The geohydrology and related stability of the dolomite aquifer underlying Ikageng: Potchefstroom

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Abstract

Following large scale sinkhole formation on the Far West Rand as a direct result of mining related dolomite dewatering, groundwater is now known as an important factor affecting the stability of cavernous dolomite. Ikageng was developed partly on dolomitic land before the direct relationship between dolomite, dewatering and sinkhole formation was clearly understood.

The Tlokwe Local Municipality (TLM) inherited the legal responsibility to ensure the safety of residents in the greater Ikageng who are at risk of subsidence and sinkhole formation. The TLM therefore initiated a dolomite risk assessment with the aim of having a dolomite risk management strategy (DRMS).

The wealth of geotechnical and geophysical data in the area were interpreted to compile a sinkhole hazard zone map of dolomitic terrain in Ikageng. This map formed the basis of the risk assessment. Geohydrological factors that might be conducive to sinkhole formation were then identified as flags, and overlain on the hazard zone map.

The single biggest threat identified in the area was the Kynoch Gypsum Tailings Dump. The Kynoch Fertilizer Factory in Potch-Industria was commissioned in 1967 and the resultant tailings facility was developed two kilometres to the west on dolomitic land. Gypsum precipitated out of a waste slurry for 35 years, leaving a 25 ha reservoir of highly toxic brine that is remobilised by rainwater. Seepage from the sides was measured to have a pH as low as 1.8, which is expected to dissolve the underlying dolomite. Sinkholes already developed on similar gypsum tailings facilities on carbonate rocks in Florida State in the United States of America.

Keywords

dolomite, aquifer, geohydrology, groundwater, sinkhole, hazard, risk assessment

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List of Abbreviations

AGES	Africa Geo-environmental Engineering & Science
bh	Borehole
BTC	Boskop-Turffontein Compartment
CGS	Council for Geoscience
DEA	Department of Environmental Affairs
DMA	Disaster Management Act
DRMP	Dolomite Risk Management Plan
DRMS	Dolomite Risk Management Strategy
DWA/DWAF	Department of Water Affairs / Department of Water Affairs and Forestry
DWS	Department of Water & Sanitation (earlier DWA/DWAF)
ERT	Electrical Resistivity Tomography
FDEP	Florida Department of Environment Protection
FWR	Far West Rand
GG	Government Gazette
GIS	Geographic Information System
GMA	Groundwater Management Area
GMU	Groundwater Management Unit
GN	Government Notice
GPR	Ground Penetrating Radar
GRU	Groundwater Resource Unit
ISP	Internal Strategic Perspective
KGTD	Kynoch Gypsum Tailings Dump
KOSH	Klerksdorp-Orkney-Stilfontein-Hartbeesfontein
KPA	Key Performance Area
Lat	Latitude
Long	Longitude
MAP	Mean annual precipitation
NDMF	National Disaster Management Framework
NEMA	National Environmental Management Act
NGA	National Groundwater Archive
No.	Number
NWA	National Water Act
OMV	Oranje Mynbou & Vervoer
PVC	Polyvinyl chloride
SANS	South African National Standards
SANAS	South African National Accreditation System
SRTM	Shuttle Radar Topography Mission
T	Transmissivity
TLM	Tlokwe Local Municipality

UN	United Nations
UNISDR	United Nations Internal Strategy for Disaster Reduction
US	United States
VCR	Ventersdorp Contact Reef
WAD	Weathered altered dolomite
WARMS	Water Resource Management System
WMA	Water Management Area
WRC	Water Research Commission
WULA	Water Use License Application

Chemistry

Al	Aluminum
Ca	Calcium
Cl	Chloride
CO_2	Carbon Dioxide
CO_3	Carbonate
Cu	Copper
EC	Electrical Conductivity
F	Fluoride
Fe	Iron
H_2O	Water
HCO_3	Bicarbonate
K	Potassium
N	Nitrogen
Na	Sodium
NH_4	Ammonium
NO_3	Nitrate
Mg	Magnesium
Mn	Manganese
Pb	Lead
pH	Measure of acidity/alkalinity
TDS	Total Dissolved Solids
SO_4	Sulphate
Zn	Zinc

Units

a	Annum (year)
^{o}C	Degrees Celsius
h	Hour
ha	Hectare
km	Kilometre
km^2	Square kilometre
L	Litre
L/s	Litres per second
m	Metre
M	Mega (million)
mamsl	Metres above mean sea level
mbgl	Metres below ground level
mg/L	Milligrams per litre (concentration)
mm	Millimetre
mm/a	Millimetres per annum (rainfall)
m^2	Square metre
m^2/d	Square metres per day (unit of aquifer transmissivity)
m^3/d	Cubic metres per day
m^3/h	Cubic metres per hour
Mm^3/a	Million cubic metres per year

1 Introduction

Due to the soluble chemical nature of dolomite[1], it is prone to sinkhole development. Sinkholes often form without warning and may lead to structural damage in buildings, and associated loss of life. In South African stratigraphy, the majority of dolomite belong to the Transvaal Supergroup, which was named after, and located mostly in the old Transvaal Province. Now divided into the North West, Gauteng, Limpopo and Mpumalanga Provinces, large areas in all four provinces are underlain by this rock type.

Residential and other types of development commenced on dolomitic terrain before the relationship between dolomite and sinkhole development was well understood. Many urban areas now exist on dolomitic terrain, which makes large scale relocation to more stable areas an expensive exercise. Around 2010 a community consisting of approximately 30 000 households west of Johannesburg were being relocated to safer ground at a cost of more than US $600 million. Today it is estimated that up to five million people reside on dolomitic terrain (Buttrick, *et al*, 2011).

It is therefore important for municipalities to be aware of the inherent risk of sinkhole formation in dolomitic areas. Municipalities are not only tasked with the zoning of new development areas underlain by dolomite, but are responsible for the safety of residents in dolomitic areas exhibiting a high risk of collapse (see Chapter 2.8).

One such municipality, the Tlokwe Local Municipality (TLM) in Potchefstroom (North West Province), initiated the quantification of risk to residents of the neighbouring township of Ikageng, which is partly underlain by dolomite. A local environmental consultant, Africa Geo-environmental Engineering and Science (AGES) was appointed to conduct a detailed dolomite risk assessment and draw up a dolomite risk management strategy (DRMS). This study involved the detail characterisation of the geology, including the geotechnical and geohydrological properties. The geohydrological investigation forms the basis of this dissertation (AGES, 2012a).

[1] Dolomite as a karst-forming rock type is discussed in Section 2.1.

1.1. Problem statement:

Sinkholes can form catastrophically and without warning. Where residential (urban or rural) or industrial areas are located on dolomitic terrain, this may lead to loss of lives. There is therefore an inherent risk involved in infrastructure development on dolomitic land that must be managed. Wherever there is existing development on dolomitic terrain that renders mass relocation impractical, the identification of the highest risk areas is necessary to determine the scale of risk that residents are exposed to.

Since areas of Ikageng neighbouring Potchefstroom is underlain by dolomite, and future extension is required, the identification of areas exhibiting a higher risk of subsidence is required by the TLM in order to manage the risks. Due to the established link between groundwater and sinkhole formation, the geohydrological character of the dolomitic aquifer underlying Ikageng forms part of the risk assessment. This dissertation investigates the geohydrological factors that can increase the risk of sinkhole formation in Ikageng.

1.2. Aim:

The aim of this dissertation is to:

- Investigate the geohydrological character of the dolomitic aquifer underlying portions of Ikageng.
- Identify areas of higher risk of subsidence based on the
    - **natural** geohydrological character of the site, and
    - human activities that might lead to **induced** sinkhole formation.
- Present the findings and recommendations as part of an integrated Dolomite Risk Management Strategy (DRMS) to the TLM.
- Investigate the possibility of using a groundwater monitoring network as an early warning system for possible sinkhole formation.

1.3. Layout

This dissertation has the following layout, numbered according to chapters:

1. The introduction gives a short background, problem statement and aim of the study.
2. A literature review of relevant information pertaining to the subject or study

area.

3. The general methodology is described.

4. The area is described in detail, ranging from location, topography, geology and geohydrology.

5. A risk assessment is performed based on the nature of the geology and geohydrology of the area. The risk assessment methodology is described here.

6. Conclusions including a summary and look ahead at possible future developments.

7. Specific recommendations regarding geohydrology and monitoring in the area that might contribute to dolomite stability.

2 Literature Review

Karst as a term refers to a style of landscape containing caves and extensive underground water systems that is developed especially on soluble rocks such as limestone, gypsum, dolomite (Ford & Williams, 2007) and evaporite (salt layers) (Yechieli *et al*, 2016). Dolomite as a karst forming rock type will be discussed next.

2.1 Origin and character of dolomite

Dolomite as a term refers to both the mineral and the rock type. The rock type consists of the minerals dolomite ($CaMg(CO_3)_2$) mixed with calcite ($CaCO_3$) and magnesite ($MgCO_3$) in various ratios and should properly be called 'dolomitic limestone' (Wagener, 1984, DWA, 2009) or dolostone (Monroe *et al*, 2007). In South Africa the vast stretches of dolomitic limestone, or dolostone is commonly referred to as dolomite, hence this term will be used further to describe the rock type rather than the mineral.

Dolomite is a chemically altered form of the sedimentary rock limestone. Limestone is formed by the accumulation of calcite precipitated from sea water, including from skeletal remains of small marine organisms. When calcium in the mineral calcite in limestone deposits is partly replaced by magnesium, the limestone is altered to dolomitic limestone (Monroe *et al*, 2007), or dolomite.

Dolomite is tested for in the field by applying a few drops of acid to the rock. It is readily dissolved by acid and the dissolution process of dolomite (or other carbonate rock types) can be observed physically. It is this dissolution process that gives dolomite its karst-forming character. Acidic groundwater has dissolved dolomite layers in the geological past into various karst features (Ford & Williams, 2007, Monroe *et al*, 2007).

The following karst features give rise to problems relating to (urban) infrastructure development (Brink, 1996):

- The development of sudden and catastrophic sinkholes (a subsidence that appears suddenly as a cylindrical and steep-sided hole in the ground).
- Gradual subsidence of the surface during the formation of dolines (a surface depression which appears slowly over a period of years).
- The occurrence of a highly compressible 'WAD'[2]

[2] Dolomitic areas in South Africa are commonly overlain by a fine grained, reddish clayey material commonly referred to as WAD. **WAD** is an acronym for ***weathered altered dolomite*** and refers to the weathered by-product or residue of dolomite dissolution (Buttrick, 1986).

Sinkholes and dolines occur as natural features in karst areas, but the formation thereof can be accelerated through human interference as indicated in Chapter 2.5.

2.2 Groundwater and cave formation

Some 750 caves occur in the Transvaal Basin (a geological term referring to the extent of the outcrops of dolomite belonging to the Transvaal Supergroup). This is 80% of all caves known in South Africa. It is stated that of these 750, most occur in a stretch between Pretoria and Potchefstroom (Martini, 2006). According to Jacobs (2011) the largest known cave system in South Africa is located in this area. A cave north of Carletonville known as Apocalypse Pothole contains passages that have been mapped for over 20 km. Most of the caves in the area are fissure caves which are strongly controlled by jointing (see Figure 2-1).

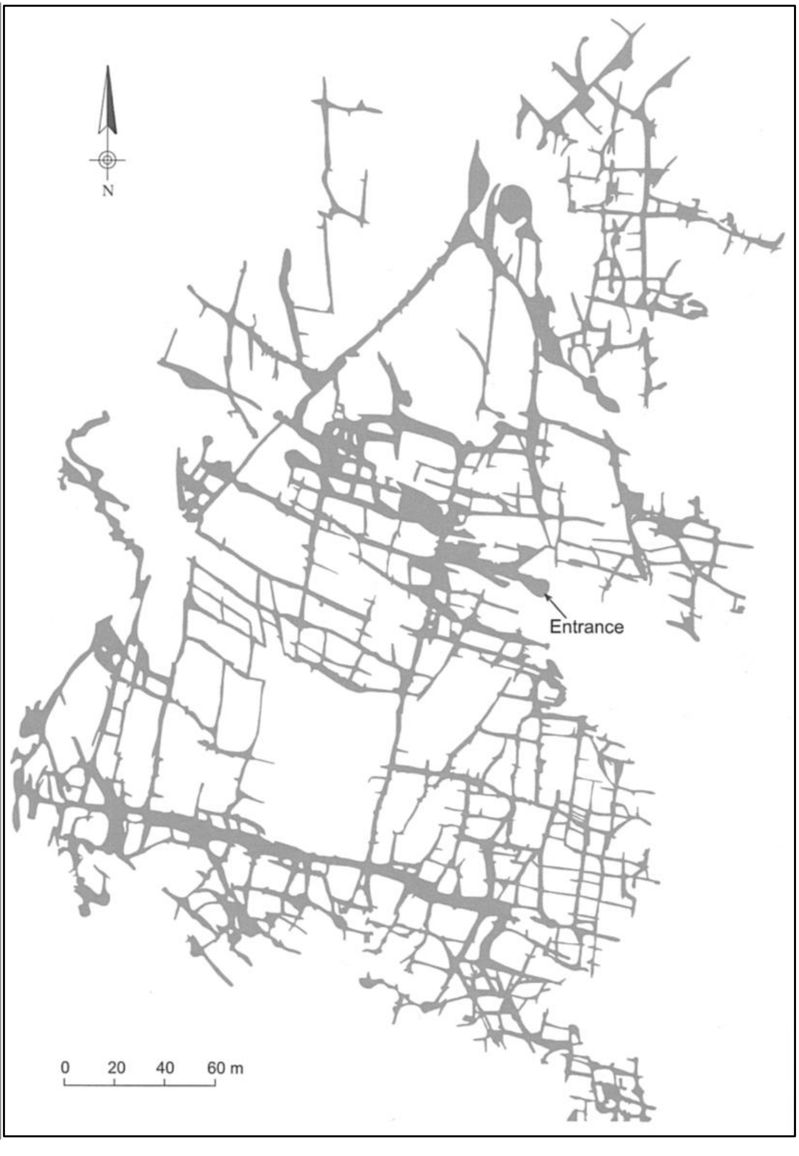

Figure 2-1: This map of the Wonderfontein Cave near Oberholzer shows how the joint network controlled cave formation (Martini, 2006).

Fissure type caves in the Far West Rand (FWR) formed in a horizontal zone 40 m above the current natural water table. Many of the fissure type caves stretch horizontally across several stratigraphic layers, leading to the conclusion that their origin is of phreatic (groundwater) origin (Martini & Kavalieris, 1976 and Martini, 2006).

The presence of caves in soluble rock implies two things:

1. Dissolution of the rock, and
2. Erosion or removal of the dissolved material.

This requires an acidifying agent that is the subject of further debate. Traditional theory on cave formation held that low concentrations of CO_2 dissolves in rainwater to form a weak carbonic acid that percolates into the ground to slowly dissolve carbonate rocks above the water table. This is called the *Vadose Theory* (diagram A in Figure 2-2).

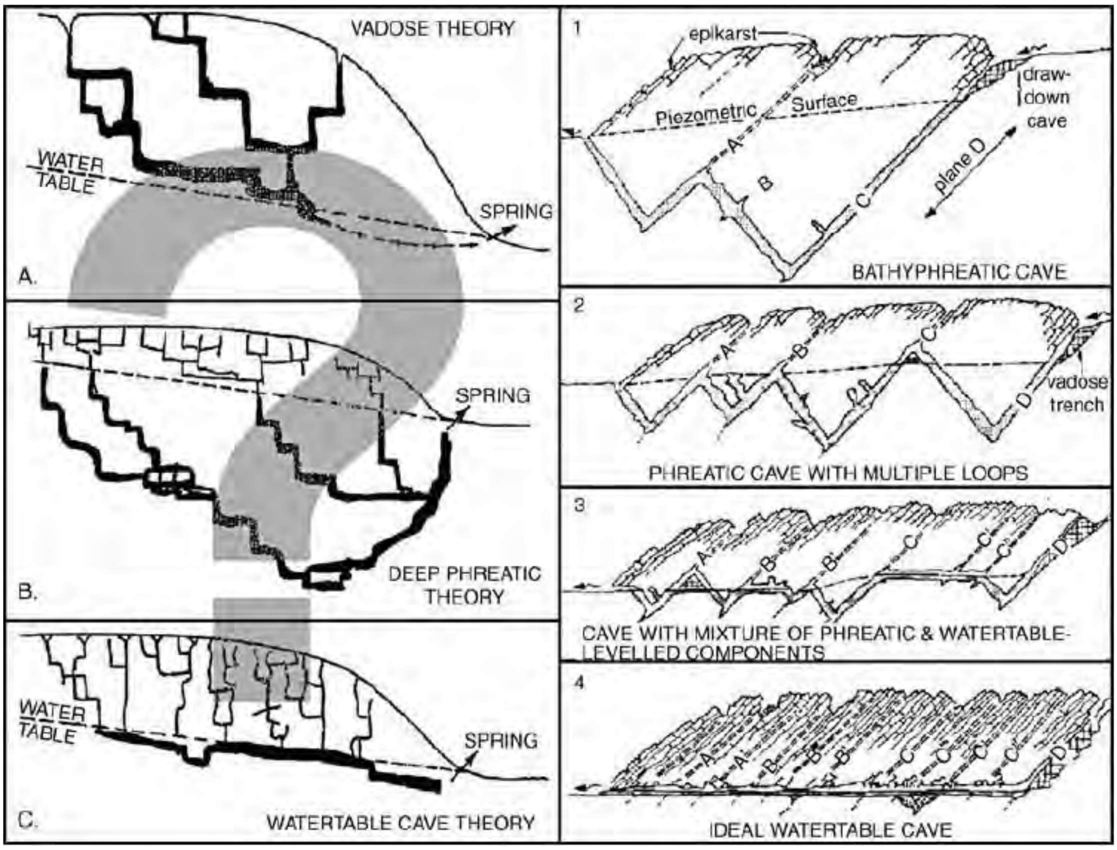

Figure 2-2: Cave formation theories (Ford & Williams, 2007).

In 1930 well-known American geomorphologist W.M. Davis argued that many cave passages were formed below the water table by ascending groundwater flow. This was based on cave maps and sections and is called the *Deep Phreatic Theory* (diagram B in Figure 2-2) (Ford & Williams, 2007). An example of this is Bushmansgat between Kuruman and Daniëlskuil, with a cavity that extends to 265 m below the water table (Martini, 2006). The problem with this theory is that CO_2 derived from the atmosphere is not a sufficient explanation for deep phreatic caves, and a subterranean acidifying agent is required.

The third theory incorporated CO_2 derived from soil in the vadose zone to acidify groundwater and is called the *Water Table Cave Theory* where cave formation propagates along the water table from the headwaters. This theory assumes a pre-existing water table (diagram C in Figure 2-2). Caves formed along the water table are called water table caves, of which the caves observed on the FWR are a prime example.

An attempt was made to reconcile the abovementioned conflicting theories with the Four State Model of cave formation (diagrams 1-4 in Figure 2-2). This model is based on the idea that the number and spacing of initial vertical fissures that channel rainwater downwards, varies significantly between karst terrains. Whereas the variation is more like a continuum in reality, four distinct states were recognised, with ideal water table caves existing in the most fractured karst terrains (Ford & Williams, 2007).

The Four State model again assumes CO_2 or some other atmospheric acidifying agent interacting with rainwater, and fails to explain deep phreatic caves like Bushmansgat.

The presence of flow stones like stalactites decorating the roofs of caves indicates that rainwater quickly becomes oversaturated in calcium carbonate, and precipitates minerals dissolved from the vadose zone (rather than becoming more acidic). The ability of weakly acidic rainwater to dissolve solid carbonate bedrock is therefore quickly neutralised, and atmospheric or soil derived CO_2 fails as a theory for the acidifying agent able to acidify groundwater to the point of dissolving and removing the volume of carbonate rock that once occupied the space. This theory can still be found in credible sources (e.g. British Geological Survey, 2015).

The fact that these voids – often of enormous size – are left after dissolution, proves that the dissolving agent also transported the dissolved material away, implying groundwater movement. Taking this into account it is therefore clear that the chemistry and movement of groundwater strongly influenced cave formation in the past, and more updated theories focus on the role of (already) slightly acidic groundwater as the main erosive agent (e.g. Monroe *et al*, 2007).

Studies have suggested that at least 10% of the caves in the Guadalupe Mountains in Texas and New Mexico were formed primarily by sulphuric acid in groundwater. This includes the famous larger caves like Carlsbad Caverns and Lechuguilla Cave. The hypothesis is based on the discovery of reaction products of sulphuric acid dissolution in the caves which includes elemental sulphur, gypsum, hydrated halloysite, allunite and other minerals. Based on this it is further postulated that 10% of major known caves around the world were formed this way (Polyak *et al*, 1998, Oard, 1998).

2.3 Natural sinkhole formation

Sinkholes form where a subsurface void (cavity) exists that acts as a receptacle to receive solid or weathered overburden, through gradual and/or catastrophic collapse. According to Brink (1996) the following conditions must exist in order for sinkholes or dolines to form:

- There must be rigid material to support the roof of the cavity. The span of the cavity must be appropriate to the strength of the material, because if the span is too great or the material too weak, a cavity will not be able to form.
- A condition of arching must form, whereby all the vertical weight must be carried.
- A void must develop below the arch.
- A reservoir must exist below the arch to accept the material which is removed from below the arch, as to enlarge the void. Some means of transportation of the material is also needed, such as flowing water.
- When a void of appropriate size has been formed, some sort of disturbing agency must arise to cause the roof to collapse.

Conditions that advance karst development were listed by Obbes (2000):

- The region should experience a moderate rainfall, and have a fluctuating water table within 30 m of the surface.
- The topography should consist of steeply incised valleys underlain by well-jointed, shallow, soluble bedrock. (The topography of the majority of the Malmani dolomite on the FWR is relatively flat).
- There should be solid dolomite, chert or diabase arches, which will support material above the cavity.
- The soluble rock should be dense, highly jointed and thinly bedded to facilitate chemical weathering. Weathering occurs in the phreatic and vadose zones (above and below the water table), and is accelerated by closely spaced fractures. A strong relationship exists between zones of fracture concentration and sinkholes, subsidence features and springs.

When a sufficiently large cavity has developed, a trigger mechanism is needed to initiate the collapse, which grows upwards towards the roof of the cavity, until it breaks through the surface and a sinkhole forms. The trigger mechanisms include:

- excessive wetting of the arch material, which decreases the soil strength and promotes collapse,
- piping, and
- the occurrence of earth quakes, which disturbs the equilibrium in the underlying material.

The unconsolidated, eluvial overburden is characterised by an increased porosity at depth as openings and conduits coalesce. Because the degree of compaction is greatest at the surface, it easily forms an arch, which is not representative of the actual strength of the arch (Brink, 1996).

From diagram 1 (Figure 2-3) it can be seen that the cavity (C) within the dolomite (D) enlarges as water saturates (W) the residual soil zone (S). In diagram 2 the water causes erosion of residual soil into the cavity, which creates a similar collapse of residual soil overburden (diagram 3) until eventually a sinkhole appears (diagram 4) which can lead to increased erosion.

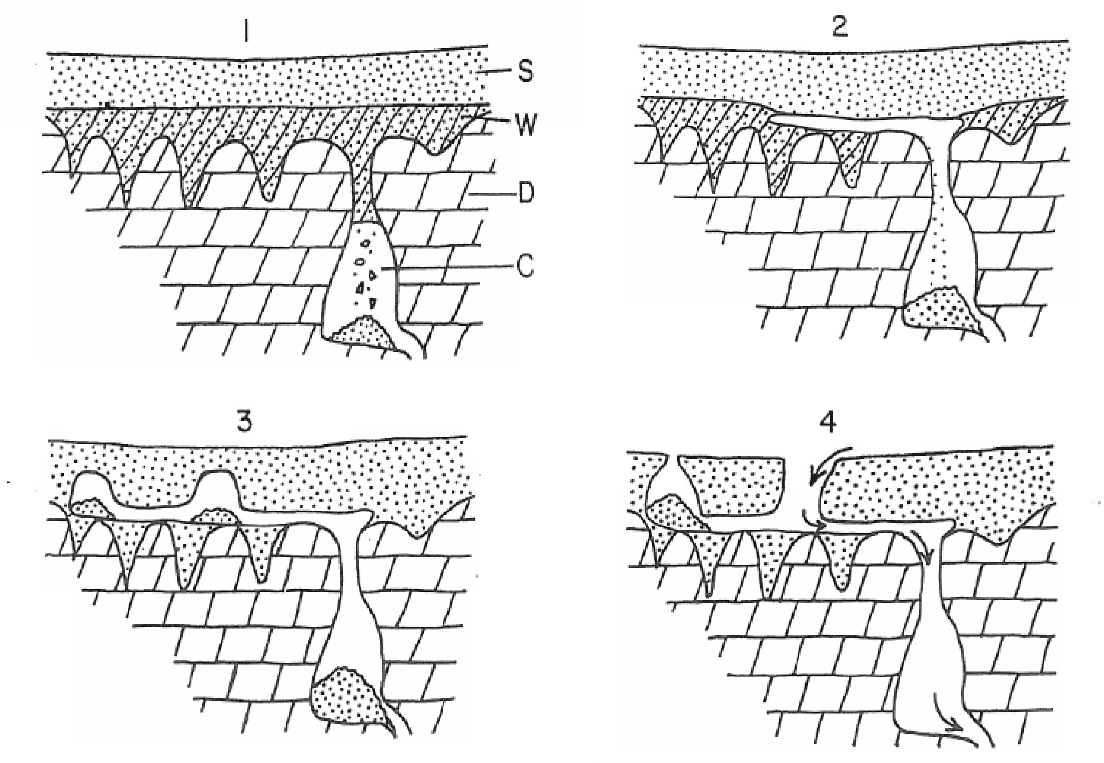

Figure 2-3: Diagram illustrating sinkhole development (Moen & Martini, 1996).

The potential instability may also be increased due to the existence of paleokarst structures. These ancient karst structures include sinkholes that have formed through the passage of geological time and refilled by debris of a different origin, such as sand or mud that has blown/washed into the sinkhole. Paleokarst structures contribute to the geological heterogeneity in dolomitic terrain and are indicative of further potential instability.

2.4 Induced sinkhole formation

There are three apparent (interconnected) methods of inducing sinkhole formation:

1. Since the large-scale sinkhole development in the Wonderfonteinspruit area occurred as soon as dewatering activities commenced, there appears to be a direct connection between dolomite stability and the hydrostatic pressure provided by a saturated subsurface. As soon as the supporting hydrostatic pressure was removed by the dewatering activities, the weight of the overburden on top of near-surface cavities exceeded a critical point, and sinkholes and dolines formed.
2. Many sinkholes form during the rainy season, and especially after periods of heavy rainfall (Moen & Martini, 1996, De Bruyn *et al*, 2000). As the unsaturated soil zone becomes saturated, the critical weight can also be exceeded whereby the supporting rock in the roof of a cavity fails to support the heavier overburden. In urban areas with poor storm water drainage, ponding of water may also lead to increased weight of the overburden in critical areas leading to sinkhole formation.
3. Rainfall also causes erosion of unconsolidated surface material through pre-existing channels into underground cavities, leading to the upward migration of cavities (see Figure 2-3). In urban areas this process might be induced by constantly leaking water infrastructure like water supply and sewerage pipelines.

It is estimated that some 650 sinkholes that formed during a 20 year period between 1984 and 2004 over a 3 700 ha stretch of dolomitic land south of Pretoria, can be attributed to the above factors (Buttrick *et al*, 2011).

2.4.1 Dewatering

The rate and extent of water level drawdown is one of the critical contributing factors to sinkhole formation. The risk of sinkhole formation in dolomitic areas are higher where the static groundwater level occurs close to surface (<30 m) and where water level fluctuations of more than six metres occur in response to pumping, or where the aquifer is dewatered (Barnard, 1999; Department of Water Affairs and Forestry (DWAF), 2006). For a detailed case study on the history of mining related dewatering and sinkhole formation in South Africa, see Section 2.5.

2.4.2 Ponding of water

After heavy rains, the ponding of water can cause sinkholes to form suddenly. Water in urban areas has its flow impeded by vertical structures like brick and concrete walls. This can add sudden weight to the surface, and soak the subsurface to the point where ingress of water into subsurface voids start, leading to erosion of weathered material as described above. It has been documented that sinkholes form due to the ponding of rainwater (Potgieter, 2012).

In Basilicata in Italy, Lake Sirino drained almost completely on numerous occasions after being affected by piping sinkholes below the lake bottom (Giampaolo *et al*, 2016).

2.4.3 Water ingress from old infrastructure

It was shown that rainwater saturating the weathered material overlying cavernous dolomite may enhance sinkhole formation under natural conditions (Figure 2-3). Similarly, where an artificial point source of water exists that feeds a continuous stream of water in similar conditions, enhanced sinkhole formation is likely. Because of residential infrastructure altering the natural conditions, point sources like leaking taps or pipelines are seen as artificial factors inducing sinkhole formation (see Photo 2-1) (Potgieter, 2012).

Photo 2-1: A sinkhole formed due to leaking water infrastructure in Waterkloof in Pretoria (Oosthuizen & Richardson, 2011).

Apart from the weathering effect of fluids on unconsolidated material overlying cavities, water infiltration from leaking sewage or water pipes has the potential to dissolve and erode dolomite at a far greater rate than its natural dissolving rate (Potgieter, 2012). This increased dissolution rate may cause underground cavities to form at greater speeds in the built-up areas than in the surrounding areas.

2.5 Background: the link between groundwater fluctuations and sinkhole formation in South Africa

The link between groundwater level fluctuations and dolomite instability will be discussed by referring to the large-scale mining related dewatering on the FWR and thousands of sinkholes that formed shortly afterwards.

The gold contained in the conglomerate layers of the Witwatersrand Supergroup was discovered on the farm Langlaagte in Johannesburg in 1886 (Winde & Stoch, 2010). The strike of the outcrop was from west to east with the dip to the south (Photo 2-2).

Photo 2-2: The site of the initial discovery of gold along the Main Reef is now a National Monument. Note the steep dip of the layering to the south (photo looking to the west). (The Heritage Portal, 2014).

This outcrop soon became known as the 'Main Reef[3]', which led to the development of Main Reef Road to transport people and equipment to the various claims that sprung

[3] The term 'reef' is not exclusive to conglomerate layers, but refers to any orebody that is being mined. In the platinum mines the orebody might be the Merensky Reef while in the Barberton Mountainland the gold reefs are quartz veins or mineralised shear zones.

up along the reef outcrop (Winde & Stoch, 2010). Main Reef Road is still in use today and links the West Rand (Randfontein/Krugersdorp) to the East Rand (Brakpan/Springs).

The dip of the reef is down to the south in this part of the Witwatersrand Basin, and as the surface mining operations followed the deeper-dipping layers, it eventually necessitated the sinking of shafts to access the ever-deeper lying orebody (Figure 2-4).

As exploration continued along strike, the West Rand and East Rand gold fields were soon discovered, and the original mining area became known as the Central Rand (Winde & Stoch, 2010). In the Central Rand area the Witwatersrand Supergroup rocks are overlain by lava from the Ventersdorp Supergroup, while in the West and East Rand gold fields the Ventersdorp lava in turn is overlain by dolomite from the Transvaal Supergroup. The dolomite once covered the Central Rand but is now partly eroded away.

Mine shafts sunk in the West Rand and East Rand gold fields, therefore had to penetrate often cavernous dolomite in order to reach the deeper gold bearing conglomerates. These subsurface cavities are ideal reservoirs for groundwater but this created flooding problems when sinking shafts. Whenever shafts would intersect crevices or cracks directly linked to higher-lying saturated cavities, the enormous water pressure from above would cause the shaft to be flooded. Much like the hydrostatic pressure in a water strike within a surface borehole would cause the intersected groundwater from the fracture to push up into the borehole.

It was not until the 1930s when a new technique (called ‘cementation’) was developed to seal off any water bearing fractures that a shaft was successfully sunk through the dolomite and underlying Ventersdorp lava into the Witwatersrand rocks (Winde & Stoch, 2010). This enabled mines to sink shafts even further south and mine at even deeper levels.

Groundwater contained in the Malmani dolomite in great volumes still managed to percolate through cracks and joints into the newly developed mining voids. Gold mines were again faced with the risk of flooding, and groundwater entering the mining voids had to continually be pumped out to surface. This increased production costs which led to the decision to dewater the overlying dolomite compartments from above rather than risk lives and production underground by escalating groundwater influx.

A four year environmental impact study was conducted after West Driefontein Gold Mine sought permission from the Government to dewater the overlying dolomite compartment. Permission was finally granted in 1964 to dewater two compartments by pumping out more water than the volume needed to recharge the compartment (while in fact mines commenced with dewatering some years before). The environmental study only predicted the drying up of springs and production boreholes located on dolomite, and failed to foresee the development of thousands of sinkholes (Photo 2-3), some with catastrophic results. A sinkhole swallowed the crusher plant at West Driefontein Gold Mine in December of 1962 in which 29 people were killed, and in 1964 a family of five died when their house disappeared down a sinkhole in Blyvooruitzicht village (Winde & Stoch, 2010).

Photo 2-3: This piece of land on the Venterspost Compartment became known as 'Sinkhole Farm' after the dewatering related sinkholes formed (Oosthuizen & Richardson, 2011).

The loss of lives prompted ground instability studies which linked sinkhole formation directly to the dewatering of the dolomite compartments (Jennings *et al*, 1965 as cited in De Bruyn *et al*, 2000). Thus the relationship between groundwater level fluctuations and sinkhole formation was realised.

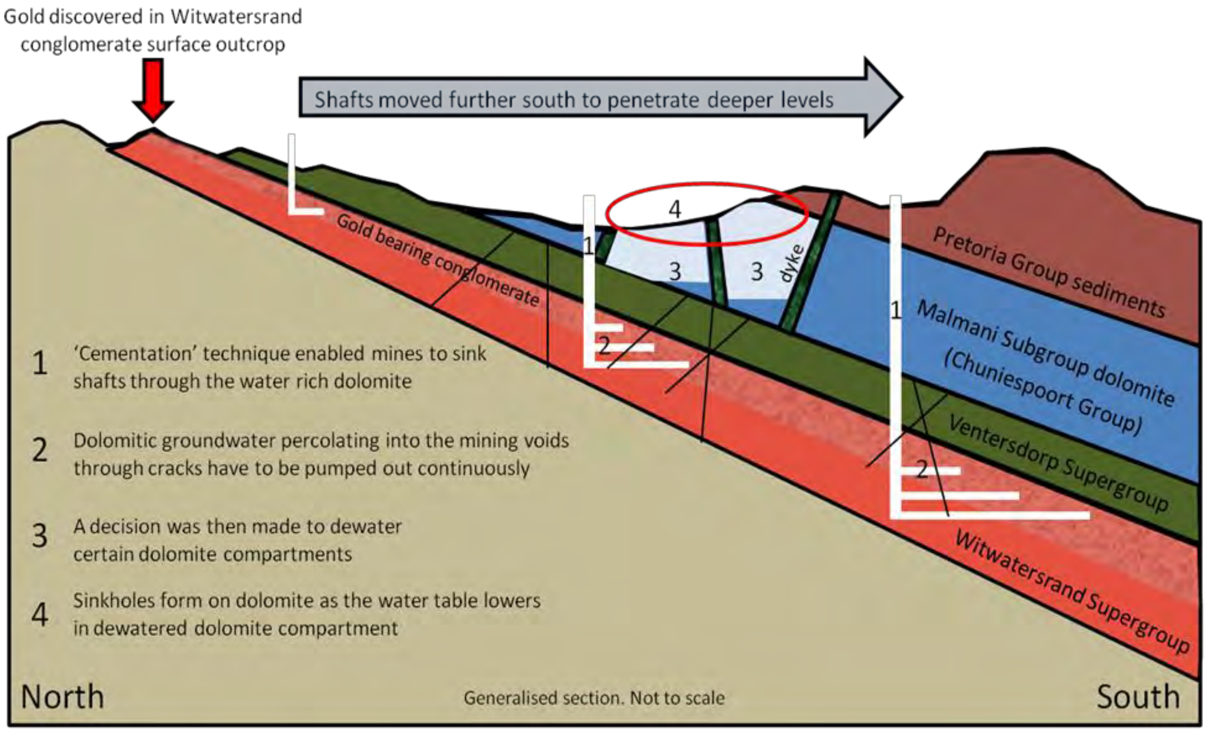

Figure 2-4: Schematic cross section indicating mining related compartment dewatering and subsequent sinkhole formation (AGES, 2012a).

2.6 History of Ikageng

The location of Potchefstroom was greatly influenced by the geology and geohydrology of the area. The initial settlement along the banks of the Mooi River in 1838 was relocated further downstream in 1841 to find soil with better drainage and agricultural potential. The first township development in Potchefstroom was known as Makweteng or Willem Klopperville and was located in the current Mieder Park area east of Walter Sisulu Avenue. This was an integrated township with both coloureds and blacks living in the same area. In 1948 the National Party came to power and began relocating residents to the current Ikageng and Promosa between 1958 and 1963 (Potgieter, 2012).

By the time that relocation was completed, the thousands of sinkholes started to form on the FWR as a direct result of dolomite dewatering. Therefore, the establishment of Ikageng on dolomite predates our understanding of the link between dolomite, dewatering and sinkhole formation.

2.7 Risk management

2.7.1 Introduction

With an increase in global population and the human footprint, disaster risk management is increasingly becoming a global challenge. Since the 1990s, disaster risk reduction as a field of practice has developed at a significant pace. Because of the link with the concept of sustainable development, many international organisations, including the United Nations (UN) have promoted this field of study (Van Riet, 2009).

The UN has attempted to provide a global reference framework for disaster related studies, and risk reduction strategies. As an introduction it is necessary to define a few terms relating to risk assessments of natural hazards: These definitions were taken from the United Nations International Strategy for Disaster Reduction's (UNISDR) publication 'Living with Risk' (United Nations, 2004:16-17):

Hazard: "*A potentially damaging physical event, phenomenon or human activity that may cause the loss of life or injury, property damage, social and economic disruption or environmental degradation…Each hazard is characterised by its location, intensity, frequency and probability*"

Vulnerability: "*The conditions determined by physical, social, economic, and environmental factors or processes, which increase the susceptibility of a community to the impact of hazards*."

Risk: "*The probability of harmful consequences, or expected losses (deaths, injuries, property, livelihoods, economic activity disrupted or environment damaged) resulting from interactions between natural or human-induced hazards and vulnerable conditions.*"

Risk Assessment or Analysis: "*A methodology to determine the nature and extent of risk by analysing potential hazards and evaluating existing conditions of vulnerability that could pose a potential threat or harm to people, property, livelihoods and the environment on which they depend*."

Capacity or Capability: "*A combination of all the strengths and resources available within a community, society or organization that can reduce the level of risk, or the effects of a disaster.*"

Coping capacity: "*The means by which people or organizations use available resources and abilities to face adverse consequences that could lead to a disaster*."

Resilience: "*The capacity of a system, community or society potentially exposed to hazards to adapt, by resisting or changing in order to reach and maintain an acceptable* *level of functioning and structure. This is determined by the degree to which the social system is capable of organizing itself to increase its capacity for learning from past disasters for better future protection and to improve risk reduction measures*."

Disaster: "*A serious disruption of the functioning of a community or a society causing widespread human, material, economic or environmental losses which exceed the ability of the affected community or society to cope using its own resources*."

Disaster Risk Management: "*The systematic process of using administrative decisions, organization, operational skills and capacities to implement policies, strategies and coping capacities of the society and communities to lessen the impacts of natural hazards and related environmental and technological disasters. This comprises all forms of activities, including structural and non-structural measures to avoid (prevention) or to limit (mitigation and preparedness) adverse effects of hazards*."

Disaster Risk Reduction: "*The conceptual framework of elements considered with the possibilities to minimize vulnerabilities and disaster risks throughout a society, to avoid (prevention) or to limit (mitigation and preparedness) the adverse impacts of hazards, within the broad context of sustainable development*."

Prevention: "*Activities to provide outright avoidance of the adverse impact of hazards and means to minimize related environmental, technological and biological disasters*."

Mitigation: "*Structural and non-structural measures undertaken to limit the adverse impact of natural hazards, environmental degradation and technological hazards*."

Preparedness: "*Activities and measures taken in advance to ensure effective response to the impact of hazards, including the issuance of timely and effective early warnings and the temporary evacuation of people and property from threatened locations*."

Early warning: "*The provision of timely and effective information, through identified institutions, that allows individuals exposed to a hazard to take action to avoid or reduce their risk and prepare for effective response*."

According to these definitions, a sinkhole forming would be seen as a **hazard**. The conditions that determine the community's susceptibility to be affected by the hazard, are defined as the **vulnerability**. The probability of harmful consequences or expected losses from a potential sinkhole is seen as the **risk**. Generally risk is expressed as a function of hazard and vulnerability as follows (United Nations, 2004):

Risk = Hazard x Vulnerability

By implication nuclear power stations and coastal residents on the east coast of Japan would be more vulnerable to a Pacific tsunami hazard than infrastructure or people living farther inland, and therefore at greater risk. Similarly communities residing on cavernous dolomite are more vulnerable to sinkholes forming than communities on i.e. shale or sandstone. Analysing the potential hazards of sinkholes forming (hazard assessment), and evaluating the conditions pertaining to the vulnerability of communities (vulnerability assessment) therefore would form the basis of risk assessment.

2.7.2 Global approaches to sinkhole risk management methodology

According to Potgieter (2012), although the karstic character of dolomite have been researched extensively, the concept of sinkhole related risk management is a relatively new concept. As recently as the early 1990's, proposed sinkhole risk assessment methodologies made no mention of subsurface characterisation by means of drilling or geophysics, but relied on mapping of existing sinkholes and geological structures to determine hazardous areas (Kemmerly, 1993).

By the turn of the millennium, the importance of determining the location of subsurface voids were recognised as a "*prerequisite risk factor"* in the risk assessment process (Table 2-1).

A regional risk assessment of karst collapse in Tangshan, China made use of the decision tree method (or fish-bone model, see Figure 2-5) and identified the following factors that influence karst collapse (Hu *et al*, 2001). Each risk factor were given a priority factor label with a percentage risk value that is further used in a risk assessment equation (Table 2-1).

The risk assessment method used (decision tree method), calculated a risk value for each unit (the main trunk of the tree corresponding to various karst areas) by summing the risk factors of the individual greater branches, each made up of several elements (smaller branches). The sum of all the elements under each factor in turn determine the weight of the factor (Figure 2-5).

Table 2-1: Risk factor ratings used in a risk assessment by Hu *et al* (2001).

Risk Factor	Label	Risk Value	Description
Prerequisite	F1	50%	Existence of subsurface voids
Intensity	F2	25%	Lithology Structure of strata (layering) Overburden thickness Distance from active faults
Triggering	F3	10%	Earthquake frequency Groundwater abstraction
Economic	F4	7.5%	Land use (urban, rural, industrial, residential) Average population density Average economic density
Mitigation	F5	7.5%	Management level of hazard prevention or loss reduction Level of hazard prevention techniques Resistance of structures to damage

The individual elements (not listed here) are given arbitrary values (between 0 and 0.5) based on the degree of risk of karst collapse attributed to each element. The authors admitted their subjectivity in this regard, whilst encouraging further study of the contribution of each element due to the complexity and interrelated nature of the different elements playing a role in sinkhole formation.

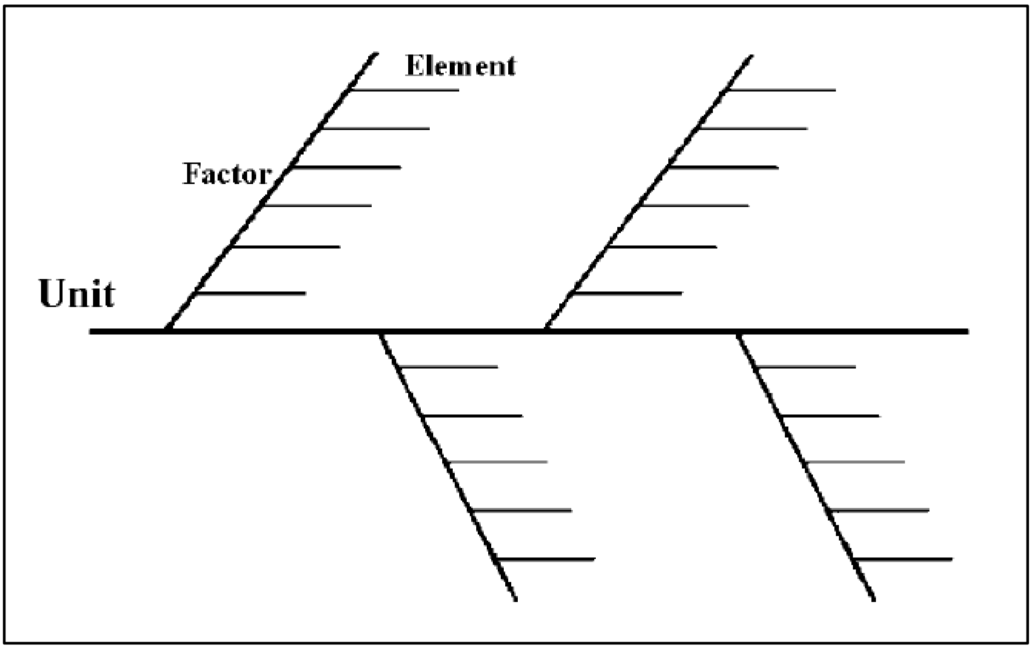

Figure 2-5: The decision tree method, or fish-bone model used by Hu *et al* (2001).

The risk assessment process involved various forms of data collection, site investigations to confirm and supplement data, and data input into a geographic information system (GIS) to represent different elements as layers and produce maps by means of spatial analyses that match the risk factors. Zones of higher and lower risk were determined by statistical analyses of all the risk factors as follows:

Low risk Risk factor score <0.35

Medium risk Risk factor score 0.35-0.6

High risk Risk factor score >0.6

No mention were however made of subsurface characterisation by means of geophysics or drilling during the risk assessment (although the existence of subsurface voids were seen as a prerequisite factor). It was however recommended by the authors to investigate the development and distribution of hidden karst features as part of the study conclusions.

The role of remote sensing techniques like aerial photography, multispectral satellite imagery and various geophysical surveys have become increasingly important to indirectly characterise the degree of subsurface karstification. Various techniques can be applied, ranging from three dimensional seismic surveys to characterise paleokarst features buried beneath more than 1 000 m of sediments (Soudet *et al*, 1994), to electrical resistivity tomography (ERT), ground penetrating radar (GPR) and microgravity surveys for shallower karst characterisation (Ford & Williams, 2007). ERT is also useful in determining the degree of groundwater saturation in karst areas (Ford & Williams, 2007, Giampaolo *et al*, 2016).

2.7.3 South African approach to sinkhole risk management methodology

According to Potgieter (2012), Greg Heath from the CGS reported following the 2008 Karst Conference held in Tallahassee in Florida in the United States (US) that South Africa is ahead of the US in terms of its risk management procedures.

In 2001 Buttrick *et al* developed a dolomite land hazard identification and risk assessment methodology for South Africa. This has become the industry standard risk assessment methodology in South Africa (and other countries), and has been validated and refined through case studies a decade later, to the point of even reducing the risk rating in some cases (Buttrick *et al*, 2011). This methodology was mostly employed during this study.

In dolomite stability investigations, most time, effort and expenses go into hazard identification and classification. The dolomite risk assessment methodology referred to above, has three key components pertaining to the hazard of sinkholes: hazard, inherent hazard, and a hazard rating.

- Hazard refers to the event of a sinkhole forming. Sinkhole hazards are further classed as small (<2 m), medium (2 – 5 m), large (5 – 15 m) and very large (>15 m) based on the diameter of the sinkhole expression on surface.
- Inherent hazard refers to the geological susceptibility of a karst terrain to a sinkhole event (determined by the geological, geotechnical and hydrogeological properties) and is ranked as low, medium or high.
- The hazard rating is expressed as low (0-0.1), medium (>0.1) or high (>10) based the expected number of events per 1 ha per 20 years. Low hazard ratings are seen as tolerable and medium and high ratings are considered intolerable (Buttrick *et al*, 2011).

It is clear that in order to define the hazard, rank the inherent hazard, or derive a hazard rating, the subsurface characteristics must be known. This includes subsurface voids or receptacles (in either the bedrock or overburden), mobilising agencies like excessive water table fluctuations or water ingress from leaking municipal services, the nature and mobilisation potential of the blanketing layer (overburden) and potential sinkhole development space.

The importance of indirect (geophysical) and direct (drilling) investigative methods is vital in determining these characteristics, which make up a significant portion of the cost of such an assessment. Geophysical surveys like ERT, GPR and gravity surveys can identify the presence of subsurface receptacles. These can be confirmed by pneumatic drilling. Information on the penetration rate, air loss, hammer rate and sample recovery are all important factors to consider.

The above information can then be used to classify dolomitic land into inherent hazard classes as documented in Table 2-2. This refers to the chance of a sinkhole occurring, as well as the likely size of the sinkhole.

The aim of the hazard classification is to develop risk management strategies. Risk on dolomitic land may broadly be managed by:

- Placing restrictions on land use (based on the inherent hazard class)
- Ensuring appropriate development,
- Establishing development requirements for
    - both above-ground and below-ground service infrastructure,

- buildings to allow for safe evacuation in the event of a hazard occurring,

- Establishing requirements for
  - The management and monitoring of surface drainage and groundwater abstraction,
  - The maintenance of water-bearing service structures, and
- The development of risk management systems to mitigate risks (Buttrick *et al*, 2011).

The above is achieved by dolomitic area designations as indicated in Table 2-3.

Table 2-2: Inherent hazard classification of dolomitic areas (Buttrick *et al*, 2011).

Inherent hazard Class	Area characterisation
Class 1 Areas	Areas characterised as reflecting a low inherent susceptibility of sinkhole formation (all sizes).
Class 2 Areas	Areas characterised as reflecting a medium inherent susceptibility of small-size (<2 m diameter) sinkhole formation
Class 3 Areas	Areas characterised as reflecting a medium inherent susceptibility of up to medium-size (2–5 m diameter) sinkhole formation.
Class 4 Areas	Areas characterised as reflecting a medium inherent susceptibility of up to large-size (5–15 m diameter) sinkhole formation.
Class 5 Areas	Areas characterised as reflecting a high inherent susceptibility of small-size (<2 m diameter) sinkhole formation.
Class 6 Areas	Areas characterised as reflecting a high inherent susceptibility of up to medium-size (2–5 m diameter) sinkhole formation.
Class 7 Areas	Areas characterised as reflecting a high inherent susceptibility of up to large-size (5–15 m diameter) sinkhole formation.
Class 8 Areas	Areas characterised as reflecting a high inherent susceptibility of up to very large size (>15 m diameter) sinkhole formation.

Table 2-3: Dolomitic area designation and related development requirements (from Buttrick *et al*, 2011).

Area designation	Development requirements
D1	No precautionary measures are required to support the development.
D2	Only general precautionary measures that are intended to prevent the concentrated ingress of water into the ground are required to support development.
D3	Precautionary measures in addition to those pertaining to the prevention of concentrated ingress of water into the ground are required to support development, i.e., selection of pipe materials and joint type that minimizes joints, is impact resistant and flexible, wet services placed above ground, limitation on wet service entries to buildings, provision of water tight services, restrictions on the placement of wet services in the vicinity of buildings and the design of buildings in which people congregate, work or sleep to enable safe evacuation in the event of sinkhole formation.
D4	Precautionary measures described for dolomite area designation D3 are unlikely to reduce the hazard rating to tolerable levels so as to support development or are considered to be uneconomic or impractical to reduce the hazard rating to tolerable levels so as to support development.

2.8 South African legislative backdrop

2.8.1 Disaster Management Act

Shortly following the 2002 World Summit on Sustainable Development (WSSD) in Johannesburg's recommendations that highlighted the unavoidable relationships between consequences of disasters and national development (United Nations, 2004), South Africa's Disaster Management Act (DMA) was promulgated on 15 January 2003 (South Africa, 2003).

The Act provides for:

- *"an integrated and co-ordinated disaster risk management policy that focuses on preventing or reducing the risk of disasters, mitigating the severity of disasters, preparedness, rapid and effective response to disasters, and post-disaster recovery*
- *the establishment of national, provincial and municipal disaster management centres*
- *disaster risk management volunteers*

- *matters relating to these issues".* (South Africa, 2005:1)

The DMA also called for the establishment of a National Disaster Management Framework (NDMF) with the aim to guide the development and implementation of disaster risk management according to the principles contained in the Act (South Africa, 2003).

The NDMF was organised into four key performance areas (KPA's), each with a different objective that addresses different sections in the DMA (Table 2-4).

Table 2-4: Key performance indicators in the NDMF (South Africa, 2005).

KPA	Description	Objective
KPA 1	Integrated institutional capacity for disaster risk management	Establish integrated institutional capacity within the national sphere to enable the effective implementation of disaster risk management policy and legislation.
KPA 2	Disaster risk assessment	Establish a uniform approach to assessing and monitoring disaster risks that will inform disaster risk management planning and disaster risk reduction undertaken by organs of state and other role players.
KPA 3	Disaster risk reduction	Ensure all disaster risk management stakeholders develop and implement integrated disaster risk management plans and risk reduction programmes in accordance with approved frameworks
KPA 4	Response and recovery	Ensure effective and appropriate disaster response and recovery by: • implementing a uniform approach to the dissemination of early warnings • averting or reducing the potential impact in respect of personal injury, health, loss of life, property, infrastructure, environments and government services • implementing immediate integrated and appropriate response and relief measures when significant events or disasters occur or are threatening to occur • implementing all rehabilitation and reconstruction strategies following a disaster in an integrated and developmental manner.

The NDMF was tabled in 2005 and requires all organs of state to conduct disaster risk assessments (South Africa, 2005).

2.8.2 Constitution of South Africa

According to the Constitution (Act 108) of South Africa (1996), the local authority has a responsibility towards the health and safety of its inhabitants:

Section 24 states: "*Everyone has the right to an environment that is not harmful to their health or well-being".*

While section 152 (1) (d) states that *"the objective of local government is to promote safe and healthy environments".*

2.8.3 Local Government Municipal Systems Act

The above-mentioned statement is confirmed by the Local Government Municipal Systems Act (Act 32 of 2000) (South Africa, 2000), Section 11(3) where the Council of a municipality "… *has the duty to (l) promote a safe and healthy environment in the municipality*".

2.8.4 National Environmental Management Act

In the principles of Chapter 1 of the National Environmental Management Act (NEMA), Act 107 of 1998, Section 2(2) it states that environmental management must place people and their needs at the forefront (South Africa, 1998a).

The term environment refers to humans and the surroundings within which we live and co-exist and that is made up of among other the land, water and atmosphere of the earth and the inter-relationship between them. When applying environmental management principles to dolomite (like other environmental aspects), it must be noted that dolomite as a rock is not managed, but rather the behaviour and activities of people that may affect dolomite (especially when it comes to geohydrology).

Environmental management is therefore directed at regulating or directing the behaviour of people in a given society through a legal framework. Where dolomite and related uncertainties are concerned, the precautionary approach is followed.

2.8.5 Geoscience Amendment Act

The Geoscience Amendment Act, (Act 16 of 2010) (South Africa, 2010) more directly addresses the responsibility of the state authority regarding areas underlain by dolomite in three scenarios indicated in Figure 2-6. Depending on the situation, documents must be submitted to the Council for Geoscience (CGS) for advice to minimise the risk of dolomite instability.

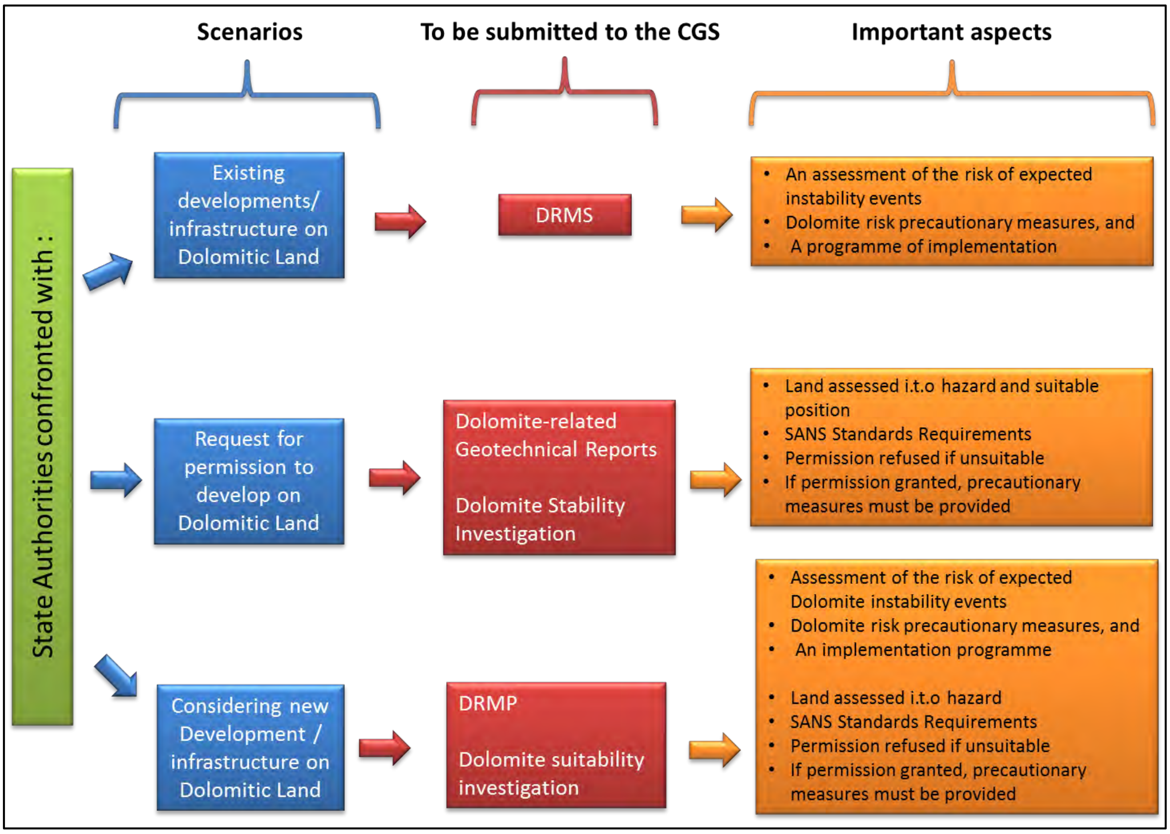

Figure 2-6: Geoscience Amendment Act requirements for development on dolomitic land (AGES, 2012a).

The responsibility of the local authority is addressed in Chapter 4 of the Geoscience Amendment Act (South Africa, 2010) where it states:

- *"All State authorities that are directly considering **development or infrastructure of their own on dolomitic land**, must prior to authorisation for development, submit to the Council for Geoscience an appropriate **Dolomite Risk Management Strategy** for advice to minimise the risk of dolomite instability events occurring;*
- *All State authorities that are **approached for permission to develop** on **dolomitic land** under their jurisdiction must, to minimise the risk of dolomitic instability events occurring, ensure that the relevant **dolomite-related geotechnical reports** … are submitted to the Council for Geoscience for review and evaluation prior to authorisation by the relevant state authority for development;*
- *All State authorities that have **existing developments or infrastructure** of their own **on dolomitic land** shall develop and submit to the Council for Geoscience an appropriate **Dolomite Risk Management Strategy** for advice, to minimise the risk of dolomite instability events occurring"*

All three of the above scenarios apply to the TLM, highlighting the need for a DRMS.

2.8.6 The National Water Act

In Chapter four of the National Water Act (NWA) (Act 36) of South Africa (1998b), the abstraction of groundwater is listed as a water use that must be regulated. This is particularly significant when dolomite occurs in the region due to the good groundwater potential associated with dolomitic aquifers. In Subsection 1 below, the act defines the way the public may use water.

Subsection 1:

A person may only use water - (a) without a license -

(i) If that water use is permissible under Schedule 1;

- *(a) Take water for reasonable domestic use in that person's household, directly from any site, water resource to which that person has lawful access;*
- *(b) Take water for use on land owned or occupied by that person, for ...*
- *(c) Store and use run-off water from a roof;*
- *(d) In emergency situations, take water from any water resource for human consumption or firefighting;*
- *(e) For recreational purposes and;*
- *(f) Discharge*
  - *a. Waste or water containing waste; or*
  - *b. Run-off water, including storm water from any residential, recreational, commercial or industrial*
  - *c. Into a canal, sea outfall or other conduit controlled by another person authorised to undertake the purification, treatment or disposal of waste or water containing waste, subject to the approval of the person controlling the canal, sea outfall or other conduit.*

(ii) If that water use is permissible as a continuation of an existing lawful use; or

(iii) If that water use is permissible in terms of a general authorisation issued under section 39; (b) if the water use is authorised by a licence under this Act; or (c) if the responsible authority has dispensed with a licence requirement under subsection (3).

A person who uses water as contemplated in Subsection (1):

a.) *Must use the water* ***subject to any condition*** *of the relevant authorisation for that use;*

b.) *Is subject to any limitation, restriction or prohibition in terms of this Act or any other applicable law*

Any water use outside Schedule 1 must be authorised, whether under a General Authorisation or a formal water use licence. Therefore, the relevant authority has the right to grant or prohibit water use (outside Schedule 1 use) where it is safe or unsafe to do so and subject to any condition.

Subject to Subsection (4), Chapter 4 of the NWA, the minister may make regulations

(a) Limiting or restricting the purpose, manner or extent of water use;

(b) Requiring that the use of water from a water resource be monitored, measured and recorded;

(c) Requiring that any water use be registered with the responsible authority.

From a dolomite risk perspective, it is important that the local government is aware of the risks associated with uncontrolled abstractions from dolomitic aquifers, and that any water use that might have a detrimental impact on dolomite stability be controlled.

When it comes to the issuing of licenses, Regulations 29 (1)(a) and (b) must be considered:

(1) A responsible authority may attach conditions to every general authorisation or license

(a) Relating to the protection of -

(i) The water resource in question;

(b) Relating to water management by -

(i) Specifying management practices and general requirements for any water use, including water conservation measures.

(ii) ***Requiring the monitoring and analysis of and reporting on every water use and imposing a duty to measure and record aspects of water use, specifying measuring and recording devices to be used****.*

3 Methodology

3.1 Literature Review

The literature review formed a very important part of the study. Research was done on the origin and character of dolomite and its propensity to karst formation. The nature of cave formation in dolomite and its relation to historical groundwater quality and quantity (levels) is explored. Shallow underground voids, or caves are necessary for sinkholes to form. The formation of sinkholes under natural and artificial (or induced) conditions were studied, as well as the triggering mechanisms for sinkholes to form. Research included looking at case studies where links between the geohydrological character and sinkhole formation was established, both locally and abroad.

The concept of risk management as well as national and international approaches to sinkhole risk assessment and management strategies were researched.

The literature review also included a section on South African legislation that guarantees a safe and healthy environment for its citizens, and governs development on dolomitic land.

3.2 Data gathering

The geologic and geohydrologic site characterisation was done by referring to existing maps, publications and groundwater data. Significant data exist in the form of maps, scientific publications and consultant reports.

This was supplemented by new data from[4]:

- field mapping of outcrops,
- geotechnical drilling and logging of chip samples, hammer penetration rate, air loss and chip sample recovery,
- geophysical surveys included gravity surveys, magnetic and electrical resistivity profiles,
- field hydrocensus surveys on the water use in the area,
- aquifer tests on boreholes to determine aquifer parameters,

[4] Note that the larger study consisted of both a geotechnical component and a geohydrological component. This dissertation stems from the geohydrological component and therefore not all of the geotechnical and geophysical data might be included here, but have all been used in the data interpretation to derive the hazard zones.

- groundwater monitoring (quality and water levels).

3.3 Data interpretation

The interpretation of geological, geophysical, geohydrological and geotechnical data formed the basis of the risk assessment by identifying areas of higher and lower sinkhole hazard. Since sinkholes form on dolomite the first step was to identify areas underlain by dolomite. Because of the scarcity of rock outcrop in the area, field mapping data needed to be filled in with drilling data. Drilling data together with geophysics data also confirmed the existence (or absence) of subsurface cavities that are a prerequisite for sinkholes to form.

The identification of sinkhole hazard areas is the first step in the risk assessment process based on the risk assessment methodology that is described in chapter 5.1.

3.4 Conclusions and recommendations

The study concluded with the identification of areas exhibiting higher and lower sinkhole hazard ratings based on the general geological character. The results of the completed risk assessment which incorporates areas of higher community vulnerability based on older residential infrastructure (see chapters 2.7 and 5.1) are not reproduced here due to the sensitive nature of the information.

The hazard zonation map formed the backdrop against which geohydrological flag conditions were demarcated that might be conducive to sinkhole formation.

This resulted in recommendations to the TLM as the client on how to mitigate certain risks and how to employ groundwater monitoring as an early warning to possible sinkhole collapse.

4 Area definition and description

Before the area of investigation is described, it is necessary to explain how it was defined during the initial study by AGES (2010). A rectangular area of investigation was arbitrarily chosen to include the entire Ikageng and surrounding areas. This 'local' study area is indicated as the 'Project Area' in Figure 4-1, and its project boundaries have no geological or geohydrological significance.

Since the dolomite underlying Ikageng forms part of a more regional outcrop of dolomite, and the geohydrological character of the local area cannot be seen in isolation, a more regional area of investigation was delineated based on accepted geohydrological boundaries. This regional area is indicated as the Welgegund Groundwater Management Area (GMA) in Figure 4-1 and will form the backdrop against which the local geohydrological character will be discussed. The Welgegund GMA will be discussed in detail in Section 4.5.

4.1 Geographic setting

Geographically the study area lies directly to the west of the town of Potchefstroom in the North West Province of South Africa (Figure 4-1). The township of Ikageng neighbours the town to the west.

4.2 Physiographic setting

4.2.1 Topography and drainage

In order to illustrate the topography and drainage of the study area, digital elevation data from the Shuttle Radar Topography Mission (SRTM) have been obtained online and depicted with a colour shader in Global Mapper (v 12) to highlight the topography around the area. Contours have been generated in the same program at 20 m intervals (see Figure 4-2).

The regional topography is mainly characterised by flat areas interrupted by isolated hills and ridges. The most prominent being hills located to the west and northwest of Potchefstroom (Ikageng) and to the northeast of Potchefstroom. These hills define the water divides that form the western and eastern boundaries of the regional study area.

The main topographical feature in the western portion of the focus area is Dassierant, a very linear ridge flanking the western side of Ikageng, striking north-northeast and dipping 50 degrees to the west.

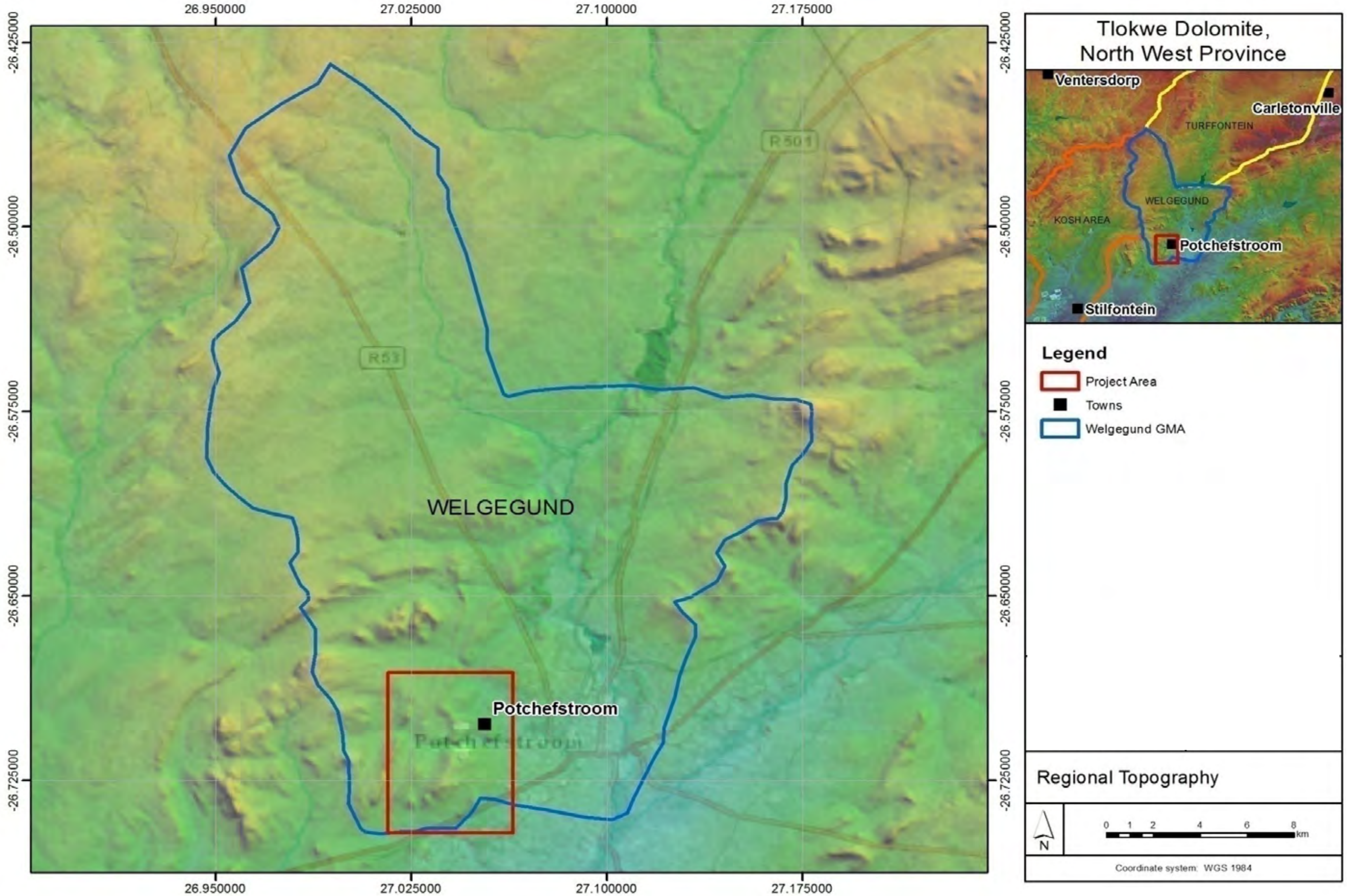

Figure 4-1: The locality of the Tlokwe focus area relative to the Welgegund GMA as regional study area.

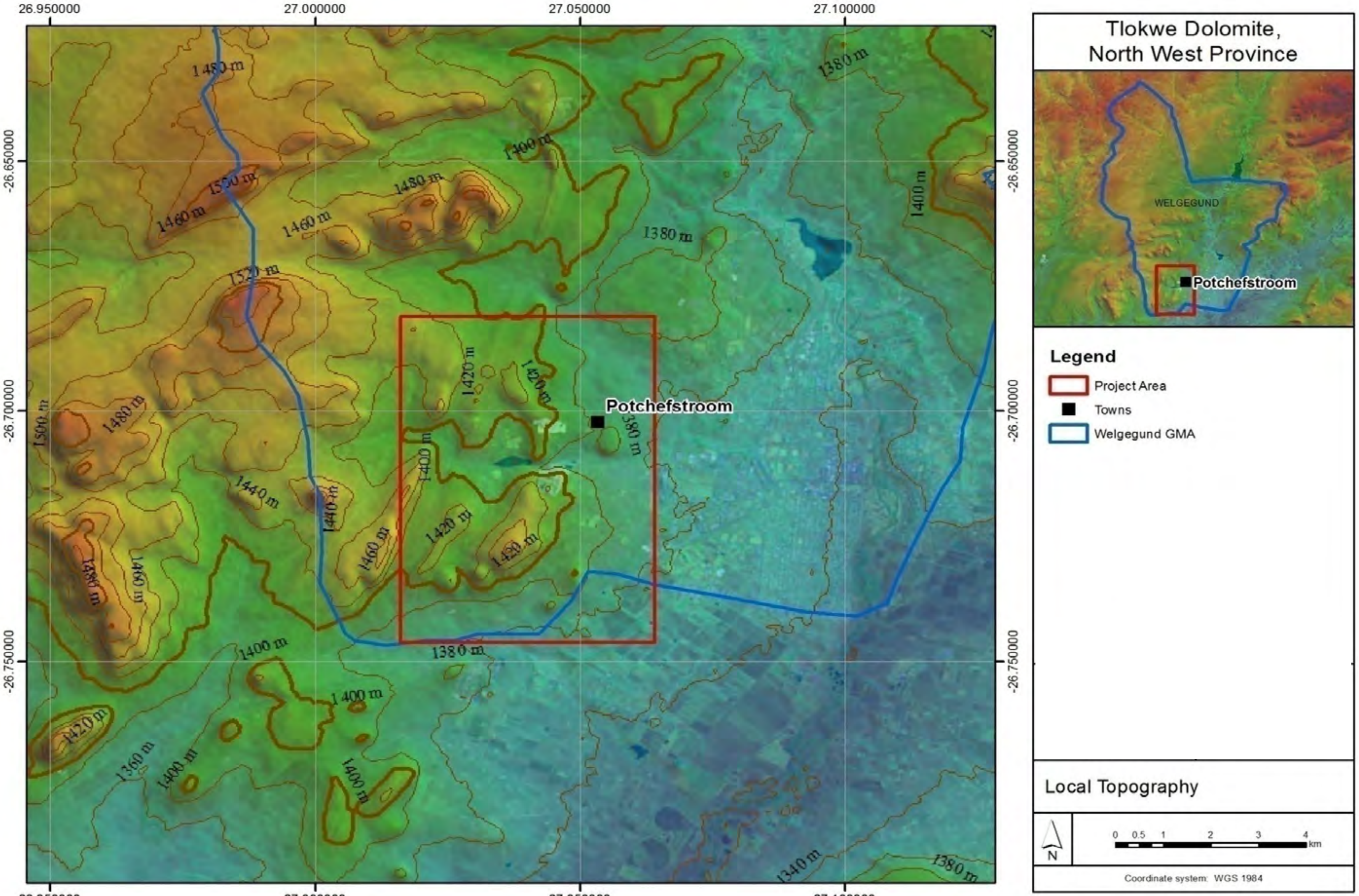

Figure 4-2: Topography of the study area. Twenty metre contour intervals generated from SRTM data.

In the centre of Ikageng the topography is characterised by a very prominent ridge with a peak elevation of roughly 1 465 mamsl. Towards the far south the topography flattens out, as well as eastwards towards the town of Potchefstroom where the gradient becomes slightly undulating to flat.

Regional surface water drainage is from the north through the Mooi River system. There is a non-perennial stream entering the Mooi River from the northwest just south of the Boskop Dam. Outside and to the east of the regional study area (Welgegund GMA), the Loopspruit joins the Mooi River just southeast of Potchefstroom.

The entire Welgegund GMA is mostly located in quaternary catchment C23H. The eastern, western and most of the southern boundary of quaternary catchment C23H defines the extent of the Welgegund GMA. The majority of the northern boundary is defined by two dykes (Figure 4-3).

Locally water enters the focus area from the hills to the west and northwest. There is a prominent drainage from west to east through the centre of the focus area namely the Spitskopspruit. This river is dammed up artificially in the Poortjie Dam where it cuts through a ridge east of Promosa from where it flows eastwards and eventually joins the Mooi River via a storm water canal through a portion of the residential area of Potchefstroom.

The local study area is mostly located in quaternary catchment C23H, with the quaternary divide between this catchment and C23L intersecting the local study area in the south. Both these quaternary catchments are on the western border of the Upper Vaal Water Management Area (WMA), with the Middle Vaal WMA located to the west of the water divide (see Figure 4-3).

4.2.2 Climatic setting

Rainfall

Historical weather data were obtained from Agrimet for a mechanical weather station (No. 19827) at Potchefstroom Agricultural Centre for the period 1914 to 2004 when the station closed. Data from a new station (No. 30649) were obtained from the same source for the period 2004 to present (March 2012). The data for 98 years of continuous monitoring are presented in Figure 4-4.

The mean annual precipitation (MAP) for Potchefstroom is 629 mm/a. The rainfall occurs mainly during the summer months (October to March) as short, intense thundershowers. The rainfall is also highly variable, varying from a maximum annual rainfall of 1 033 mm in 1996 to a minimum of 270 mm three years later.

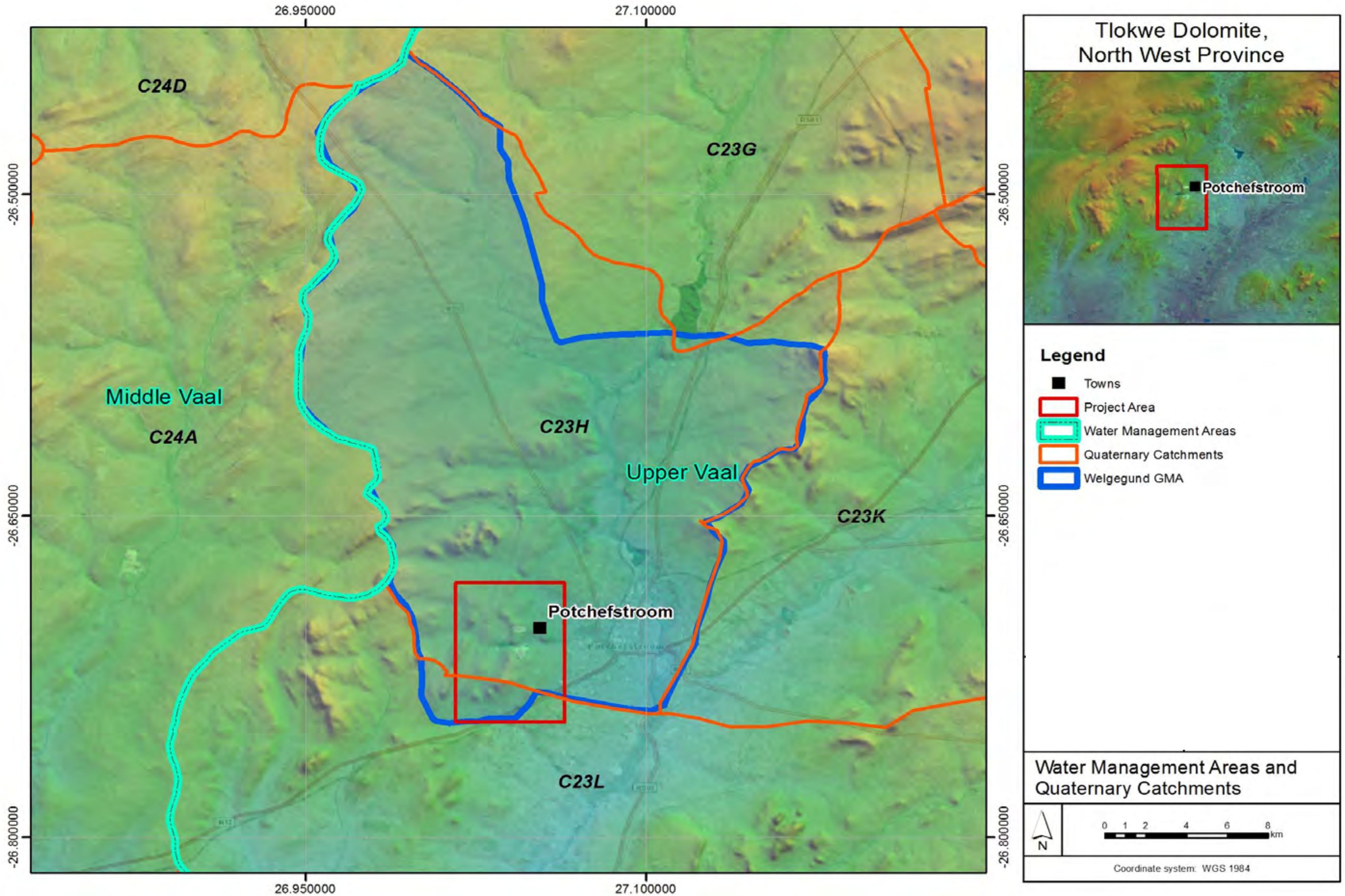

Figure 4-3: Water management areas and quaternary catchments intersecting the focus area.

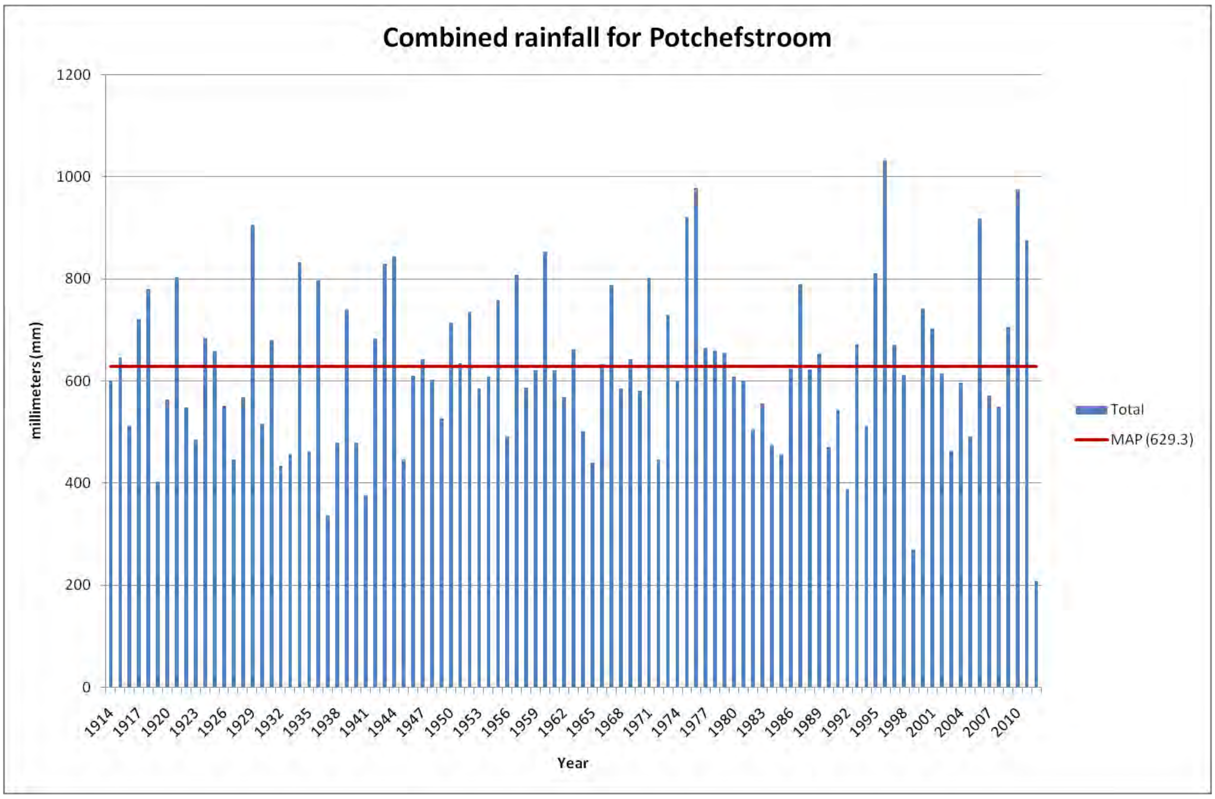

Figure 4-4: Combined rainfall data for Potchefstroom.

Temperatures

The temperature data over the same 98 year period have also been obtained. The average monthly minimum and maximum temperatures have been calculated over the entire period and graphically displayed in Figure 4-5. From this Figure it can be seen that the winter months (roughly April to September) have significantly lower minimum temperatures, frequently dropping below 0°C. The maximum temperatures are cool to mild during this time period, compared to the warm to hot maximum temperatures of the summer months. Although the average maximum temperatures during summer are below 30°C, it frequently exceeds this threshold on individual days. Minimum temperatures during the summer months average around 13-15 °C.

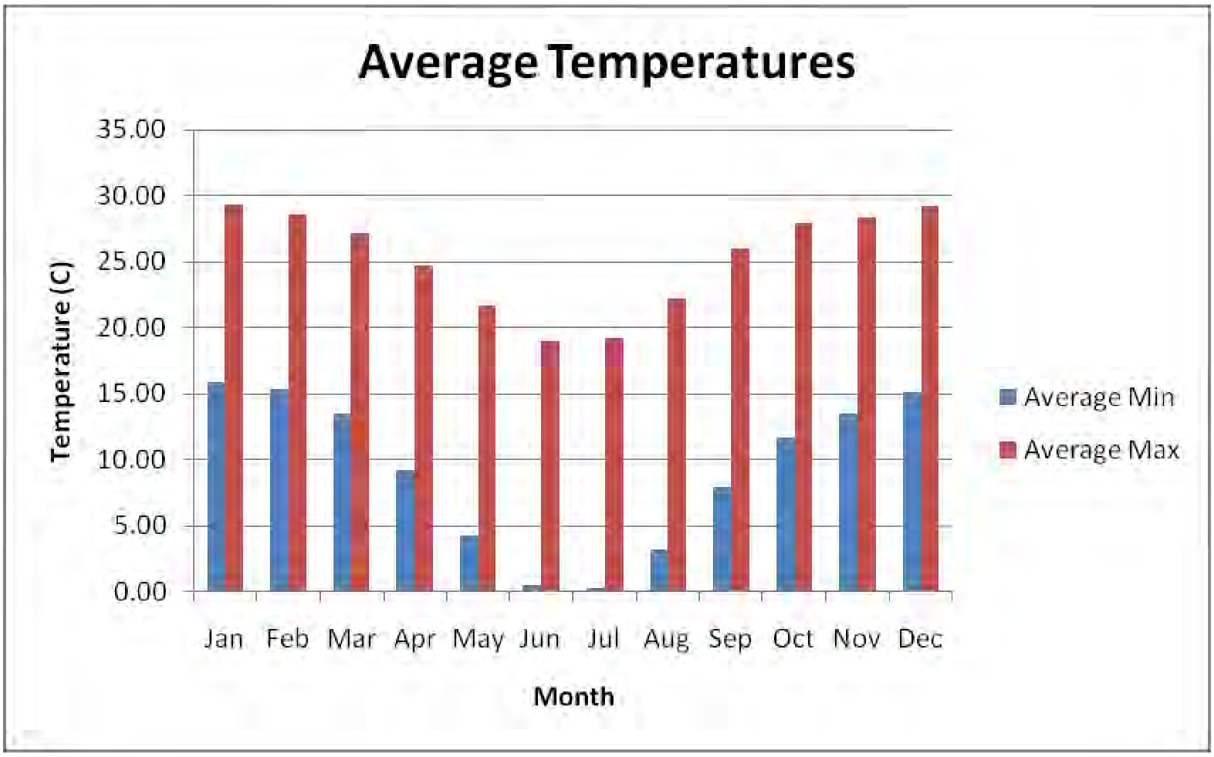

Figure 4-5: Average temperatures over Potchefstroom.

4.3 Demographic setting

According to 2011 demographic data obtained from DWA, greater Ikageng (including Lusaka and Sarafina areas) currently has around 74 000 residents. The townships of Mohadin and Promosa have 1 300 and 11 600 respectively. The city of Potchefstroom itself is home to some 34 800 people (see Figure 4-6).

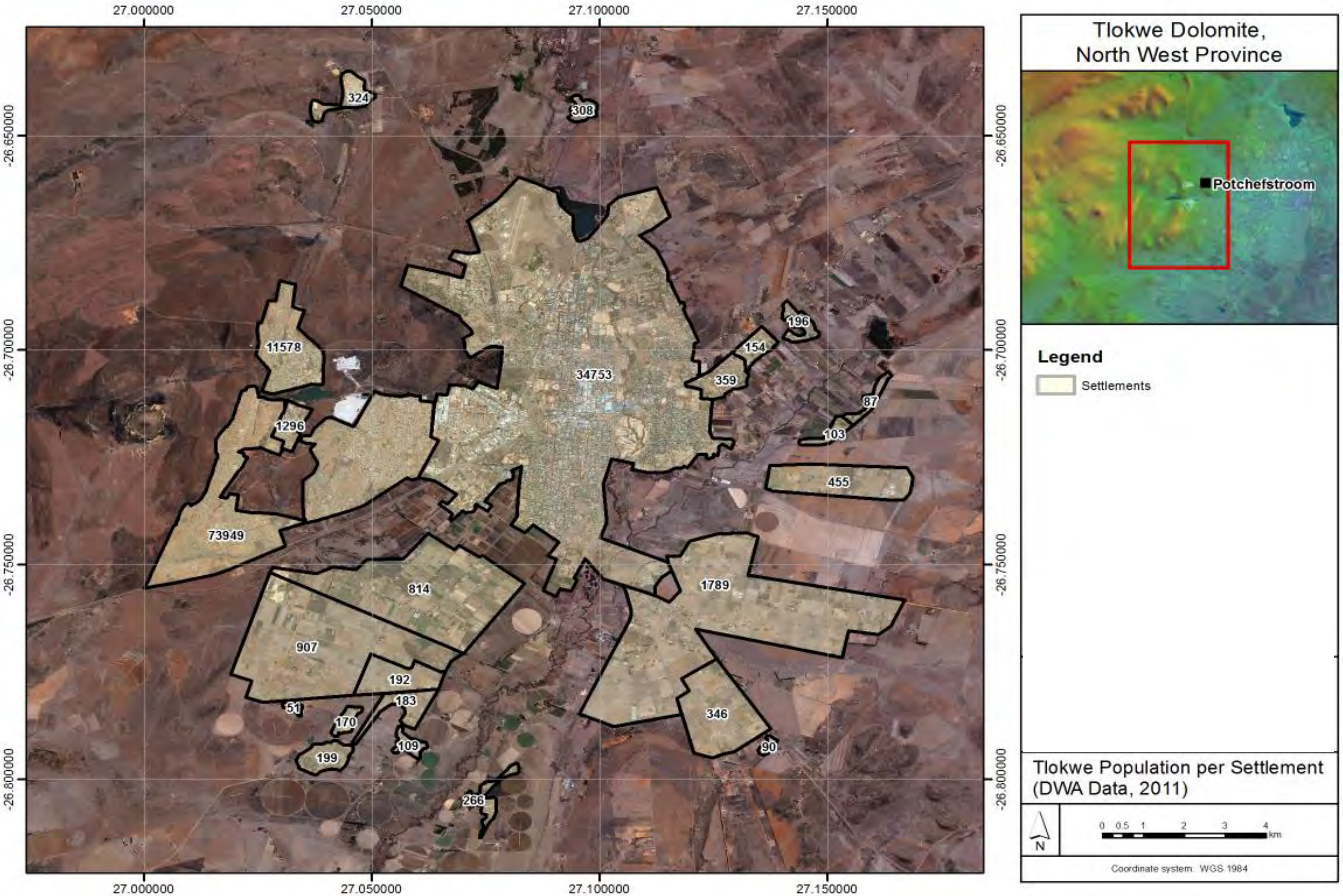

Figure 4-6: Population figures in and around the study area.

4.4 Geology

4.4.1 Introduction

A wealth of geological information exists on the area. The following maps were used in the study:

- Geological map of the Republic of South Africa and the Kingdoms of Lesotho and Swaziland, 1:1 000 000 (Keyser, 1997).

- The 1:250 000 geological map 2626 Wes-Rand (Wilkinson, 1986).

- Hand drawn map including the study area, Council of Geoscience no KF 587 (Truter, 1936).

- Map of Potchefstroom showing fifteen mile radius, Council of Geoscience no KF 589 (Mellow, 1934).

- Hand drawn regional map including the study area enlarged to a 1:35 000 scale for interpretation, Council of Geoscience no KF 588 (Lombaard, 1935).

- The Potchefstroom Dorp en Dorpsgronde Geologiese Kaart. 1:50 000 (Bisschoff, 1992). This map was of great use due to the accurate detail.

The geology (specifically the occurrence and character of dolomite) within the study area is the most important factor in determining the risk to land use and spatial development in the area. The detailed geological model played a prominent role in determining the hazard zones in Ikageng.

The geology of the study area, with special focus on dolomite land, will be discussed within the regional context of the stratigraphy, and as influenced by regional structures related to geological events such as the greater Vredefort Dome impact event.

4.4.2 Stratigraphy

The arc-shaped dolomite outcrop referred to earlier forms part of the Potchefstroom Syncline which is centred on the Vredefort Dome impact structure. It consists of sedimentary rocks from the Transvaal Supergroup which directly overlie the Ventersdorp Supergroup (mainly lavas). The Witwatersrand Supergroup (siliciclastic) sedimentary rocks, containing the various auriferous conglomerate reefs, occur below the Ventersdorp Supergroup. The famous Ventersdorp Contact Reef (VCR) is a thin but highly profitable gold bearing conglomerate layer directly below the Ventersdorp lavas.

The base of the Transvaal Supergroup consists of the Black Reef Formation comprising relatively mature quartz arenites, lesser conglomerates and subordinate mudrocks. This is overlain by the Chuniespoort Group which is subdivided into the Malmani Subgroup, followed by the Penge Formation and the Deutschland Formation.

The extensive succession of dolomite belongs to the Malmani Subgroup, and is often informally referred to as the Malmani Dolomites (Figure 4-7). The dolomite can be further divided into the **Oaktree Formation** (overlying the Black Reef Formation), a unit transitional from siliciclastic sediments to platform carbonates. It consists of between 10 and 200 m of carbonaceous shales, stromatolitic dolomites and locally developed quartzites.

	Formation	Lithologies
Malmani Subgroup	**Frisco Fm**	Stromatolitic dolomites, more shale upwards
	Eccles Fm	Erosion breccias and cherty dolomite
	Lyttelton Fm	Shale, quartzite and stromatolitic dolomite
	Monte Cristo Fm	Stromatolitic and oolitic platform carbonates
		Erosive breccias
	Oaktree Fm	Siliciclastic to platform carbonate rocks
Black Reef Fm		Mainly clastic sedimentary rocks

Figure 4-7: Schematic representation of the Malmani Subgroup lithologies.

Overlying this formation is the **Monte Christo Formation**, between 300 and 500 m thick and beginning with erosive breccias followed by stromatolitic and oolitic platform dolomites. This is overlain by the **Lyttelton Formation**, between 100 and 200 m thick and comprising shale, quartzite and stromatolitic dolomite. The overlying **Eccles Formation** can be up to 600 m thick and includes a series of erosion breccias between cherty dolomites. The **Frisco Formation** (>400 m) overlies one of the breccia units and mainly comprises stromatolitic dolomites, containing more shale towards the top. On the geological map the different dolomite formations are well defined in the area to the north of the anticline defined by the Black Reef outcrop between Krugersdorp and Ventersdorp. South of the anticline, in the Potchefstroom syncline the dolomite is grouped into the Malmani Group (Eriksson *et al*, 2006).

Regionally the Malmani dolomite from the Chuniespoort Group is overlain by 6-7 km of Pretoria Group rocks. The Pretoria Group consists of mudrocks, quartzitic sandstones, and significant interbedded basaltic-andesitic lava, conglomerate, diamictite and carbonate rocks. In the southern section of the Transvaal basin the stratigraphy of the Pretoria group is as follows:

- The basal Rooihoogte Formation consists mainly of breccia.
- It is overlain by the Bushy Bend Lava Member of the Timeball Hill Formation that otherwise consists of mudrocks and subordinate quartzite layers interbedded.
- The overlying Boshoek Formation is between 30 and 60m thick and comprises sandstone, conglomerate and localised diamictite.
- The Hekpoort Formation overlying the Boshoek consists of basaltic andesite containing significant tuff.
- The Dwaalheuwel Formation overlies the Hekpoort in the rest of the Transvaal basin, but is absent in the southern area.
- The Hekpoort is therefore overlain by the Strubenkop Formation in this area, consisting of mudrock and subordinate sandstone (Eriksson et.al, 2006). For a detailed geological map of the area see Figure 4-8.

The stretch of dolomite outcrop towards Carletonville and Westonaria is where thousands of sinkholes formed once the dolomite aquifers were dewatered to allow mining of the underlying gold bearing conglomerate. The strong link between groundwater and sinkhole formation was then realised (Winde & Stoch, 2010).

4.4.2.1 *Regional Area*

The bulk of the central portion of the Welgegund GMA is underlain by dolomite. To the northwest, the dolomite is flanked by an outcrop of the underlying Black Reef Formation, striking southwest-wards. Further west of the Black Reef, rocks from the underlying Ventersdorp Supergroup are exposed.

The dolomite ‘finger’ that can be seen on the geological map branching off towards Potchefstroom, is separated from the main dolomite arch by outcrops of overlying Timeball Hill Formation (inter-layered quartzite and shale), Boshoek and Hekpoort Formations. It is unknown to what extent the dolomite from the ‘finger’ is still connected to the main arc-shaped outcrop at depth.

The eastern edge of the dolomite outcrop is defined by the same overlying sequence of Timeball Hill, Boshoek and Hekpoort Formations. The contact is indicated on the regional geological map as being an overthrust fault from the southeast (Vredefort Dome).

Towards the far southeast, the flat-lying area is indicated to be overlain by quaternary sediments associated with the Mooi and Loopspruit Rivers.

4.4.2.2 *Local Area*

Locally the area is structurally complex, making it difficult to conceptualise the geohydrological model of the various aquifers and their extent. The dolomite ‘finger’ extends through the central part of the focus area from the north, and splits into two smaller fingers in the far south of the focus area. This smaller split mimics the larger split-off of the dolomite finger from the main arc-shaped dolomite outcrop north of Potchefstroom.

There is a strong northeast-wards strike in the strata in the western portion of the focus area, with Dassierand forming the most prominent linear ridge. This is composed of Timeball Hill Formation quartzite. Towards the central portion of the local area, this strong linear trend is gradually exchanged for more localised hills formed by dolomite and chert, although the strike of the outcrops still resemble this general trend. Towards the far east of the local area, the area is underlain by shale (Timeball Hill) and diabase.

In general the topography can be correlated to structural displacements, although this is not always clear. For instance the eastern contacts between the dolomite and shale, and shale and diabase are truncated by flat topography.

4.4.3 Structural geology

On a more regional scale, many faults and fractures were identified in the dolomite around the Potchefstroom–Fochville areas. It was pointed out by Brink (1996) that displacement is often characterised by a fault zone comprising more than one parallel-running faults, rather than a simple clean break. The reactivation of these zones gave rise to intense faulting and fracturing within the dolomite. It was also noted by Obbes (2000) that the presence of regional deformation, faulting and fracturing is evident in the heterogeneous structural deformation of the Black Reef-Malmani-Rooihoogte succession that is non-pervasive and more pronounced in the lower half of the carbonate succession. Movement vectors were derived from the orientations of thrust and low-angle normal faults, folds, deformed stromatolites, pebbles, oolites and quartz-fibre lineations (Obbes, 2000).

The structures recorded such as strike-slip faults, low angle normal faults, bedding-parallel faults, low-angle thrust faults and shear zones are testimony to the complex nature of the area. It is believed that the regional deformation in the area can be associated with major regional geological events including the Bushveld Intrusion (Truswell, 1970) and the Vredefort Impact event (Brink *et al*, 2000).

The structural geology of the local area was refined by making use of aerial photo interpretation of the following sets of data, according to the methodology described by Lattman & Ray (1965):

- Job 1064 Klerksdorp; Strip 010; Photograph 3215 to 3218; scale 1 : 50 000
- Chief Directorate: National Geo-Spatial Information; Photograph 2627CA 16 to 22; scale 1 : 10 000; Enlargement factor: x3
- Google Earth images.

All structural geological observations from previous maps, (dip and strike) as well as new field observation were added and included in the final structural geological map (Figure 4-9).

It is evident from Figure 4-9 that there are two sets of fault zones in the area; one striking east-west and one north-south. Some of the fault zones were found to be intruded by diabase dykes. The dykes are expected to be impermeable and compartmentalise the dolomite aquifer while the dyke-contact zones are expected to be fractured and permeable, allowing for increased transmissivity. A north-south trending lineament, was interpreted by GeoCon (2003) as a dyke, forming springs in the area north of the Spitskopspruit.

4.4.4 Engineering geology

Over the past two decades various geotechnical drilling projects in the local study area provided a wealth of information. The data have been collated to provide a more detailed geological model of the area. Data from these drilling logs have been plotted on a map of the local geology as interpreted by one of the pioneering geologists of the area (Bisschoff, 1992) in Figure 4-10.

Hazard and risk zone delineation of previous geotechnical studies were not always consistent in methodology. AGES (2012b) reinterpreted the data and incorporated it into their final geological interpretation and hazard zone map based on an industry standard methodology (see Chapter 5).

4.5 Geohydrology

4.5.1 Geohydrological boundaries

Since the local area boundaries were chosen arbitrarily and do not correspond with any geohydrological boundaries, the geohydrology of the local area is not independent of the regional geohydrological character.

As mentioned, the regional area of investigation is defined by the Welgegund GMA. The reasoning behind the decision to use this delineation as the regional study area will be discussed in detail in the following sections.

4.5.2 Dolomite compartments

Underground dolomite cavities are interlinked via cracks formed by joints and faults that have been widened by further dissolution. This increases permeability which leads to the high groundwater potential associated with dolomitic aquifers. The nature of the interlinked underground voids in dolomite has the effect that the countless smaller voids are now connected to form one bigger reservoir of groundwater. Currently it is estimated that the dolomite in the FWR gold mining region has a water storage capacity exceeding the full storage capacity of the Vaal Dam several times (Winde, 2010a).

After the regional dolomite succession was deposited, several impermeable syenite and dolerite dykes intruded vertically into the sedimentary sequence of rocks, compartmentalising the voids into several individual ‘compartments’ that are now hydraulically separated from each other.

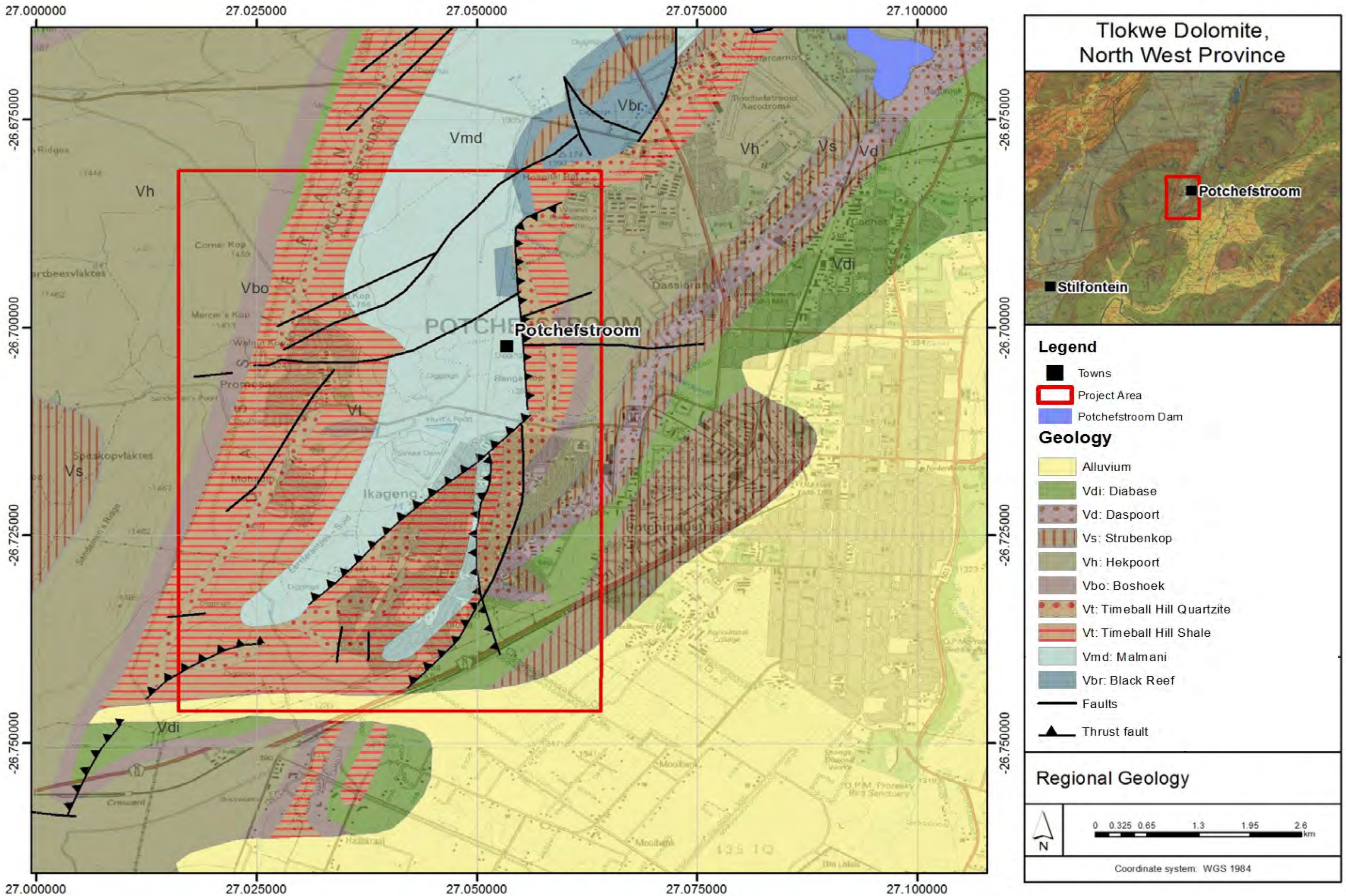

Figure 4-8: Geology of the area according to the 2626 Johannesburg geological map.

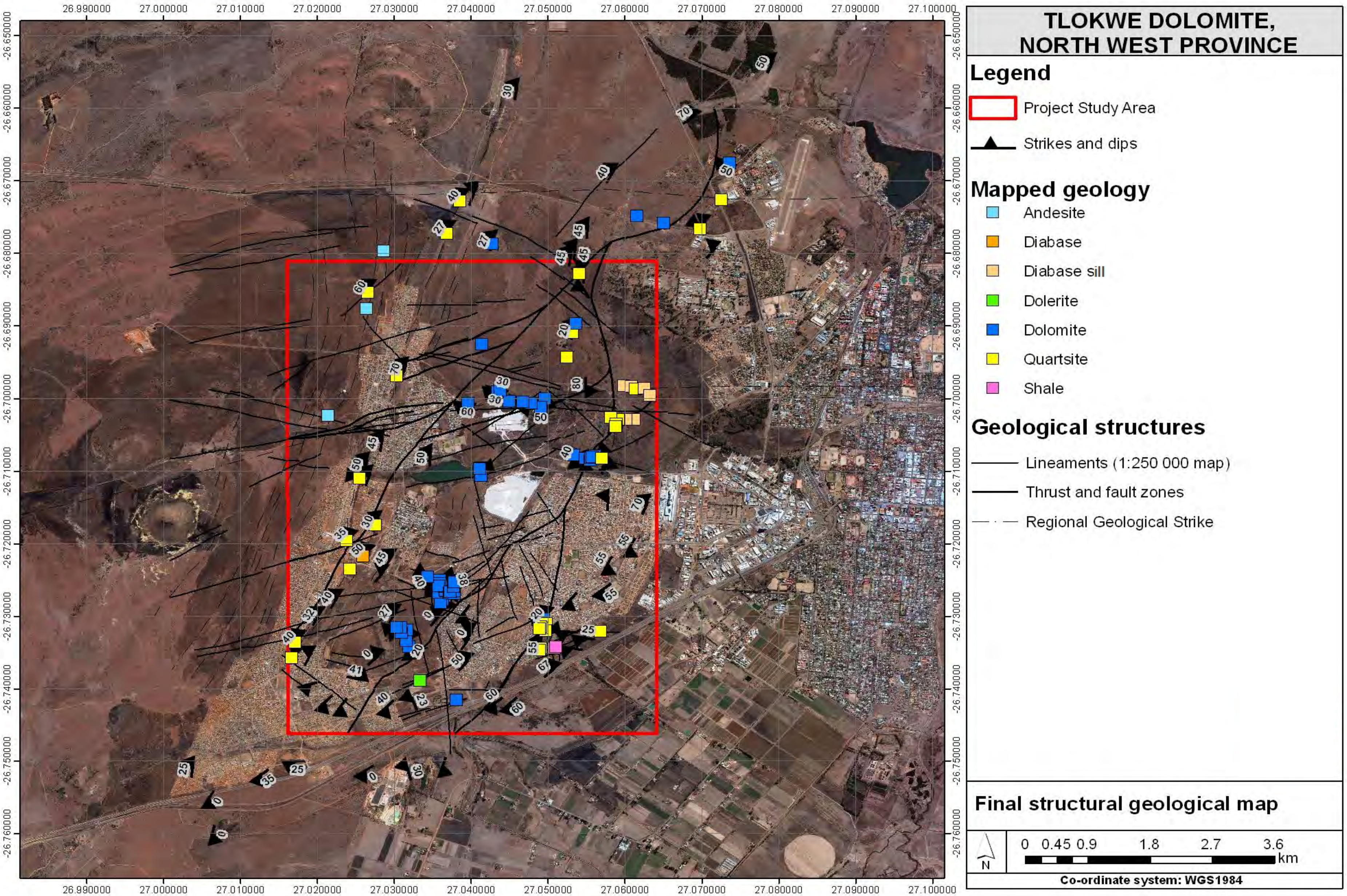

Figure 4-9: Structural map of the study area.

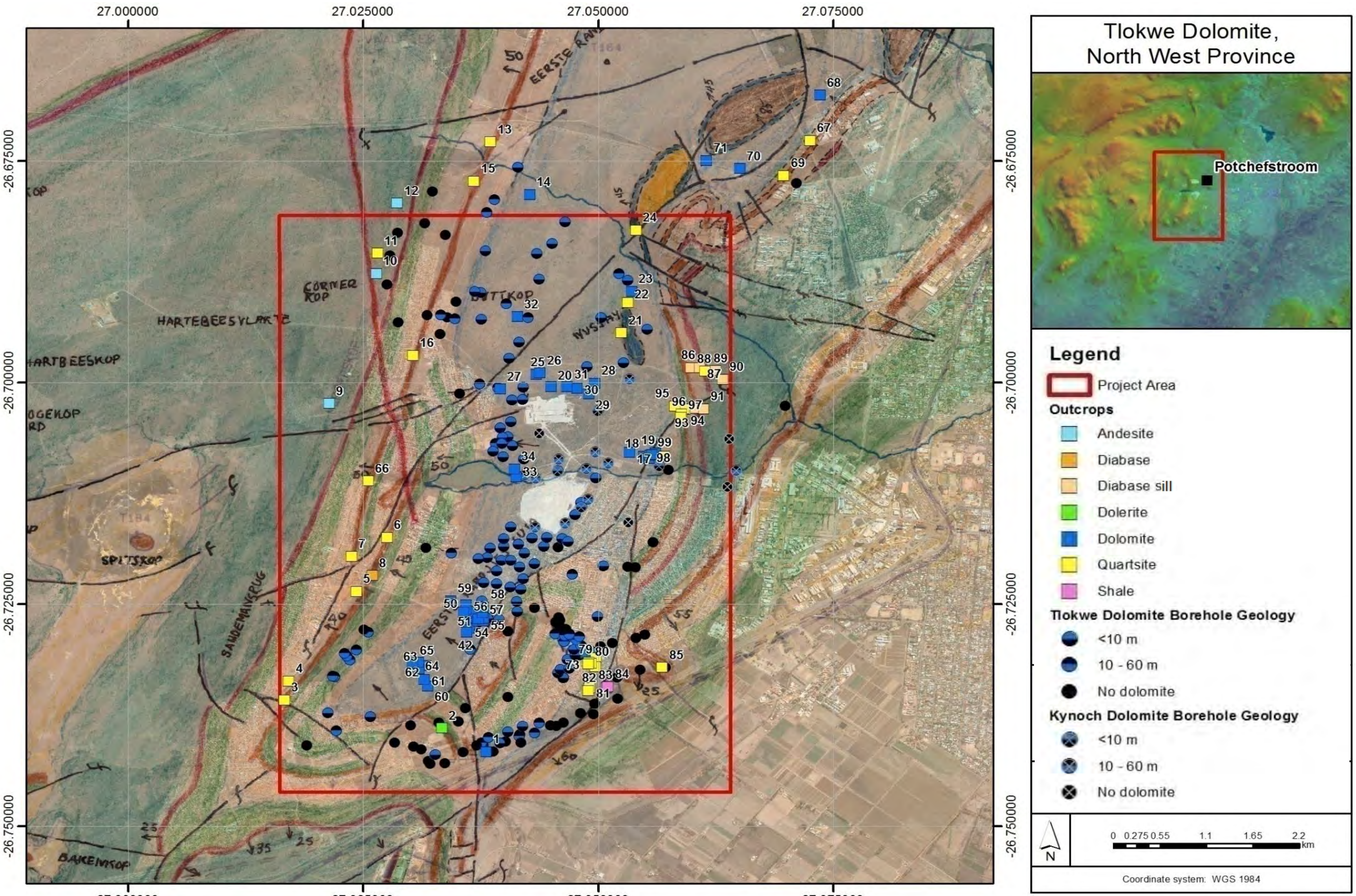

Figure 4-10: Initial local geology map (Bisschoff, 1992) with new mapping and drilling data points.

The only hydraulic interaction between two adjacent compartments would be through small cracks in the otherwise impermeable dyke (i.e. faults, joints) or on surface where surface water flows from one compartment.to the next via streams and rivers. Natural springs on dolomitic terrain are often associated with these dykes where water wells up against the impermeable boundary and decants on surface.

Work published by DWA in 2009 defined new regional dolomite compartments and groundwater units based on geohydrological characteristics (Holland & Wiegmans, 2009). The dolomite compartments have been categorised as smaller Groundwater Resource Units (GRU) that form part of bigger Groundwater Management Units (GMU) which are areas of a catchment that require consistent management actions to maintain a desired level of use or protection of groundwater.

These GMUs ultimately form part of bigger GMA that generally coincide with surface drainage boundaries (e.g. quaternary catchments) and are not limited to the extent of the dolomite outcrops. The difference between the three divisions is described below (Holland & Wiegmans, 2009) and shown in Figure 4-11.

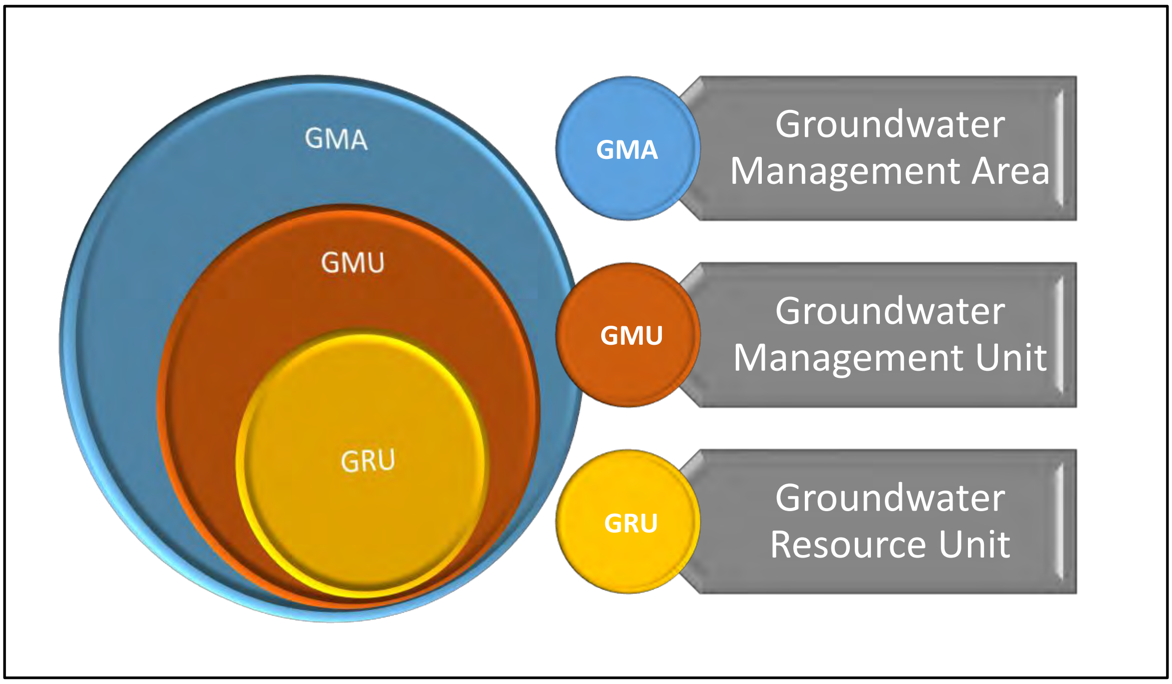

Figure 4-11: Hierarchical relationship between smaller resource units inside management units and areas.

- GMA: Does not necessarily represent a dolomite compartment or unit but consists of larger areas comprising a number of GMUs and GRUs and is delineated solely for managerial purposes.
- GMU: The GMUs are based on surface water drainage and geohydrological

considerations, each of which represents a geohydrological homogeneous zone wherein boreholes tapping the shallow groundwater system will be in hydraulic connection to some degree. In dolomite this can be seen as true ‘compartments’.

- GRU: A groundwater body that has been delineated or grouped into a single significant water resource based on one or more characteristics that are similar across that unit.

The dolomite compartment south of the Boskop Dam was previously interpreted as forming part of the Boskop-Turffontein Compartment (BTC) (see Barnard, 2000). This compartment has been subdivided by Holland & Wiegmans (2009) into the Turffontein Compartment north of the Boskop Dam, and an unnamed compartment south of the Boskop Dam that are being separated by two intersecting dykes south and west of Boskop Dam. The western boundary of the Welgegund GMA is located on a water divide between quaternary catchments C23H to the east and C24A to the west. This water divide coincidentally also forms the boundary between the Upper and Lower Vaal WMAs.

The dolomite forming the basis of the classification exercise, is indicated to cross this divide into the adjacent GMA, called the KOSH Area GMA (named after the Klerksdorp – Orkney – Stilfontein – Hartbeesfontein area) (Holland & Wiegmans, 2009). It is assumed that the dolomitic groundwater unit crossing this divide still forms part of the same homogeneous system of dolomites, and technically is not compartmentalised at this boundary.

However according to the definition of the GMU the dolomitic groundwater unit inside the Welgegund GMA can be regarded as a separate entity. It is not indicated on the map by Holland & Wiegmans (2009) as a GMU, but for the purpose of this study it was named the Welgegund GMU since it is located within the larger Welgegund GMA (Figure 4-12).

It is therefore clear from the map that the local area partly comprises the Welgegund GMU inside the Welgegund GMA (within the Upper Vaal WMA) and is separate from the Turffontein Compartment north of Boskop Dam.

It is also possible that the dolomite finger might be compartmentalised by intrusive dykes that are not yet identified, and form smaller GRUs inside the Welgegund GMU.

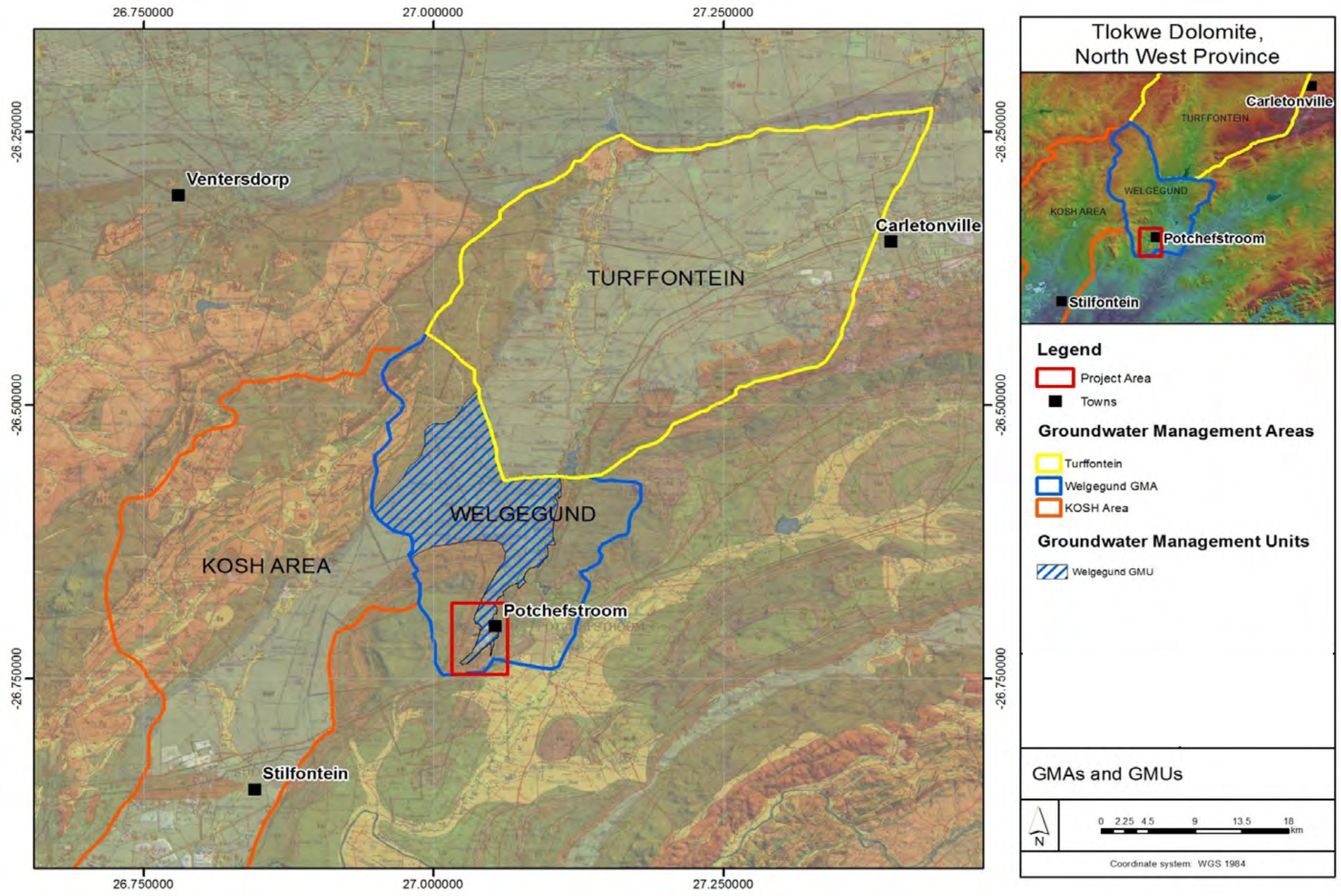

Figure 4-12: Relationship between the focus area and the Welgegund GMA and GMU (from Holland & Wiegmans, 2009).

The Welgegund GMA was therefore chosen as the regional area of investigation based on the following:

- It is assumed to form an independent groundwater unit, bounded by either impermeable dykes or water divides that act as hydrological boundaries, even though different (but interdependent) aquifers with different local characteristics are identified within this area (see next section).
- It is defined as a groundwater management area, in which the responsible authorities can exercise management rights pertaining to any groundwater activities that might have a negative impact on the dolomitic aquifer underlying the focus area.

4.5.3 Aquifer description

According to the hydrogeological map series of South Africa, three aquifer types can be distinguished in the study area. These three aquifer types are related to the degrees of porosity as will be discussed here (Table 4-1):

Table 4-1: Relationship between aquifer type and porosity.

Porosity	Origin (from Ford & Williams, 2007)	Aquifer Type
Primary	The spaces left between grains during and after deposition of sediments	Intergranular Type
Secondary	After sediments solidified to form rock, primary porosity reduces to a degree, but fractures in the hard rock creates new secondary porosity	Fractured Type
Tertiary	Especially in carbonate sedimentary rocks like dolomite, the rock is dissolved as acidic water infiltrates along fractures. This dissolution process causes tertiary porosity	Karst Type

Although no **Primary Intergranular Type** aquifers are indicated in the study area, this type of aquifer exists in combination with Fractured Type aquifers where unconsolidated weathered rock material overlie solid (but fractured) bedrock, or in limited extent along the banks of the Mooi River where unconsolidated fluvial sediments occur.

For this reason, the majority of non-dolomitic bedrock is indicated to host **Intergranular and Fractured Type** aquifers. Inside the clastic sedimentary rocks water occurs in between the individual grains (intergranular) depending on the porosity of the matrix, but is mainly transported along preferred pathways created by fractures like faults and joints. The contacts with intrusive bodies like dykes and sills also fracture the surrounding rock to create preferred pathways for groundwater movement.

Where dolomite is mapped, the groundwater is indicated to occur in tertiary porosity forming **Karst Type** aquifers.

4.5.4 Aquifer classification

The need for an aquifer classification system for South African aquifers has existed for some time and attempts were made to address this need during the early 1990s until priority was given to the issue to formalise a classification scheme by the then Department of Water and Forestry (DWAF). This culminated in the publication of the widely used and accepted ‘Parsons Classification’ Parsons (1995).

The report looked at international methodologies applied in the field, and customised a classification system for South African aquifers taking the highly fractured nature of the aquifers into account (Table 4-2).

Table 4-2: Aquifer Classification Scheme after Parsons (1995) and DWAF (1998).

Aquifer System	Defined by Parsons (1995)	Defined by DWAF (1998b)
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 reasonably available alternative sources should the aquifer be impacted upon or depleted. Aquifer yields and natural water quality are immaterial.	An aquifer, which is used to supply 50% or more of urban domestic water for a given area for which there are no reasonably available alternative sources should this aquifer be impacted upon or depleted.
Major Aquifer	High permeable formations usually with a known or probable presence of significant fracturing. They may be highly productive and able to support large abstractions for public supply and other purposes. Water quality is generally very good (<150 mS/m).	High yielding aquifer (5-20 L/s) of acceptable water quality.
Minor Aquifer	These can be fractured or potentially fractured rocks, which do not have a high primary permeability or other formations of variable permeability. Aquifer extent may be limited and water quality variable. Although these aquifers seldom produce large quantities of water, they are important both for local supplies and in supplying baseflow for rivers.	Moderately yielding aquifer (1-5 L/s) of acceptable quality or high yielding aquifer (5-20 L/s) of poor quality water.
Non-Aquifer	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 need to be considered when assessing the risk associated with persistent pollutants.	Insignificantly yielding aquifer (< 1 L/s) of good quality water or moderately yielding aquifer (1-5 L/s) of poor quality or aquifer which will never be utilised for water supply and which will not contaminate other aquifers.
Special Aquifer	An aquifer designated as such by the Minister of Water Affairs, after due process.	An aquifer designated as such by the Minister of Water Affairs, after due process.

4.5.4.1 Karst Type Aquifer

According to the Internal Strategic Perspective (ISP) of the Upper Vaal WMA, the large dolomitic aquifers in the north-western section of the WMA play a very significant role with regard to total groundwater resources in the WMA. Much of the water in the Mooi River originates as spring flow from dolomite compartments (DWAF, 2004). On a local scale this is also true as can be seen by the springs identified in the area.

The boreholes on the dolomite can have yields in excess of 20 L/s and according to GeoCon (2001) the dolomitic aquifers can have significant economic value and needs to be protected from overexploitation and pollution. The quality of the dolomitic groundwater is generally of a very high standard (DWAF, 2004), apart from local areas where groundwater pollution occurs (AGES, 2005a), and therefore the Karst Type aquifer can be classified as a **Major Aquifer** according to the aquifer classification system proposed by Parsons (1995).

4.5.4.2 Intergranular and Fractured Type Aquifer

Boreholes on the fractured clastic rock have average yields of between 1 and 2 L/s (AGES, 2005a). Higher yields of up to 5.0 L/s can be achieved on fractured rock aquifers depending on the nature of fracturing intersected, but these are exceptions rather than the norm. Groundwater quality in the area is variable. The Intergranular and Fractured Type aquifer can be classified as a **Minor Aquifer** (Table 4-2).

4.5.4.3 Other

Technically a third aquifer can be defined in the area. Due to the water retention properties of gypsum, the old gypsum tailings dump of roughly 25 ha in the centre of the focus area can be regarded as a **perched aquifer** overlying the major dolomite aquifer. The tailings dump was a product of the Kynoch Fertiliser Factory in the Industrial area of Potchefstroom, but has been decommissioned from 2006, after which the dump was acquired by Oranje Mynbou & Vervoer (OMV) for further processing of the gypsum (Figure 4-13). This perched aquifer in the Kynoch Gypsum Tailings Dump (KGTD) can be classified as a **Non Aquifer**.

Figure 4-13: Position of the tailings dump relative to the Kynoch Factory and OMV.

Due to the good municipal water supply infrastructure in the greater Potchefstroom residential area, no aquifers are classified as **Sole Source Aquifers**. It must however be noted that the source of Potchefstroom's water supply includes groundwater from the Gerhard Minnebron Spring (see the location in Figure 4-14).

4.5.5 Water use

4.5.5.1 Regional area

No mine dewatering occurs in the Welgegund GMA. The neighbouring Turffontein compartment is also not dewatered, but the effect of the mine dewatering of the compartments neighbouring the Turffontein compartment further to the east (Venterspost, Bank and Oberholzer compartments) can be seen in the flow of the Gerhard Minnebron Spring eye (Figure 4-14). The flow decreased drastically from ~25 Mm^3/a to an average of ~5 Mm^3/a since the early 1960s when mine dewatering commenced (Holland & Wiegmans, 2009). The Bank and Oberholzer eyes ceased flowing in 1959 when dewatering started (Winde & Stoch, 2010).

There are no current mining plans for gold mining within the Welgegund Compartment in the area underlying and north of Potchefstroom, although current localised prospecting projects are underway within the greater Potchefstroom Goldfield. Wits Gold has secured prospecting rights for precious minerals in the Potchefstroom

Goldfield that stretches south-westwards from current mining operations west of Carletonville towards Potchefstroom.

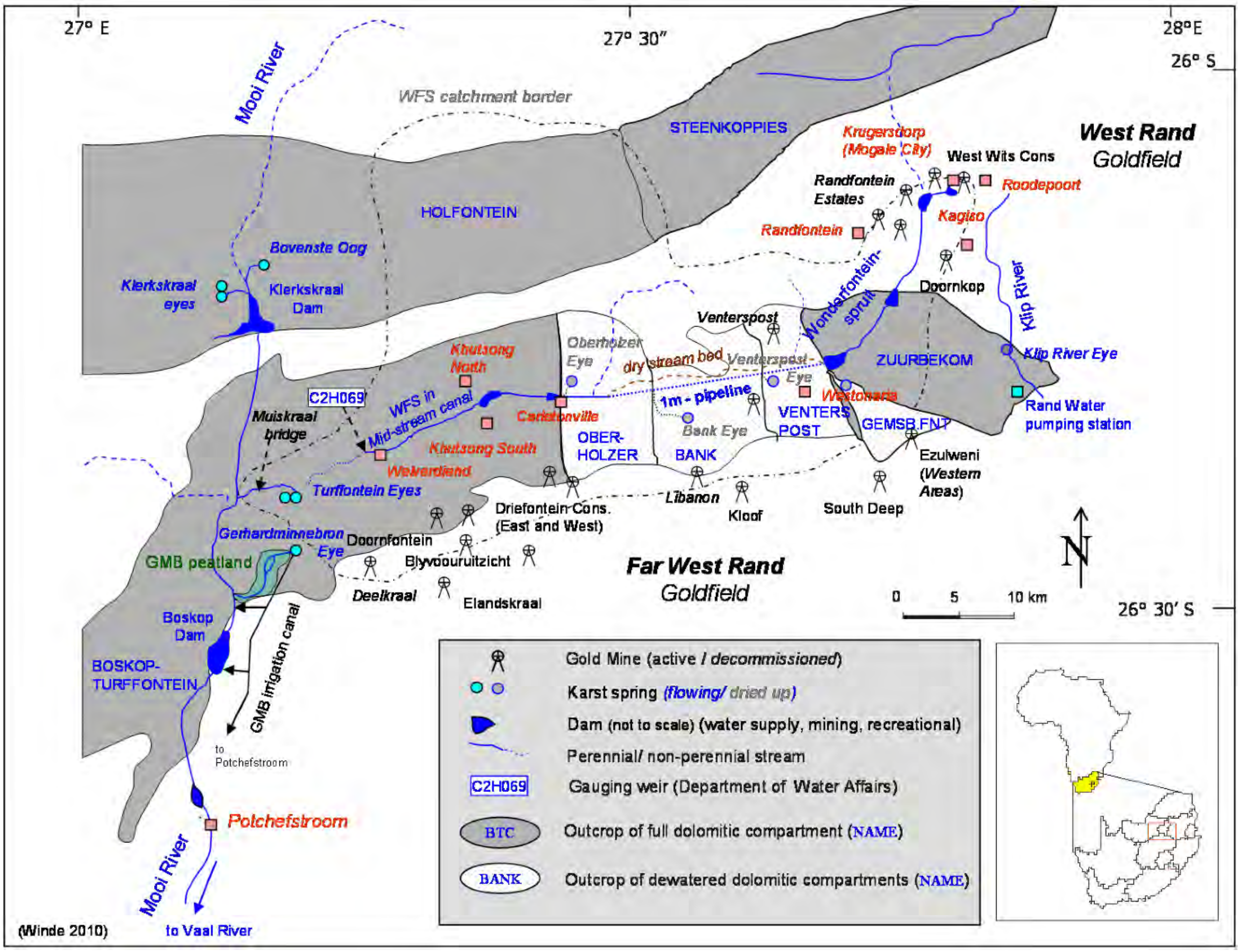

Figure 4-14: The location of dewatered dolomite compartments on the FWR (Winde & Erasmus, 2011).

The Potchefstroom Goldfields are divided into smaller prospecting projects, with the largest gold resources believed to be located in the *Potch Deeps* Project area, which is a 160 km^2 area located directly to the north of Potchefstroom. The gold resources are located at depths ranging from 3 000 to 5 000 mbgl but no immediate prospecting is planned for this project area. The only current and immediate prospecting projects occur in the Kleinfontein Project area immediately west of the current mine workings near Carletonville, with drilling that was planned in 2011 in the Boskop Project area roughly halfway between Potchefstroom and Carletonville (Wits Gold, 2010; Anon, 2013). This would fall outside of the regional study area defined by the Welgegund GMA, in the neighbouring Turffontein GMA.

The most significant water use on a regional scale is the abstraction of surface water from Boskop and Potchefstroom Dams for municipal use in the TLM area.

Groundwater is mainly used for agricultural use. Boreholes are spread throughout the regional area. Most pivot points in the Welgegund GMA are located in the alluvium of the Mooi River.

4.5.5.2 Registered Groundwater Use

No groundwater abstraction was registered at DWS within the focus area in 2016. This was confirmed by obtaining the WARMS (Water Resource Management System) database for the affected catchments from DWS. The closest registered groundwater abstraction is by Bert's Bricks' clay quarry and brick making operations located just south of the N12. This quarry is mining shale from the Timeball Hill Formation.

Several groundwater abstraction points (boreholes and springs) are registered within the Welgegund GMA, north of the focus area. Most of these points are located near the Mooi and Wonderfonteinspruit Rivers and are used for agricultural purposes (Figure 4-15).

4.5.5.3 2003 Hydrocensus

According to a 2003 census that focussed on the area surrounding the old Kynoch Factory, the groundwater use downstream (east) of the Kynoch Factory specifically was qualified from 33 abstraction boreholes to be 400 m^3/d (4.6 L/s). Water is mainly used for gardening and cleaning purposes in Potch-Industria and in the beer production process at Premier Malt (AGES, 2005a). The borehole yields identified range between 10-170 m^3/d (0.1-2 L/s) for the fractured aquifers. None of the abstraction boreholes in Potch-Industria are located on dolomite.

4.5.5.4 2009 and 2011 Hydrocensus Surveys

Hydrocensus surveys in 2009 and 2011 identified a number of abstraction boreholes throughout the focus area – some from within the dolomite (data depicted in Figure 4-16 and tabled in Table 4-3 and Table 4-4). The most notable is the Boitshoko High School located next to the Kynoch dump that solely relies on groundwater from a single borehole on the school property. The borehole is located within 200 m of the KGTD on the dolomite.

Another major abstraction borehole located on dolomite is located on the premises of OMV just north of the dump. The main supply borehole is pumped on a 24 h cycle to deliver 45 m^3/h. There is a back-up borehole close-by with similar yield. The water is being used in the processing of the gypsum mined from the old tailings dump, and some domestic use. According to OMV, a licence application for abstraction has been submitted (Muller, 2011).

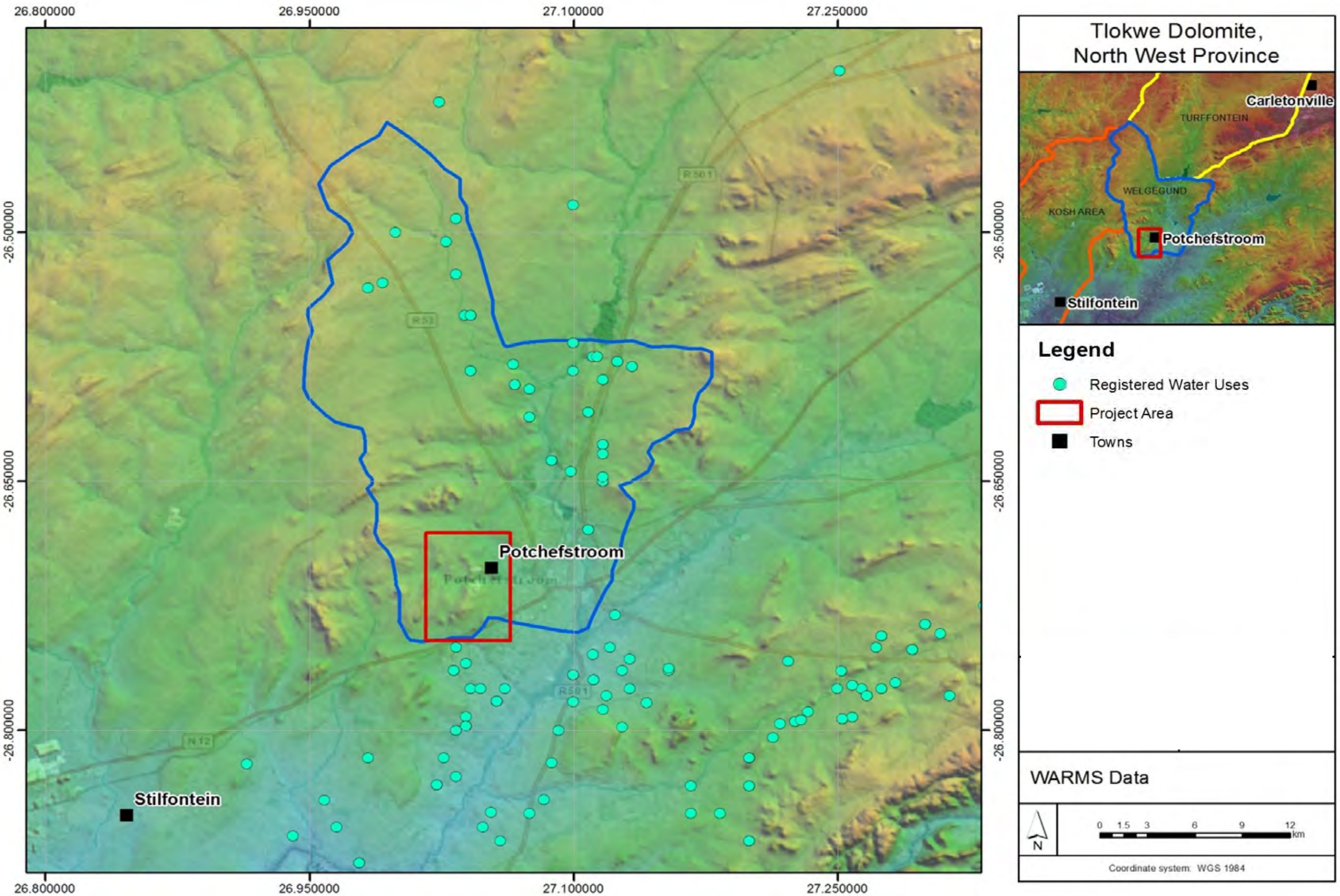

Figure 4-15: WARMS groundwater abstraction points as registered at DWS.

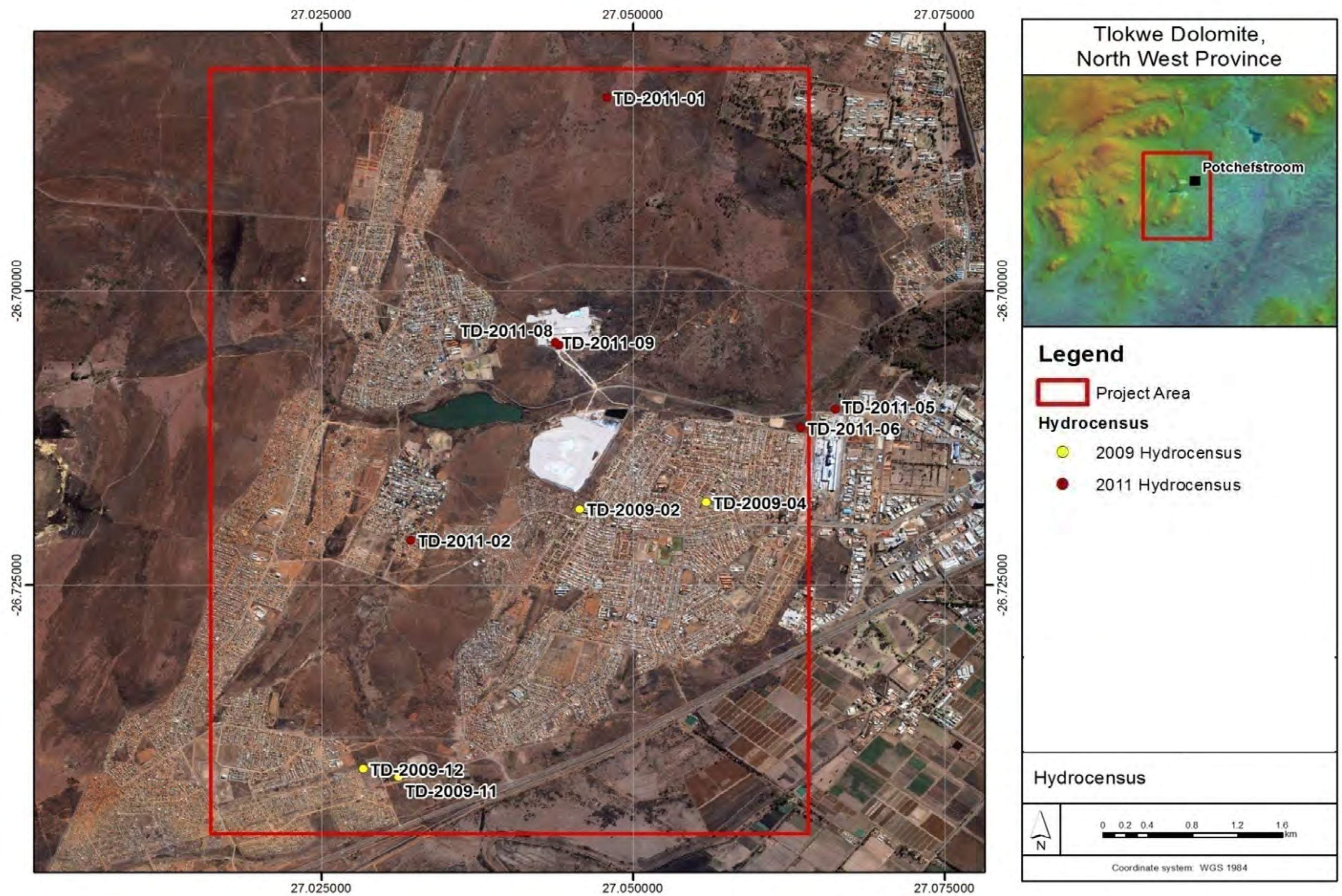

Figure 4-16: Surveyed boreholes.

Table 4-3: Hydrocensus results (2009).

BOREHOLE SITE	Site Description	Site No	TD-2009-02	TD-2009-04	TD-2009-11	TD-2009-12
		Date Visited	01-Sep-09	01-Sep-09	02-Sep-09	02-Sep-09
		Type	Borehole	Borehole	Borehole	Borehole
		Status	In use	In use	In use	Not in use
		Condition	Good	Good	Good	
		Purpose	School Supply	Supply	Garden - back-up	
		Use	School use - only source of wa	Toilets, garden	Garden & beack-up supply for school	
		Abstraction (m3/year)		3-5 m3/a		
		Site Comments	Big elevated steel tank (48m3). Close to Kynoch dump site.		Strong Borehole	Pump stolen long ago - used tc
		Site Owner	Boitshoko High School	Katlego Pub	Ikalafeng School (Special) - Kos	Eskom site
		Owner Detail	018 295 2413	4557 Moleme Street, Ikageng.	018 295 5003	018 464 6853
		Farm	Boitshoko High School	Katlego Bottle Store & Pub	Ikalafeng School (Special) - Kos	Eskom site
	Location	Lat / Long System				
		Ref Point				
		Accuracy	3.9m	3	5.6m	4.2m
		Latitude	-26.71856	-26.71804	-26.74134	-26.74064
		Longitude	27.04575	27.0562	27.0312	27.02838
		Altitude (GPS)			1374	1377
BOREHOLE EQUIPMENT	Pump	Type	Mono (unsure?)	Submersible	Submersible	
		Condition	Good	Good	Good	
		Protection Comment				
		Pump House / Fence	Fence with locked gate	behind property fence/gate		No
	Motor	Type	Electric	Electric	Electric	
		Condition	Good			
WATER	Water Levels	Can WL be measured	No	Yes	yes	
		Date measured	2009/09/01	2011/07/01	2009/09/02	
		WL Status	Pumping	Static	Recovering rapidly	
		WL Method		Dipmeter		
		WL Depth		5.1	27m	
		Datum (coller) height				
	Samples	Sampled	Yes	Yes		Yes
		Analysed	Yes	Yes		Yes
	Field Measure ments	pH				
		EC mS/m				
		TDS ppt				
		Temp				
Additional Comments			1600 people depend on BH. Water pumped slowly - often			

Table 4-4: Hydrocensus results (2011).

		Site No	TD-2011-01	TD-2011-02	TD-2011-05	TD-2011-06	TD-2011-08	TD-2011-09
BOREHOLE SITE	Site Description	Date Visited	29-Jun-11	29-Jun-11	01-Jul-11	01-Jul-11	15-Nov-11	15-Nov-11
		Type	Borehole	Borehole	Borehole	Borehole	Borehole	Borehole
		Status	Not in use	In use	In use	Destroyed	In use	Back up
		Condition		Good	Good	Sealed	Good	Good
		Purpose	Monitoring	Supply	Monitoring	Monitoring?	Supply	Supply
		Use		Domestic			Industrial, domestic	Industrial, domestic
		Abstraction (m3/year)		15-30Mm3/a estimated			~380,000	Back up
		Site Comments		borehole beneath pavmnt	Locked cap	sealed borehole	Well equipped,	Well equipped
		Site Owner			Kynoch/OMV monitoring?		OMV	OMV
		Owner Detail					Hendrik Muller	Hendrik Muller
		Farm		Mohadin residential				
	Location	Lat / Long System						
		Ref Point						
		Accuracy	3	3	3	3		
		Latitude	-26.68355	-26.72121	-26.71006	-26.71166	-26.7046	-26.70436
		Longitude	27.04791	27.03221	27.06625	27.06347	27.04412	27.04378
		Altitude (GPS)						
BOREHOLE EQUIPMENT	Pump	Type	None	Submersible	None	None	Mono	Mono
		Condition		Good			Good	Good
		Protection Comment		under pavement			Cement fence	Cement fence
		Pump House / Fence	No	No, behind yard fence	None		Cement	Cement
	Motor	Type		electric			Electric	Electric
		Condition		running 24h/d			Good	Good
WATER	Water Levels	Can WL be measured	Yes	No	No	No	No	No
		Date measured	2011/06/29					
		WL Status	Static					
		WL Method	Dipmeter					
		WL Depth	9					
		Datum (coller) height						
	Samples	Sampled						
		Analysed						
	Field Measurements	pH						
		EC mS/m						
		TDS ppt						
		Temp						
Additional Comments					Locked cap on suspected monitoring BH		Borehole pumped continuously for process	

4.5.6 Hydraulic properties

As part of the modelling report done for Kynoch Fertiliser by GeoCon (2001), the aquifer parameters were determined for the dolomite underlying the Kynoch site from the aquifer tests conducted on 11 boreholes. All of the boreholes are located on dolomite and the aquifer parameters for the dolomite aquifer have been determined through the aquifer tests and various relevant interpretations. The results show that although the water levels do not fluctuate much in the dolomite due to the high secondary permeability, there is a high degree of heterogeneity within the dolomite. The hydraulic properties of a borehole in dolomite is governed by the degree of fracturing or openings encountered during drilling.

According to GeoCon (2001), the dolomite varies from fairly impermeable (transmissivity (T) <1 m^2/d) in solid dolomite to highly transmissive (320 to >3 000 m^2/d) with open dissolution cavities (karsts). The boreholes are shown in Figure 4-17 and the results are presented in Table 4-5. Note that the borehole numbers correspond to the numbers in the report referenced, and not to final monitoring borehole numbers suggested in this dissertation.

A new groundwater monitoring borehole was drilled in Lusaka Cemetery specifically for the monitoring of groundwater levels in Ikageng in November 2011 (position indicated in Figure 4-22). This borehole (TMBH08) intersected a (partly) saturated cavity and was tested with a submersible pump for six hours (constant rate of 3.0 L/s) early in 2012. Minimal drawdown was achieved during the six hours, and a minimum T of 1 240 m^2/d was calculated for this highly fractured stretch of dolomite. This borehole is also included in Table 4-5.

Table 4-5: Borehole test results.

Borehole	Type of test	Duration (min)	Abstraction rate (m^3/d)	Final drawdown (m)	T (calculated) (m^2/d)
BH1	Step-drawdown	75	8,64	15,0	0,58
BH2	Constant rate	1 440	96,0	11,9	33,0
BH3	Constant rate	1 440	168,0	9,6	25,9
BH4	Step-drawdown	128	29,81	19,0	2,8
BH8	Constant rate	1 440	345,6	0,2	>3 000
BH9	Constant rate	1 440	1 728,0	6,3	320,0
BH10	Constant rate	1 440	1 382,4	4,2	1 190,0
BH11	Constant rate	1 440	950,4	5,3	1 020,0
BH12	Constant rate	1 440	345,6	8,6	66,4
BH14	Constant rate	1 440	114,91	17,8	10,0
BH19	Constant rate	1 440	1 296,0	3,2	2 810,0
TMBH08	Constant rate	360	259.2 (3 L/s)	0.15	> 1240

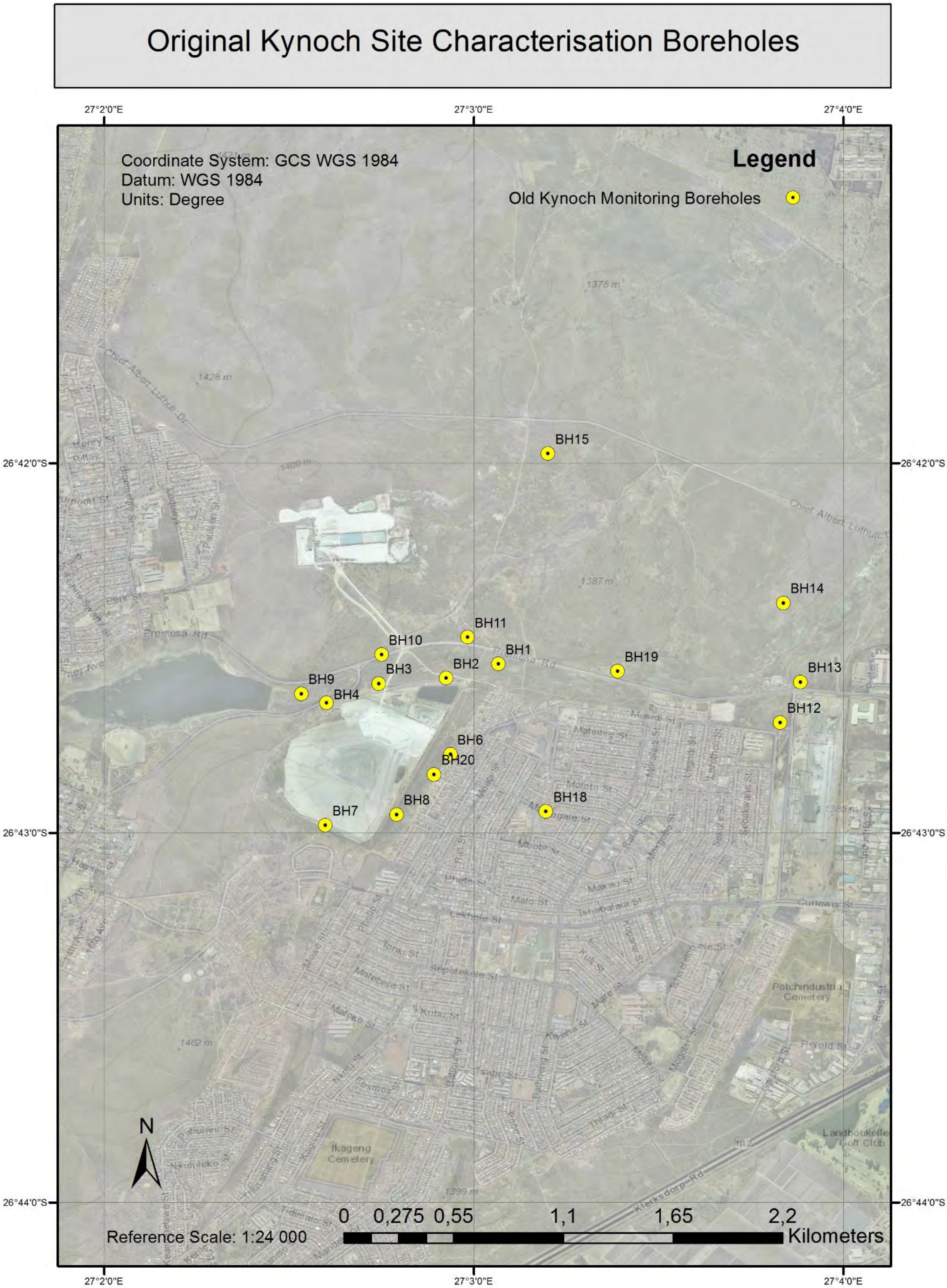

Figure 4-17: Locations of the original Kynoch site characterisation and monitoring boreholes.

4.5.7 Groundwater levels and hydraulic gradients in different aquifers

Several clusters of boreholes were drilled for various projects throughout the local area over the past several years. Where water levels were measured as part of the investigation, these data were used to correlate hydraulic gradients in different aquifers. Because the water level data were measured over periods of years, during different seasons, it is technically not possible to construct a single groundwater contour map of water levels at a specific time. This is due to seasonal fluctuations that would give a wrong interpretation.

The collar elevations of each of the coordinate points were either surveyed or interpolated from available SRTM elevation data. The static water levels were then subtracted from this elevation to give a hydraulic head elevation in metres above mean sea level (mamsl).

The borehole logs were then used to compare the water levels in dolomitic boreholes to those drilled in clastic rocks relative to the collar elevation. This was done by plotting a graph of collar elevation vs. water level elevation.

As a general rule, the hydraulic gradient in unconfined and semi-confined conditions follows or mimics the topography. Therefore a general positive correlation should exist between collar elevations and water level elevations.

4.5.7.1 Water level variations in clastic rock

Figure 4-18 indicates this correlation for several clusters of boreholes located off the dolomite, i.e. in clastic rocks. Each cluster was drilled during a particular time span after which static water levels were taken in boreholes with water strikes. The water level data in each cluster can be assumed to be a true representation of the water level at a specific time, but since the clusters were not all drilled at the same time, and water levels measured at the same time, there is a time variation (of years) in data between clusters.

Even though it is not a true representation of water levels in space and time, there is a general increase in hydraulic head with an increase in collar elevation. Furthermore it can be noted that steeper hydraulic gradients exist even within individual clusters. As an example the collars of the boreholes in the AGES Promosa cluster vary by about 10 m in topographic elevation, while the hydraulic head in the boreholes vary by almost 30 m.

4.5.7.2 Water level variations in dolomite

In contrast to this, boreholes that were confirmed to have been drilled in dolomite exhibit a flat hydraulic gradient (Figure 4-19). For example the collar elevations of the Kynoch monitoring boreholes (around the KGTD area), vary by as much as 40 m, while the hydraulic head stays constant at 1 360 mamsl. CGS data from 1995 indicate boreholes north of Promosa Road with collar elevations ranging 34 m while the head elevations vary by only five metres with an average of 1 355 mamsl.

The water levels in the abovementioned clusters were measured nine years apart, and therefore a seasonal variation of five metres is possible, meaning that the two clusters might be hydraulically connected, however this is speculative.

The two data points from the southern tip of the dolomite finger according to 2003 BKS data, indicate that the hydraulic head is between 20 – 30 m lower in elevation than around the KGTD measured just the following year. Due to the otherwise flat hydraulic gradient throughout the Kynoch cluster, this indicates that the southern tip of the dolomite finger is probably hydraulically (and possibly geologically) separated from the dolomite around the KGTD.

The locations of the borehole clusters in Figure 4-18 and Figure 4-19 can be seen in Figure 4-20.

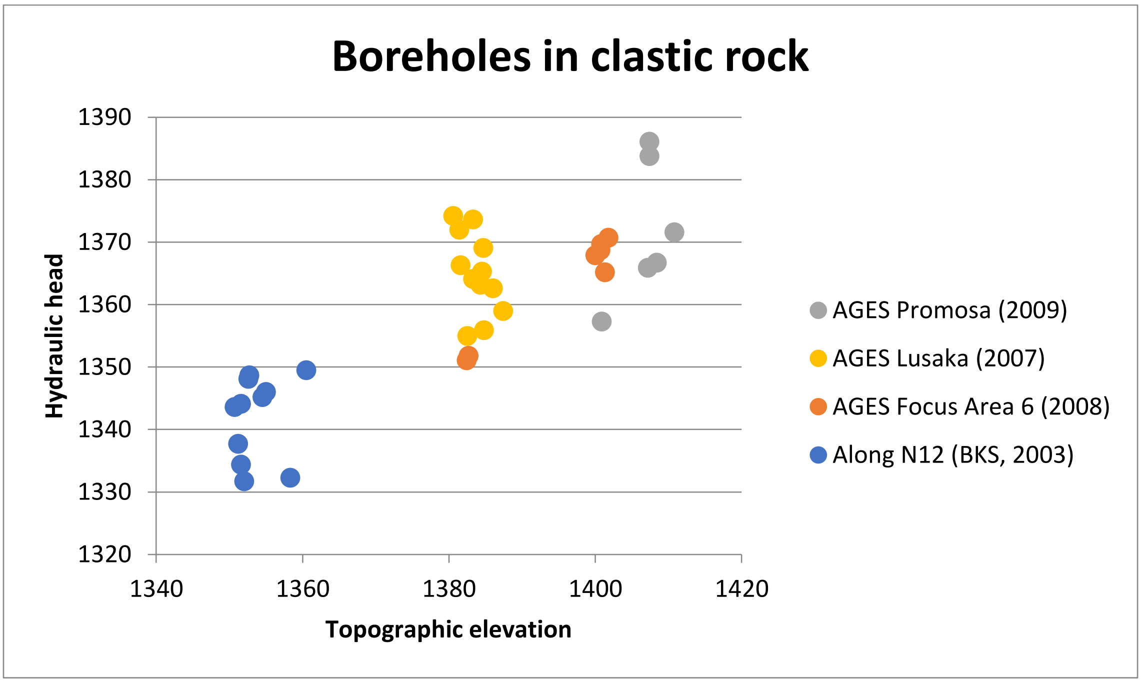

Figure 4-18: Water level variations in borehole clusters located in clastic rock.

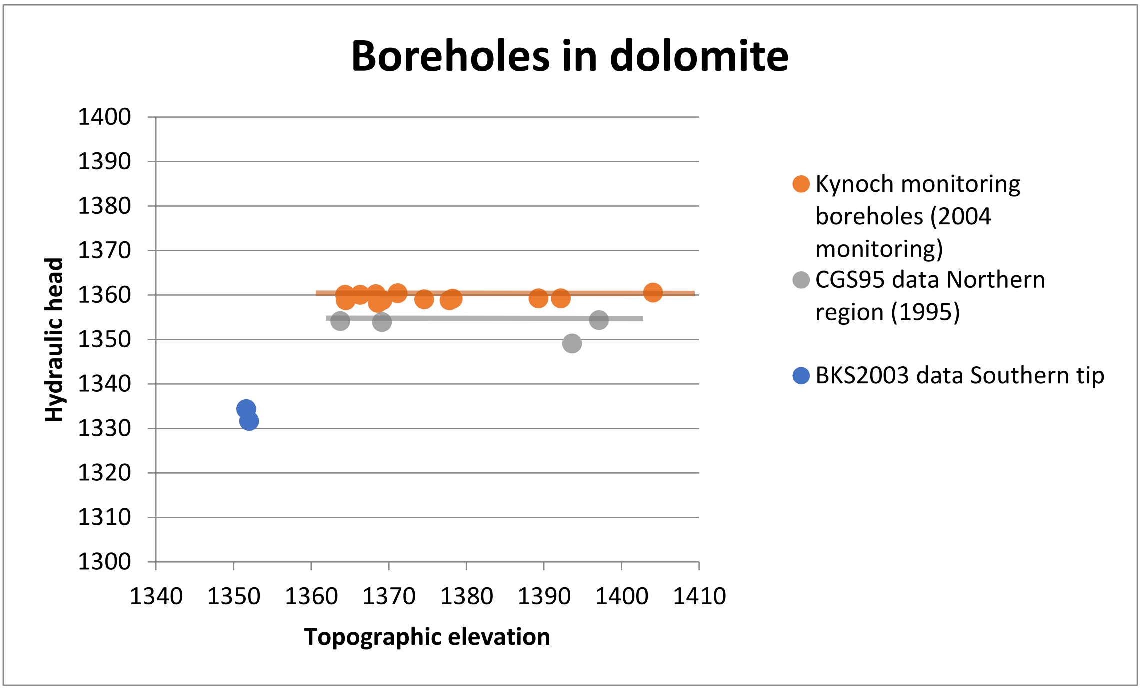

Figure 4-19: Flat hydraulic head in boreholes drilled on dolomite.

4.5.7.3 Historical groundwater levels

The initial or historical groundwater level is an important concept when it comes to groundwater related dolomite instability. In order to ascertain historical groundwater levels in the area, the National Groundwater Archive (NGA) database was consulted to find monitoring boreholes with historical data.

Only one borehole was found within a 10 km radius of the KGTD chosen as central point in Ikageng. This borehole, numbered 2626DD00261, is indicated as abandoned. It has estimated coordinates at Lat: -26.78857 Long: 26.99715 (Hartbeeshoek Datum), which plots 9.5 km southwest of the KGTD in the mapped Hekpoort andesite.

The available data only stretched from February 1968 to April 1978 (see Figure 4-21). Strong seasonal trends can be observed for the first five years. Between 1974 and 1978 however there are suspect data jumps that do not seem realistic, and might have to do with instrument calibration error. Therefore the strong downward trend after 1978 might be at a deeper depth.

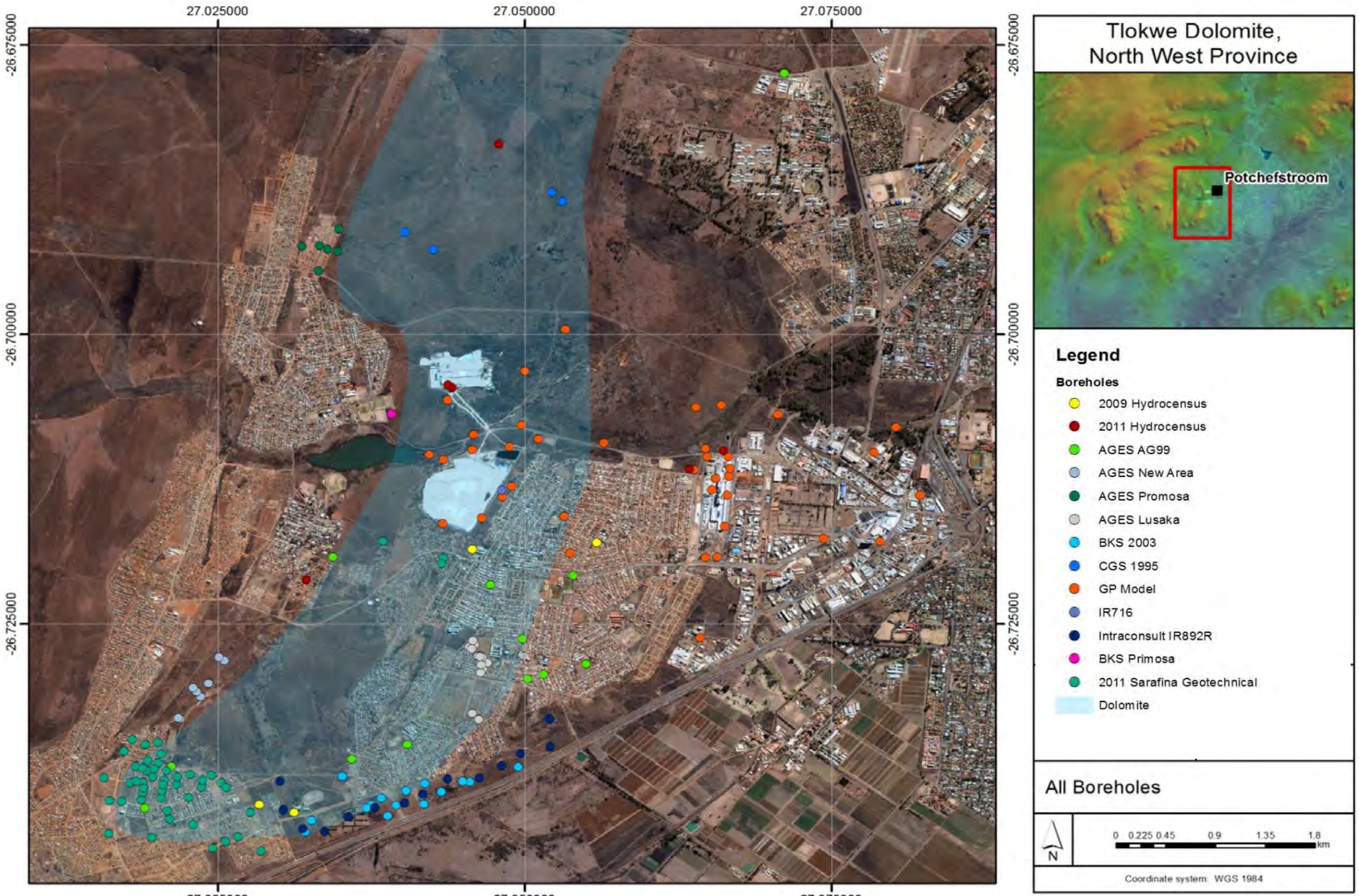

Figure 4-20: All boreholes on record in the study area (AGES, 2012a).

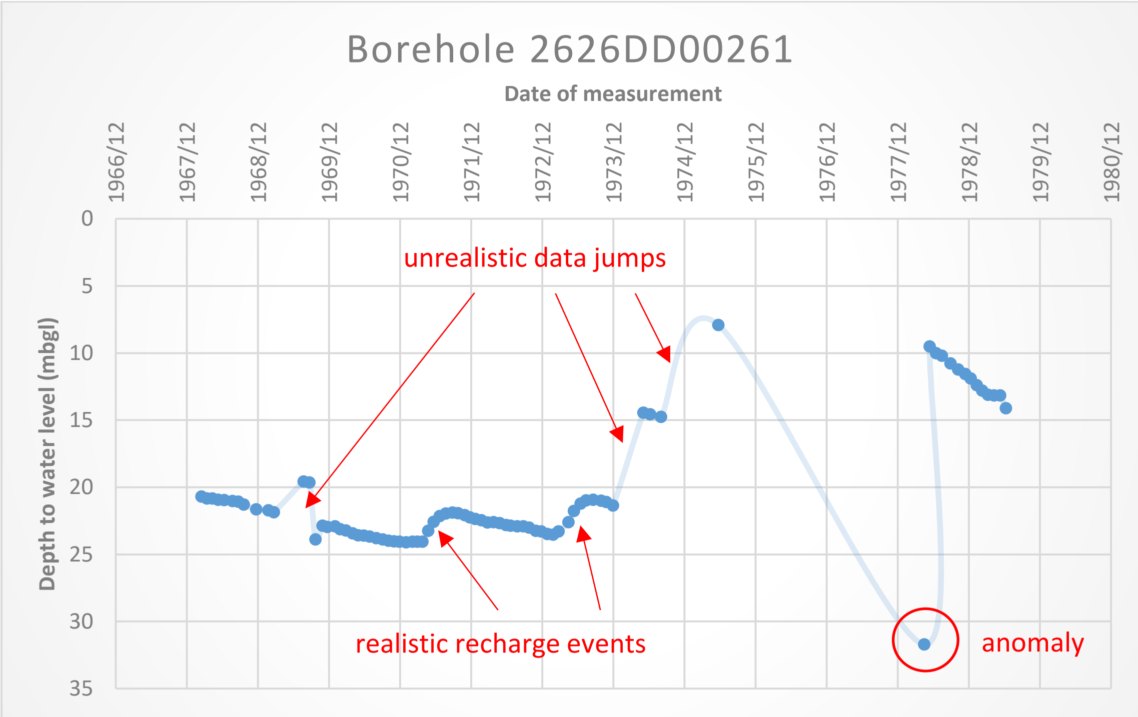

Figure 4-21: Groundwater level fluctuations in borehole 2626DD00261.

Based on the available data it is not clear whether the water levels fluctuated by more than five metres. Regardless, these measurements were in volcaniclastic rocks and not in dolomite.

4.5.7.4 Water level fluctuations in the focus area

Monitoring of water levels together with the groundwater chemistry on a continuous basis for Kynoch between 2000 and 2006. (This monitoring responsibility was taken over by OMV in 2006, but only quality monitoring took place, therefore no water level monitoring data exists between 2006 and 2011 when AGES resumed water level monitoring in Ikageng as part of this project). The locations of the boreholes are indicated in Figure 4-22. Water level monitoring data were plotted on a graph to visually represent any possible fluctuations (Figure 4-23).

Boreholes that are inactive include:

- TMBH01 which is deemed to have collapsed.
- KBH9, is under OMV's supervision and is locked with no key available.
- TMBH07 was an open borehole casing on the Eskom property, but this borehole has subsequently been fitted with a pump making monitoring impossible.
- TMBH14 which is also deemed to have collapsed. No monitoring results

exist after June 2015, and it was reported blocked in September 2015. OMV confirmed that no water samples could be taken from this borehole recently (Hlahane, 2016). This monitoring borehole (TMBH14) corresponds to BH8 (Figure 4-17).

The majority of boreholes are located on dolomite. The only exceptions are TMBH03 and TMBH07 (now inactive). Borehole TMBH04 appears to be located on the eastern extremity of the mapped dolomite, but the fluctuations experienced in the water table correspond to fluctuations in TMBH15 which is located on dolomite.

Apart from noticeable fluctuations in these two boreholes, the rest of the monitoring points exhibits fairly stable water tables. This is good sign from a dolomite stability perspective.

4.5.8 Springs

According to AGES (2005a) a spring that discharges groundwater at a rate of 300-400 m^3/d exists north of the Kynoch Factory site. It is not clear how this rate was determined. This spring occurs at the topographic lowest point in the Spitskopspruit at the contact between the dolomite and the overlying quartzite. GeoCon (2003) interpreted a north-south trending lineament in this area as a dyke which supposedly gives rise to the spring conditions. A marshy area next to the road is subsequently formed (Photo 4-1).

During the 2011 hydrocensus one of the boreholes surveyed in this area was found to be artesian, and groundwater was freely flowing from underneath the protective cap installed (Photo 4-2). This borehole is located on the eastern dolomite contact (near the spring) and was not artesian in the past according to historical monitoring records. The location of the borehole and the fact that the water table fluctuates above and below the collar elevation, makes it ideal to be fitted with a pressure transducer to measure the potentiometric surface.

No potentiometric measurements were taken during this project however.

Photo 4-1: Marshy area north of Promosa Road caused by spring conditions (2009).

Photo 4-2: OMV employee samples artesian water from old monitoring borehole BH7 during October 2011.

Photo 4-3: Salt precipitating north of the tailings dump where seepage decant was sampled.

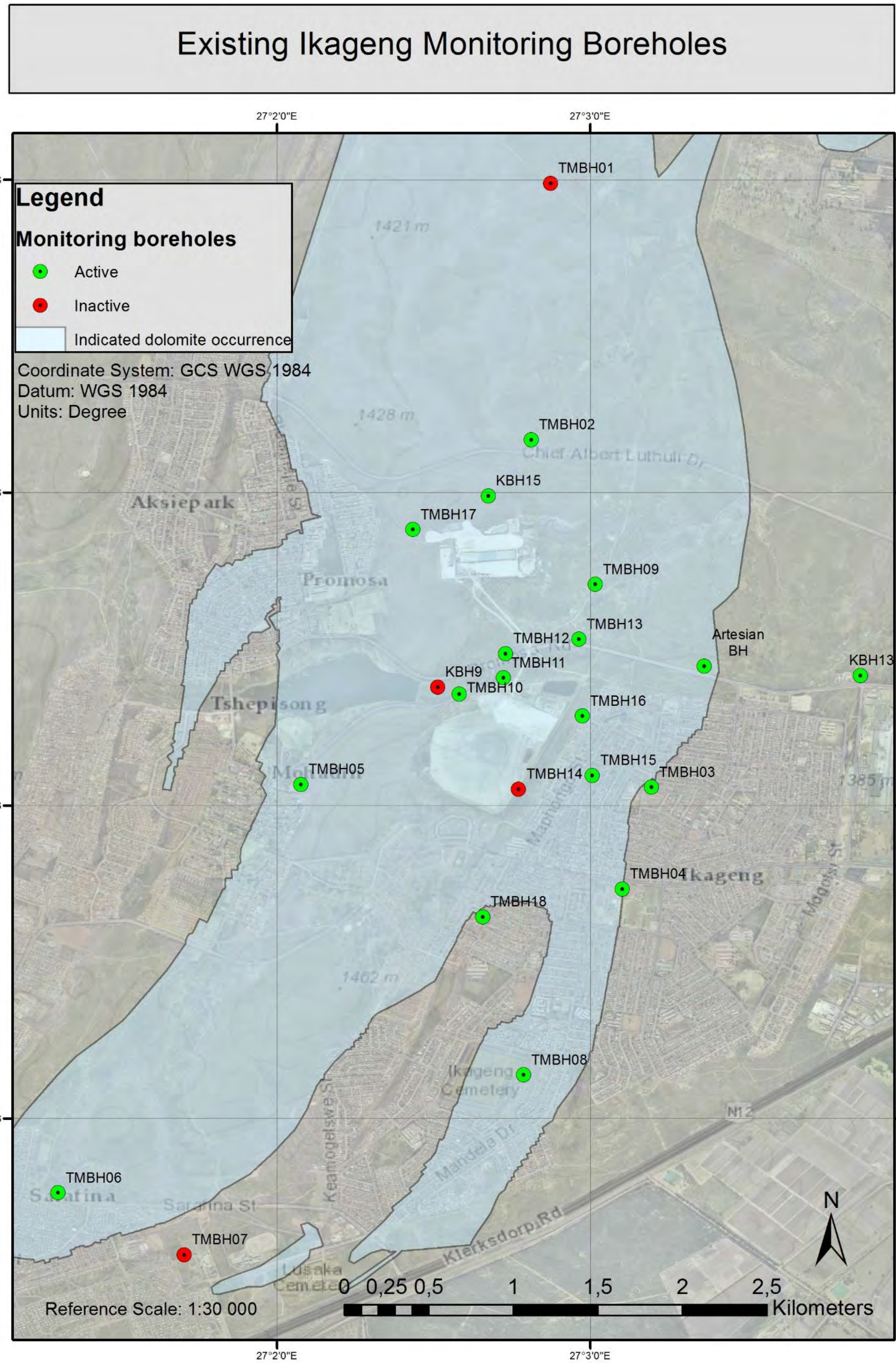

Figure 4-22: Existing monitoring borehole locations throughout Ikageng.

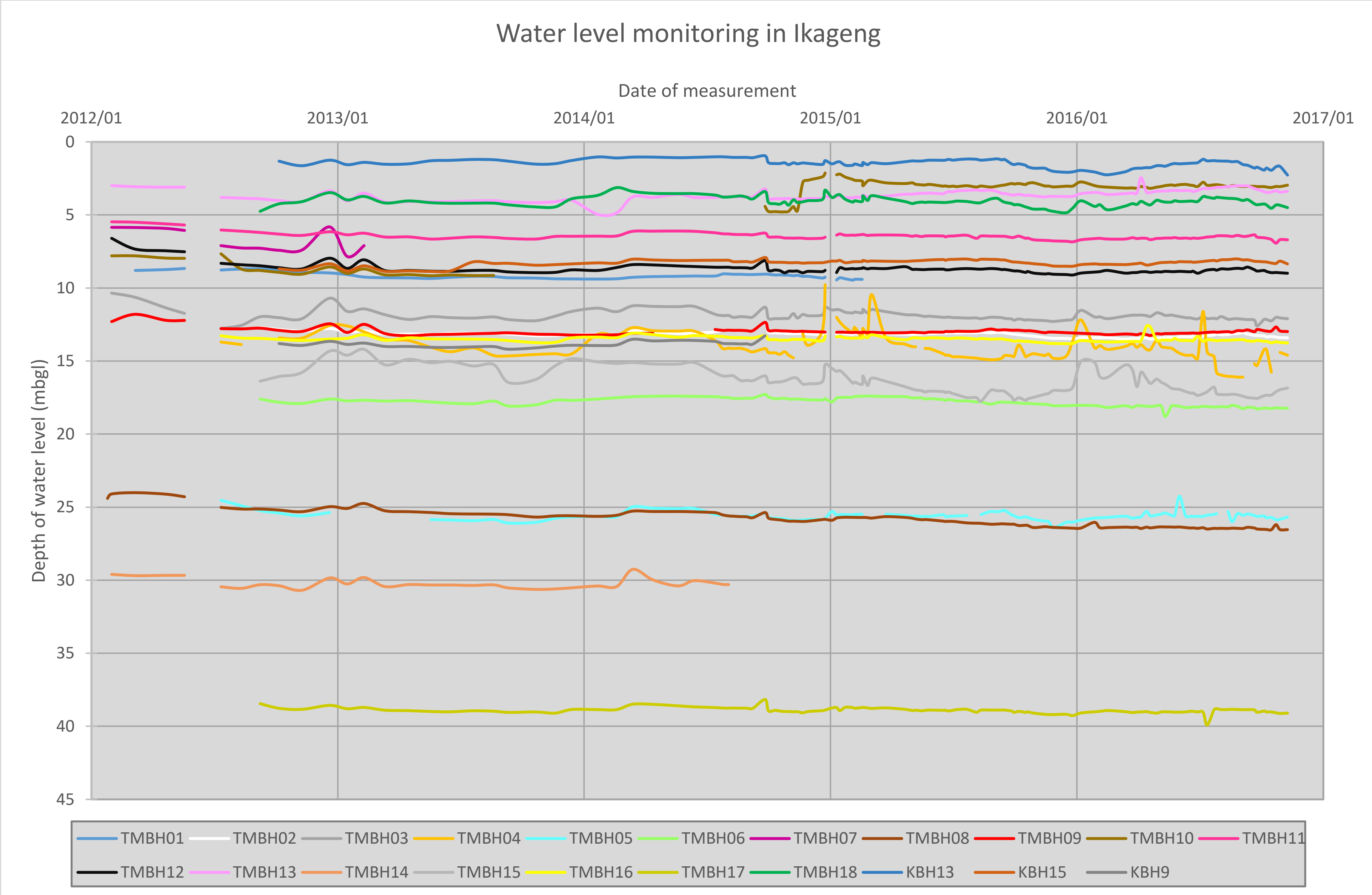

Figure 4-23: Water level monitoring in Ikageng.

4.5.9 Water quality

4.5.9.1 Surface water quality

The only surface water in the focus area is found in the Spitskopspruit, which includes the Poortjie Dam northwest of the KGTD (see Figure 4-24). The contamination potential of the KGTD has been known for several years and numerous studies were conducted on the topic since the mid 1990's. However, most of these studies focussed on the groundwater contamination from the KGTD, and storm water runoff from the old factory site itself. Seepage rates from the KGTD were determined in 2000 (during the operational phase) to be between 150 and 900 m^3/d, while the groundwater model was calibrated with a seepage rate of 180 m^3/d. (GeoCon, 2001 and AGES, 2005a).

Figure 4-24: Surface water grab samples taken in November 2011.

Due to the chemical nature of the KGTD, the site was classified as a hazardous waste facility (AGES, 2005a). The gypsum precipitated out of a slurry containing a host of dissolved metals, salts and acids. Some of the water seeping out from the sides of the tailings dump is intercepted and channelled to treatment ponds via trenches (but no longer treated according to Muller, 2011). Not all of the seepage is intercepted, and seepage was observed to decant just outside of the property boundary on the northern side where white and yellow salt crystals precipitated as a surface crust after evaporation (see Photo 4-3). No water is being added to the

KGTM currently, apart from rainwater and intercepted seepage water from the retention dam that is being pumped back on top of the dump. It is therefore unclear what volume of seepage currently reaches the underlying dolomite aquifer.

It is believed that old BH8 (see Figure 4-17) on the eastern side of the tailings dump has a disintegrated casing that causes source water to directly enter the underlying aquifer, and it was recommended to seal off this borehole to stop seepage from directly entering the aquifer (AGES, 2005a). On one monitoring run it was realised how difficult it is to measure a water level with a conventional electrical contact dipmeter. The high EC concentration in the seepage causes an electrical contact on the dipmeter even when the probe is not fully submerged. This problem was overcome by using a variable resistance dipmeter.

The monitoring of several surface water monitoring points downstream of the tailings dump was initiated (with the water at the outlet of the Poortjie Dam serving as baseline data) as part of the monitoring protocol for the Kynoch factory site and tailings dump. Currently OMV is responsible for the sampling of these points, and the author received conflicting reports in terms of whether the results are being interpreted independently by a specialist.

Two surface water grab samples were taken during November of 2011 as part of a groundwater level monitoring run. One was taken of seepage water north of the tailings dump (NW11-017 in Figure 4-24), and the other (NW11-018) was taken about 100 m downstream of the KGTD property in the Spitskopspruit at a stagnant water body, just north of the first houses in the Ikageng residential area east of the KGTD. At both locations the high salt content caused precipitation of white and yellow (salt) crystals on the edges of the water bodies.

The samples were analysed at the North West University’s chemical testing laboratory (Eco-Analytica) and the results obtained are depicted in Table 4-6.

The results of the analyses below indicate that this seepage water is **highly contaminated**. The most alarming parameter is the low (acidic) pH of ~1.8. The surface water quality is further characterised by toxic levels of various major elements and compounds. The TDS of >20,000 mg/L is indicative of the high concentrations of salts in the brine. Basically all the parameters analysed were of such high concentrations that it can be considered toxic to the environment including animal and human health. Notable is the fluoride concentrations of almost 24,000 mg/L sampled in water near the residential area (the drinking water standards for fluoride allows a limit of 1.0-1.5 mg/L (SANS 241, DWAF, (1999)).

Table 4-6: Water quality results for two surface samples near the KGTD.

		NW11-017	NW11-018
pH		1.83	1.87
EG	mS/m	4 010.00	3 710.00
TDS	mg/L	26 065.00	24 115.00
Ca	mg/L	17 670.00	16 970.00
Mg	mg/L	1 357.00	1 446.00
K	mg/L	46 860.00	43 920.00
Na	mg/L	336.10	377.70
PO4	mg/L	33 460.07	29 674.40
SO4	mg/L	2 485.12	5 927.99
NO3 (as NO3)	mg/L	741.57	643.60
NH4	mg/L	-	0.02
Cl	mg/L	786.70	712.25
HCO3	mg/L		
Fe	mg/L	250.00	199.50
Mn	mg/L	1 947.00	2 457.00
Al	mg/L	4 446.00	5 021.00
F	mg/L	17 659.12	23 795.07
Zn	mg/L	424.50	484.00
Pb	mg/L	0.12	0.14

4.5.9.2 Groundwater quality

General

During 2009, water from four boreholes were sampled for basic chemical analyses. The results are indicated in Table 4-7 while the positions of the sampling points are indicated in Figure 4-25. The results were compared and classed according to DWAF's drinking water classification guide (DWAF, 1999). Broadly the classes are as follows:

- Class 0: Ideal quality
- Class I: Good quality
- Class II: Marginal quality
- Class III: Poor quality
- Class IV: Unacceptable quality

Boreholes TD002 (Boitshoko High School) and 004 (Katlego Pub) are located in Ikageng east of the old KGTD, while TD011 (Ikalafeng School) and 012 (Eskom Sub-station) are located in Sarafina. All except TD012 were used as abstraction boreholes.

From the results it can be seen that the water east of the KGTD differs remarkably from the water in the southern part of Ikageng. The quality of samples TD002 and TD004 are similar: both samples show a distinct dolomitic origin (elevated Ca and Mg concentrations and subsequent Total Hardness) and shows signs of contamination from the tailings dump (elevated EC due to increased TDS like Cl, Na, SO_4 and NO_3).

Table 4-7: Groundwater quality (2009).

Water quality analyses for samples from Greater Ikageng Township, Tlokwe

DWAF Drinking water standards quality classes				
Class 0				
Class I				
Class II				
Class III and above				
Analaysed	2009/09/09	2009/09/09	2009/09/09	2009/09/09

Determinants	Units	Domestic standards: DWAF TWQG	Domestic standards: SANS Class II (max. allowable limit)	TD 002	TD 004	TD 011	TD 012
Physical and organoleptic requirements							
Electrical conductivity at 25°C	mS/m	<70	>150 - 370	70	70	35	18
Dissolved solids at 180°C	mg/l	<450	>1 000 - 2 400	455	455	228	117
pH value at 25°C	pH	5-9.5	4.0 - 10.0	8.28	8.06	6.9	6.78
Total Hardness**	mg/l CaCO3	<200	300-600	292	291	146	52
Macro chemical elements							
Calcium	mg/l Ca	<80	>150 - 300	61.32	60.52	38.88	9.22
Magnesium	mg/l Mg	<30	>70 - 100	33.78	33.91	11.91	7.05
Potassium as K	mg/l K	<25	>50 - 100	4.30	5.08	5.08	7.04
Sodium as Na	mg/l Na	<100	>200 - 400	24.14	24.14	10.35	11.04
Sulphate SO4	mg/l SO_4	<200	>400 - 600	93.18	91.26	8.73	1.70
Nitrate as N	mg/l as N	<6	>10.0 - 20.0	0.48	0.42	0.59	0.10
Ammonia	mg/l NH4	<1	>1.0 - 2.0	0.22	0.18	0.07	0.51
Chloride	mg/l Cl	<100	>200 - 600	33.68	34.21	9.57	3.90
Micro chemical elements							
Iron	mg/l Fe	<0.03	>0.2 - 2.0	0.027	0.001	0.001	0.004
Manganese	mg/l Mn	<0.1	>0.10 - 1.0	0.026	0.004	0.013	1.455
Copper	mg/l Cu	<1	>1.0 - 2.0	0.016	0.011	0.014	0.097
Zinc as Zn	mg/l Zn	<3	>5.0 - 10.0	0.039	0.046	0.050	0.805
Chemical Water quality	DWAF			Class I	Class I	Class 0	Class II
Microbial Water quality	DWAF						

Borehole TD011 has a more distinct dolomitic fingerprint (higher Ca and Mg) than TD012. This might be due to a different aquifer (dolomite vs. shale) in TD011 or due to the fact that water from a dolomite compartment is drawn in during pumping. This borehole is pumped significantly for general use at the school, including watering of the gardens and sports fields.

The stagnant water in TD012 also shows a high manganese concentration that is usually associated with the weathering of dolomite (WAD).

Figure 4-25: Locations of groundwater samples surveyed during 2009.

Kynoch Gypsum Tailings Dump

It is evident that the KGTD has an impact on the groundwater surrounding the site. The groundwater quality monitoring performed by OMV on a quarterly basis on the monitoring boreholes surrounding the tailings dump is collated and interpreted in an annual report by an independent consultant. These reports were not made available.

The author accompanied OMV during October 2011 on a monitoring run to ascertain the positions of the boreholes used by them. It was noted that sampling is being done using a PVC bailer inserted to the top of the water table to sample the top section just below the water table. No cognisance is therefore taken of possible water strikes at deeper depths that may allow for the migration of the plume, or stratification of water inside the casing. It is also unclear how each borehole was developed (i.e. perforated or solid PVC casing).

The boreholes are not numbered, and borehole numbers are obtained from a printed version of a borehole locality map contained in the AGES (2005b) report to Kynoch that was inherited by OMV with the sampling responsibility.

There appears to be a lack of quality control in terms of sampling protocol employed by OMV.

Oranje Mynbou & Vervoer Site

The OMV reclamation site was also identified as a possible source of groundwater pollution. The gypsum is being excavated from the dump, loaded onto trucks which dump the loads on open ground from where it gets fed into the cleaning process. It is expected that rain would leach out pollutants and, being located on dolomite, infiltrate directly into the underlying dolomitic aquifer.

Boitshoko High School water quality

The groundwater from the borehole at Boitshoko (TD002) was re-sampled in 2012 to compare with the quality of the sample in 2009. This was done after the realisation that the groundwater abstraction has the potential to draw in the pollution plume from the gypsum tailings dump. The same parameters were analysed for including fluoride after realising that fluoride was one the main constituents in the seepage water from the tailings dump. The results are tabled in Table 4-8.

From Table 4-8 it can be seen that the general classification of the water deteriorated from Class I to Class II, although this is mainly based on the total hardness and the Fe concentration. Total hardness is a function of the Ca and Mg concentrations, and although the calcium concentration decreased, the increase in magnesium in 2012 caused the total hardness count to exceed the 300 mg/L threshold (Class II). Iron was already slightly elevated (Class I) in 2009, but the concentration increased significantly in 2012 (Class II aesthetic). The rest of the constituents are of comparable concentrations, apart from Cl which is slightly higher, and K which is lower in 2012. Fluoride is within domestic standards and does not pose a health risk to the pupils. No real health risks are associated with the iron at this concentration. Should it increase, the water will take on an objectionable taste.

The two samples were however taken at different times of the year, and it is inconclusive whether deterioration of water quality takes place.

Table 4-8: Quality comparison of the water from borehole TD002 (Boitshoko High School).

Water quality analyses for samples from Boitshoko High School borehole, Tlokwe

DWAF Drinking water standards quality classes		
Class 0		
Class I		
Class II		
Class III and above		
Analysed	2009/09/09	2012/02/08

		Domestic standards			
Determinants	**Units**	**DWAF TWQG**	**SANS Class II (max. allowable limit)**	**TD 002**	**TD 002**
Physical and organoleptic requirements					
Electrical conductivity at 25°C	mS/m	<70	>150 - 370	70	65
Dissolved solids at 180°C	mg/l	<450	>1 000 - 2 400	455	423
pH value at 25°C	pH	5-9.5	4.0 - 10.0	8.28	8.1
Total Hardness**	mg/l CaCO3	<200	300-600	292	318
Macro chemical elements					
Calcium	mg/l Ca	<80	>150 - 300	61.32	47.94
Magnesium	mg/l Mg	<30	>70 - 100	33.78	48.11
Potassium as K	mg/l K	<25	>50 - 100	4.30	1.60
Sodium as Na	mg/l Na	<100	>200 - 400	24.14	25.57
Sulphate SO4	mg/l SO_4	<200	>400 - 600	93.18	91.27
Nitrate as N	mg/l as N	<6	>10.0 - 20.0	0.48	0.31
Ammonia	mg/l NH4	<1	>1.0 - 2.0	0.22	0.29
Chloride	mg/l Cl	<100	>200 - 600	33.68	41.47
Fluoride	mg/l F	<0.7	>1.0 - 1.5		0.01
Micro chemical elements					
Iron	mg/l Fe	<0.03	>0.2 - 2.0	0.027	0.400
Manganese	mg/l Mn	<0.1	>0.10 - 1.0	0.026	0.020
Copper	mg/l Cu	<1	>1.0 - 2.0	0.016	0.020
Zinc as Zn	mg/l Zn	<3	>5.0 - 10.0	0.039	0.080
Chemical Water quality	DWAF			Class I	Class II
Microbial Water quality	DWAF				

4.5.10 Geohydrological summary and conclusions

The geohydrological character of the focus area is not independent of the regional geohydrology of the areas surrounding it. Therefore the Welgegund GMA was chosen as the widest regional area with an independent geohydrological character in which context the focus area can be defined. This is also the area in which groundwater use might have an impact on the focus area and need to be investigated and managed.

Within this predefined area two main aquifer types are identified namely a Karst Type aquifer associated with the occurrence of dolomite, and Intergranular and Fractured Type aquifers associated with the clastic sedimentary and igneous rock types flanking the dolomite finger. Table 3-10 lists the differences between the two aquifer types.

Table 4-9: Differences between karst type and intergranular/fractured type aquifers.

Karst Type (dolomite) aquifer	Intergranular/Fractured Type aquifer
High groundwater potential	Low to medium potential
High Transmissivity	Low Transmissivity
High yielding boreholes (5-20 L/s)	Low to medium yielding boreholes (<5 L/s)
Shallow (flat) hydraulic gradient	Steeper, more defined hydraulic gradient
Major Aquifer	Minor Aquifer

Groundwater use in the area consists of agricultural, industrial, mining related and domestic use. The only two groundwater uses identified as possibly having a local effect on the groundwater table in the focus area is Boitshoko High School and OMV.

No mining related dewatering occurs in the regional area, although there are interest from mining companies in deeper lying gold deposits inside the neighbouring Turffontein GMA to the north of Potchefstroom.

Groundwater levels occur between 40 mbgl and surface throughout the focus area, although the water table in the dolomite is fairly constant at an elevation of 1 360 mamsl, indicating a low hydraulic gradient therefore a high transmissivity in the dolomite.

Continuous water level monitoring between 2012 and 2016 confirmed a fairly stable water table in the dolomite, apart from slight seasonal changes. This bodes well for dolomite stability which is affected by fluctuations exceeding six metres. Continued monitoring is required as an early warning system.

Springs have been reported, and one monitoring borehole was observed to be artesian on occasion.

Although signs were found of severe surface water pollution of the Spitskopspruit from the KGTD, the extent of this pollution further downstream was not further assessed.

Due to suspected lack of quality control regarding sampling procedures by OMV, the true impact of the KGTD on the quality of the surrounding dolomite aquifer is unknown. Although the dump is being removed and rehabilitated, the current impact must be ascertained.

5 Risk Assessment

5.1 Methodology

The risk assessment methodology employed in this study is based on the one developed and refined by Buttrick *et al* (2001 and 2011), as described in chapter 2.7.3. It started with the occurrence of dolomite as an initial hazard parameter as defined in Table 5-1.

Table 5-1: Dolomitic area classification.

Area classification	Description
Class A	Dolomite occurrence 0-10 m
Class B	Dolomite occurrence 10-60 m
Class C	No dolomite 0-60 m

The 10 m and 60 m thresholds were chosen because:

- Dolomite in the top 10 m are exposed to atmospheric conditions and human activity that holds a greater risk than deeper lying dolomite.
- Due to budgetary and practical constraints, an optimal borehole length of 60 m was chosen to which dolomite investigation was limited. Any dolomite between 10 m and 60 m was still seen as holding risk, albeit at a lower level than dolomite in the first 10 m. Groundwater levels extend into this zone and water table fluctuations within the first 30 m are seen as conducive to sinkhole development.
- Below 60 m, use was made of structural geological interpretations. Even where dolomite was suspected of occurring below this level, the overburden was seen as providing sufficient buffer to lower risk significantly.

The above two tables were combined in defining hazard classes. Due to the initial gaps in the geotechnical information in the study area, distinction was made between the:

- probable occurrence of dolomite (Table 5-2) and the
- measured occurrence of dolomite (Table 5-3):

These two tables enabled the compilation of a hazard zone map, divided into high, medium and low hazard zones as basis for further risk assessment (Figure 5-1). The high medium and low hazard zones were given numerical scores (Table 5-4) for further assessment based on the formula

Risk = Hazards x Vulnerability:

Table 5-2: Indicated hazard classification based on the probable dolomite occurrence.

Indicated Hazard based on the probable occurrence of dolomite	
Probable dolomite	**Rating**
Dolomite	High
Dolomite < 60m	High
20%	Medium
< 20%	Low

Table 5-3: Measured hazard based on proven inherent hazard class.

Measured Hazard based on the proven occurrence of dolomite	
Inherent Hazard Class	**Rating**
1	Low
2 – 4	Medium
5 – 8	High

Table 5-4: Sinkhole hazards are numerically rated (Potgieter, 2012).

Physical Factors (Hazard)	
Sinkhole Hazard	**Rating**
Low	1
Medium	2
High	3

The second step of the risk assessment was to combine the vulnerability of the community. The main anthropic factor used was the age of water infrastructure. The older the water infrastructure, the higher the expected possibility of leaks conducive to the formation of sinkholes.

Due to the sensitive nature of the information, the final risk zoning is not reproduced here. Instead the sinkhole hazard risk map (as reflected in 2010) was used as the basis upon which geohydrological flag factors were identified.

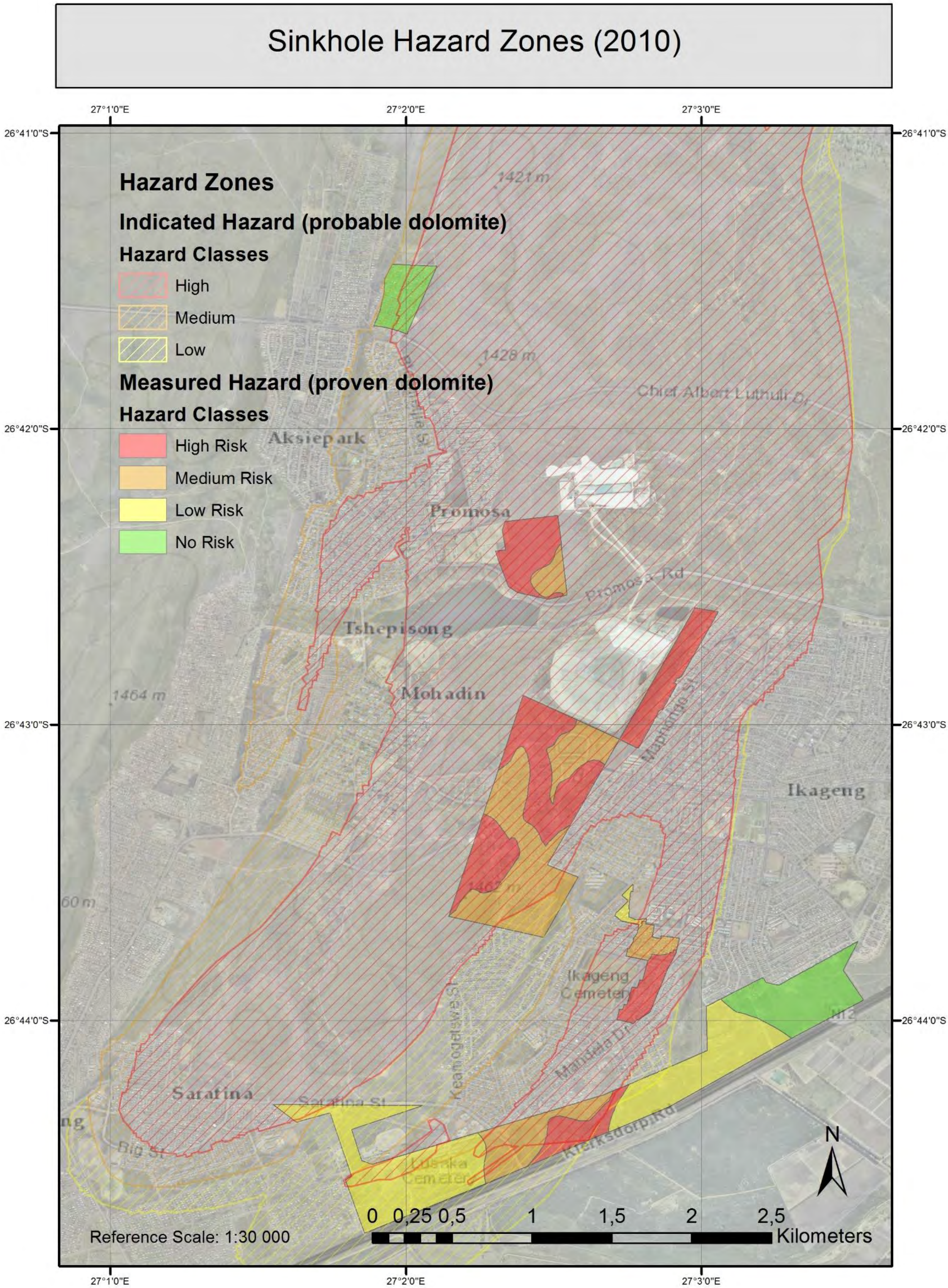

Figure 5-1: Indicated and measured hazard risk zones identified in Ikageng (modified from AGES, 2010).

5.2 Geohydrological flag factors

The primary geological conditions that were assessed in determining the hazard zones were the presence of dolomite in the near surface, and the presence of sub-surface cavities within the dolomite. The secondary conditions relate to the geohydrology.

Geohydrological factors that were identified as being potentially conducive to sinkhole formation are called ‘flags’. Geohydrological flag identification is based on the literature research (contained in this report) and current understanding of the geohydrology of the dolomite aquifer underlying greater Ikageng. These flags are indicated in Figure 5-2 and can be divided into two main groups:

1. Water quantity

- **Water table fluctuations:** It was also stated that groundwater level fluctuations of more than six metres, where the water table is less than 30 m from surface, are conducive to sinkhole formation in dolomitic terrain. Fluctuations in the water table is a function of change in storage, or quantity.

The Geoscience Amendment Act Regulation (16/2010) (South Africa, 2010) confirm the importance of a stable groundwater table by stating that “*suitable control over dolomite groundwater resources*” is needed to ensure that no fluctuation in the groundwater table may develop. It is therefore important that the Tlokwe City Council ensures that before any permission is granted to abstract water; it must be proven that abstraction will not result in affecting the water table beyond seasonal variation.

- **Ingress of water:** Sinkhole formation can often be traced to the ingress of surface water into subsurface cavities causing erosion of the weathered surface material. Sources of water might be natural ponding of water in artificially created depressions (quarries) or leaking water supply infrastructure underground. Any issues relating to the ingress of water will be flagged.
- **Ponding of water:** Areas where water accumulates (naturally or artificially) are conducive to sinkhole formation due to the potential ingress and associated erosion of weathered material, and added weight of the water pond.

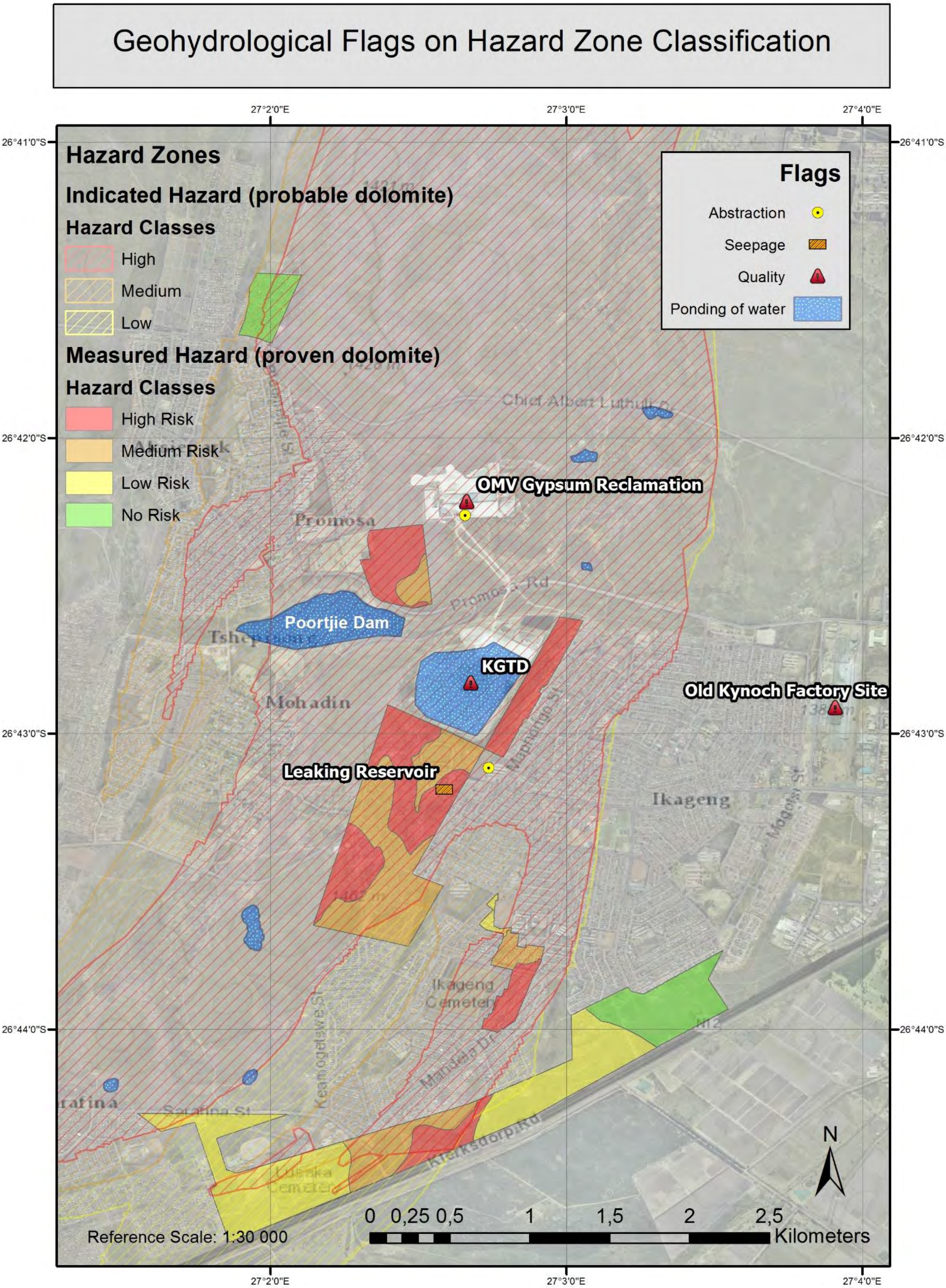

Figure 5-2: Geohydrological flag conditions relative to the hazard risk zones.

2. Water quality

It was noted in this dissertation that the formation of subsurface cavities in carbonate rocks such as dolomite and limestone is strongly correlated with the groundwater chemistry in the past, more so than the conventional theory of acid being derived from the dissolution of CO_2 in rainwater to form carbonic acid that percolates into the subsurface. This is evident in the fact that most cave systems are formed sub-parallel to the current water table, regardless of the dip of geological strata.

Acid in groundwater (particularly sulphuric acid) are believed to be responsible for the formation of at least 10% of the world's underground cave systems (see Section 2.2). Any pollution that might have a negative impact on the groundwater quality (especially pH) are therefore flagged.

5.3 Quantity Flags

5.3.1 Current groundwater abstraction flags

5.3.1.1 Boitshoko High School

The Boitshoko High School is situated next to the KGTD and relies on groundwater as sole source of water supply to the school. Water is abstracted from a borehole (TD2009-02 in Figure 4-16) located in the north-western corner of the school premises, within 200 m of the tailings dump. The estimated depth of the water table is between 30 and 40 m, but the volume abstracted is unknown. It is estimated between 60 and 100 m^3/day, with abstraction taking place during daylight hours. According to the school's janitor the borehole is placed under strain in order to supply in the high water demand of the school.

The following conditions support this water use as a flag situation with a risk to the City Council:

- The water use may cause the groundwater level to fluctuate daily giving rise to ground instability in the close vicinity. The extent of groundwater level fluctuations in the immediate vicinity is not known
- The borehole is situated within ten metres from the school's double storey buildings.
- Due to the existing borehole equipment and infrastructure it is not possible to monitor the fluctuation of the water table in the direct vicinity of the

borehole.

This borehole is located on confirmed dolomite, in between two areas measured as exhibiting a high sinkhole hazard risk classification (Figure 5-2).

5.3.1.2 *Oranje Mynbou & Vervoer (OMV)*

The gypsum dump reworking industry by Oranje Mynbou & Vervoer (OMV) is located north of the old KGTD and makes use of water supply from groundwater for the industrial process. The main abstraction borehole (borehole TD2011-09 on Figure 4-16) is being pumped at 45 m^3/h (12.5 L/s) for 24h per day and used in the OMV gypsum reclamation process (Muller, 2011). OMV applied for a water use licence from the DWA (Nell, 2011 and Muller, 2011). It is unknown whether a geohydrological investigation accompanied this application to DWA. Such an investigation should have identified the impact of abstraction on the local water table by means of hydraulic (pumping) tests, and take cognisance of the dolomite stability issue. A confirmation of the registered water uses in the area at the end of 2016 from the WARMS database confirmed that no licence has yet been approved.

This borehole too is located on inferred dolomite with a high indicated hazard.

5.3.2 Ingress of water

Water leakages from old infrastructure can be significant, and often go unnoticed making it near impossible to identify. This was indirectly assessed as part of the main risk assessment by taking into account the age of the reticulation infrastructure in various neighbourhoods (see Section 5.1). Areas with old infrastructure were seen as more vulnerable in terms of potential leaks than more modern areas. This was however not reproduced in this dissertation due to the sensitivity of the risk assessment.

Apart from water reticulation in neighbourhoods, the following were flagged:

5.3.2.1 *Leaking reservoirs*

It was mentioned that water was seen leaking out of the Ikageng West reservoirs south of Boitshoko School. This water was then observed to disappear at a geological contact on surface. It is unclear whether there are any water leaks from the bottom of the reservoir straight into the ground, which would pose a greater risk of subsidence with the concentration of water combined with the weight of water.

5.3.2.2 *Seepage from the tailings dump*

The volume of polluted water from the KGTD seeping into the underground dolomitic aquifer is unknown. The volume was estimated at between 150 and 900 m^3/d during the operational phase. After the factory was decommissioned, no new slurry is being added to the dump. The only addition comes from the seepage intercepted in trenches and channelled to the retention (treatment) ponds from where it is pumped back onto the stack without treatment. This volume is unknown.

Since the KGTD was designed in such a way as to limit runoff, it can be assumed that the majority of the rainfall falling on the tailings dump either infiltrates into the gypsum or is lost to evaporation (depending on the intensity and duration of rainfall events). A basic water balance will determine the volume of water entering the KGTD. Although the tailings is steadily being reclaimed by OMV, the size of the KGTD is still at least 20 ha, or 200 000 m^2. Based on the average rainfall calculated for Potchefstroom of 629 mm/a, a total volume of 125 800 m^3 is added to the KGTD as rainfall. Assuming a recharge percentage of 5%, 6 290 m^3 is added to the perched aquifer annually, equivalent to 17.2 m^3 per day on average. Of this, a large portion seeps out into the interception trenches, or bypasses it to seep out next to the KGTD and either evaporates or enters the Spitskopspruit. The volume that might enter the underlying dolomite aquifer as water ingress, is unknown, but is not expected to be as important from a physical erosive perspective as it is from a chemical erosive perspective (see 5.4.1).

5.3.3 Ponding of water

Areas located on the dolomite where ponding of water is likely, were identified in the field and on Google Earth. These areas were marked as blue polygons in Figure 5-2.

The most prominent areas (because of size) are Poortjie Dam, an artificial dam located mostly on dolomite, and the KGTD, a feature designed to prevent runoff of tailings water. Although the Poortjie Dam has been in existence for several decades, the fact that the majority of the dam is located on dolomite creates a sinkhole risk because of the added weight and potential for seepage. Sirino Lake in Basilicata in Italy almost emptied completely after being affected by piping sinkholes (Giampaolo *et al*, 2016).

The KGTD is flagged because it was designed to prevent runoff of rainwater. The layers of fine grained gypsum precipitate acts as a perched aquifer that retains rainwater, adding weight to the dump after significant rainfall events. The KGTD is in the process of being removed and rehabilitated, which should remove the threat within 15 years (Mathibeng, 2016).

Also included as flags are quarries and borrow pits. Several quarries exist in the open area east of OMV between Promosa Road and Chief Albert Luthuli Road between Dassierand and the Potchefstroom landfill site west of Promosa. Illegal dumping of refuse occurs here which also has a quality impact. Another significant excavation exists directly south of Mohadin, right in the middle of the indicated high hazard zone.

Fortunately the quarries and borrow pits identified above are all located outside residential areas, hence would not increase the vulnerability of residents.

5.4 Quality Flags

5.4.1 Kynoch Gypsum Tailings Dump

The biggest source of groundwater pollution, and arguably the biggest threat to dolomite stability identified in the area is the KGTD. The old Kynoch Fertiliser factory was commissioned in 1967 and operated for more than 35 years. The impact of the tailings dump on the surrounding water quality was identified in 1996. In 1999 the factory applied for a waste permit (which was granted) since the dump was classified as a hazardous waste site (AGES, 2005a).

A series of monitoring boreholes were drilled on and off-site to monitor the groundwater quality as part of the licence conditions. Currently OMV are rehabilitating the dump after acquiring the property (with liabilities). OMV continued with the monitoring of the surface and groundwater quality, but not the treatment of the seepage brine.

In the 2001 contamination modelling study undertaken by GeoCon, it was noted that part of the remedial actions recommended to contain and rehabilitate the groundwater pollution around the KGTD were to place strategically positioned boreholes around the dump to abstract the polluted groundwater for treatment. Without the abstraction of the polluted groundwater it was impossible to contain the plume (GeoCon, 2001). This treatment option never materialised as far as could be determined, meaning that the plume has been spreading for at least the past decade.

According to GeoCon (2001), the dump is also a source of radionuclides, and the

National Nuclear Regulator has issued a permit based on certain monitoring conditions. These conditions are not known. It is also not known whether OMV currently includes radionuclides as part of their monitoring framework. However, according to a 2005 water quality monitoring report for Kynoch (AGES, 2005b), the radiological public impact of the tailings dump determined that the potential dose to members of the public was below the regulatory compliance limit. There was however an increase in certain radiological parameters measured in surface water (from Poortjie Dam upstream of the KGTD) and groundwater around the KGTD between 2004 and 2005. The current radiological impact of the KGTD on surface and groundwater has not been assessed.

Photo 5-1: Photo of the reworking of the white gypsum from the tailings dump by OMV.

The effluent seepage sampled in 2011 was found to be highly acidic and contaminated (pH ~1.8). Since the gypsum (mainly $CaSO_4 \cdot 2H_2O$) precipitated out of the slurry, the brine could be considered to be oversaturated in calcium sulphate dehydrate. The underlying dolomite however, having a different chemical composition than gypsum, would be affected by this acidic effluent.

In an in-house experiment, a piece of dolomite was placed into a glass container containing a sample of the tailings effluent, and within minutes the dissolution process could be observed through small bubbles forming as the $CaMg(CO_3)_2$ dissolved. This process lasted for several hours. In effect this means that the underlying dolomite which is already karstified to a great extent (AGES, 2004a) is further being dissolved by the acidic tailings seepage at an unknown rate. If left unattended, the gypsum tailings dump as a reservoir of acid seeping into the underlying dolomite will eventually cause sinkholes to form.

5.4.1.1 Case studies: Florida sinkholes

A sinkhole formed suddenly in June 1994 underneath a gypsum tailings dump in Florida State in the United States (Photo 5-2). The gypsum tailings dump at the New Wales plant then belonged to IMC-Agrico. The sinkhole measured more than 120 m deep below the already 67 m high tailings dump surface, and the width reached a diameter of 32 m at a depth of 18 m below the surface of the tailings dump (Tihansky, 2012, thesinkhole.org, 1994).

Photo 5-2: This sinkhole formed in 1994 inside a gypsum tailings dump at the New Wales Plant outside Mulberry in Florida (from thesinkhole.org, 1994).

More recently a similar sinkhole formed underneath what appears to be the same gypsum tailings facility (Photo 5-3). News reports indicated a sinkhole formed in August 2016 underneath the gypsum tailings dump belonging to the Mosaic company's New Wales Plant (Kennedy, 2016). IMC-Agrico became IMC Phosphates Company in August of 2000, and in 2004 changed its name to Mosaic Phosphates Company (FDEP, 2015).

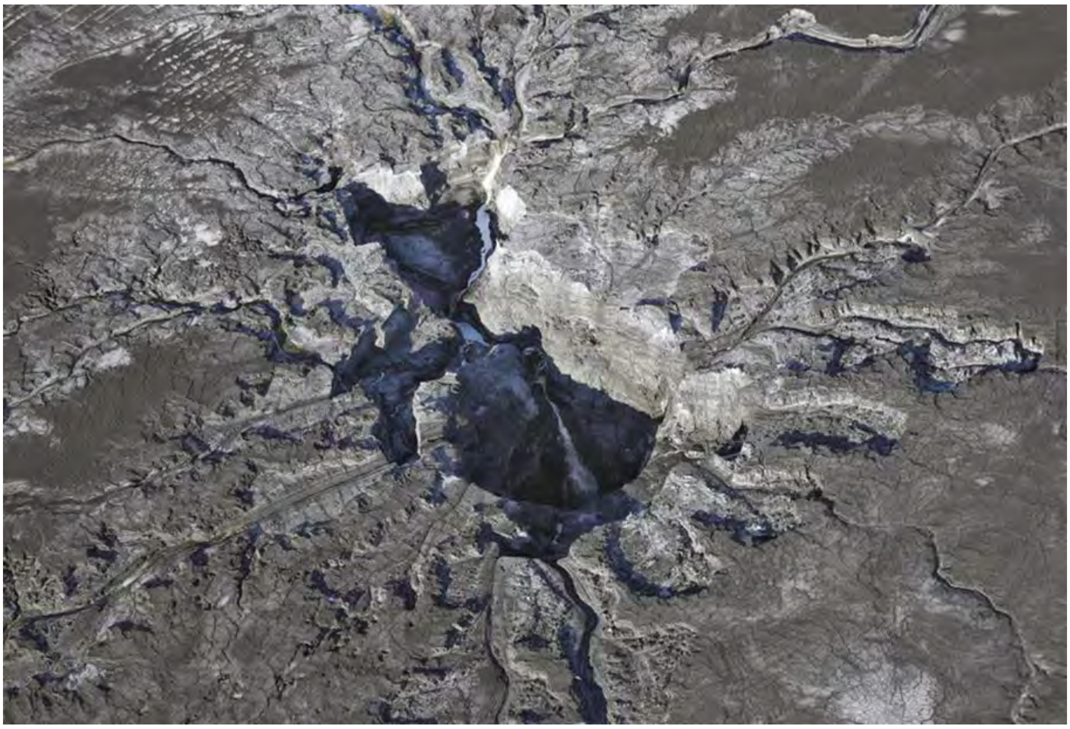

Photo 5-3: The 2016 sinkhole in what appears to be the same tailings facility (O'Meara, 2016).

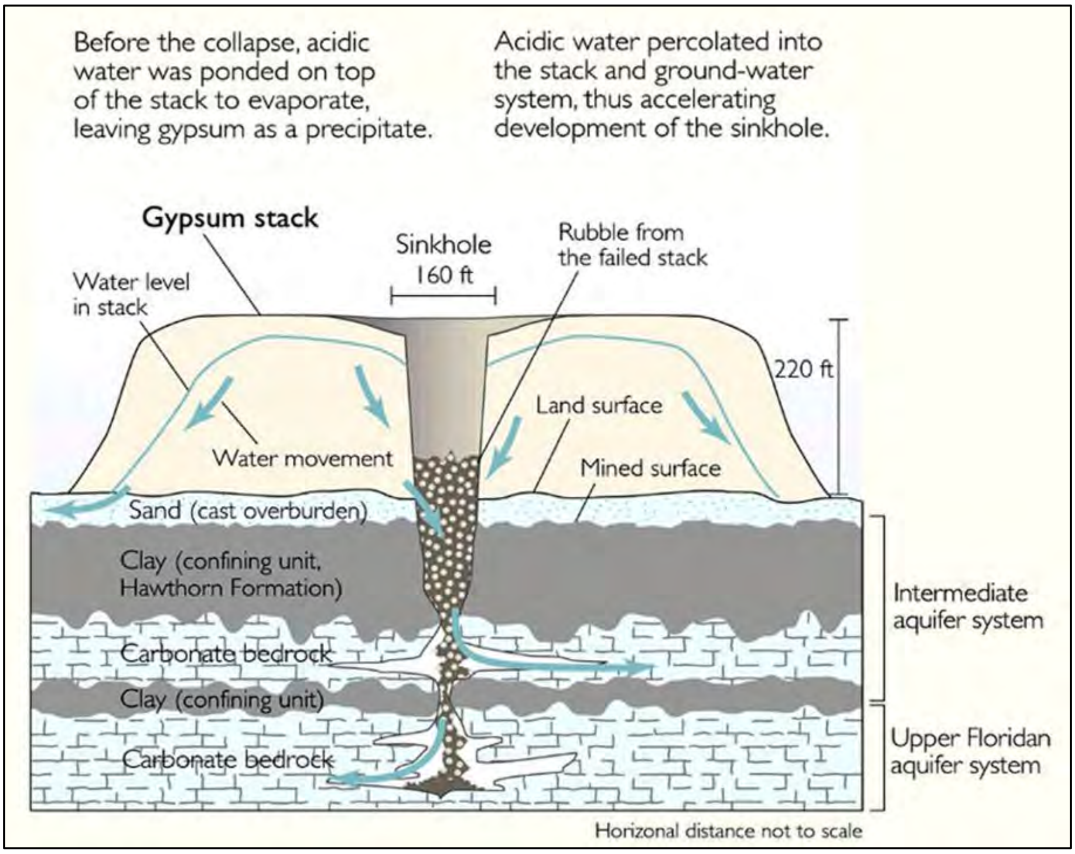

Figure 5-3: Conceptual model of sinkhole formation in gypsum tailings on top of soluble carbonate rocks (from sinkhole.org, 2016).

The overburden sand and clay in that part of Florida sustained a large phosphate mining and processing industry for years. Phospho-gypsum is the waste product of the processing of the phosphate, and is discarded in a similar fashion to South African gold mining slimes dumps. It is a tailings facility that gradually accumulates in height as process water sludge is pumped onto the surface and left to evaporate, leaving finely layered gypsum as a waste product. In America it is referred to as a 'gypsum stack' while in South Africa it is referred to as tailings (or slimes) dump, or even slimes dam.

Most of the older tailings dumps were unlined causing the sludge brine to seep down into the underlying carbonate aquifer. The acidic nature of the sludge brine (pH ~1.5) likely enlarged pre-existing subsurface cavities in the soluble carbonate rock until a critical point was reached and a sinkhole formed (sinkhole.org, 2016).

5.4.2 Old Kynoch factory

The old Kynoch factory is located between Ikageng residential area and Potch Industria. The groundwater pollution from this site was identified and investigated further by several specialists since the middle 1990's. Several point and diffuse pollution sources from the factory site were identified, polluting a shallow and deeper aquifer around the site (GeoCon, 2003).

This factory has been decommissioned in 2006, and no new pollutants are believed to be added to the aquifers. It is unknown to what extent the factory has been cleared of contaminants during the decommissioning process. The extent of the current plume is also unknown but since the factory is located off the dolomite, and on the down-gradient side of the dolomite, it does not pose a risk of increasing sinkhole hazards.

5.4.3 Oranje Mynbou & Vervoer

The OMV site where the gypsum is reworked was also identified as a possible source of groundwater pollution (GeoCon, 2001). This was based on the water quality from one borehole (BH15) northeast of the OMV site, and it was recommended that the groundwater pollution potential from the site be investigated further.

OMV moves the gypsum per truck from the tailings dump over to the reclamation site where it is dumped before being put through the cleaning process. The processing plant itself is a closed system.

The water quality from OMV (process water and groundwater from an on-site borehole) was included in the monitoring work done by AGES (2005b). The site is located on dolomite and should be continually monitored.

6 Conclusions

6.1 Summary

Following large scale sinkhole formation on the FWR as a direct result of mining related dolomite dewatering, groundwater is now known as an important factor affecting the stability of cavernous dolomite. Ikageng was developed partly on dolomitic land before the direct relationship between dolomite, dewatering and sinkhole formation was clearly understood.

The TLM inherited the legal responsibility to ensure the safety of residents in greater Ikageng who are at risk of subsidence and sinkhole formation. The TLM therefore initiated a dolomite risk assessment with the aim of having a dolomite risk management strategy.

The wealth of geotechnical and geophysical data enabled a sinkhole hazard zone map of dolomitic terrain in Ikageng, depicting the risk of sinkhole and subsidence hazards. This map formed the basis of the risk assessment. Geohydrological factors that might be conducive to sinkhole formation were then identified as flags, and overlain on the hazard zone map.

The single biggest threat identified in the area was the KGTD. The Kynoch Fertilizer Factory in Potch-Industria was commissioned in 1967 and the resultant tailings facility was developed two kilometres to the west on dolomitic land. Gypsum precipitated out of a waste slurry for 35 years, leaving a 25 ha reservoir of highly toxic brine that gets remobilised by rainwater. Seepage from the side was measured to have a pH as low as 1.8, which is expected to dissolve the underlying dolomite. Sinkholes already developed on similar gypsum tailings facilities on carbonate rocks in Florida State in the United States of America.

Apart from the potentially corrosive nature of the brine on dolomite, it acts as a pond accumulating rainwater, which has been shown to exacerbate sinkhole formation. The Poortjie Dam to the west is underlain by dolomite and can also be considered a potential hazard flag in terms of water ponding. Similarly several informal quarries and borrow pits located on dolomite were flagged as areas for potential ponding.

Continued seepage of water through weathered overburden into an underlying cavity also has a physically erosive effect that leads to sinkhole formation. It is not clear what the seepage rate from the KGTD or from Poortjie Dam is.

Areas where seepage has been observed, is from the leaking of the Ikageng West reservoirs. Water was observed to disappear into the ground at a geological contact. In residential areas where a concentration of water and sewage reticulation pipes are found, the vulnerability of residents increases because of potential leaks. The age of infrastructure was taken as a measure of vulnerability, assuming more chances of leaks forming in older infrastructure. The infrastructure classification was overlain onto the hazard zone map as part of the main risk assessment study, but was not included in this dissertation because of the sensitive nature of the information.

Because water table fluctuations are an important trigger mechanism, excessive groundwater abstraction was also flagged. The only flags are the abstraction by OMV from boreholes on dolomite to reclaim the gypsum from the KGTD, and the Boitshoko School south east of the KGTD. Although a water use licence application has been lodged by OMV in 2010, nothing has yet been granted by DWS in 2016 (Swanepoel, 2016).

The abstraction of groundwater by OMV, although large in volume, might be condoned (if drawdown are within acceptable limits), since the water is used for the reclamation of the KGTD – a more serious threat to dolomite stability.

6.2 What the future might hold

Recent media reports indicated a renewed interest of mining companies in commodities north of Potchefstroom. Mining and mineral processing inherently requires large volumes of water that must be sourced from somewhere.

It must be ensured that geohydrological impact studies accompanying the main EIA for the mining right application within the Welgegund GMA considered the impact of dewatering on the aquifer surrounding Potchefstroom. Close cooperation between the TLM and the Department of Mineral Resources is recommended where mining right applications within the Welgegund GMA is concerned. Since Water Use License Applications (WULAs) would also be a requirement, the DWS, the Department of Environmental Affairs (DEA) and the TLM will need to be involved in the decision making process.

It is doubtful whether deep level mining operations will occur in the neighbouring Turffontein GMA due to the existence of the Gerhard Minnebron spring in this compartment. Any dewatering activities in this compartment will most certainly cause the spring to dry up. The spring feeds relatively good quality water to the

Boskop and Potchefstroom Dams - the main source of municipal water to the TLM.

The impact of future water quality once mining and pumping ceases on the Far West Rand and the dolomitic aquifer is left to re-water remains a point of contention. Already mining related pollutants (uranium) are increasing in the groundwater emerging from the Gerhard Minnebron eye north of Boskop Dam (Winde, 2010a, b). It is further proposed by some that the mining activities have penetrated the separating dykes sufficiently to compromise their function as geohydrological boundaries. Therefore the individual compartments are now believed to form one big 'mega-compartment'.

The Gerhard Minnebron Eye is topographically the lowest discharge point for this new mega-compartment. Once mining ceases and the mega-compartment is left to re-water, this would form the first point of discharge of groundwater. In theory then the combined flow of all springs that were affected by the dewatering of the separate dolomite compartments can discharge at the Gerhard Minnebron eye north of Potchefstroom. The quality of the future decanting groundwater from the mega-compartment might be highly compromised, and should form the topic of future studies. It is unlikely that the water from the Gerhard Minnebron would impact on the quality of the dolomitic groundwater underlying Ikageng. The main impact would however be on the municipal water supplied by TLM.

Should the quality of water in the Boskop and Potchefstroom Dams as the primary source of water to the TLM be compromised in future, it might cause a future focus on groundwater abstraction from the dolomite. The water in the Boskop Dam shows increasingly elevated concentrations of uranium and other mining related pollutants. Due to the great groundwater potential inherent in dolomite, TLM might consider bulk groundwater abstraction from the Welgegund compartment to augment or replace the existing water supply that must continually be treated to remove the pollutants.

It is important to flag the fact that any potential well fields for bulk groundwater abstraction must be sufficiently far removed from Ikageng to prevent cones of depression from affecting the groundwater table below Ikageng. Detailed geohydrological investigations will be needed. Bulk groundwater abstraction must be so managed to ensure as little drawdown in the regional aquifer as possible to prevent sinkhole formation and subsidence in the immediate area of abstraction.

7 Recommendations

7.1 Flag recommendations

Boitshoko High School

The following actions are recommended:

- The risks of water table fluctuations and groundwater contamination from the dump must be explained to the school management board, and Department of Education must be informed.
- Alternative options for water supply to the school must be investigated and implemented in order to decommission the borehole on the school property.
- The existing borehole must be equipped as monitoring borehole and incorporated in the groundwater monitoring program.

OMV

The following recommendations are made in order to manage the risk related to the groundwater abstraction and contamination:

- According to the NWA (Act 36 of 1998) abstraction of groundwater for industrial processes, and discharge of water containing waste must be licenced by the DWS as separate water uses (South Africa, 1998a). This involves groundwater studies to determine the impact of abstraction on the aquifer, as well as to determine the impact of discharge of water containing waste on the aquifer. As part of the licence application process, the TLM should be/have been consulted as an interested and affected party.
- It must be ascertained whether these studies were conducted and what the outcomes were. Cooperation between OMV, TLM and DWS is important.
- In case of water use licences being issued, care must be taken to adhere to the monitoring protocol as part of the licencing conditions.
- It is recommended to issue the licence, since the water is used in the reclamation process of the KGTD which can be considered a much bigger threat to the stability of the already hazardous dolomite.
- OMV must take care not to redistribute the contamination to their own site in the reclamation process. Proper storm water drainage and other

protective measures must be installed to prevent the gypsum from being soaked by rainwater, and contaminants leaching out into the aquifer.

Ikageng West Reservoirs

- The observed leaks from the Ikageng West Reservoirs located on top of dolomite must be investigated and fixed.
- It is further recommended that monitoring systems be installed in the reservoirs to balance inflow and outflow in order to quantify any unknown losses.

The same can be employed at the Sonderwater Reservoirs.

7.2 Groundwater monitoring

According to the ISP of the Upper Vaal Water Management Area, the current monitoring programme for the WMA is totally inadequate. This inadequacy is blamed on a lack of internal capacity in regional DWS offices (DWAF, 2004).

The hydrology office of DWS located at Potchefstroom monitors surface water flows at monitoring stations in the Mooi River among others, as well as the water levels in several boreholes in the dolomite compartments affected by mine dewatering. These compartments however are located north of the Welgegund GMA and therefore fall outside of the regional area of investigation.

It is therefore recommended that the local DWS office be tasked with initiating and overseeing the monitoring network in Ikageng. This should be done in relationship with the TLM, and can be outsourced to a consultant.

7.3 Monitoring protocol

7.3.1 Parameters

Parameters that need to be monitored are quantity (water level) and quality related.

7.3.1.1 Water levels

The aim is to use excessive water level fluctuations as an early warning system for possible subsidence. A fluctuation of more than five metres will be seen as an early warning sign. Monitoring the correlation between water level fluctuations in different zones can also shed light on the groundwater interaction in the area.

During the course of the greater project, groundwater level monitoring was reinstated after realising its importance as an early warning system for possible sinkhole formation. Some of the original Kynoch characterisation boreholes form part of the monitoring network, while new boreholes that were drilled for dolomite characterisation were also included in the network.

The boreholes were given new numbers which are shown in Figure 4-22. The coordinates of the boreholes are shown in Table 7-1.

It is further recommended to re-drill TMBH01 since this borehole collapsed and is located in an area to the north of OMV and the KGTD where it is not expected to be influenced by any abstraction. Any regional fluctuations in the water table is therefore expected to be evident in this borehole.

TMBH14 that is deemed to have collapsed can be replaced by the borehole at Boitshoko High School, should the school be able to successfully connect municipal water supply.

Borehole KBH9 must get a new lock and key.

Table 7-1: Monitoring borehole coordinates.

Monitoring borehole	Latitude	Longitude
TMBH01	-26,68355	27,04791
TMBH02	-26,69719	27,04688
TMBH03	-26,71571	27,05327
TMBH04	-26,72114	27,05171
TMBH05	-26,71556	27,03461
TMBH06	-26,73732	27,02168
TMBH07	-26,74062	27,02839
TMBH08	-26,73104	27,04646
TMBH09	-26,70491	27,05027
TMBH10	-26,71074	27,04304
TMBH11	-26,70989	27,04539
TMBH12	-26,70860	27,04551
TMBH13	-26,70783	27,04941
TMBH14	-26,71581	27,04620
TMBH15	-26,71508	27,05013
TMBH16	-26,71192	27,04959
TMBH17	-26,70198	27,04057
TMBH18	-26,72262	27,04430
Artesian	-26,70926	27,05609
KBH13	-26,70976	27,06439
KBH15	-26,70019	27,04459
KBH9	-26,71038	27,04189

7.3.1.1 *Water quality*

The migration of the pollution plume from the KGTD is important to monitor. Especially since the dump is in the process of being rehabilitated. OMV does water sampling as part of the waste licence agreement, but there exists doubt as to the quality of the sampling protocol and therefore results. Boreholes are sampled according to old monitoring borehole numbers, but are not marked in the field (borehole numbering plates were stolen). No coordinates could be provided of each borehole, or the surface water sample locations.

The sampling depth of each borehole is also unknown and it is expected that cleaner water near the surface of the water column are sampled instead of pollution that might exist or migrate deeper down in the water column.

An in-depth audit of the sampling protocol employed by OMV is recommended, as well as the outsourcing of the sampling responsibility (which includes an annual interpretation report) to an independent geohydrological consultant. It is important to adhere to sampling guidelines as set out in Weaver *et al* (2007).

7.3.2 Sampling protocol

Water quality monitoring boreholes must be EC-profiled to ascertain the depth of the water strike. Each borehole must be sampled at the depth of the water strike with a flow-through bailer.

Water must be analysed at a SANAS accredited laboratory for a full spectrum of chemical parameters in order to determine what parameters should form part of the monitoring protocol. This should include potential radiological parameters.

7.3.3 Frequency

Water levels in the monitoring network should preferably be monitored on a monthly basis and data correlated with rainfall events as measured at the Potchefstroom meteorological station. Continuous rainfall data from the Potchefstroom weather station must be obtained to compare with water level fluctuations.

Water quality is currently being monitored by OMV on a quarterly basis. The frequency should suffice but must be compared to the protocol suggested as minimum requirements by DWS (DWAF, 1998a, c) for the monitoring at hazardous waste facilities.

7.3.4 Results interpretation

Since OMV is solely responsible for quality monitoring as required by licence conditions, it is doubtful whether the results are interpreted.

It is important that the laboratory results be interpreted independently by a qualified and experienced person and annual monitoring reports be drawn up and communicated to the affected parties, which might include DWS, TLM and OMV.

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