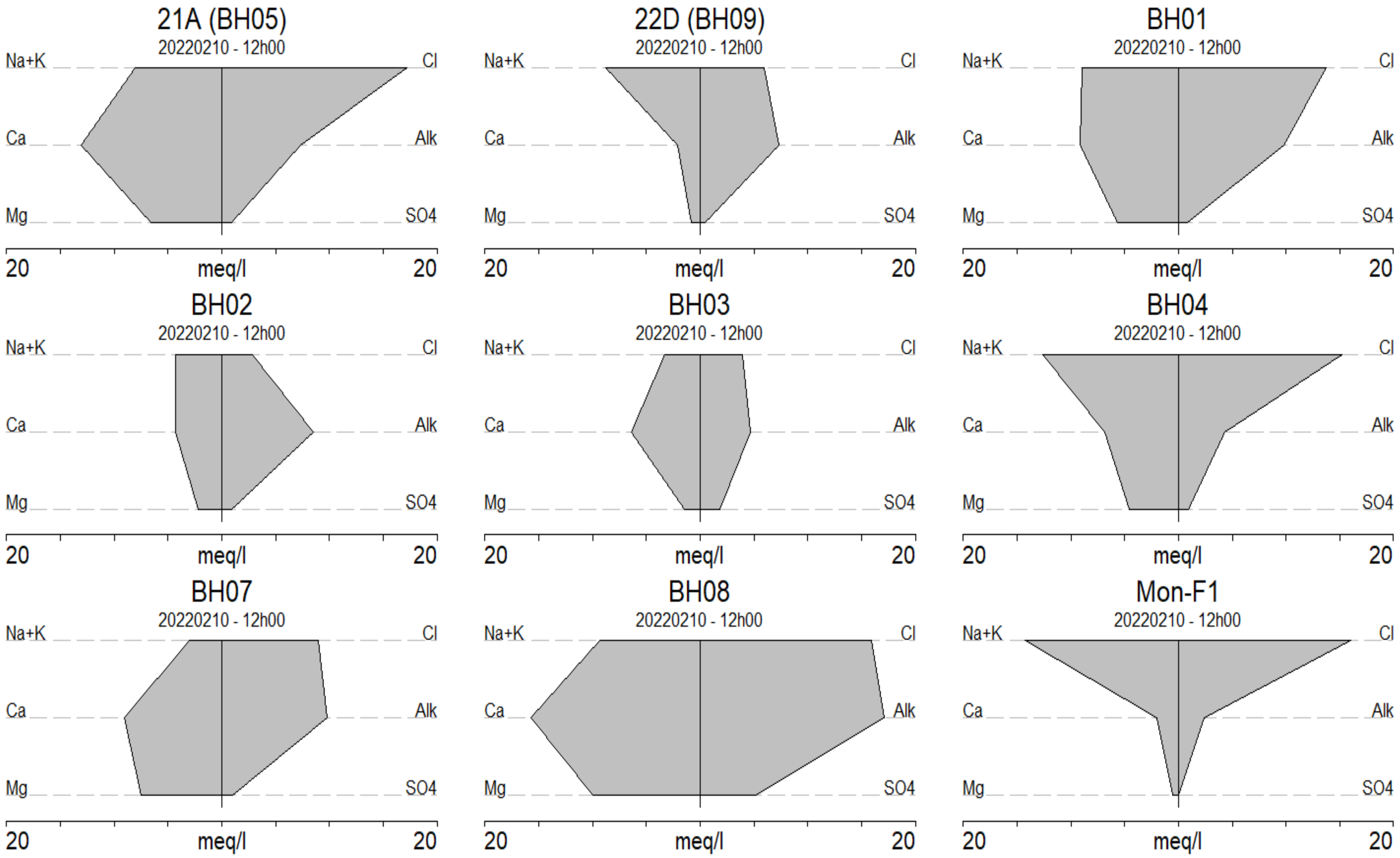


Figure 9-10 **Stiff diagrams representing the monitoring borehole groundwater sampling localities analysed.**

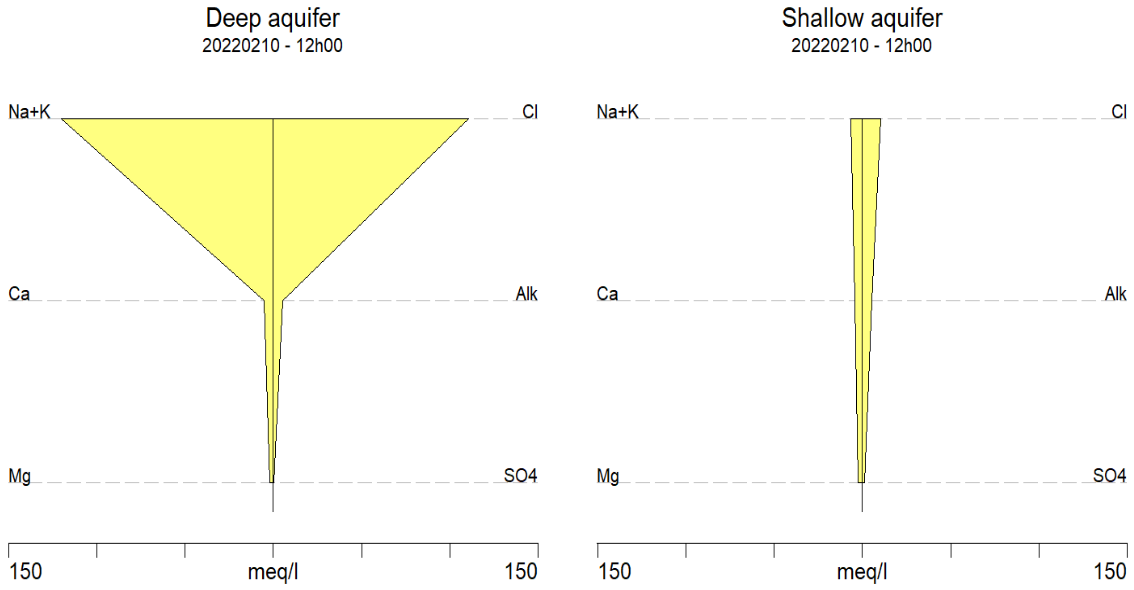


Figure 9-11 **Stiff diagrams indicating a comparison in major ion composition of the deep vs shallow aquifer(s).**

9.4.3. Expanded Durov diagram

The expanded Durov diagram is used to show hydrochemical processes occurring within different hydrogeological systems as depicted in Figure 9-12. Different fields of the diagram could be summarised as follows:

Field 01: Water (mostly fresh, clean and recently recharged) with HCO_3- and CO_3 as dominant anion and Ca as dominant cation.

Field 02: Water (mostly fresh, clean, and relatively young) that also has an Mg signature, often found in dolomitic terrain.

Field 03: Often associated with Na ion exchange between groundwater and aquifer material (sometimes in Na-enriched granites or other felsic rocks) or because of contamination effects from a source rich in Na.

Field 04: Often associated with mining related SO_4 contamination.

Field 05: Groundwater that is usually a mix of different types – either clean water from fields 1 and 2 that has undergone SO_4 and NaCl mixing/contamination or old stagnant NaCl dominated water that has mixed with clean water.

Field 06: Groundwater from field 5 that has been in contact with a source rich in Na or old stagnant NaCl dominated water that resides in Na rich host rock/material.

Field 07: Water rarely plots in this field that indicates NO_3 or Cl enrichment or dissolution.

Field 08: Groundwater that is usually a mix of different types, for example water from 2 that has undergone Cl mixing/contamination or old stagnant NaCl-dominated water that has mixed with water richer in Mg.

Field 09: Seawater or very old stagnant water that has reached the end of the geohydrological cycle (deserts, salty pans etc.), or water that has moved a long time and/or distance through the aquifer and has undergone significant ion exchange.

Most groundwater samples analysed can be classified as either Field01/ Field 02 i.e., mostly fresh, clean and relatively young with HCO3- and CO3 dominance evident indicative of an unimpacted groundwater environment or Field 03 (often associated with Na ion exchange between groundwater and aquifer material). Borehole localities BH07, BH08, HBH38, HBH44 and HBH46 can be classified as Field05, suggesting old stagnant NaCl dominated water that has mixed with clean water. Borehole localities HBH48, HBH74 can be classified as Field07 (that indicates NO_3 or Cl), BH01, BH05 and BH49 as Field08 (old stagnant NaCl-dominated water) or Mon-F1, BH04 and BH75 as Field09 (very old stagnant water). The latter suggest more stagnant and older water which may indicate a deeper aquifer or hydrostratigraphical units being targeted (Figure 9-13).

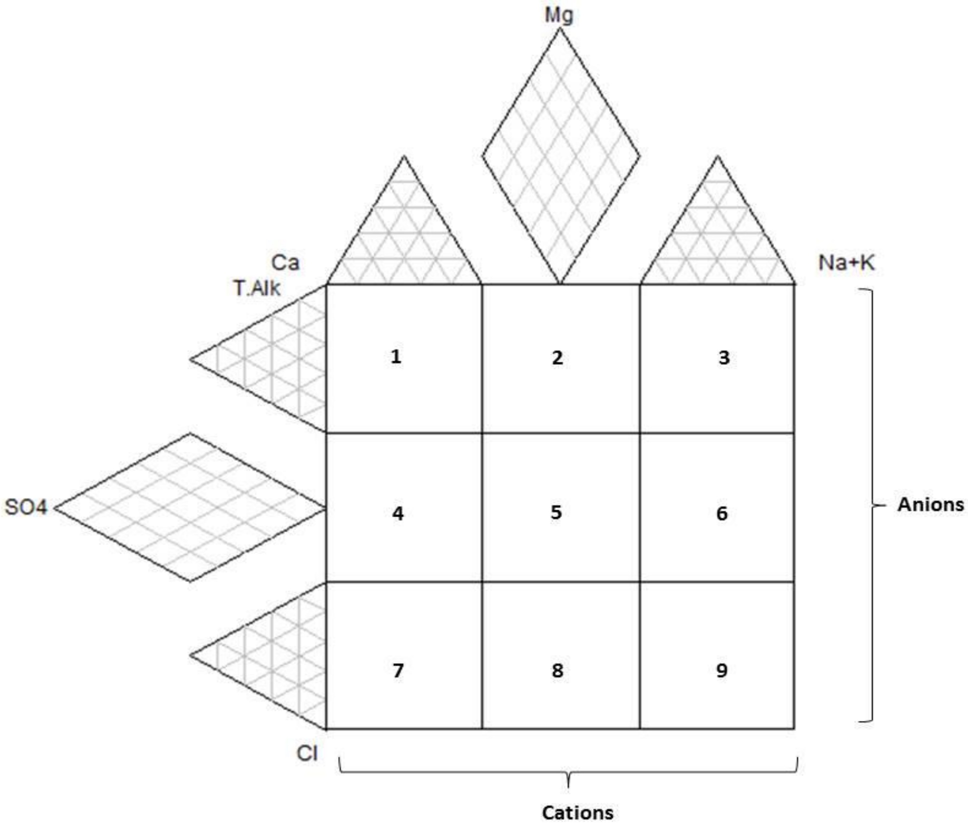


Figure 9-12 Extended Durov diagramindicating major anions and cations.

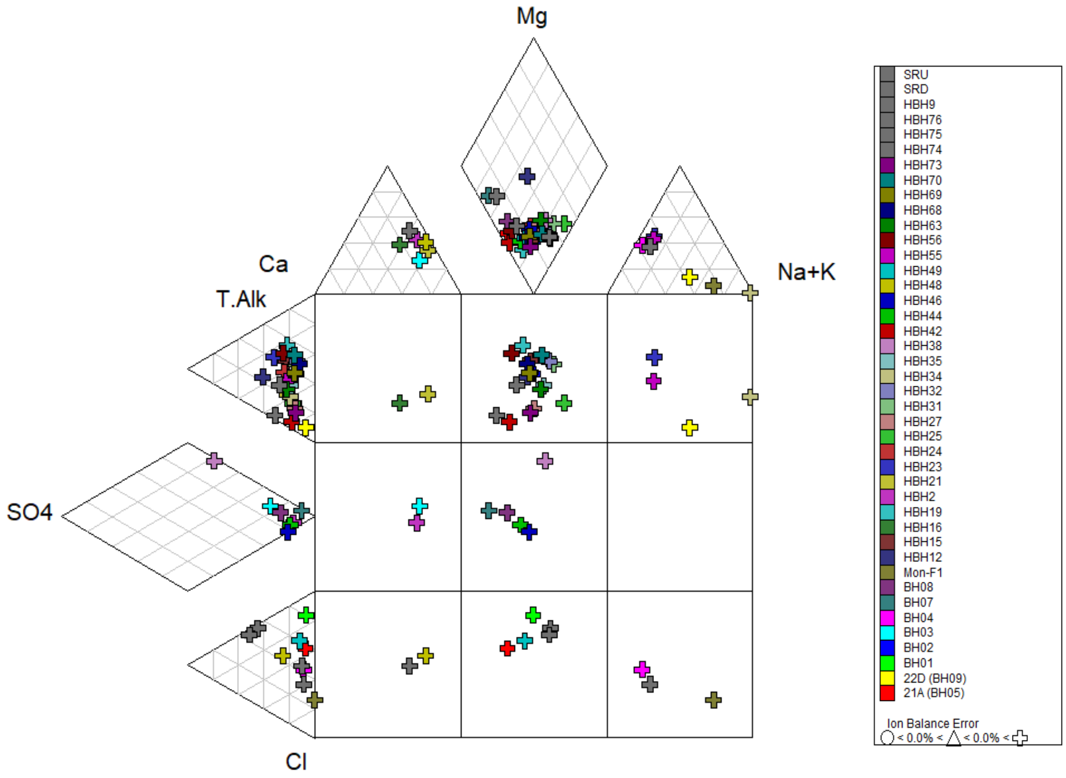


Figure 9-13 **Extended Durov diagram of water samples analysed.**

Figure 9-14 indicates a Schoeller diagram of the water samples analysed and highlights the main hydrochemical species as being Sodium-Chloride.

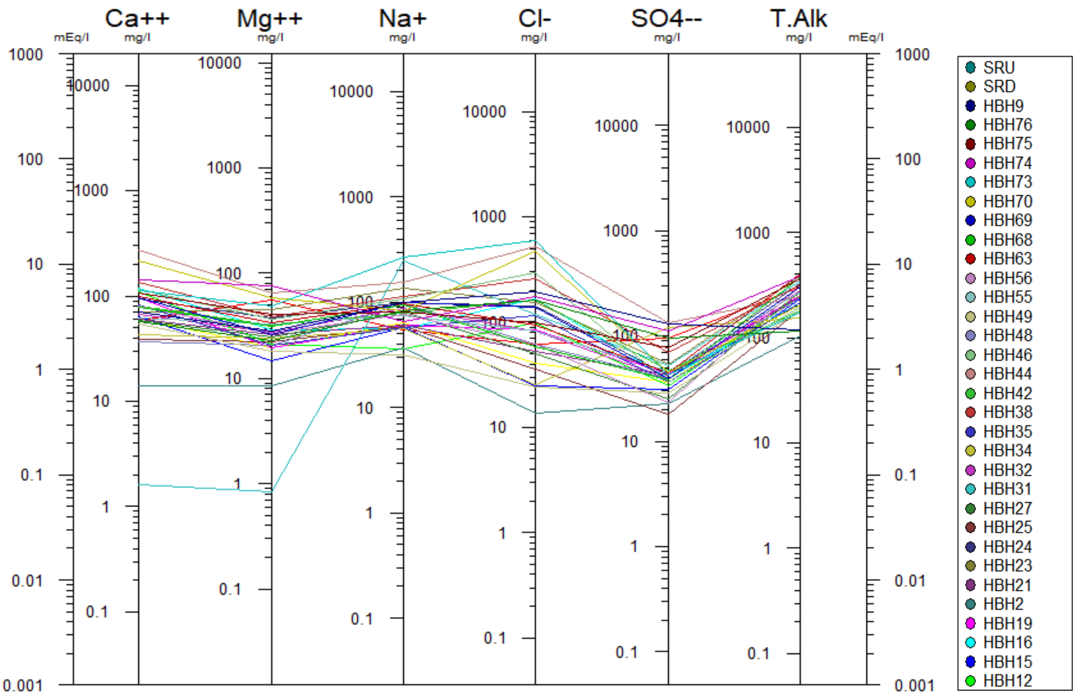


Figure 9-14 **Schoeller diagram of water samples analysed.**

10. AQUIFER CLASSIFICATION AND GROUNDWATER MANAGEMENT INDEX

The most widely accepted definition of groundwater contamination is defined as the introduction into water of any substance in undesirable concentration not normally present in water e.g., microorganisms, chemicals, waste or sewerage, which renders the water unfit for its intended use (UNESCO, 1992). The objective of this study is to formulate a risk-based framework from geological and hydrogeological information obtained as part of this investigation. Two approaches were followed in an estimation of the risk of groundwater contamination as discussed below. As part of the aquifer classification, a Groundwater Quality Management (GQM) Index is used to define the level of groundwater protection required. The GQM Index is obtained by multiplying the rating of the aquifer system management and the aquifer vulnerability. A **GQM Index = 4** was calculated for the local aquifer system and according to this estimate, a "**Medium**" level groundwater protection is required for this aquifer system.

Equation 10-1 GMQ Index.

$$\textit{GQM Index} = \boldsymbol{Aquifer\ system\ management\ x\ Aquifer\ vulnerability}$$

10.1. Aquifer classification

The aquifer classification was guided by the principles set out in South African Aquifer System Management Classification (Parsons, 1995). Aquifer classification forms a very useful planning tool which can be applied to guide the management of groundwater systems. According to the aquifer classification map of South Africa the project area is underlain by a "**Minor aquifer**" (DWS, 2013). It should however be noted that the shallow, intergranular aquifer is important to local groundwater users as it forms the sole source of water supply in the region (Lea, 2017). Furthermore, the primary riparian zone aquifer is classified as a major aquifer system due to its highly permeable nature as well as good water quality. The classifications and definitions for each aquifer system are summarised in Table 10-1.

Table 10-1 Aquifer System Management Classes (After Parsons , 1995).

Sole source aquifer	An aquifer which is used to supply 50% or more of domestic water for a given area, and for which there are no reasonable available alternative sources should the aquifer be impacted upon or depleted. Aquifer yields and natural water quality are immaterial.
Major aquifer system	Highly permeable formations, usually with a known 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 (less than 150 mS/m).
Minor aquifer system	These can be fractured or potentially fractured rocks, which do not have a high primary permeability, or other formations of variable permeability. Although these aquifers seldom produce large quantities of water, they are important both for local supplies and supplying base flow to 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 as unusable. However, groundwater flow through such rocks, although imperceptible, does take place, and needs to be considered when assessing the risk associated with persistent pollutants.
Special aquifer system	An aquifer designated as such by the Minister of Water Affairs, after due process.

10.2. Aquifer vulnerability

Aquifer vulnerability can be defined as the tendency or likelihood for contamination to reach a specified position in the groundwater system after introduction at some location above the uppermost aquifer. According to the aquifer vulnerability map of South Africa the project area is underlain by an aquifer system with a “**Moderate**” vulnerability rating (DWS, 2013).

10.3. Aquifer susceptibility

Aquifer susceptibility is a qualitative measure of the relative ease with which a groundwater body can be potentially contaminated by anthropogenic activities. According to the Aquifer susceptibility map of South Africa the project area is underlain by an aquifer system with a “**Medium**” susceptibility rating (DWS, 2013).

Table 10-2 Groundwater Quality Management Index.

Aquifer system Management qualification Class	**Points**	**Aquifer vulnerability Classification Class**	**Points**
Sole Source Aquifer System	6	High	3
Major Aquifer System	4	**Moderate**	**2**
Minor Aquifer System	**2**	Low	1
Non-Aquifer System	0		
Special Aquifer System	0-6		
GQM INDEX	**Level of protection**		
<1	Limited Protection		
1 to 3	Low Level Protection		
3 to 6	**Medium Level Protection**		
6 to 10	High Level Protection		
>10	Strictly Non- Degradation		
GQM INDEX			**4**

10.4. Groundwater contamination risk assessment

The concept of groundwater vulnerability to contamination by applying the DRASTIC methodology was introduced by Aller et al. (1987) and refined by the US EPA (United States Environmental Protection Agency). DRASTIC is an acronym for a set of parameters that characterise the hydrogeological setting and combined evaluated vulnerability: Depth to water level, Nett Recharge, Aquifer media, Soil media, Topography, Impact of the vadose zone and Hydraulic Conductivity. This method provides a basis for evaluating the vulnerability to pollution of groundwater resources based on hydrogeological parameters. Lynch et al (1994) suggests a considerable variation in terms of hydraulic conductivity in hard rock aquifers and revised this methodology to accommodate local aquifer conditions accordingly. Parameters used as part of the index are summarised in Table 10-3. The DRASTIC index (DI) can be computed using the following formula.

Equation 10-2 DRASTIC Index (Di).

$$\mathbf{Di} = DrD\lambda + RrR\lambda + ArA\lambda + Sr\,S\lambda + TrT\lambda + IrI\lambda$$

where:

D = Depth to Water Table

R = Recharge

A = Aquifer media.

S = Soil media.

T = Topographic aspect.

I = Impact of vadose zone media.

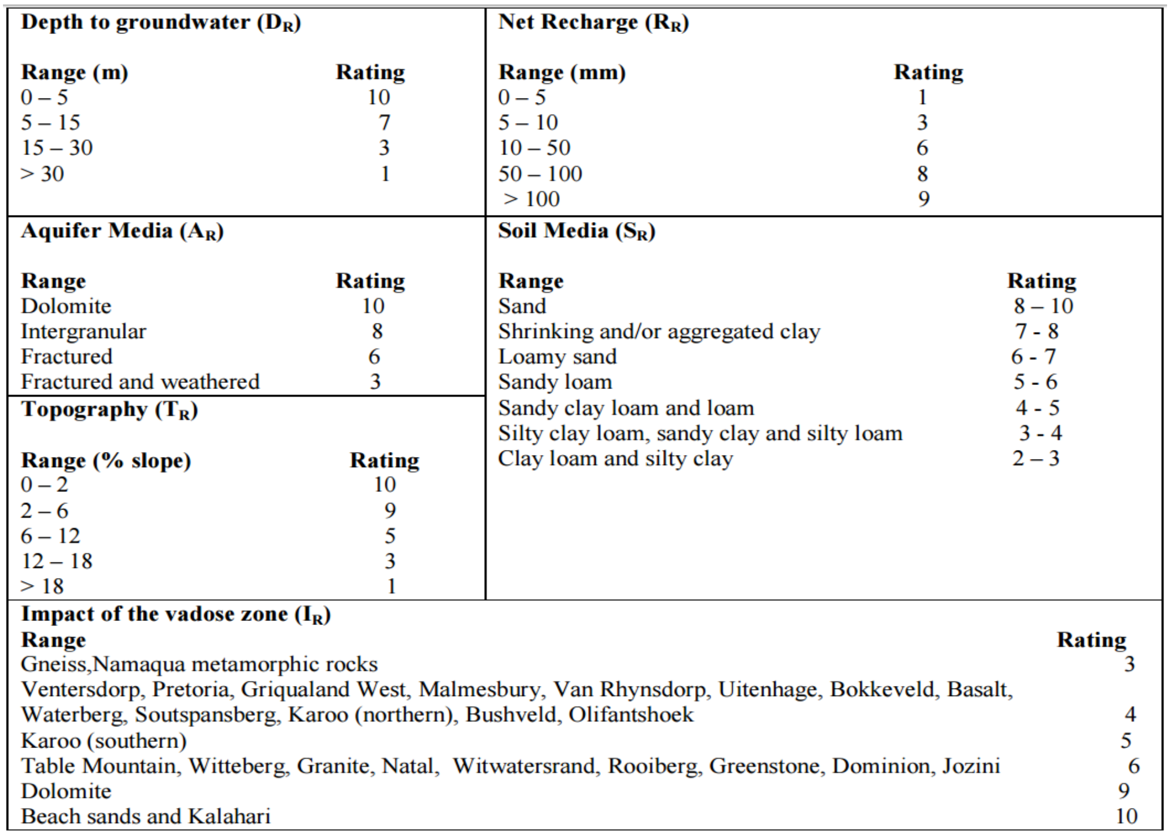
C = Conductivity.

Table 10-3 **DRASTIC Index.**

Risk/ Vulnerability	DRASTIC Index (Di)
Low	50-87
Moderate	87-109
High	109-183

Where **D, R, A, S, T, I**, and **C** are the parameters, r is the rating value, and λ the constant weight assigned to each parameter as summarised in Table 10-4 below (Lynch et al, 1994).

Table 10-4 **Ratings assigned to groundwater vulnerability parameters (Lynch et al, 1994).**



Depth to groundwater (D_R)

Range (m)	Rating
0 – 5	10
5 – 15	7
15 – 30	3
> 30	1

Net Recharge (R_R)

Range (mm)	Rating
0 – 5	1
5 – 10	3
10 – 50	6
50 – 100	8
> 100	9

Aquifer Media (A_R)

Range	Rating
Dolomite	10
Intergranular	8
Fractured	6
Fractured and weathered	3

Soil Media (S_R)

Range	Rating
Sand	8 – 10
Shrinking and/or aggregated clay	7 - 8
Loamy sand	6 - 7
Sandy loam	5 - 6
Sandy clay loam and loam	4 - 5
Silty clay loam, sandy clay and silty loam	3 - 4
Clay loam and silty clay	2 – 3

Topography (T_R)

Range (% slope)	Rating
0 – 2	10
2 – 6	9
6 – 12	5
12 – 18	3
> 18	1

Impact of the vadose zone (I_R)

Range	Rating
Gneiss,Namaqua metamorphic rocks	3
Ventersdorp, Pretoria, Griqualand West, Malmesbury, Van Rhynsdorp, Uitenhage, Bokkeveld, Basalt, Waterberg, Soutspansberg, Karoo (northern), Bushveld, Olifantshoek	4
Karoo (southern)	5
Table Mountain, Witteberg, Granite, Natal, Witwatersrand, Rooiberg, Greenstone, Dominion, Jozini	6
Dolomite	9
Beach sands and Kalahari	10

According to the DRASTIC index methodology applied, the proposed activities and associated infrastructure's risk to groundwater pollution of the aquifer system(s), is rated as "**Moderate**", **Di = 109**, (refer to Table 10-5).

Table 10-5 DRASTIC weighting factors: Shallow, intergranular aquifer.

Parameter	Range	Rating	Description	Relative weighting
Depth to water (D) (mbgl)	0 - 5	10	Refers to the depth to the water surface in an unconfined aquifer. Deeper water table levels imply lesser chance for contamination to occur. Depth to water is used to delineate the depth to the top of a confined aquifer.	5
	5 -15	**7**		
	15 - 30	3		
	> 30	1		
Net recharge (R) (mm/a)	0-5	1	Indicates the amount of water per unit area of land which penetrates the ground surface and reaches the water table. Recharge water is available to transport a contaminant vertically to the water table, horizontal with in an aquifer.	3
	5-10	**3**		
	10-50	**6**		
	50-100	8		
	> 100	9		
Aquifer media (A)	Dolomite	10	Refers to the consolidated or unconsolidated medium which serves as an aquifer. The larger the grain size and more fractures or openings within an aquifer, leads to higher permeability and lower attenuation capacity, hence greater the pollution potential.	4
	Intergranular	8		
	Fractured	6		
	Fractured and weathered	**3**		
Soil media (S)	Sand	10	Refers to the uppermost weathered portion of the vadose zone characterised by significant biological activity. Soil has a significant impact on the amount of recharge.	2
	Shrinking and/or aggregated clay	8		
	Loamy sand	6		
	Sandy loam	**5**		
	Sandy clay	4		
	Silty loam	3		
	Silty clay and clay loam	2		
Topography (T) (Slope %)	0 - 2	10	Refers to the slope of the land surface. It helps a pollutant to runoff or remain on the surface in an area long enough to infiltrate it.	1
	2 - 6	**9**		
	6 - 12	5		
	12 - 18	3		
	> 18	1		
Impact of vadose zone (I)	Gneiss, Namaqua metamorphic rocks	3	Is defined as unsaturated zone material. The significantly restrictive zone above an aquifer forming the confining layers is used in a confined aquifer, as the type of media having the most significant impact.	5
	Ventersdorp, Pretoria, Griekwaland West, Malmesbury, Van Rhynsdorp, Uitenhage, Bokkeveld, Basalt, Waterberg, Soutpansberg, Karoo (Northern), Bushveld, Olifantshoek	4		
	Karoo (Southern)	**5**		
	Table Mountain, Witteberg Granite, Natal, Witwatersrand, Rooiberg, Greenstone, Dominion, Jozini	6		
	Dolomite	9		
	Beach sands and Kalahari	10		
DRASTIC Index (Di) = 109				

10.5. Source-pathway-receptor evaluation

In order to evaluate the risk of groundwater contamination, potential sources of contamination should be identified, as well as potential pathways and receptors. The pollution linkage concept relies on the identification of a potential pollutant (i.e., source) on-site which is likely to have the potential to cause harm on a receptor by means of a pathway by which the receptor may be exposed to the contaminant (Figure 10-1).

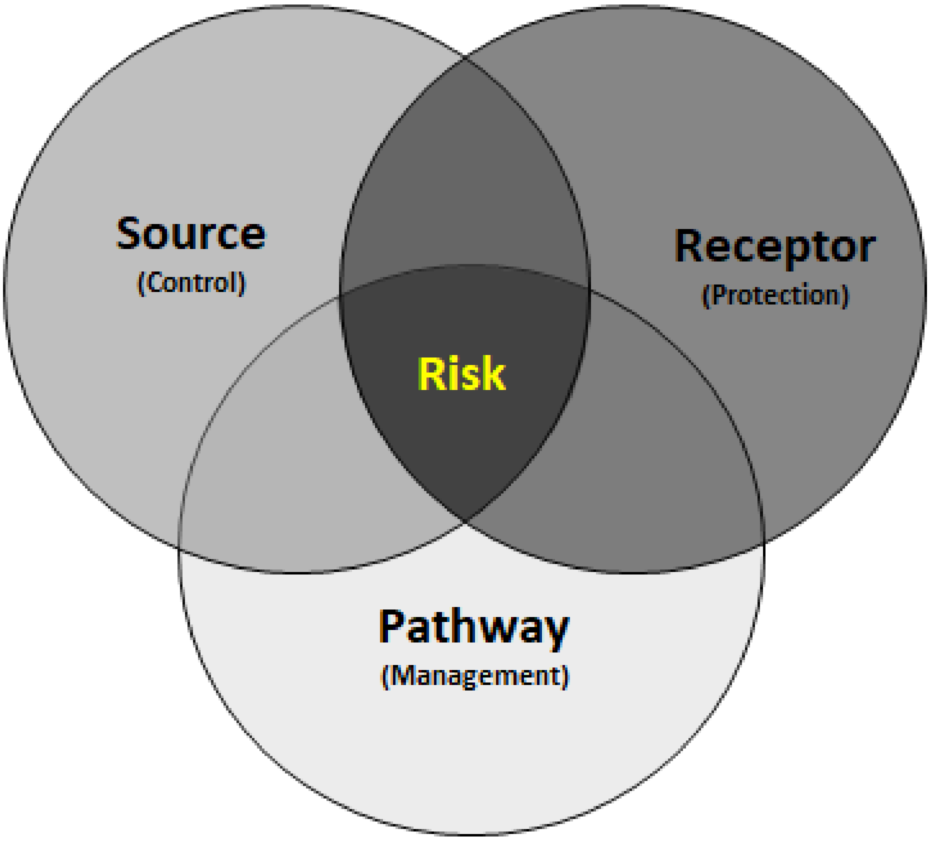


Figure 10-1 **Source pathway receptor principle.**

10.5.1. Potential sources

The following potential sources have been identified:

i. Migration of saline groundwater from the deep, fractured aquifer to the overlying, potable aquifer(s) during the gas production phase.

ii. Migration of stray gas from the deep, fractured aquifer to the overlying, potable aquifer(s) during the gas production phase.

iii. Migration of contaminants from the plant expansion waste facilities and associated infrastructure into local water resources and host aquifers.

10.5.2. Potential pathways

The following aquifer pathways have been identified:

i. Vertical flow through the unsaturated/vadose zone as well as saturated zone to the underlying intergranular and fractured rock aquifers. The rate at which seepage will take place is governed by the permeability of sub-surface soil layers and host-rock formations.

ii. Preferential flow-paths include the contact between the depth of weathering and fresh un-weathered rock, fractures, faults, joints and bedding planes. Secondary fractures may also potentially act as transport mechanisms.

iii. If not adequately sealed and suitably mitigated, gas exploration and production wells will form preferential flow paths and serve as a direct connection between the deeper, fractured aquifer and shallow, potable aquifer unit(s).

10.5.3. Potential receptors

The following receptors were identified:

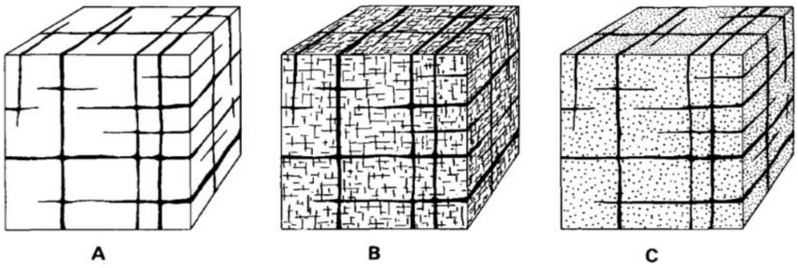
i. Shallow, inter-granular as well as the intermediate, fractured aquifer units situated within the plume migration footprint(s).

ii. Down-gradient drainages and streams including associated riparian zone aquifer system(s) and baseflow contribution.

iii. Private or neighbouring boreholes associated with relevant fracture zones and/or structures(s)if intercepted by the pollution plume migration footprint.

11. HYDROGEOLOGICAL CONCEPTUAL MODEL

The hydrogeological conceptual model consists of a set of assumptions, which will aid in reducing the problem statement to a simplified and acceptable version. Data gathered during the desk study and site investigation has been incorporated to develop a conceptual understanding of the regional hydrogeological system. Figure 11-1 depicts a generalised hydrogeological conceptual model for similar environments and illustrate the concept of primary porous media aquifers and secondary fractured rock media aquifers. In porous aquifers, flow occurs through voids between unconsolidated rock particles whereas in double porosity aquifers, the host rock is partially consolidated, and flow occurs through the pores as well as fractures in the rock. In secondary aquifers the host rock is consolidated, and porosity is generally restricted to fractures that have formed after consolidation of the rock. The weathered zone aquifer and secondary rock aquifer in the area could be classified as double porosity aquifers. Figure 11-2 depicts southeast-northwest cross section of the study area (construction phase) while Figure 11-3 depicts southeast-northwest cross section of the study area (operational phase). Refer to Figure 5-2 for spatial reference.



A: Primary porosity aquifer **B: Double porosity aquifer** **C: Secondary porosity aquifer**

Figure 11-1 Generalised conceptual hydrogeological model (after Kruseman and de Ridder, 1994).

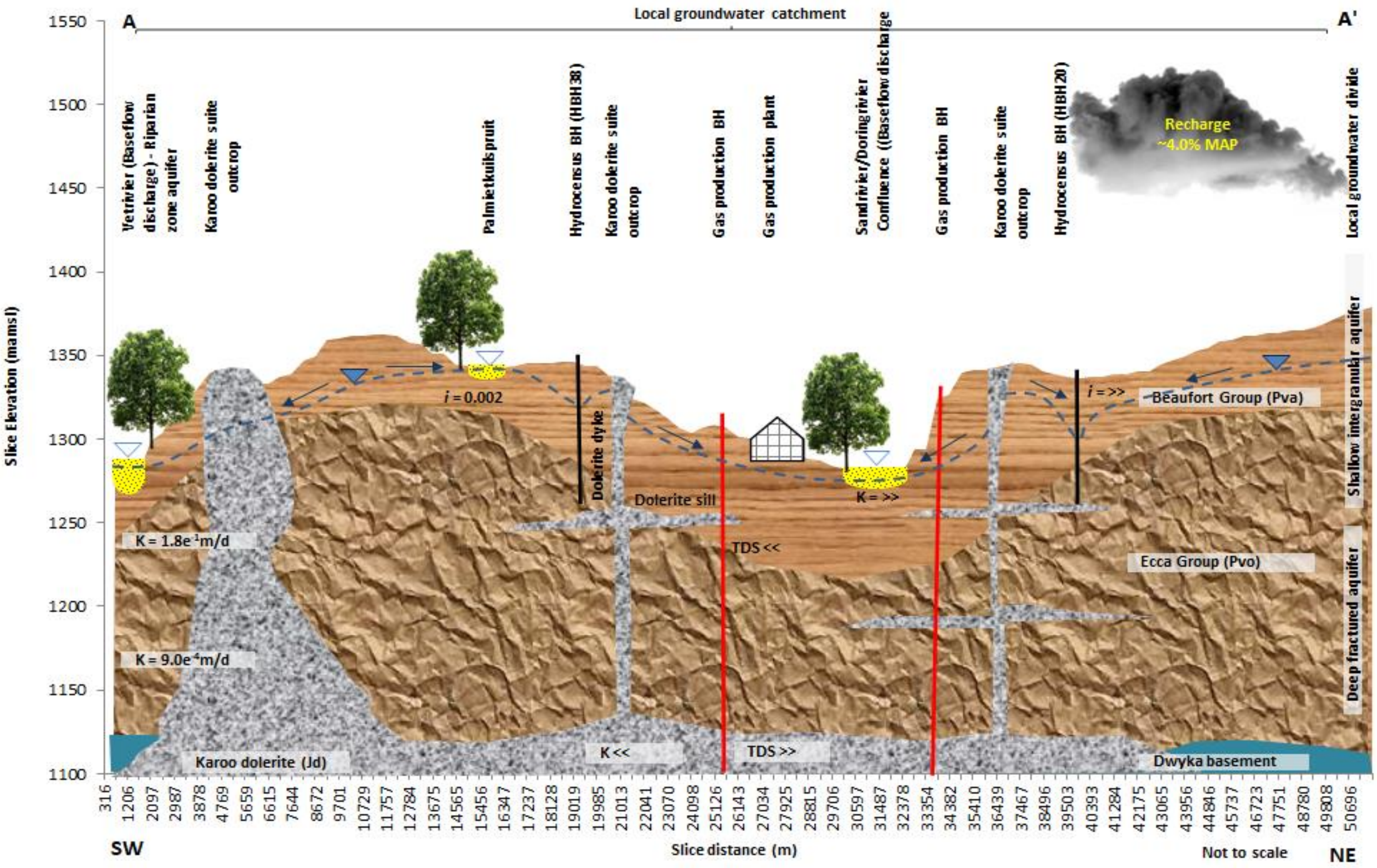


Figure 11-2 **Hydrogeological conceptual model: Southwest- Northeast cross section – Construction Phase (A-A') (Figure 5-2).**

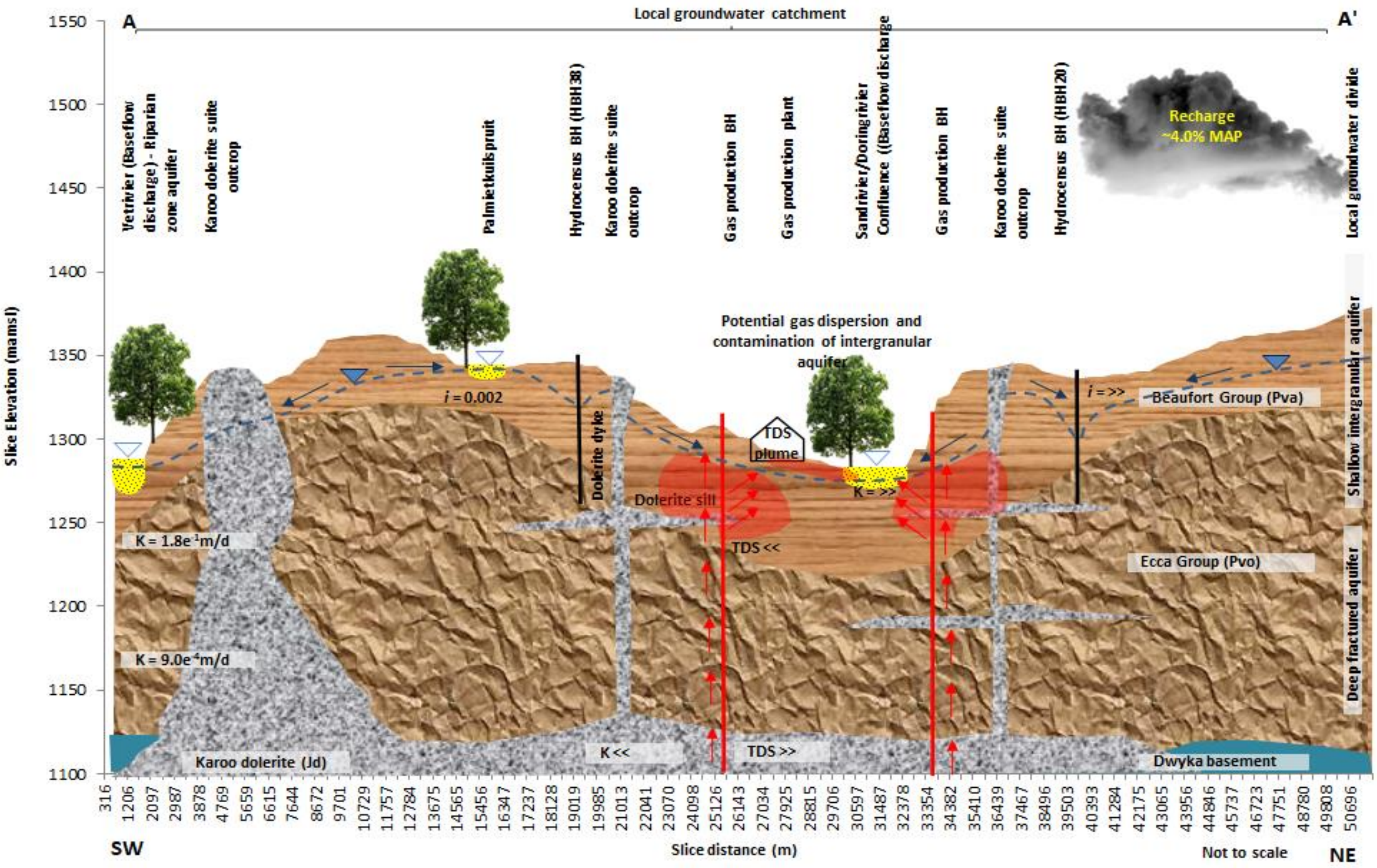


Figure 11-3 Hydrogeological conceptual model: Southwest- Northeast cross section – Operational Phase (A-A') (Figure 5-2).

12. NUMERICAL GROUNDWATER FLOW AND CONTAMINANT TRANSPORT MODEL

The purpose of a groundwater model is to serve as a tool to evaluate various water management options and scenarios.

12.1. Approach to modeling

The typical workflow and modelling approach employed is summarised in Figure 12-1 below and encompass a conceptualisation phase, calibration phase as well as a prediction phase.

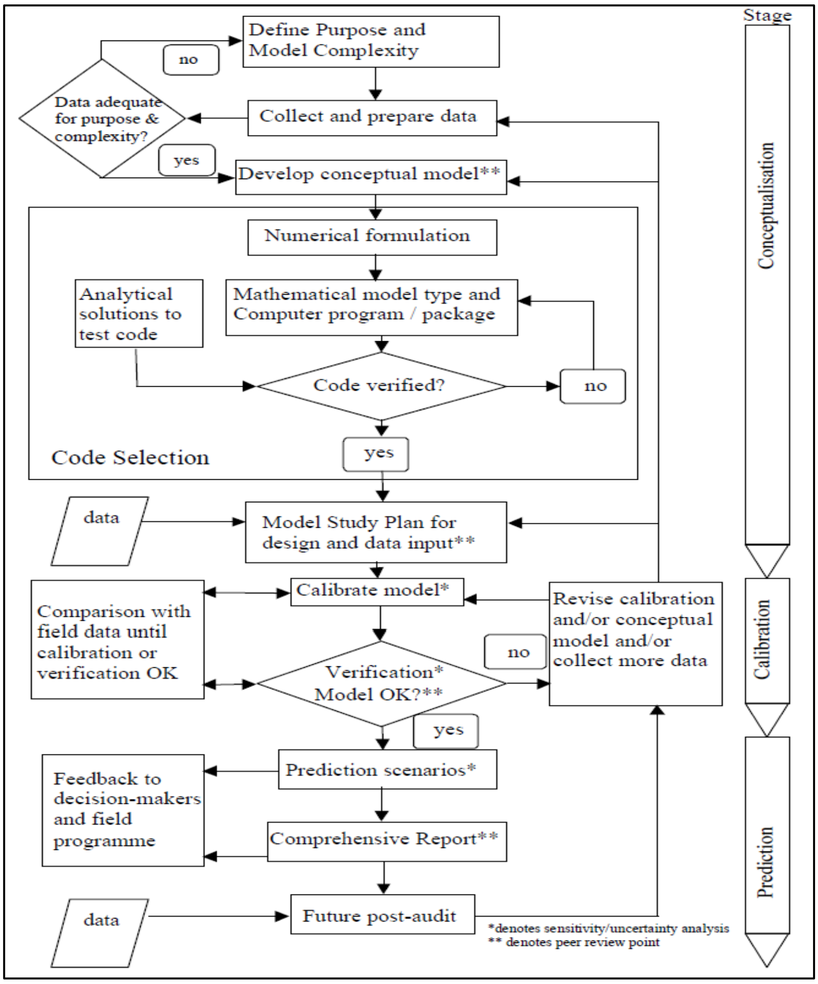


Figure 12-1 **Workflow numerical groundwater flow model development.**

In natural steady-state conditions, the net groundwater inflow from recharge is balanced by base flow and losses. The groundwater balance is given by:

Equation 12-1 **Simplified groundwater balance.**

$$Q_{Recharge} - Q_{Baseflow} + Q_{Losses} = 0$$

where:

$Q_{Recharge}$ = Groundwater inflow from rainfall recharge (m^3/d).

$Q_{Baseflow}$ = Groundwater outflow as baseflow (m^3/d).

Q_{Losses} = Groundwater outflow from other losses (m^3/d).

The piezometric gradient, which can be measured from site characterization and monitoring boreholes are known and the boreholes can be pump tested to determine the transmissivity and hydraulic conductivity. The outflow per unit length (L) of aquifer are given by Darcy's law as, q=K dh/dL where q is the Darcy flux in m/d (or $m^3/m^2/d$) and K is the hydraulic conductivity, D the aquifer thickness and dh/dl the piezometric gradient. Since K, D and the head gradient can be measured, a steady-state model can be calibrated by changing the recharge value until the measured and simulated head gradients have a small error (usually <10.0 % of the aquifer thickness).

12.2. Software application

A dynamic flow model was developed by applying the modelling package FEFLOW (Finite Element Flow) and interface (Diersch, 1979). This modelling software has been developed by WASY and is based on the partial differential equation principle. The finite element method is a numerical technique for finding approximate solutions to boundary value problems for partial differential equations.

12.3. Model development

12.3.1. Model domain

A model grid was created with global origin X: -27483.94[m] and Y: -3112580.59[m] using triangular prism type of elements. The model has a width of 57938.3[m], height of 66653.0[m], depth of 613.44[m] and spans an area of $2.36e^{+9}m^2$ with a volume of $\sim 7.34e^{+11}m^3$. The model domain was delineated based on regional drainages as well as topographical highs i.e., discharge zones and no-flow zones (Figure 12-2). Figure 12-4 shows the model finite element mesh (FEM) construction while Figure 12-6 depicts a respective cross section on which the hydrogeological conceptual model is based on.

12.3.2. Model construction

The model was constructed from FEM and consist of two layers i.e., three slices, 351 905 triangular prism elements per layer, a total of 703 810 elements for the model domain, with 177 480 nodes per slice a total of 532 440 nodes for the model domain. The mesh quality is acceptable and summarised below:

- Delaunay violating triangle: 0.70%.
- Interior holes: 0.
- Obtuse angled triangles: 0.50% > 120°, 6.40% > 90°.

Figure 12-2 **Model domain: Aerial extent.**

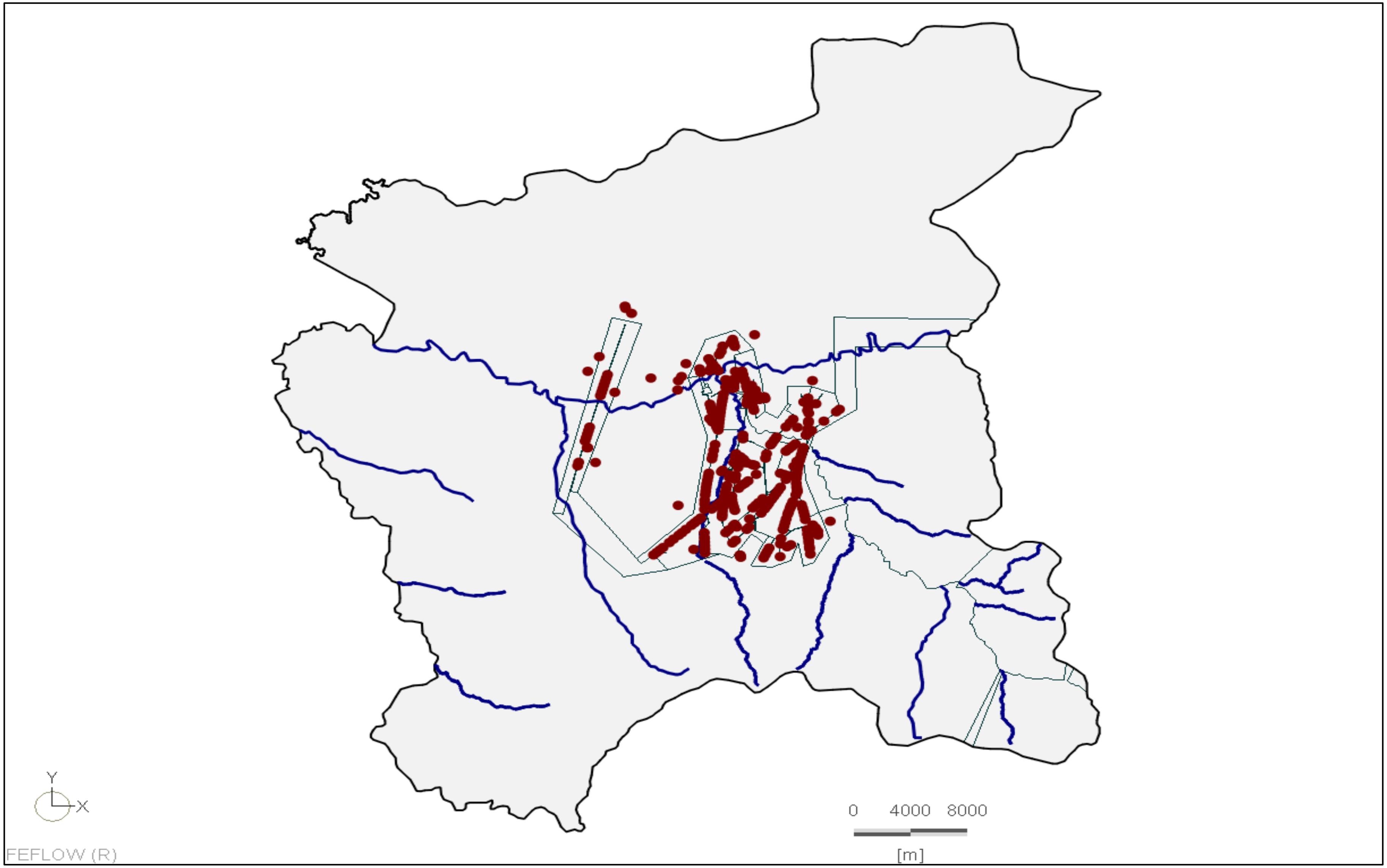


Figure 12-3 **Model domain: Supermesh view.**

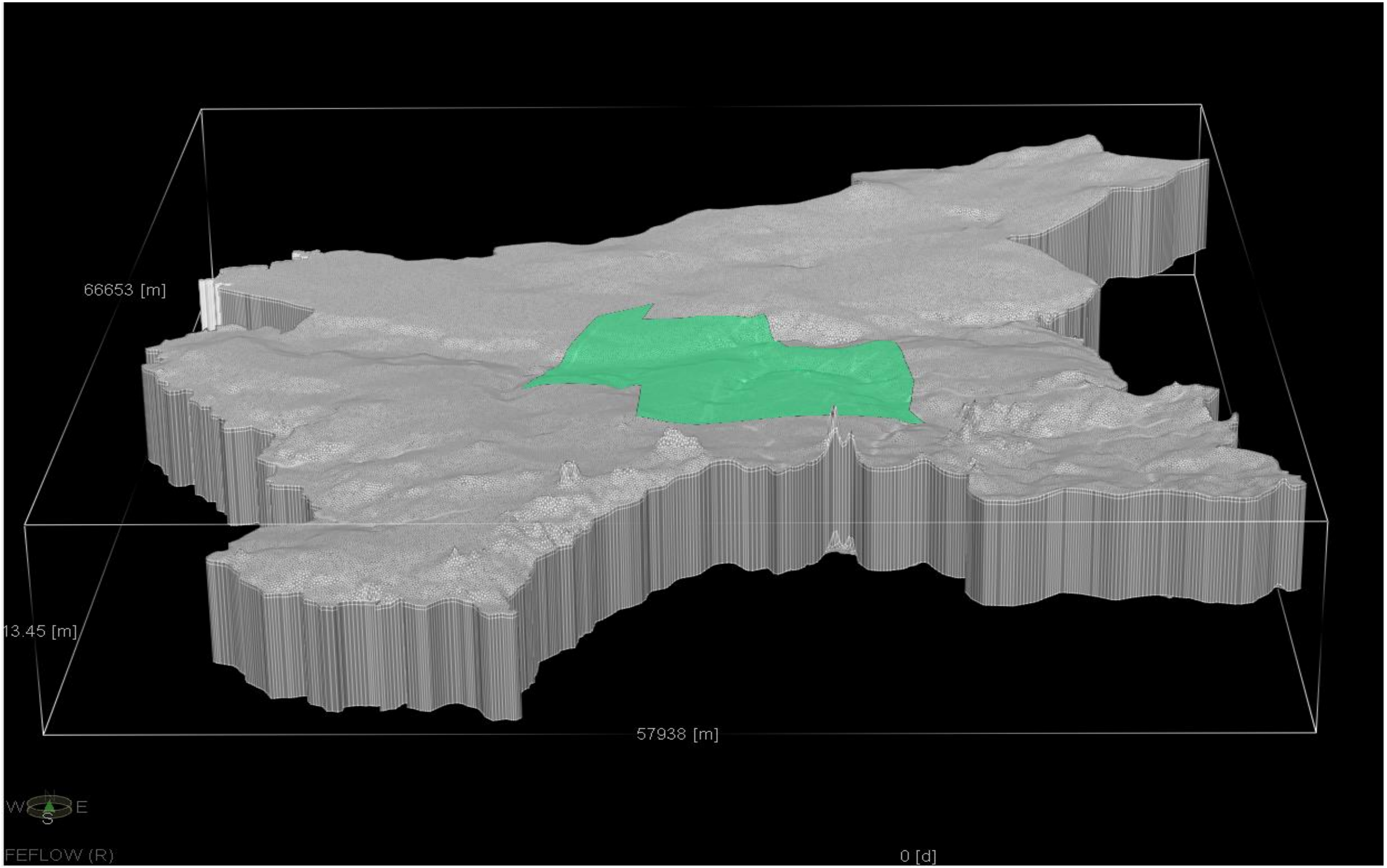


Figure 12-4 **Model domain 3-D FEM mesh view depicting a plan-view south-north orientation.**

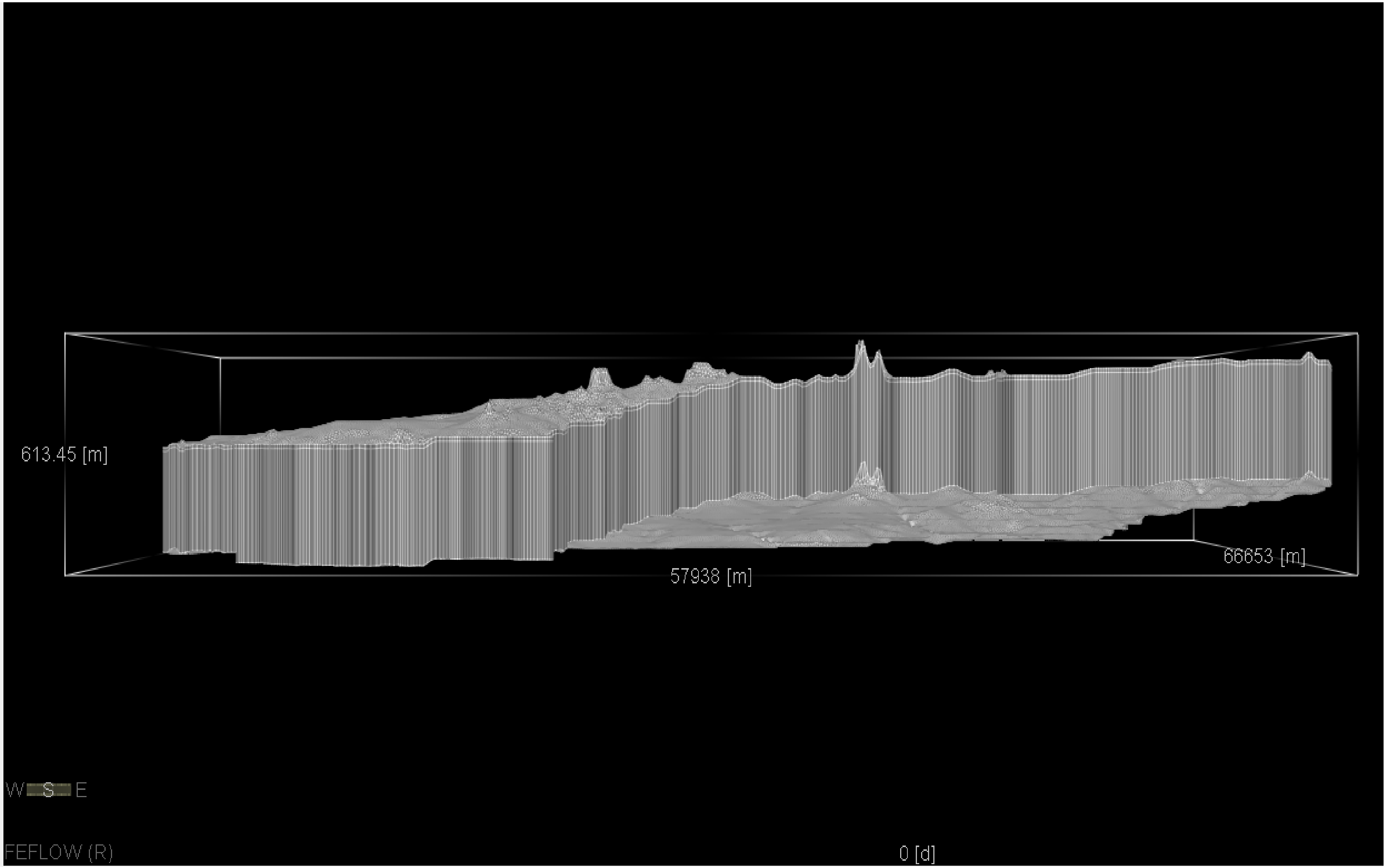


Figure 12-5 **Model domain 3-D FEM mesh view depicting a plan-view south-north orientation.**

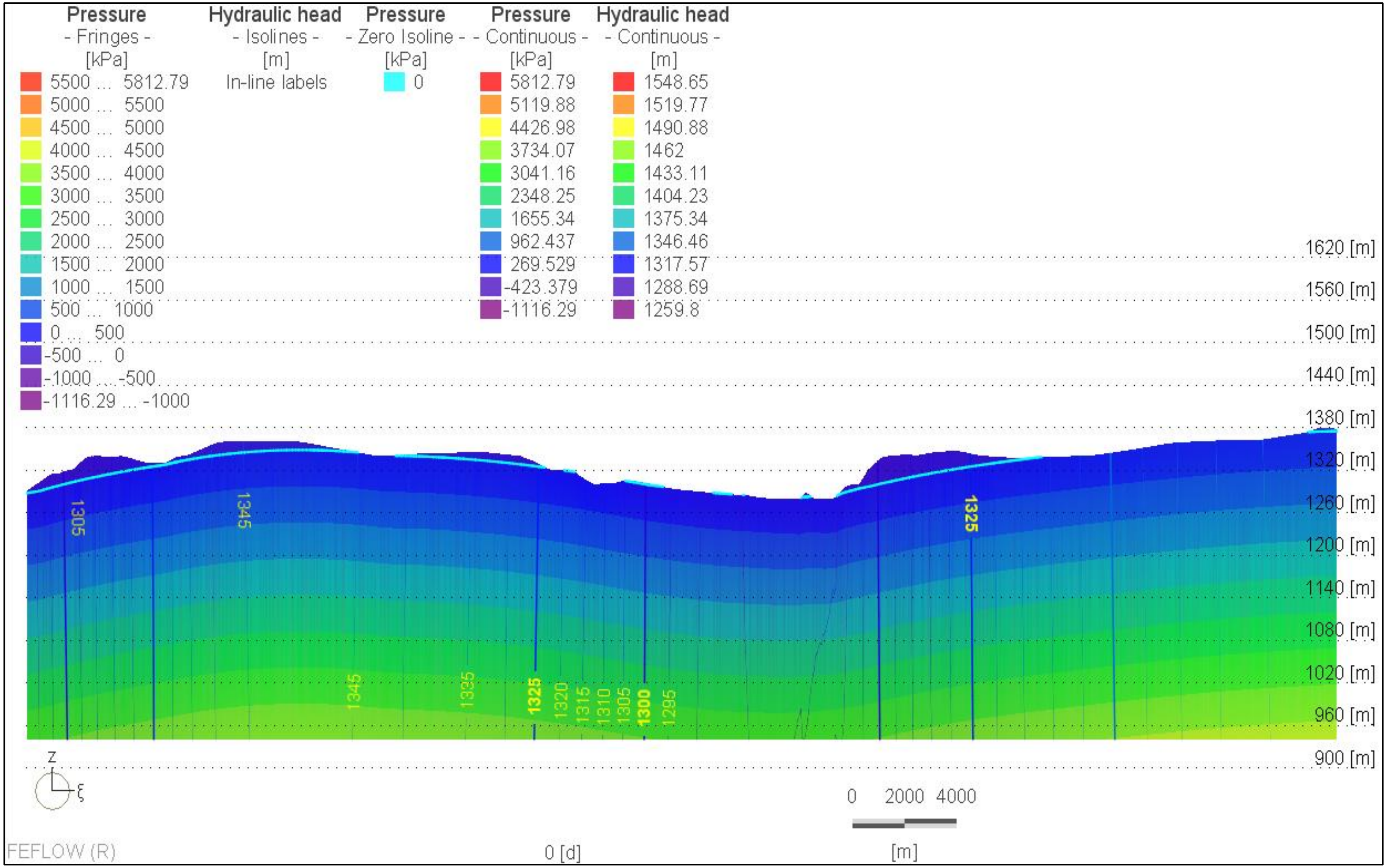


Figure 12-6 **Model domain 3-D FEM mesh view (cross sectional view southwest-northeast orientation of conceptual slice A-A').**

12.3.3. Model layers

The groundwater model consists of two layers, representing identified hydrostratigraphical units. The top layer was based on surface topography with succeeding layers developed horizontally parallel to this layer. Layer sequence and average thickness are listed below (Table 12-1):

i. Layer 01: A shallow, intergranular zone aquifer occurring in the transitional soil and weathered bedrock formations of the Beaufort Group host rock including quaternary deposits (Average thickness = 11.0m).

ii. Layer 02: A deep fractured aquifer where groundwater flow will be dictated by transmissive fracture zones that occur in the relatively competent host rock of the Ecca Group as well as Karoo dolerite Suite (Average thickness = ~300.0m).

12.3.4. Boundary conditions

For the purposes of this model, it is assumed that the lower perimeter of the model domain i.e., competent Karoo basement or Dwyka tillite/diamictite which is generally impermeable and serves to isolate the fractured Karoo aquifer from the fractured pre-Karoo aquifer units. Accordingly, this boundary is represented numerically as a “no-flow” boundary condition and was assigned as such. Topographical high perimeters (groundwater divides) were assigned as no-flow boundaries while major rivers i.e., Vetrivier, Sandrivier as well as Doringrivier were assigned as specific head boundary conditions (Dirichlet Type I) with a maximum constraint set where baseflow discharge from the model domain[8]. Figure 12-1 indicates different boundary conditions assigned within the model domain.

12.4. Model hydraulic properties

The following sections provide a brief overview of the model hydraulic parameters assigned as part of the model development and calibration.

12.4.1. Hydraulic Conductivity

Hydraulic conductivity (K) values were sourced from historical aquifer characterisation data as well as literature values published for similar hydrogeological environments. The model calibration was also used to guide refinement of aquifer parameter values[9]. Hydraulic conductivity values range from $7.50E^{-1}$m/d for alluvial deposits, $1.88E^{-1}$m/d for the weathered Beaufort Group formations and $3.750E^{-2}$m/d for the more competent Karoo dolerite formations. Hydraulic conductivity values were assigned to all major hydrostratigraphic units within the model domain as depicted in Figure 12-12 and Figure 12-7. A ratio of 1:1 for hydraulic conductivity (K) in x and y directions have been assigned, with a 1:10 ratio in the z direction i.e., anisotropic aquifer. Table 12-1 provides a summary of parameter values per layer.

---

[8] Refer to “gaining stream” assumption.

[9] It should be noted that hydraulic parameters assigned for various hydrostratigraphical units correlate well to historical models and literature values published for similar geological environments.

12.4.2. Sources and sinks

The primary source to groundwater is through recharge. An approximation of recharge for the model domain is estimated at between ~10.0mm/a assigned for denser Karoo dolerite formations to 21.96mm/a assigned to alluvial deposits including riparian zones as listed in Table 12-1 and indicated in Figure 12-8 below. Sinks in the model domain include groundwater abstraction from privately owned and community boreholes[10] as well as groundwater discharge to baseflow.

12.4.3. Storativity and specific storage

Specific storage values were assigned per hydrostratigraphical units and ranges between $1.00E^{-5}$ to $1.00E^{-1}$ as listed in Table 12-1 below.

12.4.4. Porosity

A porosity value ranging from 15.0% (alluvial deposits) to 5.0% (Weathered aquifer unit) to 1.0% (denser Karoo matrix of the deeper aquifer) was assigned per model layer as listed in Table 12-1 below.

12.4.5. Longitudinal and Transversal Dispersivities

A longitudinal dispersivity value of 5.0m was specified for the simulations (Spitz and Moreno, 1996). Bear and Verruijt (1992) estimated the average transversal dispersity to be 10 to 20 times smaller than the longitudinal dispersity. An average value of 0.5m was selected for this parameter during the simulations.

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[10] The volume of groundwater abstraction from boreholes is based on data recorded during the hydrocensus as well an assumption for the entire model catchment.

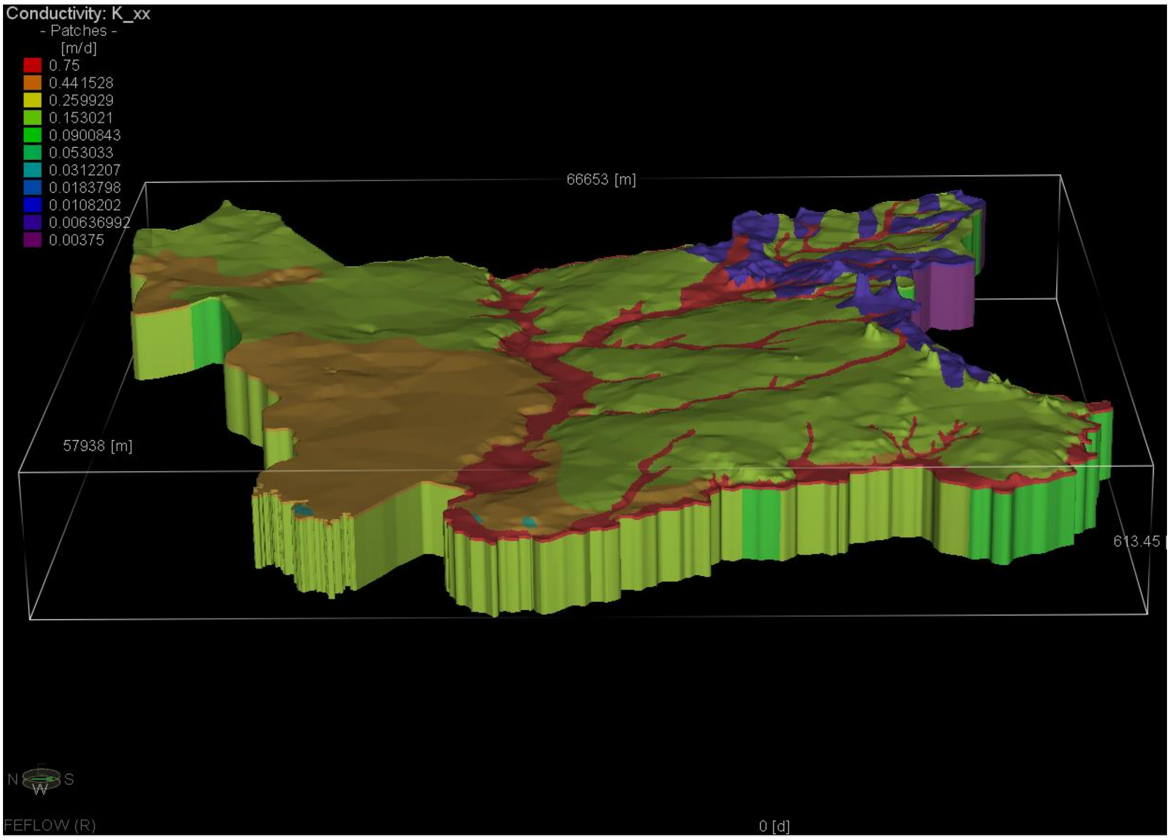


Figure 12-7 **Model development: Numerical groundwater flow model: Hydraulic conductivity distribution.**

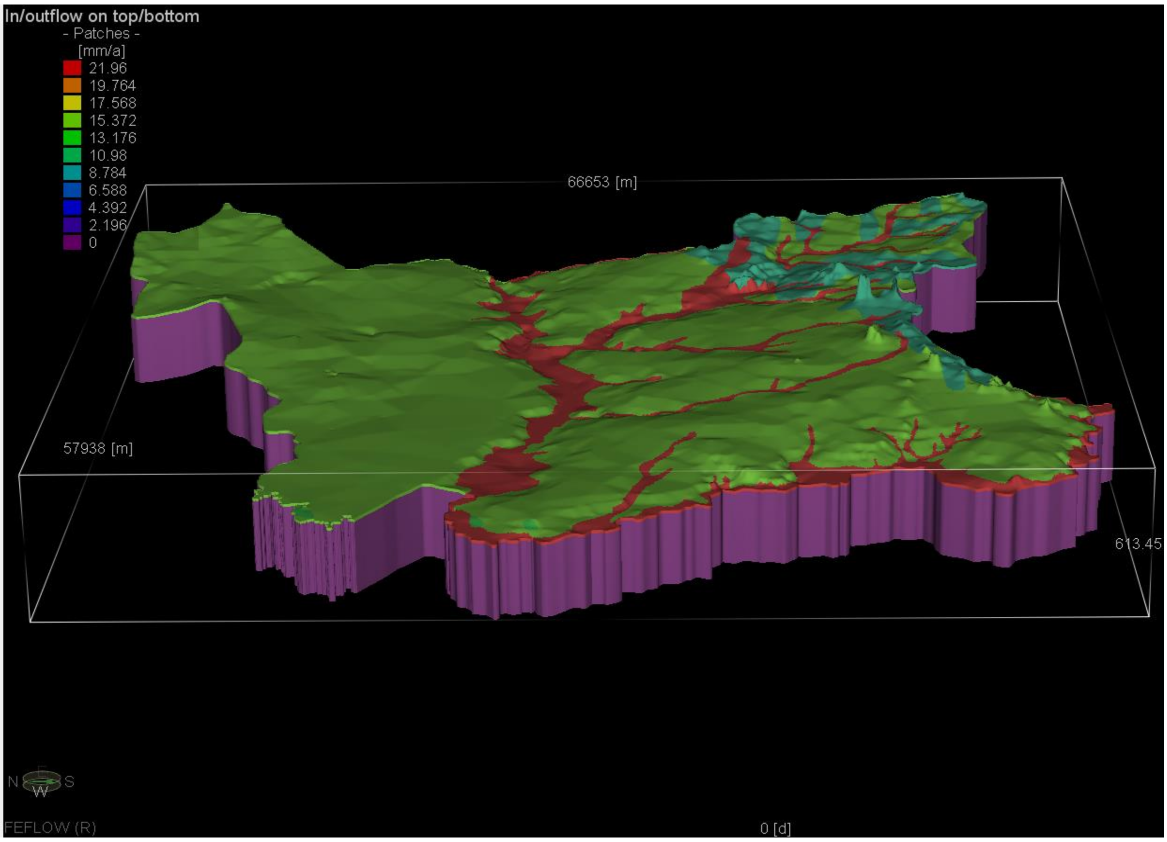


Figure 12-8 **Model development: Numerical groundwater flow model: Recharge distribution.**

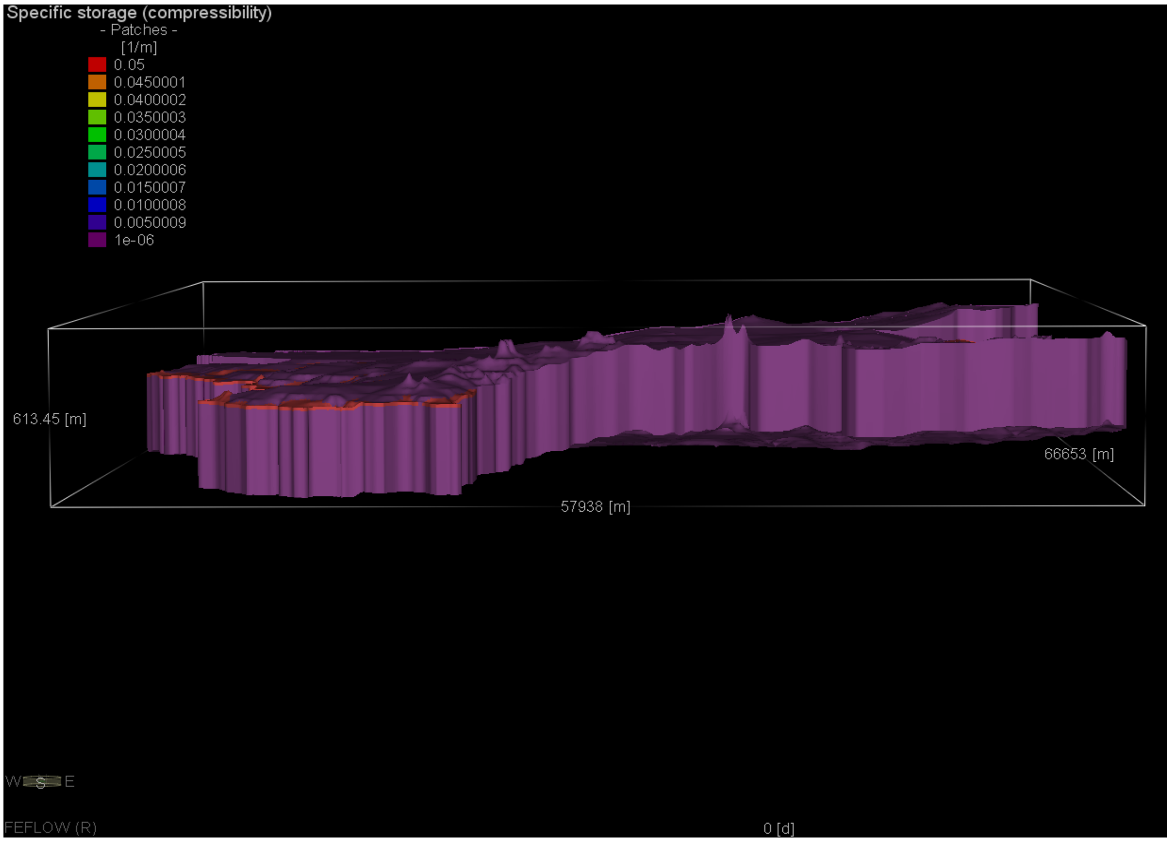


Figure 12-9 **Model development: Numerical groundwater flow model: Specific storage distribution.**

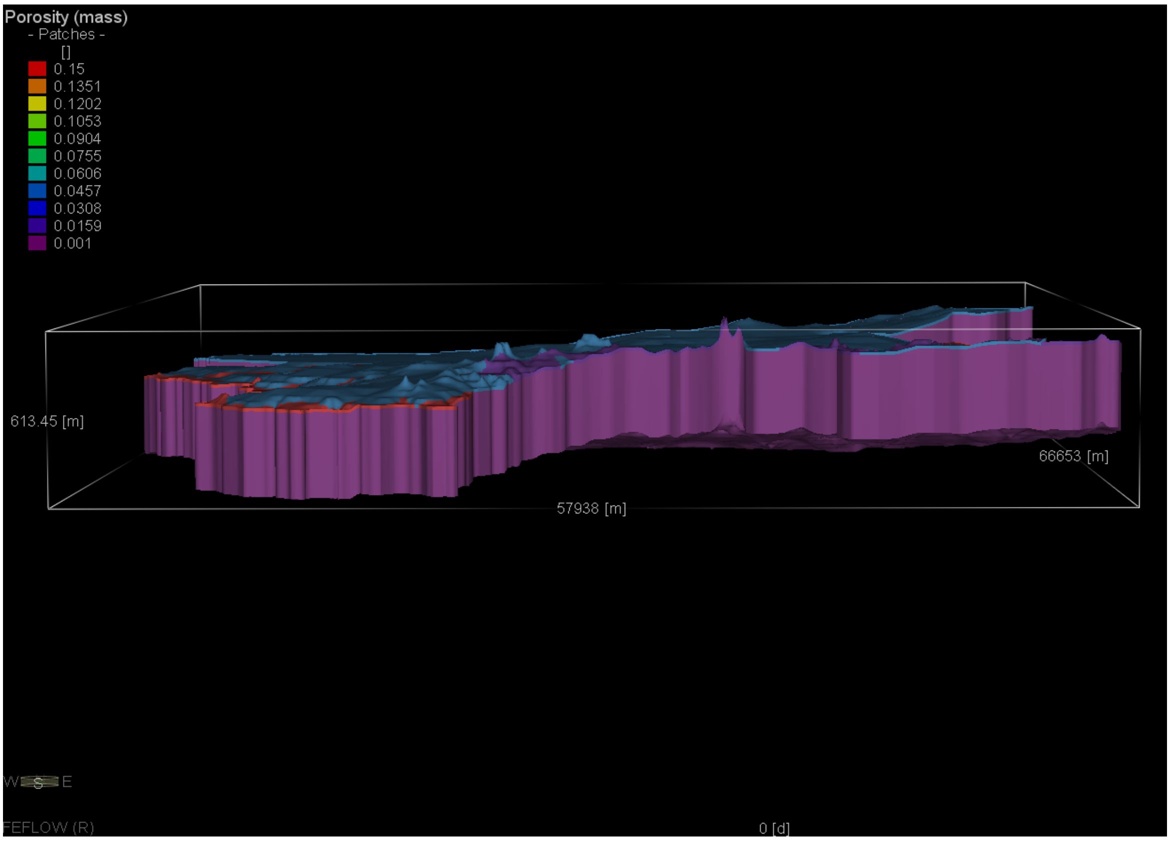


Figure 12-10 **Model development: Numerical groundwater flow model: Porosity distribution.**

Table 12-1 Model set-up: Hydraulic Parameters.

Model Layer	Hydrostratigraphic unit	Layer thickness (m)	Hydraulic Conductivity (K)		Recharge (Re)	Specific storage (Sc)	Porosity (n)
			Kx,y 1:1 (m/d)	Kz 1:10 (m/d)*	In/Outflow on top/bottom (mm/a)	Sc (1/m)	
Layer 01	Alluvial deposits	11.00	7.50E-01	7.50E-01	2.20E+01	1.00E-01	1.50E-01
	Volksrust Formation		3.75E-01	3.75E-02	1.50E+01	1.00E-03	5.00E-02
	Beaufort Group		1.88E-01	1.88E-02	1.50E+01	1.00E-03	5.00E-02
	Karoo Dolerite		7.50E-03	7.50E-04	1.00E+01	1.00E-05	1.00E-02
	Rietgat Formation		3.75E-02	3.75E-03	1.25E+01	1.00E-03	3.00E-02
Layer 02	Volksrust Formation	300.00	1.88E-01	1.88E-02	0.00E+00	1.00E-04	5.00E-03
	Beaufort Group		9.30E-02	9.30E-03		1.00E-04	5.00E-03
	Karoo Dolerite		3.75E-03	3.75E-04		1.00E-06	1.00E-03
	Rietgat Formation		1.88E-02	1.88E-03		1.00E-04	3.00E-03

***Note: Anisotropy of the alluvial, riparian zone aquifer was set at a 1:1 ratio**

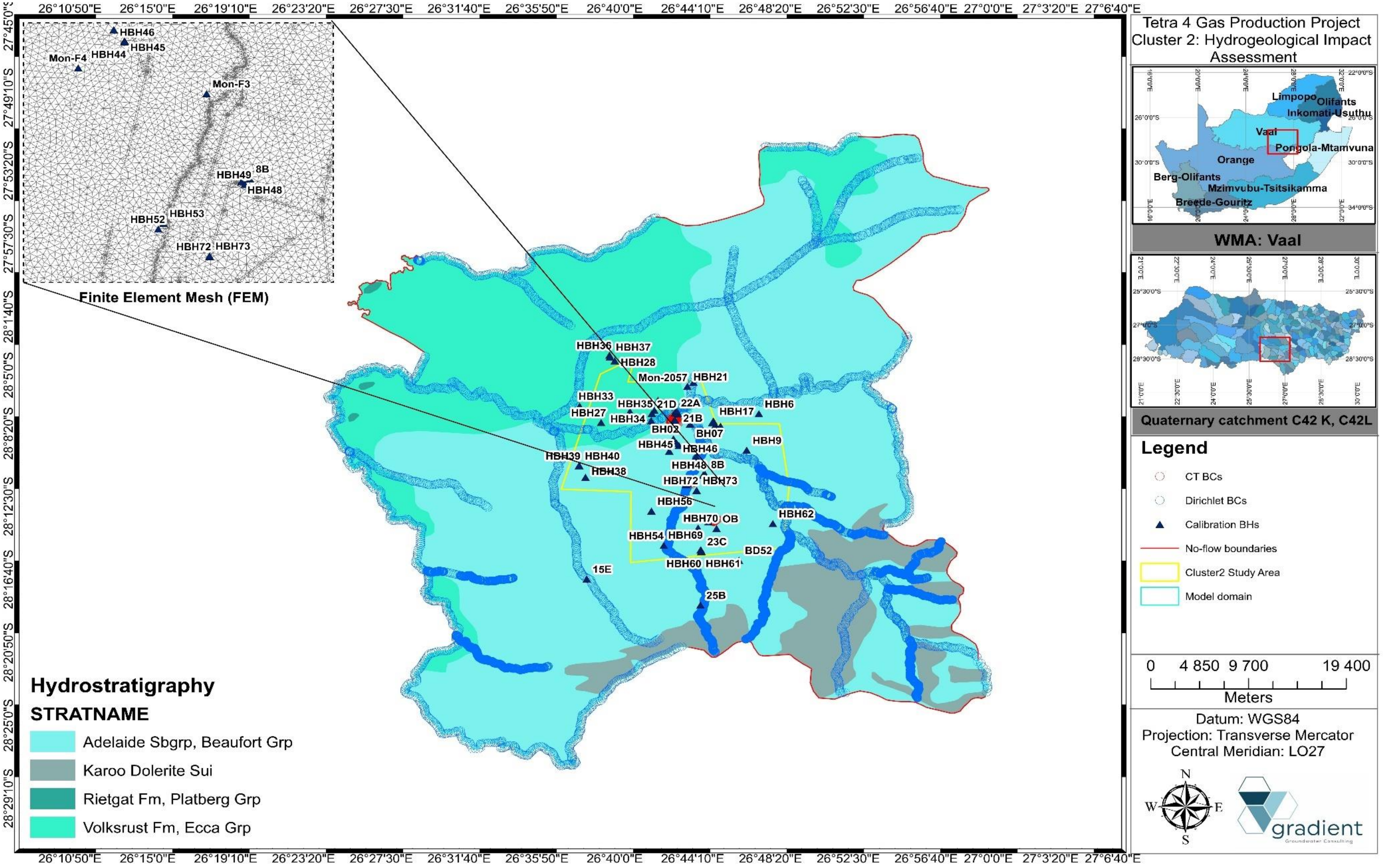


Figure 12-11 **Hydrostratigraphic units and model boundary conditions.**

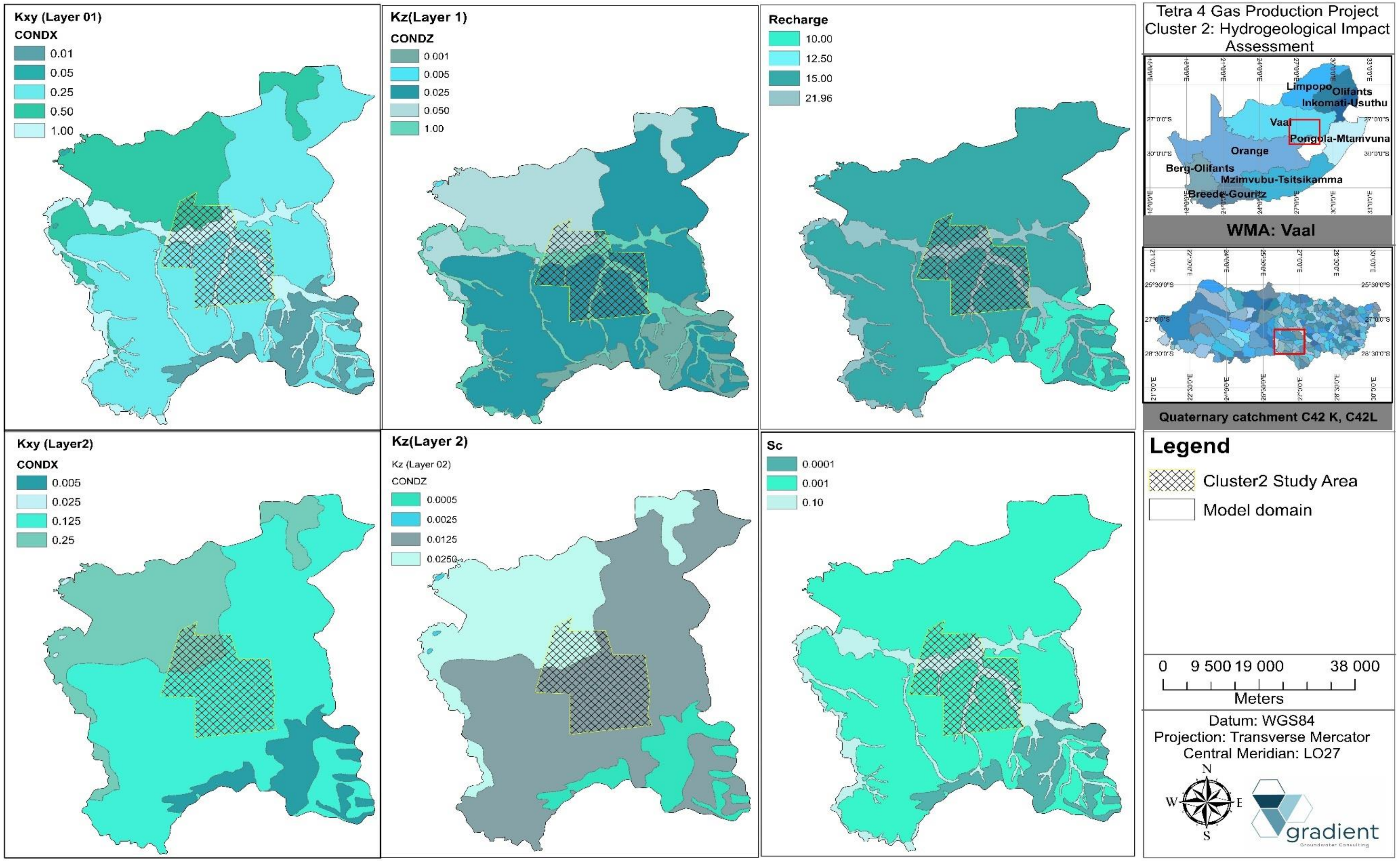


Figure 12-12 **Numerical groundwater flow model: Hydraulic properties.**

12.5. Model calibration

12.5.1. Steady state calibration (∞)

A steady state groundwater flow model was developed to simulate equilibrium conditions, i.e., pre-development conditions, which will be used as initial hydrogeological conditions for transient simulations. The model was standardised by applying the American Society for Testing Materials (ASTM) guidelines (1993), as well as methods presented in Anderson and Woesner (1992) and Spitz and Moreno (1996) case studies. Under steady state conditions, the groundwater flow equation is reduced to exclude storativity. Groundwater levels of gathered observation boreholes were simulated by varying aquifer parameters (hydraulic conductivity and recharge) until an acceptable fit between the measured and simulated hydraulic heads was obtained as summarised in Table 12-2. Observed groundwater levels were plotted against measured water levels and a correlation of ~0.95 was obtained (refer to Figure 12-13, Figure 12-14 and Figure 12-15) while Figure 12-16 indicate calibration error margin per borehole observation locality. Figure 12-17 depicts steady state hydraulic head contours and groundwater flow directions. A good correlation indicates that the developed groundwater model will accurately represent on-site conditions. The residual calibration error is expressed through the calculated; mean error (ME), mean absolute error (MAE) as well as the root mean squared error (RMSE) of the observed versus simulated heads. The RMSE was evaluated as a ratio of the total saturated thickness across the model domain and calculated errors are summarised below:

i. Mean Error (ME): -1.27m.

ii. Mean Absolute Error (MAE): 8.23m.

iii. Normalised Root Mean Square Deviation (NRMSD): 7.83% i.e., represents the deviation between observed and calibration water levels across the model domain.

Table 12-2 Steady State Model Calibration – Statistical Summary.

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)
HBH6	1308.35	1.52	1306.83	1302.18	4.65	4.65	21.65
HBH9	1314.33	10.87	1303.46	1305.66	-2.20	2.20	4.85
HBH12	1317.12	13.65	1303.47	1295.93	7.54	7.54	56.90
HBH13	1317.12	12.35	1304.77	1295.16	9.61	9.61	92.41
HBH14	1306.16	16.65	1289.51	1290.99	-1.47	1.47	2.17
HBH15	1306.16	17.74	1288.42	1291.06	-2.63	2.63	6.94
HBH16	1311.92	25.40	1286.52	1293.15	-6.64	6.64	44.08
HBH17	1306.16	11.55	1294.61	1290.82	3.80	3.80	14.43
HBH18	1312.93	16.47	1296.46	1294.76	1.69	1.69	2.87
HBH20	1341.47	1.10	1340.37	1309.66	30.71	30.71	942.80
HBH21	1316.68	2.67	1314.01	1299.86	14.15	14.15	200.14
HBH23	1313.61	3.16	1310.45	1294.19	16.26	16.26	264.32
HBH24	1296.78	8.50	1288.28	1288.69	-0.41	0.41	0.17
HBH25	1306.46	24.20	1282.26	1292.15	-9.89	9.89	97.79
HBH27	1300.84	1.40	1299.44	1287.57	11.87	11.87	140.83
HBH28	1312.85	5.02	1307.83	1310.99	-3.16	3.16	9.97
HBH31	1308.76	0.00	1308.76	1298.25	10.51	10.51	110.42
HBH33	1303.06	15.70	1287.36	1292.32	-4.96	4.96	24.59
HBH34	1282.46	26.04	1256.42	1282.22	-25.80	25.80	665.69
HBH35	1293.51	3.70	1289.81	1287.34	2.47	2.47	6.10

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)
HBH36	1311.04	2.66	1308.38	1311.39	-3.01	3.01	9.05
HBH37	1311.33	3.18	1308.15	1311.17	-3.02	3.02	9.13
HBH38	1338.24	2.94	1335.30	1318.63	16.67	16.67	277.76
HBH39	1312.52	8.26	1304.26	1307.12	-2.86	2.86	8.19
HBH40	1312.52	8.75	1303.77	1306.99	-3.22	3.22	10.38
HBH44	1318.93	8.46	1310.47	1300.07	10.41	10.41	108.28
HBH45	1318.93	8.40	1310.53	1300.18	10.35	10.35	107.21
HBH46	1314.70	14.50	1300.20	1298.69	1.51	1.51	2.29
HBH48	1325.03	11.03	1314.00	1315.69	-1.69	1.69	2.87
HBH49	1325.03	7.12	1317.91	1316.45	1.46	1.46	2.14
HBH52	1323.97	1.08	1322.89	1320.93	1.95	1.95	3.82
HBH53	1323.97	2.80	1321.17	1320.16	1.01	1.01	1.02
HBH54	1363.06	7.98	1355.08	1363.98	-8.90	8.90	79.14
HBH56	1358.94	1.79	1357.15	1349.15	8.00	8.00	63.95
HBH58	1373.57	7.95	1365.62	1373.53	-7.90	7.90	62.46
HBH59	1373.57	8.35	1365.22	1373.45	-8.22	8.22	67.63
HBH60	1371.99	12.90	1359.09	1372.66	-13.57	13.57	184.20
HBH61	1371.99	12.55	1359.44	1372.54	-13.10	13.10	171.69
HBH62	1337.84	12.70	1325.14	1342.98	-17.84	17.84	318.27
HBH69	1358.14	1.67	1356.47	1354.77	1.70	1.70	2.89
HBH70	1360.24	3.10	1357.14	1358.74	-1.60	1.60	2.55
HBH72	1332.90	1.75	1331.15	1328.33	2.82	2.82	7.96
HBH73	1332.90	1.63	1331.27	1328.21	3.06	3.06	9.36
15E	1380.01	2.20	1377.81	1374.98	2.83	2.83	8.03
21A (BH05)	1281.21	12.48	1268.74	1281.33	-12.59	12.59	158.48
21B	1281.21	0.00	1281.21	1281.19	0.02	0.02	0.00
21D	1280.00	16.09	1263.91	1281.68	-17.77	17.77	315.95
22A	1282.95	10.64	1272.31	1280.01	-7.70	7.70	59.27
22D (BH09)	1281.21	8.33	1272.89	1280.04	-7.15	7.15	51.19
23C	1373.57	5.42	1368.16	1373.42	-5.26	5.26	27.67
25B	1404.66	9.39	1395.27	1403.97	-8.70	8.70	75.69
8B	1325.03	0.00	1325.03	1315.64	9.39	9.39	88.19
BD52	1381.39	0.73	1380.66	1377.11	3.55	3.55	12.62
BH01	1283.95	23.33	1260.63	1284.80	-24.17	24.17	584.33
BH02	1308.60	10.07	1298.53	1295.69	2.84	2.84	8.06
BH07	1281.69	16.97	1264.73	1283.23	-18.51	18.51	342.47
Mon-2057	1320.23	3.09	1317.14	1303.70	13.45	13.45	180.79
Mon-F1	1290.60	21.46	1269.14	1288.23	-19.10	19.10	364.73
Mon-F3	1304.74	7.74	1297.00	1301.27	-4.27	4.27	18.22
Mon-F4	1319.62	7.69	1311.93	1304.28	7.65	7.65	58.51
Mon-HDR1	1283.95	26.71	1257.24	1284.40	-27.16	27.16	737.45
OB	1364.24	0.70	1363.54	1359.60	3.94	3.94	15.50
Average	**1322.21**	**8.91**	**1313.30**	**1314.57**	**-1.27**	**8.23**	**118.20**
Minimum	**1280.00**	**0.00**	**1256.42**	**1280.01**	**-27.16**	**0.02**	**0.00**
Maximum	**1404.66**	**26.71**	**1395.27**	**1403.97**	**30.71**	**30.71**	**942.80**
Correlation			**0.95**				
∑					**-78.62**	**510.36**	**7328.51**
1/n					**-1.27**	**8.23**	**118.20**
Root Mean Square Deviation (RMSD)					**1.13**	**2.87**	**10.87**
Normalised Root Mean Square Deviation (NRMSD) (% of water level range)							**7.83**

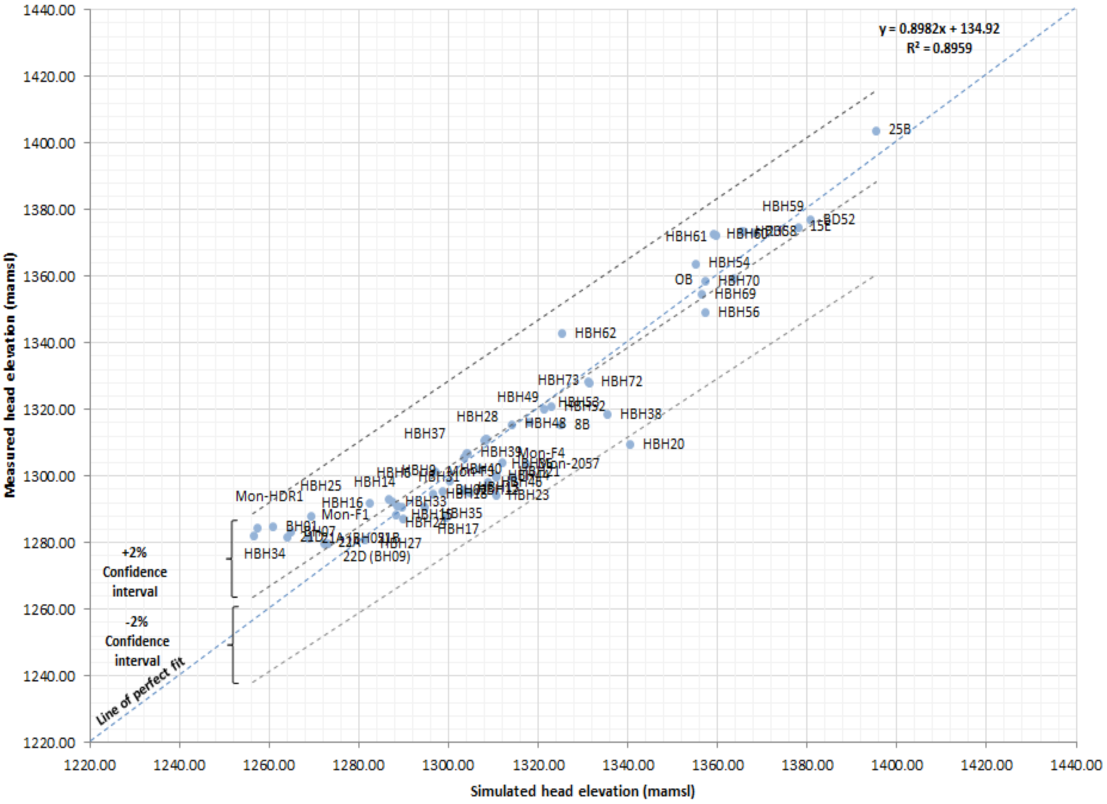


Figure 12-13 Model steady state calibration: Scatter plot of simulated vs. measured hydraulic head elevation.

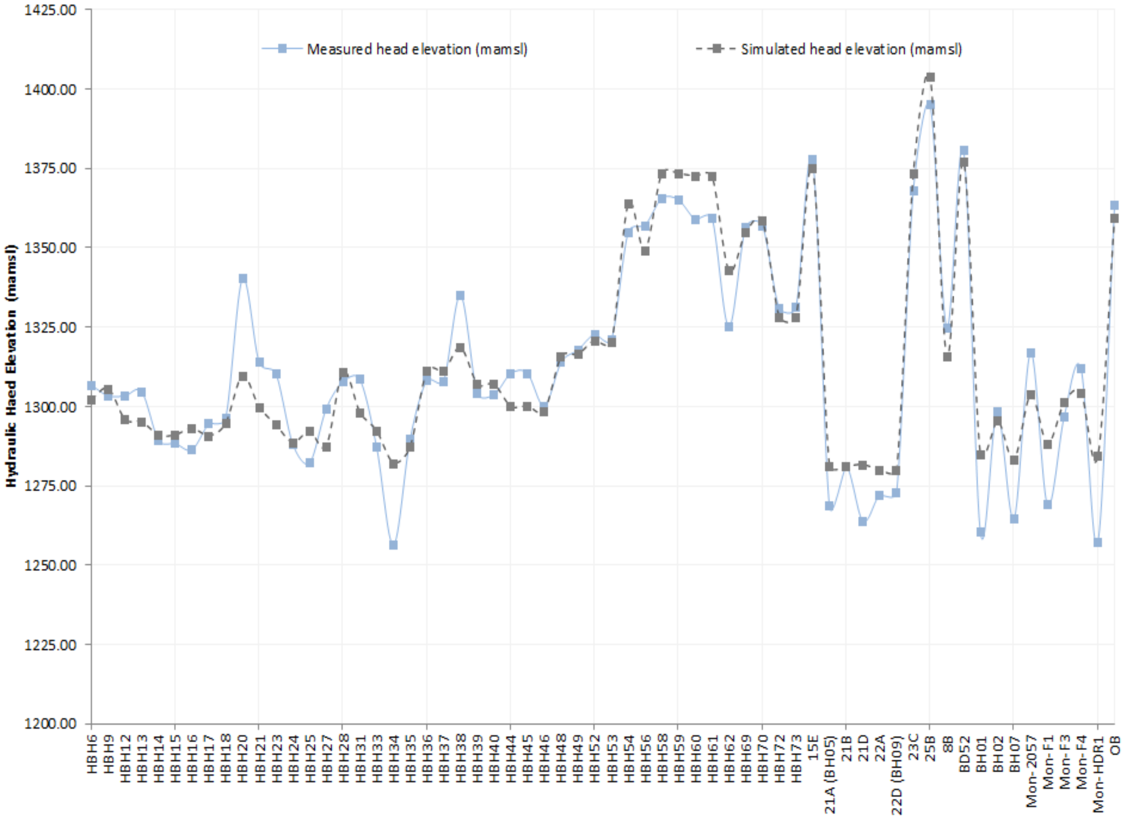


Figure 12-14 Model steady state calibration: curve of simulated vs. measured hydraulic head elevation.

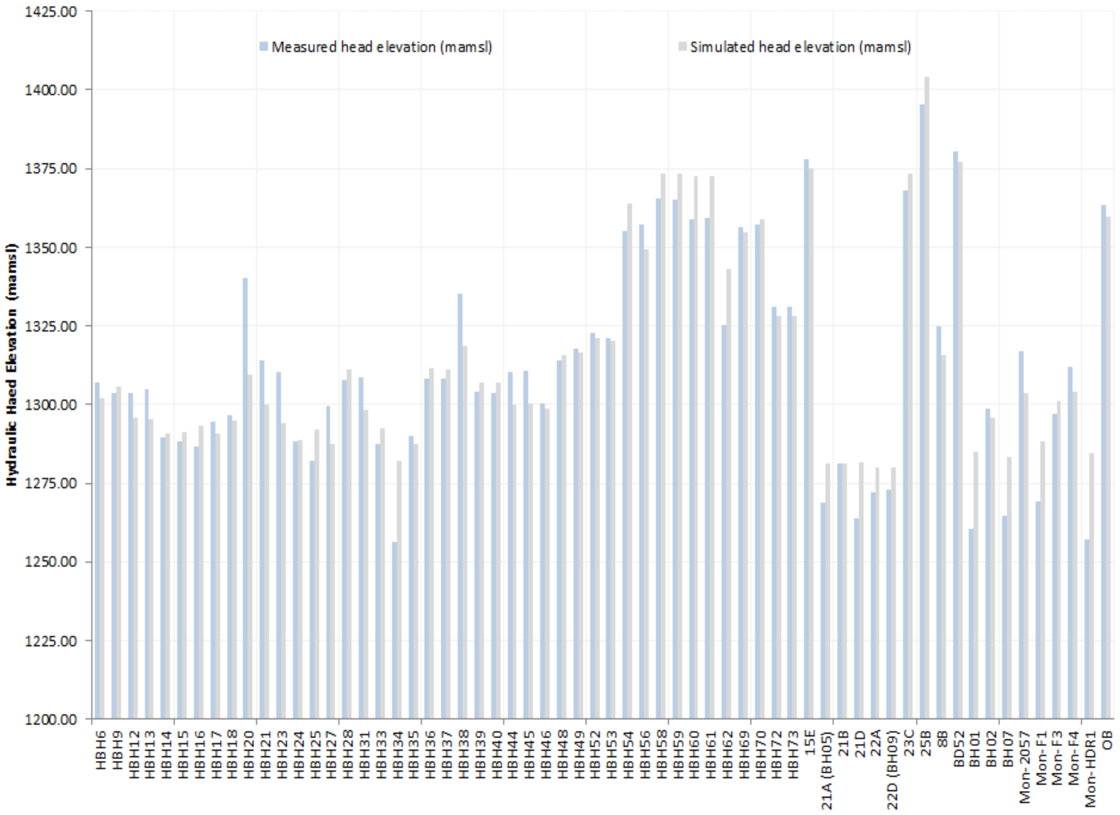


Figure 12-15 **Model steady state calibration: Bar chart of simulated vs. measured hydraulic head elevation.**

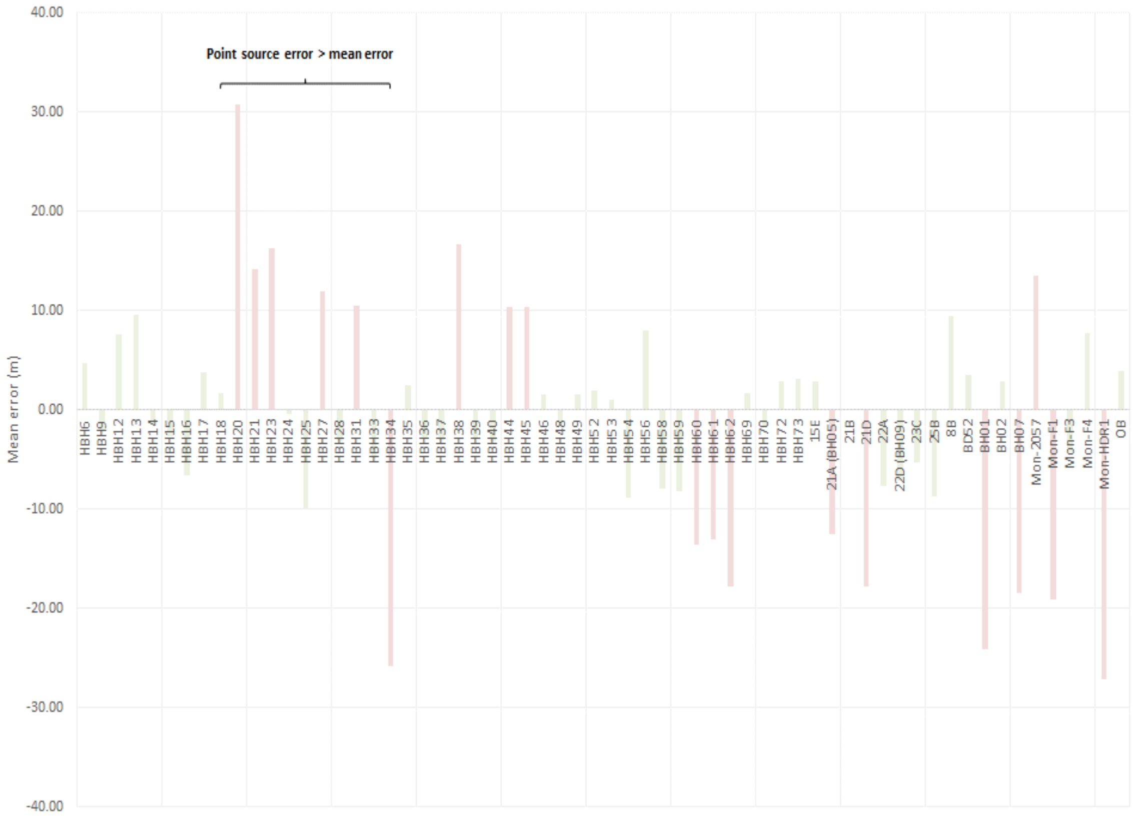


Figure 12-16 **Model steady state calibration: Bar-chart of simulated vs. measured hydraulic head elevation.**

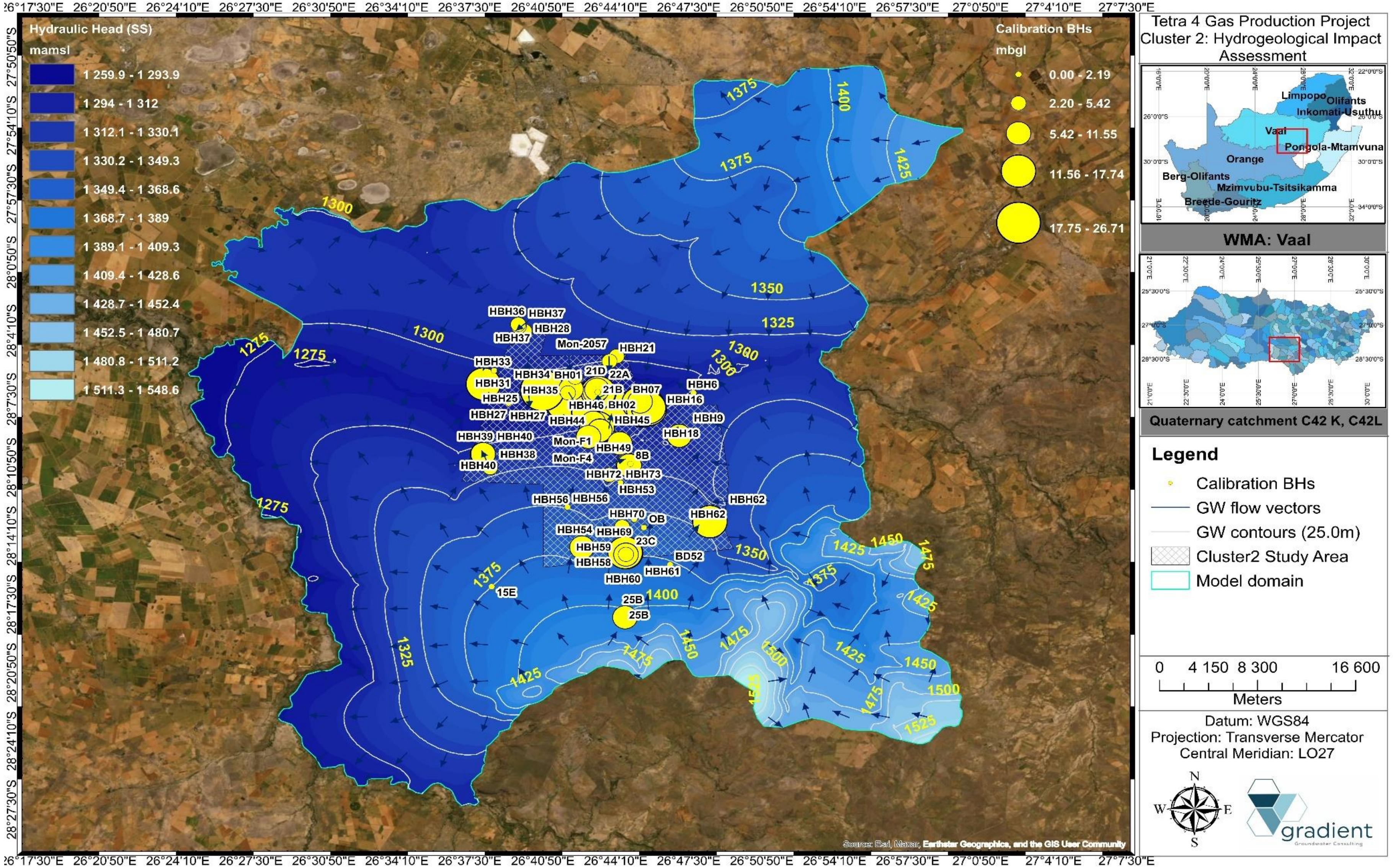


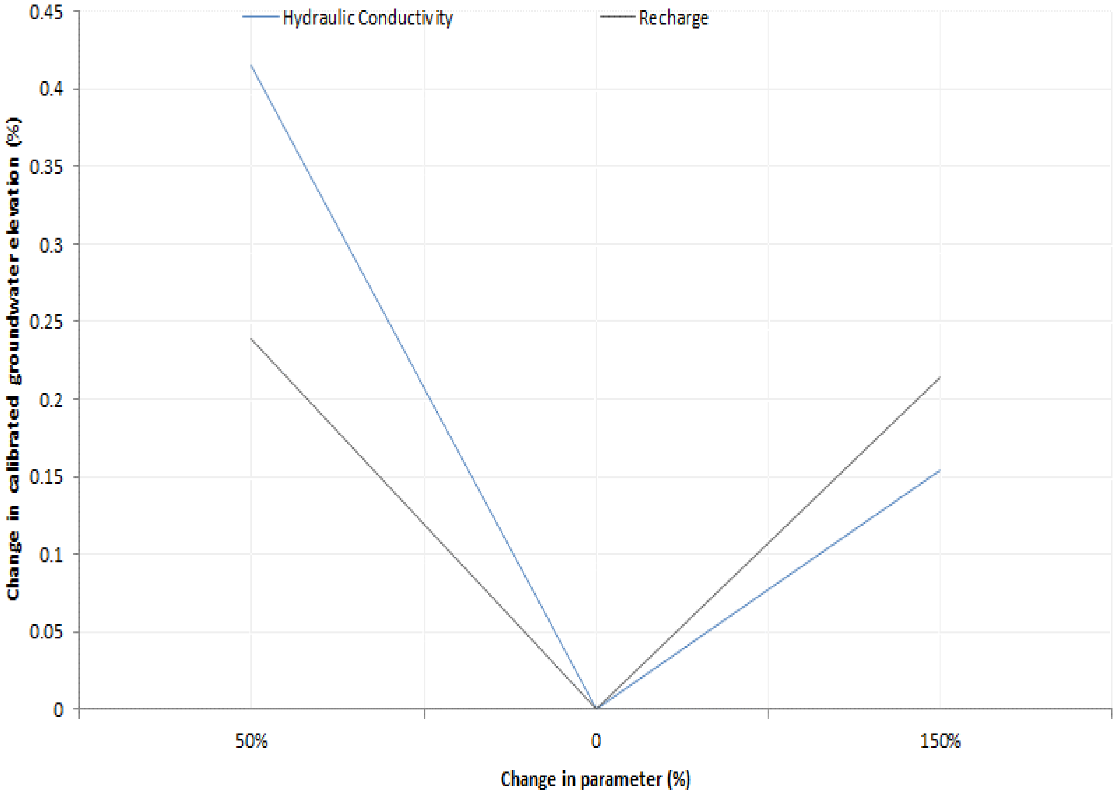
Figure 12-17 Model calibration: steady state hydraulic heads and groundwater flow direction.

12.5.2. Model sensitivity analysis

Sensitivity analysis is the study of how the uncertainty in the output of a mathematical model or system (numerical or otherwise) can be apportioned to different sources of uncertainty in its inputs (Saltelli, 2002). The process of recalculating outcomes under alternative assumptions to determine the impact of a variable under sensitivity analysis can increase the understanding of the relationships between input and output variables in a system or model as well as reduce the model uncertainty (Pannell, 1997). In order to verify the sensitivity of the calibrated model in terms of hydraulic stresses, aquifer parameters (i.e., recharge and transmissivity) were adjusted while the impact on the hydraulic head elevation evaluated at relevant on-site borehole localities. As summarised in Table 12-2 it is noted that the model tends to be more sensitive to variations in recharge, especially a downward adjustment (Figure 12-18, Figure 12-19 and Figure 12-20)[11].

Table 12-3 Steady State Model Calibration – Sensitivity analysis.

Parameter	Scenario: Base Case	Scenario: 90% of calibrated K-value	Scenario: 110% of calibrated K-value	Scenario: 90% of calibrated recharge	Scenario: 110% of calibrated recharge
Correlation	0.95	0.96	0.94	0.94	0.95
Mean Error	-1.27	-7.27	1.49	3.95	-4.42
Mean Abs Error	8.23	9.71	8.68	10.00	8.44
RMSD	10.87	12.27	11.58	12.85	11.09
NRMSD	7.83%	8.83%	8.34%	9.26%	7.99%



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[11] Recharge remains an uncertain parameter and it is difficult to estimate groundwater recharge accurately. The accurate quantification of natural recharge uncertainty is critical for groundwater management.

Figure 12-18 Model steady state calibration: sensitivity analysis for monitoring locality HBH09.

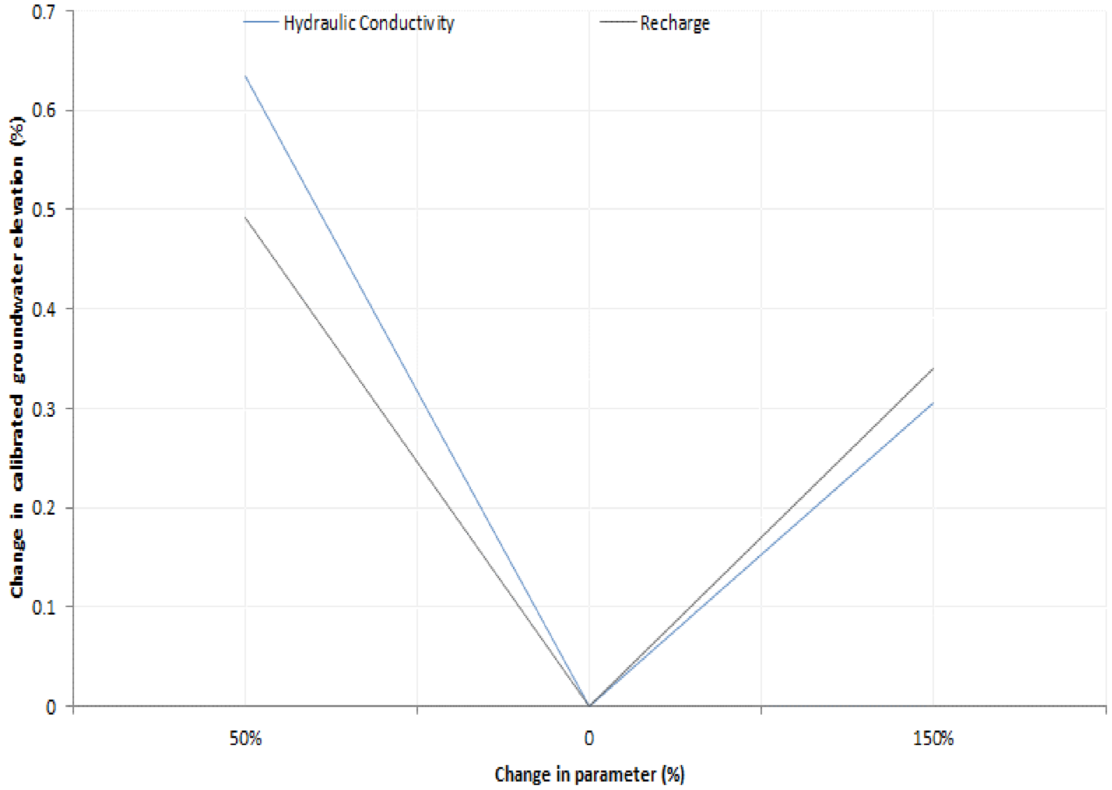

Figure 12-19 Model steady state calibration: sensitivity analysis for monitoring locality HBH28.

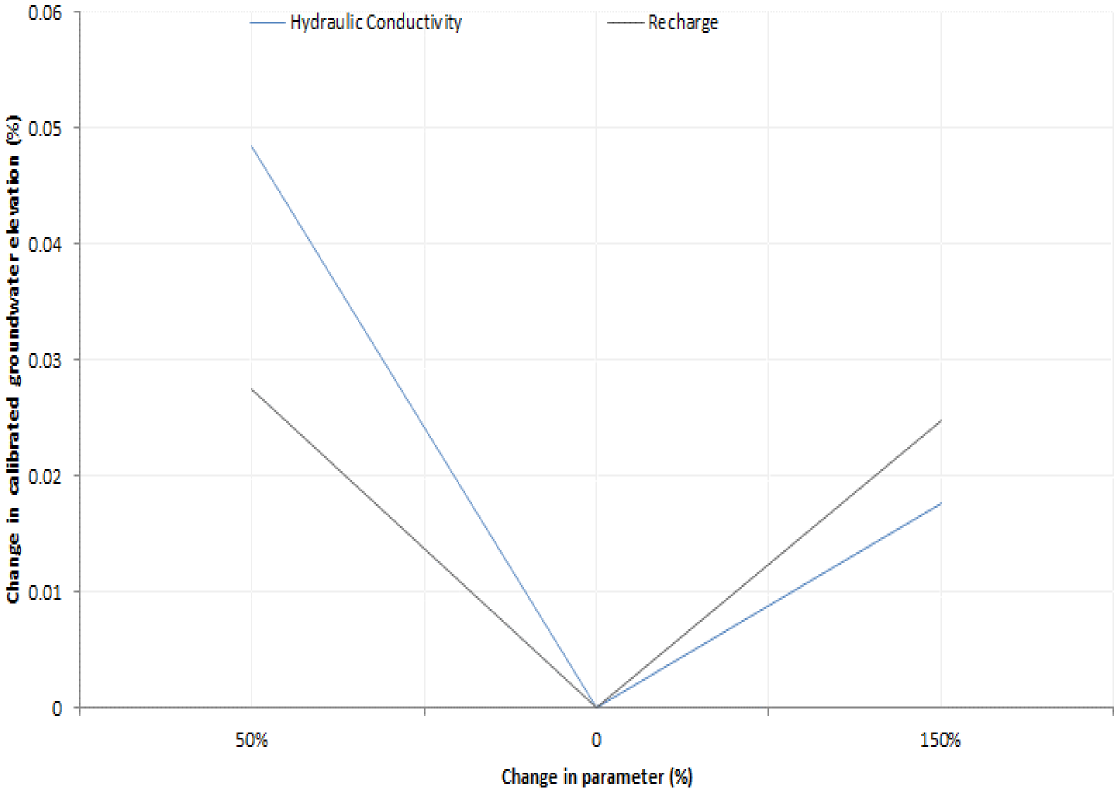

Figure 12-20 Model steady state calibration: sensitivity analysis for monitoring locality 21B.

12.6. Numerical groundwater flow model

The groundwater model is based on three-dimensional groundwater flow and may be described by the following equation (Darcy, 1856):

Equation 12-2 Groundwater flow.

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

where:

h = hydraulic head [L]

Kx,Ky,Kz = 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]

12.7. Numerical mass transport model

The mass balance equation (Bear and Verruijt, 1992) (advection-dispersion equation) of a pollutant can be expressed as follows:

Equation 12-3 Advection-dispersion.

$$\frac{\delta nc}{\delta t}=-\Delta\bullet q_{c,total}-f+n\rho\Gamma-P_c+R_c$$

where:

nc = mass of pollutant per unit volume of porous medium;

n = porosity of saturated zone;

c = concentration of pollutant (mass of pollutant per unit volume of liquid (water));

$\Delta\bullet q_{c,total}$ = excess of inflow of a considered pollutant over outflow, per unit volume of porous medium, per unit time;

f = quantity of pollutant leaving the water (through adsorption, ion exchange etc.);

$n\rho\Gamma$ = mass of pollutant added to the water (or leaving it) as a result of chemical interactions among species inside the water, or by various decay phenomena[12];

Γ = rate at which the mass of a pollutant is added to the water per unit mass of fluid;

p = density of pollutant;

Pc = total quantity of pollutant withdrawn (pumped) per unit volume of porous medium per unit time;

Rc = total quantity of pollutant added (artificial recharge) per unit volume of porous medium per unit time.

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[12] This investigation and contaminant transport model are based on a “worst-case” scenario and as such, it is assumed that no decay and/or retardation are taking place in the aquifer.

Advection and hydrodynamic dispersion are the major processes controlling transport through a porous medium. 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 refers to the stretching of a solute band in the flow direction during its transport by an advecting fluid and comprises mechanical dispersion as well as molecular diffusion. Contaminant transport scenarios serve as tool for management purposes and the simulation results indicate the expected plume migration. The latter can be used to establish additional monitoring points to be applied as transient input for model updates and re-calibration.

It should be noted that the contaminant transport scenarios serve as a tool for management purposes with advective transport simulating the potential leachate concentrations from waste facilities, however, does not include biochemical breakdown and cation/anion exchange reactions which will further retard plume migration.

Various source terms and contaminant proxies were applied as part of the mass transport migration simulations and include saline groundwater emanating from the deep, fractured aquifer from leaking gas production boreholes (TDS = 7 832.0 mg/l - based on hydrochemical analysis of water samples representing this aquifer unit) as well as contaminated water emanating at the plant footprint and evaporation dam(s) (TDS = 2000.0 mg/l).

A contaminant transport scenario was conducted simulating stray methane gas (CH_4) from leaking gas production boreholes. The drilling and operation of gas production wells could result in the migration of stray gas from the deep-seated fracture zones to formations higher up in the geological sequence. This impact has been recorded in the US where hydraulic fracturing, dewatering or a combination of these has occurred (Jackson et al, 2013). It should be stated that Tetra4 does not intend to undertake hydraulic fracturing or any well stimulation and the existing dataset suggests that no dewatering of produced water will be required. Accordingly, the risk of stray gas migration is therefore expected to be low. It should be noted that this scenario is highly unlikely under natural conditions as the production zone(s) is separated from the shallow and potable Karoo aquifer by very low permeability shale formations which will act as an aquitard towards any groundwater and stray gas migration. This is however provided that well construction, including cementation and the installation of steel casing, is sound. As such, the impact assessment evaluated represents a worst-case scenario and simulates the eventual occurrence once stray gas does reach the shallow aquifer. The mechanisms by which stray gas can migrate into the shallower potable Karoo aquifer include (*iLEH*, 2017):

- Leakage of stray gas along poorly sealed gas production wells;
- Gas leakage because of an overpressure event and barrier (casing and cementation) failure; and
- Migration of gas from deep-seated fracture zones along fractures and faults.

As methane gas reaches saturation in water at 28 milligrams per litre (mg/L) at atmospheric pressure (Eltschlager and others, 2001), this concentration was applied as source term for this scenario. According to the U.S. Environmental Protection Agency (EPA, 2011) as well as U.S. Department of the Interior, Office of Surface Mining (2011), methane concentrations below 10 mg/L are generally considered safe.

Various management scenarios were modelled for the purposes of planning and decision making with stress periods listed in Table 12-4:

i. **Scenario 01:** Steady state water balance (∞).

ii. **Scenario 02a:** Migration of saline groundwater from the deep, fractured aquifer to the overlying, potable aquifer(s) during the operational gas production phase.

iii. **Scenario 02b:** Migration of stray methane (CH_4) gas emanating from the deep, fractured aquifer to the overlying, potable aquifer(s) during the operations gas production phase.

iv. **Scenario 03:** Migration of the TDS pollution plume emanating from the plant footprint area during the operational gas production phase.

v. **Scenario 04a:** Migration of saline groundwater from the deep, fractured aquifer to the overlying, potable aquifer(s) during the post-closure and decommissioning phase (50-year and 100-year scenarios).

vi. **Scenario 04b:** Migration of stray methane (CH_4) gas emanating from the deep, fractured aquifer to the overlying, potable aquifer(s) during the post-closure and decommissioning phase (50-year and 100-year scenarios).

vii. **Scenario 05:** Migration of the TDS pollution plume emanating from the plant footprint area during the post-closure and decommissioning phase (50-year and 100-year scenarios).

Table 12-4 Summary of model stress-periods.

Stress period	Description
Year01 – Year20	Gas production operational phase
Year 21 – Year 71	50-years post closure
Year 72 – Year 121	100-years post closure

12.7.1. Scenario 01: Steady state baseline water balance (∞)

Table 12-5 summarises the groundwater catchment water balance representing baseline steady state conditions. Recharge is assumed the only source of inflow to the system and has been simulated at $1.03E^{+05}$ m^3/d, while the largest loss to the groundwater system is via baseflow, $1.02E^{+04}$ m^3/d. The imbalance of the delineated aquifer unit, ignoring internal transfer, is calculated at $1.90E^{+3}m^3/d$.

Table 12-5 Catchment water balance: Scenario 01 – Steady state baseline water balance.

Scenario 01 – Steady State Catchment Groundwater Balance			
Parameter	**Inflow (m^3/d)**	**Outflow (m^3/d)**	**Balance (m^3/d)**
Recharge (m^3/d)	1.03E+05	0.00E+00	1.03E+05
GW component of baseflow/ Dirichlet boundary conditions (m^3/d)	1.02E+03	1.02E+05	-1.01E+05
Storage Capture(-)/Release(+)(m^3/d)	2.11E+01	1.86E+01	2.50E+00
Imbalance ignoring internal transfer (m^3/d)	0.00E+00	1.99E+03	0.00E+00
Total (m^3/d)	**1.04E+05**	**1.04E+05**	**0.00E+00**

12.7.2. Scenario 02a: Migration of saline groundwater from the deep, fractured aquifer to the overlying, potable aquifer(s) during the operational gas production phase

This scenario summarises the simulated point source pollution plume migration of saline groundwater emanating from the deep, fractured aquifer should the integrity of the gas production boreholes be jeopardised i.e., leaking boreholes for the operational phase (20-year period). The TDS pollution plume extend covers a total area of approximately 414.06ha in the Karoo formations, reaching a maximum distance of ~80.0m in a radial pattern from the gas production borehole(s), and approximately 251.60ha in the alluvial deposits, reaching a maximum distance of ~200.0m in a radial pattern from the gas production borehole after a simulation period of 20-years (refer to Figure 12-23). The simulation indicates that the following neighbouring boreholes will potentially be intercepted by the simulated pollution plume HBH08, HBH41, HBH42, HBH43, HBH63, HBH72, HBH73 and HBH74. It is noted that the pollution plume does extend beyond the project boundary. Figure 12-22 indicates the expected flow pathways of particles derived from the source points and it is evident that the pollution plume migration in the denser Karoo formations is sluggish while movement in the unconsolidated alluvial deposits of the riparian zone suggest a larger flux.

Figure 12-21 summarises a time-series graph of the TDS mass load contribution to down-gradient receptors. It is evident that source term mass load contribution to existing neighbouring borehole situated near the gas production boreholes does not exceed ~800.0mg/l and ranges between 600mg/l to 700.0mg/l.

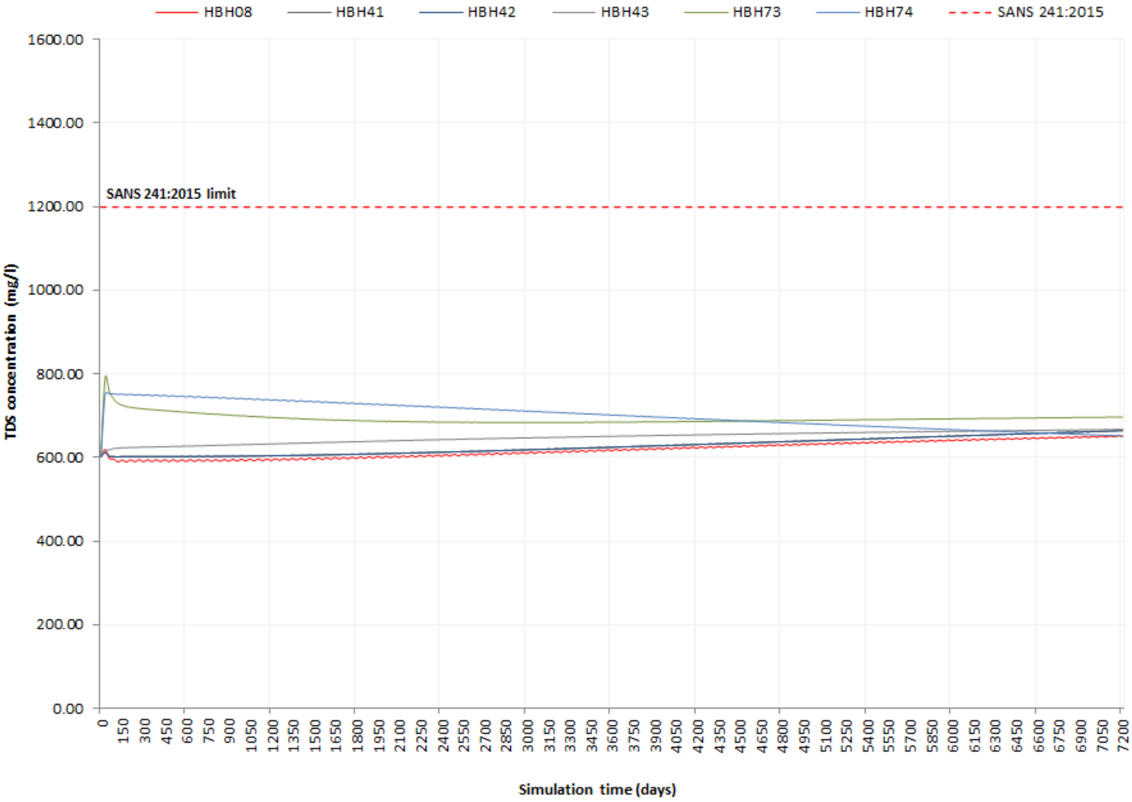

Figure 12-21 **Scenario 02a: Time-series graph indicating the TDS mass load contribution of deeper, fractured and saline aquifer on observation boreholes targetting the potable shallow, intergranular aquifer (Operational phase).**

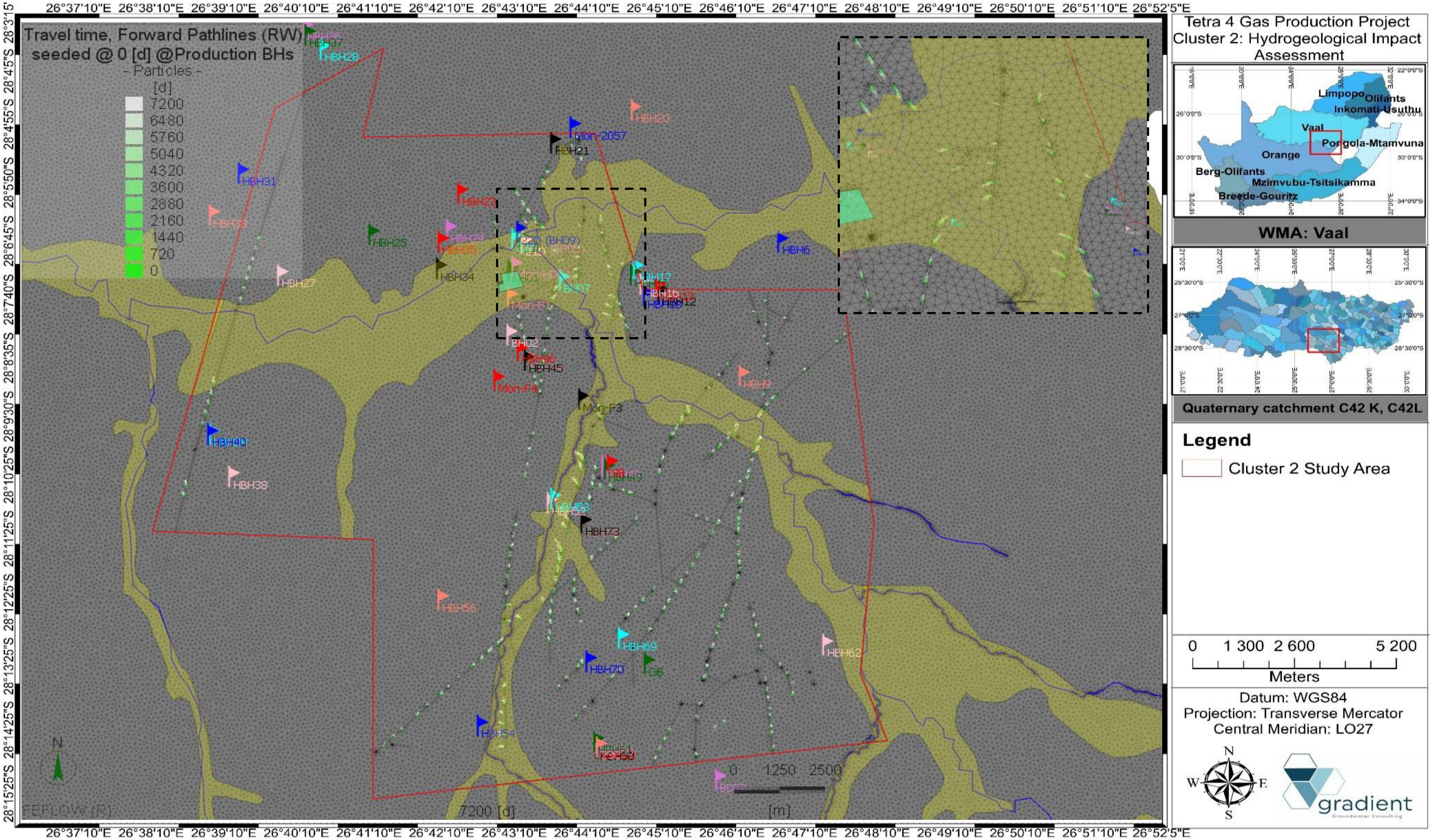

Figure 12-22 **Scenario 02: Simulated particle tracking of contaminants originating from the deeper, fractured aquifer migrating from leaking boreholes within the intergranular aquifer (Operational phase).**

Figure 12-23 **Scenario 02a: TDS pollution plume migration of contaminants originating from the deeper, fractured aquifer migrating through the intergranular aquifer (Operational phase).**

12.7.3. Scenario 02b: Migration of stray methane (CH_4) gas emanating from the deep, fractured aquifer to the overlying, potable aquifer(s) during the operational gas production phase

This scenario summarises the simulated point source pollution plume migration of stray methane (CH_4) gas emanating from the deep, fractured aquifer should the integrity of the gas production boreholes be jeopardised i.e., leaking boreholes. The CH_4 pollution plume extend covers a total area of approximately 162.74ha in the Karoo formations, reaching a maximum distance of ~50.0m in a radial pattern from the gas production borehole(s), and approximately 62.83ha in the alluvial deposits, reaching a maximum distance of ~100.0m in a radial pattern from the gas production borehole after a simulation period of 20-years (refer to Figure 12-25). The simulation indicates that the following neighbouring boreholes will potentially be intercepted by the simulated pollution plume HBH08, HBH41, HBH42, HBH43, HBH63, HBH72, HBH73 and Tetra4 monitoring borehole 11A. It is noted that the pollution plume does not extend beyond the project boundary.

Figure 12-24 summarises a time-series graph of the CH_4 mass load contribution to down-gradient receptors. It is evident that source term mass load contribution to existing neighbouring borehole situated near the gas production boreholes remains below the EPA safety threshold (2011) of 10.0mg/l and ranges between 0.01mg/l to 1.50mg/l.

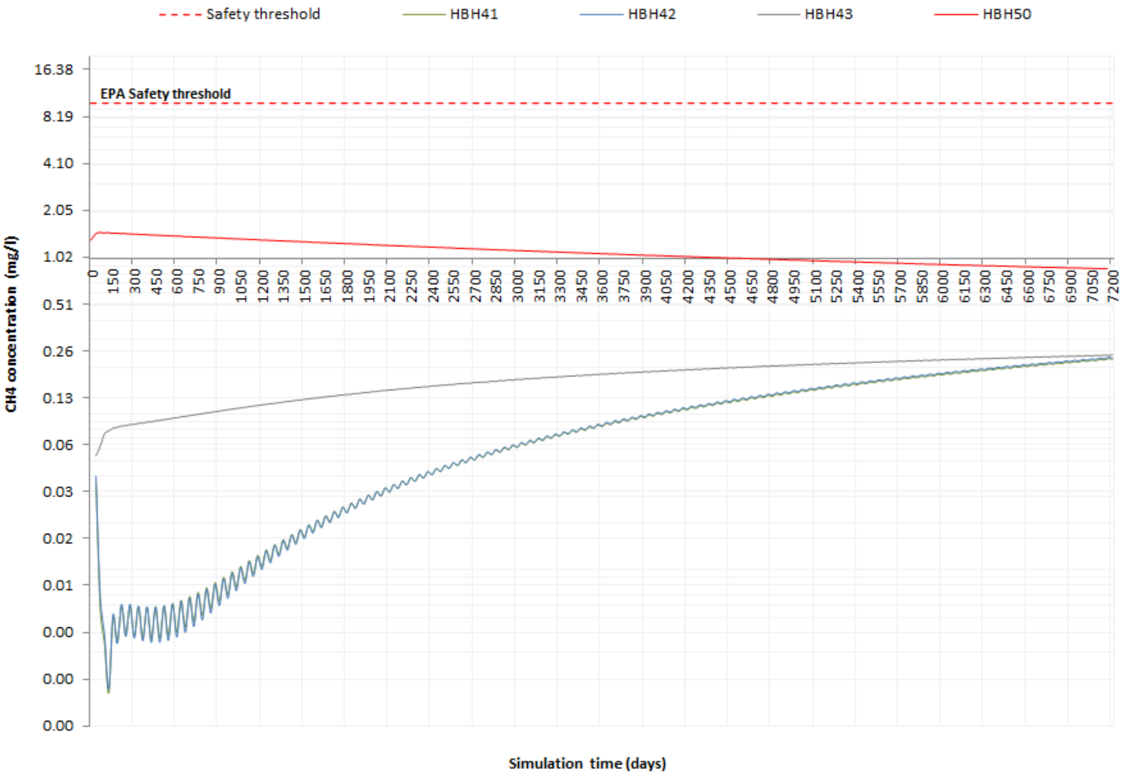

Figure 12-24 **Scenario 02b: Time-series graph indicating the CH_4 mass load contribution of deeper, fractured aquifer on observation boreholes targetting the potable shallow, intergranular aquifer (Operational phase).**

Figure 12-25 **Scenario 02b: CH_4 pollution plume migration of contaminants originating from the deeper, fractured aquifer migrating through the intergranular aquifer (Operational phase).**

12.7.4. Scenario 03: Migration of the TDS pollution plume emanating from the plant footprint area during the operational gas production phase

This scenario summarises the simulated pollution plume migration from the plant footprint areas for the operational phase. The TDS pollution plume extend covers a total area of approximately 48.80ha reaching a maximum distance of ~110.0m in a general north-northwest direction towards the lower laying drainage system(s) after a simulation period of 20-years as depicted in Figure 12-29. The simulation indicates that no neighbouring boreholes or local drainages are expected to be impacted on during the operational phase.

Figure 12-26 summarises a time-series graph of the TDS mass load contribution to down-gradient receptors[13]. It is evident that the TDS mass load contribution to down-gradient receptors increase to a concentration of between 200.0 – 800.0 mg/l, however, remains below the SANS 241:2015 limit of 1200.0mg/l for the duration of the simulation period.

Figure 12-27 depicts a model cross section of the pollution plume migration within the simulated aquifer. It is evident that the mass transport of the pollution plume is mostly limited to the shallow, intergranular aquifer.

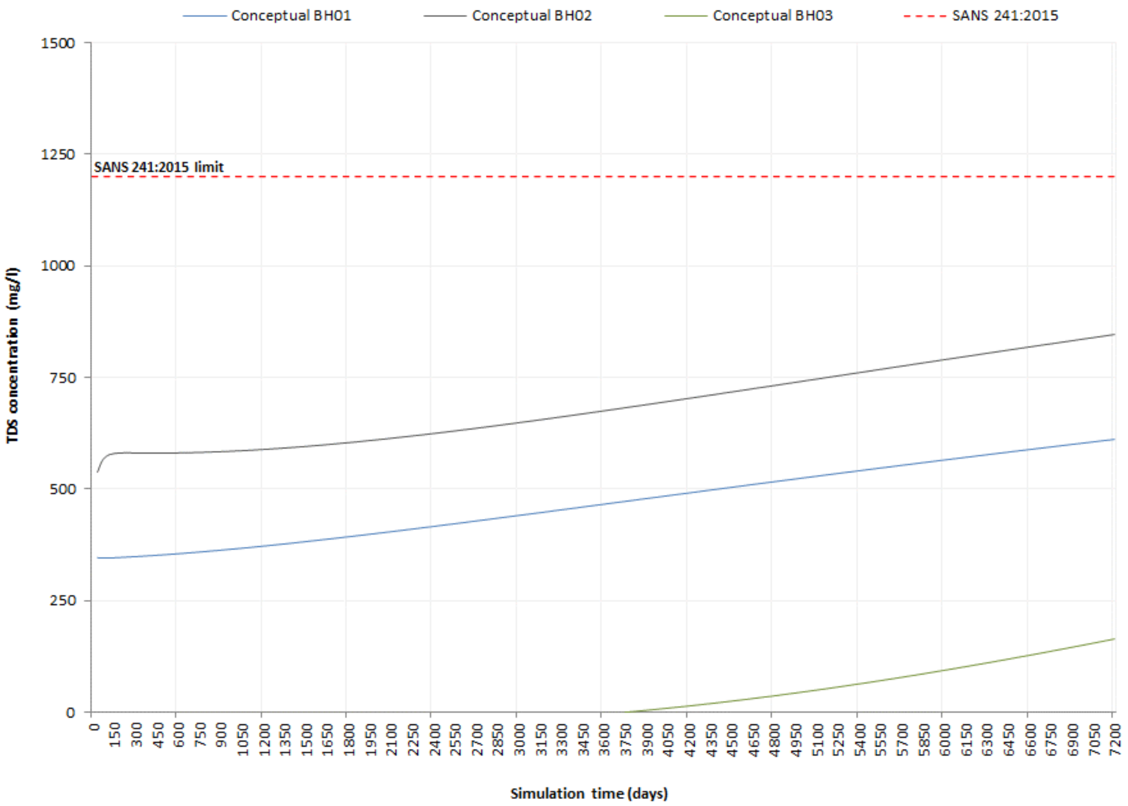

Figure 12-26 **Scenario 03: Time-series graph indicating the TDS mass load emenating from the plant footprint on down-gradient observation boreholes targetting the potable shallow, intergranular aquifer (Operational phase).**

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[13] Conceptual boreholes were used as receptors as no boreholes are situated in the direct down-gradient vicinity of the plant footprint.

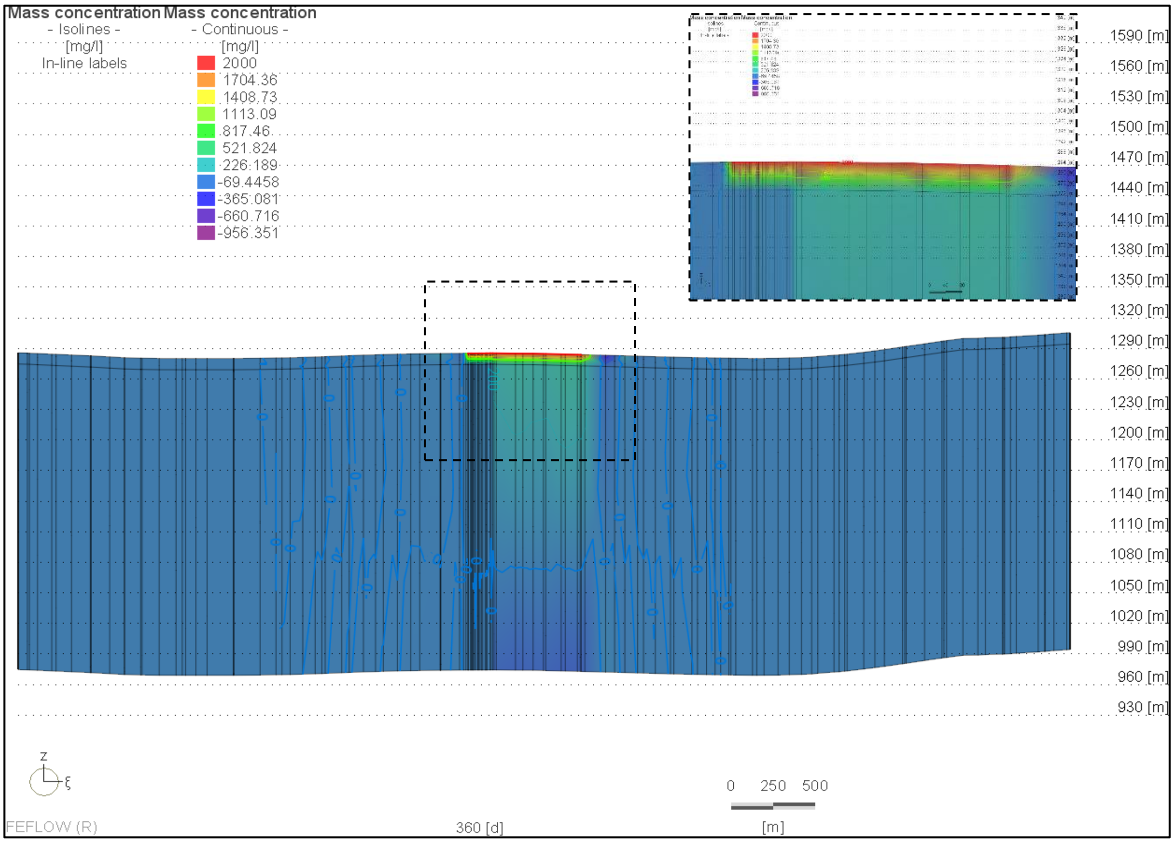


Figure 12-27 **Scenario 03: Model domain 3-D FEM mesh view (cross sectional view soutwest-northeast orientation A-A') of the TDS pollution plume originating at the plant footprint (Operational phase).**

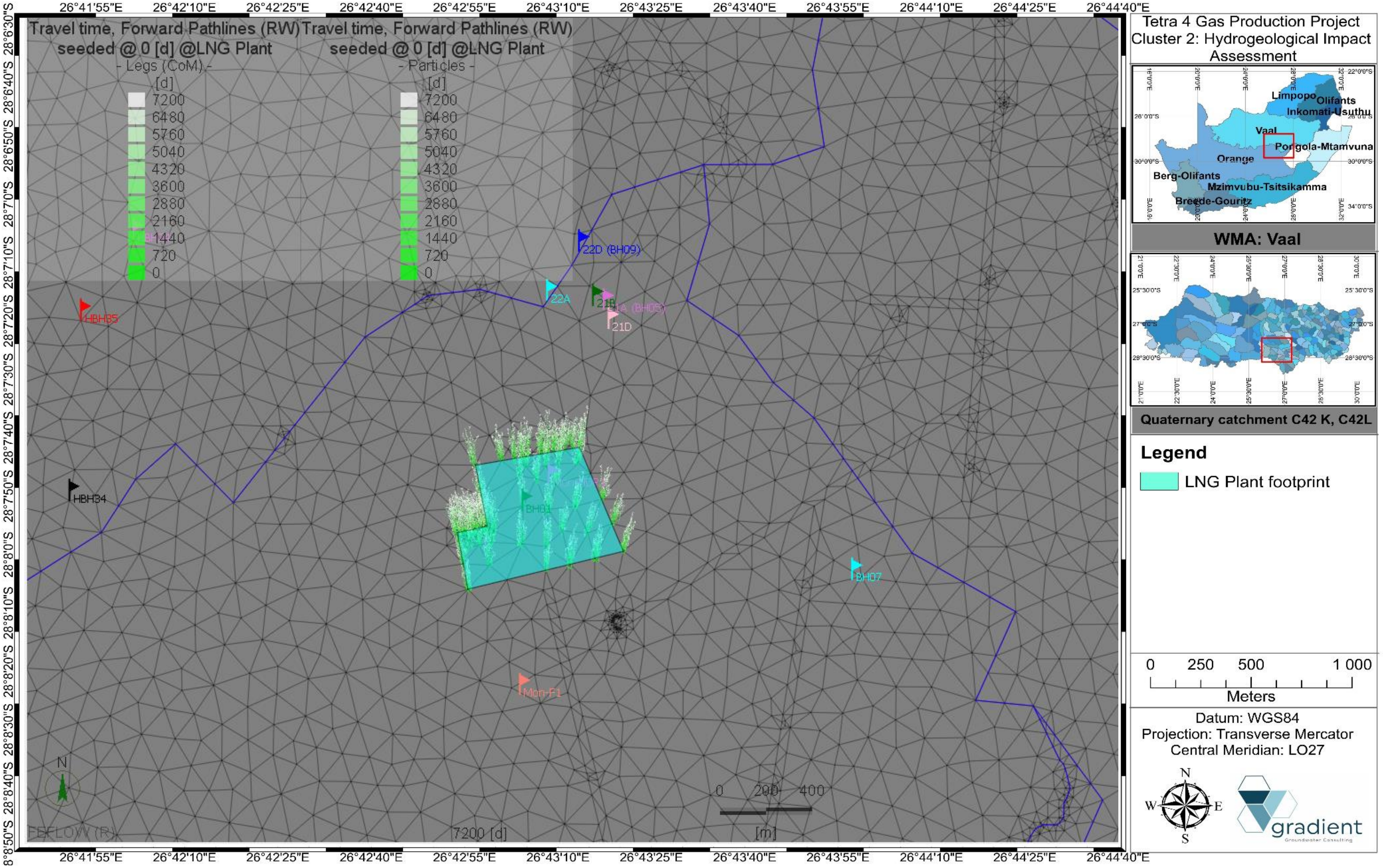


Figure 12-28 **Scenario 03: Simulated particle tracking of contaminants originating from the plant footprint within the intergranular aquifer (Operational phase).**

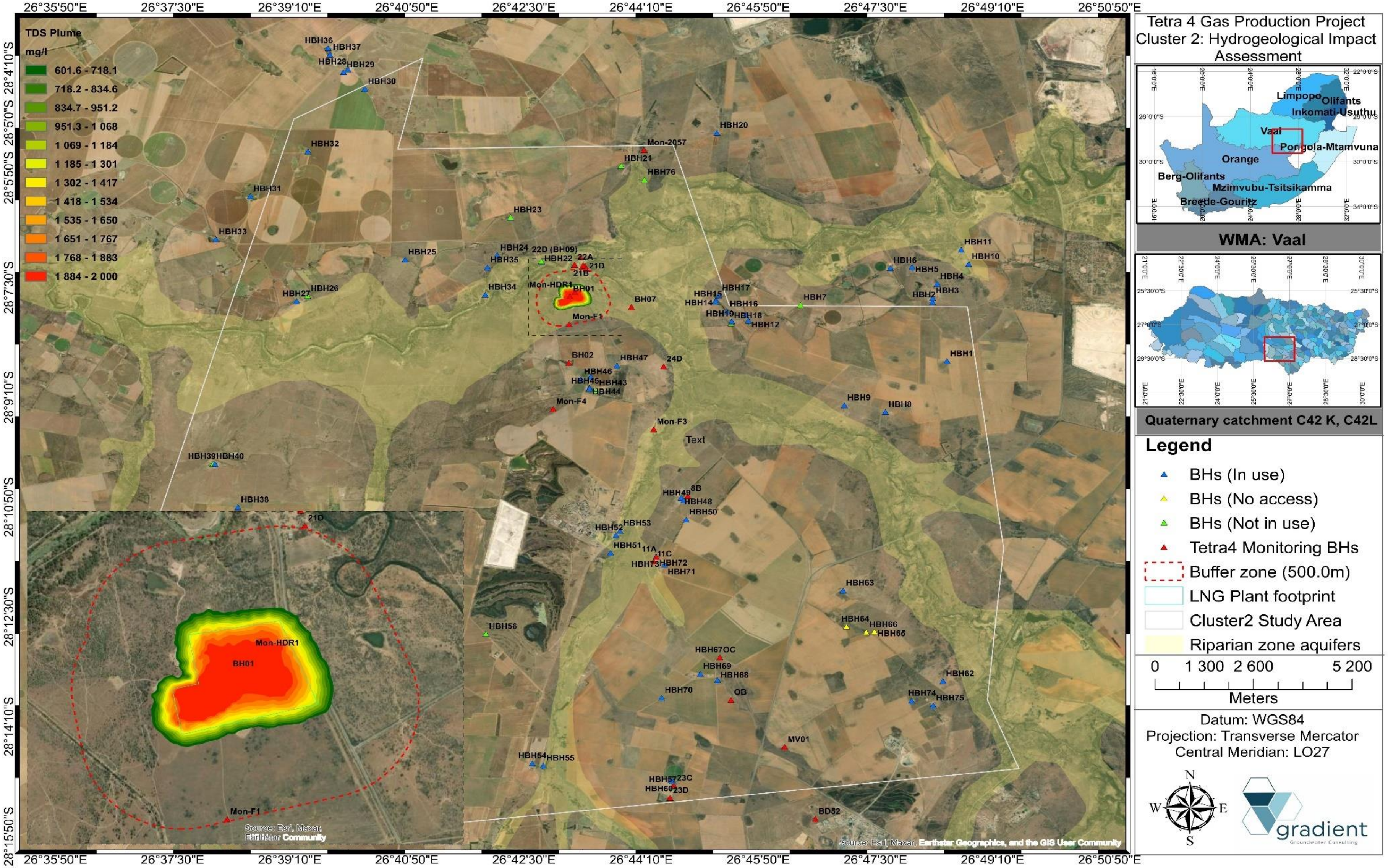


Figure 12-29 Scenario 03: TDS pollution plume migration of contaminants originating from the plant footprint within the intergranular aquifer (Operational phase).

12.7.5. Scenario 04a: Migration of saline groundwater from the deep, fractured aquifer to the overlying, potable aquifer(s) during the post-closure and decommissioning phase (50-year and 100-year scenarios)

This scenario summarises the simulated point source pollution plume migration of saline groundwater emanating from the deep, fractured aquifer should the integrity of the gas production boreholes be jeopardised i.e., leaking boreholes for the post-closure phase. The TDS pollution plume extend covers a total area of approximately 643.70ha in the Karoo formations, reaching a maximum distance of ~100.0m in a radial pattern from the gas production borehole(s), and approximately 392.70ha in the alluvial deposits, reaching a maximum distance of ~250.0m in a radial pattern from the gas production borehole(s) after a simulation period of 50-years.

The TDS pollution plume extend covers a total area of approximately 1 456.42ha in the Karoo formations, reaching a maximum distance of ~150.0m in a radial pattern from the gas production borehole(s), and approximately 769.70ha in the alluvial deposits, reaching a maximum distance of ~350.0m in a radial pattern from the gas production borehole(s) after a simulation period of 100-years (refer to Figure 12-32). The simulation indicates that the following neighbouring boreholes will potentially be intercepted by the simulated pollution plume HBH08, HBH41, HBH42, HBH43, HBH48, HBH50, HBH63, HBH72, HBH73, HBH74 as well as Tetra4 monitoring boreholes Mon 2057 and 11A. It is noted that the pollution plume does not extend beyond the project boundary.

Figure 12-31 indicates the expected flow pathways of particles derived from the source points and as noted earlier, it is evident that the pollution plume migration in the denser Karoo formations is sluggish while movement in the unconsolidated alluvial deposits of the riparian zone suggest a larger flux. Figure 12-21 summarises a time-series graph of the TDS mass load contribution to down-gradient receptors. It is evident that source term mass load contribution to existing neighbouring and monitoring boreholes situated near the gas production boreholes ranges between 650.0mg/l to >1200.0mg/l. It is noted that the SANS241:2015 limit is exceeded at borehole localities HBH63 and Mon 2057.

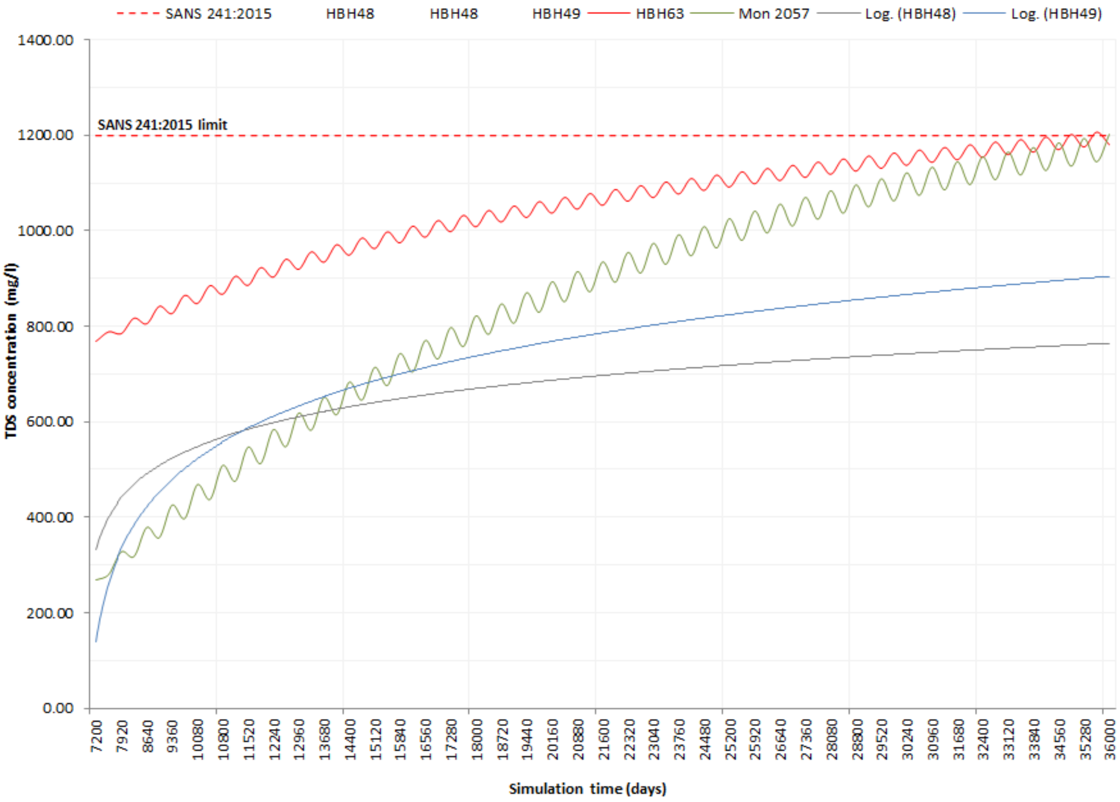


Figure 12-30 **Scenario 04a: Time-series graph indicating the TDS mass load contribution of deeper, fractured and saline aquifer on observation boreholes targetting the potable shallow, intergranular aquifer (Post-closure phase).**

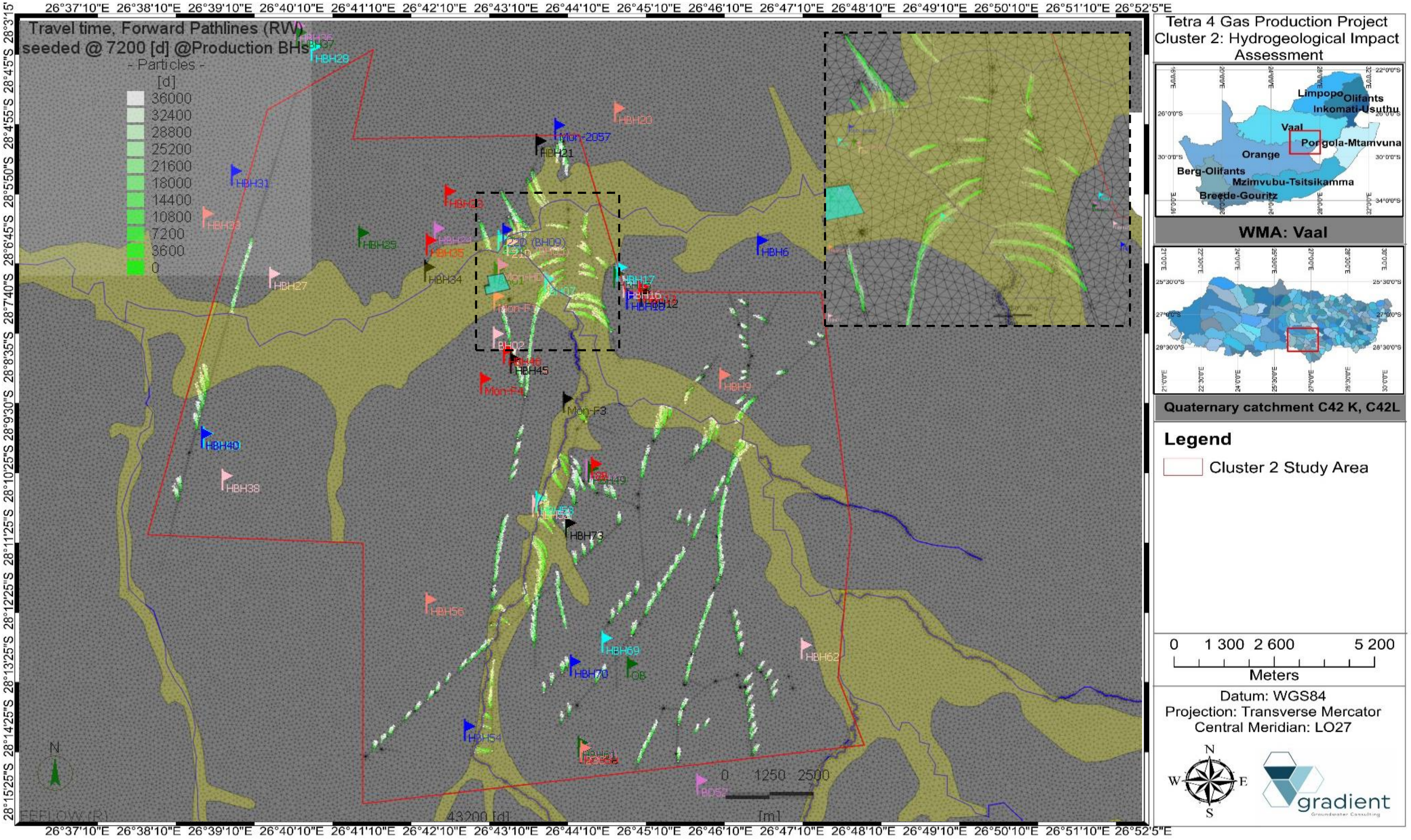


Figure 12-31 **Scenario 04: Simulated particle tracking of contaminants originating from the deeper, fractured aquifer migrating from leaking boreholes within the intergranular aquifer (Post-closure phase).**

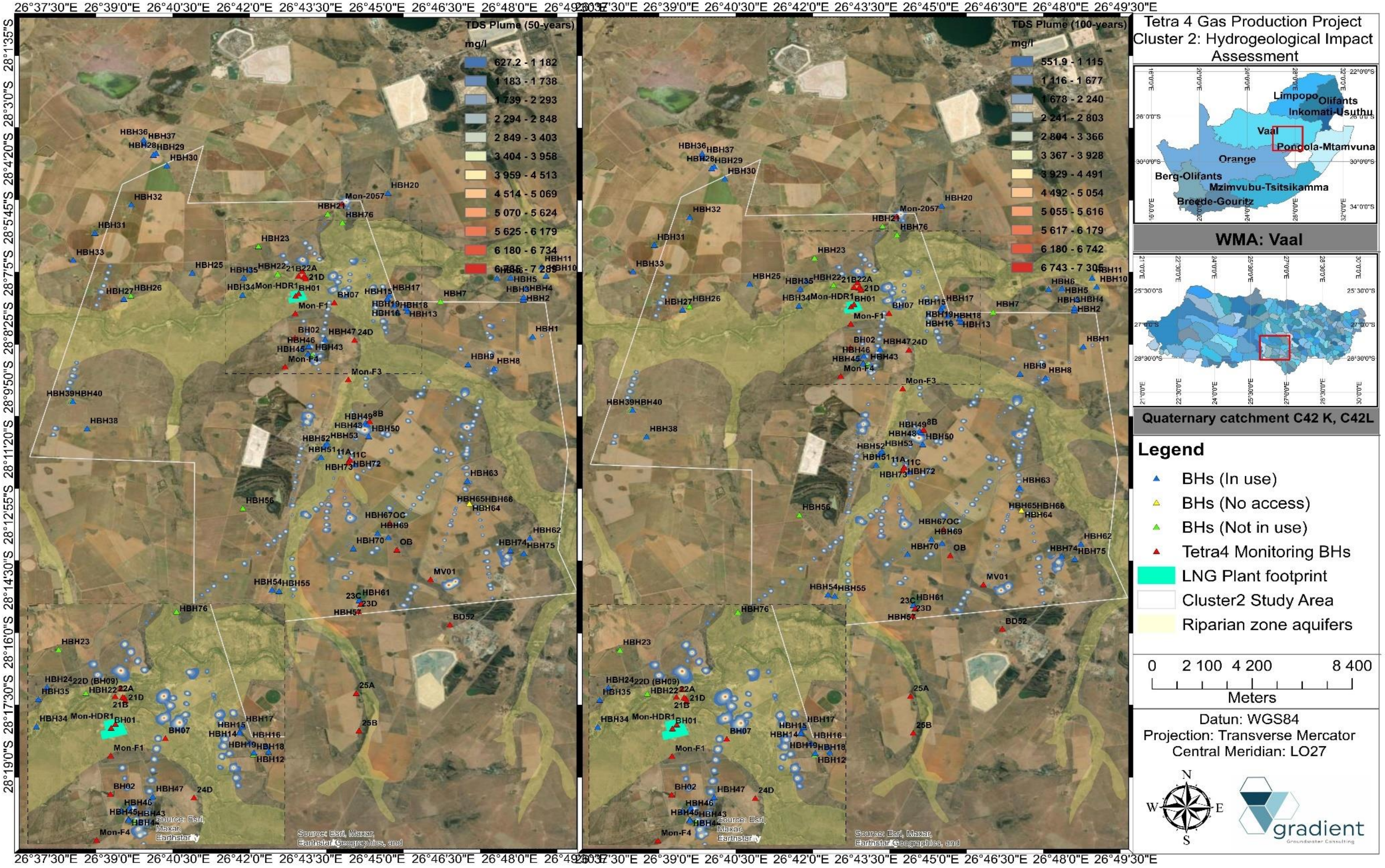


Figure 12-32 Scenario 04a: TDS pollution plume migration of contaminants originating from the deeper, fractured aquifer migrating through the intergranular aquifer (Post-closure phase).

12.7.6. Scenario 04b: Migration of stray methane (CH_4) gas emanating from the deep, fractured aquifer to the overlying, potable aquifer(s) during the post-closure and decommissioning phase (50-year and 100-year scenarios)

This scenario summarises the simulated point source pollution plume migration from of stray methane (CH_4) gas emanating from the deep, fractured aquifer should the integrity of the gas production boreholes be jeopardised i.e., leaking boreholes for the post-closure phase. The CH_4 pollution plume extend covers a total area of approximately 414.06ha in the Karoo formations, reaching a maximum distance of ~80.0m in a radial pattern from the gas production borehole(s), and approximately 141.37ha in the alluvial deposits, reaching a maximum distance of ~150.0m in a radial pattern from the gas production borehole(s) after a simulation period of 50-years.

The CH_4 pollution plume extend covers a total area of approximately 643.70ha in the Karoo formations, reaching a maximum distance of ~100.0m in a radial pattern from the gas production borehole(s), and approximately 392.70ha in the alluvial deposits, reaching a maximum distance of ~250.0m in a radial pattern from the gas production borehole(s) after a simulation period of 100-years (refer to Figure 12-34). The simulation indicates that the following neighbouring boreholes will potentially be intercepted by the simulated pollution plume HBH08, HBH41, HBH42, HBH43, HBH48, HBH49, HBH63, HBH72, HBH73 as well as Tetra4 monitoring boreholes Mon 2057 and 11A. It is noted that the pollution plume does not extend beyond the project boundary.

Figure 12-33 summarises a time-series graph of the CH_4 mass load contribution to down-gradient receptors. It is evident that source term mass load contribution to existing neighbouring and monitoring boreholes situated near the gas production boreholes ranges between 0.50mg/l to ~2.0mg/l, however, remains below the EPA safety threshold (2011) of 10.0mg/l.

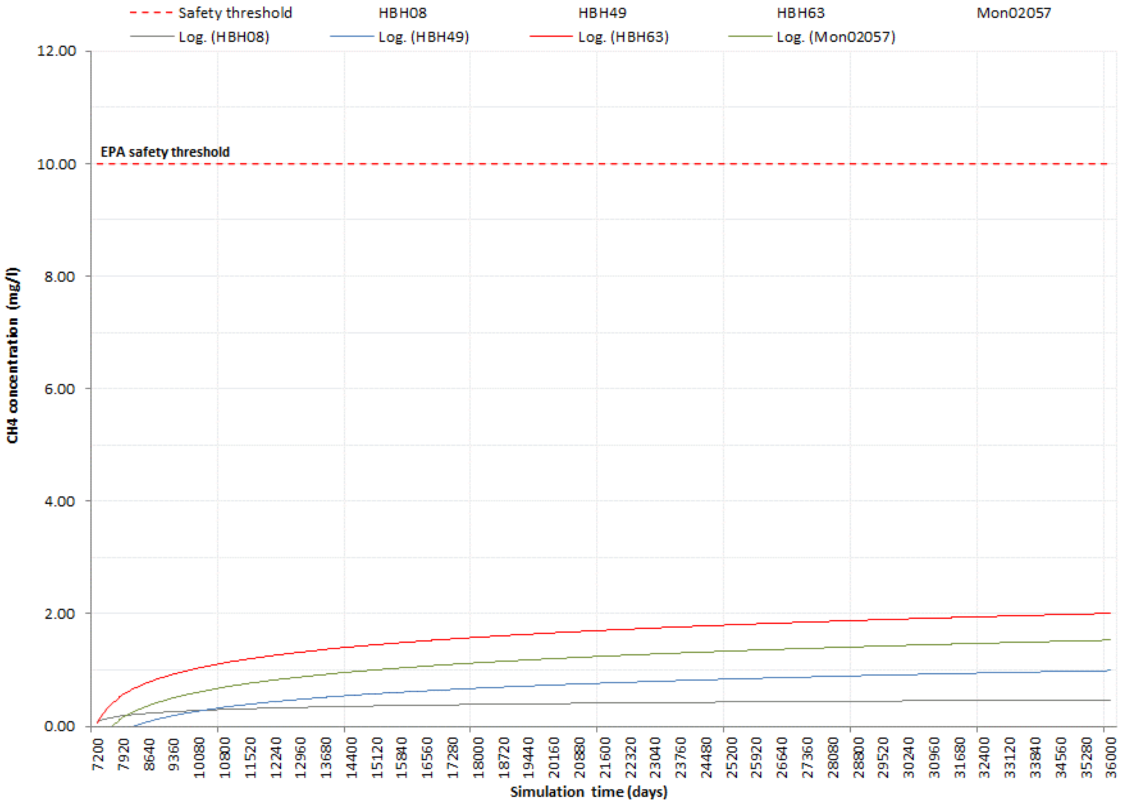


Figure 12-33 **Scenario 04b: Time-series graph indicating the CH_4 mass load contribution of waste facilities on down-gradient receptors.**

Figure 12-34 Scenario 04b: CH_4 pollution plume migration of contaminants originating from the deeper, fractured aquifer migrating through the intergranular aquifer (Post-closure phase).

12.7.7. Scenario 05: Migration of the TDS pollution plume emanating from the plant footprint area during the post-closure and decommissioning phase (50-year and 100-year scenarios)

This scenario summarises the simulated pollution plume migration from the plant footprint areas for the post-closure phase. The TDS pollution plume extend covers a total area of approximately 54.8ha reaching a maximum distance of ~170.0m in a general north-northwest direction towards the lower laying drainage system(s) after a simulation period of 50-years and covers a total area of approximately 71.20ha reaching a maximum distance of ~300.0m in a general north-northwest direction towards the lower laying drainage system(s) after a simulation period of 100-years as depicted in Figure 12-39.

Figure 12-37 and Figure 12-38 indicates the expected flow pathways of particles for the 50- and 100-years simulation periods respectively, and it is evident that the pollution plume potentially reaches the local drainages system down-gradient of the plant footprint during the post-closure phase.

Figure 12-35 summarises a time-series graph of the TDS mass load contribution to down-gradient receptors. It is evident that the TDS mass load contribution to down-gradient receptors increase to a concentration above the SANS 241:2015 limit of 1200.0mg/l for the post-closure simulation period.

Figure 12-36 summarises a time-series graph of the TDS mass load percentage contribution to down-gradient river receptors of the Sandrivier and Doringrivier. It is evident that the TDS mass load contribution increases to a percentage of ~10.0% to the Sandrivier where the mass load contribution to the Doringrivier increase to a percentage of ~2.0% for the duration of the post-closure simulation period.

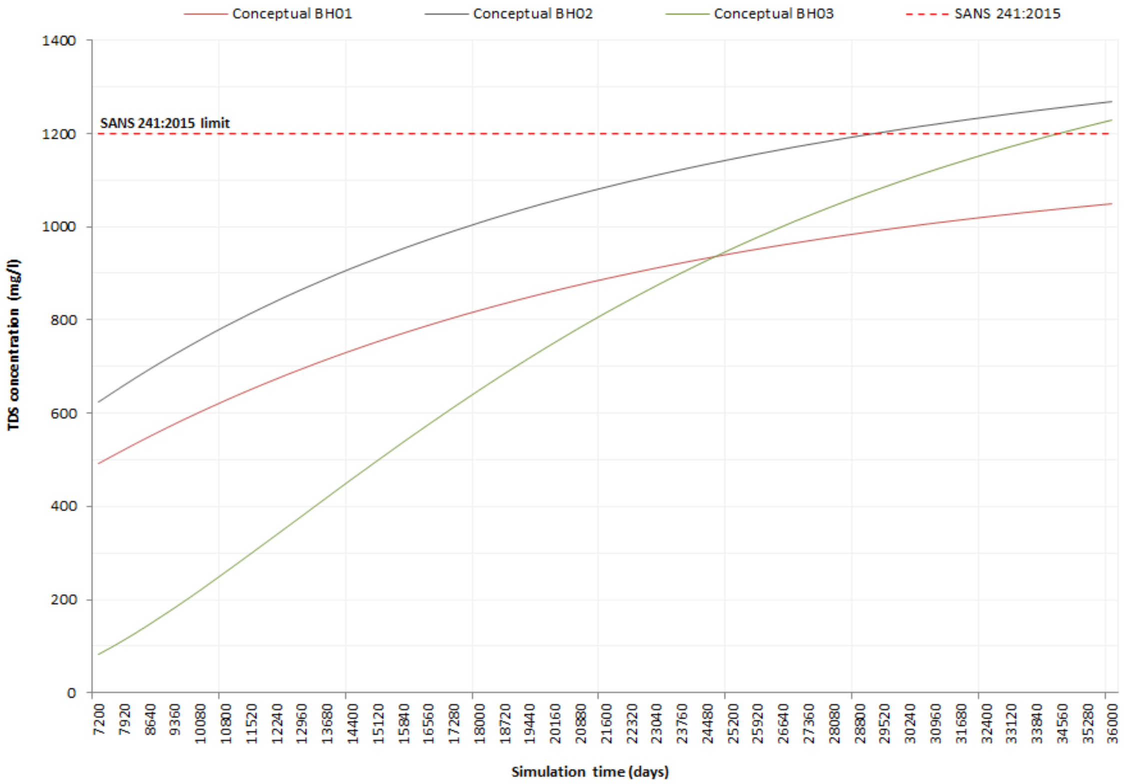


Figure 12-35 Scenario 05: Time-series graph indicating the TDS mass load emenating from the plant footprint on down-gradient observation boreholes targetting the potable shallow, intergranular aquifer (Post-closure phase).

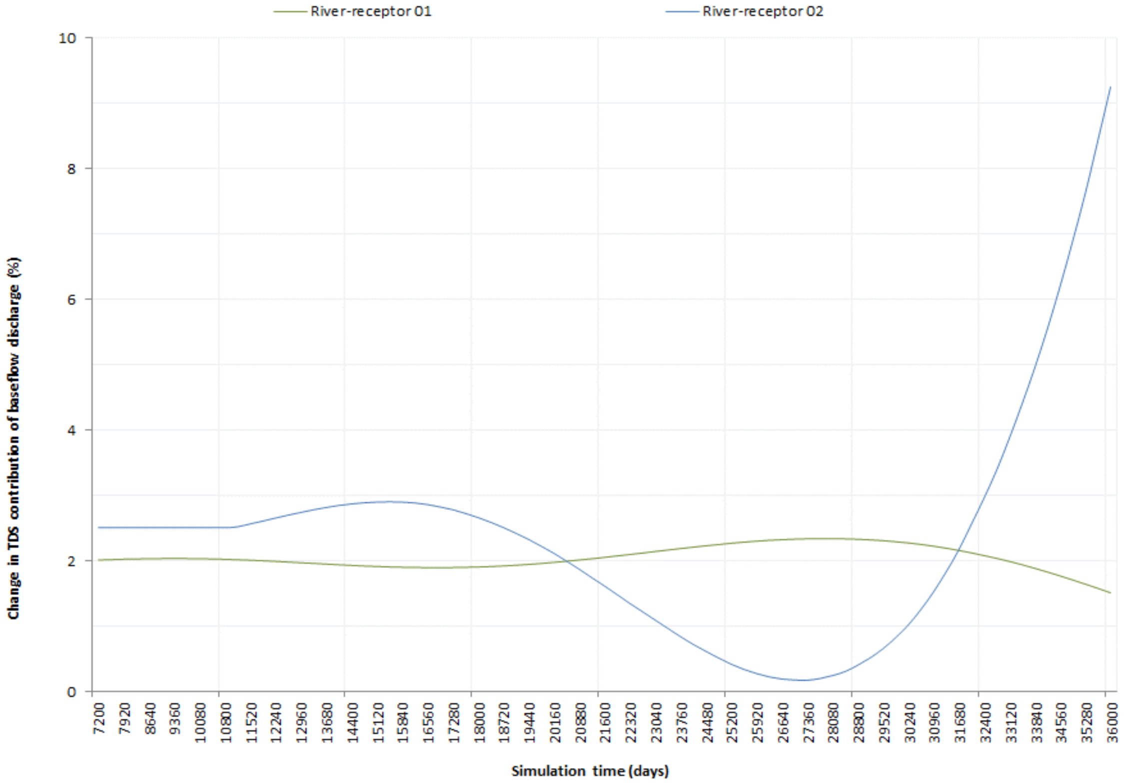


Figure 12-36 Scenario 05: Time-series graph indicating the TDS mass load emenating from the plant footprint on down-gradient river receptors expressed as the percentage change in salt load (Post-closure phase).

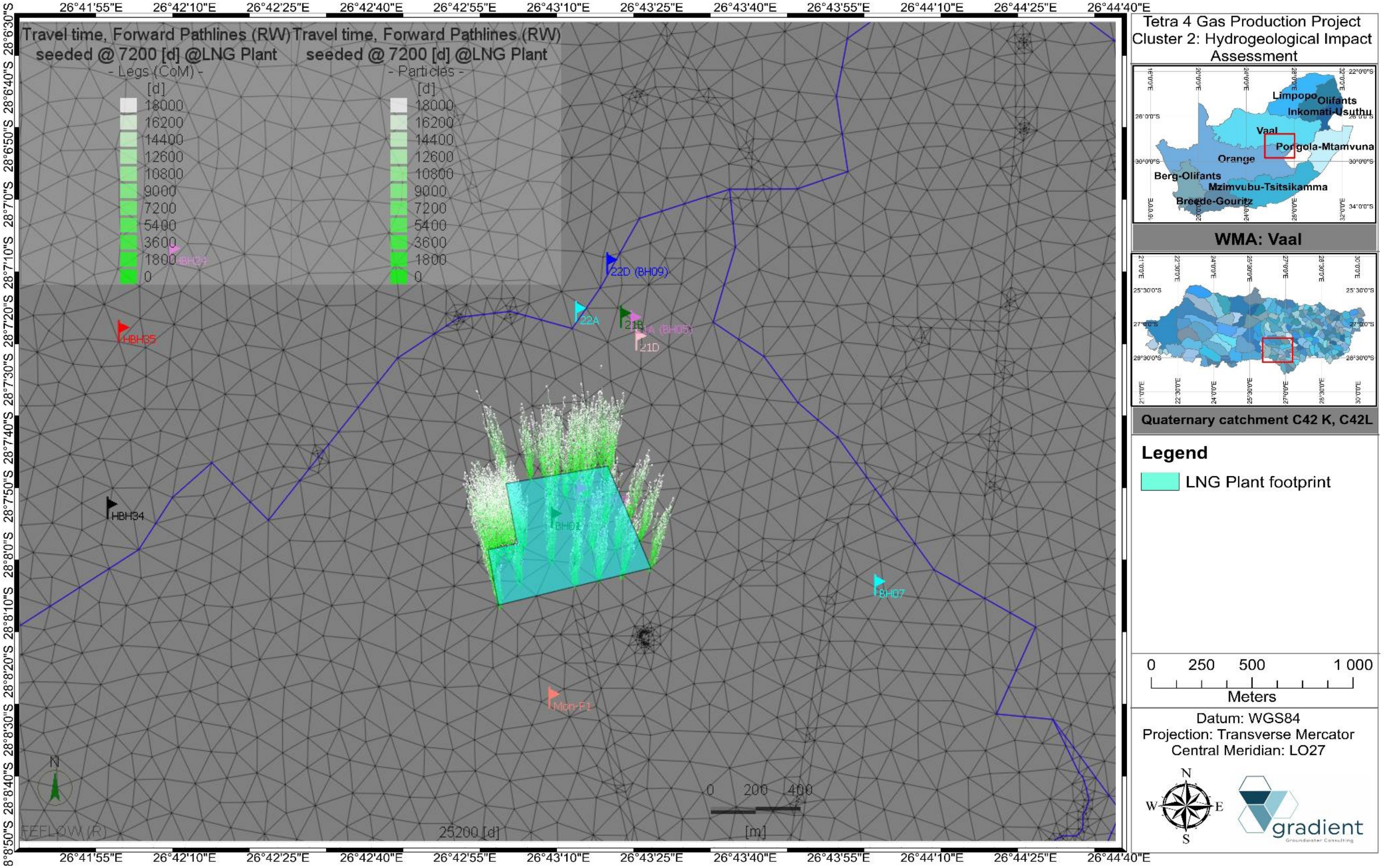


Figure 12-37 **Scenario 05: Simulated particle tracking of contaminants originating from the plant footprint within the intergranular aquifer (50-years post-closure).**

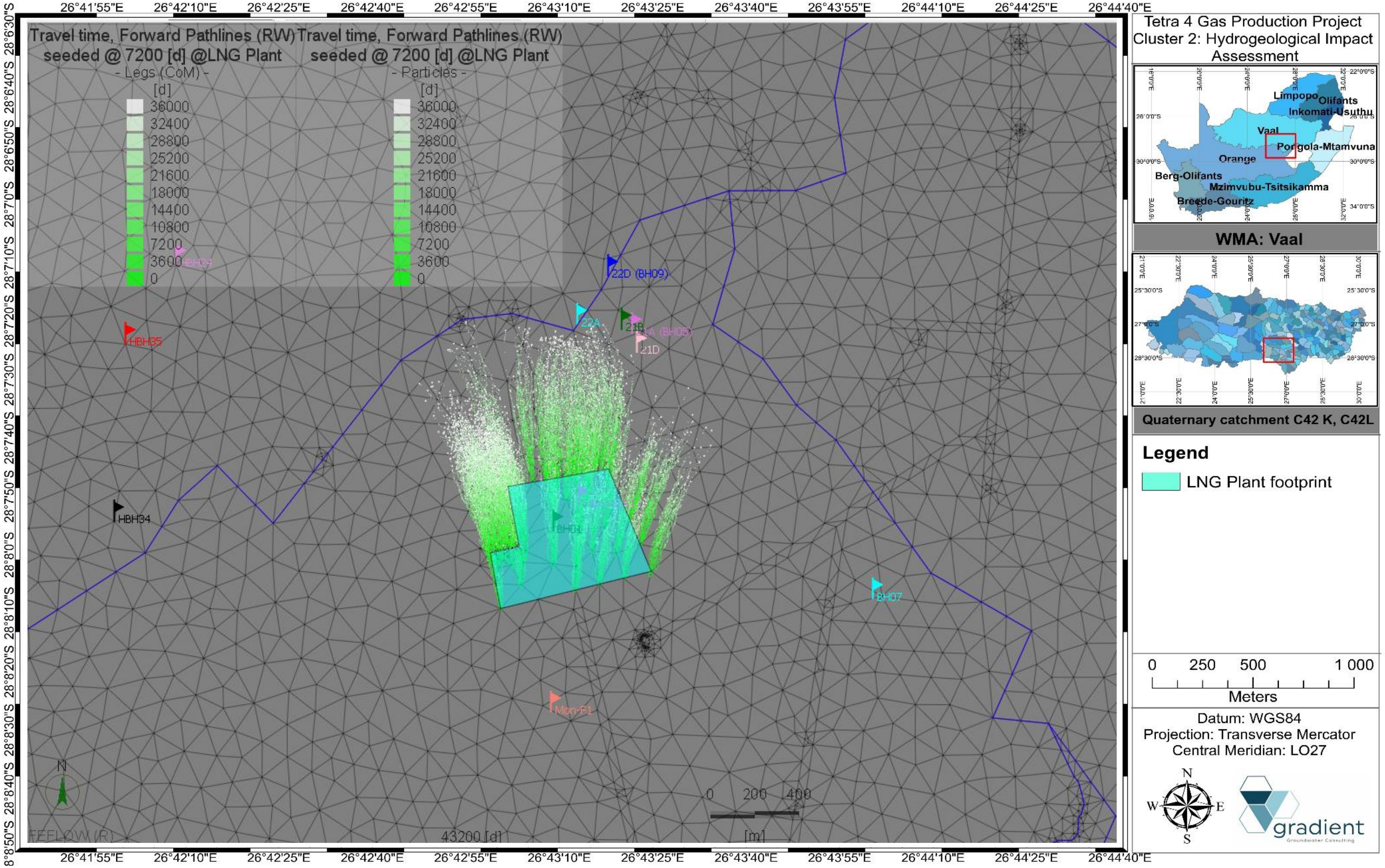


Figure 12-38 **Scenario 05: Simulated particle tracking of contaminants originating from the plant footprint within the intergranular aquifer (100-years post-closure).**

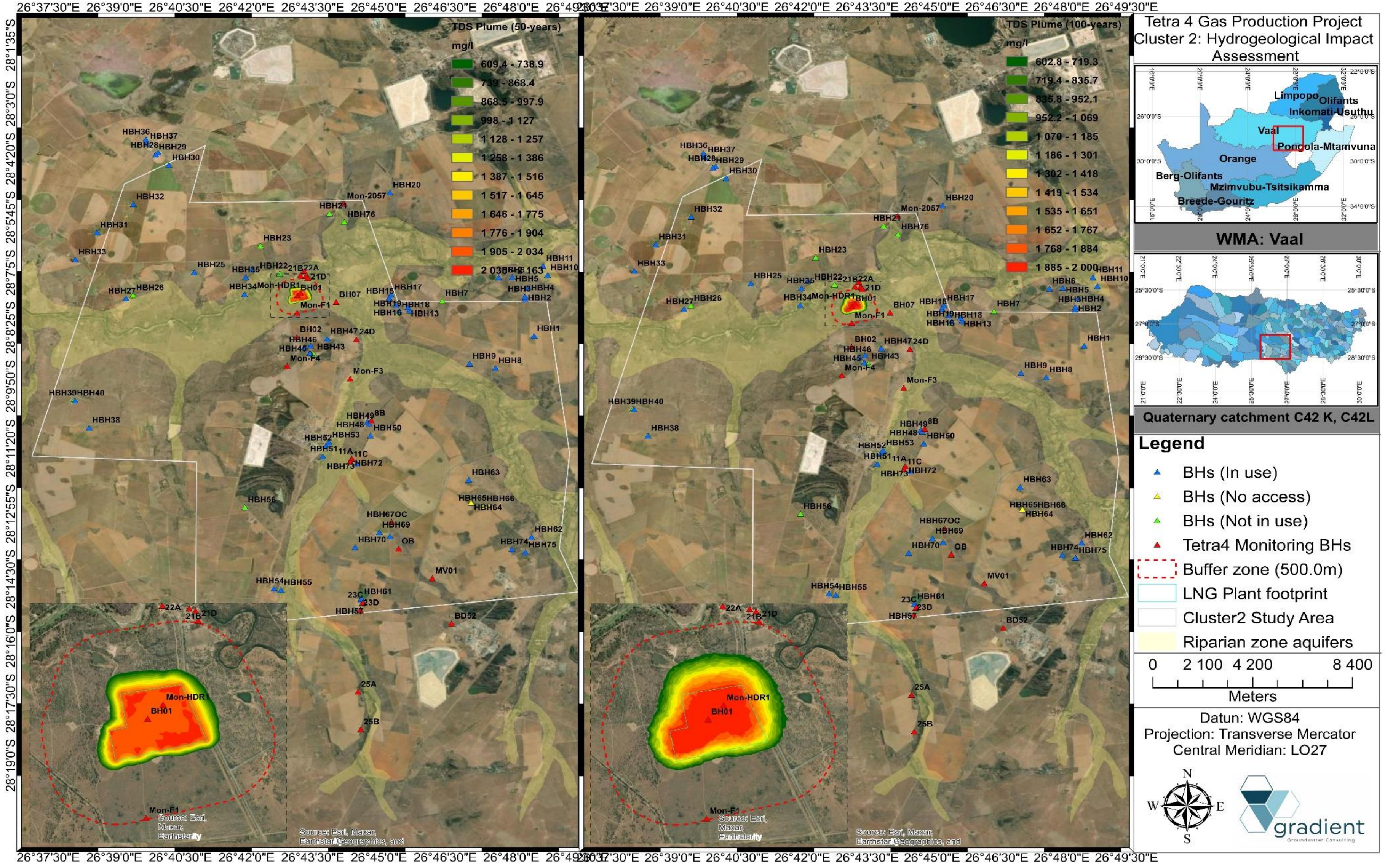


Figure 12-39 **Scenario 05: TDS pollution plume migration of contaminants originating from the plant footprint within the intergranular aquifer (Post-closure phase).**

13. ENVIRONMENTAL IMPACT ASSESSMENT

Identification of potential impacts and ratings related to the proposed activities are briefly discussed below.

13.1. Methodology

An impact can be defined as any change in the physical-chemical, biological, cultural and/or socio-economic environmental system that can be attributed to human and/or other related activities. The impact significance rating methodology 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 **N**ature, **E**xtent, **D**uration, **M**agnitude, and **R**eversibility) and relate this to the probability/ likelihood (**P**) of the impact occurring. This determines the environmental risk. 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. Where possible, mitigation measures will be recommended for impacts identified.

13.2. Determination of 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 the following equation:

Equation 13-1 Impact Consequence.

$$\mathbf{C} = (\boldsymbol{E} + \boldsymbol{D} + \boldsymbol{M} + +\boldsymbol{R})(\boldsymbol{N4})$$

Each individual aspect in the determination of the consequence is represented by a rating scale as defined in Table 13-1 below with Table 13-2 summarising the probability scorings.

Table 13-1 **Criteria for Determining Impact Consequence.**

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

Table 13-2 **Probability scoring.**

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

The result is a qualitative representation of relative **ER** associated with the impact. **ER** is therefore calculated by applying the following equation:

Equation 13-2 Impact Consequence.

$$\mathrm{ER} = \boldsymbol{C} \,.\, \boldsymbol{P}$$

The outcome of the environmental risk assessment will result in a range of scores, ranging from 1 through to 25 as summarised in Table 13-4. These **ER** scores are then grouped into respective classes as described in Table 13-4.

Table 13-3 Determination of Environmental Risk.

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

Table 13-4 Significance classes.

Environmental Risk Score	Low (i.e., where this impact is unlikely to be a significant environmental risk)	< 9
	Medium (i.e., where the impact could have a significant environmental risk)	≥ 9 - <17
	High (i.e., where the impact will have a significant environmental risk)	≥ 17

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.

13.3. Impact prioritization

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

i. Cumulative impacts; and

ii. 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. 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 13-5.

Table 13-5 **Criteria for Determining Prioritisation.**

Cumulative Impact (C)	Considering the potential incremental, interactive, sequential, and synergistic cumulative impacts, it is unlikely that the impact will result in spatial and temporal cumulative change	Low (1)
	Considering the potential incremental, interactive, sequential, and synergistic cumulative impacts, it is probable 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 highly probable/ definite that the impact will result in spatial and temporal cumulative change	High (3)
Irreplaceable loss of Resource (LR)	Where the impact is unlikely to result in irreplaceable loss of resources	Low (1)
	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	Medium (2)
	Where the impact may result in the irreplaceable loss of resources of high value (services and/or functions)	High (3)

The impact priority is therefore determined as follows:

Equation 13-3 **Impact Consequence.**

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

The result is a priority score which ranges from 3 to 9 and a consequent **PF** ranging from 1 to 2 (Refer to Table 13-6 below).

Table 13-6 **Determination of Prioritisation Factor.**

Priority	Ranking	Prioritisation factor
2	Low	1
3	Medium	1.125
4	Medium	1.25
5	Medium	1.375
6	High	1.5

In order to determine the final impact significance (Table 13-7), 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 full ranking class, if all the priority attributes are high (i.e., if an impact comes out with a 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 13-7 **Final Environmental Significance Rating.**

Value	Description
≤ -20	High negative (i.e., where the impact must have an influence on the decision process to develop in the area).
> -20 ≤ -10	Medium negative (i.e., where the impact could influence the decision to develop in the area).
> -10	Low negative (i.e., where this impact would not have a direct influence on the decision to develop in the area).
0	No impact
< 10	Low positive (i.e., where this impact would not have a direct influence on the decision to develop in the area).
≥ 10 < 20	Medium positive (i.e., where the impact could influence the decision to develop in the area).
≥ 20	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 will be used to provide a quantitative comparative assessment of the alternatives being considered. In addition, professional expertise and opinion of the specialists and the environmental consultants will be applied to provide a qualitative comparison of the alternatives under consideration. This process will identify the best alternative for the proposed project.

13.4. Impact Identification and significance ratings

It should be noted that vast areas within the study area have been subjected to historical mining activities and, as such, reflect modified to highly modified present ecological status. A total number of >15 000 historical exploration wells have been drilled throughout the study area, some of which remain uncased and unsealed. The latter may act as preferential pathways and conduits for groundwater flow and contaminant transport mechanisms. As mentioned earlier an impact can be defined as any change in the physical-chemical, biological, cultural and/or socio-economic environmental system that can be attributed to human and/or other related activities. Accordingly, this already highly modified zones should form part of the impact significance rating and risk approach. Impacts and significant ratings associated different project phases are briefly discussed below.

13.4.1. Construction phase: Associated activities and impacts

Refer to Table 13-8 for a summary of the impact risk matrix and significance ratings for the construction phase. During the construction phase the environmental significance rating of groundwater quality impacts on down-gradient receptors are rated as **medium negative** without implementation of remedial measures and **low negative** with implementation of proposed mitigation measures. The main impacts associated with the construction phase activities include the following:

1. Groundwater deterioration and siltation due to contaminated stormwater run-off from the construction area (Table 13-9).
2. Poor quality leachate may emanate from the construction camp which may have a negative impact on groundwater quality (Table 13-10).
3. Mobilisation and maintenance of heavy vehicle and machinery on-site may cause hydrocarbon contamination of groundwater resources (Table 13-11).
4. Poor storage and management of hazardous chemical substances on-site may cause groundwater pollution (Table 13-12).

Table 13-8 Impact assessment and significant rating: Construction phase summary.

Impact	IMPACT DESCRIPTION	PRE - MITIGATION							POST - MITIGATION							IMPACT PRIORITISATION	
No.	Impact	Nature	Extent	Duration	Magnitude	Reversibility	Probability	Pre-mitigation ER	Nature	Extent	Duration	Magnitude	Reversibility	Probability	Post-mitigation ER	Priority Factor	Final score
Construction phase																	
1	Groundwater deterioration and siltation due to contaminated stormwater run-off from the construction area.	-1	2	2	2	2	2	-4.00	-1	2	2	1	2	1	-1.75	1.00	-1.75
2	Poor quality leachate may emanate from the construction camp which may have a negative impact on groundwater quality.	-1	3	2	3	3	3	-8.25	-1	2	2	2	3	2	-4.50	1.25	-5.63
3	Mobilisation and maintenance of heavy vehicle and machinery on-site may cause hydrocarbon contamination of groundwater resources.	-1	3	5	4	4	3	-12.00	-1	2	5	4	4	2	-7.50	1.25	-9.38
4	Poor storage and management of hazardous chemical substances on-site may cause groundwater pollution.	-1	3	2	3	3	3	-8.25	-1	2	2	2	3	2	-4.50	1.25	-5.63

Table 13-9 Risk assessment matrix and significant scoring: Construction phase impact 01.

Impact Name	**Groundwater deterioration and siltation due to contaminated stormwater run-off from the construction area.**				
Alternative	**Alternative 1**				
Phase	**Construction**				
Environmental Risk					
Attribute	**Pre-mitigation**	**Post-mitigation**	**Attribute**	**Pre-mitigation**	**Post-mitigation**
Nature of Impact	-1	-1	Magnitude of Impact	2	1
Extent of Impact	2	2	Reversibility of Impact	2	2
Duration of Impact	2	2	Probability	2	1
Environmental Risk (Pre-mitigation)					-4.00
Mitigation Measures					
Mitigation Measures	i. Develop a stormwater management plan in accordance with GN704 in order to separate dirty/contact water from clean water circuits. All water retention structures, process water dams; storm water dams, retention ponds etc. should be constructed to have adequate freeboard to be able to contain water from 1:50 year rain events. ii. All construction should take place during the dry season, as far as possible. iii. Location of construction camps must be carefully considered and within the approved area to ensure that the site does not impact on sensitive areas identified during the Environmental Assessment phase or field work. iv. Sites must be located, where possible, on previously disturbed areas. v. Every effort must be made to keep the footprint as small as possible.				
Cumulative Impacts					1
Considering the potential incremental, interactive, sequential, and synergistic cumulative impacts, it is unlikley that the impact will result in spatial and temporal cummulative change.					
Degree of potential irreplaceable loss of resources					1
The impact is unlikely to result in irreplaceable loss of resources.					
Prioritisation Factor					1.00
Final Significance					-1.75

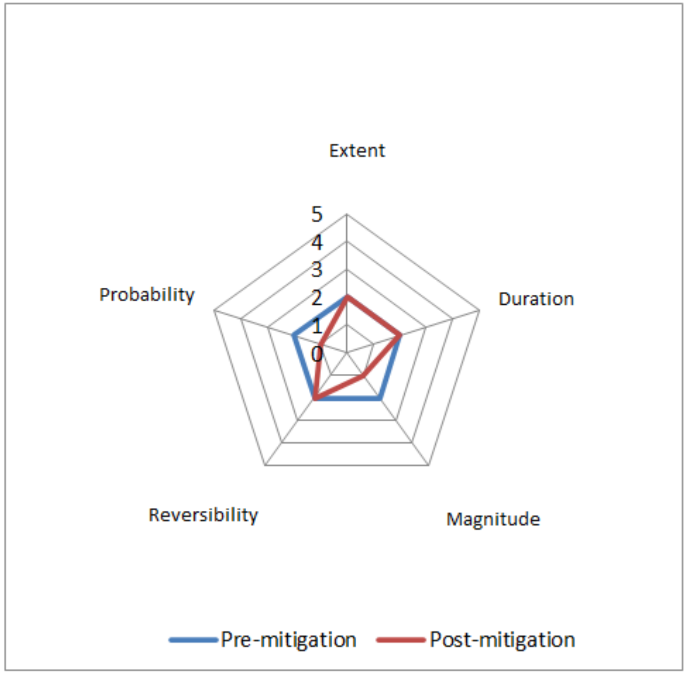


Table 13-10 Risk assessment matrix and significant scoring: Construction phase impact 02.

Impact Name	**Poor quality leachate may emanate from the construction camp which may have a negative impact on groundwater quality.**				
Alternative	**Alternative 1**				
Phase	**Construction**				
Environmental Risk					
Attribute	**Pre-mitigation**	**Post-mitigation**	**Attribute**	**Pre-mitigation**	**Post-mitigation**
Nature of Impact	-1	-1	Magnitude of Impact	3	2
Extent of Impact	3	2	Reversibility of Impact	3	3
Duration of Impact	2	2	Probability	3	2
Environmental Risk (Pre-mitigation)					-8.25
Mitigation Measures					
Mitigation Measures	i. Develop a stormwater management plan in accordance with GN704 in order to separate dirty/contact water from clean water circuits. All water retention structures, process water dams; storm water dams, retention ponds etc. should be constructed to have adequate freeboard to be able to contain water from 1:50 year rain events. ii. All construction should take place during the dry season, as far as possible. iii. Location of construction camps must be carefully considered and within the approved area to ensure that the site does not impact on sensitive areas identified during the Environmental Assessment phase or field work. iv. Sites must be located, where possible, on previously disturbed areas. v. Any excess sand, stone and cement must be removed or reused from site on completion of the construction period and disposed at a registered disposal facility. Certificates of safe disposal for general and recycled waste must be maintained and retained on file.				
Cumulative Impacts					2
Considering the potential incremental, interactive, sequential, and synergistic cumulative impacts, it is probable that the impact will result in spatial and temporal cummulative change.					
Degree of potential irreplaceable loss of resources					2
The impact may result in the irreplaceable loss (cannot be replaced or subsitituted) of resources but the value (services and/or functions) of these resources is limited.					
Prioritisation Factor					1.25
Final Significance					-5.63

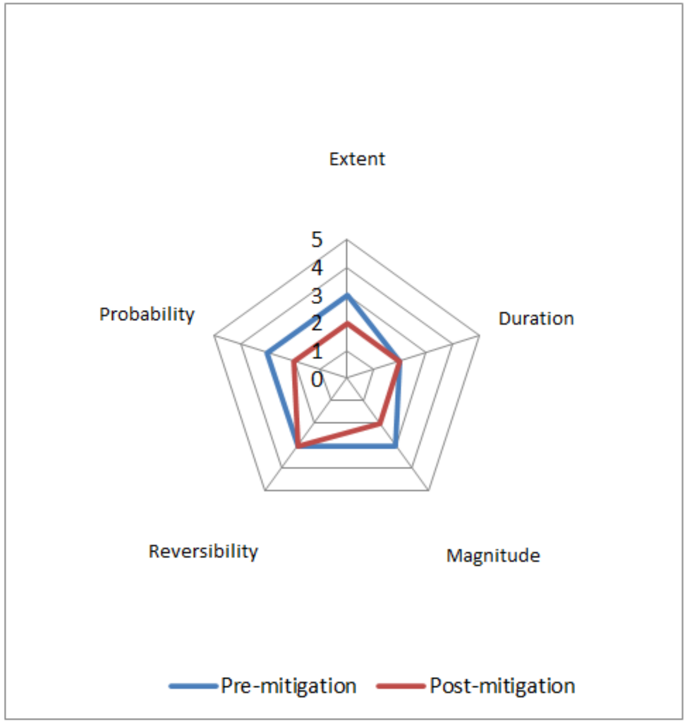


Table 13-11 Risk assessment matrix and significant scoring: Construction phase impact 03.

Impact Name	**Mobilisation and maintenance of heavy vehicle and machinery on-site may cause hydrocarbon contamination of groundwater resources.**				
Alternative	**Alternative 1**				
Phase	**Construction**				
Environmental Risk					
Attribute	**Pre-mitigation**	**Post-mitigation**	**Attribute**	**Pre-mitigation**	**Post-mitigation**
Nature of Impact	-1	-1	Magnitude of Impact	4	4
Extent of Impact	3	2	Reversibility of Impact	4	4
Duration of Impact	5	5	Probability	3	2
Environmental Risk (Pre-mitigation)					-12.00
Mitigation Measures					
Mitigation Measures	i. Construction vehicles and machinery must be serviced and maintained regularly in order to ensure that oil spillages are limited. Spill trays must be provided if refuelling of operational vehicles is done on site. Further to this spill kits must be readily available in case of accidental spillages with regular spot checks to be conducted. ii. During servicing of vehicles or equipment, especially where emergency repairs are effected outside the workshop area, a suitable drip tray must be used to prevent spills onto the soil. iii. Leaking equipment must be repaired immediately or be removed from site to facilitate repair. iv. Workshop areas must be monitored for oil and fuel spills. v. An appropriate number of spill kits must be available and must be located in all areas where activities are being undertaken.				
Cumulative Impacts					2
Considering the potential incremental, interactive, sequential, and synergistic cumulative impacts, it is probable that the impact will result in spatial and temporal cummulative change.					
Degree of potential irreplaceable loss of resources					2
The impact may result in the irreplaceable loss (cannot be replaced or subsitituted) of resources but the value (services and/or functions) of these resources is limited.					
Prioritisation Factor					1.25
Final Significance					-9.38

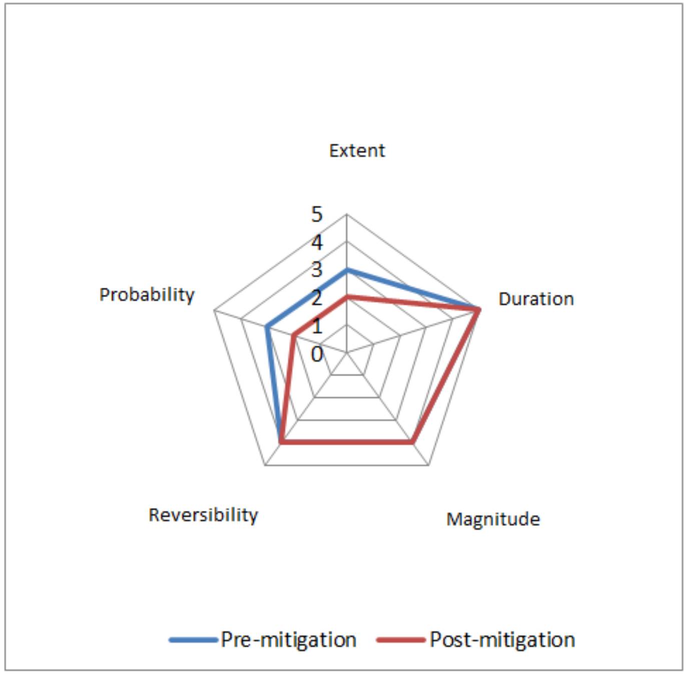
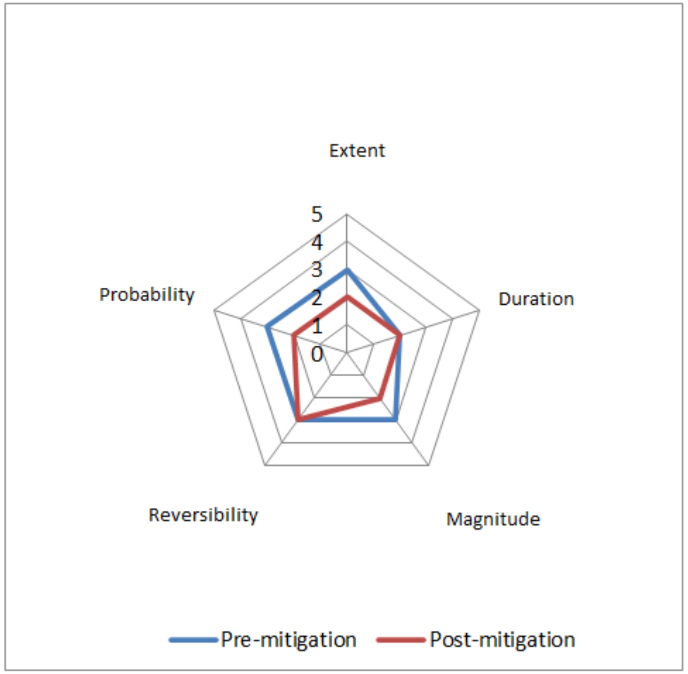


Table 13-12 Risk assessment matrix and significant scoring: Construction phase impact 04.

Impact Name	**Poor storage and management of hazardous chemical substances on-site may cause groundwater pollution.**				
Alternative	**Alternative 1**				
Phase	**Construction**				
Environmental Risk					
Attribute	**Pre-mitigation**	**Post-mitigation**	**Attribute**	**Pre-mitigation**	**Post-mitigation**
Nature of Impact	-1	-1	Magnitude of Impact	3	2
Extent of Impact	3	2	Reversibility of Impact	3	3
Duration of Impact	2	2	Probability	3	2
Environmental Risk (Pre-mitigation)					-8.25
Mitigation Measures					
Mitigation Measures	i. All hazardous substances used on-site should have an applicable Material Safety Data Sheet (MSDS) to provide information regarding the hazards, emergency response, protective measures and correct storage methodology. ii. Hazardous substance containment facilities to be used during operational phase should comply with the relevant hazardous substance storage legislation in order to ensure spillages are contained. iii. All hazardous substances and material used on-site should be stored in a dedicated, closed-off facility with an impervious floor and bunded area to prevent seepage and/or run-off in case of accidental spills.				
Cumulative Impacts					2
Considering the potential incremental, interactive, sequential, and synergistic cumulative impacts, it is probable that the impact will result in spatial and temporal cummulative change.					
Degree of potential irreplaceable loss of resources					2
The impact may result in the irreplaceable loss (cannot be replaced or subsitituted) of resources but the value (services and/or functions) of these resources is limited.					
Prioritisation Factor					1.25
Final Significance					-5.63



13.4.2. Operational phase: Associated activities and impacts

Refer to Table 13-13 for a summary of the impact risk matrix and significance ratings for the construction phase. During the operational phase the environmental significance rating of groundwater quality impacts on down-gradient receptors are rated as **medium** to **high negative** without implementation of remedial measures and **low** to **medium negative** with implementation of proposed mitigation measures. The main impacts associated with the operational phase activities include the following:

1. Migration of saline groundwater from the deep, fractured aquifer to the overlying, potable aquifer(s) during the gas production phase (Table 13-14).
2. Migration of stray methane (CH_4) gas from the deep, fractured aquifer to the overlying, potable aquifer(s) during the gas production phase. (Table 13-15).
3. Groundwater pollution as a result of wastewater spills and seepage from the evaporation dams (Table 13-16).
4. Poor quality leachate may emanate from the plant footprint area which may have a negative impact on groundwater quality (Table 13-17).
5. Mobilisation and maintenance of heavy vehicle and machinery on-site may cause hydrocarbon contamination of groundwater resources (Table 13-18).
6. Poor storage and management of hazardous chemical substances on-site may cause groundwater pollution (Table 13-19).
7. Leakage of harmful substances from tanks, pipelines or other equipment may cause groundwater pollution (Table 13-20).
8. Leachate of contaminants used in the drilling mud sump(s) to the intergranular, potable aquifer(s) during the operational phase (Table 13-21).

Table 13-13 Impact assessment and significant rating: Operational phase summary.

Impact	IMPACT DESCRIPTION	PRE - MITIGATION							POST - MITIGATION							IMPACT PRIORITISATION	
No.	Impact	Nature	Extent	Duration	Magnitude	Reversibility	Probability	Pre-mitigation ER	Nature	Extent	Duration	Magnitude	Reversibility	Probability	Post-mitigation ER	Priority Factor	Final score
Operational phase																	
1	Migration of saline groundwater from the deep, fractured aquifer to the overlying, potable aquifer(s) during the gas production phase.	-1	3	5	5	5	4	-18.00	-1	3	5	4	4	3	-12.00	1.25	-15.00
2	Migration of stray gas from the deep, fractured aquifer to the overlying, potable aquifer(s) during the gas production phase.	-1	3	5	5	5	4	-18.00	-1	3	5	4	4	3	-12.00	1.25	-15.00
3	Groundwater pollution as a result of wastewater spills and seepage from the evaporation dams.	-1	3	5	4	4	3	-12.00	-1	2	5	4	4	2	-7.50	1.25	-9.38
4	Poor quality leachate may emanate from the plant footprint area which may have a negative	-1	3	5	4	4	3	-12.00	-1	2	5	4	4	2	-7.50	1.25	-9.38

Impact	IMPACT DESCRIPTION	PRE - MITIGATION							POST - MITIGATION							IMPACT PRIORITISATION	
No.	Impact	Nature	Extent	Duration	Magnitude	Reversibility	Probability	Pre-mitigation ER	Nature	Extent	Duration	Magnitude	Reversibility	Probability	Post-mitigation ER	Priority Factor	Final score
	impact on groundwater quality.																
5	Mobilisation and maintenance of heavy vehicle and machinery on-site may cause hydrocarbon contamination of groundwater resources.	-1	3	2	3	3	3	-8.25	-1	2	2	2	3	2	-4.50	1.25	-5.63
6	Poor storage and management of hazardous chemical substances on-site may cause groundwater pollution.	-1	3	5	4	4	3	-12.00	-1	2	5	4	4	2	-7.50	1.25	-9.38
7	Leakage of harmful substances from tanks, pipelines or other equipment may cause groundwater pollution.	-1	3	5	4	4	3	-12.00	-1	2	5	4	4	2	-7.50	1.25	-9.38
8	Leachate of contaminants used in the drilling mud sump(s) to the intergranular, potable aquifer(s)	-1	2	3	3	4	4	-12.00	-1	1	3	2	3	3	-6.75	1.00	-6.75

Impact	**IMPACT DESCRIPTION**	**PRE - MITIGATION**							**POST - MITIGATION**							**IMPACT PRIORITISATION**	
No.	**Impact**	Nature	Extent	Duration	Magnitude	Reversibility	Probability	Pre-mitigation ER	Nature	Extent	Duration	Magnitude	Reversibility	Probability	Post-mitigation ER	Priority Factor	Final score
	during the operational phase.																

Table 13-14 Risk assessment matrix and significant scoring: Operational phase impact 01.

Impact Name	**Migration of saline groundwater from the deep, fractured aquifer to the overlying, potable aquifer(s) during the gas production phase.**				
Alternative	**Alternative 1**				
Phase	**Operation**				
Environmental Risk					
Attribute	**Pre-mitigation**	**Post-mitigation**	**Attribute**	**Pre-mitigation**	**Post-mitigation**
Nature of Impact	-1	-1	Magnitude of Impact	5	4
Extent of Impact	3	3	Reversibility of Impact	5	4
Duration of Impact	5	5	Probability	4	3
Environmental Risk (Pre-mitigation)					-18.00
Mitigation Measures					
Mitigation Measures	i. All exploration wells should be sealed-off with a combination of casing and grouting to ensure isolation of the saline water from the host-aquifer(s). ii. Development and implementation of an integrated groundwater monitoring program evaluating hydrochemistry will serve as early warning and detection mechanism to implement mitigation measures. iii. Monitoring results should be evaluated and reviewed on a biannual basis by a registered hydrogeologist for interpretation and trend analysis for submission to the Regional Head of Department. Based on the water quality results, the monitoring network should be refined and updated every three to five years based on hydrochemical results obtained to ensure optimisation and adequacy of the proposed localities. iv. The calibrated groundwater flow model should be updated on a bi-annual basis as newly gathered monitoring results become available in order to be applied as groundwater management tool for future scenario predictions.				
Cumulative Impacts					2
Considering the potential incremental, interactive, sequential, and synergistic cumulative impacts, it is probable that the impact will result in spatial and temporal cummulative change.					
Degree of potential irreplaceable loss of resources					2
The impact may result in the irreplaceable loss (cannot be replaced or subsitituted) of resources but the value (services and/or functions) of these resources is limited.					
Prioritisation Factor					1.25
Final Significance					-15.00

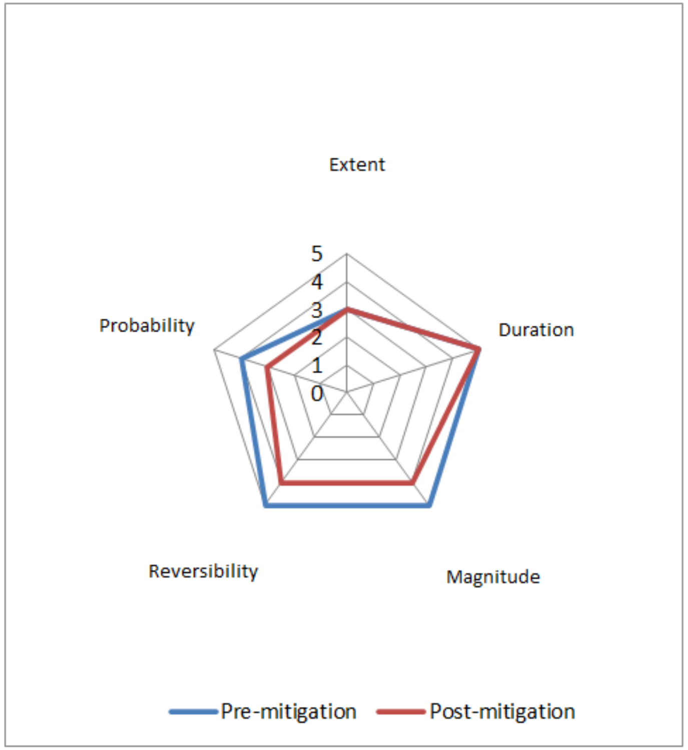


Table 13-15 Risk assessment matrix and significant scoring: Operational phase impact 02.

Impact Name	**Migration of stray gas from the deep, fractured aquifer to the overlying, potable aquifer(s) during the gas production phase.**				
Alternative	**Alternative 1**				
Phase	**Operation**				
Environmental Risk					
Attribute	**Pre-mitigation**	**Post-mitigation**	**Attribute**	**Pre-mitigation**	**Post-mitigation**
Nature of Impact	-1	-1	Magnitude of Impact	5	4
Extent of Impact	3	3	Reversibility of Impact	5	4
Duration of Impact	5	5	Probability	4	3
Environmental Risk (Pre-mitigation)					-18.00
Mitigation Measures					
Mitigation Measures	i. All exploration wells should be sealed-off with a combination of casing and grouting to ensure isolation of the gas from the host-aquifer(s). ii. Development and implementation of an integrated groundwater monitoring program evaluating hydrochemistry will serve as early warning and detection mechanism to implement mitigation measures. iii. Monitoring results should be evaluated and reviewed on a biannual basis by a registered hydrogeologist for interpretation and trend analysis for submission to the Regional Head of Department. Based on the water quality results, the monitoring network should be refined and updated every three to five years based on hydrochemical results obtained to ensure optimisation and adequacy of the proposed localities. iv. The calibrated groundwater flow model should be updated on a bi-annual basis as newly gathered monitoring results become available in order to be applied as groundwater management tool for future scenario predictions.				
Cumulative Impacts					2
Considering the potential incremental, interactive, sequential, and synergistic cumulative impacts, it is probable that the impact will result in spatial and temporal cummulative change.					
Degree of potential irreplaceable loss of resources					2
The impact may result in the irreplaceable loss (cannot be replaced or subsitituted) of resources but the value (services and/or functions) of these resources is limited.					
Prioritisation Factor					1.25
Final Significance					-15.00

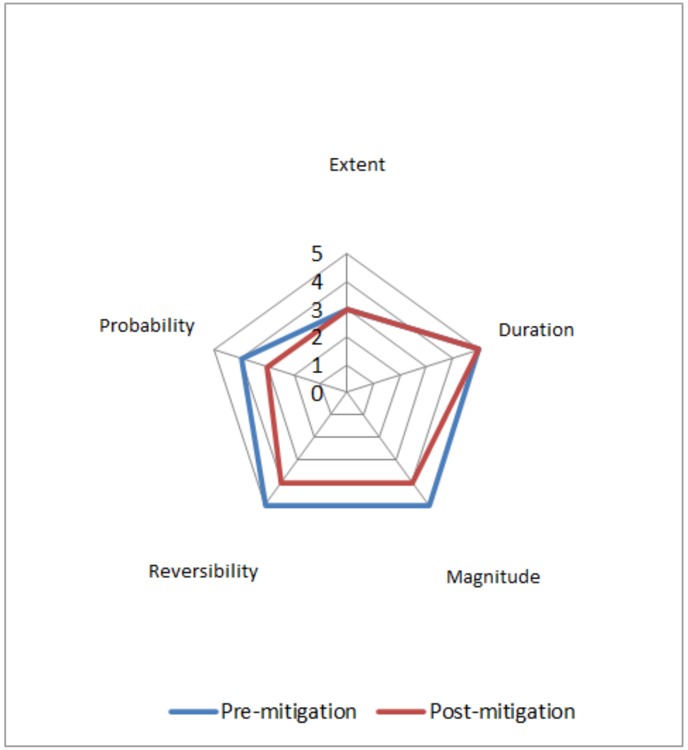


Table 13-16 **Risk assessment matrix and significant scoring: Operational phase impact 03.**

Impact Name	**Groundwater pollution as a result of wastewater spills and seepage from the evaporation dams.**				
Alternative	**Alternative 1**				
Phase	**Operation**				
Environmental Risk					
Attribute	**Pre-mitigation**	**Post-mitigation**	**Attribute**	**Pre-mitigation**	**Post-mitigation**
Nature of Impact	-1	-1	Magnitude of Impact	4	4
Extent of Impact	3	2	Reversibility of Impact	4	4
Duration of Impact	5	5	Probability	3	2
Environmental Risk (Pre-mitigation)					-12.00
Mitigation Measures					
Mitigation Measures	i. Develop a stormwater management plan in accordance with GN704 in order to separate dirty/contact water from clean water circuits. All water retention structures, process water dams; storm water dams, retention ponds etc. should be constructed to have adequate freeboard to be able to contain water from 1:50 year rain events. ii. Development and implementation of an integrated groundwater monitoring program evaluating hydrochemistry will serve as early warning and detection mechanism to implement mitigation measures. iii. An appropriately sized spill kit must kept onsite and available at all times. The spill kit size must be relevant to the scale of the activities involving the use of hazardous substances. iv. An appropriate number of spill kits must be available and must be located in all areas where activities are being undertaken. v. The responsible operator must have the required training to make use of the spill kit in emergency situations.				
Cumulative Impacts					2
Considering the potential incremental, interactive, sequential, and synergistic cumulative impacts, it is probable that the impact will result in spatial and temporal cummulative change.					
Degree of potential irreplaceable loss of resources					2
The impact may result in the irreplaceable loss (cannot be replaced or subsitituted) of resources but the value (services and/or functions) of these resources is limited.					
Prioritisation Factor					1.25
Final Significance					-9.38

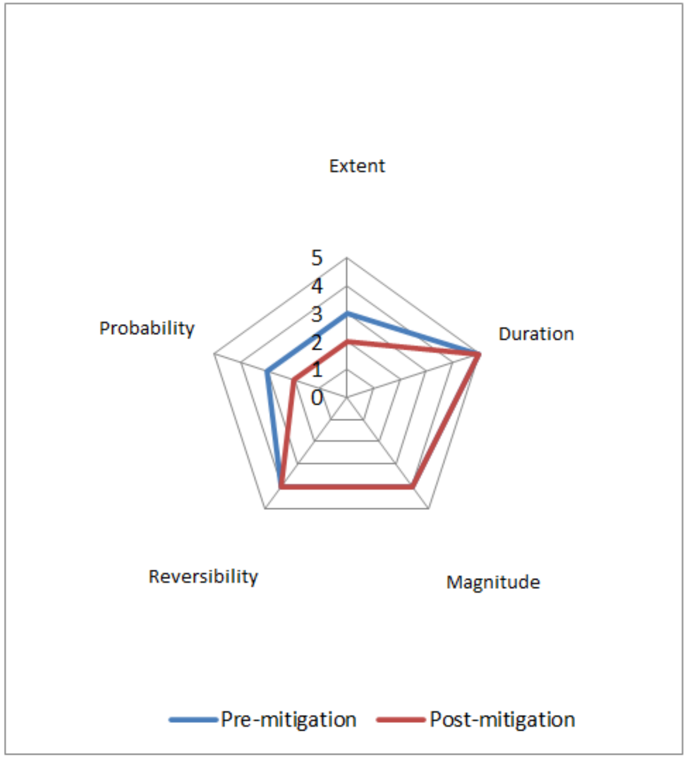


Table 13-17 Risk assessment matrix and significant scoring: Operational phase impact 04.

Impact Name	**Poor quality leachate may emanate from the plant footprint area which may have a negative impact on groundwater quality.**				
Alternative	**Alternative 1**				
Phase	**Operation**				
Environmental Risk					
Attribute	**Pre-mitigation**	**Post-mitigation**	**Attribute**	**Pre-mitigation**	**Post-mitigation**
Nature of Impact	-1	-1	Magnitude of Impact	4	4
Extent of Impact	3	2	Reversibility of Impact	4	4
Duration of Impact	5	5	Probability	3	2
Environmental Risk (Pre-mitigation)					-12.00
Mitigation Measures					
Mitigation Measures	i. Develop a stormwater management plan in accordance with GN704 in order to separate dirty/contact water from clean water circuits. All water retention structures, process water dams; storm water dams, retention ponds etc. should be constructed to have adequate freeboard to be able to contain water from 1:50 year rain events. ii. Plant areas must be fitted with a containment facility for the collection of dirty water. This facility must be impervious to prevent soil and groundwater contamination. Ii. iii. The plant area must have a concrete slab that is sloped to facilitate runoff into a collection sump.				
Cumulative Impacts					2
Considering the potential incremental, interactive, sequential, and synergistic cumulative impacts, it is probable that the impact will result in spatial and temporal cummulative change.					
Degree of potential irreplaceable loss of resources					2
The impact may result in the irreplaceable loss (cannot be replaced or subsitituted) of resources but the value (services and/or functions) of these resources is limited.					
Prioritisation Factor					1.25
Final Significance					-9.38

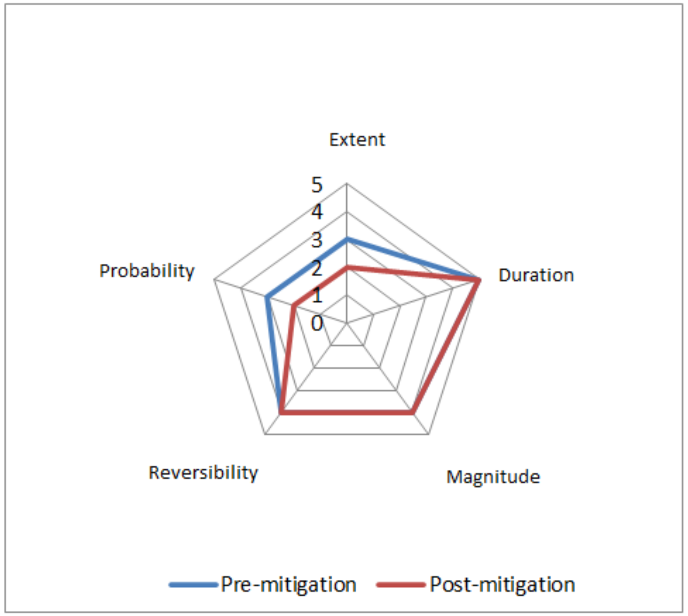


Table 13-18 Risk assessment matrix and significant scoring: Operational phase impact 05.

Impact Name	**Mobilisation and maintenance of heavy vehicle and machinery on-site may cause hydrocarbon contamination of groundwater resources.**				
Alternative	**Alternative 1**				
Phase	**Operation**				
Environmental Risk					
Attribute	**Pre-mitigation**	**Post-mitigation**	**Attribute**	**Pre-mitigation**	**Post-mitigation**
Nature of Impact	-1	-1	Magnitude of Impact	3	2
Extent of Impact	3	2	Reversibility of Impact	3	3
Duration of Impact	2	2	Probability	3	2
Environmental Risk (Pre-mitigation)					-8.25
Mitigation Measures					
Mitigation Measures	i. Operational vehicles and machinery must be serviced and maintained regularly in order to ensure that oil spillages are limited. Spill trays must be provided if refuelling of operational vehicles is done on site. Further to this spill kits must be readily available in case of accidental spillages with regular spot checks to be conducted. ii. During servicing of vehicles or equipment, especially where emergency repairs are effected outside the workshop area, a suitable drip tray must be used to prevent spills onto the soil. iii. Leaking equipment must be repaired immediately or be removed from site to facilitate repair. iv. Workshop areas must be monitored for oil and fuel spills, and a suitable oil/water separator should be in place where maintenance work on vehicles and equipment can be performed. . v. An appropriate number of spill kits must be available and must be located in all areas where activities are being undertaken.				
Cumulative Impacts					2
Considering the potential incremental, interactive, sequential, and synergistic cumulative impacts, it is probable that the impact will result in spatial and temporal cummulative change.					
Degree of potential irreplaceable loss of resources					2
The impact may result in the irreplaceable loss (cannot be replaced or subsitituted) of resources but the value (services and/or functions) of these resources is limited.					
Prioritisation Factor					1.25
Final Significance					-5.63

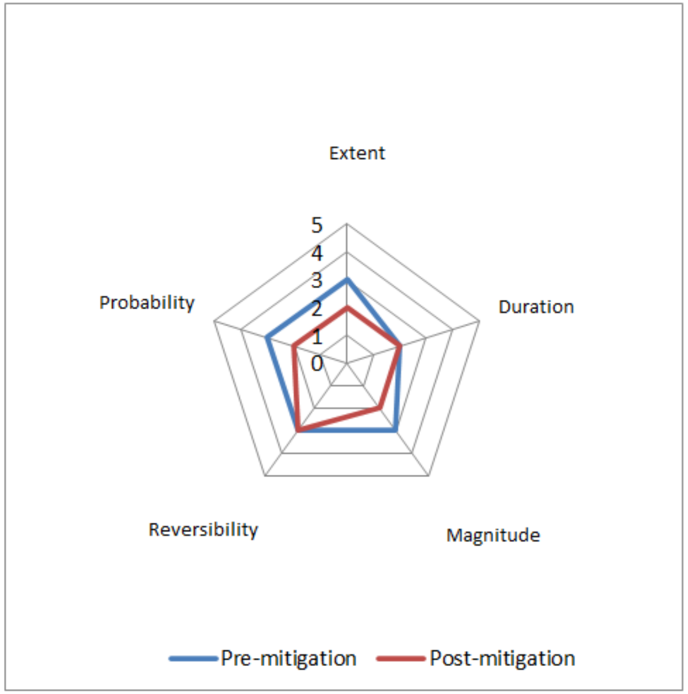


Table 13-19 Risk assessment matrix and significant scoring: Operational phase impact 06.

Impact Name	**Poor storage and management of hazardous chemical substances on-site may cause groundwater pollution.**				
Alternative	**Alternative 1**				
Phase	**Operation**				
Environmental Risk					
Attribute	**Pre-mitigation**	**Post-mitigation**	**Attribute**	**Pre-mitigation**	**Post-mitigation**
Nature of Impact	-1	-1	Magnitude of Impact	3	2
Extent of Impact	3	2	Reversibility of Impact	3	3
Duration of Impact	2	2	Probability	3	2
Environmental Risk (Pre-mitigation)					-8.25
Mitigation Measures					
Mitigation Measures	i. All hazardous substances used on-site should have an applicable Material Safety Data Sheet (MSDS) to provide information regarding the hazards, emergency response, protective measures and correct storage methodology. ii. Hazardous substance containment facilities to be used during operational phase should comply with the relevant hazardous substance storage legislation in order to ensure spillages are contained. iii. All hazardous substances and material used on-site should be stored in a dedicated, closed-off facility with an impervious floor and bunded area to prevent seepage and/or run-off in case of accidental spills. iv. An appropriately sized spill kit must kept onsite and available at all times. The spill kit size must be relevant to the scale of the activities involving the use of hazardous substances. v. The responsible operator must have the required training to make use of the spill kit in emergency situations.				
Cumulative Impacts					2
Considering the potential incremental, interactive, sequential, and synergistic cumulative impacts, it is probable that the impact will result in spatial and temporal cummulative change.					
Degree of potential irreplaceable loss of resources					2
The impact may result in the irreplaceable loss (cannot be replaced or subsitituted) of resources but the value (services and/or functions) of these resources is limited.					
Prioritisation Factor					1.25
Final Significance					-5.63

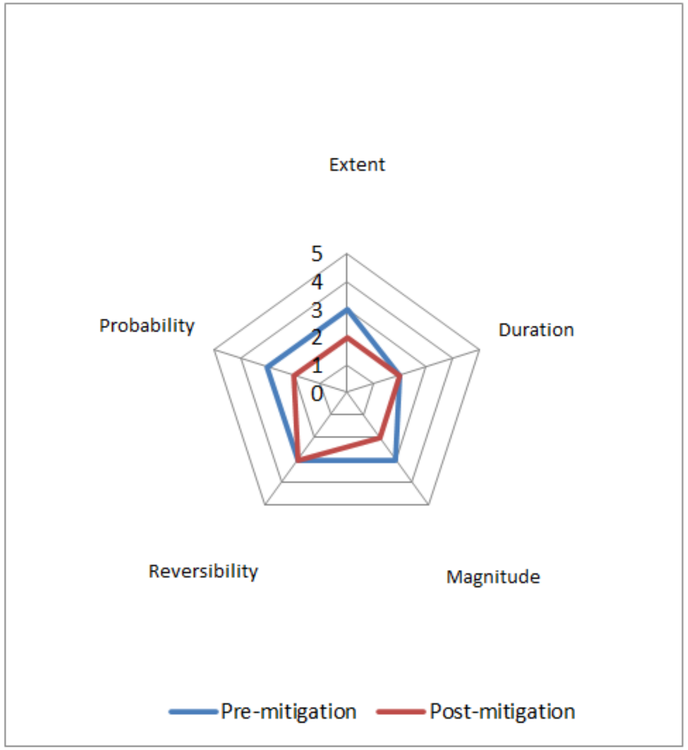


Table 13-20 Risk assessment matrix and significant scoring: Operational phase impact 07.

Impact Name	**Leakage of harmful substances from tanks, pipelines or other equipment may cause groundwater pollution.**				
Alternative	**Alternative 1**				
Phase	**Operation**				
Environmental Risk					
Attribute	**Pre-mitigation**	**Post-mitigation**	**Attribute**	**Pre-mitigation**	**Post-mitigation**
Nature of Impact	-1	-1	Magnitude of Impact	4	4
Extent of Impact	3	2	Reversibility of Impact	4	4
Duration of Impact	5	5	Probability	3	2
Environmental Risk (Pre-mitigation)					-12.00
Mitigation Measures					
Mitigation Measures	i. Leaking equipment must be repaired immediately or be removed from site to facilitate repair. ii. Annual external audits should be conducted to ensure that pipelines and waste facilities are maintained and functioning effective and according to licence conditions. iii. The Licensee shall appoint a suitably qualified and responsible person to give effect to all recommendations as stipulated in specialist reports to ensure compliance to licence conditions pertaining to activities in order to ensure that potential impact(s) are minimised, and mitigation measures proposed are functioning effectively. iv. Development and implementation of an integrated groundwater monitoring program evaluating hydrochemistry will serve as early warning and detection mechanism to implement mitigation measures. v. Monitoring results should be evaluated and reviewed on a biannual basis by a registered hydrogeologist for interpretation and trend analysis for submission to the Regional Head of Department. Based on the water quality results, the monitoring network should be refined and updated every three to five years based on hydrochemical results obtained to ensure optimisation and adequacy of the proposed localities.				
Cumulative Impacts					2
Considering the potential incremental, interactive, sequential, and synergistic cumulative impacts, it is probable that the impact will result in spatial and temporal cummulative change.					
Degree of potential irreplaceable loss of resources					2
The impact may result in the irreplaceable loss (cannot be replaced or subsitituted) of resources but the value (services and/or functions) of these resources is limited.					
Prioritisation Factor					1.25
Final Significance					-9.38

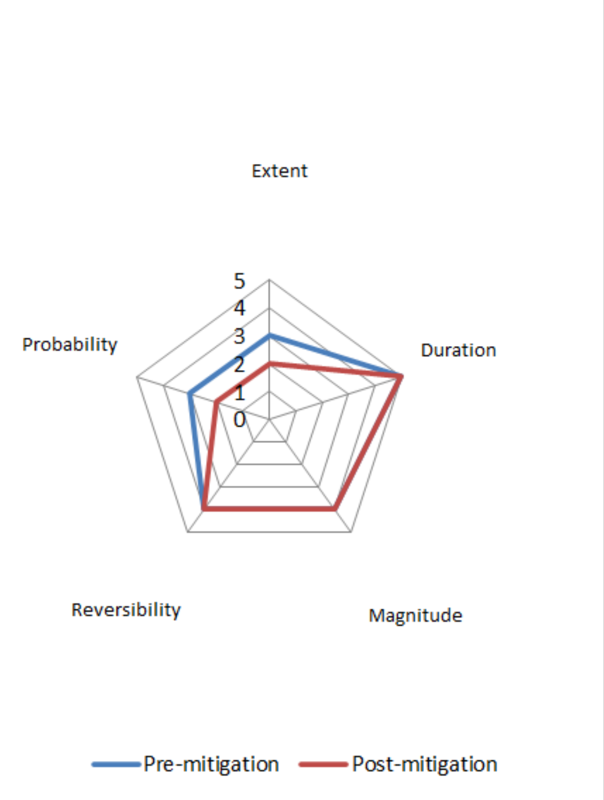
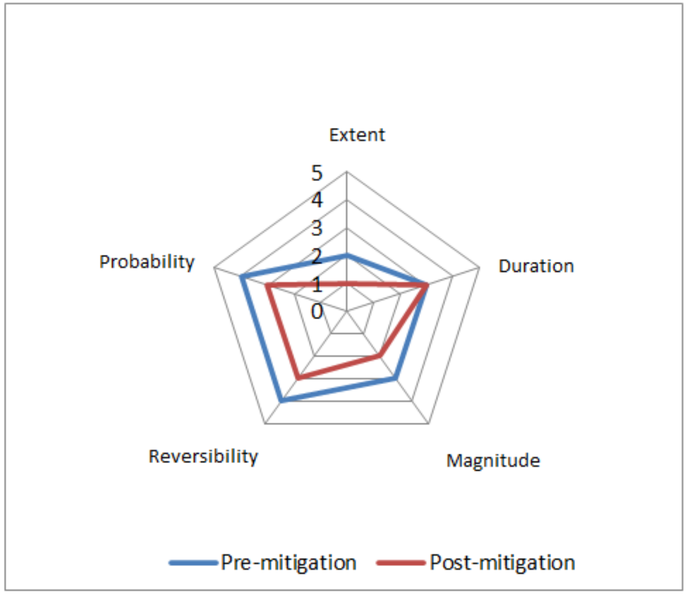


Table 13-21 Risk assessment matrix and significant scoring: Operational phase impact 08.

Impact Name	**Leachate of contaminants used in the drilling mud sump(s) to the intergranular, potable aquifer(s) during the operational phase.**				
Alternative	**Alternative 1**				
Phase	**Operation**				
Environmental Risk					
Attribute	**Pre-mitigation**	**Post-mitigation**	**Attribute**	**Pre-mitigation**	**Post-mitigation**
Nature of Impact	-1	-1	Magnitude of Impact	3	2
Extent of Impact	2	1	Reversibility of Impact	4	3
Duration of Impact	3	3	Probability	4	3
Environmental Risk (Pre-mitigation)					-12.00
Mitigation Measures					
Mitigation Measures	i. All actively used drill mud sumps should be adequately liner with an appropriate barrier system in order to isolate and prevent seepage of contaminants from the host aquifer. Furthermore, a biodegradeable polymer should be used as drilling lubricant. i. A rehabilitation plan must be developed based on site-specific issues and performed in accordance to best practise guidelines and guided by the closure and rehabilitation plans. ii. An ECO must be appointed to oversee the rehabilitation phase, and ensure least possible harm to biodiversity and ensure compliance to the rehabilitation plan.				
Cumulative Impacts					1
Considering the potential incremental, interactive, sequential, and synergistic cumulative impacts, it is unlikley that the impact will result in spatial and temporal cummulative change.					
Degree of potential irreplaceable loss of resources					1
The impact is unlikely to result in irreplaceable loss of resources.					
Prioritisation Factor					1.00
Final Significance					-6.75



13.4.3. Post-operational and decommissioning phase: Associated activities and impacts

Refer to Table 13-22 for a summary of the impact risk matrix and significance ratings for the construction phase. During the decommissioning and post-closure phase the environmental significance rating of groundwater quality impacts on down-gradient receptors are rated as **medium negative** without implementation of remedial measures and **low** to **medium negative** with implementation of proposed mitigation measures. The main impacts associated with the post-closure and decommissioning phase activities include the following:

1. Migration of saline groundwater from the deep, fractured aquifer to the overlying, potable aquifer(s) during the borehole closure and decommissioning phase (Table 13-23).
2. Migration of stray methane (CH_4) gas from the deep, fractured aquifer to the overlying, potable aquifer(s) borehole closure and decommissioning phase (Table 13-24).
3. Groundwater pollution as a result of wastewater spills and seepage from the evaporation dams (Table 13-25).
4. Poor quality leachate may emanate from the plant footprint area which may have a negative impact on groundwater quality (Table 13-26).
5. De-mobilisation of heavy vehicle and machinery as part of the decommissioning phase on-site may cause hydrocarbon contamination of groundwater resources (Table 13-27).

Table 13-22 Impact assessment and significant rating: Decommissioning and closure phase summary.

Impact	**IMPACT DESCRIPTION**	**PRE - MITIGATION**							**POST - MITIGATION**							**IMPACT PRIORITISATION**	
No.	**Impact**	Nature	Extent	Duration	Magnitude	Reversibility	Probability	Pre-mitigation ER	Nature	Extent	Duration	Magnitude	Reversibility	Probability	Post-mitigation ER	Priority Factor	Final score
Decommissioning phase																	
1	Migration of saline groundwater from the deep, fractured aquifer to the overlying, potable aquifer(s) during the borehole closure and decommissioning phase.	-1	3	3	5	5	4	-16.00	-1	2	2	4	4	3	-9	1.25	-11.25
2	Migration of stray gas from the deep, fractured aquifer to the overlying, potable aquifer(s) borehole closure and decommissioning phase.	-1	3	3	5	5	4	-16.00	-1	2	2	4	4	3	-9	1.25	-11.25
3	Groundwater pollution as a result of wastewater spills and seepage from the evaporation dams.	-1	3	3	3	4	2	-6.50	-1	2	2	2	3	1	-2.25	1.13	-2.53

Impact	**IMPACT DESCRIPTION**	**PRE - MITIGATION**							**POST - MITIGATION**							**IMPACT PRIORITISATION**	
No.	**Impact**	Nature	Extent	Duration	Magnitude	Reversibility	Probability	Pre-mitigation ER	Nature	Extent	Duration	Magnitude	Reversibility	Probability	Post-mitigation ER	Priority Factor	Final score
4	Poor quality leachate may emanate from the plant footprint area which may have a negative impact on groundwater quality.	-1	3	3	3	4	2	-6.50	-1	2	2	2	3	1	-2.25	1.13	-2.53
5	De-mobilisation of heavy vehicle and machinery as part of the decommissioning phase on-site may cause hydrocarbon contamination of groundwater resources.	-1	3	3	3	4	2	-6.50	-1	2	2	2	3	1	-2.25	1.13	-2.53

Table 13-23 Risk assessment matrix and significant scoring: Decommissioning and closure phase impact 01.

Impact Name	**Migration of saline groundwater from the deep, fractured aquifer to the overlying, potable aquifer(s) during the borehole closure and decommissioning phase.**				
Alternative	**Alternative 1**				
Phase	**Decommissioning**				
Environmental Risk					
Attribute	**Pre-mitigation**	**Post-mitigation**	**Attribute**	**Pre-mitigation**	**Post-mitigation**
Nature of Impact	-1	-1	Magnitude of Impact	5	4
Extent of Impact	3	2	Reversibility of Impact	5	4
Duration of Impact	3	2	Probability	4	3
Environmental Risk (Pre-mitigation)					-16.00
Mitigation Measures					
Mitigation Measures	i.Contractor to prepare a consolidated site-specific closure/sealing plan to be submitted for approval. The plan should include a detailed description of the following aspects: -Calliper Logging should be conducted to identify and investigate potential blockages/cavities within well. -Cement Bond Logging should be performed to investigate the current integrity of the casing and cementation. -Contractor to determine the most suitable and appropriate closure, sealing and rehabilitation strategy with specific focus on the plugging method to ensure no vertical gas and/or fluid movements within the well. -Develop cement formulation for cementing the entire well annulus. -Develop cement formulation to top-up “no bond” or “poor bond” cemented sections between casing and formation walls – ensure cement seals and does not disperse into porous formations. -Cement formulations and volumetric calculations to be approved by well engineer/cement specialist. -Contractor must ensure cement mixture seals the entire well length along the well annulus. -Cement plugs must be stacked along the full length and diameter of the well to surface (open hole section above the packer as well as the upper casing) to ensure efficient redundancy. -All plugs must be tagged to ensure successful placement. -Cementation extent: Should be from end of hole (bottom of well) to surface. -Cementation technique: Squeeze technique - this displacement method minimizes the contamination of the cement by being able to displace fluid within the well, thus allowing for a more stable well plug. Contractor must also make use of wiper plugs for cement displacement. -Contractor to conduct cement top-ups along the annulus and existing cemented sections showing “no bond” or “poor bond” from logging results. -A surface / shallow cement plug (+/ 50m below ground Level) must be set, and the well casing must be cut and capped 1 m below ground level to remove the wellhead and all casing above this point. -Integrity of the plugs must be confirmed by setting weight down on the upper most plug (using the drill string) as well as a differential pressure test for 4 hours at determined pressure with less than 10% bleed over the period. Pressure test data to be captured in 15-minute intervals for the entire 4-hour testing period. ii. Development and implementation of a post-closure groundwater monitoring program evaluating hydrochemistry will serve as early warning and detection mechanism to implement mitigation measures.				
Cumulative Impacts					2
Considering the potential incremental, interactive, sequential, and synergistic cumulative impacts, it is probable that the impact will result in spatial and temporal cummulative change.					
Degree of potential irreplaceable loss of resources					2
The impact may result in the irreplaceable loss (cannot be replaced or subsitituted) of resources but the value (services and/or functions) of these resources is limited.					
Prioritisation Factor					1.25
Final Significance					-11.25

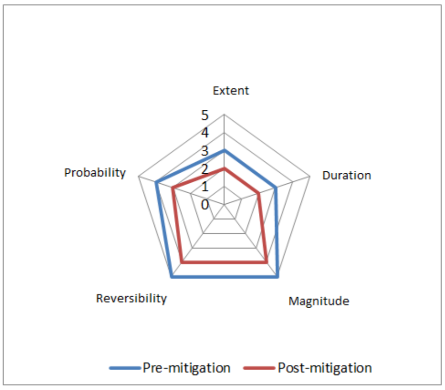


Table 13-24 Risk assessment matrix and significant scoring: Decommissioning and closure phase impact 02.

Impact Name	**Migration of stray gas from the deep, fractured aquifer to the overlying, potable aquifer(s) borehole closure and decommissioning phase.**				
Alternative	**Alternative 1**				
Phase	**Decommissioning**				
Environmental Risk					
Attribute	**Pre-mitigation**	**Post-mitigation**	**Attribute**	**Pre-mitigation**	**Post-mitigation**
Nature of Impact	-1	-1	Magnitude of Impact	5	4
Extent of Impact	3	2	Reversibility of Impact	5	4
Duration of Impact	3	2	Probability	4	3
Environmental Risk (Pre-mitigation)					-16.00
Mitigation Measures					
Mitigation Measures	i.Contractor to prepare a consolidated site-specific closure/sealing plan to be submitted for approval. The plan should include a detailed description of the following aspects: -Calliper Logging should be conducted to identify and investigate potential blockages/cavities within well. -Cement Bond Logging should be performed to investigate the current integrity of the casing and cementation. -Contractor to determine the most suitable and appropriate closure, sealing and rehabilitation strategy with specific focus on the plugging method to ensure no vertical gas and/or fluid movements within the well. -Develop cement formulation for cementing the entire well annulus. -Develop cement formulation to top-up "no bond" or "poor bond" cemented sections between casing and formation walls – ensure cement seals and does not disperse into porous formations. -Cement formulations and volumetric calculations to be approved by well engineer/cement specialist. -Contractor must ensure cement mixture seals the entire well length along the well annulus. -Cement plugs must be stacked along the full length and diameter of the well to surface (open hole section above the packer as well as the upper casing) to ensure efficient redundancy. -All plugs must be tagged to ensure successful placement. -Cementation extent: Should be from end of hole (bottom of well) to surface. -Cementation technique: Squeeze technique - this displacement method minimizes the contamination of the cement by being able to displace fluid within the well, thus allowing for a more stable well plug. Contractor must also make use of wiper plugs for cement displacement. -Contractor to conduct cement top-ups along the annulus and existing cemented sections showing "no bond" or "poor bond" from logging results. -A surface / shallow cement plug (+/ 50m below ground Level) must be set, and the well casing must be cut and capped 1 m below ground level to remove the wellhead and all casing above this point. -Integrity of the plugs must be confirmed by setting weight down on the upper most plug (using the drill string) as well as a differential pressure test for 4 hours at determined pressure with less than 10% bleed over the period. Pressure test data to be captured in 15-minute intervals for the entire 4-hour testing period. ii. Development and implementation of a post-closure groundwater monitoring program evaluating hydrochemistry will serve as early warning and detection mechanism to implement mitigation measures.				
Cumulative Impacts					2
Considering the potential incremental, interactive, sequential, and synergistic cumulative impacts, it is probable that the impact will result in spatial and temporal cummulative change.					
Degree of potential irreplaceable loss of resources					2
The impact may result in the irreplaceable loss (cannot be replaced or subsitituted) of resources but the value (services and/or functions) of these resources is limited.					
Prioritisation Factor					1.25
Final Significance					-11.25

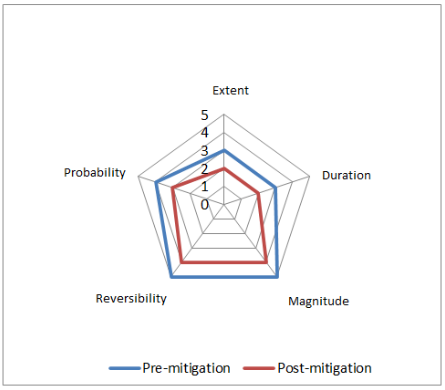


Table 13-25 Risk assessment matrix and significant scoring: Decommissioning and closure phase impact 03.

Impact Name	**Groundwater pollution as a result of wastewater spills and seepage from the evaporation dams.**				
Alternative	**Alternative 1**				
Phase	**Decommissioning**				
Environmental Risk					
Attribute	**Pre-mitigation**	**Post-mitigation**	**Attribute**	**Pre-mitigation**	**Post-mitigation**
Nature of Impact	-1	-1	Magnitude of Impact	3	2
Extent of Impact	3	2	Reversibility of Impact	4	3
Duration of Impact	3	2	Probability	2	1
Environmental Risk (Pre-mitigation)					-6.50
Mitigation Measures					
Mitigation Measures	i. Develop a stormwater management plan in accordance with GN704 in order to separate dirty/contact water from clean water circuits. All water retention structures, process water dams; storm water dams, retention ponds etc. should be constructed to have adequate freeboard to be able to contain water from 1:50 year rain events. ii. Development and implementation of a post-closure groundwater monitoring program evaluating hydrochemistry will serve as early warning and detection mechanism to implement mitigation measures. iv. A rehabilitation plan must be developed based on site-specific issues and performed in accordance to best practise guidelines and guided by the closure and rehabilitation plans. v. An ECO must be appointed to oversee the rehabilitation phase, and ensure least possible harm to biodiversity and ensure compliance to the rehabilitation plan.				
Cumulative Impacts					1
Considering the potential incremental, interactive, sequential, and synergistic cumulative impacts, it is unlikley that the impact will result in spatial and temporal cummulative change.					
Degree of potential irreplaceable loss of resources					2
The impact may result in the irreplaceable loss (cannot be replaced or subsitituted) of resources but the value (services and/or functions) of these resources is limited.					
Prioritisation Factor					1.13
Final Significance					-2.53

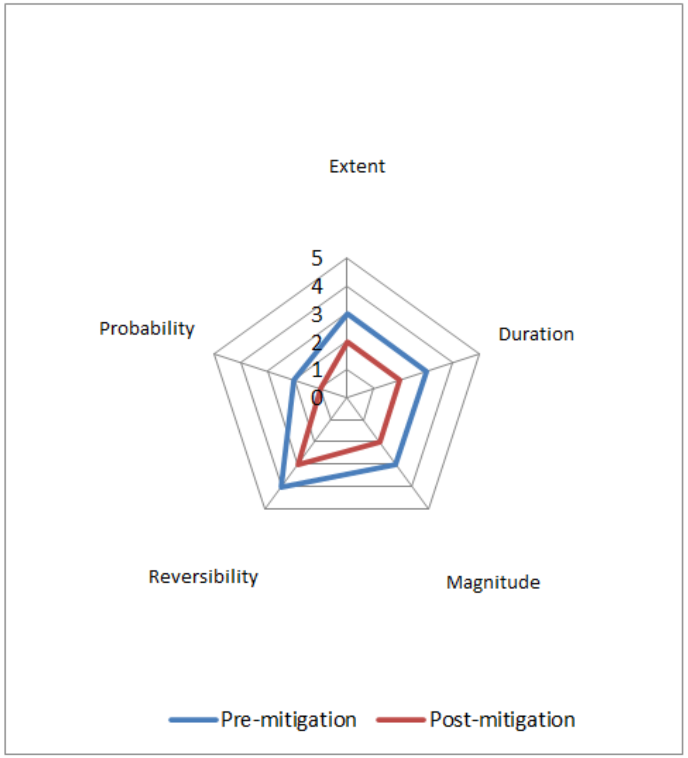


Table 13-26 **Risk assessment matrix and significant scoring: Decommissioning and closure phase impact 04.**

Impact Name	**Poor quality leachate may emanate from the plant footprint area which may have a negative impact on groundwater quality.**				
Alternative	**Alternative 1**				
Phase	**Decommissioning**				
Environmental Risk					
Attribute	**Pre-mitigation**	**Post-mitigation**	**Attribute**	**Pre-mitigation**	**Post-mitigation**
Nature of Impact	-1	-1	Magnitude of Impact	3	2
Extent of Impact	3	2	Reversibility of Impact	4	3
Duration of Impact	3	2	Probability	2	1
Environmental Risk (Pre-mitigation)					-6.50
Mitigation Measures					
Mitigation Measures	i. Develop a stormwater management plan in accordance with GN704 in order to separate dirty/contact water from clean water circuits. All water retention structures, process water dams; storm water dams, retention ponds etc. should be constructed to have adequate freeboard to be able to contain water from 1:50 year rain events. ii. Development and implementation of a post-closure groundwater monitoring program evaluating hydrochemistry will serve as early warning and detection mechanism to implement mitigation measures. iv. A rehabilitation plan must be developed based on site-specific issues and performed in accordance to best practise guidelines and guided by the closure and rehabilitation plans. v. An ECO must be appointed to oversee the rehabilitation phase, and ensure least possible harm to biodiversity and ensure compliance to the rehabilitation plan.				
Cumulative Impacts					1
Considering the potential incremental, interactive, sequential, and synergistic cumulative impacts, it is unlikley that the impact will result in spatial and temporal cummulative change.					
Degree of potential irreplaceable loss of resources					2
The impact may result in the irreplaceable loss (cannot be replaced or subsitituted) of resources but the value (services and/or functions) of these resources is limited.					
Prioritisation Factor					1.13
Final Significance					-2.53

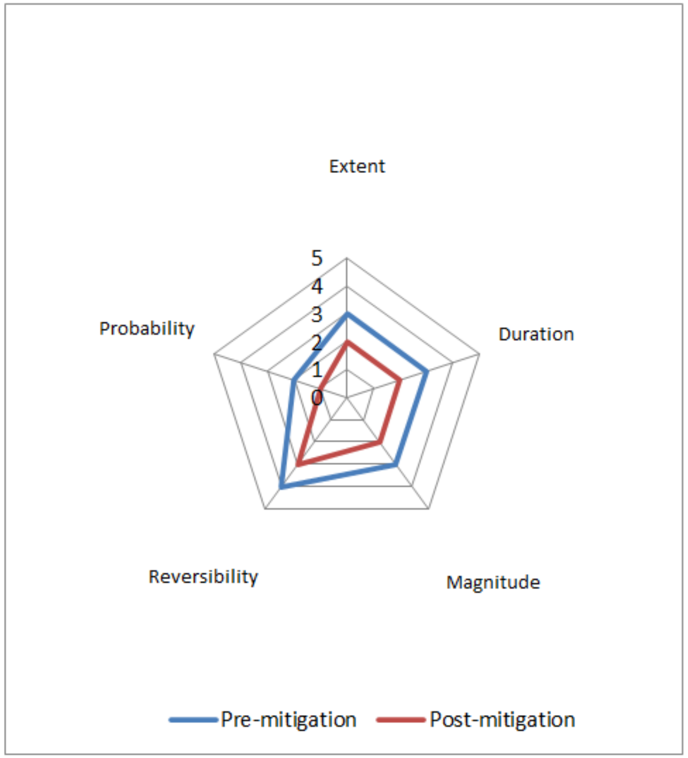
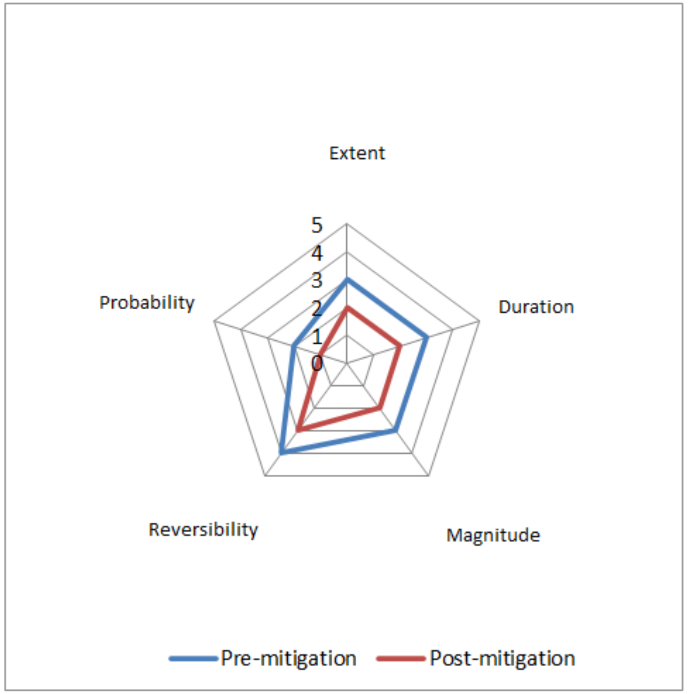


Table 13-27 Risk assessment matrix and significant scoring: Decommissioning and closure phase impact 05.

Impact Name	**De-mobilisation of heavy vehicle and machinery as part of the decommissioning phase on-site may cause hydrocarbon contamination of groundwater resources.**				
Alternative	**Alternative 1**				
Phase	**Decommissioning**				
Environmental Risk					
Attribute	**Pre-mitigation**	**Post-mitigation**	**Attribute**	**Pre-mitigation**	**Post-mitigation**
Nature of Impact	-1	-1	Magnitude of Impact	3	2
Extent of Impact	3	2	Reversibility of Impact	4	3
Duration of Impact	3	2	Probability	2	1
Environmental Risk (Pre-mitigation)					-6.50
Mitigation Measures					
Mitigation Measures	i. Operational vehicles and machinery must be serviced and maintained regularly in order to ensure that oil spillages are limited. Spill trays must be provided if refuelling of operational vehicles is done on site. Further to this spill kits must be readily available in case of accidental spillages with regular spot checks to be conducted. ii. During servicing of vehicles or equipment, especially where emergency repairs are effected outside the workshop area, a suitable drip tray must be used to prevent spills onto the soil. iii. Leaking equipment must be repaired immediately or be removed from site to facilitate repair. iv. Workshop areas must be monitored for oil and fuel spills, and a suitable oil/water separator should be in place where maintenance work on vehicles and equipment can be performed. . v. An appropriate number of spill kits must be available and must be located in all areas where activities are being undertaken.				
Cumulative Impacts					1
Considering the potential incremental, interactive, sequential, and synergistic cumulative impacts, it is unlikley that the impact will result in spatial and temporal cummulative change.					
Degree of potential irreplaceable loss of resources					2
The impact may result in the irreplaceable loss (cannot be replaced or subsitituted) of resources but the value (services and/or functions) of these resources is limited.					
Prioritisation Factor					1.13
Final Significance					-2.53



13.5. Hydrogeological sensitivity

Based on the findings of this investigation and outcomes of the impact assessment a hydrogeological sensitivity map was generated, highlighting groundwater zones which will be sensitive to contamination and should form part of the monitoring protocol. Refer to Table 13-28 for a summary of identified hydrogeological sensitive areas with a spatial representation depicted in Figure 13-1.

Table 13-28 Hydrogeological sensitivity rating (after EIMS).

Sensitivity rating	Description	Hydrogeological component identified	Motivation	Weighting
Low	The inherent feature status and sensitivity is already degraded. The proposed development will not affect the current status and/or may result in a positive impact. These features would be the preferred alternative for mining or infrastructure placement.	All areas not included in either the moderately of highly sensitive zones as identified.	This area excludes groundwater receptors or sensitive areas identified as part of the assessment.	-1
Moderate	The proposed development will negatively influence the current status of the feature to a moderate degree of modification.	A zone of 450m around the proposed gas production wells situated within the primary porosity aquifer associated with alluvium material deposited in flood plains. A zone of 250m around the proposed gas production wells situated within the Karoo formations. A buffer zone of 50m along identified fault zones traverse the project area.	These aquifers cover a substantial portion of the study area and are limited to a zone of variable width and depth. The alluvial aquifer is specifically vulnerable to contamination as it there is a direct connectivity with rivers and streams and associated high permeability. This aquifer is moderately susceptible to impacts from contaminant sources originating within this buffer zone as point source pollution. The intergranular Karoo aquifer can be classified as a secondary porosity aquifer and is generally unconfined with phreatic water levels. Due to higher effective porosity (n) this aquifer is most susceptible to impacts from contaminant sources. This aquifer is moderately susceptible to impacts from contaminant sources originating within this buffer zone as point source pollution. Fault zones targeted as part of the gas production operation can serve as potential preferred pathways for groundwater flow and contaminant transport.	+1

Sensitivity rating	Description	Hydrogeological component identified	Motivation	Weighting
High	The proposed development will negatively influence the current status of the feature to a high degree of modification.	A zone of 350m around the proposed gas production wells situated within the riparian zone primary porosity aquifer associated with alluvium material deposited in flood plains. A zone of 150m around the proposed gas production wells situated within the Karoo formations.	These aquifers cover a substantial portion of the study area and are limited to a zone of variable width and depth. The alluvial aquifer is specifically vulnerable to contamination as it there is a direct connectivity with rivers and streams and associated high permeability. This aquifer is highly susceptible to impacts from contaminant sources originating within this buffer zone as point source pollution. The intergranular Karoo aquifer can be classified as a secondary porosity aquifer and is generally unconfined with phreatic water levels. Due to higher effective porosity (n) this aquifer is highly susceptible to impacts from contaminant sources originating within this buffer zone as point source pollution.	+1

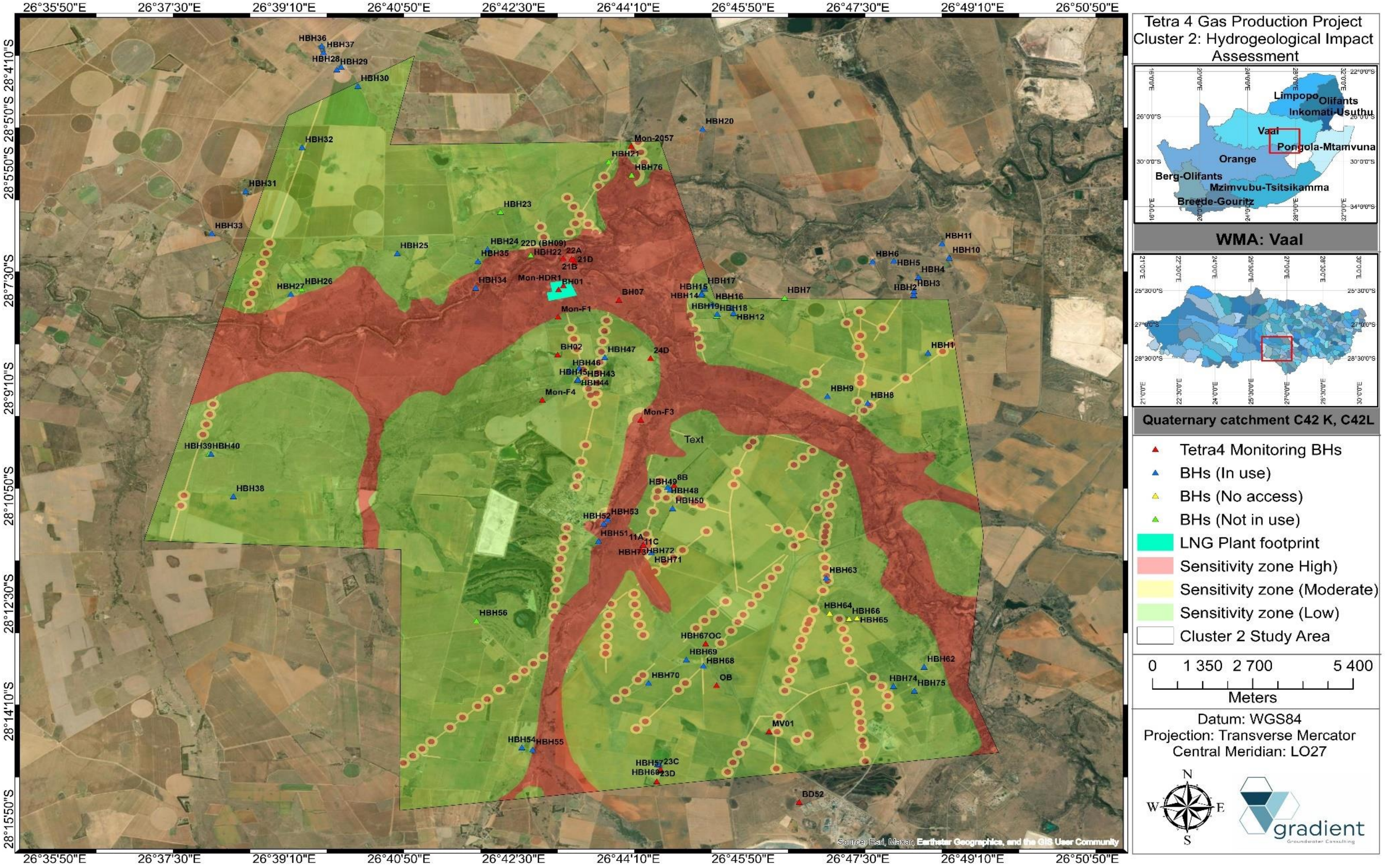


Figure 13-1 **Hydrogeological sensitivity map.**

14. GROUNDWATER MANAGEMENT PLAN

The purpose of the groundwater management plan is to provide a guideline and framework for the applicant to identify, mitigate and minimize potential impacts of the proposed operations on sensitive environmental and groundwater receptors. This management plan is applicable to the construction, operational and decommissioning/ post-closure phases of the project.

14.1. Potential impacts and associated risks

The following main impacts and associated risks have been identified as part of the groundwater impact assessment:

i. Contamination of the shallow, intergranular aquifer caused by migration of saline water and/or stray methane gas from the deep, fractured aquifer. If the gas wells are constructed and sealed off to protect the shallow potable Karoo aquifers, the impacts associated with the project can be minimised.

ii. Groundwater pollution as a result of wastewater spills and seepage from the plant footprint area as well as potential leachate from hazardous chemical substances on-site.

iii. Leakage of harmful substances from tanks, pipelines or other equipment may cause groundwater pollution.

iv. Hydrocarbon contamination of groundwater resources caused by heavy vehicle and machinery on-site.

v. Leachate of contaminants used in the drilling mud sump(s) to the intergranular, potable aquifer(s) during the operational phase.

14.2. Key responsibilities

The following management and mitigation measures should be implemented as part of the integrated groundwater management plan. The applicant will be responsible for compliance with the proposed groundwater management plan. Operational staff should implement the following measures:

i. The Licensee shall appoint a suitably qualified and responsible person to give effect to all recommendations as stipulated in specialist reports to ensure compliance to licence conditions pertaining to activities to ensure that potential impact(s) are minimised, and mitigation measures proposed are functioning effectively.

ii. An ECO must be appointed to oversee the rehabilitation phase and ensure least possible harm to biodiversity and ensure compliance to the rehabilitation plan.

iii. Compile annual reports that will be submitted to the applicable regulatory authorities.

iv. Annual external audits should be conducted to ensure that waste facilities are maintained and functioning effectively and according to licence conditions.

v. Any water use activity exercised in terms of Section 21 of the National Water Act (Act 36 of 1998) should be authorised.

vi. Listed environmental activities should be authorised in terms of the National Environmental Management Act (Act 107 of 1998).

14.3. Mitigation and management

To follow is a brief description of mitigation and management measures to be implemented per phase.

14.3.1. Construction phase: Management and mitigation measures

Mitigation and management measures associated with the construction phase activities include the following:

i. Areas where vegetation has been cleared shall be rehabilitation as soon as possible to minimise erosion. Erosion control measures should be put in place where it is deemed necessary.

ii. Clean surface water runoff to be diverted around disturbed areas and discharged to the downstream catchment zones.

iii. Develop and implement a stormwater management plan in accordance with GN704 to separate dirty/contact water from clean water circuits.

iv. Location of construction camps must be carefully considered and within the approved area to ensure that the site does not impact on sensitive areas identified during the Environmental Assessment phase or field work.

v. Sites must be located, where possible, on previously disturbed areas and e very effort must be made to keep the footprint as small as possible.

vi. All construction should take place during the dry season, as far as possible.

vii. Any excess sand, stone and cement must be removed or reused from site on completion of the construction period and disposed at a registered disposal facility. Certificates of safe disposal for general and recycled waste must be maintained and retained on file.

viii. Hazardous substance containment facilities to be used during construction phase should comply with the relevant hazardous substance storage legislation to ensure spillages are contained.

ix. All hazardous substances used on-site should have an applicable Material Safety Data Sheet (MSDS) to provide information regarding the hazards, emergency response, protective measures and correct storage methodology.

x. All hazardous substances and material used on-site should be stored in a dedicated, closed-off facility with an impervious floor and bunded area to prevent seepage and/or run-off in case of accidental spills.

xi. The use of all materials, fuels and chemicals which could potentially leach into groundwater must be controlled.

xii. Construction vehicles and machines must be serviced and maintained regularly to ensure that oil spillages are limited.

xiii. Workshop areas must be monitored for oil and fuel spills.

xiv. Spill trays must be provided if refuelling of construction vehicles is done on site. Further to this spill kits must be readily available in case of accidental spillages.

xv. Employees must be trained in terms of emergency response towards bulk chemical and hydrocarbon spillages.

xvi. An appropriate number of spill kits must be available and must be in all areas where activities are being undertaken.

xvii. Leaking equipment must be repaired immediately or be removed from site to facilitate repair.

xviii. An integrated groundwater water monitoring program should be developed and implemented to ensure that groundwater monitoring is conducted and to formulate groundwater baseline conditions to be used as benchmark for future comparison.

14.4. Operational phase: Management and mitigation measures

Mitigation and management measures associated with the operational phase activities include the following:

i. All exploration wells should be sealed-off with a combination of casing and grouting to ensure isolation of the gas from the host-aquifer(s). Well design will be undertaken according to designs developed by a qualified well engineer.

ii. Daily inspections of drilling pads, pipelines, compressors and the helium plant must be implemented.

iii. Development and implementation of an integrated groundwater monitoring program evaluating hydrochemistry as well as water levels will serve as early warning mechanism to implement mitigation measures.

iv. The existing groundwater flow model should be recalibrated with time-series monitoring data on a biennial basis to be applied as water management tool. Scenario predictions and model simulations should be conducted and interpreted by an external and independent specialist.

v. Mining vehicles and machinery must be serviced and maintained regularly to ensure that oil spillages are limited. Spill trays must be provided if refuelling of operational vehicles is done on site. Further to this spill kits must be readily available in case of accidental spillages with regular spot checks to be conducted.

vi. Plant areas must be fitted with a containment facility for the collection of dirty water. This facility must be impervious to prevent soil and groundwater contamination.

vii. The plant area must have a concrete slab that is sloped to facilitate runoff into a collection sump.

viii. Hazardous substance containment facilities to be used during operational phase should comply with the relevant hazardous substance storage legislation to ensure spillages are contained.

ix. Develop and implement a stormwater management plan in accordance with GN704 to separate dirty/contact water from clean water circuits. All water retention structures, process water dams; storm water dams, retention ponds etc. should be constructed to have adequate freeboard (0.8m below overflow level) to be able to contain water from 1:50 year rain events.

x. Leaking equipment must be repaired immediately or be removed from site to facilitate repair.

xi. A rehabilitation plan must be developed based on site-specific issues and requirements including soft and hard engineering interventions and revegetation.

xii. All actively used drill mud sumps should be adequately liner with an appropriate barrier system to isolate and prevent seepage of contaminants from the host aquifer. Furthermore, a biodegradable polymer should be used as drilling lubricant.

xiii. A rehabilitation plan must be developed based on site-specific issues and performed in accordance to best practise guidelines and guided by the closure and rehabilitation plans.

xiv. Monitoring results should be evaluated on a quarterly basis by a suitably qualified person for interpretation and trend analysis and submitted to the Regional Head: Department of Water and Sanitation. Based on the water quality results, the monitoring network should be refined and updated every three to five years based on hydrochemical results obtained to ensure optimisation and adequacy of the proposed localities.

14.5. Post-operational and decommissioning phase: Management and mitigation measures

Mitigation and management measures associated with the post-operational and decommissioning phase activities include the following:

i. In the event that the casing and/or cementation in a well failure, the well can become a high-permeability conduit for saline water and stray gas from deep-seated formations to the overlying shallow Karoo aquifers. All exploration wells should be sealed-off with a combination of casing and grouting to ensure isolation of the gas from the host-aquifer(s).

ii. The contractor should prepare a consolidated site-specific closure/sealing plan to be submitted for approval. The plan should include a detailed description of the following aspects:

  - Calliper Logging should be conducted to identify and investigate potential blockages/cavities within well.
  - Cement Bond Logging should be performed to investigate the current integrity of the casing and cementation.
  - Contractor to determine the most suitable and appropriate closure, sealing and rehabilitation strategy with specific focus on the plugging method to ensure no vertical gas and/or fluid movements within the well.
  - Contractor to prepare a consolidated site-specific closure/sealing plan to be submitted for approval.
  - Develop cement formulation for cementing the entire well annulus.

- Develop cement formulation to top-up “no bond” or “poor bond” cemented sections between casing and formation walls – ensure cement seals and does not disperse into porous formations.
- Cement formulations and volumetric calculations to be approved by well engineer/cement specialist.
- Contractor must ensure cement mixture seals the entire well length along the well annulus. Cement plugs must be stacked along the full length and diameter of the well to surface (open hole section above the packer as well as the upper casing) to ensure efficient redundancy.
- All plugs must be tagged to ensure successful placement.
- Cementation extent: Should be from end of hole (bottom of well) to surface.
- Cementation technique: Squeeze technique - this displacement method minimizes the contamination of the cement by being able to displace fluid within the well, thus allowing for a more stable well plug. Contractor must also make use of wiper plugs for cement displacement.
- Contractor to conduct cement top-ups along the annulus and existing cemented sections showing “no bond” or “poor bond” from logging results.
- A surface / shallow cement plug (+/ 50m below ground Level) must be set, and the well casing must be cut and capped 1 m below ground level to remove the wellhead and all casing above this point.
- Integrity of the plugs must be confirmed by setting weight down on the upper most plug (using the drill string) as well as a differential pressure test for 4 hours at determined pressure with less than 10% bleed over the period. Pressure test data to be captured in 15-minute intervals for the entire 4-hour testing period.
- Contractor to prepare a comprehensive project report containing the following:
    - Calliper and CBL logging results;
    - Cement formulations and Material Safety Datahseets of all additives;
    - Cementation methodology and photographs;
    - Recorded pressure test data;
    - Well tagging photographs and coordinates;
    - Surface rehabilitation photographs.

iii. Well-specific plugging requirements should be implemented to protect the shallow potable Karoo aquifers at closure. The integrity of the seals will be pressure tested before the well decommissioning can be signed-off.

iv. A surface casing vent flow test should be conducted to determine whether gas or liquid or a combination thereof is escaping from the casing. If gas is detected during this test, additional seals should be designed and implemented.

v. Development and implementation of a post-closure groundwater monitoring program evaluating hydrochemistry will serve as early warning and detection mechanism to implement mitigation measures.

vi. A rehabilitation plan must be developed based on site-specific issues and performed in accordance to best practise guidelines and guided by the closure and rehabilitation plans.

vii. All preferred groundwater flow pathways which are in direct connection with surface topography i.e., unrehabilitated mine exploration boreholes should be sealed off and rehabilitated according to best practise guideline.

viii. It is expected that post-closure the generated pollution plume and local groundwater contamination footprint will decay and be diluted by rainfall recharge, however the lasting effect and subsequent impact on neighbouring borehole qualities should be monitored with alternative water supply sources or compensation measures available for nearby users if impacted on.

15. MONITORING

A monitoring program consists of taking regular measurements of the quantity and/or quality of a water resource at specified intervals and at specific locations to determine the chemical, physical and biological nature of the water resource and forms the foundation on which water management is based. Monitoring programmes are site-specific and need to be tailored to meet a specific set of needs or expectations. DWAF Best Practice Guideline – G3: Water Monitoring Systems (DWA, 2006), as illustrated in Figure 15-1 used as guideline for the development of this water monitoring program.

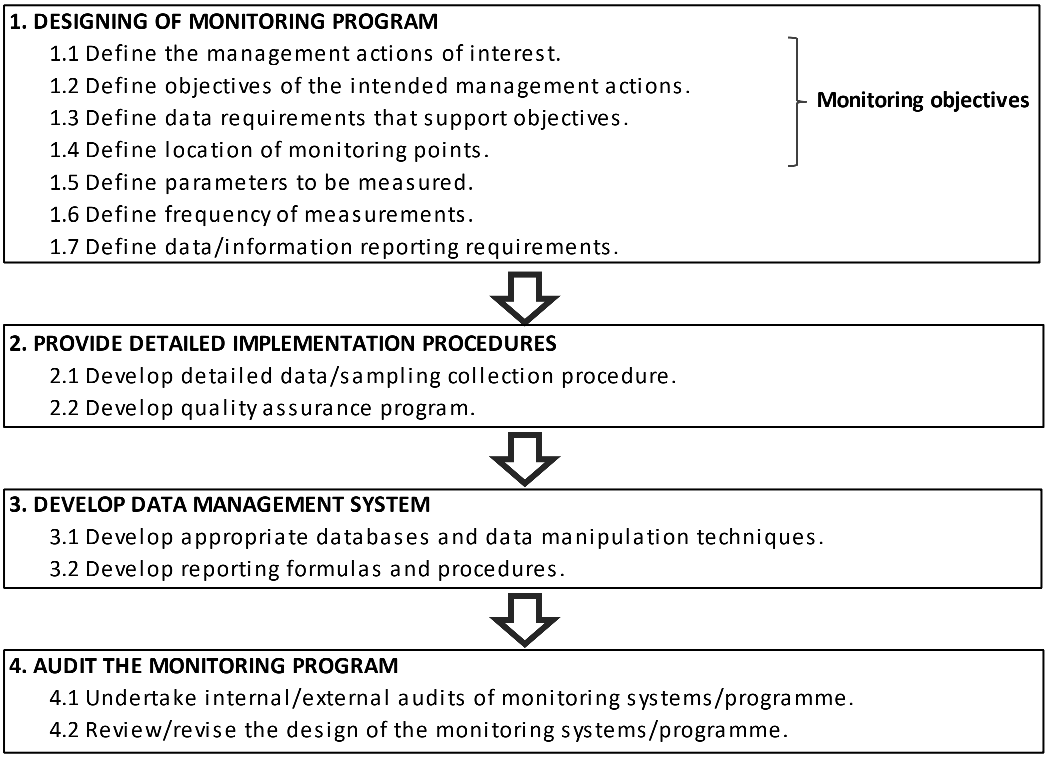


Figure 15-1 Monitoring programme (DWA, 2006).

15.1. Monitoring Objectives

Monitoring, measuring, evaluating and reporting are key activities of the monitoring programme. These actions are designed to evaluate possible changes in the physical and chemical nature of the aquifer and geo-sphere to detect potential impacts on the groundwater. This will ensure that management is timely warned of problems and unexpected impacts that might occur and can be positioned to implement mitigation measures at an early stage. Key objectives of monitoring are:

i. To provide reliable groundwater data that can be used for management purposes.

ii. The early detection of changes in groundwater quality and quantity.

iii. Provide an on-going performance record on the efficiency of the Water Management Plan.

iv. Obtain information that can be used to redirect and refocus the Water Management Plan.

v. Determine compliance with environmental laws, standards and the water use licence and other environmental authorizations.

15.2. Monitoring network

Tetra4 does have an existing monitoring protocol and network in place which was implemented das part of the phase I operations. It is recommended that additional monitoring boreholes be established down-gradient of the plant expansion footprint to evaluate the expected mass load contribution to environmental and groundwater receptors. Drilling localities for the two proposed new boreholes should be determined by means of a geophysical survey to target lineaments and weathered zones acting as preferred groundwater flow pathways and contaminant transport mechanisms. Table 15-1 summarises the proposed updated and revised monitoring network and program, with relevant information depicted in Figure 15-2. Privately owned, neighbouring boreholes situated within high impact risk areas have been included into the existing monitoring network on a bi-annual basis (after the wet and dry rainy seasons) whereas all other borehole identified as part of the hydrocensus user survey should be visited and analsyed on an annual basis. In the event that monitoring of gas production wells indicates gas leaks, casing or cementation failure and the frequency of hydrocensus boreholes are increased to monthly, the analysis must include the full set of elements.

15.3. Determinants for analysis

Baseline and background water quality results should be evaluated to set a site-specific limit per parameter and applied as benchmark for monitoring purposes. Supplementary guidelines i.e., Water Use Licence (WUL) conditions as well as WMA Resource Quality Objectives (RQO) should also be considered as part of the monitoring protocol. All monitoring localities should be subjected to an initial comprehensive water quality analysis to evaluate hydrochemical composition and identify potentially elevated parameters going forward[14]. Chemical variables to form part of the sampling run are listed below. Groundwater monitoring boreholes should be analysed for the following chemical constituents:

i. ***Physical and aesthetic determinants:*** pH, Electrical Conductivity (EC), Total Dissolved Solids (TDS) and Total Hardness.

ii. ***Macro determinants:*** Total Alkalinity (MAlk), Sulphate (SO_4), Nitrate (NO_3), Chloride (Cl), Fluoride (F), Calcium (Ca), Magnesium (Mg), Potassium (K) and Sodium (Na).

iii. ***Micro determinants:*** Aluminium (Al), Iron (Fe), Manganese (Mn), Cadmium (Cd), Total Chromium (Cr), Chromium (VI), Arsenic (As), Copper (Cu), Uranium (U), Nickel (Ni), Lead (Pb), Cobalt (Co) and Zinc (Zn), dissolved Methane (CH_4), dissolved Ethane (C_2H_6).

iv. ***Organic determinants:*** Total Oil and Grease, Dissolved Organic Carbon (DOC), Total Organic Carbon (TOC), TPH GRO C6-C10, TPH C28-C40.

15.4. Water levels

Water levels should be monitored to evaluate the impact of existing groundwater abstraction on aquifer storage and replenishment including privately owned, neighbouring boreholes.

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[14] It is recommended that a comprehensive water quality analysis be repeated annually. Also note that should additional parameters be requested in existing permits/licence conditions, these should be adhered to.

15.5. Monitoring frequency

Groundwater monitoring, i.e., water level measurements and quality analysis should be conducted on a quarterly basis at existing Tetra4 boreholes (included newly proposed monitoring localities down-gradient of the plant area) whereas water level and water quality monitoring at privately owned boreholes should be conducted on a bi-annual basis. Water quality reports summarising monitoring results should be submitted to the Regional Head of the Department within timeframes as stipulated in the WUL conditions.

15.6. Sampling procedure

The sampling procedure for groundwater should be done according to the protocol by Weaver, 1992. The actions can be summarised as follows:

1. Calibrate the field instruments before every sampling run. Read the manufacturers manual and instructions carefully before calibrating and using the instrument.
2. Bail the borehole.
3. Sample for chemical constituents – remove the cap of the plastic 1 litre sample bottle, but do not contaminate inner surface of cap and neck of sample bottle with hands. Fill the sample bottle without rising.
4. Leave sample air space in the bottle (at least 2.5 cm) to facilitate mixing by shaking before examination.
5. Replace the cap immediately.
6. Complete the sample label with a water-resistant marker and tie the label to the neck of the sample bottle with a string or rubber band. The following information should be written on the label.
   - A unique sample number and description
   - The date and time of sampling
   - The name of the sampler
7. Place sample in a cooled container (e.g., cool box) directly after collection. Try and keep the container dust-free and out of any direct sunlight. Do not freeze samples.
8. Complete the data sheet for the borehole.

See to it that the sample gets to the appropriate laboratory as soon as possible, samples for chemical analysis should reach the laboratory preferably within seven days.

Table 15-1 Revised monitoring network and programme.

Monitoring locality	Latitude	Longitude	Locality description	Monitoring frequency		Parameters
				Water quality	Water level	
Existing monitoring boreholes						
11A	-28.193137	26.739703	Existing Tetra4 Monitoring borehole	Quarterly	Quarterly	As in Section 15.3
11C	-28.194320	26.739080	Existing Tetra4 Monitoring borehole	Quarterly	Quarterly	
15E	-28.277361	26.641556	Existing Tetra4 Monitoring borehole	Quarterly	Quarterly	
21A (BH05)	-28.119556	26.722806	Existing Tetra4 Monitoring borehole	Quarterly	Quarterly	
21B	-28.119389	26.722333	Existing Tetra4 Monitoring borehole	Quarterly	Quarterly	
21D	-28.120278	26.723028	Existing Tetra4 Monitoring borehole	Quarterly	Quarterly	
22A	-28.119194	26.720306	Existing Tetra4 Monitoring borehole	Quarterly	Quarterly	
22D (BH09)	-28.117306	26.721722	Existing Tetra4 Monitoring borehole	Quarterly	Quarterly	
23C	-28.251048	26.743863	Existing Tetra4 Monitoring borehole	Quarterly	Quarterly	
23D	-28.254167	26.742944	Existing Tetra4 Monitoring borehole	Quarterly	Quarterly	
24D	-28.144972	26.741444	Existing Tetra4 Monitoring borehole	Quarterly	Quarterly	
25A	-28.287028	26.742056	Existing Tetra4 Monitoring borehole	Quarterly	Quarterly	
25B	-28.302167	26.743083	Existing Tetra4 Monitoring borehole	Quarterly	Quarterly	
8B	-28.177728	26.747135	Existing Tetra4 Monitoring borehole	Quarterly	Quarterly	
BD52	-28.259487	26.777427	Existing Tetra4 Monitoring borehole	Quarterly	Quarterly	
BH01	-28.127231	26.719194	Existing Tetra4 Monitoring borehole	Quarterly	Quarterly	
BH02	-28.144047	26.718938	Existing Tetra4 Monitoring borehole	Quarterly	Quarterly	
BH07	-28.129905	26.733792	Existing Tetra4 Monitoring borehole	Quarterly	Quarterly	
Mon-2057	-28.090217	26.736790	Existing Tetra4 Monitoring borehole	Quarterly	Quarterly	
Mon-F1	-28.134285	26.719059	Existing Tetra4 Monitoring borehole	Quarterly	Quarterly	
Mon-F3	-28.160855	26.739085	Existing Tetra4 Monitoring borehole	Quarterly	Quarterly	
Mon-F4	-28.155733	26.715230	Existing Tetra4 Monitoring borehole	Quarterly	Quarterly	
Mon-HDR1	-28.126232	26.720356	Existing Tetra4 Monitoring borehole	Quarterly	Quarterly	
MV01	-28.241273	26.770132	Existing Tetra4 Monitoring borehole	Quarterly	Quarterly	
OB	-28.229342	26.757408	Existing Tetra4 Monitoring borehole	Quarterly	Quarterly	
OC	-28.218611	26.754778	Existing Tetra4 Monitoring borehole	Quarterly	Quarterly	
Existing boreholes in private use						
HBH01	-28.156508	26.794027	Borehole in private use for livestock purposes. Monitoring pollution plume migration from gas production boreholes	Bi-annually	Bi-annually	As in Section 15.3
HBH08	-28.156508	26.794027	Borehole in private use for livestock purposes. Monitoring pollution plume migration from gas production boreholes	Bi-annually	Bi-annually	

Monitoring locality	Latitude	Longitude	Locality description	Monitoring frequency		Parameters
				Water quality	Water level	
HBH27	-28.128449	26.654374	Borehole in private use for domestic and livestock purposes. Monitoring pollution plume migration from gas production boreholes	Bi-annually	Bi-annually	
HBH39	-28.169627	26.635037	Borehole in private use for domestic and livestock purposes. Monitoring pollution plume migration from gas production boreholes	Bi-annually	Bi-annually	
HBH41	-28.147466	26.724128	Borehole in private use for domestic and irrigation purposes. Monitoring pollution plume migration from gas production boreholes	Bi-annually	Bi-annually	
HBH42	-28.147499	26.724159	Borehole in private use for domestic and irrigation purposes. Monitoring pollution plume migration from gas production boreholes	Bi-annually	Bi-annually	
HBH43	-28.151021	26.725400	Borehole not in use. Monitoring pollution plume migration from gas production boreholes	Bi-annually	Bi-annually	
HBH48	-28.178267	26.745580	Borehole in private use for domestic and livestock purposes. Monitoring pollution plume migration from gas production boreholes	Bi-annually	Bi-annually	
HBH49	-28.178856	26.746212	Borehole in private use for domestic and livestock purposes. Monitoring pollution plume migration from gas production boreholes	Bi-annually	Bi-annually	
HBH50	-28.183719	26.746794	Borehole in private use for domestic and livestock purposes. Monitoring pollution plume migration from gas production boreholes	Bi-annually	Bi-annually	
HBH63	-28.201657	26.783977	Borehole in private use for livestock purposes. Monitoring pollution plume migration from gas production boreholes	Bi-annually	Bi-annually	
HBH66	-28.212197	26.789505	Borehole in private use for livestock purposes. Monitoring pollution plume migration from gas production boreholes	Bi-annually	Bi-annually	
HBH72	-28.193122	26.739700	Borehole not in use. Monitoring pollution plume migration from gas production boreholes	Bi-annually	Bi-annually	
HBH73	-28.193009	26.739636	Borehole in private use for domestic and livestock purposes. Monitoring pollution plume migration from gas production boreholes	Bi-annually	Bi-annually	
HBH74	-28.229587	26.800249	Borehole in private use for domestic and livestock purposes. Monitoring pollution plume migration from gas production boreholes	Bi-annually	Bi-annually	
Newly proposed monitoring boreholes						
Mon BH01	-28.123973	26.721958	New monitoring borehole down-gradient of the production plant serving as Doringrivier receptor	Quarterly	Quarterly	As in Section 15.3
Mon BH02	-28.124473	26.717889	New monitoring borehole down-gradient of the production plant serving as Sandrivier receptor	Quarterly	Quarterly	

Notes: All remaining boreholes as identified during the hydrocensus user survey conducted, should be included into the monitoring network on an annual basis.

Figure 15-2 **Updated integrated groundwater monitoring network.**

16. CONCLUSIONS

The following conclusions were derived from the outcomes of this investigation:

The project area's surficial geology comprises mostly aeolian sands, quaternary deposits and isolated outcrops of the Karoo Supergroup i.e., dolerite and sandstone/ shales, while the greater study area is generally also underlain by rocks of the Witwatersrand Supergroup as well as the Ventersdorp Supergroup. Isolated patches within the study area are also covered by alluvial sand deposits which is mainly associated with the Sand and Doringriver floodplains and constrained by drainage patterns and riparian zones. The primary source of gas originates from the Witwatersrand Supergroup as well as the shallower Karoo sediments.

The site is predominantly underlain by an intergranular and fractured aquifer system (d2) with the aquifer media consisting mainly of fractured and weathered compact argillaceous strata. According to Vegter's groundwater regions delineated (2000) the study area can be classified as falling under the North-eastern Pan Belt region.

For the purposes of this investigation, four main hydrostratigraphic units/aquifer systems can be inferred in the saturated zone:

i. **A shallow quaternary and recent types of sediments** (unconfined) are characteristically a primary porosity aquifer associated with alluvium material deposited in flood plains of the main rivers traversing the study area. These aquifers cover a large portion of the study area and are limited to a zone of variable width and depth. The alluvial aquifer is specifically vulnerable to contamination as it there is a direct connectivity with rivers and streams and associated high permeability.

ii. **A shallow, intergranular aquifer** (unconfined to semi-confined) occurring in the transitional soil and weathered bedrock formations of the Karoo Supergroup rocks underlain by more consolidated bedrock. Groundwater flow patterns usually follow the topography, discharging as natural springs at topographic low-lying areas. Usually, this aquifer can be classified as a secondary porosity aquifer and is generally unconfined with phreatic water levels. Due to higher effective porosity (*n)* this aquifer is most susceptible to impacts from contaminant sources.

iii. **An intermediate, fractured aquifer** (semi-confined to confined) where pores are well-cemented and do not allow any significant flow of water. Groundwater flow is dictated by transmissive secondary porosity structures such as bedding plane fractures, faults, contact zones as well as fracture zones that occur in the relatively competent Karoo Supergroup host rock. Fractured sandstones, mudstones and shales sequences are considered as fractured rock aquifers holding water in storage in both pore spaces and fractures. This aquifer system usually displays semi-confined or confined characteristics with piezometric heads often significantly higher than the water-bearing fracture position. Although generally low yielding, this aquifer is important to local groundwater users as it forms the sole source of water supply in the region (Lea, 2017).

iv. **A deeper, fractured aquifer** (semi-confined to confined) where pores are well-cemented and do not allow any significant flow of water. Groundwater flow is dictated by transmissive secondary porosity structures such as bedding plane fractures, faults and contact zones fracture zones that occur in the relatively competent Ventersdorp and Witwatersrand Supergroups host rock. Volcanic formations of the Ventersdorp lavas can also act as aquicludes, restricting the vertical movement of groundwater. Fractured quartzites of the Witwatersrand Supergroup are considered as fractured rock aquifers holding water in storage in both pore spaces and fractures. Groundwater yields, although more heterogeneous, can be expected to be higher than the weathered zone aquifer. This aquifer system usually displays semi-confined or confined characteristics with piezometric heads often significantly higher than the water-bearing fracture position.

The water in the deep aquifers is naturally saline due to their marine depositional history. It should be noted that the shallow potable Karoo aquifers are separated from deep aquifer systems associated with the Ventersdorp and Witwatersrand Supergroup formations by the 30.0m thick dolerite sill (which may act as an aquitard) that extends across the study area and by the 65.0m thick Dwyka Tillite sedimentary deposit acting as an aquiclude. It should furthermore be noted that, under natural conditions, there is very limited hydraulic connectivity between the deep, fractured and shallow, intergranular aquifers.

The hydraulic conductivity of sedimentary formations such as evident on site can range from $10E^{-6}$ – $10E^{-2}$ m/d. Historical aquifer tests results confirm that the permeability of the shales is very low ($9E^{-4}$m/d). The hydraulic conductivity of fractured igneous rocks (i.e., dolerite) varies between $10E^{-6}$ – $10E^{-1}$ m/d, while conductivity values for un-fractured igneous rocks (i.e., fresh dolerite sill) ranges between $10E^{-9}$ – $10E^{-6}$ m/d. The hydraulic conductivity of quaternary deposits and alluvial pockets associated with the drainage system i.e., riverbed aquifers can be orders higher and can vary between $10E^{-2}$ – $10E^{1}$ m/d.

An approximation of recharge for the study area is estimated at ~4.0% of MAP i.e., ~21.69mm/a.

A total of 78 groundwater receptors i.e., boreholes, artesian wells, wind pumps as well as surface water features were visited as part of the hydrocensus user survey which are largely applied for livestock watering and domestic water supply purposes. Of the boreholes recorded, the majority are in use (>78.0%) while ~17.0% are not currently being utilized.

The unsaturated zone within the study area is in the order of 0 (fully saturated to surface) to >26.0m with a mean thickness of approximately ~9.0m. It should be noted that due to the argillaceous nature of the host aquifer(s) the shallow water levels observed at some of the borehole localities can be attributed to clay/silt lenses and be indicative of perched aquifer conditions and not necessarily represent the vadose zone.

Artesian conditions were observed at three of the boreholes visited namely HBH31, 21B as well as 8B which can be indicative of semi-confined to confined aquifer conditions present or perched aquifer conditions. The minimum water level was recorded at 0.0mbgl, while the deepest water level was measured at borehole locality Mon-HDR1 (26.71mbgl).

It is noted that most water levels suggest a decrease in water levels and recovering trend. The latter can be attributed the onset of the wet cycle and above average rainfall events experienced with rainfall recharge replenishing aquifer storage. It can be observed that there is a definite a relatively quick response to rainfall, suggesting that recharge of the shallow, intergranular aquifer takes place without a prolonged lag effect.

Statistical analyses of the water level trends furthermore suggest that the local groundwater system is in quasi-steady state conditions.

Analysed data indicate that the surveyed water levels correlate very well to the topographical elevation (R^2 <0.98). Accordingly, it can be assumed that the regional groundwater flow direction is dictated by topography. Bayesian interpolation was used to interpolate the groundwater levels throughout the study area. The inferred groundwater flow direction will be towards the lower laying drainage system(s) traversing the project area from where groundwater will discharge as baseflow. The groundwater flow direction within the southern catchment of the Sandrivier and Doringrivier, also in the vicinity of the proposed plant expansion footprint, will be in a general northern direction, whereas the groundwater flow direction within the northern catchment of the study area will be mostly in a south to southwestern direction.

The average groundwater gradient (i) of the shallow, weathered aquifer in the vicinity of the proposed plant expansion footprint is relatively flat and calculated at a mean of 0.002, with a maximum of 0.003 in a south to north orientation and a minimum of 0.001 in a general southeast to northwest orientation.

The expected seepage rate from contamination originating at the proposed plant expansion footprint as well as associated infrastructure is estimated at an average of approximately 1.26m/a, with a maximum distance of ~2.20m/a in a southern to northern direction.

Under natural conditions this area exhibits certain regions where there is pronounced interaction between surface and groundwater and regional drainages can be generally classified as influent or gaining stream systems. The alluvial associated with the floodplains of the Sand - and Doringrivier forms a primary aquifer and is directly connected with surface water resources, especially during high flow conditions.

The hydrochemical results of the hydrocensus boreholes water samples analysed suggest the overall ambient groundwater quality is good with most macro and micro determinants falling within or below the SANS 241:2015 limits. Groundwater can be described as neutral, saline to very saline and hard to very hard. The groundwater quality is impacted by the geological formations, which were deposited in shallow marine environments and are therefore naturally saline.

It is observed that most of the boreholes indicate elevated Nitrate (NO_3) concentrations. The latter may be attributed to the agricultural land-use activities dominating the greater study area with elevated NO_3 concentrations potentially derived from leachate of fertilizer to the local aquifer. It is noted that borehole localities with elevated NO_3 concentrations are generally situated within or directly down-gradient of planted crop areas as well as near surface water features.

Surface water quality can be classified as moderate to good with Aluminium (Al) and Iron (Fe) being slightly elevated. It should be noted that there is not a significant change in the downstream water quality compared to the upstream quality with an increase in Aluminium (Al), however all surface water samples analysed suggest elevated heavy metal concentrations i.e., Al and Fe.

Three distinct categories can be observed, Category A: Calcium-Bi-carbonate dominance which suggest a recently recharged and unimpacted groundwater environment (majority of samples), Category B: Calcium-

Magnesium-Chloride dominance which indicate a static and disordinate environment as well as Category C: Sodium-Potassium-Bi-carbonate dominance which indicate an area of dynamic groundwater environments.

The surface water samples analysed can be categorized as having Calcium-Magnesium-Chloride dominance which indicate a static and disordinate environment, one would except a more Calcium-Bi-carbonate signature from an unpolluted surface water source, however baseflow discharge present from the saline groundwater resource will have an impact on the salinity of the surface water resources as is evident.

Comparison of different hydrochemical signatures observed suggest on-site boreholes to target a shallow, inter-granular aquifer unit as well as a deeper (possibly intermediate, fractured aquifer unit) being more saline.

The Sodium-Potassium-Chloride dominance of the deep, fractured aquifer groundwater suggest extremely saline conditions as expected.

According to the aquifer classification map of South Africa the project area is underlain by a “Minor aquifer”. It should however be noted that the shallow, intergranular aquifer is important to local groundwater users as it form the sole source of water supply in the region. Furthermore, the primary riparian zone aquifer is classified as a major aquifer system due to its highly permeable nature as well as good water quality.

A GQM Index = 4 was calculated for the local aquifer system and according to this estimate, a “Medium” level groundwater protection is required for this aquifer system. According to the DRASTIC index methodology applied, the existing/proposed activities and associated infrastructure’s risk to groundwater pollution of the shallow, intergranular aquifer is rated as “Moderate”, Di = 109.

A numerical groundwater flow and mass transport migration model was developed and calibrated in steady state based on gathered site characterisation information which was applied as initial hydrogeological conditions for transient simulations.

A scenario was simulated representing point source pollution plume migration of saline groundwater emanating from leaking boreholes targeting the deep, fractured aquifer for the operational phase (20-year period). The TDS pollution plume extend covers a total area of approximately 414.06ha in the Karoo formations, reaching a maximum distance of ~80.0m in a radial pattern from the gas production borehole(s), and approximately 251.60ha in the alluvial deposits, reaching a maximum distance of ~200.0m in a radial pattern from the gas production borehole(s) after a simulation period of 20-years. The simulation indicates that the following neighbouring boreholes will potentially be intercepted by the simulated pollution plume HBH08, HBH41, HBH42, HBH43, HBH63, HBH72, HBH73 and HBH74.

It can be noted that the pollution plume migration in the denser Karoo formations is sluggish while movement in the unconsolidated alluvial deposits of the riparian zone suggest a larger flux.

It is evident that source term mass load contribution to existing neighbouring borehole situated near the gas production borehole(s) does not exceed ~800.0mg/l and ranges between 600mg/l to 700.0mg/l

A scenario was simulated representing point source pollution plume migration of stray methane (CH_4) gas emanating from leaking boreholes targeting the deep, fractured aquifer for the operational phase (20-year period). The CH_4 pollution plume extend covers a total area of approximately 162.74ha in the Karoo formations, reaching a maximum distance of ~50.0m in a radial pattern from the gas production borehole(s), and approximately 62.83ha in the alluvial deposits, reaching a maximum distance of ~100.0m in a radial pattern from the gas production borehole(s) after a simulation period of 20-years. The simulation indicates that the following neighbouring boreholes will potentially be intercepted by the simulated pollution plume HBH08, HBH41, HBH42, HBH43, HBH63, HBH72, HBH73 and Tetra4 monitoring borehole 11A.

It is noted that the source term mass load contribution to existing neighbouring borehole situated near the gas production borehole(s) remains below the EPA safety threshold (2011) of 10.0mg/l and ranges between 0.01mg/l to 1.50mg/l.

A scenario was simulated with a pollution plume migration from the plant footprint areas for the operational phase. The TDS pollution plume extend covers a total area of approximately 48.80ha reaching a maximum distance of ~110.0m in a general north-northwest direction towards the lower laying drainage system(s) after a simulation period of 20-years. The simulation indicates that no neighbouring boreholes or local drainages are expected to be impacted on during the operational phase.

It is evident that the TDS mass load contribution to down-gradient receptors increase to a concentration of between 200.0 – 800.0 mg/l, however, remains below the SANS 241:2015 limit of 1200.0mg/l for the duration of the simulation period.

It can be noted that the mass transport of the pollution plume is mostly limited to the shallow, intergranular aquifer.

A scenario was simulated representing point source pollution plume migration of saline groundwater emanating from leaking boreholes targeting the deep, fractured aquifer for the post-closure phase. The TDS pollution plume extend covers a total area of approximately 643.70ha in the Karoo formations, reaching a maximum distance of ~100.0m in a radial pattern from the gas production borehole(s), and approximately 392.70ha in the alluvial deposits, reaching a maximum distance of ~250.0m in a radial pattern from the gas production borehole(s) after a simulation period of 50-years. The TDS pollution plume extend covers a total area of approximately 1 456.42ha in the Karoo formations, reaching a maximum distance of ~150.0m in a radial pattern from the gas production borehole(s), and approximately 769.70ha in the alluvial deposits, reaching a maximum distance of ~350.0m in a radial pattern from the gas production borehole(s) after a simulation period of 100-years. The simulation indicates that the following neighbouring boreholes will potentially be intercepted by the simulated pollution plume HBH08, HBH41, HBH42, HBH43, HBH48, HBH50, HBH63, HBH72, HBH73, HBH74 as well as Tetra4 monitoring boreholes Mon 2057 and 11A.

It is noted that source term mass load contribution to existing neighbouring and monitoring boreholes situated near the gas production boreholes ranges between 650.0mg/l to >1200.0mg/l. Furthermore, it is observed that the SANS241:2015 limit is exceeded at borehole localities HBH63 and Mon 2057.

A scenario was simulated representing point source pollution plume migration of stray methane (CH_4) gas emanating from leaking boreholes targeting the deep, fractured aquifer for the post-closure phase. The CH_4

pollution plume extend covers a total area of approximately 414.06ha in the Karoo formations, reaching a maximum distance of ~80.0m in a radial pattern from the gas production borehole(s), and approximately 141.37ha in the alluvial deposits, reaching a maximum distance of ~150.0m in a radial pattern from the gas production borehole(s) after a simulation period of 50-years. The CH_4 pollution plume extend covers a total area of approximately 643.70ha in the Karoo formations, reaching a maximum distance of ~100.0m in a radial pattern from the gas production borehole(s,) and approximately 392.70ha in the alluvial deposits, reaching a maximum distance of ~250.0m in a radial pattern from the gas production borehole(s) after a simulation period of 100-years. The simulation indicates that the following neighbouring boreholes will potentially be intercepted by the simulated pollution plume HBH08, HBH41, HBH42, HBH43, HBH48, HBH49, HBH63, HBH72, HBH73 as well as Tetra4 monitoring boreholes Mon 2057 and 11A.

It is evident that source term mass load contribution to existing neighbouring and monitoring boreholes situated near the gas production boreholes ranges between 0.50mg/l to ~2.0mg/l, however, remains below the EPA safety threshold (2011) of 10.0mg/l.

A scenario was simulated with a pollution plume migration from the plant footprint areas for the post-closure phase. The TDS pollution plume extend covers a total area of approximately 54.8ha reaching a maximum distance of ~170.0m in a general north-northwest direction towards the lower laying drainage system(s) after a simulation period of 50-years and covers a total area of approximately 71.20ha reaching a maximum distance of ~300.0m in a general north-northwest direction towards the lower laying drainage system(s) after a simulation period of 100-years. It is evident that the pollution plume potentially reaches the local drainages system down-gradient of the plant footprint during the post-closure phase.

It is observed that the TDS mass load contribution to down-gradient receptors increase to a concentration above the SANS 241:2015 limit of 1200.0mg/l for the post-closure simulation period. It is noted that the TDS mass load contribution increases to a percentage of ~10.0% to the Sandrivier where the mass load contribution to the Doringrivier increase to a percentage of ~2.0% for the duration of the post-closure simulation period.

It should be noted that vast areas within the study area have been subjected to historical mining activities and, as such, reflect modified to highly modified present ecological status. A total number of >15 000 historical exploration wells have been drilled throughout the study area, some of which remain uncased and unsealed. The latter may act as preferential pathways and conduits for groundwater flow and contaminant transport mechanisms. As mentioned earlier an impact can be defined as any change in the physical-chemical, biological, cultural and/or socio-economic environmental system that can be attributed to human and/or other related activities. Accordingly, this already highly modified zones should form part of the impact significance rating and risk approach.

During the construction phase the environmental significance rating of groundwater quality impacts on down-gradient receptors are rated as **medium negative** without implementation of remedial measures and **low negative** with implementation of proposed mitigation measures. The main impacts associated with the construction phase activities include the following:

i. Groundwater deterioration and siltation due to contaminated stormwater run-off from the construction area.
ii. Poor quality leachate may emanate from the construction camp which may have a negative impact on groundwater quality.
iii. Mobilisation and maintenance of heavy vehicles and machinery on-site may cause hydrocarbon contamination of groundwater resources.
iv. Poor storage and management of hazardous chemical substances on-site may cause groundwater pollution.

During the operational phase the environmental significance rating of groundwater quality impacts on down-gradient receptors are rated as **medium** to **high negative** without implementation of remedial measures and **low** to **medium negative** with implementation of proposed mitigation measures. The main impacts associated with the operational phase activities include the following:

i. Migration of saline groundwater from the deep, fractured aquifer to the overlying, potable aquifer(s) during the gas production phase.
ii. Migration of stray methane (CH_4) gas from the deep, fractured aquifer to the overlying, potable aquifer(s) during the gas production phase.
iii. Groundwater pollution because of wastewater spills and seepage from the evaporation dams.
iv. Poor quality leachate may emanate from the plant footprint area which may have a negative impact on groundwater quality.
v. Mobilisation and maintenance of heavy vehicle and machinery on-site may cause hydrocarbon contamination of groundwater resources.
vi. Poor storage and management of hazardous chemical substances on-site may cause groundwater pollution.
vii. Leakage of harmful substances from tanks, pipelines or other equipment may cause groundwater pollution.
viii. Leachate of contaminants used in the drilling mud sump(s) to the intergranular, potable aquifer(s) during the operational phase.

During the decommissioning and post-closure phase the environmental significance rating of groundwater quality impacts on down-gradient receptors are rated as **medium negative** without implementation of remedial measures and **low** to **medium negative** with implementation of proposed mitigation measures. The main impacts associated with the post-closure and decommissioning phase activities include the following:

i. Migration of saline groundwater from the deep, fractured aquifer to the overlying, potable aquifer(s) during the borehole closure and decommissioning phase.
ii. Migration of stray methane (CH_4) gas from the deep, fractured aquifer to the overlying, potable aquifer(s) borehole closure and decommissioning phase.
iii. Groundwater pollution because of wastewater spills and seepage from the evaporation dams.
iv. Poor quality leachate may emanate from the plant footprint area which may have a negative impact on

groundwater quality.

v. De-mobilisation of heavy vehicle and machinery as part of the decommissioning phase on-site may cause hydrocarbon contamination of groundwater resources.

The most significant impact of the project on the regional groundwater regime is deterioration of the potable Karoo aquifer water quality as well as modification of the riparian zone primary porosity aquifer associated with alluvium material deposited in flood plains. Groundwater is the sole water resource to the landowners and rural communities within the study area and can thus be classified as a sole source aquifer. It can be concluded that, should the prescribed mitigation and management measures, as stipulated in the groundwater management plan, be implemented and honoured, the impacts associated with the project phases can be minimised. It is important that an integrated groundwater monitoring program be developed and applied serving as an early warning and detection mechanism to implement mitigation measures. The calibrated groundwater flow model should be applied as groundwater management tool for future scenario predictions.

17. RECCOMMENDATIONS

The following recommendations are proposed following this investigation:

i. Mitigation and management measures as set out in the groundwater management plan should be implemented as far as practically possible. It should be noted that the mitigation and management measures recommended in this report should be incorporated into the existing EMPr groundwater management plan and do not substitute the existing mitigation measures, but rather supplement them.

ii. Any development and/or drilling which takes place within the primary porosity aquifer associated with alluvium material deposited in flood plains must be avoided where possible and restricted if it cannot be avoided.

iii. The identified hydrogeological sensitive areas and buffer zones delineated as part of this assessment must be adhered to during the construction and operational phase activities. It is recommended that a localised hydrocensus user survey be performed within a 500.0m radius of each proposed gas production borehole situated within the riparian zone(s) and 350.0m radius of each proposed gas production borehole situated within the Karoo formations in order to identify the presence of other sensitive groundwater receptors and/or private boreholes. Accordingly, the gas production well design must take the results of the hydrocensus into consideration, specifically with regard to the planning and placement of boreholes as part of future drilling programmes.

iv. Additional monitoring boreholes should be established down-gradient of the existing and proposed plant expansion footprints to evaluate the mass load contribution to sensitive environmental and groundwater receptors. Drilling localities should be determined by means of a geophysical survey to target lineaments and weathered zones acting as preferred groundwater flow pathways and contaminant transport mechanisms.

v. It is recommended that the revised monitoring program as set out in this report should be implemented and adhered to. It is imperative that monitoring be conducted to serve as an early warning and detection system. Monitoring results should be evaluated on a bi-annual basis by a suitably qualified person for interpretation and trend analysis and submitted to the Regional Head: Department of Water and Sanitation.

vi. The numerical groundwater flow modelling assumptions should be verified and confirmed. The calibrated groundwater flow model should be updated on a biennial basis as newly gathered monitoring results become available to be applied as groundwater management tool for future scenario predictions.

vii. All preferred groundwater flow pathways which are in direct connection with surface topography such as decommissioned gas production boreholes as well as historical mining exploration boreholes should be sealed off and rehabilitated according to best practise guidelines.

18. REFERENCES

Alloway, B. J. 1995. Heavy metals in soils – Second Edition. Blackie Academic & Professional.

American Society for Testing and Materials, 1993. Standard Guide for Application of a Ground-Water Flow Model to a Site-Specific Problem. ASTM. Standard D 5447-93, West Conshohocken, PA.

Anderson, M.P. and Woessner, W.W., 1992. Applied Groundwater Modelling. Academic Press, Inc., San Diego, CA., 381 p.

Aller, L., Bennet, T., Lehr, J.H., Petty, R.J. and Hacket, G. 1987. DRASTIC: A standardized system for evaluating groundwater pollution using hydrological settings. Prepared by the National Water Well Association for the US EPA Office of Research and Development, Ada, USA.

Aquiworx software. 2014. Version 2.5.2.0. Centre for Water Sciences and Management at the North-West University.

Barnard, H. C., 2000. An explanation of the 1:500 000 general Hydrogeological Map. Kroonstad 2726.

Bean, J.A., 2003. A critical review of recharge estimation methods used in southern Africa. PhD thesis, (unpubl). University of the Free State, South Africa.

Bear, J. 1979. Hydraulics of Groundwater. Dover Publications, Inc. Mineola, New York. ISBN-13:978-0-486-45355-2.

Botha JF, Verwey JP, Van der Voort I, Vivier JJP, Buys J, Colliston WP and Loock JC, 1998. Karoo Aquifers – Their Geology, Geometry and Physical Properties, WRC Report No 487/1/98, August 1998.

Bredenkamp, D., Botha, L.J., Van Tonder, G.J. and Janse van Rensburg, H., 1995. Manual on qualitative estimation of groundwater recharge and aquifer storativity, based on practical hydro-logical methods. Water Research Commission, TT 73/95. ISBN 1 86845 1763.

Chief Directorate. Surveys and Mapping. 2003. Cape Town, 2826BA, 2826BB, 2826BC, 2826BD [Map]. Edition 9. Scale 1:50,000. Mowbray, South Africa: Chief Directorate of Surveys and Mapping.

Council of Geoscience geological map sheet 2826 (Winburg)(1:250 000).

Council for Scientific and Industrial Research (CSIR) and South African National Biodiversity Institute (SANBI), 2020. *Generic Environmental Management Programme (EMPr) for Gas Pipeline Infrastructure.* CSIR Report Number: CSIR/SPLA/EMS/IR/2019/0073/B.

Department of Environment, Forestry and Fisheries: 2021. *Identification of a generic environmental management programme relevant to an application for environmental authorisation for the development or expansion of gas transmission pipeline infrastructure*. Government Notice No. 44481.

Department of Water Affairs: Directorate Hydrological Services, 2012. Aquifer classification of South Africa.

Department of Water Affairs: Directorate Hydrological Services, 2012. Aquifer susceptibility of South Africa.

Department of Water Affairs: Directorate Hydrological Services, 2012. Aquifer vulnerability of South Africa.

Department of Water Affairs and Forestry, South Africa. 2004. Internal Strategic Perspective: Middle Vaal Water Management Area. Prepared by PDNA, WMB and WRP on behalf of the Directorate National Water Resources Planning. Report no. 09/000/00/0304.

Department of Water Affairs and Forestry Directorate. 2008. Best Practice Guideline – G3: Water Monitoring Systems. ISBN978-0-9814156-0-4.

Department of Water Affairs and Forestry Directorate. 2008. Best Practice Guideline - G5: Water Management Aspects for Mine Closure. ISBN978-0-9814156-0-4.

EIA Regulations, 2017. Government Notice (GN) R982.

EIMSa, 2016. Scoping Report, Tetra4 Production Right Environmental Impact Assessment and Environmental Management Programme for the Proposed Cluster 1 Gas Production near Virginia, Free State Province, and Volume 1 of 3, undated.

EIMSb, 2016. Issues and Response Report, Tetra4 Production Right Environmental Impact Assessment and

Environmental Management Programme for the Proposed Cluster 1 Gas Production near Virginia, Free State Province, Volume 1 of 3, EIMS Ref. 1109, PASA Ref, 12/4/1/07/2/2, undated.

ESRI basemaps, 2022.

Fetter, C.W. 1994. Applied Hydrogeology. Pearson new international edition. 4th Edition. Pearson Education Limited. ISBN-13: 978-0130882394.

Freeze, R. Allan, and John A. Cherry. 1979. Groundwater. Prentice Hall Inc., New Jersey.

Google Earth, 2022. 6.0.12032 Beta.

Johnson, MR. Anhauser, CR., Thomas, RJ., 2006. The geology of South Africa. Council for Geoscience. ISBN 1-919908-77-3.

Kruseman, G.P, de Ridder, N.A., 1994. Analysis and Evaluation of Pumping Test Data. International Institute for Land Reclamation and Improvement/lLRI (2000). ISBN 90 70754 207.

Lea, I. 2017. *Tetra 4 Cluster 1 Production Right EIA Hydrogeological Specialist Report.* Report No iLEH-EIMS MOL-1 05-15.

Lynch, S.D., Reynders, A.G. and Schulze, R.E., 1994: A DRASTIC approach to groundwater vulnerability mapping in South Africa. SA Jour. Sci., Vol. 93, pp 56 - 60.

Pannell, D., 1997. *Sensitivity analysis of normative economic models: theoretical framework and practical strategies*. Agricultural Economics, 1997, vol. 16, issue 2, 139-152.

Parsons, R, 1995. A South African Aquifer System Management Classification, Water Research Commission, WRC Report No KV 77/95.

PASA, 2021. Virginia Production Right Gas Well Closure, Abandonment and Rehabilitation Guidelines. REF#: 12/4/1/07/2/2 PR.

Piper, A., 1944. *A graphic procedure in the geochemical interpretation of water-analyses*. Transactions, American Geophysical Union. 25 (6): 914–928.

Spitz, K. and Moreno, J., 1996. *A Practical Guide to Groundwater and Solute Transport Modelling*. A Wiley-Interscience publication.

SANS 241: 2015. South African National Standards: Physical, aesthetic, operational and chemical determinants for drinking water.

Schulze, R. 1989. ACRU: Background, Concepts and Theory. Report 35, Agricultural Catchments Research Unit, Department of Agricultural Engineering, University of Natal, Pietermaritzburg, South Africa.

Shango, 2016. Development of exploration strategies for gas plays in the Virginia, Kroonstad and Heilbron areas, Report No SS0530/15, prepared by Shango Solutions, dated 20 January 2016.

Spitz, K. and Moreno, J., 1996. A Practical Guide to Groundwater and Solute Transport Modelling. A Wiley-Interscience publication.

Steyl, G, Van Tonder, GJ, and Chevallier, L, 2012. State of the art: Fracking for shale gas exploration in South Africa and the impact on water resources, WRC Report No KV 294/11, dated February 2012.

Tetra 4. 2022. Tetra 4 Cluster 1 monthly groundwater monitoring data.

van Tonder and Xu, 2000. Program to estimate groundwater recharge and the Groundwater Reserve.

Water Research Commission (WRC), 2012. Water Resources of South Africa.

WR 2012. Rainfall and meteorological data.

Vegter, JR., DWS and WRC, 1995. Groundwater Resources of the Republic of South Africa.

Vegter, JR., 2006. Hydrogeology of Groundwater Region 26: Bushmanland. WRC Report No TT 285/06.

Weaver, MC. Cave, L. and Talma, AS. 1992. *Groundwater Sampling (Second Edition).* WRC Report TT303/07.

Younger, P.L., R.S., 2007. Groundwater in the environment: An introduction. Blackwell Publishing.

19. APPENDIX A: RAINFALL DATA (RAINFALL ZONE 4C4)

Year	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Total
1920	45.0	34.3	57.4	48.7	62.9	123.0	31.7	31.1	0.1	0.0	0.2	3.1	437.5
1921	14.7	129.2	198.3	101.3	19.0	53.2	1.4	24.4	20.4	0.0	11.8	1.3	575.0
1922	32.6	112.4	79.8	53.0	109.8	29.2	42.9	27.3	17.2	8.4	9.4	0.7	522.7
1923	36.9	40.7	14.1	72.8	63.8	107.6	11.3	3.9	0.2	0.1	3.9	62.4	417.6
1924	63.6	128.4	101.9	99.0	36.7	194.4	64.0	27.8	6.0	0.1	0.3	16.6	738.9
1925	16.1	17.0	34.2	72.8	101.4	61.1	17.6	2.5	1.0	0.1	0.4	23.3	347.6
1926	53.0	41.2	60.6	99.0	36.1	91.9	14.0	0.1	0.1	30.2	3.0	2.1	431.2
1927	39.2	22.0	66.3	141.2	40.1	102.3	38.8	0.9	0.7	0.1	4.2	21.9	477.5
1928	41.3	50.6	42.8	135.5	30.9	74.6	19.4	30.6	42.0	19.6	18.1	81.5	587.0
1929	10.7	73.7	100.8	71.6	61.1	71.8	39.1	13.8	4.0	4.7	2.9	1.3	455.5
1930	31.8	31.2	48.5	116.3	74.5	65.2	134.1	0.1	6.7	20.9	0.8	1.1	531.1
1931	73.9	119.0	32.2	26.4	83.4	58.6	8.1	1.1	1.3	0.1	0.2	9.7	413.9
1932	10.4	62.4	97.3	12.0	29.1	52.2	40.4	3.3	3.4	0.1	0.8	7.0	318.4
1933	18.0	147.8	102.0	264.8	57.4	72.6	49.0	86.7	13.1	31.3	9.9	6.1	858.7
1934	76.1	125.8	68.9	36.1	63.8	83.9	54.6	14.8	2.3	0.1	8.4	14.3	549.2
1935	20.7	95.6	81.9	66.8	75.9	104.0	35.1	30.8	0.1	0.1	0.1	0.9	511.8
1936	41.8	212.6	38.6	141.1	71.5	56.3	13.0	3.6	0.1	0.4	0.5	15.9	595.3
1937	1.5	24.2	64.1	127.2	122.1	20.6	48.1	13.3	18.8	7.6	12.5	3.0	463.1
1938	94.0	13.6	68.4	101.4	123.7	29.6	5.5	25.7	2.7	30.1	31.0	4.6	530.3
1939	61.5	85.0	27.0	30.0	68.8	88.7	44.7	10.0	13.7	0.2	0.7	23.7	453.7
1940	2.8	94.5	68.5	145.9	91.1	37.7	53.8	0.2	0.2	2.7	0.2	14.9	512.3
1941	59.6	9.8	24.9	110.0	63.9	104.7	62.5	11.1	0.1	0.1	43.9	6.7	497.1
1942	87.2	68.4	137.1	83.3	71.0	82.5	102.3	112.4	0.1	52.6	51.8	11.7	860.3
1943	103.1	155.2	135.1	67.2	140.4	52.9	0.7	16.5	51.7	0.1	0.2	38.8	761.9
1944	60.4	86.0	12.5	51.5	55.3	112.7	5.7	13.3	0.1	3.2	0.2	0.7	401.6
1945	14.3	19.2	28.0	129.3	68.0	121.8	33.3	26.6	0.1	0.1	0.1	2.0	442.6
1946	84.8	34.1	53.4	54.0	52.0	58.6	72.9	5.5	0.1	10.5	0.3	26.4	452.4
1947	39.3	60.4	129.0	86.1	38.9	214.2	67.1	15.2	0.1	0.1	0.1	4.1	654.5
1948	34.1	57.8	11.6	64.9	31.9	55.8	15.0	10.1	4.9	3.6	8.8	5.7	304.2
1949	38.1	51.0	106.5	65.1	64.8	88.2	92.0	58.1	4.9	12.2	20.1	2.9	603.9
1950	39.8	37.0	107.9	77.5	47.5	72.8	71.2	19.1	9.2	10.8	7.2	4.0	504.0
1951	45.6	18.2	24.2	54.1	91.2	47.3	21.3	0.7	2.4	30.0	0.4	7.2	342.6
1952	51.2	83.9	137.4	22.2	138.2	40.8	50.3	6.9	0.1	0.1	8.4	1.3	540.9
1953	72.4	68.5	50.1	48.6	125.3	108.8	13.1	14.8	14.0	1.6	0.1	2.4	519.8

Year	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Total
1954	7.5	36.3	67.9	159.4	127.7	32.1	71.0	27.2	10.6	2.0	0.2	1.9	543.9
1955	38.9	50.6	86.2	35.1	161.7	103.9	15.5	40.5	0.5	0.1	0.1	19.7	552.8
1956	103.3	51.0	145.3	132.6	43.3	58.1	33.7	2.6	29.0	21.3	21.6	130.3	772.2
1957	119.3	62.5	121.1	182.5	33.4	47.6	48.6	27.6	0.4	0.0	0.1	21.9	665.0
1958	22.6	40.6	99.1	54.8	41.0	37.6	74.2	54.7	1.4	31.7	0.1	2.8	460.5
1959	57.7	49.7	79.5	37.3	70.9	75.9	50.4	7.7	3.0	14.1	24.0	10.3	480.3
1960	37.5	39.4	116.1	69.1	37.3	45.3	97.7	34.7	36.6	4.5	6.5	2.3	527.1
1961	1.3	105.6	37.9	38.6	89.4	79.6	46.2	2.5	0.1	0.0	1.1	8.4	410.6
1962	35.0	61.5	51.9	119.9	46.7	65.0	71.5	28.4	18.8	8.0	0.0	0.7	507.3
1963	34.5	83.5	51.4	48.0	29.0	99.4	36.7	6.4	21.7	0.1	14.7	1.5	426.8
1964	94.9	20.0	116.7	83.2	12.6	17.5	44.4	1.9	8.4	20.7	0.2	7.5	427.9
1965	40.2	53.5	20.9	108.8	69.9	25.1	6.9	1.4	10.2	0.1	0.3	7.3	344.3
1966	36.6	45.1	73.8	190.8	155.0	76.4	71.5	49.4	0.7	0.2	1.3	3.2	704.1
1967	52.8	75.0	34.5	22.4	15.2	68.8	56.5	56.0	0.0	2.6	14.0	1.3	399.0
1968	31.7	27.8	85.8	31.9	39.5	78.6	56.4	98.4	6.5	0.0	6.6	4.0	467.2
1969	85.8	26.9	53.9	72.4	38.1	23.9	22.1	27.9	15.1	25.1	1.7	18.6	411.4
1970	52.0	60.5	103.3	105.3	59.9	52.9	54.9	36.0	0.0	0.5	0.1	0.0	525.3
1971	31.9	47.6	87.3	123.8	140.4	98.2	22.4	5.8	8.9	0.1	0.0	0.0	566.3
1972	36.9	30.6	17.8	56.0	110.5	44.3	51.8	1.6	0.0	7.3	27.1	46.1	430.0
1973	32.8	51.8	64.4	188.4	102.3	84.3	65.8	3.7	0.4	0.0	8.8	5.2	607.9
1974	20.8	181.2	71.5	128.7	94.0	85.1	37.7	16.0	2.2	5.7	4.3	29.6	676.8
1975	22.8	95.9	96.8	154.3	129.0	69.7	46.1	23.7	17.2	0.0	0.4	24.0	679.9
1976	99.0	69.2	61.4	94.1	50.8	110.6	21.3	1.5	0.6	0.0	2.4	62.9	573.9
1977	53.9	26.5	59.8	76.1	70.9	100.2	96.7	0.0	7.7	0.5	8.2	21.9	522.5
1978	30.0	41.7	56.7	92.5	70.1	15.7	10.0	23.9	1.7	33.9	78.2	9.8	464.2
1979	35.6	92.0	42.8	31.2	79.1	55.1	11.6	4.5	0.0	0.3	1.2	90.8	444.2
1980	5.1	151.4	49.4	103.8	122.2	55.3	21.0	6.5	5.7	0.0	55.7	6.3	582.5
1981	38.3	61.5	101.3	75.7	26.5	48.8	126.9	0.9	3.7	17.9	0.0	20.7	522.2
1982	91.1	50.4	39.6	41.3	52.5	22.4	25.7	8.0	15.4	22.7	0.3	2.9	372.2
1983	95.9	99.6	31.8	47.7	22.1	79.1	10.4	19.6	0.3	1.9	21.8	3.5	433.8
1984	67.1	83.1	52.7	53.1	78.8	78.9	7.9	1.5	12.5	0.0	0.1	2.8	438.4
1985	76.9	34.2	77.2	73.0	12.8	58.6	48.6	3.5	20.6	0.0	18.0	10.0	433.3
1986	62.6	118.4	71.4	45.2	80.0	46.8	33.3	0.3	0.1	8.9	23.4	156.0	646.5
1987	25.6	116.1	58.2	29.2	117.1	174.9	78.3	23.5	8.1	3.2	5.3	31.2	670.7
1988	149.5	67.9	80.2	111.2	127.6	54.8	46.8	27.5	7.6	0.8	2.4	0.5	676.8
1989	42.9	53.8	51.4	43.8	107.6	88.9	65.3	2.1	9.6	10.4	2.7	3.0	481.4

Year	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Total
1990	17.5	25.8	30.8	166.8	66.7	116.7	5.4	1.5	8.0	0.5	0.0	41.0	480.7
1991	88.8	37.6	62.7	21.3	16.0	16.4	14.4	0.0	0.0	3.4	36.1	0.1	296.8
1992	51.4	170.0	39.9	64.3	82.7	46.2	27.0	3.7	0.6	0.0	7.9	2.9	496.5
1993	92.9	41.5	94.1	62.9	97.9	52.2	38.9	0.0	0.3	0.2	0.0	1.7	482.7
1994	31.6	40.5	46.8	84.0	42.9	101.6	21.3	39.1	0.4	0.0	13.1	3.8	425.1
1995	61.0	75.5	137.8	90.7	100.7	71.1	130.6	43.6	0.0	35.3	10.6	23.9	780.8
1996	58.0	129.4	49.6	124.4	39.6	110.3	97.0	61.8	10.4	25.4	6.6	28.5	740.9
1997	29.5	72.3	90.2	126.2	61.1	154.9	12.3	0.5	0.0	0.0	0.2	16.6	563.9
1998	25.3	161.7	103.5	100.7	59.4	41.3	18.5	46.5	0.5	0.0	0.1	2.6	560.1
1999	53.6	19.5	125.9	96.7	33.3	113.5	25.7	30.6	3.1	0.1	0.1	20.7	522.8
2000	95.1	54.9	123.1	41.7	45.5	85.9	120.8	28.7	20.6	3.1	24.4	3.6	647.4
2001	111.0	76.0	175.9	78.2	62.1	40.1	37.7	27.3	2.7	0.1	50.1	10.2	671.3
2002	24.4	32.9	84.2	72.9	75.2	88.7	45.1	7.4	0.0	0.0	7.6	14.3	452.6
2003	21.2	79.3	26.3	50.3	57.7	108.5	24.2	0.0	12.3	9.1	5.8	5.9	400.6
2004	11.6	31.9	60.1	145.2	72.6	48.3	31.5	21.8	2.7	0.0	0.0	0.7	426.4
2005	45.5	61.1	26.2	130.8	104.5	63.4	11.5	7.2	0.0	0.0	48.3	10.0	508.4
2006	30.3	40.8	43.6	26.8	22.2	4.6	34.2	2.3	19.5	0.0	0.0	39.8	264.1
2007	86.2	82.9	74.2	137.0	21.4	93.7	6.3	48.3	4.0	0.0	0.0	0.0	554.1
2008	59.1	148.2	41.7	85.7	97.6	36.5	4.9	56.0	19.6	10.4	8.3	8.6	576.6
2009	86.2	52.0	115.5	201.1	44.1	25.6	36.7	13.2	0.0	0.0	0.0	0.0	574.4
Geometric mean	**49.6**	**69.0**	**72.0**	**87.2**	**69.8**	**72.4**	**42.3**	**19.8**	**7.0**	**6.8**	**9.3**	**15.9**	**521.0**
Minimum	**1.3**	**9.8**	**11.6**	**12.0**	**12.6**	**4.6**	**0.7**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**264.1**
Maximum	**149.5**	**212.6**	**198.3**	**264.8**	**161.7**	**214.2**	**134.1**	**112.4**	**51.7**	**52.6**	**78.2**	**156.0**	**860.3**
Standard deviation	**30.3**	**42.5**	**37.8**	**47.5**	**35.7**	**37.5**	**30.8**	**22.1**	**9.7**	**11.0**	**14.8**	**25.8**	**121.5**

20. APPENDIX B: WATER QUALITY ANALYSIS LABORATORY CERTIFICATES

21. APPENDIX C: SPECIALIST CURICULUM VITAE