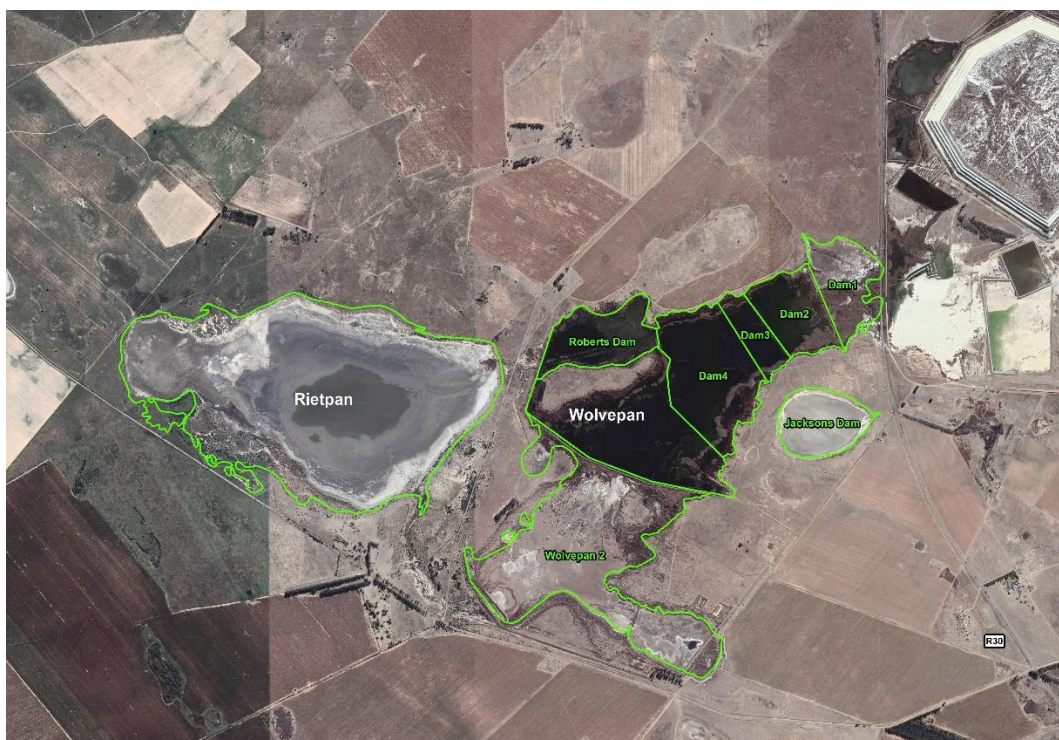


# Beatrix Mine Hydrogeological Study – Wolvepan and Rietpan Evaporation Dams

Report Prepared for  
**Sibanye-Stillwater**  
**Beatrix Mine**

SRK Report Number 535697/3



Report Prepared by



October 2019

# Beatrix Mine Hydrogeological Study – Wolvepan and Rietpan Evaporation Dams

## Sibanye-Stillwater

1 Hospital Street  
Libanon  
Westonaria  
1780  
South Africa

## SRK Consulting (South Africa) (Pty) Ltd.

The Administrative Building  
Albion Spring  
183 Main Rd  
Rondebosch 7700  
Cape Town  
South Africa

e-mail: [simrie@srk.co.za](mailto:simrie@srk.co.za)  
website: [www.srk.co.za](http://www.srk.co.za)

Tel: +27 (0) 21 659 3060  
Fax: +27 (0) 21 685 7105

**SRK Project Number 535697**  
**October 2019**

### Compiled by:

Sheila Imrie  
Principal Hydrogeologist  
Email: [simrie@srk.co.za](mailto:simrie@srk.co.za)

### Peer Reviewed by:

Gert Nel  
Partner

### Authors:

Gert Nel; Sheila Imrie; Annalisa Vicente

## Statement of SRK Independence

Neither SRK nor any of the authors of this Report have any material present or contingent interest in the outcome of this Report, nor do they have any pecuniary or other interest that could be reasonably regarded as being capable of affecting their independence or that of SRK.

SRK has no beneficial interest in the outcome of the assessment which is capable of affecting its independence.

## Disclaimer

The opinions expressed in this Report have been based on the information obtained by SRK Consulting (South Africa) (Pty) Ltd (SRK) from various sources such as the Department of Water and Sanitation (DWS), the National Groundwater Archive (NGA) and others listed under References. SRK has exercised due care in reviewing the obtained information. Whilst SRK has compared the available data with expected values, the accuracy of the results and conclusions from the review are entirely reliant on the accuracy and completeness of the available data. SRK does not accept responsibility for any errors or omissions in the supplied information and does not accept any consequential liability arising from commercial decisions or actions resulting from them. Opinions presented in this report apply to the site conditions and features as they existed at the time of SRK's investigations, and those reasonably foreseeable. These opinions do not necessarily apply to conditions and features that may arise after the date of this Report, about which SRK had no prior knowledge nor had the opportunity to evaluate.

# Contents

Acronyms and Abbreviations .....	vi
Glossary .....	vii
<b>1 Introduction and Scope .....</b>	<b>1</b>
1.1 Background .....	1
1.2 Location .....	1
1.3 Study Area .....	1
<b>2 Site Visit, Hydrocensus and Data Collation .....</b>	<b>4</b>
2.1 Previous Studies .....	4
2.2 Site Visit .....	4
2.3 Hydrocensus .....	4
<b>3 Baseline Environment .....</b>	<b>7</b>
3.1 Geography .....	7
3.1.1 Climate .....	7
3.1.2 Topography and Drainage .....	8
3.1.3 Geology .....	8
3.2 Geohydrology .....	11
3.2.1 Aquifer Classification and Vulnerability .....	11
3.2.2 Shallow Aquifer System (Karoo Sediments) .....	12
3.2.3 Recharge .....	14
3.2.4 Borehole Network .....	14
3.2.5 Aquifer Hydraulic Properties .....	18
<b>4 Mining Impact Characterisation .....</b>	<b>20</b>
4.1 Source – Pathway – Receptor Assessment .....	20
4.1.1 SPR Methodology .....	20
4.2 SPR for Wolvepan and Rietpan Complex .....	20
4.2.1 Sources .....	20
4.2.2 Pathways .....	20
4.2.3 Receptors .....	21
4.2.4 Mitigation Measures .....	21
4.2.5 SPR Linkages .....	21
4.3 Analytical Model .....	24
4.3.1 Transport Processes .....	24
4.3.2 Analytical Model Approach .....	24
4.3.3 Assumptions and Limitations .....	25
4.3.4 Model Inputs .....	26
4.3.5 Contaminant plume footprint .....	27
<b>5 Conclusions and Recommendations .....</b>	<b>30</b>
<b>6 References .....</b>	<b>31</b>

## Tables

Table 2-1: Hydrocensus Boreholes July 2019.....	5
Table 3-1: Monthly Rainfall Data Measured at Beatrix Mine from 2007 to 2018.....	7
Table 3-2: Yearly rainfall data measured at Beatrix Mine from 2008 to 2018 .....	7
Table 3-3: Ratings for the aquifer quality management classification system .....	11
Table 3-4: Borehole network summary.....	14
Table 3-5: Aquifer Hydraulic Properties.....	19
Table 4-1: Summary of SPR Linkages for Wolvepan and Rietpan Complex .....	22
Table 4-2: Analytical model inputs.....	26

## Figures

Figure 1-1: Locality Map .....	2
Figure 1-2: Mine Infrastructure .....	3
Figure 2-1: Hydrocensus Boreholes (July 2019) .....	6
Figure 3-1: Long-term monthly average rainfall at Beatrix Mine from 2007 – 2018 .....	7
Figure 3-2: Long-term yearly average rainfall at Beatrix Mine from 2008 – 2018 .....	8
Figure 3-3: Topography and Drainage .....	9
Figure 3-4: Regional Geology.....	10
Figure 3-5: Geohydrology .....	13
Figure 3-6: Mean Annual Recharge (mm/a) .....	16
Figure 3-7: Borehole Network.....	17
Figure 4-1: Wolvepan and Rietpan- Potential SPR Linkages.....	23
Figure 4-2: Analytical Model Inputs with Observed Data .....	28
Figure 4-3: Simulated Contaminant Plume Footprint .....	29

## Acronyms and Abbreviations

a	annum
ADE	Advection-dispersion equation
c.	<i>circa</i> (approximately)
Cl	Chloride
Cu	Copper
DMR	Department of Mineral Resources
DWS	Department of Water and Sanitation
EC	Electrical conductivity
EIA	Environmental Impact Assessment
EMP	Environmental Management Program/Plan
EMPR	Environmental Management Program Report
EVT	Evapotranspiration
Fe	Iron
GW	Groundwater
GRAII	Groundwater Resource Assessment II
hr	hour
IWULA	Integrated Water Use Application
K	hydraulic conductivity
l/s	litres per second
m	metres
m <sup>3</sup> /hr	cubic metres per hour
mamsl	metres above mean sea level
mbgl	metres below ground level
mm	millimetres
mm/a	millimetres per annum
N/A	Not Applicable
PCD	Pollution Control Dam
RD	Rock Dump
RWD	Return Water Dam
S	Storativity

Sibanye	Sibanye Gold (Pty) Ltd.
SO <sub>4</sub>	Sulfate
SRK	SRK Consulting (South Africa) (Pty) Ltd.
TDS	Total dissolved salts
TSF	Tailings Storage Facility
WUL	Water Use Licence
WULA	Water Use Licence Application
U	Uranium

## Glossary

Aquifer	A formation, group of formations, or part of a formation that contains sufficient saturated permeable material to store and transmit water; and to yield economical quantities of water to boreholes or springs. An aquifer is the storage medium from which groundwater is abstracted.
Environmental Impact Assessment	A process of evaluating the environmental and socio-economic consequences of a proposed course of action or project.
Environmental Management Plan	A description (in an EIA Report or separate document) of the means (or the environmental specification) for achieving environmental objectives and targets during all stages of a specific proposed activity.
Fault	A zone of displacement in rock formations resulting from forces of tension or compression in the earth's crust. Faults can form conduits for groundwater movement and groundwater contamination; as well as impermeable zones where metamorphism of the rocks have taken place.
Formation	A body of rock identified by lithic characteristics and stratigraphic position. Different formations have different hydrogeological properties.
Fracture	Any break in a rock including cracks, joints and faults. Fractures can form the main conduits for groundwater flow. They can also form pathways for the movement of contamination.
Groundwater	Water found in the subsurface in the saturated zone below the water table. Groundwater is a source of water and is an integral part of the hydrological system.
Hydraulic Conductivity	Measure of the ease with which water will pass through the earth's material; defined as the rate of flow through a cross-section of one square metre under a unit hydraulic gradient at right angles to the direction of flow (m/d).
Hydrogeology	In South Africa the term geohydrology and hydrogeology are used interchangeably. In theory hydrogeology is the study of geology from the perspective of its role and influence in hydrology, while geohydrology is the study of hydrology from the perspective of the influence on geology.

Mitigation measures	Natural or engineered measures that are intended to avoid and / or minimise or enhance an impact, depending on the desired effect. These measures are ideally incorporated into a design at an early stage.
Porosity	The ratio of the volume of void spaces in a rock or sediment to the total volume of the rock or sediment.
Recharge area	An area over which recharge occurs. Recharge is crucial for the ongoing replenishment of aquifers and their sustainable use, and recharge areas thus require protection.
Recharge	The addition of water to the saturated zone, either by the downward percolation of precipitation or surface water and/or the lateral migration of groundwater from adjacent aquifers. Recharge is crucial for the ongoing replenishment of aquifers.
Secondary aquifer	An aquifer in which groundwater moves through secondary openings and interstices, which developed after the rocks were formed. Approximately 90% of aquifers in South Africa are secondary in nature.
Specific yield	The ratio of the volume of water a rock or soil will yield by gravity drainage to the volume of the rock or soil.
Storativity	The volume of water released from storage per unit of aquifer storage area per unit change in head.
Transmissivity	The rate at which water of a prevailing density and viscosity is transmitted through a unit width of an aquifer or confining bed under a unit hydraulic gradient.
Vadose Zone	Unsaturated zone between the surface and the water table and includes the saturated capillary fringe.
Water table	The upper surface of the saturated zone of an unconfined aquifer at which pore pressure is equal to that of the atmosphere. It marks the top of the groundwater body.

# 1 Introduction and Scope

## 1.1 Background

The Sibanye Gold (Pty) Ltd. (trading as Sibanye-Stillwater) Beatrix Operations appointed SRK Consulting South Africa (Pty) Ltd (hereafter referred to as SRK) to undertake an updated groundwater management study for the Beatrix operations located in the Free State Province.

The Beatrix Operations of Sibanye-Stillwater have numerous old order water use authorisations, and as such have applied for a new Integrated Water Use Application (IWULA). The IWULA was submitted in 2011 and is nearing finalisation. In the interim the water permits and exemptions, as well as the Environmental Monitoring Programme Report (EMPR), dated 2004, have guided water management at Beatrix. Therefore, to ensure responsible and proactive water management is performed in lieu of the pending Water Use Licence (WUL) several updated studies in terms of surface- and groundwater management were required.

SRK collated historical reports and models, analysed available information and data (particularly covering the period 2006 to 2018), undertook a hydrocensus, developed an updated conceptualisation and used an analytical approach to undertake a hydrogeological assessment of the Wolvepan and Rietpan area.

This report summarises the results of the updated groundwater management study for the Wolvepan / Rietpan evaporation dams (hereafter referred to as "Study Area").

Groundwater management and numerical modelling undertaken at Beatrix Shafts 1, 2 and 3 and Beatrix #4 Shaft are discussed in a separate report.

## 1.2 Location

The Beatrix Mine has been in operation since 1983 and is located approximately 40 kilometres (km) south of the town of Welkom in the Free State and 280 km south-west of the city of Johannesburg in the Gauteng Province of South Africa (Figure 1-1). The operations consist of Shafts 1 to 4 as well as the Wolvepan and Rietpan evaporation dams. The Study Area is situated approximately 7 km south of Welkom, next to the R30.

## 1.3 Study Area

The Study Area is located in the eastern portion of the quaternary catchment C43B. The Study Area has no major perennial and non-perennial rivers within its immediate vicinity. The closest river, being the Sand River, is located c.10 km to the south of the Wolvepan and Rietpan evaporation dams.

The Wolvepan and Rietpan Complex is subdivided into nine evaporation dams in total (Figure 1-2), namely, Wolvepan 1, Wolvepan 2, Rietpan, Roberts Dam, Jacksons Dam, Dam 1, Dam 2, Dam 3 and Dam 4. The nine evaporation dams operate as three distinctive dams, namely the Wolvepan, Rietpan and Jacksons Dam (a natural pan storing stormwater only). The Wolvepan and Rietpan Complex forms part of the Beatrix operations, however are not actively used currently. In the past these evaporation dams were used for disposal of excess water received from Shafts 1, 2, 3 and 4 by means of a pipeline, however due to vandalism this pipeline is no longer in service. The dams also previously received water from the Harmony operations, but this has also ceased, as all water generated through the Harmony operations is being utilised by the mine itself. Storm water runoff from the Harmony areas also enters the system.

The main current sources of water to the evaporation dams are rainfall and rainfall runoff, seepage from the Harmony TSF, as well as unregulated illegal discharges from the Welkom Theronia Waste Water Treatment Works and Toronto Pan and other unclassified sources flowing into the series of evaporation dams, via the Flamingo Pan and various surface canals.

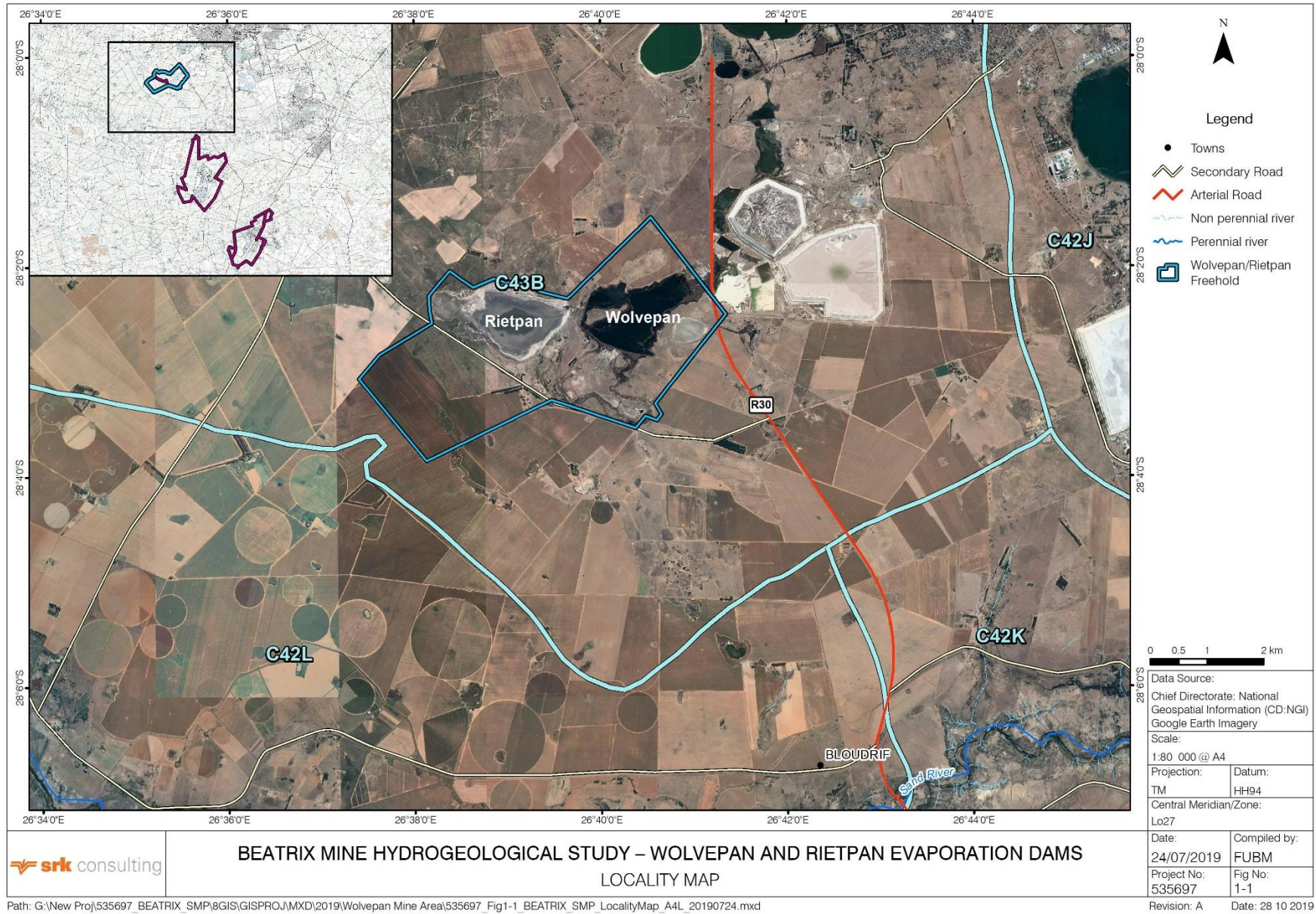


Figure 1-1: Locality Map

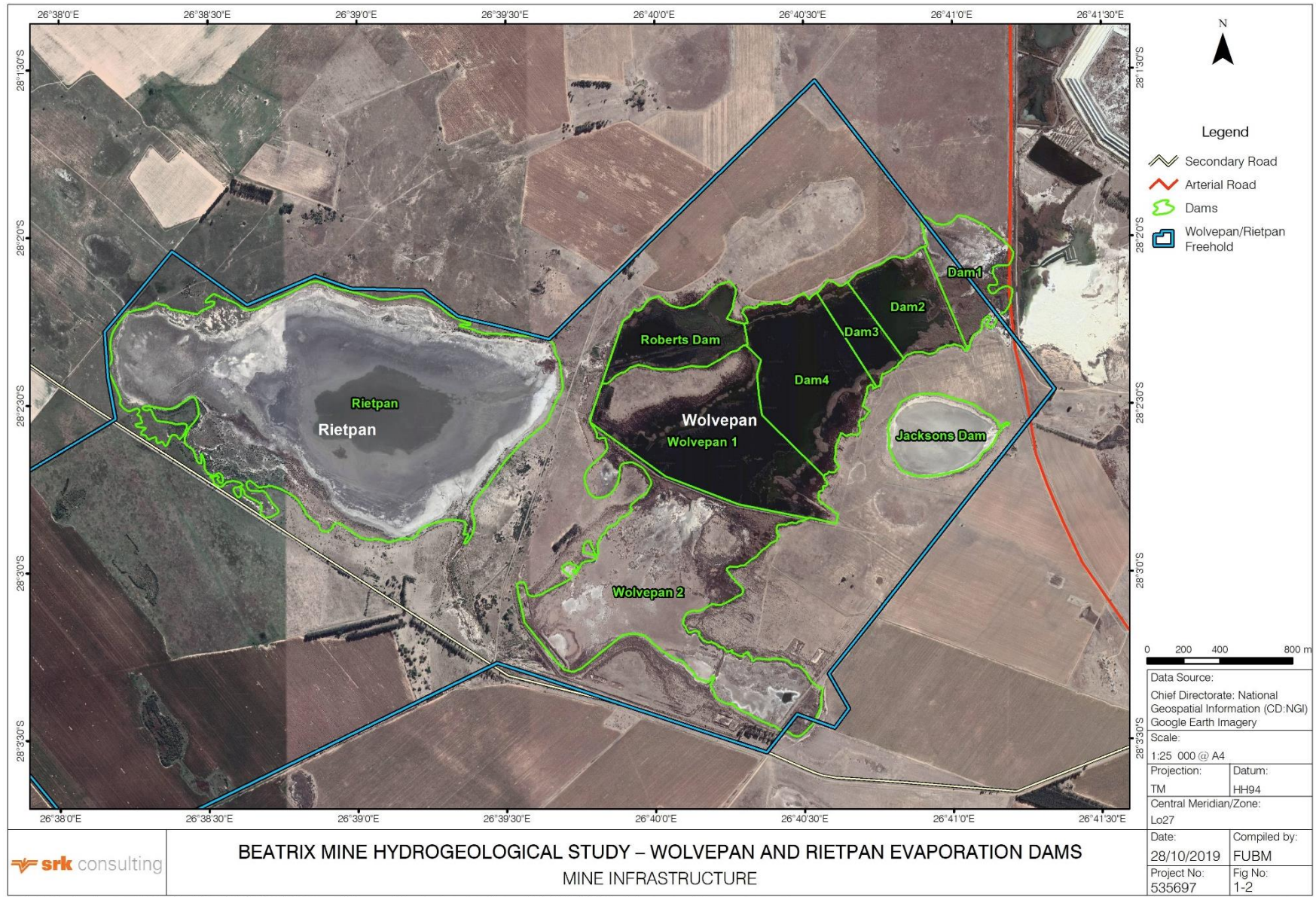


Figure 1-2: Mine Infrastructure

## 2 Site Visit, Hydrocensus and Data Collation

### 2.1 Previous Studies

Information on the geology and hydrogeology of the project site was sourced from literature, along with data obtained directly from the mine and SRK's hydrocensus. The most relevant of these reports are:

- Excerpts of an Environmental Management Programme (EMPR, 2004); and
- Lower Vet River Water Quality Situation Analysis, with Special Reference to the OFS Goldfields. CE Herold, WV Pitman, AK Bailey, I Taviv. Report to the Water Research Commission by Stewart Scott Incorporated, WRC Report No 523/1/96.

### 2.2 Site Visit

An SRK team comprising Sheila Imrie, Connan Hempel, Gert Nel and Chris Esterhuysen visited the mine in October 2018 and met with Alfonzo le Roux and Hennie Pretorius. After the meeting Mr Le Roux took the SRK team on a fieldtrip to the area in the vicinity of Beatrix Shaft 1, 2 and 3 and Beatrix #4 Shaft, followed by the Wolvepan and Rietpan Complex area.

### 2.3 Hydrocensus

In July 2019 SRK conducted a hydrocensus around the Wolvepan and Rietpan Complex, aiming to detect existing boreholes that are situated within 2 km. The hydrocensus involved visiting the farms that border the complex. The names and contact details of the farm owners were not available at the time of the hydrocensus and the owners could not be contacted prior to the hydrocensus. Each farm had to be visited to receive permission to enter the land and record data on the boreholes. The following difficulties prevented a thorough survey of all boreholes:

- Physical obstructions. Farms had security gates in place and these were locked. There was no contact number or means of communicating the purpose of the visit;
- Farm Silwerstraal included the entire area north of Rietpan and Wolvepan up to St Helena Goldmine and has been turned into a wildlife sanctuary where herbivores (e.g. buck and buffalo) and carnivores (e.g. lions) are kept. There are several windmills on this site, but access requires the company of a trained and armed guard. This area was therefore excluded from the hydrocensus as prior arrangements with the owner are required;
- Hostility. Some farm owners bluntly refused access to their land although the purpose of the visit / hydrocensus was made clear to them. Some farmers contacted their neighbours telephonically and urged them not to allow the SRK staff member on their properties; and
- Safety. In cases where access could be gained onto a property, vicious, unattended dogs were encountered, preventing further access to the farmhouse.

Table 2-1 and Figure 2-1 shows the boreholes identified during the July 2019 hydrocensus.

**Table 2-1: Hydrocensus Boreholes July 2019**

Farm	Borehole ID	Latitude	Longitude	Equipment	Owner	Contact No.
The Prairie	D33 1 WM	-28.05032	26.69351	Windmill		
	B39	-28.05029	26.69333	Not equipped - open BH		
	D33 2 WM	-28.05123	26.69007			
Bospan	B7	-28.06979	26.66654	Submersible		
	B10	-28.07048	26.66552	Windmill		
	B8	-28.07471	26.67058	Submersible		
	B8B	-28.07473	26.6706	Submersible		
	BSP WM	-28.06883	26.66521			
Wolwepan	B4	-28.06521	26.66173	Not equipped - closed	Burger Naude	084 445 1341
	B5	-28.06445	26.66185	Submersible		
	B15	-28.06608	26.66227	Submersible		
Silwerstraal	B22	-28.01153	26.63043	Windmill	H.S. van der Walt	057 352 8690
Doornkuil	GV WM	-28.01167	26.62491	Windmill		

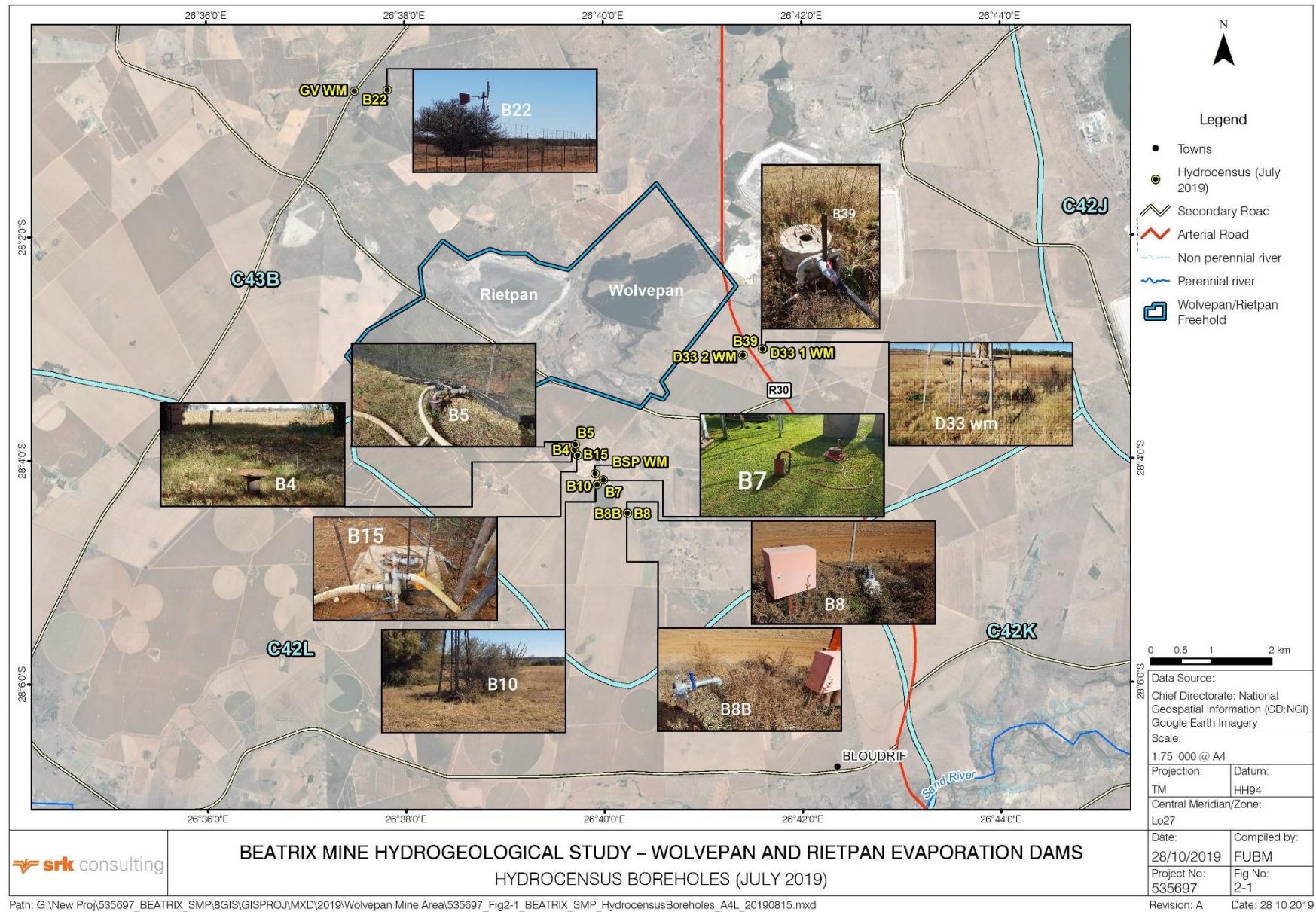


Figure 2-1: Hydrocensus Boreholes (July 2019)

## 3 Baseline Environment

### 3.1 Geography

#### 3.1.1 Climate

The climate of the area is typical of a semi-arid region with cool dry winters (May to September) and warm wet summers (October to April). More than 79% of rainfall occurs within the summer months as thunderstorms and showers, peaking in the month of January. These storms are generally localised and naturally occur between 40 to 60 times per year on average (Golder Associates, 2012).

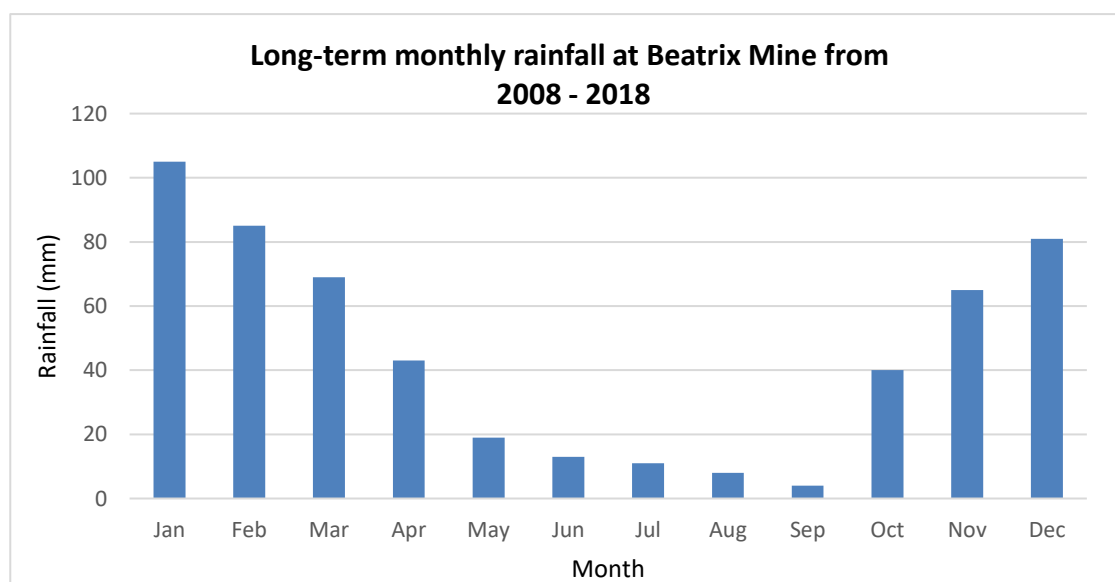
Rainfall data was measured at the Beatrix Mine weather station over a period of 12 years from November 2007 to November 2018. Long-term monthly average rainfall values are presented in Table 3-1 and Figure 3-1 below. It is evident that the low rainfall months (May to September) experience an average of 11.44 mm/month, whereas high rainfall months (October to April) obtain an average of 70.11 mm/month. January has the highest rainfall, whereas September has the lowest.

Long-term yearly average rainfall values are presented in Table 3-2 and

Figure 3-2, which shows a variable trend in rainfall over the years. 2010 and 2016 received the highest yearly rainfall of 869.3 mm/a and 691.3 mm/a respectively. The long-term monthly average for all recorded years is 577 mm/a. Mean annual evaporation at the Beatrix Mine is c.2 000 mm/a (Department of Water Affairs and Sanitation's Hydrological Database).

**Table 3-1: Monthly Rainfall Data Measured at Beatrix Mine from 2007 to 2018**

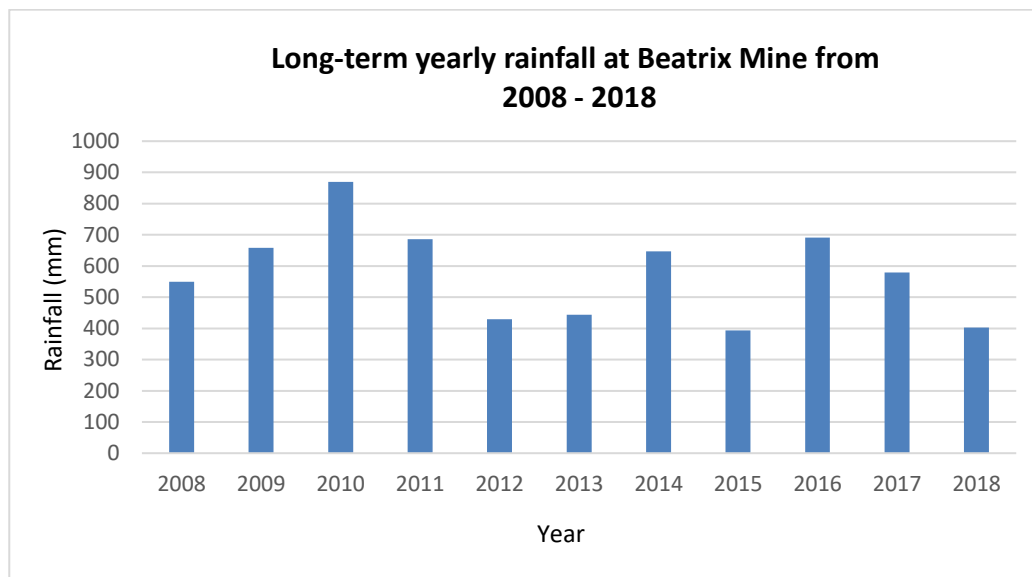
Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Average (mm)	105	85	69	43	19	13	11	8	4	40	65	81



**Figure 3-1: Long-term monthly average rainfall at Beatrix Mine from 2007 – 2018**

**Table 3-2: Yearly rainfall data measured at Beatrix Mine from 2008 to 2018**

Year	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018
Average (mm)	549	658	869	685	429	443	646	393	691	580	403



**Figure 3-2: Long-term yearly average rainfall at Beatrix Mine from 2008 – 2018**

### 3.1.2 Topography and Drainage

The study area falls within the quaternary drainage region of C43B. Regionally, the Beatrix Mine is located within the Vaal Drainage region which has a total catchment area of 196 293 km<sup>2</sup>. Locally, the study area is surrounded by hills (c.1 350 m above mean sea level) in the east which slope in a northeast direction (Figure 3-3). The eastern hills create a slight topographical difference of c.50 m from the Wolvepan and Rietpan Complex, indicating that the topographical relief is minor and limited to low, gently sloped hills. The Wolvepan and Rietpan Complex are relatively flat with the Rietpan evaporation dam at c.1 310 mamsl.

The study area has no major perennial rivers within its immediate vicinity (Figure 3-3). The closest river, being the Sand River, is located c.10 km to the south. Therefore, it is unlikely that groundwater provides a significant contribution to surface water base flow.

### 3.1.3 Geology

Regionally, the Ecca Group sandstone and shales from the Karoo Sequence underlie the area. The underlying Karoo-shales are classified as carbonaceous or micaceous shales (Visser 1989). Tertiary-Quaternary sediments from the Kalahari Group cover the Karoo Sequence. The younger Kalahari deposits cover the majority of the study area which comprise of quaternary aeolian sands (red and grey aeolian dune sand) with alluvial gravel found in the paleo-drainage systems (Figure 3-4). The thickness of the Kalahari sediments varies between 1 and 65m (GFSA Reports, 1988), and a clay layer is found in-between the sands at a depth of c.2 to 15 mbgl. This layer is a pedological horizon rather than a geological layer and formed during the illuviation of fine particles (clay) downwards. In about the total area the clay horizon is enriched with calcareous material derived from weathered shales and dolerites (Harmse, 1967). Interspersed Adelaide geological formations are found in the east of the study area which comprises of very fine to coarse grained sandstone, mudstone and shale. In addition, Dolerite is found in the south of the study area (Figure 3-4).

Locally, the Wolvepan and Rietpan Complex predominantly consists of quaternary sands with dispersed sections of alluvium, calcified alluvium and river gravel (Figure 3-4).

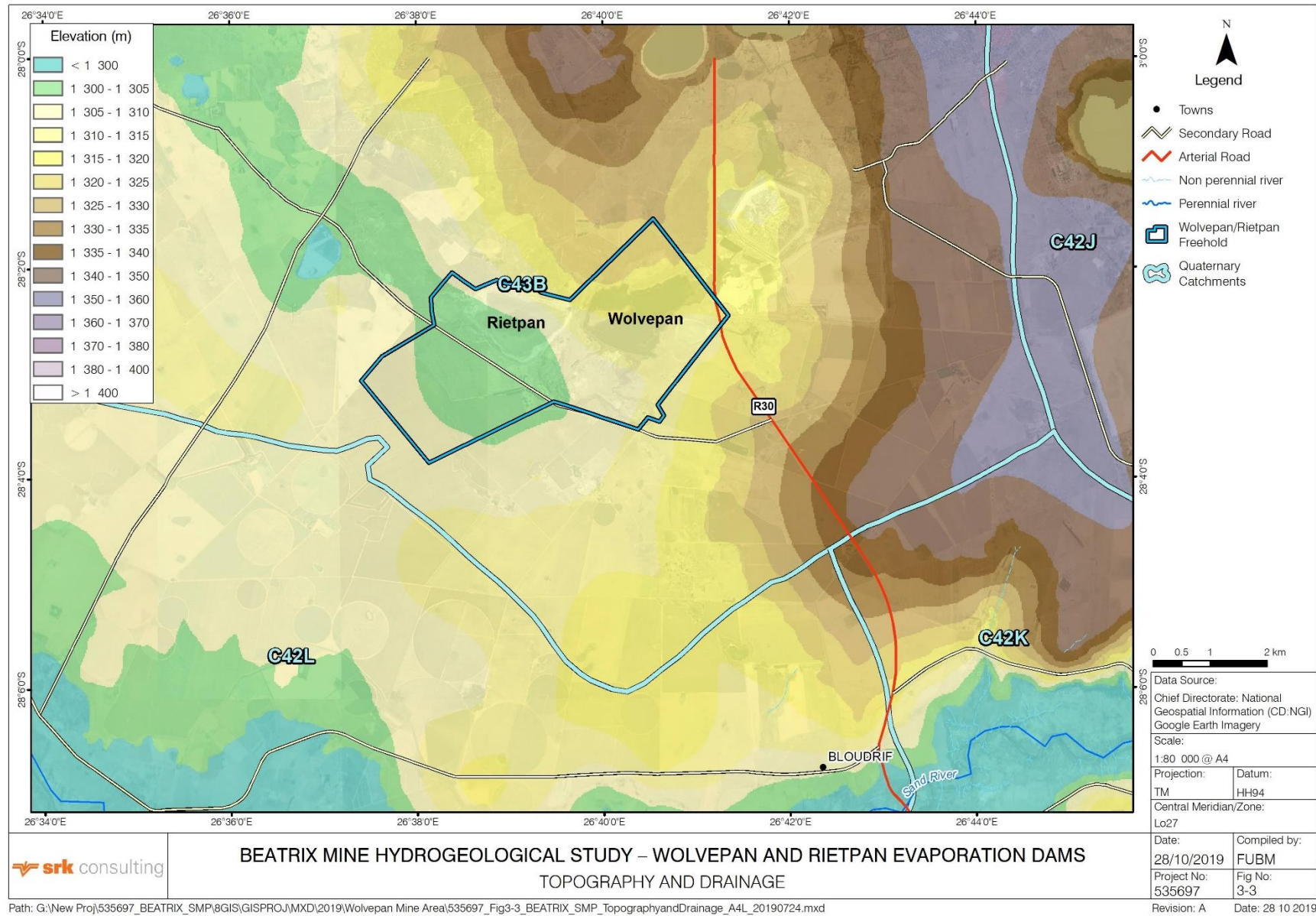


Figure 3-3: Topography and Drainage

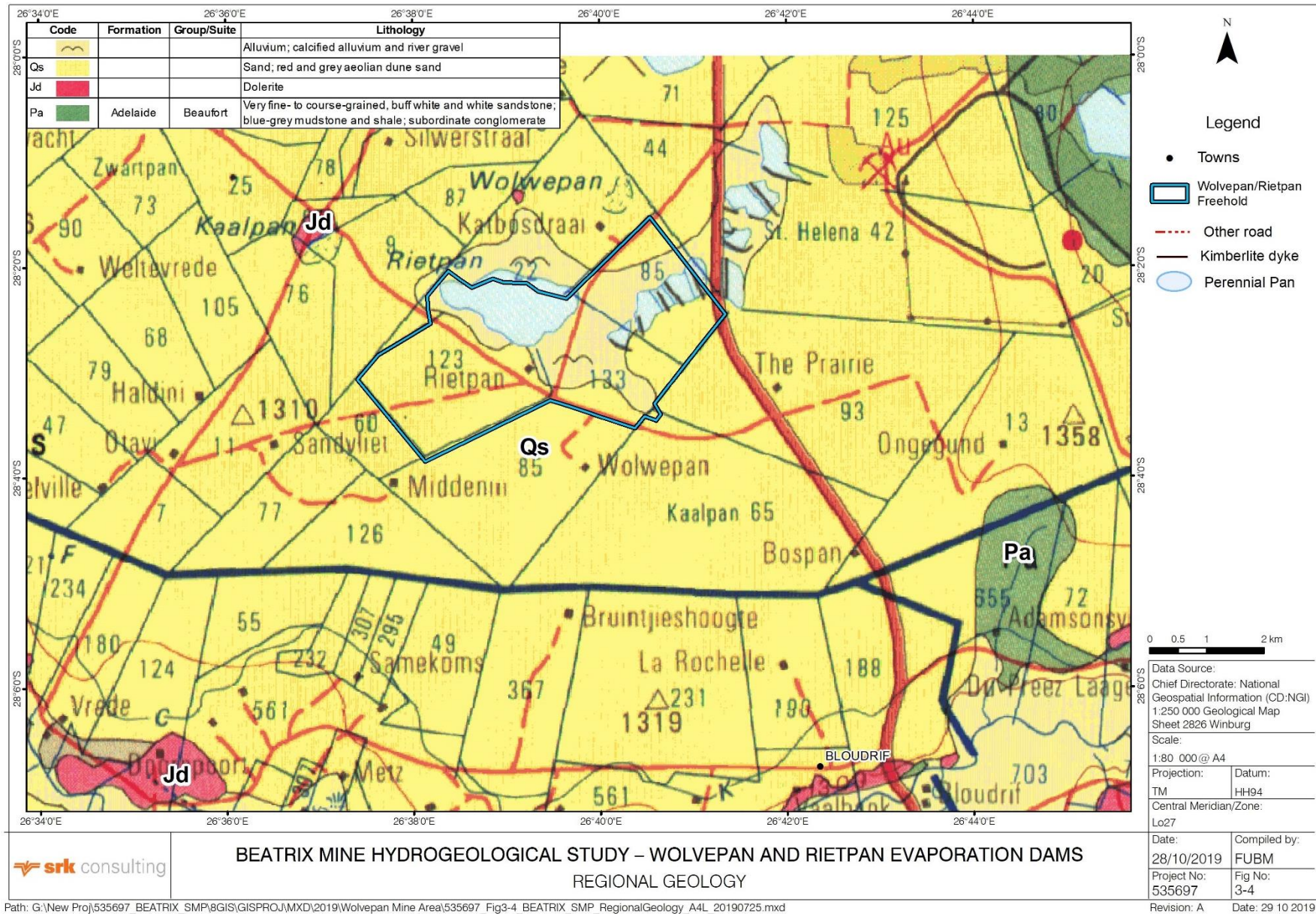


Figure 3-4: Regional Geology

## 3.2 Geohydrology

### 3.2.1 Aquifer Classification and Vulnerability

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

Other uses include:

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

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

The South African Aquifer System Management Classification (Parsons, 1995) is presented by five major classes<sup>1</sup>:

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

The DWS Aquifer Classification Map of South Africa (DWS, 2012) presents three classes of aquifers, namely:

- Poor;
- Minor; and
- Major.

The aquifer in the site area is classified as a 'Minor' aquifer system, according to the DWS classification system (DWS, 2012).

A second variable classification is needed for sound decision making, as the ability of an aquifer to yield water to a user is not adequately stated. In this case it was decided to use the vulnerability of the aquifer to contamination (as described below) as a second parameter. A weighting and rating approach is then used to decide on the appropriate level of ground water protection (Table 3-3).

**Table 3-3: Ratings for the aquifer quality management classification system**

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

<sup>1</sup> Definitions are provided in the report glossary

### 3.2.2 Shallow Aquifer System (Karoo Sediments)

Four aquifer types are present beneath the Wolvepan/Rietpan area. These are namely:

1. *“A shallow perched water table aquifer formed in the weathered zone /soil horizon. As well as on the contact of the transported horizon and reworked horizon and on the contact of the weathered material/soil horizon and the unweathered bedrock”;*
2. *“A secondary aquifer formed by fracturing of the Karoo sediments (faults, bedding plane fractures, expansion fractures etc.)”;*
3. *“Secondary aquifers associated with the contact zones of the dolerite (dykes and sills)”;* and
4. *“A secondary aquifer associated with the limited jointing and fracturing of the dolerite dykes and sills (aquitard).” (GPT, 2009).*

Only two main aquifers (listed as 1 and 2 above) are of focus due to the shallow nature of the study area.

Infiltration from rainfall and any surface / near-surface water deposits (including contamination), flow both vertically and horizontally with the flow direction. The distance and velocity are dictated by changes in hydraulic conductivity of the various sedimentary layers, weathered layers and igneous rocks.

The spread of near-surface deposited contaminants towards surface water features, e.g. rivers / streams, are dependent on the extent of the perched water table caused by weathering of sedimentary rock, the contamination load, composition and hydraulic gradient. The potential contamination of the secondary aquifers are associated with the fractured sedimentary rock, the hydraulic gradient, the presence of deeper igneous rock (dolerite) and groundwater abstractions within and around the contaminant discharge region.

Based on existing literature, there is limited data (e.g. borehole logs) to predict contaminant flow in any specific direction, both horizontally and vertically, however it can be assumed that numerous major and minor horizontal fractures do exist in the host rock on bedding planes, expansion joints etc. These conductive zones effectively interconnect the strata of the Karoo sediments (sandstone and shale), both vertically and horizontally into a single, but highly heterogeneous and anisotropic unit (GPT, 2009).

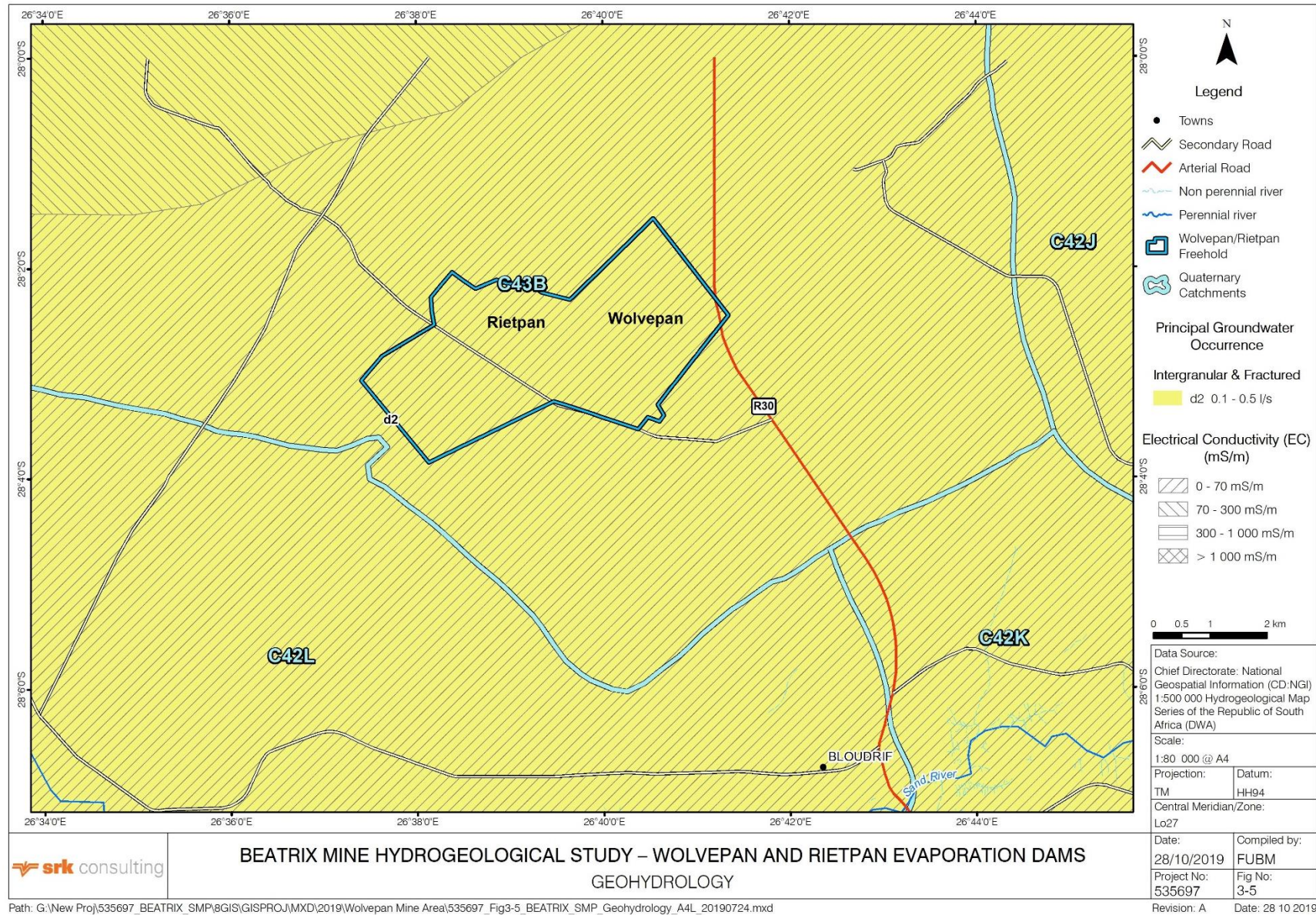


Figure 3-5: Geohydrology

### 3.2.3 Recharge

Figure 3-6 shows recharge rates obtained from the Groundwater Resource Assessment II (GRAII) dataset (DWAF, 2005). In the study area, they range from 2 to 8 mm/a. Recharge occurs mainly on the higher lying terrain in the north, which receives between 6 and 8 mm/a. The centre of the study area receives 3 to 6 mm/a, whereas the lowest recharge of 2 to 4 mm/a occurs along the southern boundary of the study area.

According to Bredenkamp et al. (2006), the general accepted value for recharge on Karoo sediments is 3% of MAP. According to Xu and Van Tonder (2001), semi-arid Karoo environments experience a c.0.7% recharge during the dry years and c.1.2% recharge during the wet years. It is therefore likely that groundwater recharge ranges between 0.7 and 3% of MAP in the study area.

### 3.2.4 Borehole Network

There are currently 36 boreholes which form part of the Beatrix Mine borehole network within the Study Area, of which 18 are monitored (shown in Figure 3-6/Figure 3-7). Monitored boreholes are classified as boreholes which were sampled between 2017 and 2018 (within the last two years). The monitoring programme at the Beatrix Mine provides water quality measurements for 27 constituents/parameters on a quarterly basis from 2005 to 2018. Borehole information, including the co-ordinates, elevations, water quality parameters (EC and pH), monitoring status and date sampled are presented in Table 3-4 below:

**Table 3-4: Borehole network summary**

BH ID	Latitude	Longitude	EC (mS/m)	pH	Status	Year
STH_B121	-30028.4	-3109131	297	8	Monitored	2018
STH_B122	-29864.4	-3109192	301	7.9	Monitored	2018
STH_B132	-33688.1	-3108525	85	7.7	Monitored	2018
STH_B135	-38956.7	-3100260	233	7.5	Monitored	2018
STH_B139	-39450.5	-3099646	245	7.8	Monitored	2018
STH_B140	-40216.4	-3099371	104	8.2	Monitored	2018
STH_B142	-38496.5	-3098934	216	7.7	Monitored	2017
STH_B144	-40216	-3099494	239	7.8	Monitored	2018
STH_B146	-38211	-3102782	66	8	Monitored	2017
STH_B15	-33367	-3106215	103	8.2	Monitored	2017
STH_B160	-35004.1	-3106620	102	7.6	Monitored	2017
STH_B179	-28495	-3111097	83	7.7	Monitored	2018
STH_B22	-36253.6	-3099759	306	7.9	Monitored	2018
STH_B27	-36880.6	-3100222	210	7.9	Monitored	2018
STH_B32	-30177.6	-3104082	213	8	Monitored	2018
STH_B39	-31494.8	-3101685	350	7.8	Monitored	2017

BH ID	Latitude	Longitude	EC (mS/m)	pH	Status	Year
STH_B5	-33859.5	-3105847	106	8	Monitored	2018
STH_B7	-32793.8	-3106121	303	7.7	Monitored	2018
STH_B26A	-34616	-3099200	216	8.1	Non-monitored	2016
STH_B26	-34559.7	-3099784	232	7.8	Non-monitored	2016
STH_B2	-34108.8	-3104616	109	7.9	Non-monitored	2009
STH_B23	-35511.1	-3101388	176	7.9	Non-monitored	2012
STH_B25	-34666.1	-3100770	273	7.8	Non-monitored	2015
STH_B1	-32834.2	-3101350	222	7.1	Non-monitored	2011
STH_B126	-32947.5	-3109815	69	7.3	Non-monitored	2009
STH_B134	-39202	-3100445	172	7.4	Non-monitored	2012
STH_B148	-37936.2	-3103335	149	8.4	Non-monitored	2007
STH_B15A	-33203.5	-3106091	105	8.5	Non-monitored	2011
STH_B15B	-33176.5	-3105968	147	7.8	Non-monitored	2009
STH_B223	-31369.7	-3107718	124	9.5	Non-monitored	2012
STH_B27A	-36989.2	-3100438	226	7.2	Non-monitored	2009
STH_B30	-38270.2	-3101366	206	8	Non-monitored	2012
STH_B8	-32520.5	-3106213	51	7.5	Non-monitored	2006
STH_B13	-29953.8	-3106206	103	8	Non-monitored	2011
STH_B14	-39430	-3105864	120	7.6	Non-monitored	2012
STH-B20	-32787.4	-3098487	*NS	NS	Non-monitored	NS

\*NS = Not Sampled

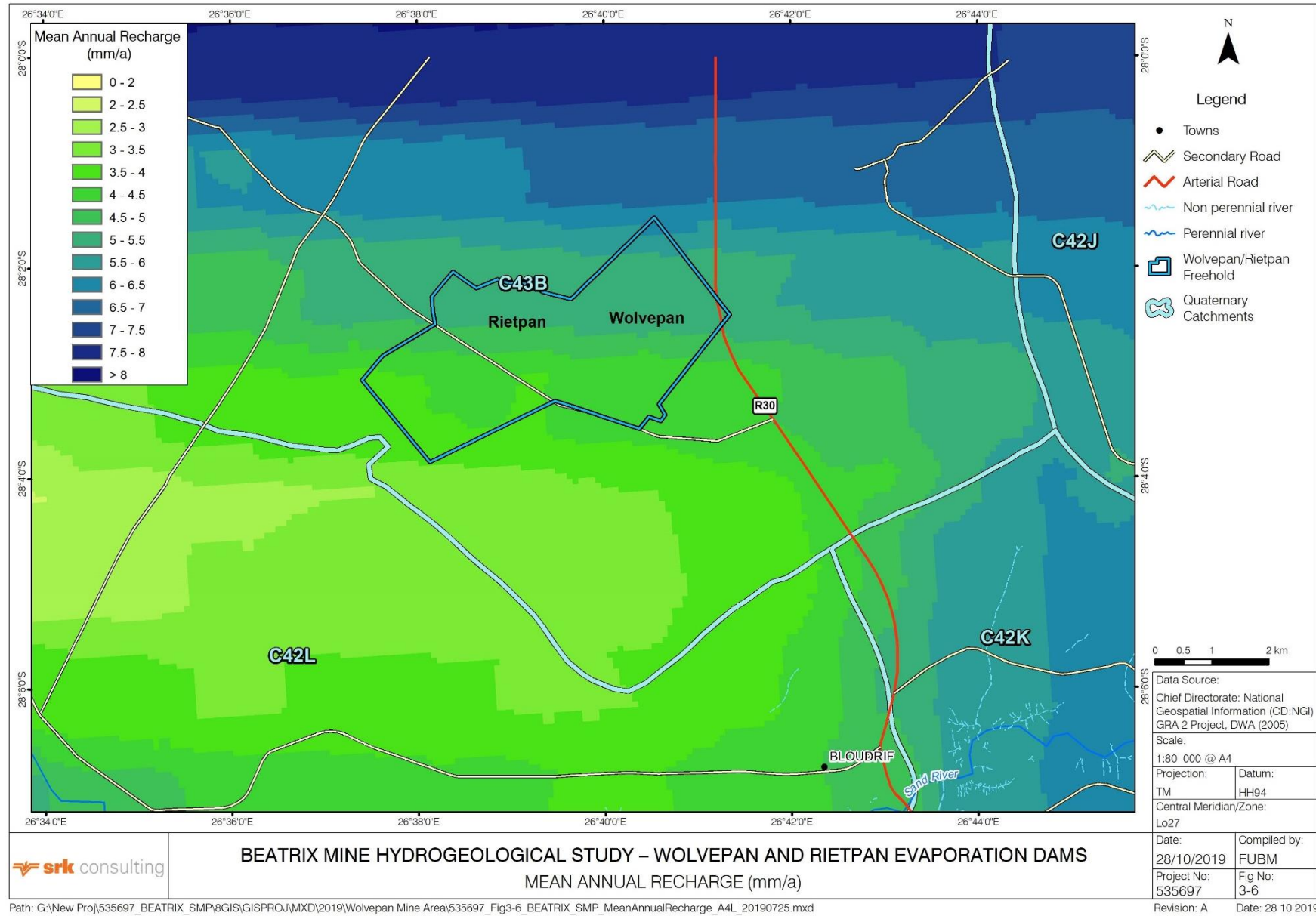


Figure 3-6: Mean Annual Recharge (mm/a)



Figure 3-7: Borehole Network

### 3.2.5 Aquifer Hydraulic Properties

Limited aquifer testing data was readily available for this study, therefore information on the aquifer hydraulic properties were sourced from literature. All hydraulic property values in accordance to literature are tabulated in Table 3-5 below. Based on previous studies, four distinct geological properties related to hydraulic conductivities are present, namely the:

1. Weathered zone - A primary aquifer which consists of weathered sandy fine clay and soils (Adelaide Subgroup), approximately 12 to 50 m thick; and
2. Fractured Karoo Rock – A secondary aquifers which consist of fractured rock with sandstones and mudstones. SRK interprets this to constitute water strikes of boreholes drilled into sedimentary rock (i.e. sandstone and shale).

The hydraulic conductivity values for the weathered zone range from  $10^{-6}$  m/d to 10 m/d, with a good representative value being  $c.10^{-1}$  to  $10^{-2}$  m/d. The fractured rock hydraulic conductivity values range from  $10^{-8}$  m/d to  $10^{-2}$  m/d. The fractured rock in this area is known to decrease in hydraulic conductivity with depth by approximately two to three orders of magnitude.

Storativity values are highly variable, ranging from  $5 \times 10^{-10}$  to 0.19. According to Xu and Van Tonder (2001), a representative storativity value of Karoo sediments is 0.19.

**Table 3-5: Aquifer Hydraulic Properties**

Zone Name	Lithology	Thickness	K Estimate (m/d)	S Estimate	Source
<b>Primary Aquifer</b>					
Adelaide Subgroup Weathered sandy clay with very fine texture		12			Alluvial and Lacustrine Deposits Brink (1979) and Partridge et al. (1985)
		50	0.42		Groundwater Management Report Phase 2: Numerical Groundwater Model And Management Program (GPT, 2010)
			0.017 – 17.28		Physical and Chemical Hydrogeology (Dominico and Schwartz, 1990)
		16			Brink (1979)
			$10^{-2} - 10^2$		Freeze and Cherry (1979)
			0.002		Morris and Johnson (1967) and Mercer et al. (1982)
			$10^{-3} - 10^{-6}$		Terzaghi and Peck (1948, 1967)
			0.1728 – 0.00864		Silin-Bekchurin (1958)
			0.19	(Xu and Van Tonder, 2001)	
<b>Secondary Aquifer (Bedrock)</b>					
Highly Fractured	Highly fractured rock with sandstones and mudstones	50	0.01		Groundwater Management Report Phase 2: Numerical Groundwater Model And Management Program (GPT, 2010)
		50	0.042		Groundwater Management Report Phase 2: Numerical Groundwater Model And Management Program (GPT, 2010) – After calibration
			0.00046 - 0.148		Groundwater Management Report: Evaluation of Hydrogeological Data At Beatrix Gold Mine And The Development Of A Groundwater Management Model (GPT, 2009)
			$10^{-4} - 10^{-8}$		Heath (1983)
Medium Fractured	Medium fractured rock with sandstones and mudstones	50	0.001		Groundwater Management Report Phase 2: Numerical Groundwater Model And Management Program (GPT, 2010)
		50	0.0042	$5 \times 10^{-10}$	Groundwater Management Report Phase 2: Numerical Groundwater Model And Management Program (GPT, 2010) – After calibration
Dykes	Dolerite dykes and sills		10		Groundwater Management Report Phase 2: Numerical Groundwater Model And Management Program (GPT, 2010)
			0.0000017 – 0.936		Groundwater Management Report: Evaluation of Hydrogeological Data At Beatrix Gold Mine And The Development Of A Groundwater Management Model (GPT, 2009)

## 4 Mining Impact Characterisation

Seepage of process water from the evaporation dams results in mounding and the spread of a contamination plume which subsequently impacts the quality of groundwater in the area. In this report section, the source-pathway-receptor (SPR) approach is used to conceptually analyse the potential impact from both evaporation dams.

### 4.1 Source – Pathway – Receptor Assessment

#### 4.1.1 SPR Methodology

The SPR methodology is used to determine whether a potential risk of harm to humans or to environmental components could exist as a result of the disposal of waste at a specific facility. Three factors are assessed, namely:

- The characteristics of the situation or contaminant (**source**/waste);
- The **receptor/s**, i.e. naturally occurring water such as groundwater and surface water and also the vulnerability of the receptor (the so-called 'population at risk,' i.e. human beings and/or the receiving environment) exposed to the situation or characteristics; and
- The **pathways** of transport and exposure.

This implies that although there may be a source of contamination, however, if there are no pathways of transport and exposure, or if there are no receptors that could be affected by the source, then the urgency of remediation is deemed less than when receptors have already been negatively impacted. On the other hand, if there are consequences, it is often not possible to change the characteristics of the source, and management measures should be aimed at preventing transport and exposure pathways from reaching receptors, such as through the establishment of suitable buffer zones or barrier systems that will protect the receptor from the source.

### 4.2 SPR for Wolvepan and Rietpan Complex

#### 4.2.1 Sources

The Wolvepan and Rietpan Complex are subdivided into nine evaporation dams in total (Figure 1-2), namely, Wolvepan 1, Wolvepan 2, Rietpan, Roberts Dam, Jacksons Dam, Dam 1, Dam 2, Dam 3 and Dam 4. Together they constitute the contamination sources.

#### 4.2.2 Pathways

The following potential contaminant migration **pathways** are identified:

1. Surface run-off from groundwater discharge and / or spillages. This mechanism is potentially the fastest means for contaminants to spread;
2. Open and buried tunnels, trenches and stormwater channels (i.e. any water drainage system);
3. Unsaturated media (surface soils, vadose zones between the sources and the saturated media). Seepage water will migrate downwards under gravity through the unsaturated primary aquifer until it reaches the groundwater table in the primary aquifer. The rate of movement is in the order of 100 m/a to 200 m/a; and
4. Groundwater flow within fully saturated soil and rock media. The rate of groundwater flow is very slow and is in the order of 5 m/a, with the predominant flow being along preferential pathways

such as contact zones and fractured rocks. Whereas pathways 1, 2 and 3 may occur intermittently, subsurface flow occurs continuously.

The degree to which the groundwater has been contaminated is a function of the quality of the contamination source, the rate of infiltration, and attenuating processes in the subsurface. Important attenuation processes at the site include:

- Dispersion due to mixing occurring along and perpendicular to the groundwater flow path;
- Dilution by less contaminated water such as rainfall recharge and cleaner groundwater from up gradient of the site;
- Sorption of contaminants to soil particles;
- Diffusion, which results from concentration gradients within the plume; and
- Radioactive decay.

### 4.2.3 Receptors

The potential receptors of contamination could include:

- Surface water bodies, down gradient;
- Groundwater, as a natural resource; and
- Groundwater users. These include existing boreholes and springs that are used by individuals outside the mine area.

### 4.2.4 Mitigation Measures

The following mitigation measures have been implemented by the mine:

- Groundwater Monitoring. The mine undertakes regular monitoring (monthly, quarterly, bi-annually, as per the monitoring programme) of groundwater quality to check for any alterations in predicted contamination plume movement.

### 4.2.5 SPR Linkages

To identify risk that may trigger the need for remediation / containment, potential **SPR linkages** must be tested to determine if they can be classified as being at risk (i.e. complete linkage). These are shown on Figure 4-1. For the purpose of the SPR assessment, the groundwater flow direction is taken the same as the surface drainage, i.e. west, southwest towards the Sand River and ultimately the Vaal River. Localised drainage (surface and near-surface) is also expected to occur in a north-western direction, towards Kaalpan.

#### **RW SPR1 – Receptor Groundwater**

For this linkage, groundwater, as a natural resource, is investigated to determine whether the natural groundwater quality of the area (background groundwater quality) has been impacted. The groundwater quality prior to mining is not known. The groundwater quality of the monitored boreholes varies from 66 to 306 mS/m, with the majority of the lower EC concentrations occurring south of the evaporation dams.

#### **RW SPR 2 – Receptors Sand River and Kaalpan**

The Sand River is located c.10 km to the south and Kaalpan is located c.4 km to the north-west. These are not part of the current monitoring network, however their location is considered sufficiently distant

from the evaporation dams for surface contaminant flow to be unlikely. Any groundwater flow linkage would take hundreds of years due to the slow flow rate of groundwater in the area (c.5 m/a).

### **RW SPR 3 – Receptor Private Boreholes (groundwater users)**

The hydrocensus conducted in July 2019 corresponded with the groundwater database of the mine and with their groundwater monitoring wells. Three of the four groundwater monitoring boreholes that are situated south of the Study Area, show electrical conductivities < 150 mS/m. Six of the eight monitoring boreholes that occur west / north-west of the evaporation pans contain EC values of > 150 mS/m (200 to 306 mS/m). However, all private groundwater users are > 800 m away and beyond the monitoring boreholes which show no impact. At a groundwater flow rate of c.5 m/a, even if directly flowing in the direction of a recipient borehole and with no dilution or attenuation, it would take 160 years before these points were reached from the evaporation dams.

**Table 4-1: Summary of SPR Linkages for Wolvepan and Rietpan Complex**

SPR Ref.	Receptor	SPR Linkage Completed (Yes/No)
RW SPR 1	Groundwater (as natural resource)	Background groundwater quality shows SPR linkage is unlikely. However, there is a lack of pre-mining data and thus continued monitoring and assessment of trends is of high priority.
RW SPR 2	Sand River and Kaalpan	Distances indicate SPR linkage is unlikely, however monitoring at the nearest point of the Sand River and Kaalpan is recommended for inclusion in the monitoring network.
RW SPR 3	Groundwater users	No private users within likely contaminant plume area, however users should be notified if contamination is detected in the local mine monitoring network.

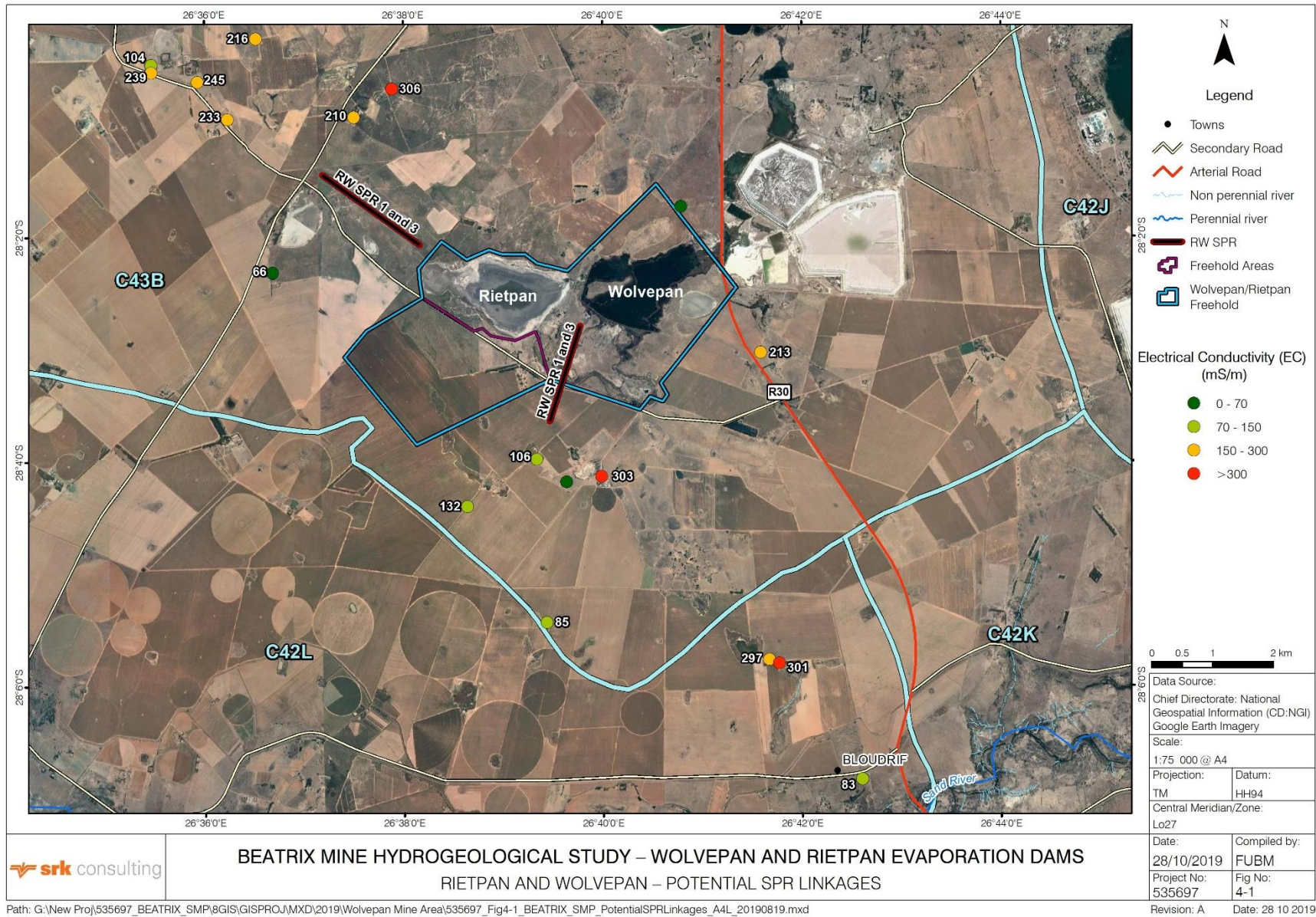


Figure 4-1: Wolvepan and Rietpan- Potential SPR Linkages

## 4.3 Analytical Model

### 4.3.1 Transport Processes

Mass transport modelling in this context refers to the simulation of water contamination or pollution due to deteriorating water quality in response to anthropogenic disturbance of the natural environment.

Transport through an aquifer medium is mainly controlled by the following:

1. Advection: This 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  $x = Vt$ .
2. Hydrodynamic dispersion: This comprises two processes:
  - Mechanical dispersion is the process whereby the initially close group of labelled particles are spread in a longitudinal as well as in a transverse direction because of the velocity distribution (as a result of varying microscopic streamlines) that develops at the microscopic level of flow around the grain particles of the porous medium. Although this spreading is both in the longitudinal and transversal direction of flow, it is primarily in the former direction. Very little spreading can be caused in the transversal direction by velocity variations alone.
  - Molecular diffusion mainly causes transversal spreading, by the random movement of the molecules in the fluid from higher contaminant concentrations to lower ones. It is thus clear that if  $V = 0$ , the contaminant is transported by molecular diffusion only or in other words the higher the velocity of the groundwater, the less the relative effect of molecular diffusion on the transportation of a labelled particle.

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

### 4.3.2 Analytical Model Approach

Solute transport models solve two equations, one for groundwater flow and one for solute transport. The governing equation for solute transport is commonly referred to as the advection-dispersion equation (ADE), which is based on the principle of mass conservation for solutes. ADE equations can be solved by either numerical or analytical methods.

Analytical methods involve the solution of the partial differential equations using calculus based on the initial and boundary value conditions. A fixed gradient boundary condition was chosen for this study as the mass of contaminants over the domain are proportional to the length of time of the seepage. The Sauty (1980) partial differential equation was used to solve the one-dimensional dispersion / contaminant spread from the Wolvepan and Rietpan evaporation dams (Figure 1-2). The Sauty (1980) equation is as follows:

$$C = \frac{C_o}{2} \left[ \operatorname{erfc} \left( \frac{L - v_x t}{2\sqrt{DLt}} \right) - \exp \left( \frac{v_x L}{D_L} \right) \operatorname{erfc} \left( \frac{L + v_x t}{2\sqrt{DLt}} \right) \right]$$

Where:

$C$  = Concentration

$C_o$  = Source concentration

$\operatorname{erfc}$  = Complementary error function value

- $L$  = Length  
 $v_x$  = Vertical velocity  
 $t$  = Time  
 $D_L$  = Longitudinal hydrodynamic dispersion

To calculate the Sauty (1980) equation above, the following parameters are solved for using the equations below:

The calculation of input parameter  $v_x$  is:

$$v_x = \frac{K}{n_e} \frac{dh}{dl}$$

Where

- $v_x$  = Vertical velocity  
 $K$  = Hydraulic conductivity  
 $n_e$  = Effective porosity  
 $\frac{dh}{dl}$  = Hydraulic gradient

The calculation of the input parameter  $D_L$  is:

$$D_L = \alpha_L v_x + D_L$$

Where:

- $D_L$  = Longitudinal hydrodynamic dispersion  
 $\alpha_L = 0.83(\log L)^{2.414}$   
 $v_x$  = Vertical velocity  
 $L$  = Length

### 4.3.3 Assumptions and Limitations

The following assumptions were taken during the development of the analytical model:

- Historical groundwater data displays an inconsistency in water quality measurements over the period of 2005 to 2018, therefore the latest groundwater quality measurements were used to calibrate the model's flow regime. The lack of consistent monitoring data may lead towards a discrepancy between water quality data due to seasonal variation and may limit the ability to fully analyse trends over time;
- To construct a detailed estimation of the recharge of over the study area, algorithms developed by the Department of Water Affairs and Forestry (2005) for the Groundwater Resource Assessment II (GRAII) were used. Quantifying recharge in accordance to the GRAII database, assumes that the recharge over the area is representative of these values;
- Limited hydraulic tests were conducted within the study area, thus information regarding the quantification of groundwater parameters (such as hydraulic conductivity and storage) are based on literature for typical formations and model calibration to water levels. This method results in a far greater uncertainty than if pumping test data were available, resulting in a higher level of uncertainty; and
- The Sauty (1980) analytical equation assumes that the contaminated water moves from the evaporation dams into the aquifer as a line source. Therefore, the rate of contaminant seepage

is considered to be constant, with the seepage mass of the solute being proportional to the duration of the seepage.

The following limitation of the model is noted:

- Analytical methods are limited to simple geometry thus the aquifer for is calculated as being homogenous in nature (Fetter et. al., 2018).

#### 4.3.4 Model Inputs

Analytical model inputs (as shown in Table 4-2 and on Figure 4-2) are based on the following conceptual model assumptions:

- The study site has an average elevation of c.1 300 mamsl, with minor topographical relief which is limited to slow, gently sloping hills. Groundwater levels also have a low hydraulic gradient which is calculated to be c.0.007;
- The study area experiences a semi-arid climate. The annual average rainfall for the area is c.600 mm/a and the associated groundwater recharge from rainfall is c.3% over the study site. Thus, natural recharge does not have a significant role in dilution during the time-scale of the analytical model and can be excluded from the calculations by assuming a worst-case of zero dilution;
- The primary aquifer within the study region consists of weathered sandy fine clay and soils approximately 12 to 50 m thick, with a hydraulic conductivity ranging from c.0.01 to 0.10 m/d and a specific yield (effective porosity) of c.0.1 m/d;
- Three distinctive dams, namely the Wolvepan, Rietpan and Jacksons Dam, serve as contaminant sources. These contaminant sources were assumed to be in operation since the start of mine in 1982 to mine closure in 2025;
- The constituents of potential concern are chloride (Cl), sulfate (SO<sub>4</sub>), iron (Fe), copper (Cu) and uranium (U); and
- A total of seven monitoring points are located in a 2 km radius, of which six are groundwater points (boreholes B1, B2, B23, B25, B32, and B39) and one is a surface point (Wolvepan Evaporation Dam) (Figure 4-2).

**Table 4-2: Analytical model inputs**

Parameter	Unit	Value
Hydraulic conductivity	m/d	0.1
Hydraulic gradient	m	0.007
Specific yield (effective porosity)	-	0.1
Diffusion coefficient for Cl (D)	m <sup>2</sup> /d	1.73 x 10 <sup>-4</sup>
Concentration of source (C <sub>0</sub> )	mS/m	1 500 (100%)
Concentration of background (C)	mS/m	150 (10%)
Longitudinal dynamic dispersivity (α <sub>L</sub> )	m	7
Longitudinal hydrodynamic dispersion (D <sub>L</sub> )	m <sup>2</sup> /d	0.70

### 4.3.5 Contaminant plume footprint

The current contaminant plume (2019) was modelled and assessed against the physical and chemical characteristics of the area (Figure 4-2). The plume was derived from the migration of the contaminants emanating from the Wolvepan and Rietpan complex. Comparatively assessing the latest water quality data against the simulated 2019 contaminant plume, the following can be noted:

- The Wolvepan Evaporation Dam displayed significantly higher EC concentrations (c.1 500 mS/m) than the surrounding boreholes, located at distances of c.500 m and further from the dams and with EC's of <400 mS/m. The high concentrations are found within the contaminant plume, whereas lower concentrations are outside of the contaminant plume, which validates the simulated plume extent;
- Similarly, the Wolvepan Evaporation Dam displayed very high SO<sub>4</sub> concentrations (c.3 000 mg/L), whereas the surrounding boreholes displayed significantly lower concentrations (<250 mg/L). Thus, SO<sub>4</sub> was the constituent of concern which showed the greatest variation in concentration. The distinct difference in concentrations between the dam and the boreholes, further validate the extent of the contaminant plume; and
- The highest borehole concentration within a 2 km radius from the seepage zones is found at B39, which is the closest borehole (c.200 m) to the contaminant plume. Although, this borehole displays high concentrations relative to surrounding boreholes, the concentrations remain well below the source concentration which validates that the contaminant plume has not yet reached this borehole.

Three contaminant plume footprints were analytically modelled from the start of mine in 1982 to 2019 (current), 2025 (mine closure) and 2050 (25 years post-closure) (Figure 4-3). The following can be noted:

- The contamination plume extends radially outwards from the shape of the seepage areas (evaporation dams);
- The current mining year (2019) modelled contaminant footprint extends c.266 m from the seepage sources;
- By 2025 (mine closure) the modelled contaminant footprint has expanded to c.295 m from the seepage sources;
- In 2050 (25 years post-closure) the modelled contaminant footprint extends a distance of c.443 m from the seepage zones, although within the plume the concentrations will decrease with dilution with fresh water recharge;
- The only borehole likely to be intercepted by the contaminant plume is B39 and this is modelled to occur between 2025 and 2050 (post mine closure); and
- The simulated contaminant plumes are unlikely to reach surrounding private boreholes and rivers due to the slow migration of the plume and the receptors being located at reasonable distances (> c.2.5 km) from the contaminant sources (evaporation dams).

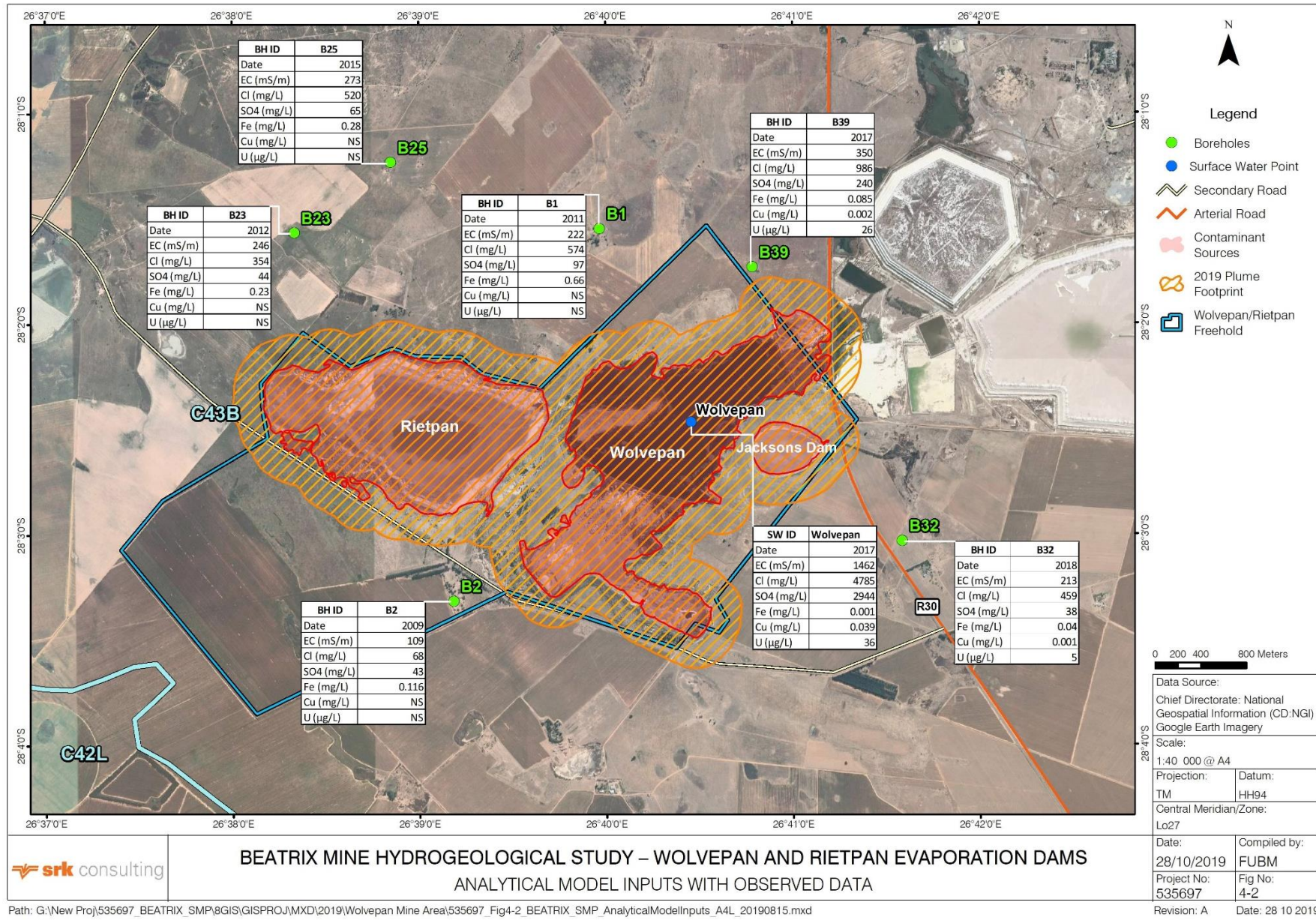


Figure 4-2: Analytical Model Inputs with Observed Data

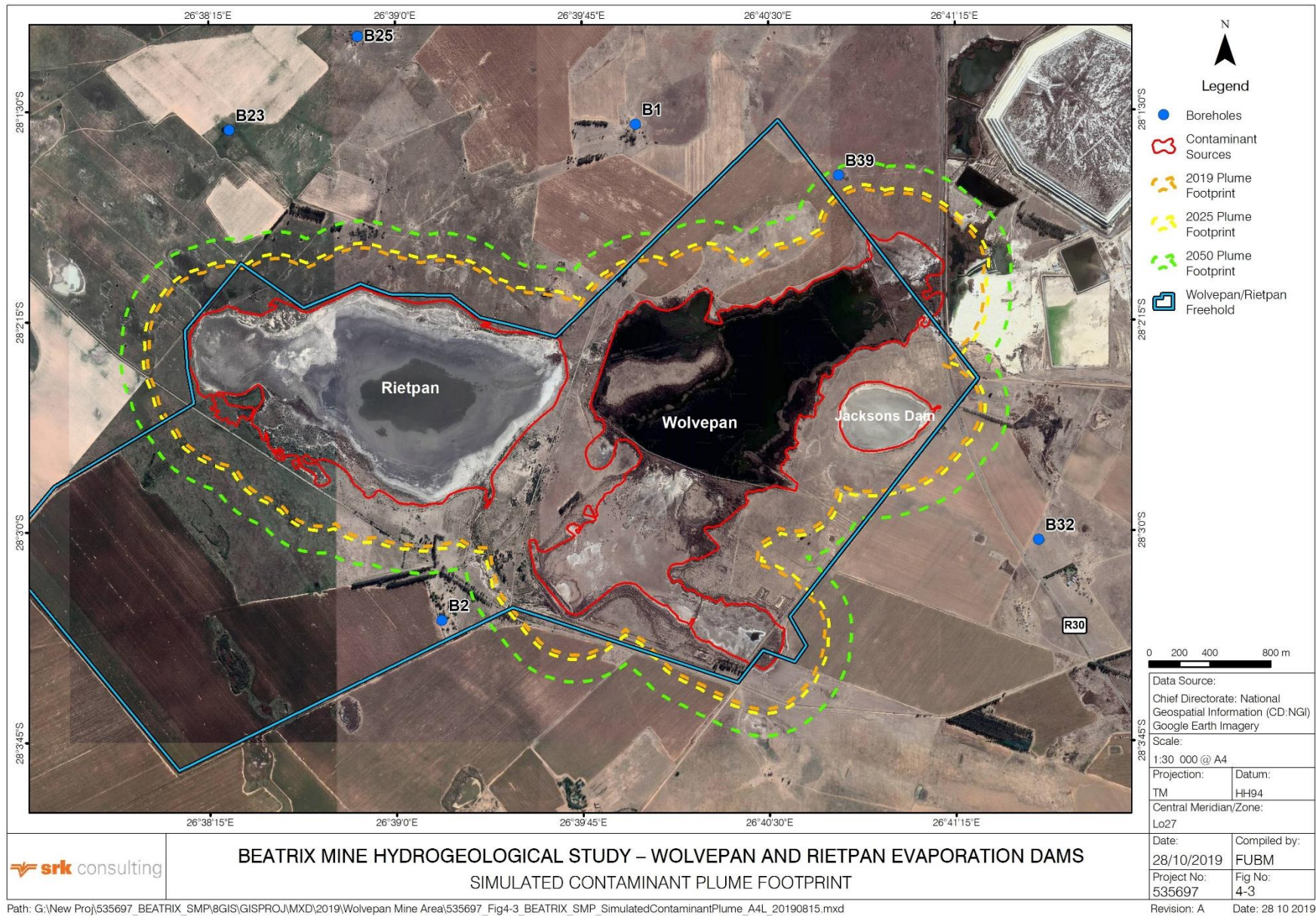


Figure 4-3: Simulated Contaminant Plume Footprint

## 5 Conclusions and Recommendations

Based on the information presented and discussed above, the following key findings are presented:

- An SPR study was undertaken using the latest Beatrix Mine monitoring data and the potential contaminant plume was subsequently modelled analytically;
- The contamination plume extends radially outwards from the shape of the seepage areas (evaporation dams);
- The simulated contaminant plume for the current period (2019) corresponds to water quality concentrations from the Beatrix groundwater and surface water monitoring network. This validates the simulated analytical contaminant plume extent;
- The contaminants undergo a slow migration/spread of c.300 m at 25 years post-closure. This is attributed to the low hydraulic gradient and groundwater flow rates in Study Area;
- The contaminant plume is likely to intercept borehole B39 by the year 2050 and has the potential to intercept B2 in the proceeding years. These are both Beatrix mine monitoring boreholes and should be useful in monitoring the plume migration; and
- The simulated contaminant plumes are unlikely to reach the rest of the surrounding boreholes due to the slow migration of the plume and the receptors being located at a sufficient distance (c.2.5 km) from the contaminant sources (evaporation dams).

The following recommendations are presented:

- Borehole B39 should continue to be regularly monitored as it serves as an early warning plume detection borehole for contaminants moving from the source in a north-east direction and is likely to be intersected first by the contaminant plume;
- Borehole B2 should be included in the monitoring network (sampled on a quarterly basis) as it is located within close proximity (c.200 m) of the simulated 2050 contaminant plume footprint and will provide early detection of plume migration to the south-west of the site; and
- The monitoring network would benefit from a review in the Study Area to ensure efficiency and appropriate coverage of water quality data over space and time. This should be done in the context of this SPR study and predicted contaminant plume footprint and to ensure protection/early warning of plume movement towards receptors. Where boreholes are situated closely together, priority boreholes should be identified and superfluous boreholes removed from the regular monitoring network.

Further detailed recommendations are discussed in the previous Beatrix Mine Hydrogeological Study report (SRK,2019).

## 6 References

- Bredenkamp, D.B., Botha, L.J., Van Tonder, G.J., And Van Rensburg, H.J. Manual On Quantitative Estimation Of Groundwater Recharge And Aquiferstorativity. Wrc Report No Tt73/95, Isbn No: 1868451763, 1995.
- Brink A.B.A (1979). *Engineering Geology of Southern Africa*, Building Publication Pretoria, Vol.4
- Department of Water Affairs and Forestry (1996). *South African Water Quality Guidelines, Volume 5, Agricultural Water Use, Livestock Watering*. Pretoria. South Africa
- Department of Water Affairs and Forestry (2005). *The Groundwater Resource Assessment Phase 2 (GRA2) Project*. South Africa.
- Department of Water Affairs and Forestry (2006). *Groundwater Resource Directed Measures (2006) GRDM Manual, Water Research Commission with support from FETWater, WRC Project*
- Domenico, P.A. and F.W. Schwartz, (1990). *Physical and Chemical Hydrogeology*, John Wiley & Sons, New York.
- Fetter, C.W., Boving, T., Kremer, D. (2018). *Contaminant Hydrogeology*, Macmillan College Publishing Co., 2018
- Freeze, R. A. and Cherry, J. A. (1979). *Groundwater*. Prentice- Hall Inc., Englewood Cliffs, NJ
- Geo Pollution Technologies (GPT) (2009). *Groundwater Management Report Phase 2: Numerical Groundwater Model and Management Program. Beatrix Gold Mine no. 1,2,3 and 4 Shaft*. Reference Number: BEA/10/060. March 2010.
- Golder Associates (2012). *Beatrix Gold Mine Interim Closure Plan, 2012*. Report No 11613344-11038-1.
- Harmse. H.J. VON M. (1967). Soil genesis in the Highveld Region of South Africa. D.Sc. dissertation. Rijks University, Utrecht.
- Parsons, R and Conrad, J (1998) *Explanatory Notes for the Aquifer Classification Map of South Africa*. Prepared for Water Research Commission, WRC Report No. KV 116/98. ISBN-1-86845-456-8.
- Partridge, T.C., Robson, J.F., Harris, G.M and Hamilton, D.J. (1985). *Surface mine plant on alluvium mantled by transported soils of mixed origin: Beatrix Gold Mine, Orange Free State*. *Engineering Geology of South Africa*, pp. 284-251.
- Sauty, J.P., (1980). An analysis of Hydrodispersive Transfer in Aquifers, *Water Resources Research*, 16(1), 145-158. South African National Drinking Water Standard (SANS) 241: 2005: *Drinking Water Specification*, Edition 6.
- South African National Drinking Water Standard (SANS) 241: 2011: *Drinking Water*, Edition 1.
- Visser, J.N.J., (1989). The Permo-Carboniferous Dwyka Formation of Southern Africa: deposition by a predominantly subpolar marine ice sheet. *Palaeogeography, Palaeoclimatology, Palaeoecology* 70, 377–391
- van Tonder, Gerrit and Xu, Yongxin: *RECHARGE program to Estimate Groundwater Recharge*, June 2000. Institute for Groundwater Studies, Bloemfontein RSA.

## Prepared by

SRK Consulting - Certified Electronic Signature


 **srk consulting**  
535697/43764/Report  
2287-3839-8795-IMRS-28/10/2019  
*S. Imrie*  
This signature has been printed digitally. The Author has given permission for its use for this document. The details are stored in the SRK Signature Database

---

Sheila Imrie Pr. Sci. Nat.  
Principal Hydrogeologist

## Reviewed by

SRK Consulting - Certified Electronic Signature

 **srk consulting**  
535697/43771/Report  
1372-2360-9996-COES-04/11/2019  
*Gert Nel*  
This signature has been printed digitally. The Author has given permission for its use for this document. The details are stored in the SRK Signature Database

---

p.p. Gert Nel Pr. Sci. Nat.  
Partner and Principal Hydrogeologist

All data used as source material plus the text, tables, figures, and attachments of this document have been reviewed and prepared in accordance with generally accepted professional engineering and environmental practices.