

**Advances in dolomite land risk assessment for safe
development within the current legislative framework: the
case of Khutsong North in Merafong City, Gauteng
Province, South Africa**

By

Sifiso Obert Ngubelanga

Dissertation submitted in fulfilment of the requirements for the degree,

M.Sc. in Engineering Geology

Faculty of Natural and Agricultural Sciences

University of Pretoria

Supervisor: Prof. JL van Rooy

January 2023

ABSTRACT

At least 45% of the Merafong City Local Municipality (MCLM) is underlain by dolomite of the Malmani Sub-Group, Chuniespoort Group of the Transvaal Supergroup. The current research area, Khutsong North Townships (KNT's), is directly underlain by chert-rich dolomite of the Monte Christo Formation and is considered to be 100% dolomite land. Such terrain has a notorious reputation in South Africa due to its susceptibility to the formation of ground instability events, and thousands of people currently reside and work on such land.

In the past, an uncontrolled land use was common in building practice and this led to the development of geologically unsuitable land, i.e. dolomite land. The current South African National Standard (SANS) 1936:2012 – a deemed-to-satisfy standard, requires that geotechnical and/ or dolomite stability investigations be conducted on all dolomite land earmarked for development and that, appropriate precautionary measures be implemented to ensure safe and sustainable land use. However, Khutsong North was established around 1957 and no legislated requirements for conducting geotechnical studies were available at the time.

This research aims to assess scientific advances made over time and influence of dolomite land risk assessment for safe development within the current building legislative framework. Various classification systems/ methods aimed at evaluating the stability of dolomite sites in South Africa have been proposed since the 1970's. As such, a number of dolomite land risk assessment (geotechnical) studies have been conducted across the research area since 1980.

A total of 219 ground instability (sinkhole & subsidence) events have been recorded in KNT's between 1975 and year-2020. No lives are reported to have been lost during this period, but several houses are either damaged or have been completely destroyed by this phenomena and wet services network is critically affected. Therefore, the accepted method for dolomite land hazard and risk assessment – "Method of Scenario Supposition" described by Buttrick et al (2001) and existing data (borehole, events and erven size distribution) were used to calculate hazard rating, compile vulnerability and risk map of the KNT's.

In line with the objectives of this research, historic site zoning (from 1997 & 2013 studies) and scientific advances in determining the Inherent Hazard Class (IHC) were used to investigate possible influence, (1) on the extent of allowable development over time since Buttrick et al (2001) and later promulgation of SANS 1936:2012, and (2) of the current building legislation in ensuring that a tolerable hazard rating is achieved in Khutsong North.

However, compliance with SANS 1936 technical requirements have not been fully enforced in the research area including non-implementation of the Dolomite Risk Management Strategy (DRMS). Furthermore, the relevant authority has not replaced the broken wet services with those that are SANS 1936 compliant.

DECLARATION

I, SIFISO OBERT NGUBELANGA declare that the thesis is my own work and it is hereby submitted for the degree, Master of Science in Engineering and Environmental Geology at the University of Pretoria. In my knowledge, it has not been submitted before for any degree or examination to any other tertiary institution.

Signature:.....

Date:.....

ACKNOWLEDGEMENTS

I would like to thank the following:

- First and foremost, I would like to thank God the almighty, for it is by his grace that I had strength to embark on this research and able to present this theses.
- I am deeply indebted to my supervisor, Prof JL van Rooy from the University of Pretoria, who tirelessly went through various editing and always offered guiding comments during this research including the write-up of the thesis.
- Special thanks are also due to Council for Geoscience (CGS) for granting me permission to undertake the research as well as its management and technical staff for their valuable input and assistance during this research.
- I feel honoured to have been mentored by Mr Isak Venter during his days at CGS and whom I still interact with from time to time. He shaped my thinking particularly on broader issues pertaining to problem soils in South Africa including safe development of dolomite land and. It is my hope that this study adds value to the engineering geology fraternity and the building practice, and that it triggers a conversation on the current building regulations in so far as these relates to the impact of geological hazards.
- Last but not least, my wife Khanyisile and our children (Aphile, Bayanda and Zamanhleko) for being tolerant and patient with me, especially while my mind was focused on this research.

TERMINOLOGY

(As defined in SANS 1936:2012 Part 1 to 4)

Competent Person: A person who is qualified by virtue of his experience, qualifications, training and in-depth contextual knowledge of development on dolomite land to:

- a. Plan and conduct geotechnical site investigations for the development of dolomite land, evaluate factual data, develop a geological model, derive interpretative data and formulate an opinion relating to the outcomes of such investigations;
- b. Develop and inspect for compliance the necessary precautionary measures required on dolomite land to enable safe and sustainable developments to take place;
- c. Develop dolomite risk management strategies; or
- d. Investigate the cause of an event and participate in the development of the remedial measures required

Dolomite area designation: classification of dolomite areas in terms of the extent of mitigation required to achieve and maintain a tolerable hazard.

Dolomite land: land underlain by dolomite or limestone residuum or bedrock (or both), within the Malmani and Campbell Rand Subgroup, typically at depths of no more than:

- a. **60 m** in areas where no de-watering has taken place and the local authority has jurisdiction, is monitoring and has control over the groundwater levels in the areas under consideration; or
- b. **100 m** in areas where de-watering has taken place or where the local authority has no jurisdiction or control over groundwater levels

Dolomite residuum: weathering product derived from the weathering and decomposition of dolomite.

Dolomite Risk Management Strategy: process of using scientific, planning, engineering and social processes, procedures and measures to manage an environmental hazard, and encompasses policies and procedures set in place to reduce the likelihood of sinkholes and subsidences occurring on dolomite land.

Event: occurrence of a sinkhole or subsidence on dolomite land. *In the context of this study the term 'event' also include ground cracks and maybe used interchangeably with the phrase 'ground instability event(s)'.*

Geo-professional: practitioner of geotechnical engineering or engineering geology who is registered in any category of registration provided for in the relevant national legislation.

Hazard: source of potential harm (a hazard can be a risk source, i.e. an element which alone or in combination has the intrinsic potential to give rise to risk).

Hazard rating: number of events that can potentially occur per hectare over a 20-year period.

Inherent Hazard: potential for an event (sinkhole or subsidence) to develop in a particular ground profile on dolomite land.

Inherent Hazard Class (IHC): classification system whereby a site is characterized in terms of eight standard inherent hazard classes, denoting the likelihood of an event (sinkhole or subsidence) occurring, as well as its predicted size (diameter).

Original groundwater level (OWL): mean groundwater level in the dolomite water aquifer, expressed as a depth below natural ground level or elevation above mean sea level (or both), about which the seasonal fluctuation occurs.

Return period: effect recurrence interval – estimate of the average interval of time between events of a certain size.

Risk: effect of uncertainty on objectives (risk is often expressed in terms of a combination of the consequences of an event and the associated likelihood of occurrence).

Sinkhole: feature that occurs suddenly and manifests itself as a hole in the ground.

Subsidence: shallow, enclosed depression.

Tolerable hazard: where the number of events experienced is less than 0.1 event per hectare per 20 years (preferably tending to 0 per hectare), i.e. a return period of an event occurring on 1 ha of more than 200 years.

TABLE OF CONTENTS

CHAPTER 1 – INTRODUCTION.....	1
1.1 BACKGROUND.....	1
1.2 PROBLEM STATEMENT	4
1.3 RESEARCH OBJECTIVES AND SCOPE.....	5
1.4 RESEARCH AREA.....	5
1.5 AVAILABLE DATA	9
CHAPTER 2 – LITERATURE REVIEW	12
2.1 KARST DEVELOPMENT	12
2.1.1 Dolomite within the Transvaal Basin	12
2.1.2 Weathering of dolomite	14
2.1.3 Mechanism of sinkhole and subsidence formation	15
2.2 GEOLOGY AND HYDROLOGY	20
2.2.1 Regional geology	20
2.2.2 Geology of Khutsong North Townships	21
2.2.3 Regional hydrology	24
2.3 DOLOMITE LAND CLASSIFICATION SYSTEMS	27
2.4 APPLICABLE LEGISLATION	30
2.4.1 The South African building legislation and the regulatory process.....	30
2.4.2 Land use regulation on karst terrains in the United States	33
CHAPTER 3 – DATA GATHERING AND RESEARCH METHODOLOGY	35
3.1 PRE-FIELDWORK PHASE (DESKTOP STUDY)	35
3.2 FIELDWORK PHASE.....	38
3.3 POST-FIELDWORK PHASE	40
CHAPTER 4 – DATA ANALYSIS AND INTERPRETATION	42
4.1 PERCUSSION BOREHOLE DATABASE	42
4.2 DEPTH TO DOLOMITE BEDROCK	45
4.3 EVENTS (SINKHOLE & SUBSIDENCE) DATABASE.....	49
4.3.1 Type and statistical analysis of events occurring in Khutsong North.....	51
4.3.2 Quality of events database.....	53

4.3.3	Consequence of events occurring in Khutsong North.....	56
4.3.4	Event size distribution	62
4.4	DEPTH TO DOLOMITE BEDROCK COMPARED AGAINST EVENT SIZE.....	65
CHAPTER 5 – CASE STUDY: A DESK TOP STUDY AND SINKHOLE HAZARD DETERMINATION FOR KHUTSONG NORTH TOWNSHIPS.....		68
5.1	BACKGROUND.....	68
5.2	GEOLOGICAL SETTING	69
5.3	HYDROLOGICAL SETTING	70
5.4	HAZARD CLASSIFICATION AND OCCURRENCE OF EVENTS.....	73
5.4.1	Hazard classification and zoning	73
5.4.2	Calculating events per hectare.....	76
5.4.4	Hazard rating of KNT's compared to that of Centurion CBD	81
CHAPTER 6 – KHUTSONG NORTH DOLOMITE RISK ASSESSMENT.....		82
6.1	BACKGROUND ON RISK ASSESSMENT PRINCIPLES	82
6.2	HAZARD ZONATION AND HAZARD RATING MAP OF KHUTSONG NORTH.....	83
6.2.1	Hazard Zonation Map – Intraconsult (1997)	83
6.2.2	Hazard Zonation Map – VGIconsult (2013)	86
6.2.3	Hazard Rating Map	89
6.3	VULNERABILITY MAP OF KHUTSONG NORTH	91
6.4	DOLOMITE RISK MAP OF KHUTSONG NORTH	94
6.5	COMPARISON BETWEEN THE 1997 AND 2013 STABILITY ASSESSMENTS ...	96
CHAPTER 7 – CONCLUSION.....		97
CHAPTER 8 – RECOMMENDATIONS AND FUTURE RESEARCH		99
REFERENCES.		101
APPENDICES		

LIST OF FIGURES

Figure 1: Shows only Khutsong Proper existed in 1985 (Google Earth Images, 2022).....	2
Figure 2: Shows great spatial expansion and densification since 1985 (Google Earth Images, 2022).....	2
Figure 3: Shows the newly constructed Khutsong 30ML reservoir (Google Earth Images, 2022).	3
Figure 4: Locality Map.	7
Figure 5: Khutsong North Townships and surrounding informal settlements.	8
Figure 6: Dolomite Stability Reports boundaries and CGS ENGEODE file numbers, Khutsong North.....	10
Figure 7: Percussion boreholes and sinkhole positions, Khutsong North.	11
Figure 8: Distribution of the Malmani Subgroup dolomites within the Transvaal Basin (modified from CGS Map, 2013)	13
Figure 9: A conceptual cross-section through a typical dolomite profile in South Africa (modified from SANS 1936-1, 2012).	14
Figure 10: Diagram depicting the mechanism of sinkhole and subsidence formation in an ingress scenario (Modified from CGS drawings, 2008).....	16
Figure 11: Recently collapsed arch forming a small sinkhole (Photo from CGS Database). ..	17
Figure 12: A typical cross-section through a small sinkhole.	18
Figure 13: Recent caving of the ground surface forming a subsidence (Photo from CGS Database).	18
Figure 14: A typical cross-section through a compaction subsidence.	19
Figure 15: Map showing depth to dolomite bedrock head below ground surface, Khutsong North.....	22
Figure 16: Extract from a published 1:250 000 (2626 West Rand, 1986) Geological Map showing the position of the research area within Merafong LM.....	23
Figure 17: Dolomite Groundwater Compartments of the FWR region (modified from Brink, 1979).	26
Figure 18: Summary of the current building legislation and regulatory process.	32
Figure 19: Examples of the available reports used during this research.	36
Figure 20: An example of available newspaper articles.....	37
Figure 21: Extract from a published 1:50 000 (2627 AD Carletonville, 2006) Topographic Map.....	38
Figure 22: A very large sinkhole (>15m diameter) at Nxumalo Road, Khutsong Proper.....	39
Figure 23: Blocked and back-ponding sewage effluent flowing into open field and sinkholes.	39

Figure 24: An example of the data sets compiled on a GIS (ArcMap®) database.	41
Figure 25: Spatial distribution of the available borehole data, Khutsong North.	43
Figure 26: Showing the number of boreholes drilled per township.	44
Figure 27: Showing the percentage of boreholes per townships.	44
Figure 28: Boreholes with confirmed and unconfirmed bedrock in each of the zones.....	46
Figure 29: Showing the percentage of confirmed depth to dolomite bedrock in each zone.	47
Figure 30: Spatial representation of depth to dolomite bedrock head, Khutsong North.	48
Figure 31: Spatial distribution of the available events record, Khutsong North.....	50
Figure 32: Showing the percentage distribution of events per township, Khutsong North. ...	52
Figure 33: Showing the percentage distribution of events type, Khutsong North.	52
Figure 34: Showing the percentage distribution of events per cause, Khutsong North.	53
Figure 35: Yearly occurrence of ground instability events with 1995 records, Khutsong North.....	54
Figure 36: Yearly occurrence of ground instability events without 1995 records, Khutsong North.....	55
Figure 37: A very large sinkhole causing damage to main Nxumalo Road, Khutsong Proper.	56
Figure 38: Trail of destruction to housing at Adatite Street, Khutsong Proper.	57
Figure 39: A subsidence forming against the house casing a severe wall distress, Khutsong Extension 3.	58
Figure 40: Sewage damming against the wall, Khutsong Extension 3.....	58
Figure 41: An example of a media article reporting on the Khutsong sinkhole situation.	59
Figure 42: Damage to a bulk water supply pipeline, Carletonville area.	60
Figure 43: Brocken, blocked and back ponding sewer line at Adatite Street, Khutsong Proper.	61
Figure 44: A decommissioned Khutsong Main Reservoir, border of Khutsong Extension 3 and 6.	61
Figure 45: Showing events distribution per size category, Khutsong North.	64
Figure 46: Showing percentage distribution of events per size category, Khutsong North...	64
Figure 47: Depth to dolomite bedrock compared to events distribution, Khutsong North.	67
Figure 48: Position of the Khutsong North within the Malmani Subgroup Formations in the FWR region (after Wolmarans, 1984 modified by Winde and Erasmus, 2011).	70
Figure 49: Geohydrological section through dolomite compartments of the FWR (after Brink, 1979 modified by Winde and Erasmus, 2011).....	72
Figure 50: Percentage of percussion boreholes in each of the inherent hazard category. ...	74

Figure 51: The distribution of the available percussion boreholes and inherent hazard category.	75
Figure 52: Hazard Zonation Map of Khutsong North, after Intraconsult (1997).	85
Figure 53: Hazard Zonation Map of Khutsong North, after VGIconsult (2013).	88
Figure 54: A generalized hazard rating map of the formal townships, Khutsong North.	90
Figure 55: Regional vulnerability map with erven sizes and event positions, Khutsong North.	92
Figure 56: Regional risk map based on the hazard rating, Khutsong North.	95

LIST OF TABLES

Table 1: Summary of the Malmani Subgroup (modified after Johnson <i>et al</i> , 2006).....	20
Table 2: Inherent hazard category and anticipated events per hectare in 20-years.....	28
Table 3: Inherent hazard class and specified-size event (after Buttrick <i>et al</i> , 2001).	28
Table 4: Summary of the available boreholes drilled across the research area.....	42
Table 5: Available borehole records and their depth dolomite bedrock.....	46
Table 6: Summary of the available record of events occurring in KNT's.....	49
Table 7: Suggested scale of sinkhole sizes (Buttrick <i>et al</i> , 2001).....	63
Table 8: Depth to bedrock depth compared against known event sizes.	65
Table 9: Summary of ingress and dewatering scenarios.	71
Table 10: Inherent hazard category and the number percussion boreholes.....	73
Table 11: The available number of events and percentage recorded per size category.	76
Table 12: Inherent hazard category and the number of ground instability events.	77
Table 13: Inherent hazard category and the ground instability events statistics.	78
Table 14: Actual number of events per hectare over a 20-years period in Khutsong North..	79
Table 15: Dolomite stability zones and appropriate development, after Intraconsult (1997).	84
Table 16: Dolomite Hazard Zones and their description, after VGIconsult (2013).....	87
Table 17: The distribution and interpretation of events over a 20-year period.	89

LIST OF ACRONYMS

BTC	–	Boskop-Turffontein Compartment
CADMO	–	Carbonate Area District Model Ordinance
CGS	–	Council for Geoscience
DMA	–	Disaster Management Act
DRMS	–	Dolomite Risk Management Strategy
FWR	–	Far West Rand
GIS	–	Geographic Information Systems
GW	–	Groundwater
GWC	–	Groundwater Compartment
KNT's	–	Khutsong North Townships
KRPC	–	Karst Resource Planning Committee
IHC	–	Inherent Hazard Class
MCLM	–	Merafong City Local Municipality
MDRMC	–	Merafong Dolomite Risk Management Committee
NDHS	–	National Department of Human Settlement
NDMC	–	National Disaster Management Centre
NHBRC	–	National Home Builders Registration Council
RDSPF	–	Regional Dolomite Strategic Planning Framework
SANS	–	South African National Standard
SFDRR	–	Sendai Framework for Disaster Risk Reduction
UNISDR	–	United Nations International Strategy for Disaster Reduction
WRDM	–	West Rand District Municipality

CHAPTER 1 – INTRODUCTION

1.1 BACKGROUND

In South Africa, the term “Dolomite Land” has a negative connotation due to its association with damaging effects of sinkholes and subsidences as described in Bezuidenhout and Enslin (1969), Jennings *et al* (1965), Jennings (1966a), Brink (1979), Buttrick *et al*, 2001) and Buttrick *et al*, 2011).. Buttrick *et al* (2011) indicated that at least four to five million people in South Africa reside or work on dolomite land. According to the available information from the Council for Geoscience’s (CGS) ENGEODE Database, at least 45% of Merafong City Local Municipality (MCLM) is underlain by dolomite of the Malmani Sub-Group, Chuniespoort Group of the Transvaal Supergroup and the Khutsong North Townships (KNT’s) are entirely on an area considered to be dolomite land.

The current South African National Standard (SANS) 1936:2012 requires that geotechnical and/or dolomite stability investigations be conducted on all dolomite land earmarked for development and that, appropriate precautionary measures be implemented to ensure safe and sustainable land use. However, the current KNT’s area was established over 60 years ago (around 1956) when no legislated requirements or deemed-to-satisfy rules for conducting geotechnical studies were in place at the time.

Available records show that the first geotechnical study was conducted in Khutsong North during 1980 and most of the associated Dolomite Stability Reports (DSR’s) are on record at the CGS ENGEODE Database. From the available DSR’s produced over the last 40 years, it is apparent that hazardous conditions, deemed not suitable for residential development, exist across the region of KNT’s.

However, the MCLM has continued to approve building projects in KNT’s without strictly enforcing the SANS 1936:2012 requirements. Therefore, a steady spatial densification at KNT’s has taken place since the first house was constructed over 60 years ago and that directly translates into an increased number of people per hectare and higher density of wet services network in the area. Google Earth images, Figure 1 to 3 were used to illustrate spatial change across Khutsong North over time.



Figure 1: Shows only Khutsong Proper existed in 1985 (Google Erath Images, 2022).

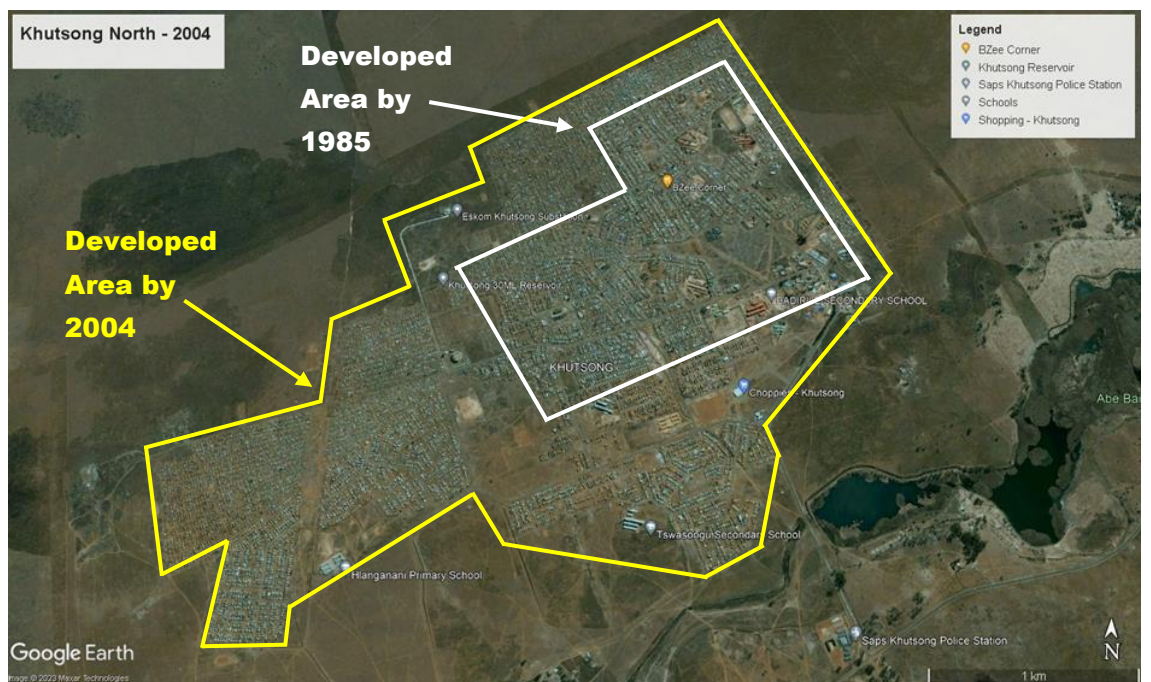


Figure 2: Shows great spatial expansion and densification since 1985 (Google Erath Images, 2022).

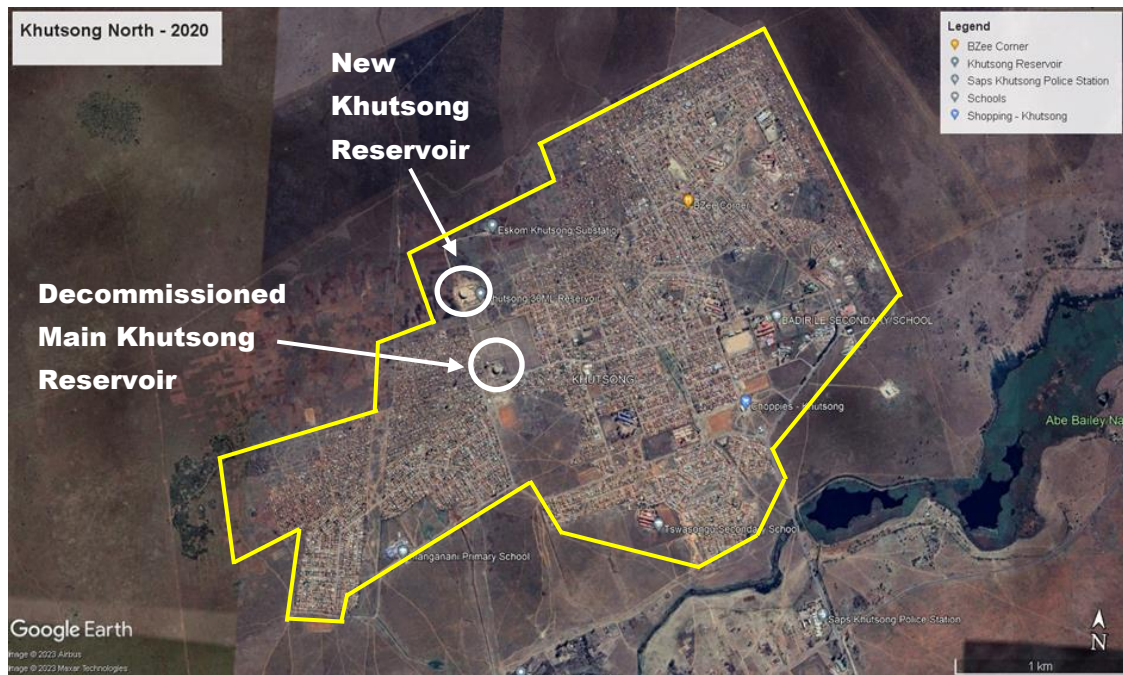


Figure 3: Shows the newly constructed Khutsong 30ML reservoir (Google Erath Images, 2022).

Figure 2 and 3 therefore depict a very limited spatial expansion, if any, between 2004 and 2020. However, spatial densification has continued post the implementation of SANS 1936 in 2012. Considering the distribution of ground instability events as observed from existing records, concentrated within the built-up areas, it is prudent to assume therefore that the spatial densification has had a direct impact on the region's vulnerability to the identified dolomite land hazards, as well as the hazard rating of the KNTs.

To date, numerous sinkholes and subsidences have occurred within the research area causing widespread damage to houses and most notably, the destruction of wet services infrastructure.

In order to guide safe development of dolomite land, areas where a high inherent hazard of ground instability events exists need to be identified, assessed and appropriately managed. Sinkhole and subsidence events affect the positioning, design, maintenance and sustainability of infrastructure. An advanced understanding of these karst systems therefore becomes necessary (Dippenaar *et al*, 2018). This is primarily to monitor, control and regulate urbanization of dolomite land or development on karst terrains. An adequate amount of relevant information (boreholes, some gravity maps and sinkhole

records) is available from the CGS ENGEODE Database to at least attempt a first order dolomite land risk assessment for KNT's.

In addition to that, various classification systems have been proposed since the 1970's in an attempt to evaluate dolomite land and determine the associated inherent hazard class (IHC) or dolomite risk in South Africa (Van Rooy, 1996). A performance based method currently used to ensure safe development of dolomite land in South Africa was originally developed by Buttrick during 1992 and is described in Buttrick and Van Schalkwyk (1995). However, omissions in this method were identified by Buttrick and van Schalkwyk (1998) and the necessary adjustments were later described in Buttrick *et al* (2001). Coetzee and Van Niekerk (2013) further proposed a new method which strives to bridge the gap between the existing scientific knowledge and the applicable legislation.

Therefore, it is clear that significant advances in evaluating dolomite land have been made over the past thirty years. However, it is unfortunate that the application of legislated technical requirements for dolomite risk assessments and its influence at the apex of decision making remains minimal under the current legislative framework.

1.2 PROBLEM STATEMENT

The area of Khutsong North Townships (KNT's) has experienced a steady increase in the rate of ground instability events and / or their destructive effects, between 2000 and 2020. These events resulted in widespread damage to dwelling houses and most notably, the destruction of wet services infrastructure.

This study addresses the following research questions:

- How has the enforcement of dolomite stability investigations, use of historic site zonation and available ground instability event records improved land use planning?
- How has the classification of dolomite land changed over time and to what extent has the advances in determining the IHC or risk influenced the decisions on permissible land use?
- Is the legislative framework supportive of implementing available scientific and technical information, specifically pertaining to geohazards, e.g. sinkholes on dolomite land?

1.3 RESEARCH OBJECTIVES AND SCOPE

The aim of this research project is to understand the geological hazard related to dolomite ground instability events affecting the area of Khutsong North within the broader context of risk management on dolomite land. This study has the following main objectives:

- To develop a better understanding of the geological model of Khutsong North in relation to the occurrence of sinkholes and subsidences, i.e. compile events database and undertake a literature review (classification systems & applicable legislation)
- To review the advances made in dolomite risk assessment and hazard determination over time using KNT's as benchmark
- To use the available ground instability events record over the last 45 years (1975 to 2020), the rate of instability events, size distribution and depth to solid dolomite bedrock to quantify vulnerability of the study area to the identified hazard. Also take into consideration the external influences such as drainage and leaking wet services infrastructure
- Make recommendations regarding the suitability of land usage (i.e. erven sizes) in KNT's based on the hazard rating for sinkhole and subsidence formation, in line with the requirements as stipulated in the SANS 1936-1:2012
- To add to the current body of knowledge on sinkholes and subsidences occurring in the Greater Khutsong Area (GKA), which include the KNT's

1.4 RESEARCH AREA

The Greater Khutsong Townships are located approximately 12 km by road north-west of the town of Carletonville, in Merafong City Local Municipality, West Rand District Municipality, Gauteng Province, South Africa. The development and densification of the KNT's is not only limited to formal housing and structures, but also include all informal settlements located on the north-eastern and northern boundaries (Figure 4).

Khutsong North is bounded by the Abe Bailey Provincial Nature Reserve in the north, R500 Road in the east and the Wonderfontein Spruit in the South. The research area as delineated in Figure 5, will collectively be referred to as the Khutsong North Townships

(KNT's), i.e. Khutsong Proper, Khutsong North Extensions 1 to 6 and the immediate surroundings including the informal settlements.

The research area as described above covers a surface area of approximately **1 318 hectares**, but the current build-up area is approximately **501 hectares** in extent. The site is characterized by a flat to gently sloping topography, sloping towards the Wonderfontein Spruit in the South. The surface elevation of the area varies between 1493 metres above mean sea level (mamsl) in the eastern corner, to 1468 mamsl in the south western corner.

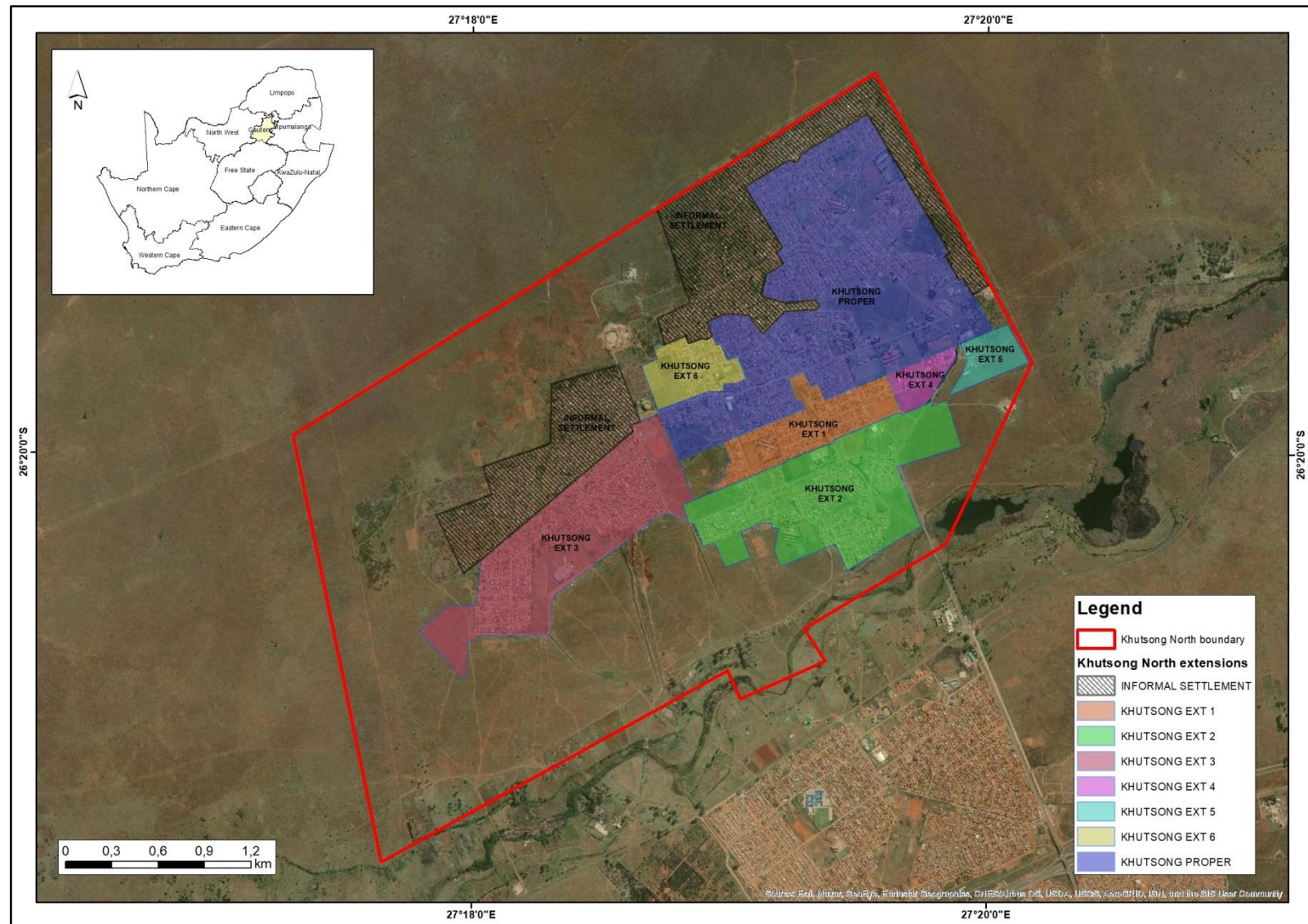


Figure 5: Khutsong North Townships and surrounding informal settlements.

1.5 AVAILABLE DATA

The following data are available and were used in this research:

- ***Dolomite Stability Reports (DSR's):*** - Reports falling within the delineated research area were extracted from the CGS National Dolomite Databank. Their report boundaries have been plotted on the CGS ENGEODE Database and comprise a total of 30 DSR's (Figure 6) with a list of the available reports attached in Appendix A
- ***Percussion Boreholes:*** - These were drilled as part of the dolomite stability investigations which forms the basis of the DSR's. A total of 313 percussion boreholes (Figure 7) have been drilled across the study area. A list of all the boreholes in the Khutsong North is provided in Appendix B
- ***Gravity Survey:*** - These surveys are also conducted as part of the dolomite stability investigations and are critical in positioning the percussion boreholes. The only reasonable, available and most recent gravity map was obtained from a report, Report No. VGI3606 dated October 2013 and this survey was conducted on a 42m grid. However, this map covers 2 (Khutsong Proper & Khutsong Extension 6) of the 7 formal Khutsong North Extensions, as such not used in this research

Also, various other project specific gravity surveys were conducted at different scale within the research area making it difficult to use for the current regional study

- ***Sinkhole Database:*** - The ground instability events data originate from various sources, i.e. MCLM, consulting Geo-professionals, literature, etc. A consolidated record of these events is currently kept at the CGS ENGEODE Database and a list of all the available records occurring within the Khutsong North is provided in Appendix C. The recorded 219 ground instability events are shown on Figure 7
- 1:250 000-scale Geological Map, 2626 West Rand (1986)
- Google Earth Imagery, © 2021 AfriGIS (Pty) Ltd
- 1:50 000-scale Topographical Map, 2627AD Carletonville (2006)

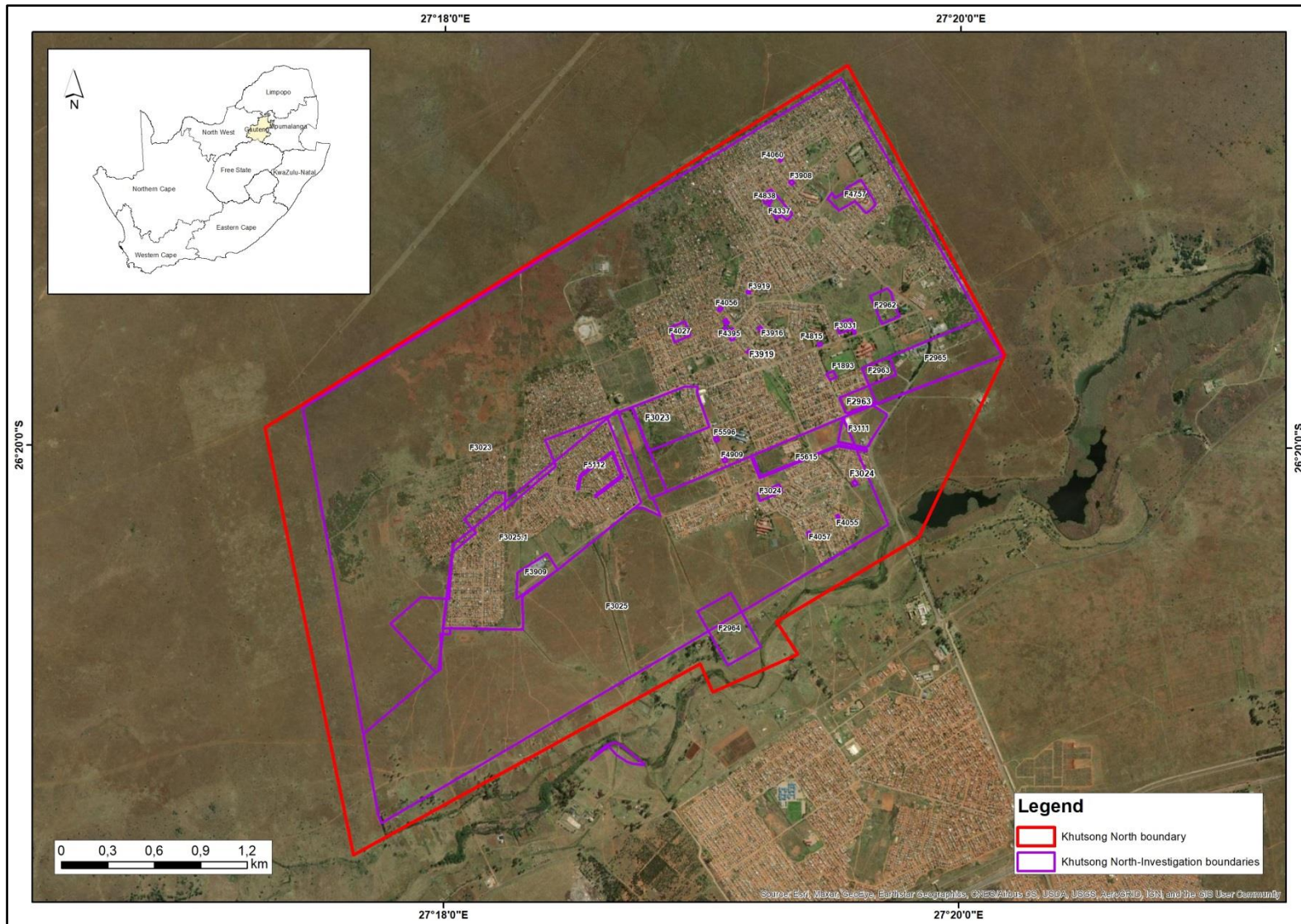


Figure 6: Dolomite Stability Reports boundaries and CGS ENGEODE file numbers, Khutsong North.

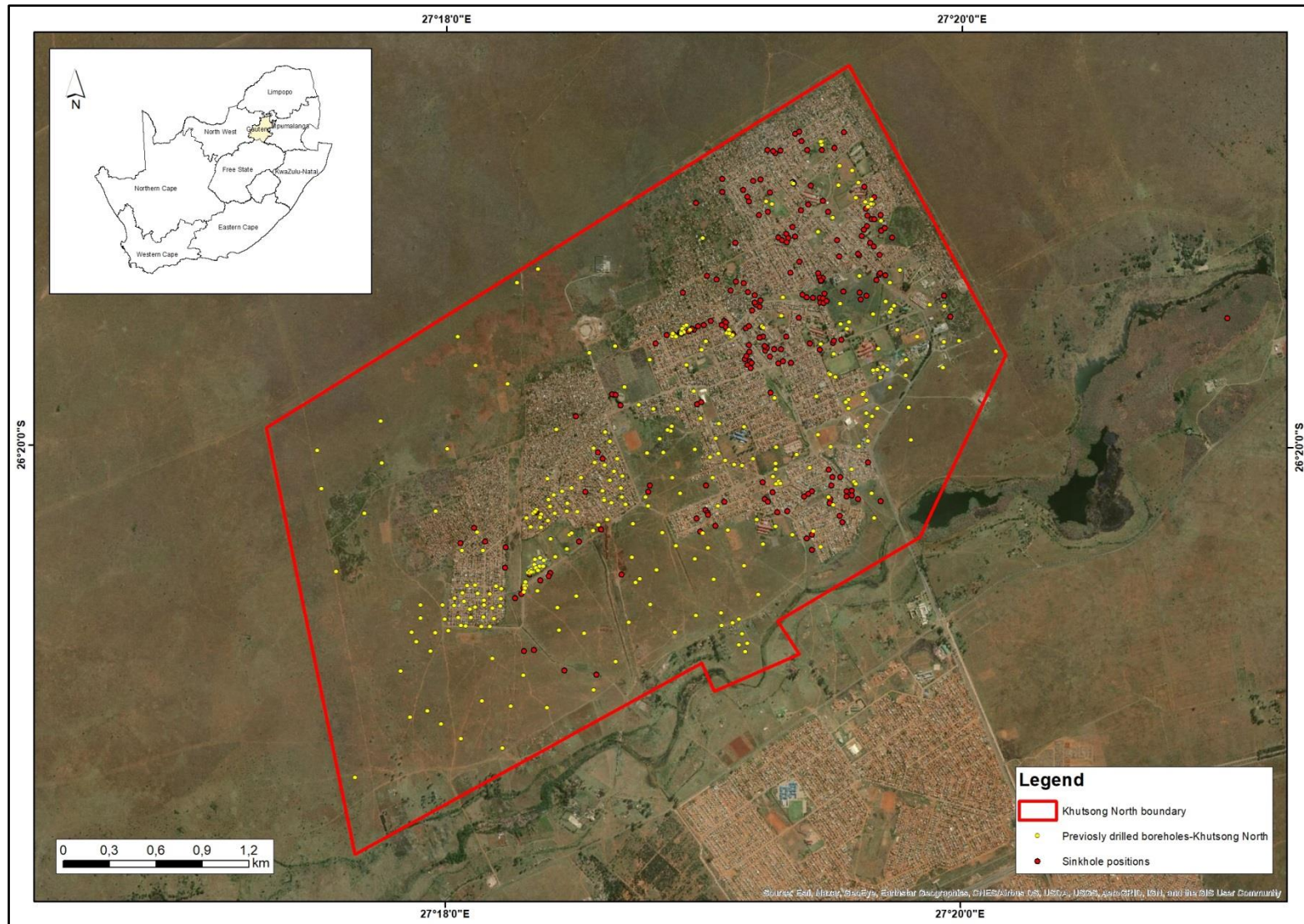


Figure 7: Percussion boreholes and sinkhole positions, Khutsong North.

CHAPTER 2 – LITERATURE REVIEW

2.1 KARST DEVELOPMENT

2.1.1 Dolomite within the Transvaal Basin

Proterozoic rocks of the Transvaal Supergroup are distributed across four provinces of South Africa, namely Gauteng, Limpopo, Mpumalanga and North West (Figure 8).

The carbonate sedimentary strata of the Transvaal Supergroup are confined within the Chuniespoort Group and, occurrence of chert and dolomite in the Transvaal Basin is limited to the Malmani Subgroup, also known to host well developed karst systems. According to Dippenaar *et al* (2018), these rocks formed through chemical and organic precipitation of calcium and magnesium carbonates from inland basins, resulting in the remnant stromatolitic structures. Initial deposition of these rocks is believed to be limestone, with dolomite and chert representing secondary replacement of the limestone (Brink, 1979). Brink (1979), further indicates that strata of the Chuniespoort Group occupy an area of some 15 000 km² in the northern region of South Africa (formerly known as Transvaal) forming two broad arcs and described the distribution as follows:

- To the west of South Africa, these rocks cross the Botswana border near Lobatsi
- In the southern Transvaal region, these encircle the younger rocks of the Pretoria Group in the vicinity of Potchefstroom and small patches of the Bushveld Granites
- Chuniespoort Group is subdivided into seven formations, the lower five of these excluding the Black Reef, consist almost entirely of chert and dolomite
- In the central areas, including the Far West Rand of the Gauteng Province, the Chuniespoort Group is represented by the four lowermost formations of the Malmani Subgroup
- To the north-east, Limpopo and Mpumalanga Province, the entire Chuniespoort Group succession is underlain by a basal unit of the Transvaal Supergroup, Wolkberg Group

Large portions of the Gauteng Province (approximately 25% of the land) are underlain by dolomites of the Malmani Subgroup, which is susceptible to the formation of surface instability events like sinkholes and subsidences. The occurrence of these hazards is evident in the Far West Rand region where hundreds of events have been recorded including Khutsong.

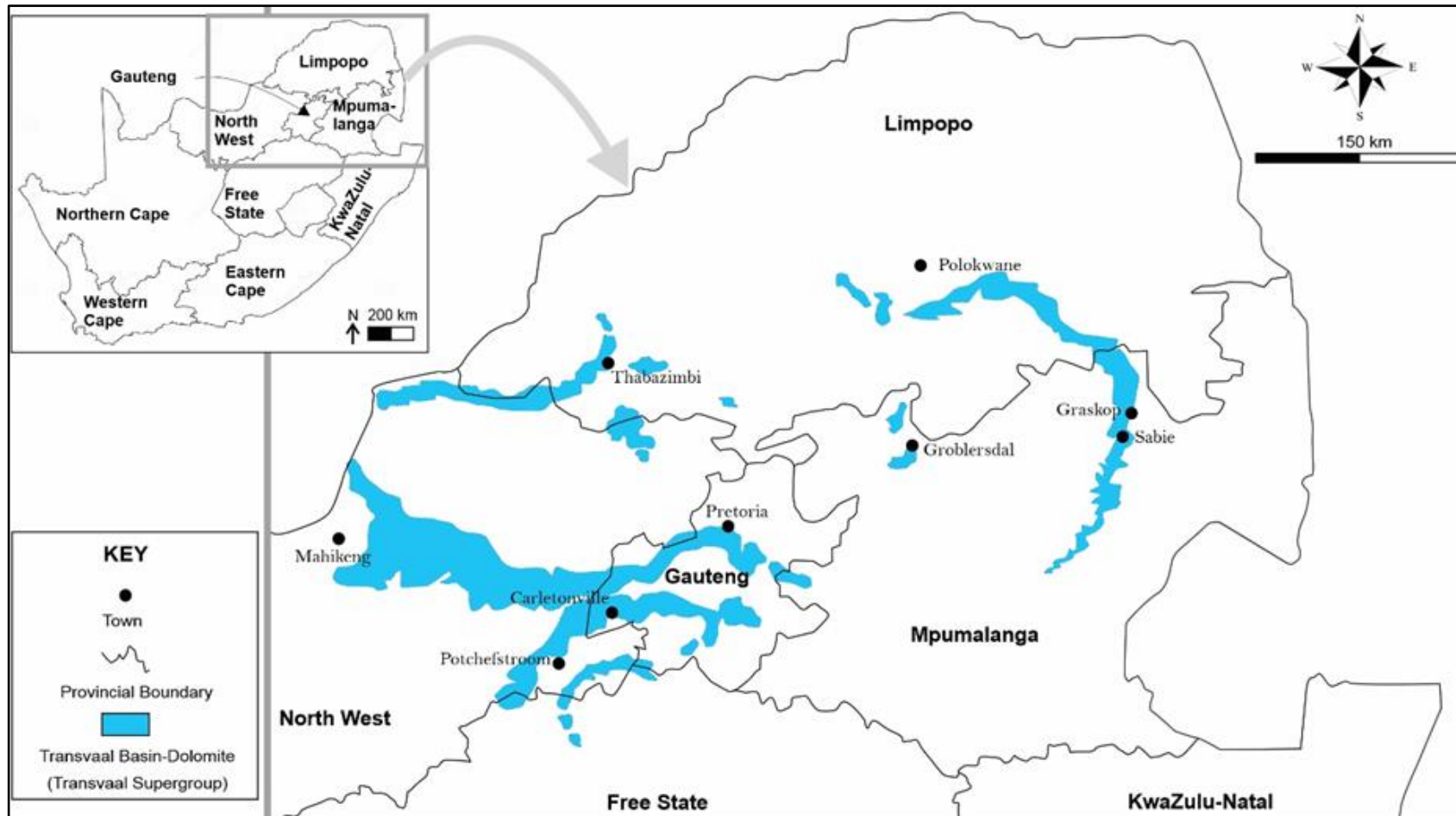


Figure 8: Distribution of the Malmani Subgroup dolomites within the Transvaal Basin (modified from CGS Map, 2013)

2.1.2 Weathering of dolomite

Dolomite is a carbonate rock, and it contains a large proportion of the mineral dolomite, with a typical chemical composition of $\text{CaMg}(\text{CO}_3)_2$. The dolomite rock which occurs in the Malmani Subgroup comprises of a series of alternating bands of “insoluble chert” and “soluble dolomite”. This intercalated pattern aided by geological discontinuities promotes preferential weathering within the dolomite rock mass.

The weathering process in dolomite has been described by various researchers including Jennings *et al* (1965), Jennings (1966a), Brink (1979) and is well summarised in the *Guideline for engineering geological characterisation and development of dolomite land* (2003) and later SANS 1936-Part 1 of 2012.

The process of weathering within dolomite land is relatively fast compared to other rock types and it results in a vertically zoned succession of residual products, which is characterized by dissolutional “Karst” landforms. A conceptual model through a typical dolomite profile as adapted from SANS 1936 is depicted in Figure 9.

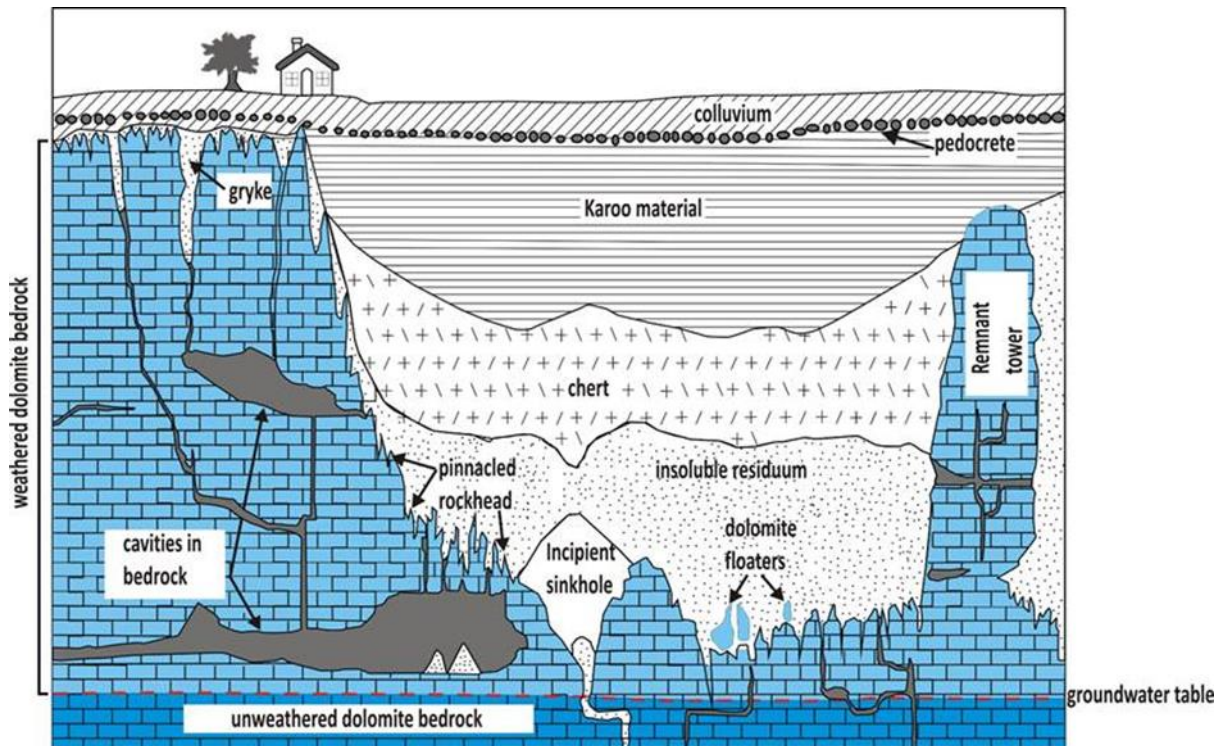


Figure 9: A conceptual cross-section through a typical dolomite profile in South Africa (*modified from SANS 1936-1, 2012*).

Karst is a distinctive terrain developed on soluble rock with landforms related to efficient underground drainage (Waltham and Fookes, 2003). Karst related dissolution landforms develop best on competent, fractured carbonate rocks like limestone and dolomite. These landforms are known to be associated with dolomite land in South Africa. The hard rock dolomite is usually followed by an upward succession of residual products (weathered dolomite, wad, chert and residual chert) that is overlain by younger transported formations or is intruded by igneous dykes and sheets (Brink, 1979). The residual mantle in dolomite terrains can be extremely irregular (Martini, *in* Johnson *et al*, 2006).

The overburden (residual and transported soils) mantling the dolomite bedrock often varies in origin, geotechnical properties, porosity and permeability. Buttrick *et al* (2001) explains that the inherent risk for sinkhole formation is a reflection of the geotechnical characteristics of the materials in the overburden.

Therefore, topography and drainage, the thickness and nature of overburden, the depth and expected fluctuations of the groundwater level, and the presence of geological structures (faults, fractures, cavities, etc.) collectively influence the risk of sinkhole and subsidence formation on dolomite land.

2.1.3 Mechanism of sinkhole and subsidence formation

Jennings (1966a), described ground instability events in dolomite land as taking place in one of two ways, i.e. as a gradual or caving “subsidence” or a rapid and catastrophic subsidence defined as “sinkhole”. Furthermore, Jennings *et al* (1965), Jennings (1966a), Brink (1979) and Brink (1996) described the mechanism of sinkhole and subsidence formation in detail. They argued that these events can form either due to concentrated ingress of water or dewatering scenario.

Given sufficient time and the correct triggering mechanisms, ground instability events in the form of sinkholes and subsidences may occur naturally, but may also be triggered by human activities. Infiltrating water from leaking wet services infrastructure or surface ponding from poorly managed surface drainage and groundwater level drawdown acting on the low-density material may result in subsurface erosion.

However, for the purpose of this research, only the scenario of water ingress will be considered for formation of sinkhole and subsidence events. A typical mechanism for the development of these events in an ingress scenario is illustrated in Figure 10.

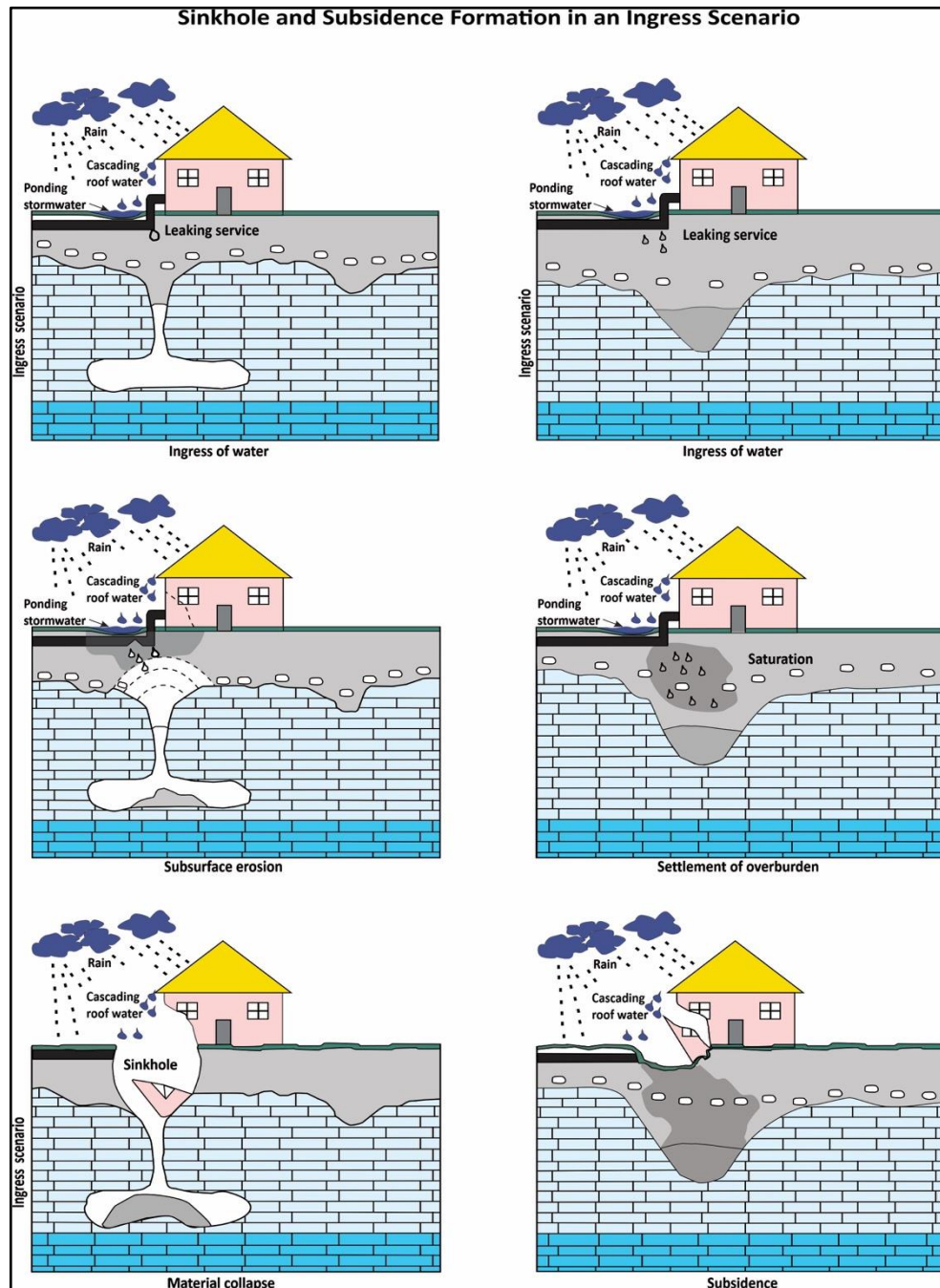


Figure 10: Diagram depicting the mechanism of sinkhole and subsidence formation in an ingress scenario (Modified from CGS drawings, 2008).

Based on the previous research and publications e.g. Jennings (1966a) and Brink (1996), SANS 1936-1:2012 prescribes five concurrent conditions that are necessary before a ground instability event can occur:

- 1) Adjacent stable or rigid material must form abutments for the roof of the void
- 2) A condition of arching has to develop in the residuum
- 3) A void/ receptacle must develop below the arch in the residuum
- 4) A void/ receptacle of appropriate size must exist below the arch to accept mobilizing material
- 5) A triggering agency has to be introduced to cause the final roof arch to collapse

Figure 11 and 12 show a recently collapsed arch (crown) forming a small sinkhole in Khutsong North



Figure 11: Recently collapsed arch forming a small sinkhole (Photo from CGS Database).

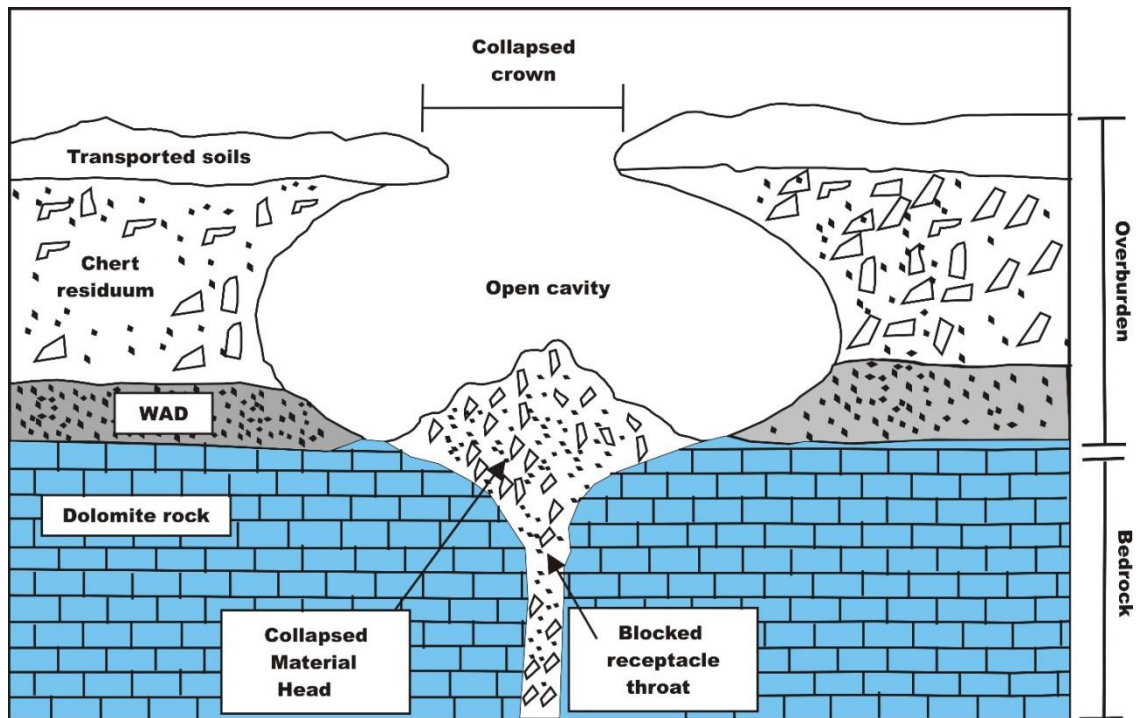


Figure 12: A typical cross-section through a small sinkhole.

Figure 13 and 14 show a recent caving of the ground surface forming a small compaction subsidence in Khutsong North.



Figure 13: Recent caving of the ground surface forming a subsidence (Photo from CGS Database).

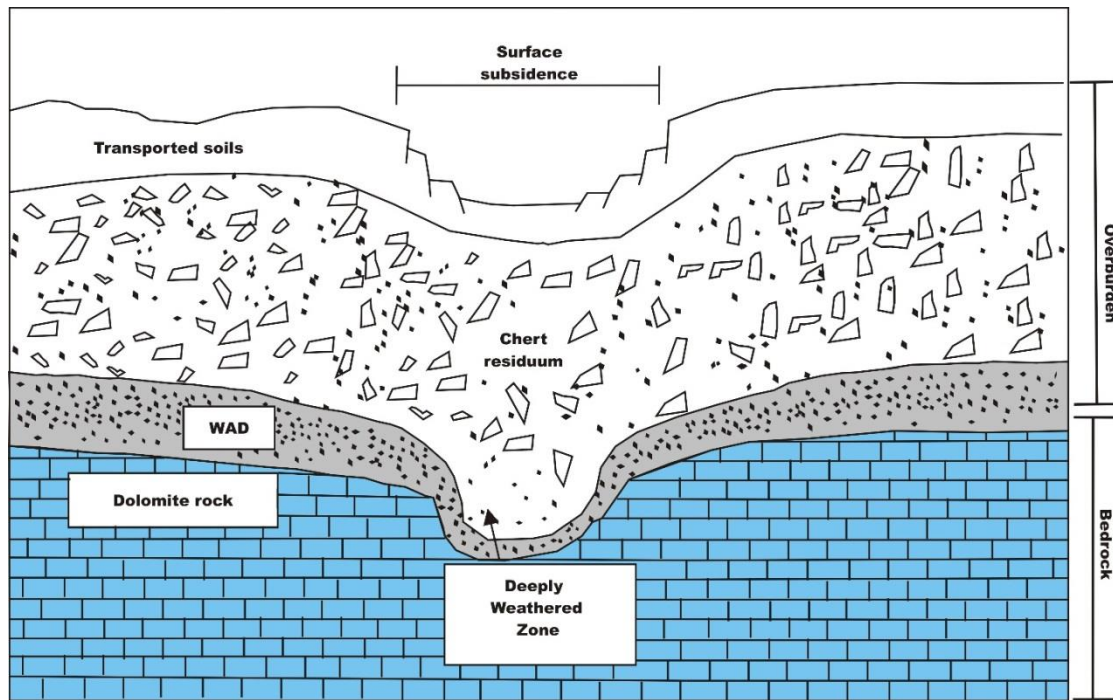


Figure 14: A typical cross-section through a compaction subsidence.

Jennings (1966a), also concluded that with passage of time the two types of ground instability events might ultimately look very much alike and that the only distinct difference lies in their rate of occurrence.

Urbanization and earth materials are considered critical factors contributing to the development of sinkhole and subsidence on karst terrains. A structure built on dolomitic subsoil, be it house, office block, industrial plant, road, railway line, dam, etc. might be exposed to danger of subsidence (Jennings, 1966a).

Therefore, increased urbanization of dolomite land around major metropolitan (City of Ekurhuleni, Johannesburg and Tshwane) areas of the Gauteng Province, have resulted in densely populated townships like Khutsong, thereby exacerbating the risk posed by dolomite rock in terms of surface instability events. These events occur primarily due to the loss of roof support and eventual collapse of the existing subsurface cavities.

Given the highly heterogeneous and anisotropic distribution of earth materials in dolomitic karst areas, risks posed due to surface instability resulting from regional dewatering and water ingress become increasingly complex (Dippenaar *et al*, 2018).

According to the published 1:250 000-scale Geological Map, 2626 West Rand (Government Printer, 1986) Figure 16, the Malmani Subgroup is undifferentiated in the FWR region. However, Wolmarans, (1984, *in* Richardson, 2013) mapped the region as being underlain by the chert-rich Monte Christo Formation. Therefore, the research area (Khutsong North Townships) is directly underlain by Monte Christo Formation.

Structurally, the FWR region is characterized by Hartebeestfontein Anticline (Basement Granite-gneiss) in the north, Wonderfontein Valley (dolomite & isolated Karoo rocks) in the center and Gatsrand Hills (resistant Pretoria Group quartzite) to the south. The strata are regionally dipping towards the south and Brink (1979) indicates fairly steep dip angles of 45° measured at Driefontein quarries.

The region is also characterized by generally north-south trending faults and igneous dykes of both pre- and post-Transvaal times. During post-Transvaal times, the dolomite weathered to great depths resulting in deep subsurface bedrock palaeo-valleys on which Karoo sediments were later deposited. Today, these sediments occur as isolated outliers of remnant Karoo strata found in the region mainly south of the Wonderfontein Spruit. However, according to the published 1:250 000 map these Karoo outliers are absent in the research area as it occurs north of the Wonderfontein Spruit, i.e. the Khutsong North Townships.

2.2.2 Geology of Khutsong North Townships

Unconsolidated materials classified as recent deposits are present across the research. These are expected to mantle the residual material and hard rock (dolomite) geology at depth as confirmed by existing percussion borehole records. Both the unconsolidated deposits and the residual dolomite materials vary in thickness, sedimentological and geotechnical properties. The existing boreholes data set reviewed during this research have broadly intersected the following horizons:

- ***Transported (alluvium, colluvium & aeolian) soils:*** - This horizon is generally thin (i.e. 1 m to 5 m) or absent in localized areas. However, occasional thick sequences of non-dolomitic transported soils, particularly aeolian sand, silt and clay occur in the research area as intersected by some boreholes, suggest the presence of more recent palaeo-features such as palaeo-sinkholes or valleys. The positions of these palaeo-features are represented by the isolated pockets of deep (circular

or semi-linear) features in dolomite bedrock (Figure 15), which dominate Extension 1, 2 and 4, and then parts of Extension 3 and 5.

- **Chert and dolomite residuum:** - This horizon is of variable thickness (i.e. 5 m to > 60 m) and composition, i.e. chert-rich residuum with traces of wad or residual intrusive material in places. Sample and air loss were recorded in a number of boreholes, also the depth and extent of the poor conditions vary across the region
- **Hard rock dolomite:** - Bedrock horizon was also intersected at variable depths, i.e. mainly at a depth greater than 15m from the surface, extending down to more than 60m as shown in Figure 15 and Appendix B

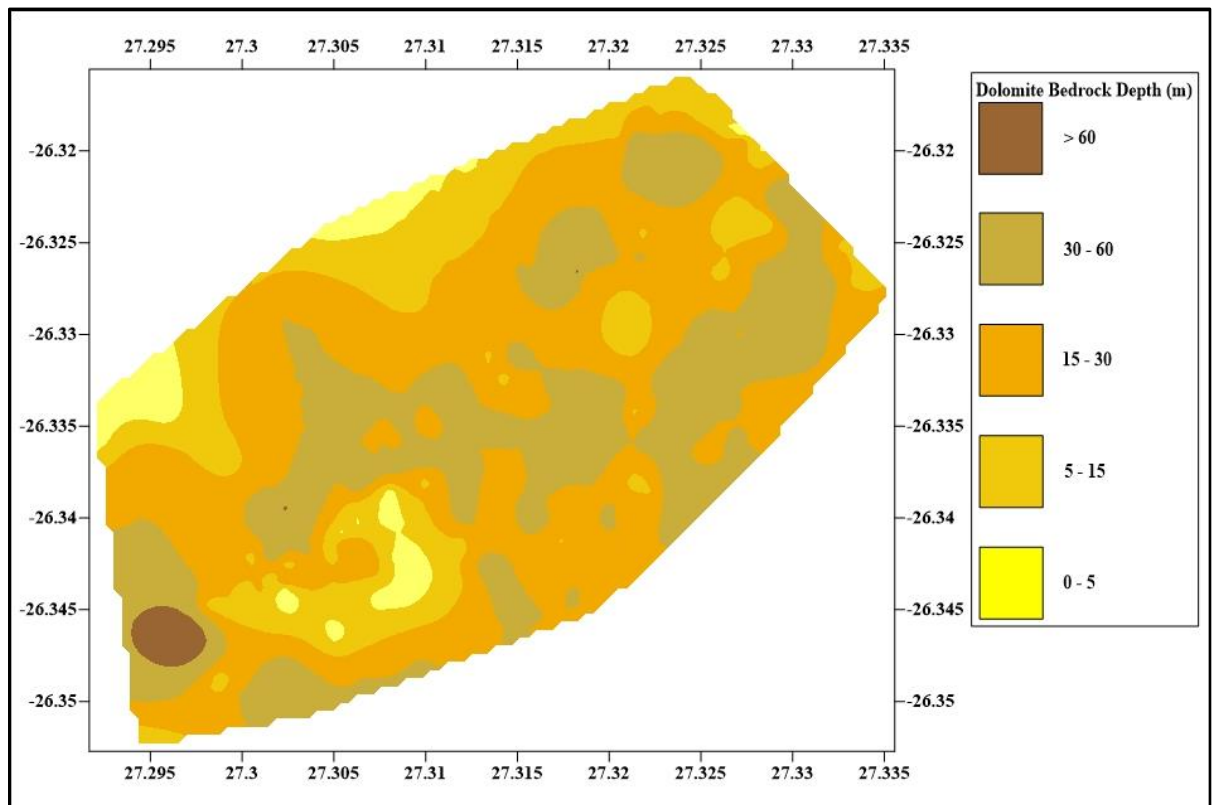


Figure 15: Map showing depth to dolomite bedrock head below ground surface, Khutsong North.

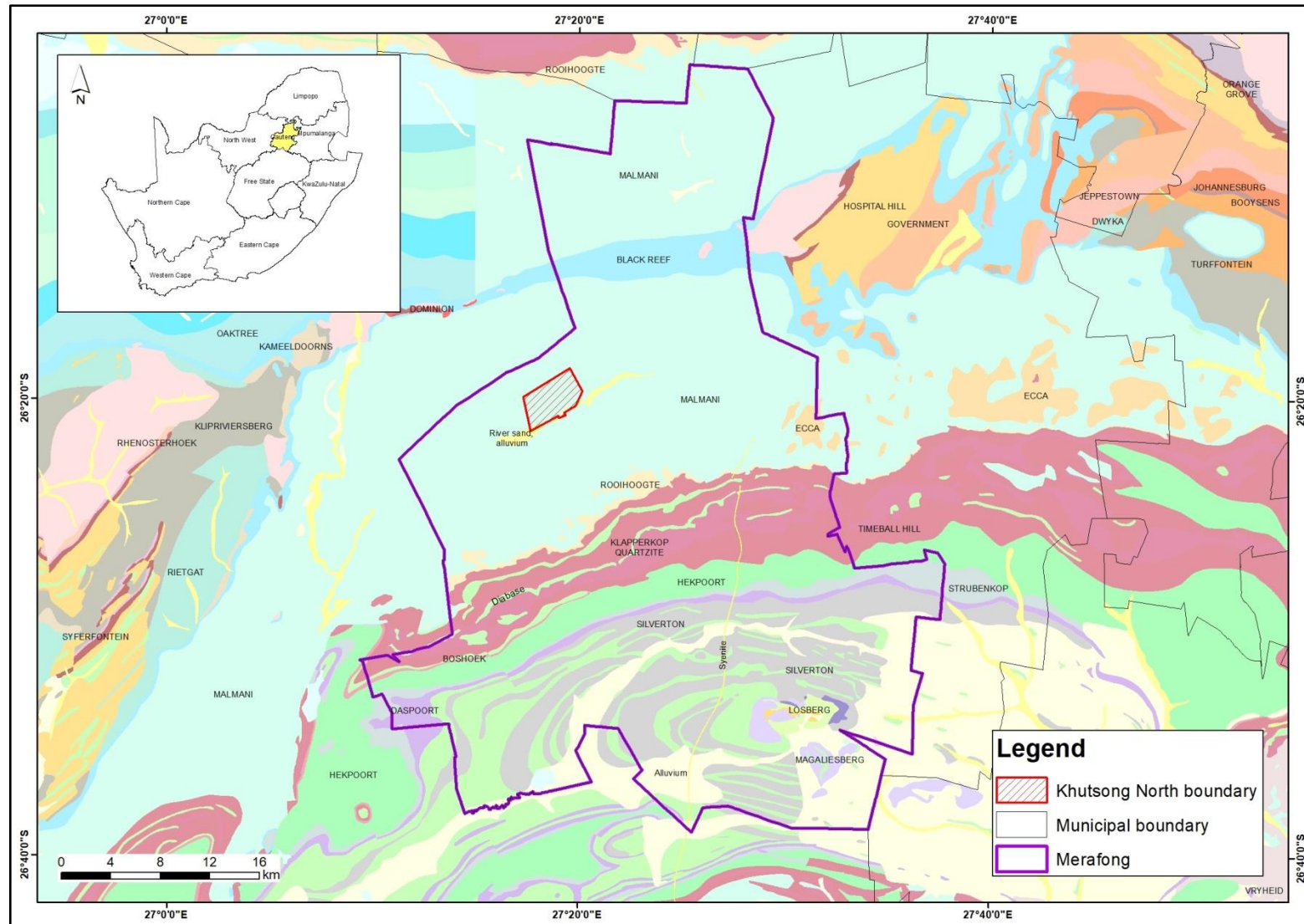


Figure 16: Extract from a published 1:250 000 (2626 West Rand, 1986) Geological Map showing the position of the research area within Merafong LM.

2.2.3 Regional hydrology

Groundwater Compartments (GWC) created by intrusive dykes exist in the dolomite terrain as natural subsurface water containers. Brink (1979) stated that a number of igneous intrusions, in the form of dykes trending slightly east of north, divide the dolomite beneath the Wonderfontein pediment into a number of groundwater compartments. In the Far West Rand (FWR) region these compartments are bounded to the north by Archaean Granite of the Hartebeestfontein Anticline and by the dipping Pretoria Group rocks in the south.

According to Kleywegt and Pike, (1982, *in* Richardson, 2013), on the FWR (areas from Westonaria to Carletonville, within the West Rand District Municipality - WRDM), the width of the generally north-south trending syenite dykes varies from 6 m to 60 m. Most of the GWC's in the region were dewatered to allow for safe mining.

Dewatering by the gold mines started when the quantity of water pumped from the underground exceeds the natural rate of replenishment (Brink, 1979). Ground instability events on dolomite terrains are mainly due to either concentrated ingress of water (leaking pipeline, storm water ponding, etc.) or dewatering (lowering of a water table), and their frequency of occurrence is directly related to either of the two scenarios.

However, according to the existing information from previous investigations (VGIconsult Report VGI3606, 2013) and scientific publications (e.g. Jennings *et al*, 1965, Jennings, 1966, Bezuidenhout and Enslin, 1969 and Brink, 1979), the KNT's is located within the non-dewatered Boskop-Turffontein Compartment (BTC), Figure 17. No known compartmentalising dykes are located near the research area and the Oberholzer Dyke forms the eastern boundary of the BTC.

As observed from the existing percussion borehole logs, the depth to groundwater (GW) in the BTC is generally greater than 60 m from the surface. According to Winde and Erasmus (2011), the GW level is currently some 60 m below surface in the Boskop-Turffontein Compartment. Only seven of the available 313 boreholes drilled across Khutsong North Townships (KNT's) recorded GW at depths ranging from 3m to 36m below surface. However, this may only be attributed to a localized-perched water table occurring within the areas directly underlain by either Karoo or intrusive rocks.

It is important to note that, no active hydra station (monitoring borehole) is available in the vicinity of the research area and this does not allow for a conclusive dolomite risk assessment as required in terms of the current deemed-to-satisfy rules stipulated in the SANS 1936:2012. Also of concern is that, localized abstraction (i.e., for domestic or agricultural usage) are known to occur within the BTC and this could negatively impact the ground stability in the immediate vicinity of such abstraction points.

2.3 DOLOMITE LAND CLASSIFICATION SYSTEMS

Various classification systems have been proposed since the 1970's in an attempt to determine the inherent hazard class (IHC) through risk assessment studies, manage and mitigation risk associated with dolomite land in South Africa. The ultimate objective of these classification systems is to identify high hazard areas considered generally as unsuitable for housing development, and to allow for safe land use planning and development processes. An advantage of using a classification system is that it provides everyone involved with a standard approach to the identified problem. Van Rooy (1996), provided a summary for each of the classification systems developed and published in South Africa prior to 1996.

The classification system or method currently used in determining the dolomite hazard in South Africa was originally developed by Buttrick during 1992 and later described in Buttrick and van Schalkwyk (1995) as the "Method of Scenario Supposition". Buttrick and van Schalkwyk (1998) indicated that this method was developed before the concept of appropriate development and compulsory precautionary measures. As a result, the 1995 method could not be easily integrated into existing government land use planning and development processes.

Subsequently, Buttrick *et al* (2001) proposed adjustments to the existing 1995 method to consider both the risk and hazard for development on dolomite land. The basic philosophy after the 2001 adjustments was therefore that with increasing probability of more catastrophic events occurring, the density of development should decrease. If development is really required on the more hazardous land, design and construction costs would have to increase to improve safety or enhance developability of such land. This improved version of the method allowed for dolomite land hazard identification, characterization, stability analysis and the development of risk mitigation strategies.

Improved dolomite land assessment and characterization method meant that inherent hazard categories (Low, Medium & High) can be defined, specific size events can be anticipated and hazard rating be calculated using events data over a 20-year period. Table 2 show inherent hazard categories and the anticipated events per hectare in a 20-year period as described by Buttrick and van Schalkwyk (1995) and Buttrick *et al* (2001).

Table 2: Inherent hazard category and anticipated events per hectare in 20-years

Inherent Hazard Category	Anticipated Events per Hectare in a 20-year period (<i>Buttrick and van Schalkwyk, 1995</i>)	Anticipated Events per Hectare in a 20-year period (<i>Buttrick et al, 2001</i>)
Low	0.0	$0 \leq 0.1$
Medium	0.07	$>0.1 \leq 0.1$
High	0.7	> 1.0

Buttrick *et al* (2001) also produced an updated table showing inherent hazard class (IHC 1 - 8) ratings and the expected size of an event in any given hazard class area, which was later adopted into the South Africans National Standard (SANS) 1936 of 2012 as presented in Table 3:

Table 3: Inherent hazard class and specified-size event (after Buttrick *et al*, 2001).

Statistical occurrence of sinkholes and subsidence					
Inherent Hazard Class (IHC)	Small Sinkhole (<2m)	Medium Sinkhole (2 – 5m)	Large Sinkhole (5 – 15m)	Very Large Sinkhole (>15m)	Subsidence
1	Low	Low	Low	Low	Low
2	Medium	Low	Low	Low	Medium
3	Medium	Medium	Low	Low	Medium
4	Medium	Medium	Medium	Low	Medium
5	High	Low	Low	Low	High
6	High	High	Low	Low	High
7	High	High	High	Low	High
8	High	High	High	High	High

According to Buttrick and van Schalkwyk (1995), risk characterisation can only be determined if the profile is assumed to be “abused”, if the land has a “high risk of large sinkholes forming and it retains that characterisation irrespective of the development type. A move from the 1995 to an improved 2001 method saw a focus in the site developability or suitability for a specific type development and risk mitigation strategies were introduced.

The basic philosophy of this characterization method is therefore that, with increased inherent risk of more catastrophic events, development density should decrease, construction cost increase and that development risk must remain acceptable (Buttrick *et al*, 2001)

However, when considering practical implementation of this method, a gap seemed to exist between the scientific advancements and legislation, hence, the proposal for a “Performance Based Approach to the Development of Dolomite Land” described in Watermeyer *et al* (2008), and the “Performance Based Approach to Dolomite Risk Management” described in Buttrick *et al* (2011), which has since been adopted into the deemed-to-satisfy rules and the promulgation of the South African National Standard (SANS 1936:2012).

The scientific research which culminated in the 2011 publication confirmed and demonstrated that the approach to the mitigation of hazards through risk management can improve the hazard rating of dolomite land. Oosthuizen (2013) also indicates that, Buttrick *et al* (2011) distinguished between low, medium and high inherent risk for sinkhole formation based on the susceptibility of the subsurface profile with particular reference to the susceptibility of the blanketing layer to mobilization. This research provided the much needed data and insights to refine and/ or expand upon the current South African methodology to cover the full spectrum of developments in a manner which is capable of being included in legislative frameworks governing the development of dolomite land, both locally and internationally (Buttrick *et al*, 2011).

Furthermore, Coetzee and van Niekerk (2013) proposed a “Disaster Risk Assessment Methodology for Communities underlain by Dolomite”. This method strives to bridge the gap between the existing scientific advancements and the applicable legislation. It is described as a tool for assessing a total disaster risk in terms of the National Disaster Management Framework (NDMF, 2005).

Coetzee and Van Niekerk (2013) also stated that “in order to develop the methodology, basic principles of disaster risk assessment, encapsulated in the notation **Risk (R) = Hazard (H) x Vulnerability (V)**, was applied to provide a vehicle to quantify hazard and vulnerability aspects related to dolomite risk. Specifically existing knowledge on inherent dolomite risk classes (hazard component) was aligned to issues of vulnerability (in this case ageing water infrastructure) to attain a total dolomite disaster risk score for a specific area”.

The method's primary objective is to ensure alignment of the existing scientific knowledge (inherent dolomite risk classes) with the disaster risk management theory and the applicable legislation aimed at facilitating the government land use planning and development processes.

In addition to the scientific advancements made in the dolomite land classification, dolomite risk management is equally accepted as a critical tool that can improve the hazard rating of areas classified as dolomite land. Potgieter *et al* (2016), recommended the need to integrate a Dolomite Risk Management Programme (DRMP) into the Local Governance in South Africa and their research identified three main role players to enforce existing and new dolomite related by-laws, namely legal, institutional and society. It is imperative that there is a fine balance amongst the three pillars of sustainable development and this should be the case for new and existing communities with development on dolomite land (Potgieter *et al*, 2016),

Therefore, various classification systems or methods for identification, assessment, analysis, management and mitigation of dolomite risk have been developed in South Africa since the mid-1970's. It is also evident that tremendous advancements have been made on the scientific front since the first system in 1975 to influence safe development of dolomite land. However, challenges seem to exist when considering the practical implementation of the scientific advancements within the current building legislation.

2.4 APPLICABLE LEGISLATION

2.4.1 The South African building legislation and the regulatory process

Densification of urban areas directly impact on the frequency and extent of ground instability events as well as various other natural hazards. Land use regulation is generally the responsibility of local authorities in South Africa. The areas classified as "Dolomite Land" have a negative connotation due to the perceived association with negative effects of sinkhole and subsidence formation, *inter alia*, damage to housing, infrastructure and in rare cases, loss of life.

However, avoiding development on such land is practically impossible as it occurs across five of the nine provinces in the Republic.

Under section 24 of the Constitution of South Africa, (Act 108 of 1996), the right to a safe environmental and protection thereof has been elevated to a basic human right. In the context of safe and sustainable building practice, more particularly post-1994, a series of statutes have been promulgated to provide a regulatory system for building control.

In addition to the Constitution, the National Building Regulations and Building Standards (Act 103 of 1977) as amended, and the National Building Regulations (NBR's) have been promulgated to promote uniformity in the law relating to the erection of buildings. Section 17 of this Act provides a legislative framework on which a set of minimum mandatory building requirements are established to give effect to Section 24 of the Constitution. This framework is guided by a principle that any conditions of the land which is deemed dangerous to property and/ or life must be investigated as required in terms of Section 12 of the principal Act 103 of 1977.

The Constitution and Act 103 of 1977 identify local authorities as leading agents responsible for the administration of the NBR's functional requirements, and control of the on-site activities on building projects. A key requirement in the NBRBSA is that if in the opinion of local authority, conditions of the land on which a building was or is being or is to be erected, is showing signs of becoming dangerous to property and/ or life, such conditions must be investigated.

However, other provincial and national departments also have the legislative authority to implement the so called "Strategic Integrated Projects" under Infrastructure Development (Act 23 of 2014) and without prior approval of the local authority. This division of responsibilities between spheres of government has a potential to create challenges in the building regulatory process.

The importance of consistent adherence to a judicious process by all persons (decision makers, contractors and site owners) involved in the building practice and regulatory process is critical in ensuring safe development. This requires the formation of strong legislated partnerships with national scientific institution(s) and industry experts to allow for sharing of contextual scientific expertise.

The objective is to publish a technical paper discussing the current South African legislation pertinent to building practice and in the context of dolomite inherent hazard. However, a schematic representation of the current South African building legislation and regulatory process is summarised in Figure 18.

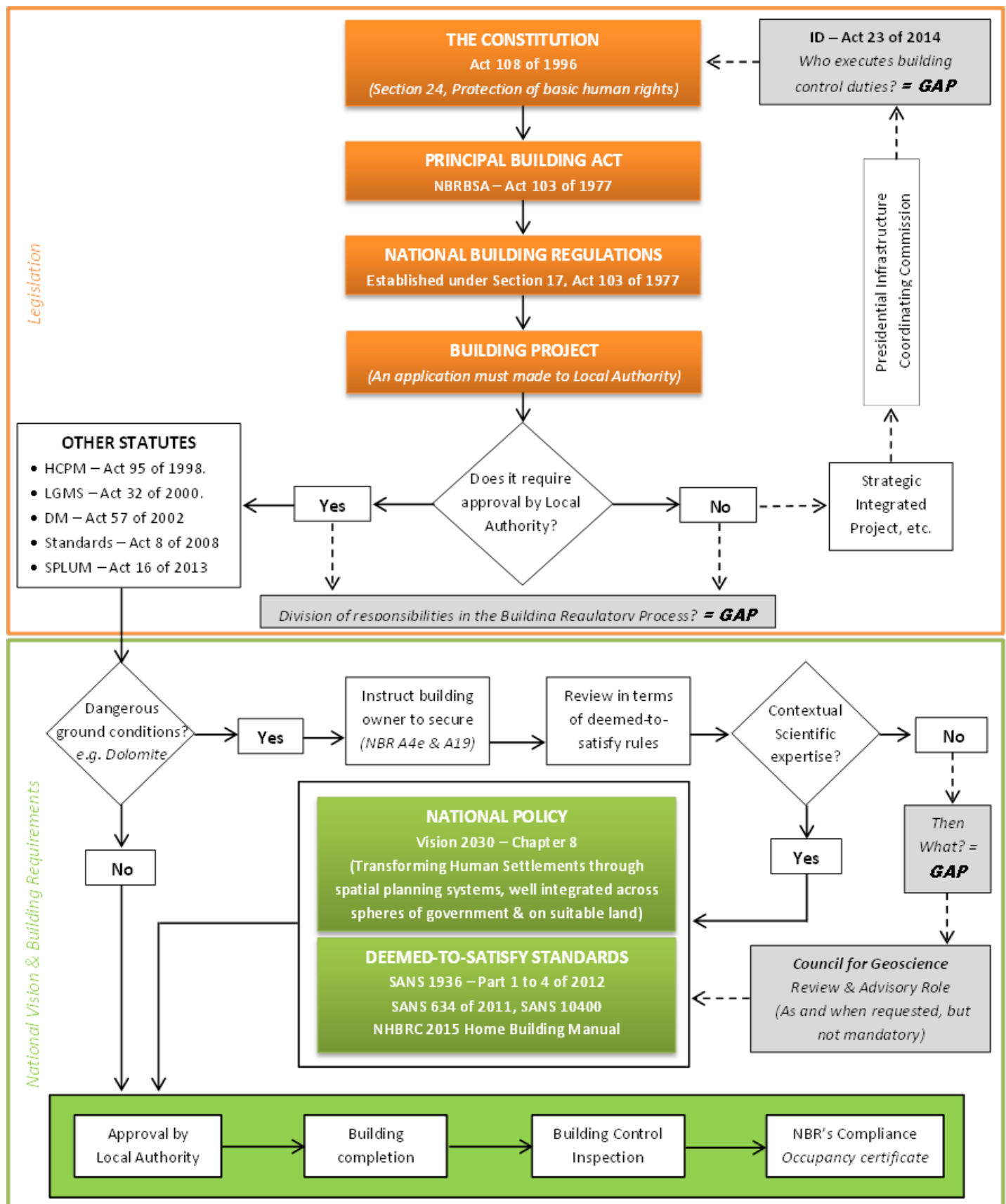


Figure 18: Summary of the current building legislation and regulatory process.

2.4.2 Land use regulation on karst terrains in the United States

According to Richardson (2003), “Types and intensities of land use in karst terrain directly impact the frequency and extent of subsidence, flooding and other hazards. Land use regulation generally falls to local governments in the United States and approximately 15% of the continental land is underlain by karst terrain. Often, areas are developed without knowledge of the presence of karst terrain or consideration of the potential hazards. When problems arise years after development has occurred, communities must attempt to remedy the issues after the fact, in a reactive fashion”.

A similar situation exists in South Africa where past-laws allowed land use approvals on unsuitable or potentially hazardous land and without enforcing the requirement to conduct geotechnical investigations necessary to identify and quantify geological hazards prior to the development. This situation has created a huge financial burden for the state to bear when implementing remedial actions after e.g. sinkhole damage. The common issue with respect to preventing and mitigating negative impacts of development on karst terrain (dolomite land) pertains to which sphere of government holds the power to regulate land use development. Richardson (2003) also suggested that this is a problematic issue in the United States.

In broad terms, the United States Constitution and similarly to the South African Constitution seem to position the local governments as the leading agents responsible for land use planning and control. At the same time, the United States Constitution does not provide ultimate powers for local governments to control land use planning and development. As such, provinces, States and other departments have the legislative powers to implement building projects without prior approval by local governments. In practice, land use planning and control forms one of the few areas within which the legislative framework generally grants local governments broad discretion to regulate development (Richardson, 2003).

According to Richardson (2003), various regulatory approaches have been adopted across the United States to limit impact of building on karst terrains. Some of the regulatory approaches adopted in the United States are as follows:

- Effort to regulate karst impacts must begin with data collection and education
- Karst Resource Planning Committee (KRPC) is formed to address the perceived need to educate the public with respect to karst hazards
- KRPC publishes articles and brochures aimed at land use planners, government officials and the general public

- KRPC draft a model ordinance for use by localities addressing development in karst terrain
- KRPC organizes workshops aimed at local government officials focused on legal liabilities and cost issues, responding to locality concerns
- Local governments employ zoning ordinances, overlay zoning, and subdivision ordinances to regulate the land use impacts of development on karst
- Delineation of buffer zones around karst features (i.e. sinkholes, rock outcrops, etc.) within which regulation limits or prohibits development.
- Adopt performance standards and policy to minimize impacts of development on karst terrains including stormwater management
- The Carbonate Area District Model Ordinance (CADMO) requires landowners to undertake geotechnical investigation or study at the landowner's expense, prior to undertaking any development activity
- Development may not commence without approval of the plan by the local government and if approved, a permit is issued with development conditions

Research in the two countries (South Africa and the United State) have demonstrated that efforts to regulate hazard impact on karst terrains must begin with data collection and then education. The United States seem to have adopted a clear regulatory approach to limit the impact through the establishment of formal structures like KRPC and the CADMO legislative requirements. The same cannot be said for South Africa where only the deemed-to-satisfy standard pronounces the requirement to undertake geotechnical investigations. Important to note also about South Africa, is lack of a single regulatory process in building practice which takes into account the geological hazards and the division of responsibilities between spheres of government in implementing building projects.

CHAPTER 3 – DATA GATHERING AND RESEARCH METHODOLOGY

This section details the methodology used during this research in data identification, gathering (desktop study), site walk-over surveys (mapping), field images, compilation, verification and data preparation for analysis. The research methodology is divided into three phases described below:

3.1 PRE-FIELDWORK PHASE (DESKTOP STUDY)

This sub-section encompasses identification and gathering of all available data records (dolomite stability reports, sinkholes & subsidences) relevant to this research (Figure 6 and 7, and Figures 19 - 21).

Data sets were obtained from:

- Dolomite Stability reports from the CGS Dolomite Databank
- Situation Report by CoGHSTA Gauteng Province
- Merafong City Council Resolutions
- Available research theses and scientific papers
- Media articles. (CGS and Merafong City archives)
- Boreholes & ground instability events (CGS and Merafong City). Co-ordinates are not included for each instability event, although this is available from the CGS)
- 1:50 000-scale Topographic Sheet, 2627AD Carletonville (Government Printer, 1994)
- Google Earth® Imagery

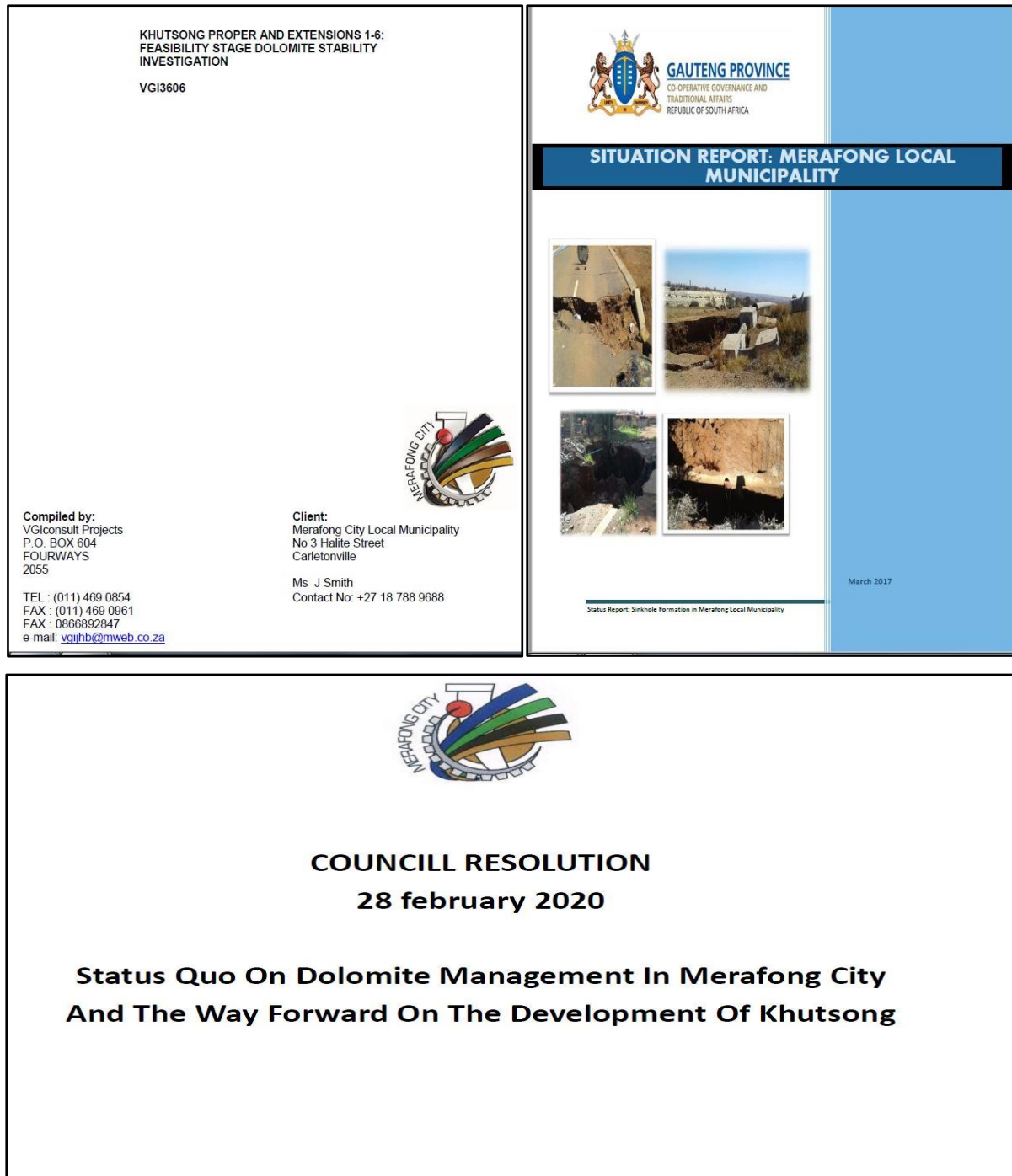


Figure 19: Examples of the available reports used during this research.

Sinkhole havoc for Khutsong community

9th June 2017 | [Thabo Molelekwa](#)



The community of Khutsong in the Merafong municipality is living in fear as sinkholes open up all over the area, damaging the infrastructure.

Khutsong resident Mbongeni Skosana said a sinkhole less than a metre long opened up in his yard last August.

Figure 20: An example of available newspaper articles.

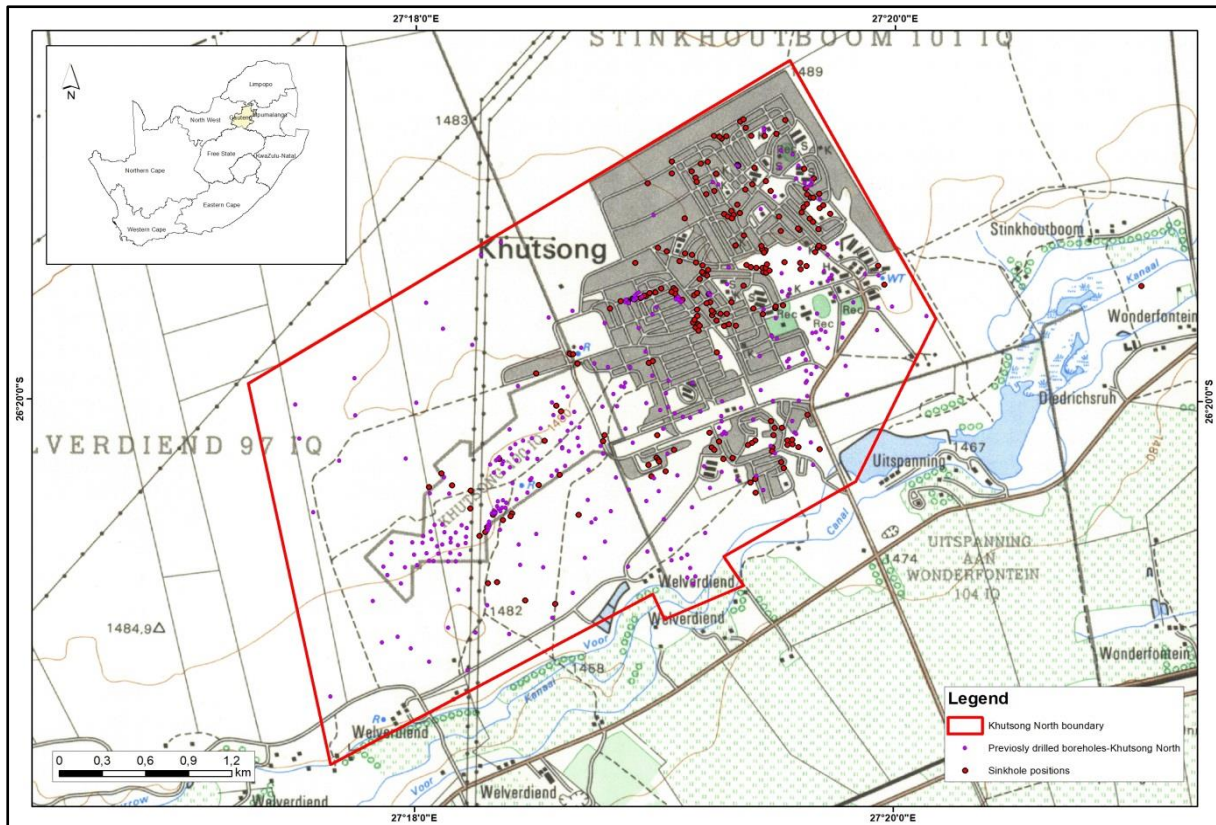


Figure 21: Extract from a published 1:50 000 (2627 AD Carletonville, 2006) Topographic Map.

It is important to note that large percentage of the data gathered and used for this research was incomplete, with one or more parameters missing, i.e. a sinkhole (data point) may be recorded with date but no diameter, depth or cause recorded. All the relevant reports stored in the CGS Dolomite Databank were extracted and the factual information copied and assimilated for the study area. The point data were plotted, digitised and presented in a Geographic Information Systems (GIS) spatial package (ArcMap® 10.1.4). This dataset allowed the application of currently accepted assessment methodologies. Most observations are from third parties and only limited data was collected by the author.

3.2 FIELDWORK PHASE

This sub-section encompasses site walk-over surveys, mapping of open sinkholes and sewer leakage and sewage ponding areas (Figure 22 and 23). Site walk-over surveys were conducted to allow first hand observations on the geology of the area and anthropogenic issues like the widespread ponding of sewage across KNT's. These

surveys also allowed for capturing of visual evidence of specific open sinkholes and any other possible external influence.



Figure 22: A very large sinkhole (>15m diameter) at Nxumalo Road, Khutsong Proper.



Figure 23: Blocked and back-ponding sewage effluent flowing into open field and sinkholes.

3.3 POST-FIELDWORK PHASE

This sub-section encompasses data compilation, verification and data preparation for analysis as described below:

Data compilation:

- Maps presenting visual distribution and/ or analysis of different data sets were produced using GIS software. Only dolomite related sinkholes and subsidences were considered for this research. The GIS Database held at CGS contains information, as far as available. This research made use of all available sinkholes and subsidence data relevant to the study area to the end of 2020

Data verification:

- Data sets from databases (CGS and Merafong City) were verified as far as possible by systematically reviewing historical maps, records, reports, scientific publications and the published 1:50 000-scale topographic map, 2627AD Carletonville
- Maps and point data (boreholes and sinkholes) contained in reports submitted to CGS are continuously georeferenced in a GIS system
- Reports without maps usually indicate a street/ road name and data points without coordinates were geographically located
- While locations maybe approximate, generally it is assumed that if a sinkhole or subsidence has been indicated on the map, it has occurred in the vicinity
- The biggest challenge faced was the verification of the historical events as these may no longer be visible on the ground or have been rehabilitated. The accuracy of the databases cannot be guaranteed and these should be accepted only as an estimation of events recorded in KNT's. According to officials from Merafong City, some sinkholes from the past were simply backfilled with mine solid waste before any records were made

Data preparation:

Once all the data sets (boreholes and ground instability events) were gathered, compiled and verified, these were reviewed and prepared for method guidance on factors to be analysed. The review process revealed gaps in the available information of both borehole and ground instability events databases and as a consequence of that, the main attributes to be considered during data analysis are as follows:

- Boreholes with confirmed (valid) versus unconfirmed (invalid) bedrock in line with current standard practice, i.e. 6m into solid bedrock or 60m depth
- Invalid boreholes are not considered for analysis
- Valid boreholes are to be used for bedrock topography analysis
- The date of occurrence to determine the frequency of events over time
- The type of occurrence to examine if sinkholes or subsidences are more prevalent within the study area
- The size distribution of events across the study area
- The rate of new events over the last 20 years, i.e. year-2000 to 2020

Figure 24 show an example of different data sets stored and analysed using the GIS software.

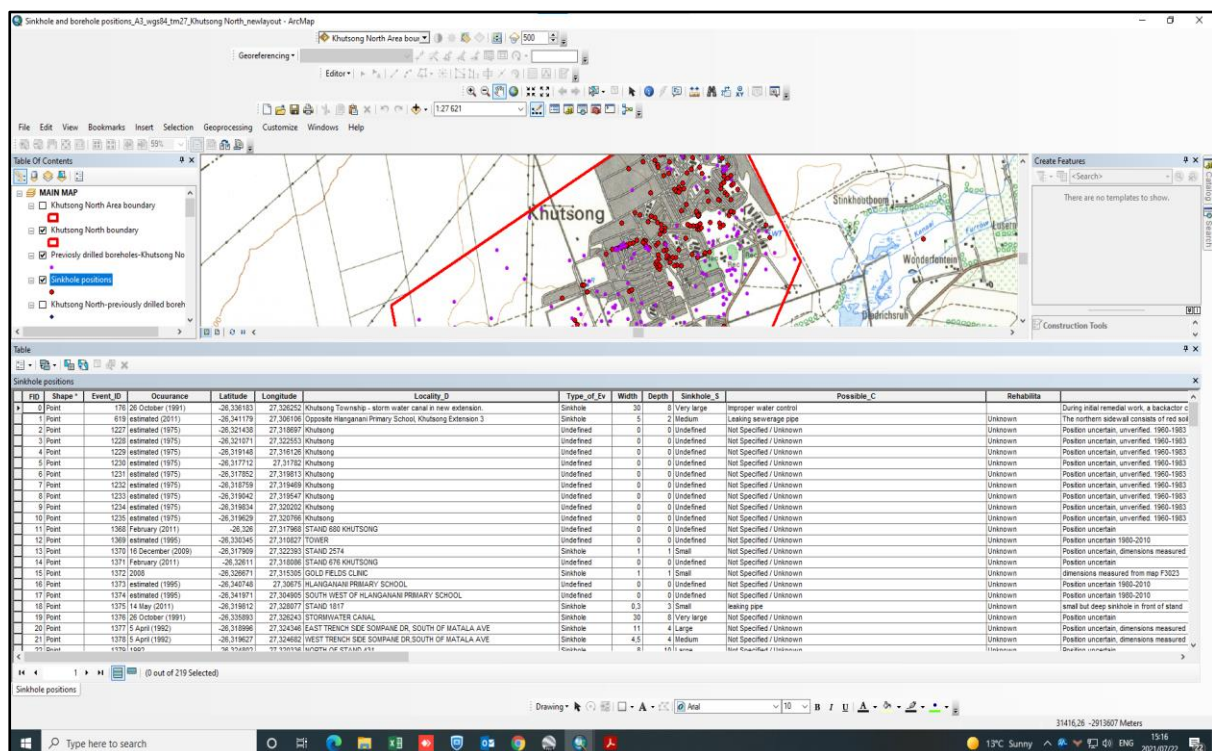


Figure 24: An example of the data sets compiled on a GIS (ArcMap®) database.

CHAPTER 4 – DATA ANALYSIS AND INTERPRETATION

4.1 PERCUSSION BOREHOLE DATABASE

A total of 313 boreholes have been drilled across KNT's and surrounding areas which cover a surface area of approximately 1 318 hectares (ha). This constitutes 0.24 boreholes (more than the 0.15 minimum number of BH's recommended for an area >200 ha in extent) per hectare and these were used to assess the dolomite stability conditions, conduct hazard assessment and zonation of the research area.

Some boreholes fall just outside the periphery of the build-up (formal townships) areas (Figure 25) but within the demarcated research area. The borehole record held at CGS is continuously being updated as dolomite stability reports with factual data are submitted and the available borehole records are presented in Appendix B. Table 4 below shows the number of available borehole records and their distribution across various townships.

Important to note, all these boreholes were drilled decades after the Khutsong North was established and therefore, were never used to guide decisions on spatial planning.

Table 4: Summary of the available boreholes drilled across the research area.

Township Name	Total Surface Area (Ha)	No. of BH's Drilled	% of all BH's Drilled	Borehole Coverage (BH/Ha)
Khutsong Ext 1	35	13	4	0.37
Khutsong Ext 2	96	40	13	0.41
Khutsong Ext 3	97	104	33	1.07
Khutsong Ext 4	10	8	3	0.80
Khutsong Ext 5	11	4	1	0.36
Khutsong Ext 6	20	9	3	0.45
Khutsong Proper	207	67	21	0.32
Informal Settlement	164	7	2	0.04
Undeveloped Areas	678	61	20	0.09
Total	1 318	313	100	

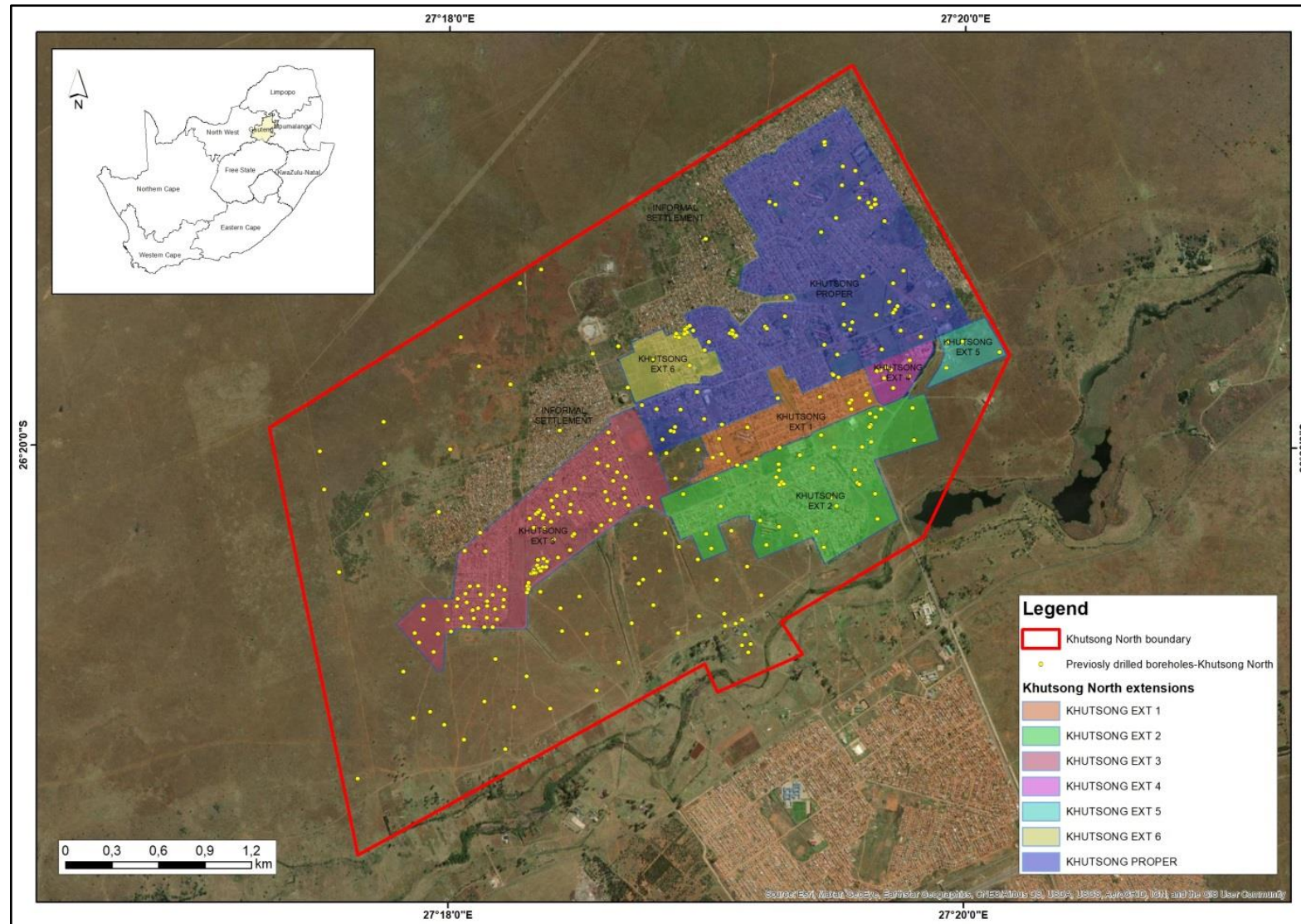


Figure 25: Spatial distribution of the available borehole data, Khutsong North.

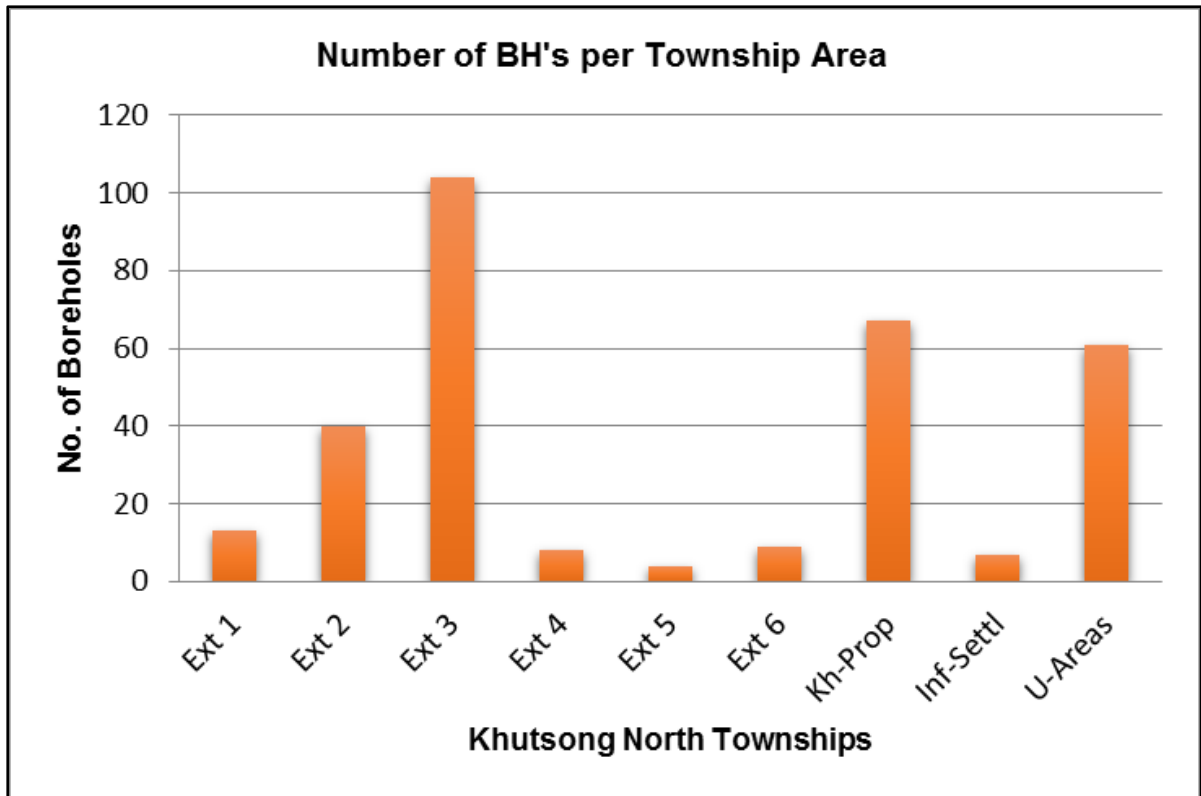


Figure 26: Showing the number of boreholes drilled per township.

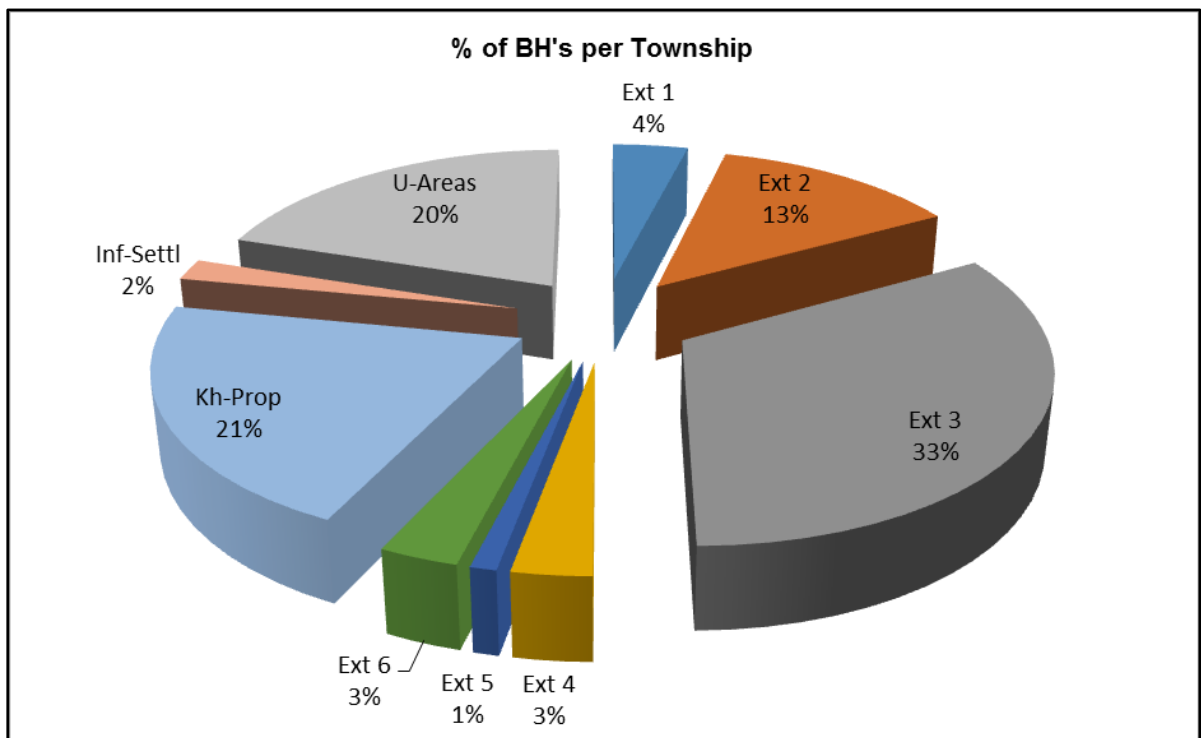


Figure 27: Showing the percentage of boreholes per townships.

From the borehole distribution as shown in Figure 25 to 27 and Table 4, the following observations were made:

- Based on the spatial distribution, it is evident that borehole data is not evenly distributed across the research area
- More boreholes were drilled within the 97 hectare Khutsong Extension 3, i.e. 104 or 33% of the boreholes drilled across KNT's. This translate to 1.07 boreholes per hectare which is three times more than the 0.3 minimum required number of boreholes per hectare as stipulated in Table 1 of SANS 1936 Part 2 of 2012 for an area of >50.0 but ≤100 hectares in extent
- The second highest number of boreholes was drilled within the 207 hectare Khutsong Proper, i.e. 67 or 21% of the boreholes drilled across KNT's. This translate to 0.32 boreholes per hectare which is two times more than the 0.15 minimum required number of boreholes per hectare as stipulated in Table 1 of SANS 1936 Part 2 of 2012 for an area of >200 hectares in extent. This is the least coverage of all other formal townships in terms of borehole per hectare
- In general, the minimum frequency of boreholes required in dolomite areas for a feasibility-level investigation and township establishment in terms of Table 1 of SANS 1936 Part 2 of 2012 has been met for all Khutsong North formal townships

4.2 DEPTH TO DOLOMITE BEDROCK

Depth to dolomite bedrock within the research area is irregular with a minimum depth to bedrock of 1.5 m and a maximum of greater than 60 m, the deepest bedrock head was confirmed at 66 m depth. It is important however, to note that some boreholes (23%) were terminated before solid bedrock was intersected. These were not included in the bedrock statistics and analysis as they are considered invalid for a dolomite stability assessment in terms of the current accepted practice. Table 5 shows the available borehole records and their depth to dolomite bedrock.

For the purpose of analysing depth to solid bedrock, depth to dolomite bedrock was divided into five zones, namely, 0-5 m, 5-15 m, 15-30 m, 30-60 m and >60 m. Figure 28 and 29 indicates the distribution of depth below ground surface at which dolomite bedrock was intersected. Based on this division, of the 242 valid boreholes the majority, 153 (63%) intersected dolomite bedrock between 15 m and >60 m depth. Only 89 (37%)

intersected dolomite bedrock at depths shallower than 15 m. It is therefore assumed that dolomite bedrock in the research area is mainly deeper than 15 m.

Table 5: Available borehole records and their depth dolomite bedrock.

Dolomite Bedrock Depth Zones (m)	No. of BH with Confirmed Bedrock Depth	% of BH's with Confirmed Bedrock Depth	No. of BH's Terminated Before Bedrock	% of 313 Total Terminated Before Bedrock
Zone 0 - 5	34	14	0	-
Zone 5 - 15	55	23	0	-
Zone 15 - 30	68	28	7	2
Zone 30 - 60	83	34	54	17
Zone >60	2	1	10	4
Total	242	100	71	*23

**Represent the percentage of the total boreholes (313) terminated before solid dolomite bedrock.*

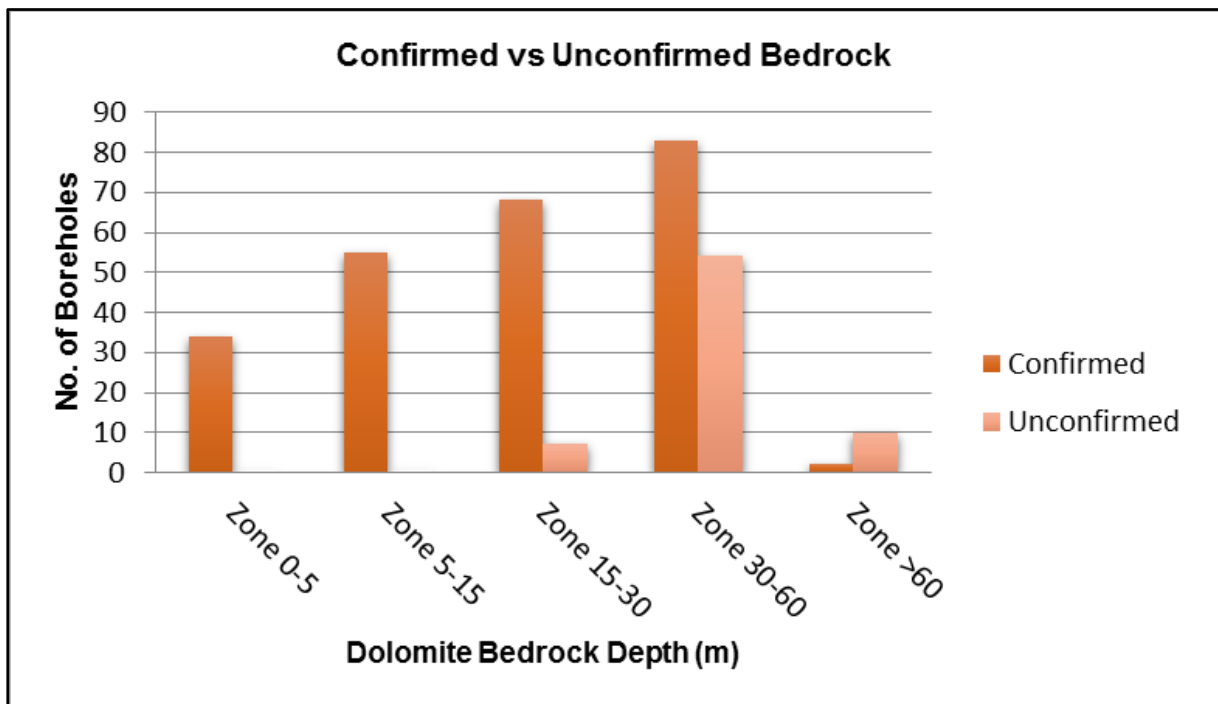


Figure 28: Boreholes with confirmed and unconfirmed bedrock in each of the zones.

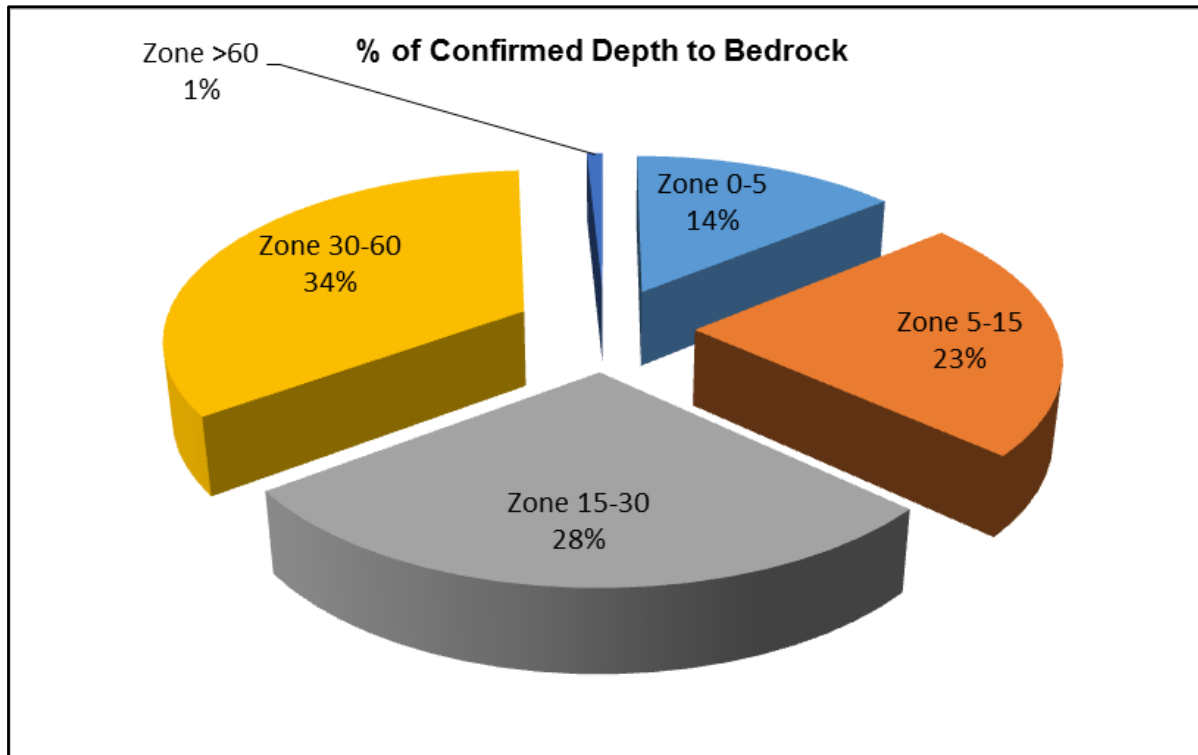


Figure 29: Showing the percentage of confirmed depth to dolomite bedrock in each zone.

Figure 30 visually indicates the highly variable depth to dolomite bedrock. From the depth to dolomite bedrock analysis the following is noted for the research area:

- Deep dolomite bedrock (>15 m below surface) dominates the KNT's formal build-up areas with small patches of <15 m of bedrock depth in Khutsong Proper
- Shallower dolomite bedrock (0-5 m below surface) occurs in patches south of Khutsong Extension 3 and north of informal settlement areas
- A deeper dolomite bedrock (>60 m below surface) patch is present in the area west of Khutsong Extension 3

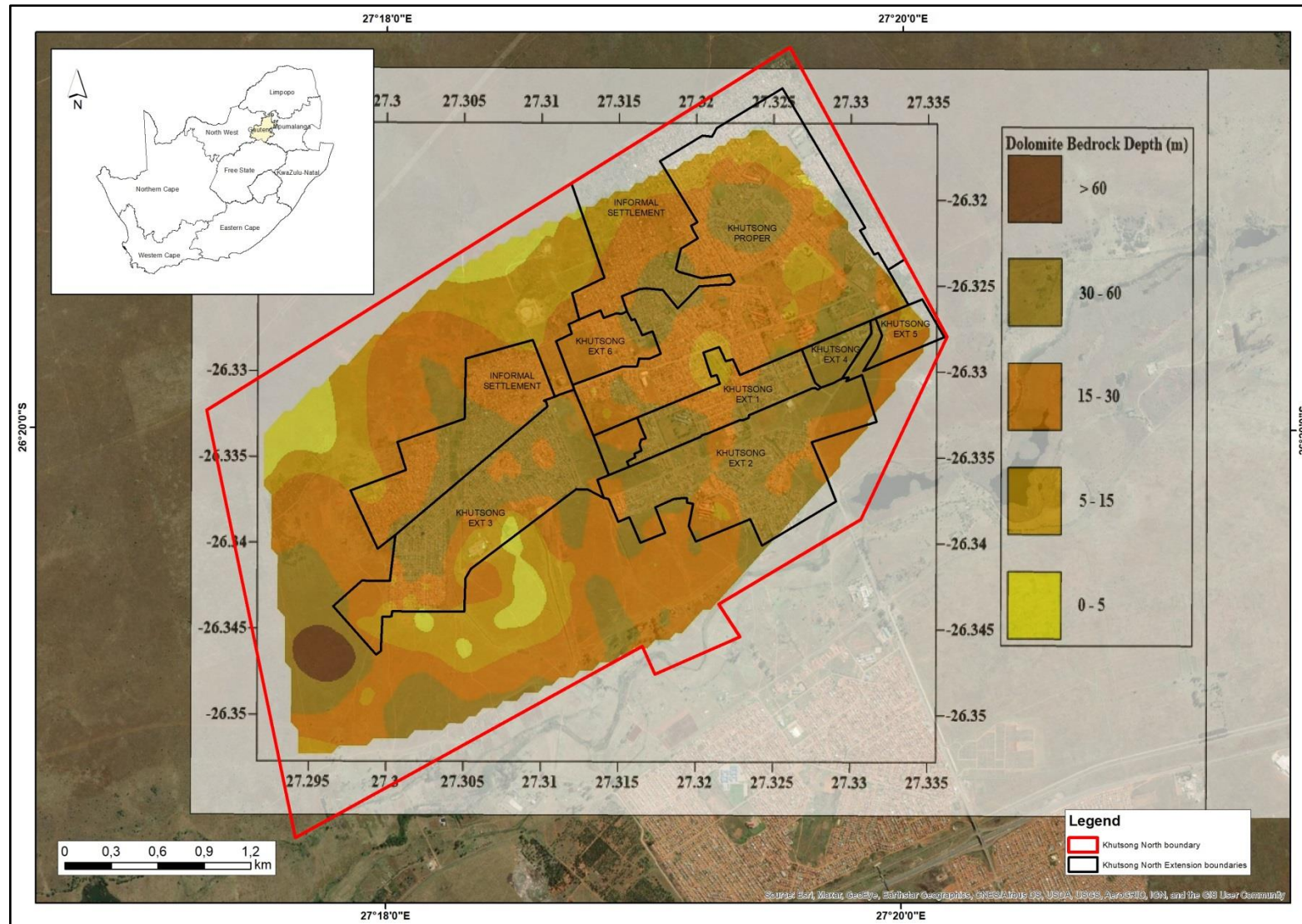


Figure 30: Spatial representation of depth to dolomite bedrock head, Khutsong North.

4.3 EVENTS (SINKHOLE & SUBSIDENCE) DATABASE

According to the available records, a total of 219 ground instability events (cracks, sinkhole & subsidence) have been recorded across KNT's and surrounding areas since 1975. The CGS database is continuously being updated or reviewed and a large number of sinkholes do not have a complete record. The available records are presented in Appendix C, Figure 31 to 33 and Table 6. It should be noted that the events database is sensitive or confidential and not readily accessible to the public and only limited information is therefore made available on each event in this dissertation.

Table 6: Summary of the available record of events occurring in KNT's.

Township Name	Total Surface Area (Ha)	No. of Events per Township	% of all Recorded Events
Khutsong Ext 1	35	1	0
Khutsong Ext 2	96	32	15
Khutsong Ext 3	97	17	8
Khutsong Ext 4	10	0	0
Khutsong Ext 5	11	0	0
Khutsong Ext 6	20	9	4
Khutsong Proper	207	124	57
Informal Settlement	164	20	9
Undeveloped Areas	678	16	7
Total	1 318	219	100

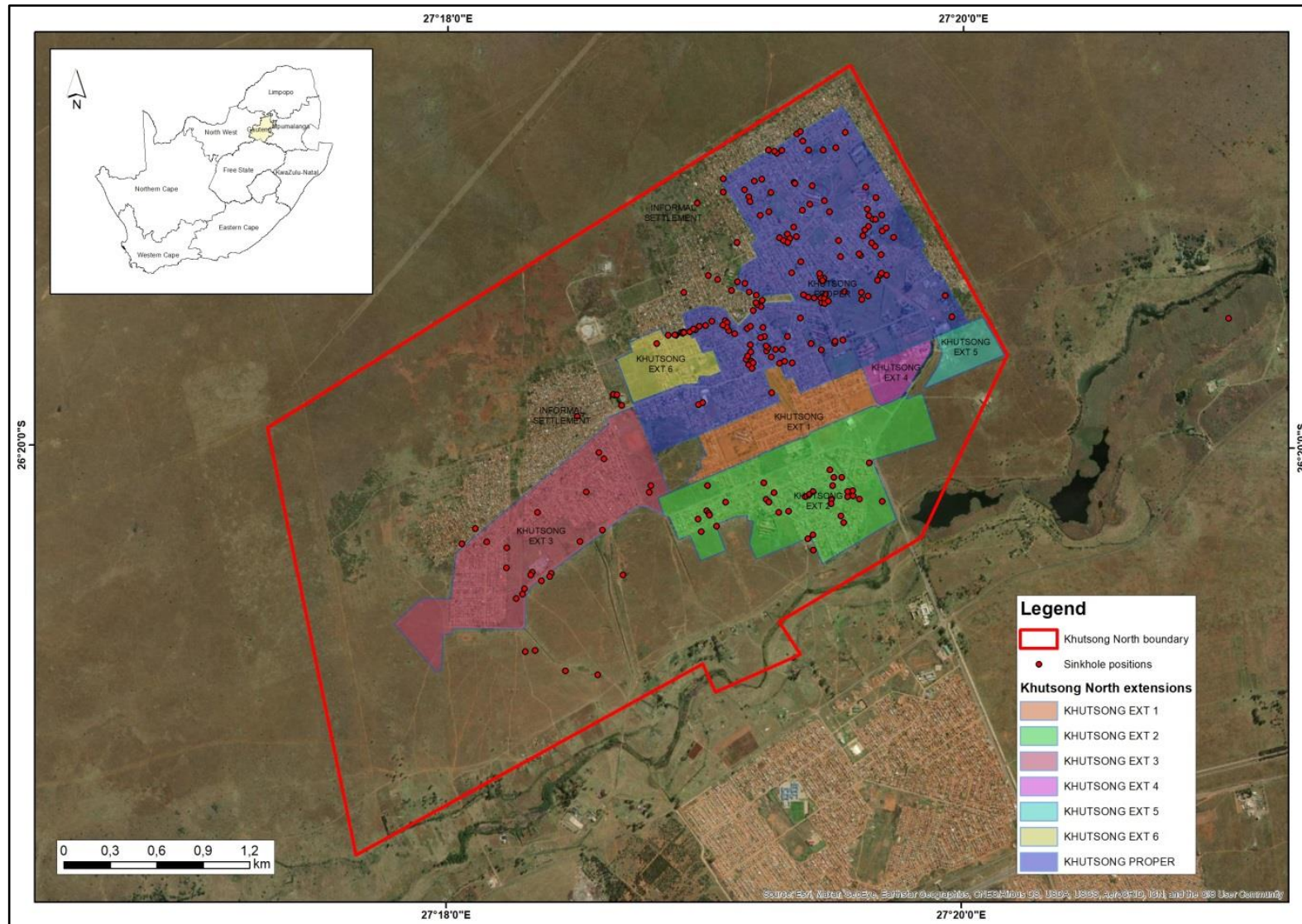


Figure 31: Spatial distribution of the available events record, Khutsong North

4.3.1 Type and statistical analysis of events occurring in Khutsong North

The following is noted or derived from the KNT's events database:

- The largest reported event (sinkhole) with ID 1439 is in Khutsong Proper. It is estimated to have occurred during 1995 with unspecified possible cause and have dimensions of 65 m width x 10 m deep
- The deepest recorded event is 10 m and a number of events falling in the very large category recorded this depth. These were recorded mainly in Khutsong Proper, Khutsong Extension 2 and 3
- Only one ground crack event was recorded (ID 4828) to have occurred between Khutsong tower and pump house. It is located just north of north-eastern corner of Khutsong Extension 3 and west of the south-western corner of Khutsong Extension 6
- A total of 124 (57%) events occurred in Khutsong Proper, 32 (15%) in Khutsong Extension 2 and 17 (8%) in Khutsong Extension 3. Other events to make up the 219 occurred either in other townships or the undeveloped surrounding areas
- The oldest known event(s) is estimated to have occurred during 1975 and the most recent event is recorded to have occurred during 17 August 2020
- 172 (79%) of the available records in the database have information about the type of events occurred. From this available information, 87 (40%) were recorded as sinkholes, 84 (38%) as subsidences and only one was recorded as a crack. A total of 47 (22%) were recorded as undefined. Figure 32 and 33 shows the distribution of events occurring in Khutsong North
- The research area is underlain entirely by the Monte Christo Formation and therefore, all the events (sinkholes and subsidences) in KNT's occurred in this geological formation.

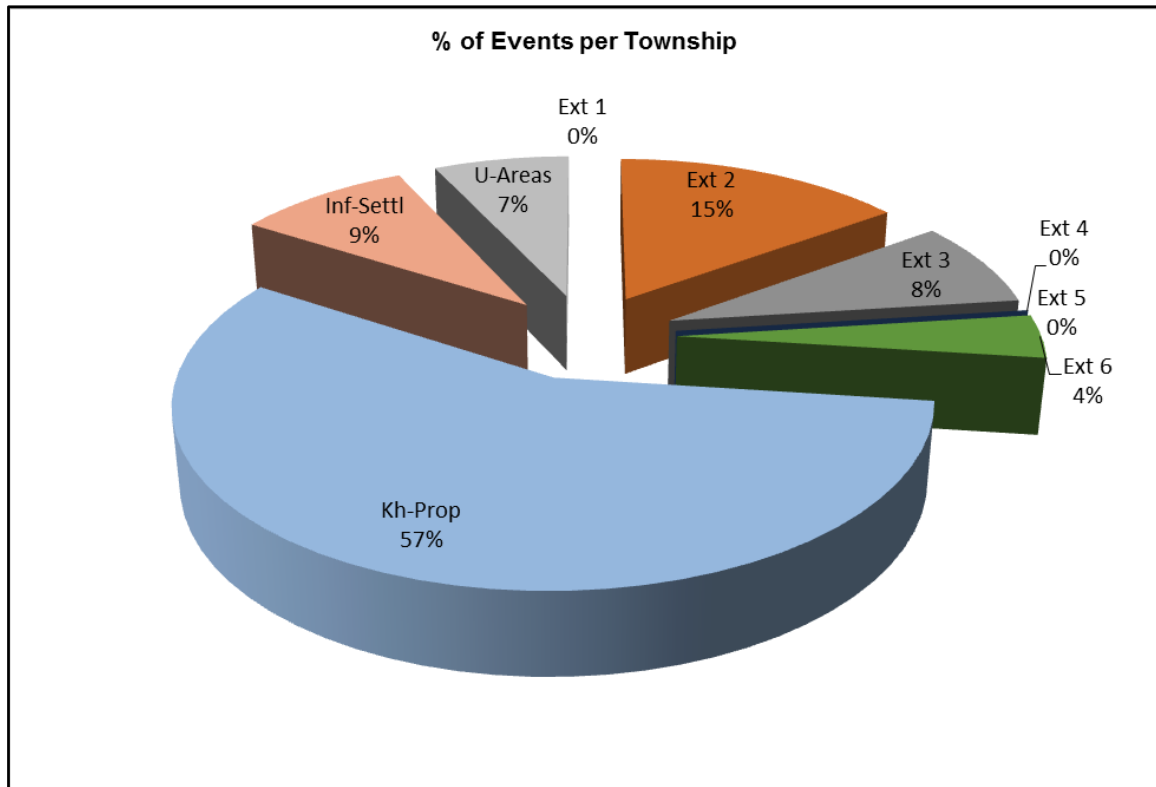


Figure 32: Showing the percentage distribution of events per township, Khutsong North.

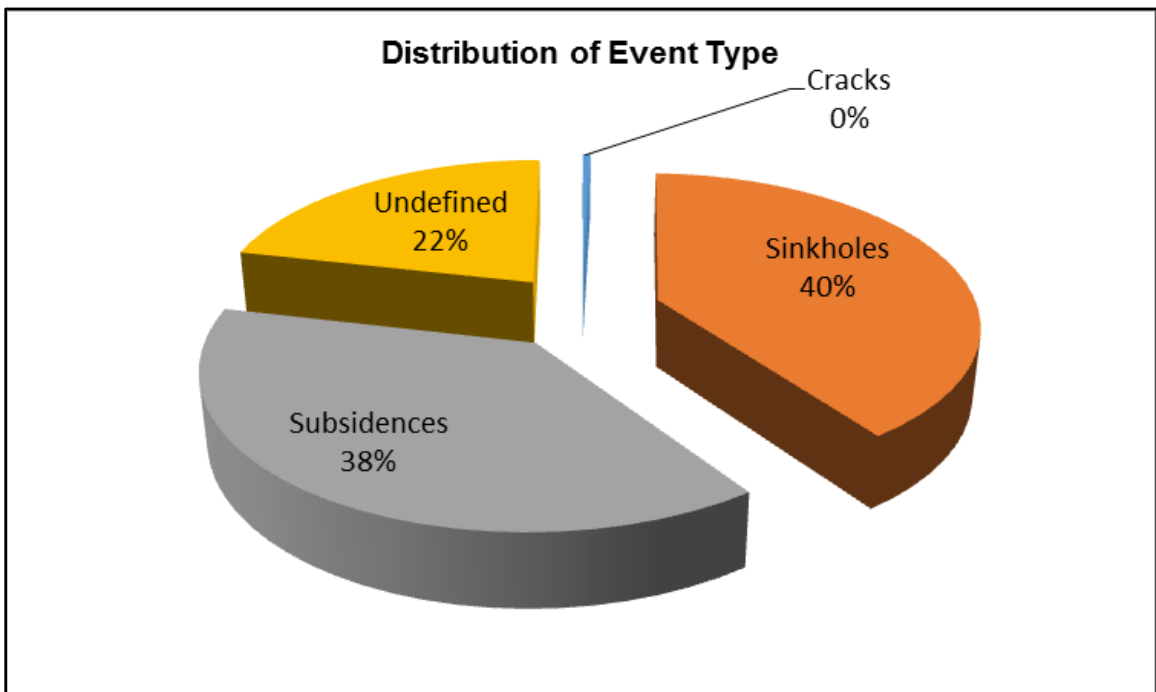


Figure 33: Showing the percentage distribution of events type, Khutsong North.

4.3.2 Quality of events database

The CGS undertakes a process to verify all reported dolomite ground instability events and this is ongoing as events are reported or information get submitted. It should be noted however that the reporting to CGS is not enforced and/ or the general public (affected persons and authorities) may not be aware of the reporting requirements. As such, there could be more events that have occurred within the KNT's, but were either not reported or just backfilled without creating any record of an event resulting in the loss of information regarding those events.

Only 48 (22%) of the events in the database have information regarding the possible cause of the crack, sinkhole or subsidence formation, i.e. 41 (19%) of events were formed as a result of leaking wet services or manhole overflow and 7 (3%) as a result of poor storm water management. Unfortunately, a total of 171 (78%) of the events in the database did not have any information regarding the cause of an event and are recorded as not specified. Figure 34 shows the distribution of the cause of event across the research area.

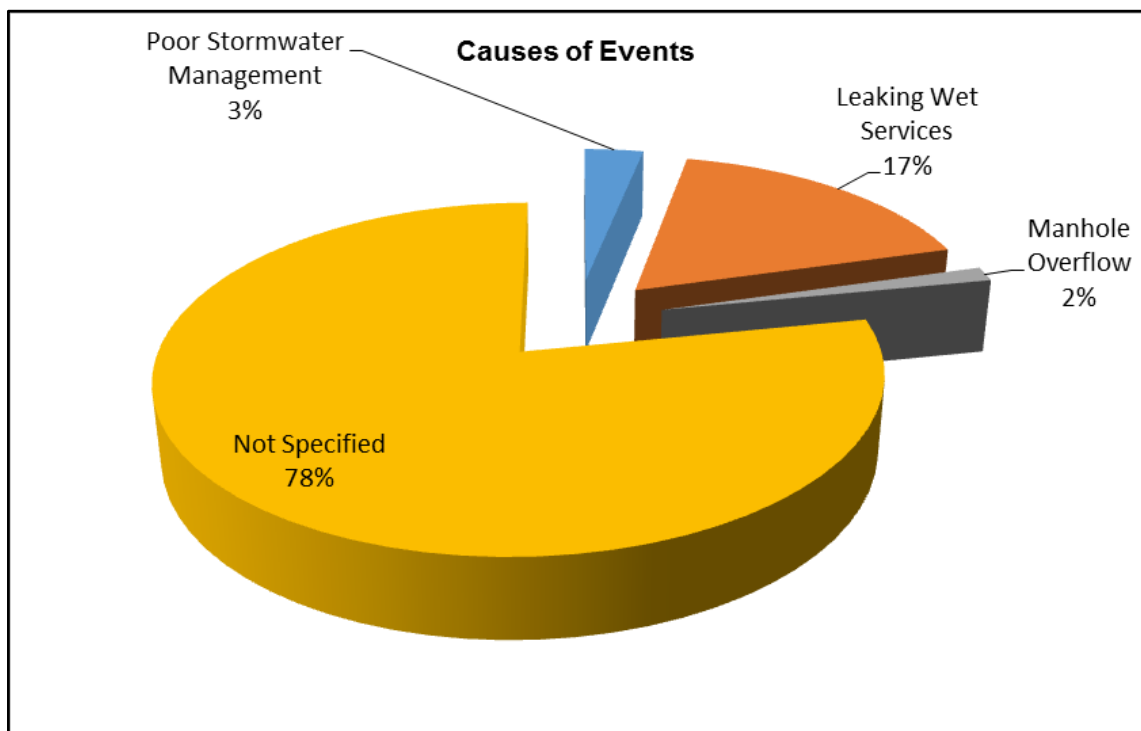


Figure 34: Showing the percentage distribution of events per cause, Khutsong North.

Figure 35 and 36 shows the yearly occurrence of events across the KNT's and the surrounding areas. Most of the event data points only have estimated date of occurrence, with only 48 (22%) have at least the month and the year of occurrence. The year 1995 is estimated to have recorded the most ground instability events in the history of the research area, i.e. 129 (59%) of the total events record. The average number of events per year occurring within the research area, with and without the 1995 records is as follows:

- With 1995 records: Average = 11.5 events year
- Without 1995 records: Average = 4.7 events per year

A big spike in the events database for 1995 is definitely flawed as the occurrence dates for most events recorded pre-year 2000 was only estimated. As such, events estimated to have occurred during 1995 might have occurred much earlier but were only documented during that year.

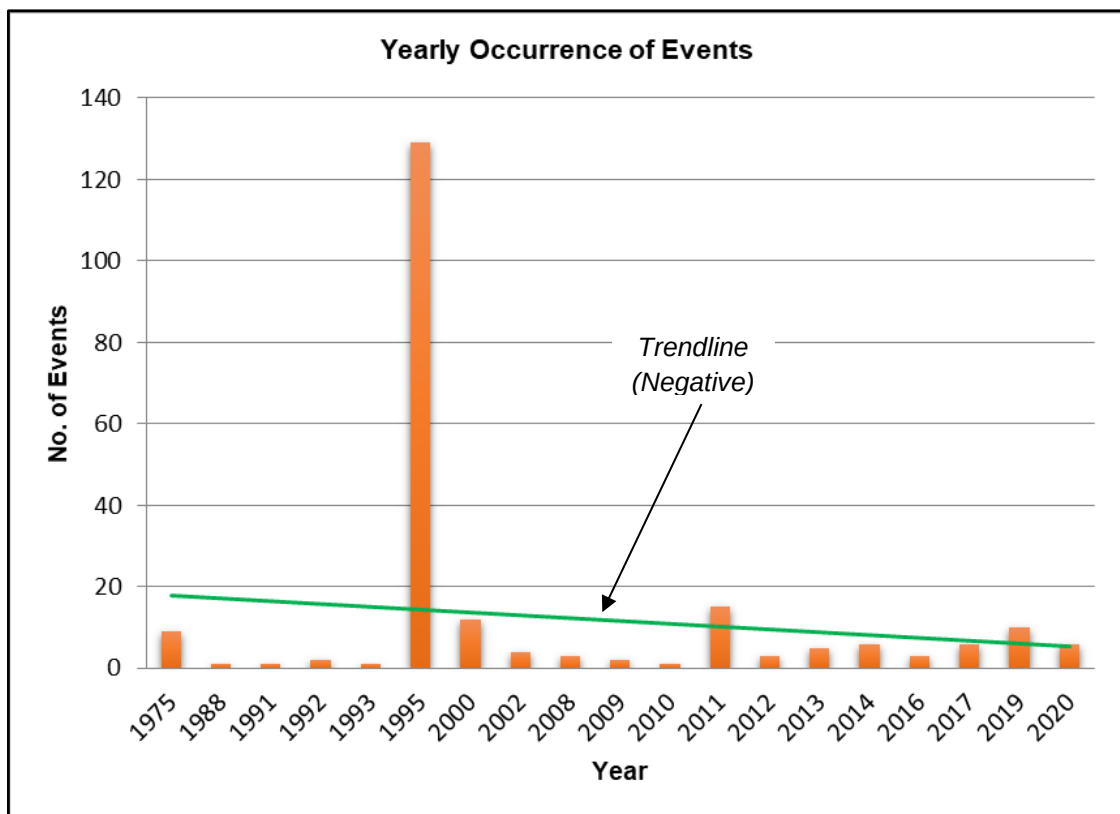


Figure 35: Yearly occurrence of ground instability events with 1995 records, Khutsong North.

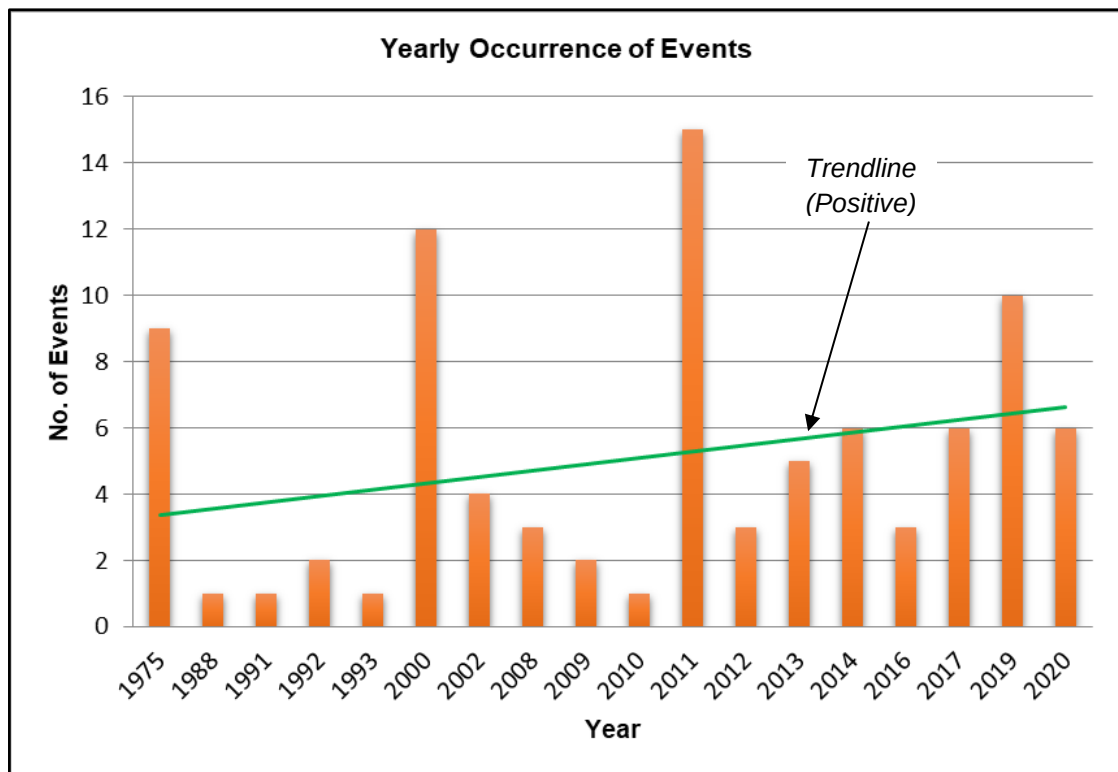


Figure 36: Yearly occurrence of ground instability events without 1995 records, Khutsong North.

Figures showing yearly events record indicated problems with quality of the database, more particularly the number of events estimated to have occurred during 1995. Based on the yearly distribution of events and their estimated dates of occurrence, it is prudent to assume that not all the events occurring within KNT's were recorded or some events could also predate 1975. Also, an important inference could be made from an events dataset as presented in Figure 35 and 36, more particularly when considering a trendline in data analysis with or without the 1995 record of events. A trendline in data analysis with the 1995 records shows a steady decrease (negative) in the yearly frequency of events occurring between 1975 and 2020, however, a positive trendline is observed for data analysis conducted without the 1995 records.

It is therefore concluded that, if a regular and dependable recording of events is not prioritized on dolomite land, this may prohibit a credible process for hazard characterization, hazard rating and vulnerability analysis of such areas.

4.3.3 Consequence of events occurring in Khutsong North

The consequences of sinkhole and subsidence formation in the KNT's have led to the demolition of many houses, damaged properties and infrastructure (wet services, storm water and roads), which has resulted in the loss of years of investments by both the state and individual home owners. MCLM has adopted various actions with the primary objective to manage the hazardous dolomite situation in Khutsong. During the last 20 years, the MCLM City Council have commissioned regional dolomite stability investigations, approved re-settlement plans and adopted a comprehensive Dolomite Risk Management Strategy (DRMS – 2005 by VGIconsult), all these are good decisions on paper but lack of implementation means that in practice these serves no purpose.

Sinkhole formation in particular, has caused water and sewer network failure leading to unacceptable low-levels of basic service delivery creating serious health risk for thousands of Khutsong residents. Below are some pictures and media headlines showing events that have occurred within the KNT's including the surrounding areas.

Impact on housing:

A total of 25 100 residential units falling within the “extremely high risk dolomite zones” were identified during 2004 for resettlement from KNT's.

Figure 37 indicates the damage to two houses caused by a very large sinkhole on a busy Nxumalo Road in Khutsong Proper. This sinkhole was reported as being caused by decaying old wet services infrastructure traversing the area.



Figure 37: A very large sinkhole causing damage to main Nxumalo Road, Khutsong Proper.

Figure 38 shows a trail of destruction caused by a series of sinkholes that occurred in Adatite Street, Khutsong Proper. These sinkholes occurred due to poor storm water management, which caused damage to water and sewer lines leading to widespread leaking and back ponding of sewage.



Figure 38: Trail of destruction to housing at Adatite Street, Khutsong Proper.

Figure 39 and 40 shows a subsidence forming against the house wall causing severe wall distress (cracks) and structural deformation in Khutsong Extension 3. This subsidence was caused by a leaking sewer/ waste water pipe from the house.



Figure 39: A subsidence forming against the house casing a severe wall distress, Khutsong Extension 3.



Figure 40: Sewage damming against the wall, Khutsong Extension 3.

Figure 41 shows media coverage and interviews with affected residents living in Adatite Street, Khutsong Proper. Residents expressed fear as their houses are being swallowed-up by sinkholes.

Sinkholes pose a danger for Khutsong residents

Friday 28 February 2020 - 5:24am

Facebook Twitter Email +

Sinkholes pose a danger for Khutsong residents

KHUTSONG, JOHANNESBURG

Copy link

194

The houses that others were moved to are not good enough.

MARGRET PILANI | RESIDENT

eNCA

BREAKING NEWS MBALULA: PLANS AFOOT TO TURN AROUND PRASA'S FORTUNES

Residents of Khutsong on the West Rand of Johannesburg are living in fear as dwellings are being swallowed up by sinkholes. The area was reported unsafe as far back as 1997. Courtesy #DStv403

JOHANNESBURG - Residents of Khutsong on the West Rand of Johannesburg are living in fear as dwellings are being swallowed up by sinkholes. The area was reported unsafe as far back as 1997. Years later, families continue to be left homeless as they wait for the municipality to move them. The sinkholes are spreading and causing damage and destruction in their wake.

Figure 41: An example of a media article reporting on the Khutsong sinkhole situation.

Impact on municipal infrastructure:

The provision of human settlements comes along with massive infrastructure development to provide critical services such as water, sewer, storm water reticulation and roads. Most of these critical infrastructural developments have either been damaged or destroyed in Khutsong.

Figure 42 shows a bulk water supply pipeline linking a reservoir to Khutsong South, Khutsong North Extensions and Waverdiend that fell into a sinkhole, leaving many homes and businesses without piped water for months.



Figure 42: Damage to a bulk water supply pipeline, Carletonville area.

Figure 43 shows an overflow from a municipal manhole due to back ponding of sewer and effluent is now flowing into an existing sinkhole in Khutsong Proper. The back ponding has caused problems for residents in Adatite Street and the situation means that some basic human rights have been violated, i.e. the right to an environment that is not harmful to their health or well-being as sewer effluent is back ponding into house toilets.



Figure 43: Broken, blocked and back ponding sewer line at Adatite Street, Khutsong Proper.

Figure 44 shows Khutsong Main Reservoir (Khutsong North) and related infrastructure. In 2015, the floor of the main reservoir failed likely due to a sinkhole leading to a severe leaking and water losses. The reservoir was decommissioned in July 2016 due to flooding of the surrounding areas and subsidence formation.



Figure 44: A decommissioned Khutsong Main Reservoir, border of Khutsong Extension 3 and 6.

Risk always exist on dolomite land, but it can be managed through implementation of appropriate precautionary measures, as set out in SANS 1936 Part 3 of 2012. A basic principle should be borne in mind when considering development of dolomite land that can be expressed as follows:

Dolomite Hazard + Dolomite Risk Management Strategy = Acceptable Risk

An area maybe declared to have “Acceptable Risk” if the identified dolomite (geological) hazard is managed through a pro-active Dolomite Risk Management Strategy (DRMS) consisting of elements such as the following:

- Appropriate development
- Appropriate precautionary measures
- Appropriate design and density of wet services infrastructure
- Pro-active maintenance of wet services infrastructure
- Appropriate design and maintenance of storm water management
- Continuous awareness and vigilance
- Detailed and complete record (database) of instability events

A DRMS for MCLM was developed and approved by the City Council in 2005. However, this strategy has not yet been implemented.

4.3.4 Event size distribution

Buttrick *et al* (2001) modified sinkhole size categories and these have since been adopted into the current deemed-to-satisfy standard (SANS 1936) for safe development of dolomite land. These categories are based on the potential development space of a sinkhole and are widely used to refer to sinkholes sizes during dolomite stability analysis. Table 7 below shows sinkhole size categories as proposed by Buttrick *et al* (2001).

Table 7: Suggested scale of sinkhole sizes (Buttrick *et al*, 2001).

Maximum Potential Development Space	Maximum Diameter of Surface Manifestation (m)	Suggested Terminology
Small potential development space	<2	Small sinkhole
Medium potential development space	2 – 5	Medium-size sinkhole
Large potential development space	5 – 15	Large sinkhole
Very large potential development space	>15	Very large sinkhole

From the available information in the database and based on the size categories indicated in Table 7, Figure 45 and 46 show event size distributions in the KNT's area. A total of 172 of the 219 events has information about their sizes. Only 8% of events occurring in the research area fall within the small size category (<2 m in diameter) followed by 20% in the medium size category (2 to 5 m diameter). The large size category (5 to 15 m diameter) make-up 34% and very-large size category (>15 m diameter) contributes 38% of the total events.

Therefore, 72% of events recorded across the KNT's and surroundings were greater than 5 m in diameter and generally indicative of a thick overburden. These records fit-in well with the dominant depth to dolomite bedrock summarized in Table 5.

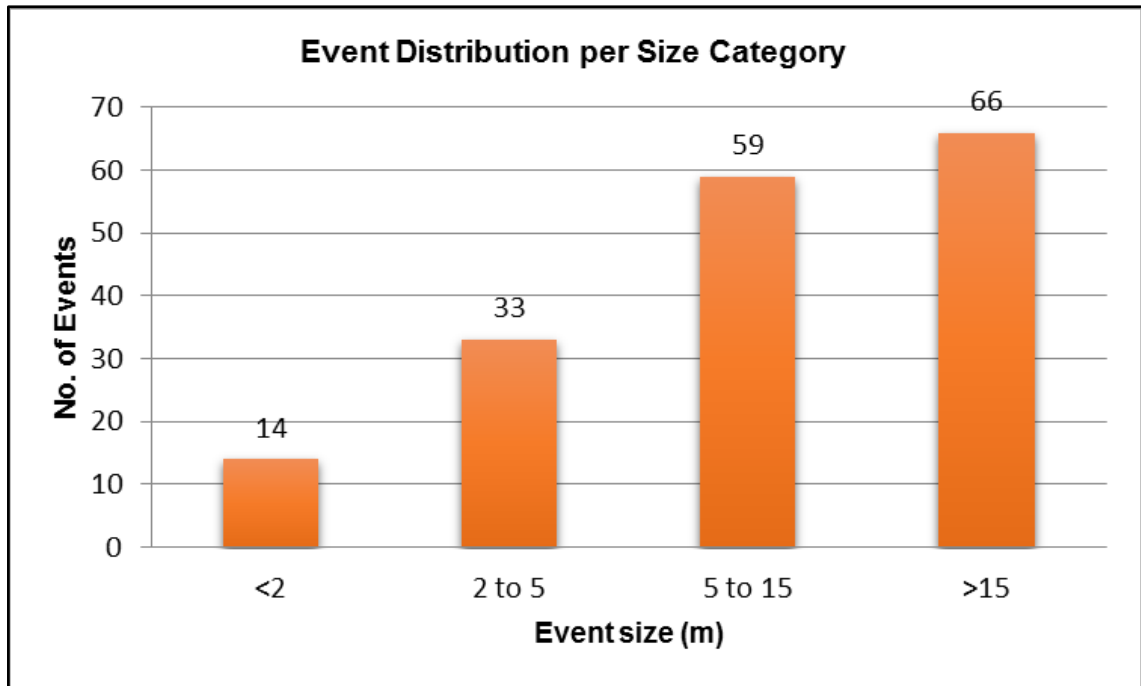


Figure 45: Showing events distribution per size category, Khutsong North.

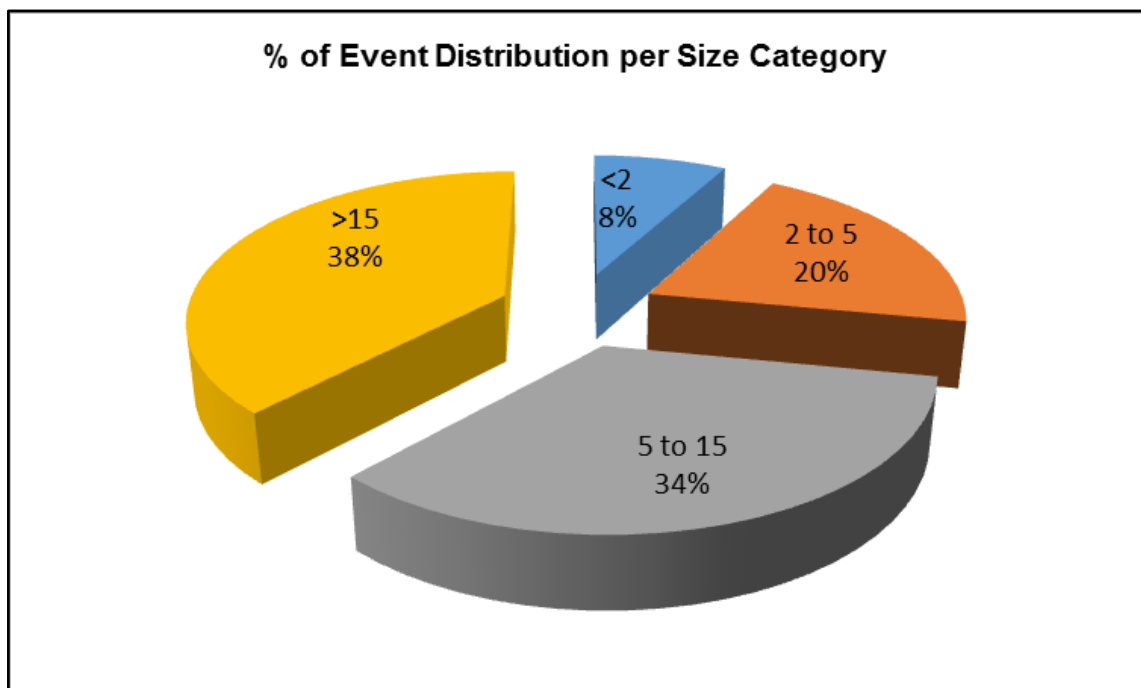


Figure 46: Showing percentage distribution of events per size category, Khutsong North.

4.4 DEPTH TO DOLOMITE BEDROCK COMPARED AGAINST EVENT SIZE

In terms of the “Modified Method of Scenario Supposition”, risk characterization for sinkhole formation is based on a list of factors and prevailing scenario. One of the most important factors is depth to dolomite bedrock and it is assumed that depth to dolomite bedrock head has a direct influence on the size of event that could develop.

In order to establish the correlation between event (sinkhole) sizes and the depth to solid dolomite bedrock, the available records of boreholes drilled across KNT’s was used. Based on the sinkhole size categories as proposed by Buttrick *et al* (2001), using only the valid borehole (confirmed bedrock depth) data and event records with known event diameters are indicated in Table 8.

Table 8: Depth to bedrock depth compared against known event sizes.

1	2	3	4	5
Dolomite Bedrock Depth Below Surface (m)	% of BH’s with Confirmed Bedrock Depth	Expected Event Size (m)	% of Events at Specific Size Category	% Variance
0 – 5	14	Small (<2)	8	6
5 – 15	23	Medium (2 – 5)	20	3
15 – 30	28	Large (5 – 15)	34	6
>30	35	V. Large (>15)	38	3

Column 2: Based on the data from Figure 29.

Column 4: Based on the data from Figure 46.

In general, events size distribution also corresponds well with the confirmed dolomite bedrock, as indicated in Table 5. The research area is therefore dominated by deep (>15m) dolomite bedrock and more events (72%) falling within large to very large category have been recorded across KNT’s.

The relative good correlation supports the notion that depth to dolomite bedrock has a direct influence on the expected size of events in a given area. This correlation however, always needs to be verified through factual data from further drilling investigations conducted adjacent to the known sinkhole events. However, further drilling investigations were not part of the current research objectives. Using the available borehole database, it was therefore not always possible to confirm this correlation with a greater degree of confidence.

Figure 47 shows that the dolomite bedrock in the research area is mainly deeper than 15m below surface and more ground instability events have either been recorded in areas where dolomite bedrock occur at depths ranging between 15m to 30m from surface, transition zones or along infrastructure (wet services, roads, etc.) lines.

As indicated in Section 2.2.2 of this dissertation, occasional pockets of thick non-dolomitic transported soils (aeolian sand, silt and clay) occur in the research area and these suggest the presence of more recent palaeo-features (palaeo-valleys). Since no geotechnical investigations or detailed mapping was conducted prior to the establishment of KNT's, such areas were never avoided for development. Depending on the type of material that have filled these palaeo-valleys, such features may act as aquitards and help slow down the process of subsurface erosion or have a positive influence on the occurrence of instability events in places.

The positions of these palaeo-features maybe represented by the isolated pockets of thick overburden or deep (>30) dolomite bedrock, which dominate Extension 1, 2 and 4, and limited parts of Extension 3, 5 and Khutsong Proper. From the statistical analysis of the events distribution, it is also noted that no instability event was reported in Khutsong North Extension 4 and 5, while only one event was report in Extension 1. However, no palaeo-feature focused geotechnical investigations or detailed mapping was conducted during this research to confirm the link between the non-occurrence of events and nature of the infill material in palaeo-features. Therefore, spatial distribution of events in the research area may be linked either to anthropogenic activities (i.e. the age of individual townships, age of wet services or leaking, their spatial densities and storm water ponding) or even more importantly, the gaps in the available database.

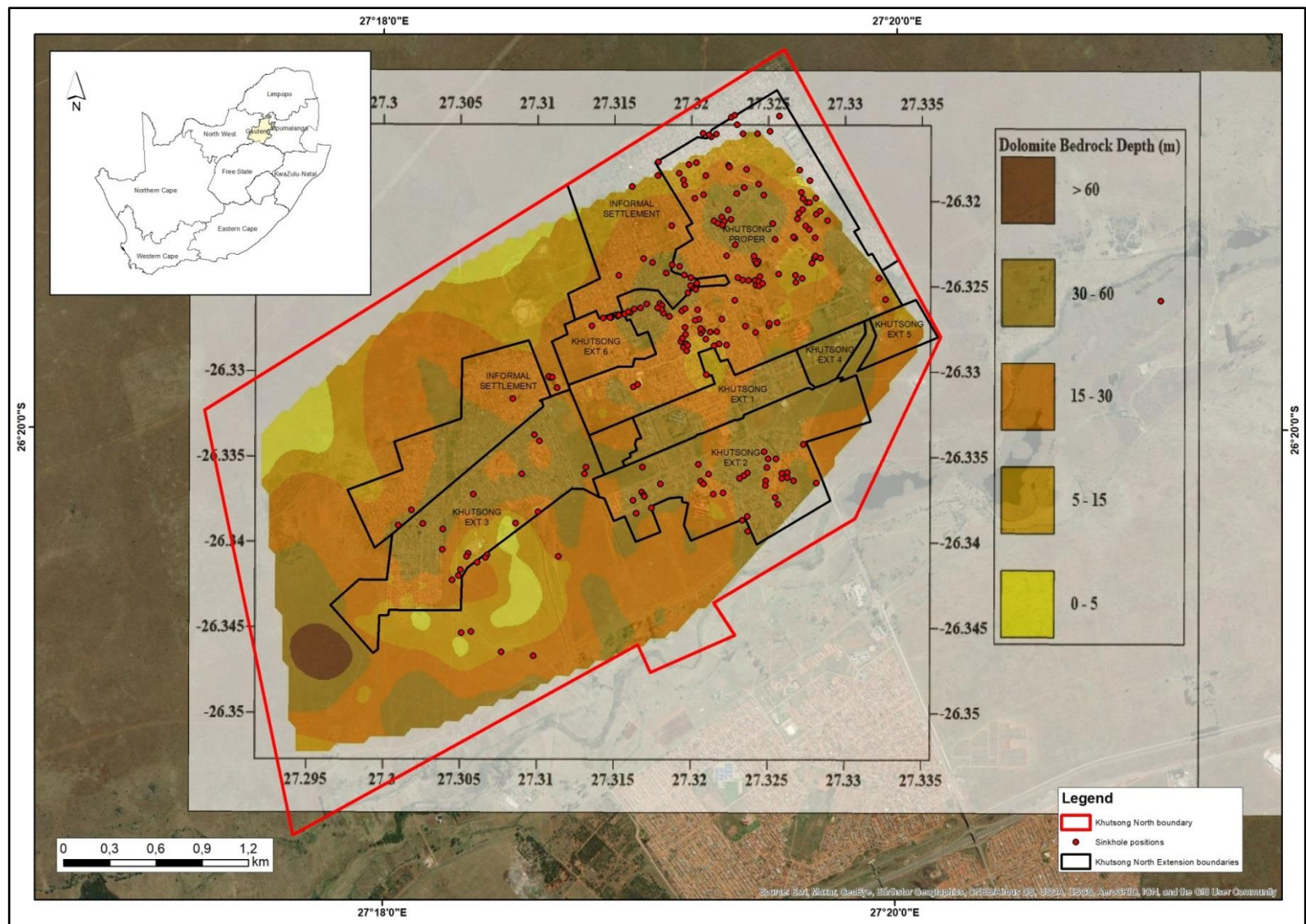


Figure 47: Depth to dolomite bedrock compared to events distribution, Khutsong North.

CHAPTER 5 – CASE STUDY: A DESK TOP STUDY AND SINKHOLE HAZARD DETERMINATION FOR KHUTSONG NORTH TOWNSHIPS

5.1 BACKGROUND

Safe development of dolomite land is based on the understanding of geological, geotechnical, structural and hydrological settings, hazard characterisation using accepted methods, establishment and maintenance of appropriate mitigation measures, and gathering of a complete record of ground instability events. In South Africa, the term “Dolomite Land” has a negative connotation due to its association with damaging effects of sinkholes and subsidences (Buttrick *et al.* 2001). Such damaging effects have been discussed in Section 4.3.3 of this dissertation. According to Jennings (1966a), a structure built on dolomite subsoil, be it a house, office block, industrial plant, road, railway line, dam, etc., might be exposed to the danger of subsidence.

Various dolomite stability studies have been undertaken across KNT's since 1980 (report boundaries, Figure 6) in order to understand the geotechnical conditions of the underlying strata and these generally concluded that the region is dominated by high risk dolomite land. Usually, such studies include compilation of data sets (boreholes, trial pits, geophysical data and ground instability event records) used during site characterization and decision making process on the permissible land use types or appropriate mitigation measures required.

According to the VGIconsult (2013) study, twelve sinkholes were recorded in the research area between 1956 and 1987 (i.e. 12 events in 31 years), while sixty two sinkholes were recorded between 1986 and 1995 (i.e. 62 events in 9 years). These numbers alone seem to suggest that as urban development increases, occurrence of dolomite related instability events also increases in Khutsong North.

Therefore, given the prevailing situation in KNT's and using the available data sets (geological, geotechnical, geohydrological and events record), a unique opportunity is presented to at least attempt to determine the origins of the hazard and calculate the hazard rating for the research area.

5.2 GEOLOGICAL SETTING

Sinkholes and subsidences are essentially geological phenomena (Jennings, 1966a). Consequently, it is important that the professional team responsible for any building project on dolomite land understand the geological setting and the mechanisms involved in the weathering of dolomite rock. It is also a general understanding that the stratigraphic position and chert content give different geotechnical behaviour patterns across the dolomite formations in South Africa, i.e. chert-rich (wad-poor) dolomite formations usually record more sinkhole and subsidence occurrences.

According to Roux (1984) and Wolmarans (1984) *in* Richardson (2013), the stratigraphic position and high chert content can already give an indication of the likelihood of sinkhole and subsidence formation. Wolmarans (1996) further suggested that the high chert content of the Eccles (>10%) and Monte Christo Formation (0 to 10%) promotes differential leaching with associated subsurface cavity formation. According to Richardson (2013), the largest percentage of events (36%) have occurred on the chert-rich Monte Christo Formation of the Malmani Subgroup.

However, according to the published 1:250 000-scale Geological Map (2626 West Rand), Malmani Subgroup is undifferentiated in the FWR region and this has always left unanswered questions when one attempt to explain the phenomenon of increased sinkhole formation in the KNT's, and more so because, Khutsong is located within the non-dewatered BTC.

Contrary to the published 1:250 000 geological map, Winde and Erasmus (2011), have recently modified an unpublished map by Wolmarans (1984) showing different Formations of the Malmani Subgroup in the FWR and this map (Figure 48) places the KNT's entirely on the chert-rich (wad-poor) Monte Christo Formation, which is known to be highly susceptible to sinkhole formation.

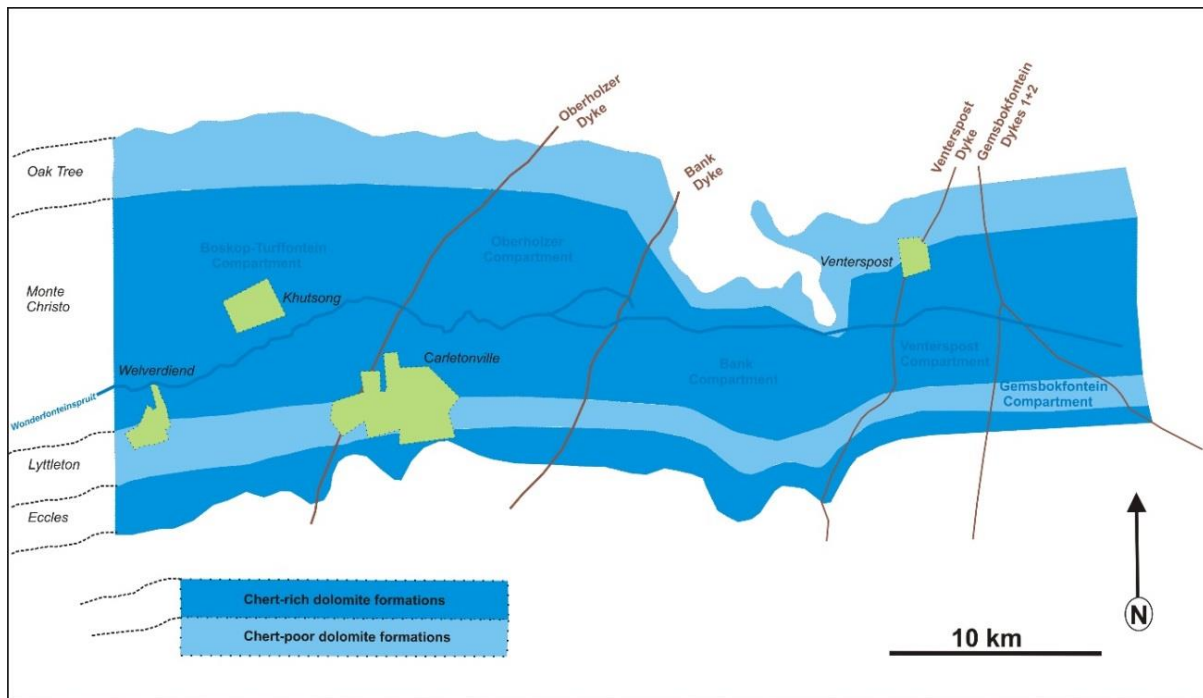


Figure 48: Position of the Khutsong North within the Malmani Subgroup Formations in the FWR region (after Wolmarans, 1984 modified by Winde and Erasmus, 2011).

However, the stratigraphic position of the KNT's alone does not fully explain the sudden increase in the sinkhole and subsidence formation in the area or the extent of their damaging effects. Reasons for a steady increase (confirmed by Figure 36) in the events occurrences may include the area being underlain by chert-rich dolomite formation in a zone of the Boskop-Turffontein Compartment (BTC) that is naturally dewatered and subjected to an urban induced concentrated water ingress (Winde and Erasmus, 2011).

5.3 HYDROLOGICAL SETTING

Dolomite related ground instability events are usually induced by human activity, but may also occur naturally. The primary trigger mechanisms include concentrated ingress of surface water (ingress scenario) or lowering of the groundwater table (dewatering scenario). These two possible scenarios may arise either naturally or artificially as a result of human activities and are summarised in Table 9.

Table 9: Summary of ingress and dewatering scenarios.

Scenario	Natural Occurrence	Artificial Occurrence (Due to human influence)
Dewatering	• Due to severe drought. • Change in ground surface topography.	• Excessive pumping of groundwater either for agricultural purposes and use in mining activities or due to lowering of water table to allow for safe mining.
Ingress	• Natural ponding of rain water. • Swallow holes	• Leaking wet services (water & sewer lines). • Poorly designed/ managed stormwater drainage systems.

Most of the FWR Dolomite Groundwater Compartments were artificially dewatered to allow for safe mining of gold resources and today, the groundwater level is generally greater than 60 m below ground level providing space for subsurface erosion. However, some compartments including the BTC, on which the Khutsong North is located, are known to have not been affected by this artificial lowering of the water table.

Therefore, the current deep (>60m from surface) groundwater level measured within this compartment is generally attributed to the natural dewatering as explained in the scientific literature like Bezuidenhout and Enslin (1969), Brink (1979), Winde and Erasmus (2011).

Brink (1979) discusses the issue of natural groundwater lowering within some Groundwater Compartments (GWC's) of the FWR during the post-African period of minor incision of the Wonderfontein Spruit. During this period, erosion base would have been lowered, pre-existing cavities exposed and masses of fine-grained materials transported into the deeper lying receptacles or cavities. This situation would trigger accelerated subsurface erosion by ingress of water from stormwater and/ or leaking wet services resulting in continuous widening of pre-existing cavities, which would eventually lead to collapse of the final arch due to lack of support forming a sinkhole at surface.

In this context, it is worth noting that the observed sudden increase of sinkhole and subsidence formation in the KNT's may be related to a recent (past few decades or century) natural drop in the groundwater table coupled with increased urban densification, but the scale and impact of this natural dewatering is yet to be quantified. According to Gutierrez *et al* (2014), impacts and hazards associated with karst are rapidly increasing as development expands upon karst-areas without proper planning taking into account the peculiarities of these environments, and this has led to an escalation of karst-related engineering problems. Activities associated with development normally, result in a disturbance of the metastable conditions previously prevalent in the dolomite karst environment (Buttrick and Roux, 1993).

Also, decades of surface erosion has the potential to lower the topographic surface in the lower (western) part of BTC and thus, causing the water table to intersect with surface plane. Therefore, lowering of the topographic surface over time, might result in the continuous lowering of water table intersection plane, as such, this may have resulted in the natural groundwater level drawdown at BTC.

The suggested reasons for increased ground instability events coincide well with the location of the KNT's, which is in close proximity to the Oberholzer Dyke forming the upper (eastern) boundary of the BTC. These reasons also fit-in well with the groundwater table reported in various Dolomite Stability Investigations (DSI's) conducted across the research area, generally at 60m below surface. A typical groundwater table across various GWC's of the FWR is illustrated in Figure 49.

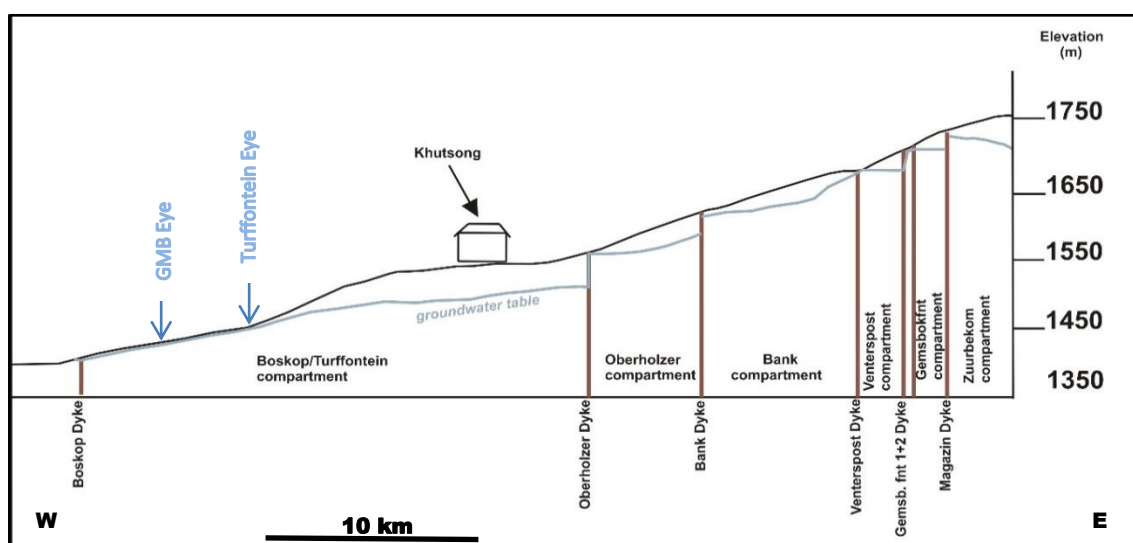


Figure 49: Geohydrological section through dolomite compartments of the FWR (after Brink, 1979 modified by Winde and Erasmus, 2011).

It is also important to note the position of Gerhard Minnebron (GMB) and Turffontein Eye (the natural decanting points) in relation to Khutsong, and in the context of the suggested natural dewatering. In summary, over geological time when erosion takes place on the lower (western) part of the BTC, the topographic surface will be lowered and thus, the two natural decanting points resulting in the lowering of the GW table.

5.4 HAZARD CLASSIFICATION AND OCCURRENCE OF EVENTS

Hazard identification, classification and use of the events record to determine hazard rating are some of the critical steps in the evaluation of sites on dolomite land. The available percussion boreholes (313) were used to classify the research area and a record of events (219 recorded over a period of 45 years, i.e. 1975 to 2020) was used to calculate the number of ground instability events per hectare occurring in the Khutsong North, an area where sinkhole and subsidence hazard has been established.

5.4.1 Hazard classification and zoning

The available individual percussion boreholes (313) drilled across the research area were each assigned an IHC and then grouped into Low, Medium and High hazard zones in line with the current practice (Table 10). Important to note, all these boreholes were only drilled decades after the Khutsong North was established.

Table 10: Inherent hazard category and the number percussion boreholes.

Inherent Hazard Category	Inherent Hazard Class (IHC)	No. of boreholes	Percentage (%)
Low	IHC 1 and 2	1	0.32
Medium	IHC 3 and 4	189	60.38
High	IHC 5 to 8	123	39.30
Total		313	100

Based on Table 10, Figure 50 and 51, it can be concluded that over 99% of the boreholes drilled in the research area classify as having a Medium to High Hazard rating, with only 0.32% being classified as representing Low Hazard. Medium to High hazard conditions therefore prevail in the research area.

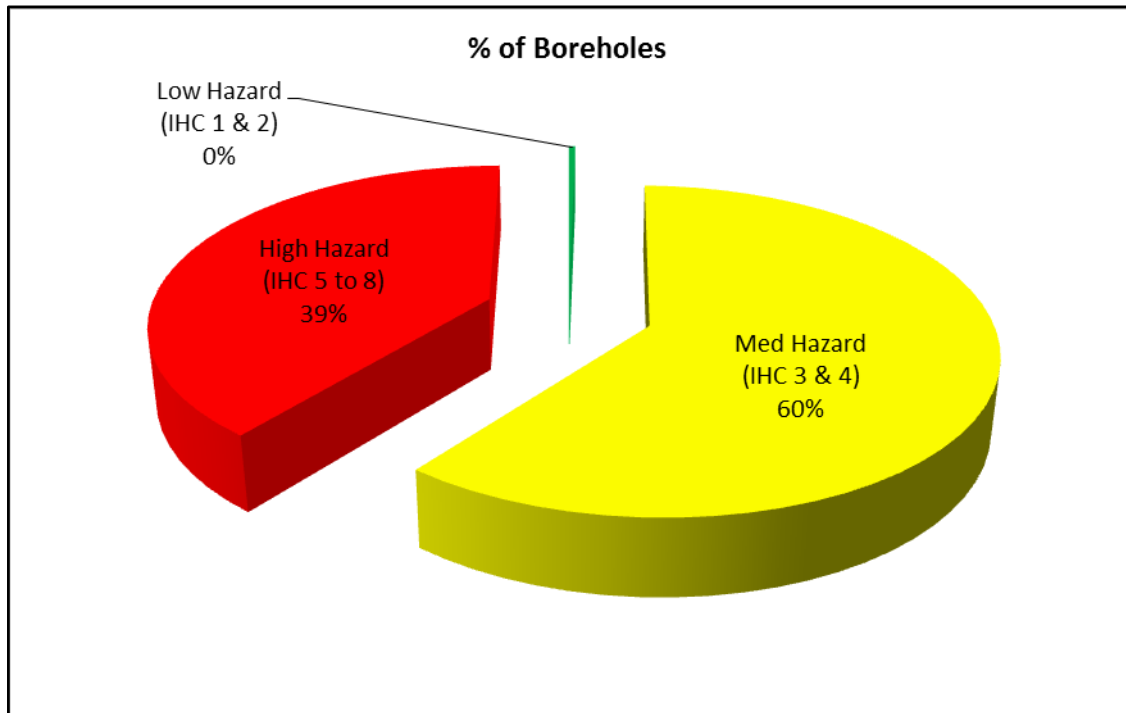


Figure 50: Percentage of percussion boreholes in each of the inherent hazard category.

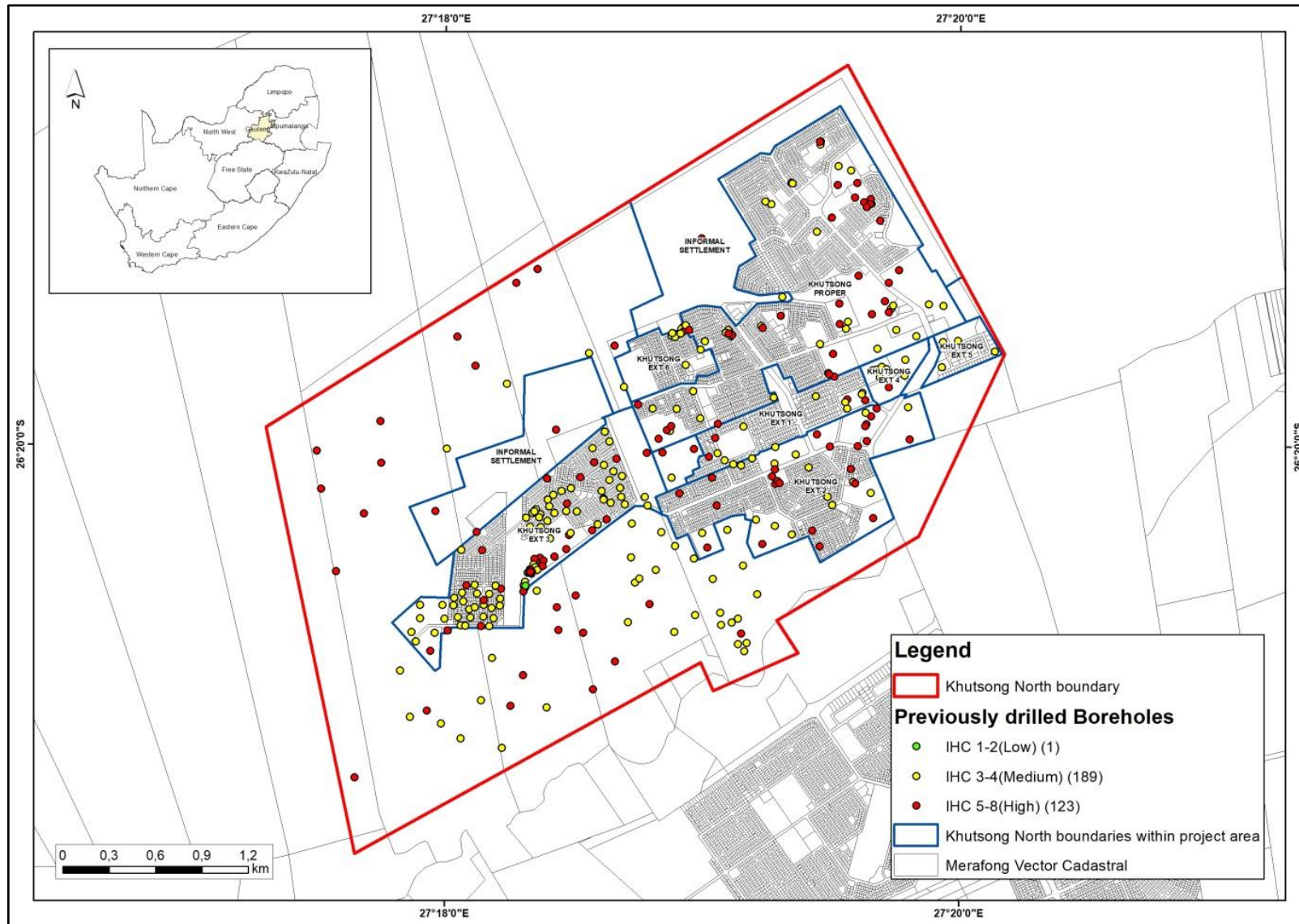


Figure 51: The distribution of the available percussion boreholes and inherent hazard category.

5.4.2 Calculating events per hectare

The actual record of 219 events occurring during a period 1975 to 2020 across the research area is currently kept at the CGS ENGEODE Database and was used to calculate the number of events per size category. This data set was also manipulated to determine the number of events per hectare occurring in Khutsong North and ultimately, the hazard rating for the study area. Table 11 presents the available number of events per size category over time.

Table 11: The available number of events and percentage recorded per size category.

Inherent Hazard Category (Event Size in meters)	Number of Events – all time	Percentage – all time (%)	Number of Events – last 20 years	Percentage – last 20 years (%)
Undefined	47	22	23	32
Small (<2m)	14	6	13	19
Medium (2 – 5m)	33	15	16	23
Large (5 – 15m)	59	27	14	20
Very Large (>15m)	66	30	4	6
TOTAL	219*	100 %	70	100 %

Using the combination of available event records and the prevailing geological, zones of Low, Medium and High hazard areas were indicated on a base map with the total surface area assigned to each hazard class presented in Table 12.

Table 2 in Section 2.3, as proposed by Buttrick and Van Schalkwyk (1995) the expected number of events can be predicted in the Khutsong North region for Low, Medium and High Hazard Class zones, and each of these zones are presented in Table 12. From this table, it is noticed that most events occurred in the high hazard area, which also represent the largest surface area.

Table 12: Inherent hazard category and the number of ground instability events.

Inherent Hazard Category	Surface Area (ha)	No. of Events (1975 to 2020)	% of Events
Low	27	0	0
Medium	222	40	18
High	252	179	82
Total	501	219	100

Therefore, based on the information presented in Table 12 the expected number of events in each of hazard class areas could be calculated as follows (Area in Hectares multiplied by the corresponding value in Table 2):

Low Hazard	-	$27 \times 0 = 0$ events
Medium Hazard	-	$222 \times 0.07 = 15.5$ events
High Hazard	-	$252 \times 0.7 = 176.4$ events
Total	-	191.9 predicted number events

This method indicates that a total of 192 events could have been expected to occur over the last 45 years (1975 to 2020) across the research area. This figure indicates that the expected number of events predicted per hectare, as proposed by Buttrick and van Schalkwyk (1995), is almost equal to what was actually recorded.

Although the number of events (192) predicted using Buttrick and van Schalkwyk (1995) values is less than the actual number (219) recorded, but these numbers correlates quite well.

Furthermore, although the correlation in the high risk area is good, there seems to be a very poor correlation between the predicted and actual number of occurrences for the medium hazard areas.

Using the information presented in Table 12, the Khutsong North region shows that each of the inherent hazard category has recorded the following actual number of events per hectare over the last 45 years:

Low Hazard	-	0/27 = 0 events/ ha
Medium Hazard	-	40/222 = 0.2 events/ ha
High Hazard	-	179/252 = 0.7 events/ ha

In order to compare the predicted (192) events and the actual (219) events per hectare within a time period that Buttrick and Van Schalkwyk (1995) and Buttrick *et al* (2001) proposed, the following two methods can be used:

- Method A:** Events per hectare as shown above can be calculated to indicate events per year, and then recalculated to present data over a 20-year period, or
- Method B:** A 20-year period can be selected from the available database, i.e. the first 20-year period (1975 to 1995) and/ or the last 20-year period (2000 to 2020)

If a first 20-year period (1975 to 1995) is considered, a total of 149 events have occurred across the KNT's, but if the last 20-year period (2000 to 2020) is considered, only 70 events have occurred. In addition, the number of events per hectare occurred during the two time periods was calculated for each of the Low, Medium and High Hazard category, and the results are presented in Table 13.

Table 13: Inherent hazard category and the ground instability events statistics.

Inherent Hazard Category	Surface Area (ha)	No. of Events (1 st 20 years)	% of Events (1 st 20 years)	No. of Events (last 20 years)	% of Events (last 20 years)
Low	27	0	0	0	0
Medium	222	27	18	12	17
High	252	122	82	58	83
Total	501	149	100	70	100

Using the information presented in Table 13, the Khutsong North region shows that each of the hazard category areas has recorded the following actual number of events per hectare over the two periods (1st 20 year and last 20 years).

Therefore, the number of events per hectare over a 20-year period for KNT's was calculated using the two methods and the results are presented in Table 14.

Table 14: Actual number of events per hectare over a 20-years period in Khutsong North.

Inherent Hazard Category	Method A (Actual Events per Ha /45*20)	Method B	
		Selected Period (1975 to 1995)	Selected Period (2000 to 2020)
Low	0	0	0
Medium	0.09	0.12	0.05
High	0.31	0.48	0.23

It is evident that there is a difference in the actual number of events that has occurred in Khutsong North and the anticipated number as proposed by Buttrick and Van Schalkwyk (1995) and Buttrick *et al* (2001). There could be a number of reasons for this which may include the following:

- If a twenty year period is considered, it is dependent on which twenty year period is used, as can be noted from the two columns (Table 9) showing two different time periods in the available events database
- The region of KNT's is generally considered as abused land dominated by high risk dolomite. Major issue of leaking wet services and poorly managed stormwater systems have been reported, at least since 1997 (24 years). Also, this area does not have an active Dolomite Risk Management Plan (DRMP) as required in terms of SANS 1936:2012

A general observation derived from the actual events as presented in Table 14 for Method B is that less events have occurred during the last twenty year period (year-2000 to 2020) when compared to first twenty year period 1975 to 1995. This observation is obviously in contrast with the prevailing situation in KNT's, where sinkhole and

subsidence formation post year-2000 have caused unprecedented damage to critical infrastructure (housing, wet services and bulk water supply). However, risk analysis is dependent on a credible record of events and in that context, one must first question the quality of the available events data recorded pre- year-2000, as discussed in Section 4.3.2 of this dissertation. Some events might have occurred pre-1975 but were only documented few years later. Therefore, these results must be considered with caution.

A more focused and data quality driven observation is that, when analysing events data without the 1995 records, sinkhole and subsidence formation across KNT's have increased over the last 20-years (year-2000 to 2020) as confirmed by a positive trendline in Figure 36. Such an observation therefore, further highlights how crucial a dependable data record is towards determining hazard rating and strengthening risk governance on geologically hazard prone areas like the dolomite land.

In conclusion, the overall results of the hazard determination desk top study into the KNT's sinkhole problem correlate well with the conclusions of the previous studies in that the area is dominated by "high risk dolomite", which is highly susceptible to the formation of ground instability events. Dominant "hazard rating" calculated using the Buttrick and Van Schalkwyk (1995) proposed method also confirms problematic geological conditions in the region. Furthermore, the situation could be worse if the influence of the following factors is considered:

- The research area is large and does not represent a realistic outcome since both the boreholes and events are not evenly distributed
- The accuracy of the available events record is questionable in that most of the events occurrence date is estimated compared to the area used by Buttrick and van Schalkwyk (1995) where a more reliable database from a controlled military area was used
- The region of KNT's is situated under the Merafong City where dolomite risk management has not taken place, and therefore, generally referred to as an abuse land

Therefore, a detailed research study similar to that described in Buttrick *et al* (2011) is required to fully understand the prevailing KNT's sinkhole situation and to once again highlight guidelines for data collection requirements, analysis and implementation of dolomite risk mitigation strategies in line with the current applicable legislation.

5.4.4 Hazard rating of KNT's compared to that of Centurion CBD

Dolomite hazard determination and hazard rating for KNT's conducted during the current research has been necessitated by the prevailing sinkhole and subsidence disaster resulting in a wide spread damage to critical infrastructure in that area. Khutsong North is not unique in that it is located on dolomite land and was established decades prior to the implementation SANS 1936 like many other densely developed areas including the Centurion CBD in Pretoria. However, KNT's have been on the news more in recent times (post year-2000) due to the dolomite related sinkhole problem and was officially declared a disaster area during November 2016.

In calculating the hazard rating for KNT's, a total of 219 events were considered to have occurred in an area covering a surface area of 1318 hectares over a period of almost 45 years (1975 to 2020), available records. When a complete record of events occurring in the research area is considered, 1 sinkhole has occurred in every 6.02 hectares or 0.17 events /ha. However, if a 20-year period is considered, then it depends which 20-year period is used, i.e. 1975 to 1995 of year-2000 to 2020. Therefore, if the last 20-year period is used, only 70 events have occurred in the KNT's area, i.e. 1 sinkhole every 18.83 hectares, which translate into 0.05 events / ha over a 20 year period.

Similar studies have been conducted elsewhere including "*The hazard of sinkhole formation in the Centurion CBD and surrounding areas*", by Oosthuizen (2013). According to Oosthuizen (2013), a total of 119 sinkholes have occurred in the entire Centurion CBD area, covering a surface area of 1657 hectares over a period of almost 40 years. The study concluded that if a complete record of events occurring in that area is considered, then 1 sinkhole has occurred in every 13.9 hectares or 0.07 events /ha. However, if a 20-year period is considered, from 1990 to 2010, only 52 sinkholes have occurred in the Centurion CBD area, i.e. 1 sinkhole every 31.86 hectares, which translate into 0,03 events / ha over a 20 year period.

Comparing the KNT's hazard rating calculated during the current research and that of the Centurion CBD, it is evident that more events per hectare have occurred in KNT's as opposed to the Centurion CBD. When the overall record of events is considered for each of these areas, 0.17 events/ ha have occurred in KNT's and only 0.07 events/ ha in the Centurion CBD. Therefore, KNT's area is more susceptible to dolomite related hazards than the Centurion CBD.

CHAPTER 6 – KHUTSONG NORTH DOLOMITE RISK ASSESSMENT

6.1 BACKGROUND ON RISK ASSESSMENT PRINCIPLES

The importance of risk assessment to manage consequences of sinkhole and subsidence formation is critical in areas classified as dolomite land. In the context of increased ground instability events occurring across the KNT's, it is recommended that dolomite land risk assessment adopt the principles of a Dolomite Risk Management (SANS 1936-4:2012), Policy Framework for Disaster Risk Management (South Africa, 2005) and Sendai Framework for Disaster Risk Reduction (SFDRR), 2015. The Sendai Framework is built on elements which ensure continuity and it also articulates the following:

- Need for improved understanding of risk in all its dimensions to allow integrated land use planning, i.e. hazard characteristics, exposure and vulnerability
- Strengthening of risk governance across all spheres of government
- Strong emphasis on accountability for risk management by all involved
- Preparedness to respond to an identified risk
- Recognition of various relevant stakeholders and their roles
- Mobilization of risk-sensitive investments and strengthening community resilience to disasters
- Establishment of risk-informed policies and hazard mitigation measures

Risk assessment is a complex process, it generally begins with data gathering and the definition of a scope required for assessing a potential risk, i.e. the dolomite risk. Once that is completed, the process moves to conducting the actual risk assessment with specific objectives including risk identification, reduction, management and mitigation measures. In order to understand the concept of dolomite risk assessment and management in the South African context, the different definitions related to this concept – as defined by Buttrick & van Schalkwyk (1995), Buttrick *et al* (2001), Buttrick *et al* (2011) and later adopted by SANS 1936 of 2012 must be clearly understood.

It is important also to accept that while many stakeholders may be involved in the process, various factors come into play and ultimately, performing an effective risk assessment comes down to four core elements, i.e. risk identification, risk analysis, risk evaluation and risk communication. The results of these elements are subsequently presented as Hazard, Vulnerability and Risk Maps in Section 6.2 to 6.4 below:

6.2 HAZARD ZONATION AND HAZARD RATING MAP OF KHUTSONG NORTH

The first step in the effective risk assessment process is compilation of a hazard map to highlight areas that are affected by or are susceptible to an identified risk. Hazard maps help determine the risk to infrastructure or risk of living in certain areas, i.e. areas considered to be Dolomite Land. As such, previous dolomite stability assessments and resulting hazard zonation maps, associated borehole data and available ground instability event records were reviewed to assess the extent of the dolomite (geological) risk faced by the community of Khutsong North.

In line with the objectives of this research, historic site zoning (from 1997 & 2013 studies) and scientific advances in determining the Inherent Hazard Class (IHC) were used to investigate possible influence on the extent of allowable development over time since the scenario supposition method (Buttrick *et al.*, 2001; SANS 1936:2012).

6.2.1 Hazard Zonation Map – Intraconsult (1997)

A dolomite stability desk top study was conducted during 1997 (Intraconsult, 1997) at the request of the then Carletonville Town Council. The study focused on areas of Khutsong Proper and Khutsong Extension 1 to 6, and the results of this study were presented in their report, “Khutsong: Dolomite Stability and related aspects – the way forward” dated November 1997. The primary objective was to assist the local authority with planning processes and policy formulation concerning the safe development of dolomite land.

The available information (limited gravity, percussion boreholes, geohydrological and ground instability event records) were analysed, permitting the formulation of a broad perspective on the potential subsurface conditions of the study area. Based on the analysis conducted at the time, the study area was sub-divided into four Primary Stability Zones for the purpose of developing a strategy to manage the future dolomite risk, Figure 52 and Table 15.

Table 15: Dolomite stability zones and appropriate development, after Intraconsult (1997)

Dolomite Stability Zone	Description	Appropriate Development
1	Area designated as reflecting a low to medium risk of sinkhole and subsidence formation with respect to water ingress.	Open stands may be considered for erection of houses and light commercial/ industrial use provided those have not experienced ground instability.
2	Area designated as reflecting a medium risk of sinkhole and subsidence formation with respect to water ingress.	Open stands may be considered for erection of houses and light commercial/ industrial use provided those have not experienced ground instability.
3	Area designated as reflecting a medium to high risk of sinkhole and subsidence formation with respect to water ingress.	Stands in this area should generally not be developed for residential purposes, but may be considered for parks gardens and other non-residential use.
4	Area designated as reflecting a high risk of sinkhole and subsidence formation with respect to water ingress.	Stands in this area should generally not be developed.

The study concluded that inadequate geotechnical information existed in certain sections of the KNT's precluding a definitive stability characterisation of the region and that 90% of the land was unsuitable for residential development.

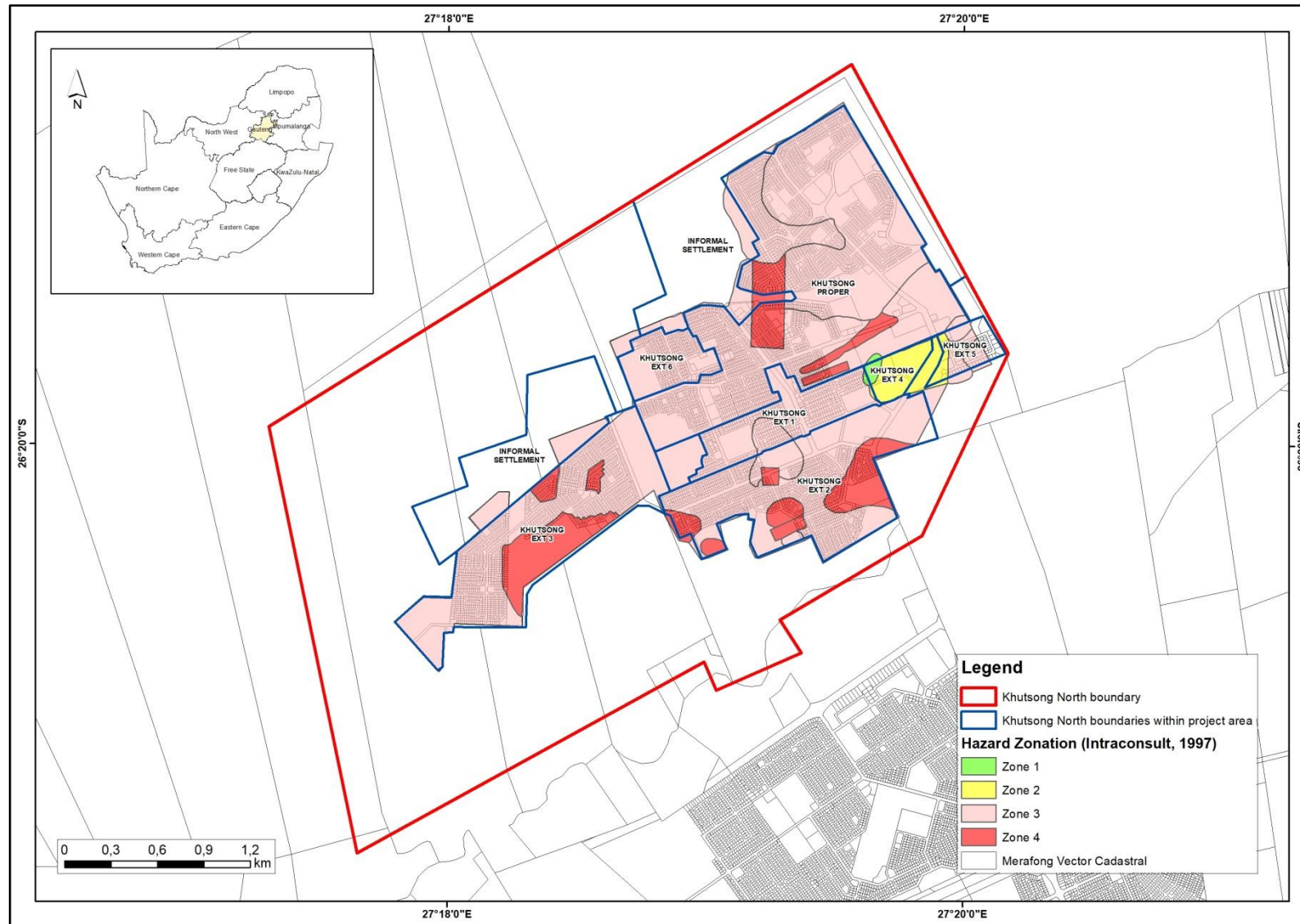


Figure 52: Hazard Zonation Map of Khutsong North, after Intraconsult (1997).

6.2.2 Hazard Zonation Map – VGIconsult (2013)

In 2013, Merafong City Local Municipality (MCLM) appointed VGIconsult to undertake a feasibility-level study. This study also focused in the same areas as the 1997 study of Khutsong Proper and Khutsong Extension 1 to 6, and the results of this study were presented in their report, “Khutsong Proper and Khutsong Extension 1 to 6: Feasibility Stage Dolomite Stability Investigation” dated October 2013. Amongst other objectives, the study was aimed at providing guidance on the new development approach for Khutsong North, issues related to Dolomite Risk Management and upgrading of infrastructure.

This investigation included a review of existing data, commissioning of infill gravity surveys, undertaking drilling, analysis and reporting. Based on the existing information, additional data gathered and the clear guidelines for development of dolomite land provided in SANS 1936:2012, the site was characterised in terms of five (Figure 52) primary Inherent Hazard Class (IHC) areas, described in Table 16.

According to the 2013 study, the functional requirements as stipulated in the SANS 1936:2012 deemed-to-satisfy standard, permits the achievement of the following objectives:

- Update of the previous Hazard Zonation, i.e. from the 1997 study
- Protection of existing formal townships – Exploring alternative solutions as opposed to relocation
- Infill planning – Identification of areas for potential densification
- Upgrading of existing infrastructure – Indicates the level of requisite for appropriate upgrade and design of wet services
- Dolomite Risk Management – Outlining the requirements to achieve a tolerable hazard rating for formal Khutsong North Townships

Table 16: Dolomite Hazard Zones and their description, after VGIconsult (2013).

Dolomite Hazard Zone	Inherent Hazard Class	Description
1	3(5/6)/I/1	Areas largely reflecting <i>Medium susceptibility of medium size events</i> and sub-areas reflecting <i>High susceptibility of small-to-medium size event</i> with respect to ingress of water, and <i>Low susceptibility of all-size events</i> with respect to dewatering.
2	4(6/7)/I/1(4)	Areas largely reflecting <i>Medium susceptibility of large size events</i> and sub-areas reflecting <i>High susceptibility of medium-to-large size event</i> with respect to ingress of water, and <i>Low susceptibility of all-size events</i> (sub-areas reflecting <i>medium susceptibility of small-to-medium size event</i>) with respect to dewatering.
3	6/7/I/1(4)	Areas largely reflecting <i>High susceptibility of medium-to-large size events</i> , and <i>Low susceptibility of all-size events</i> (sub-areas reflecting <i>medium susceptibility of small-to-medium size event</i>) with respect to dewatering.
4	1(7)/I/7	Areas largely reflecting <i>Low susceptibility of all-size events</i> and sub-areas reflecting <i>High susceptibility of large size event</i> with respect to ingress of water, and <i>High susceptibility of large-size events</i> with respect to dewatering.
5	5-7/I/1/7	Areas largely reflecting <i>High susceptibility of small-to-large size events</i> with respect to ingress of water, and <i>Low-to-High susceptible of large size events</i> with respect to dewatering.

The study concluded that a significantly improved understanding of the subsurface conditions was achieved, which then allowed for consideration of certain land use types on the undeveloped areas under strict adherence to SANS 1936:2012 requirements, i.e. exclusion of the sub-areas of poor stability conditions (IHC 6, 7 & 8) in Dolomite Hazard Zones 1 and 2.

In general, the 2013 hazard zonation map (Figure 53) showed that large portions of the existing formal townships can be protected as opposed to relocation and that more land could be considered for certain types of developments including residential, subject to implementation of site specific precautionary measures in terms of the SANS 1936-Part 1 to 4 of 2012.

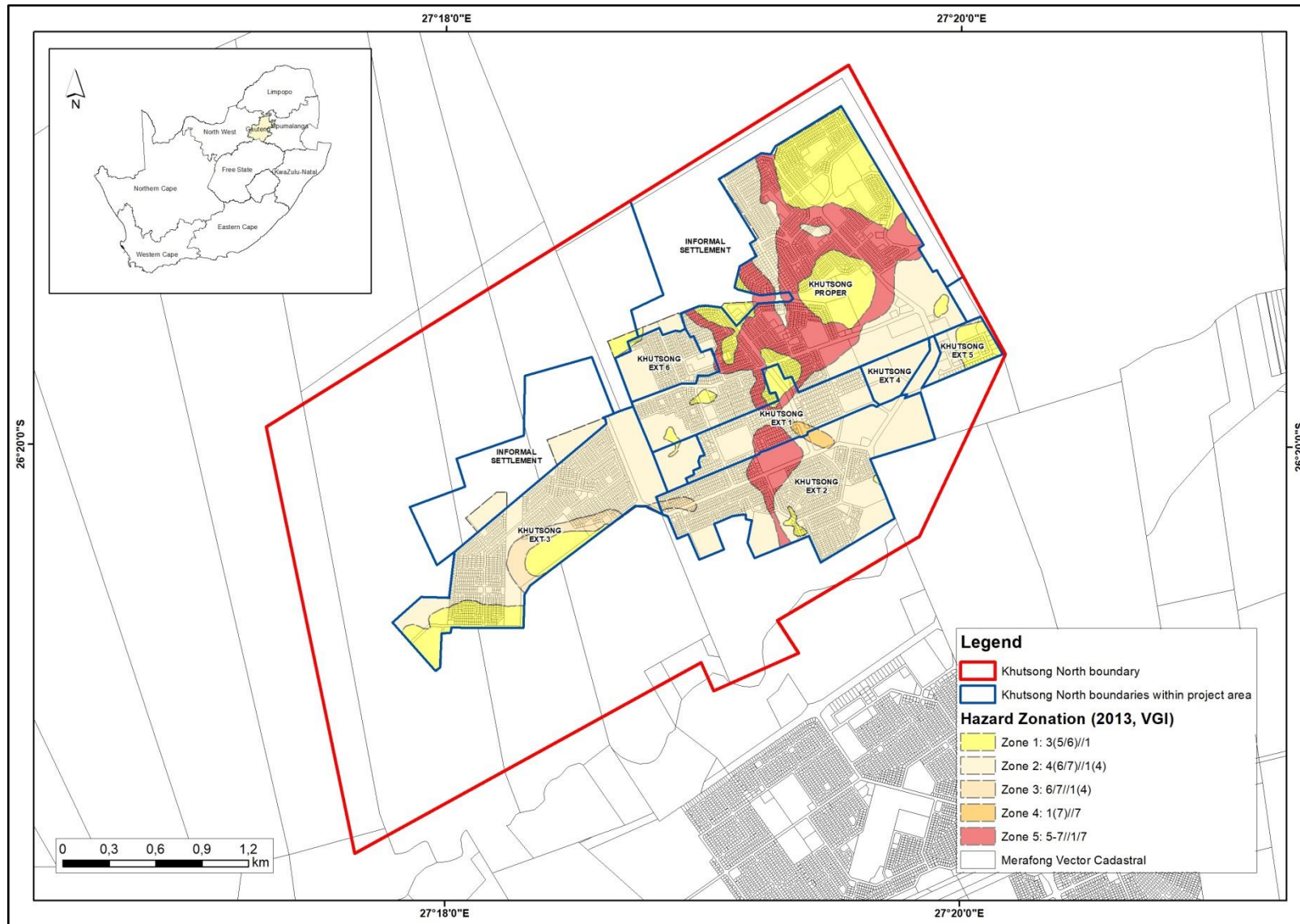


Figure 53: Hazard Zonation Map of Khutsong North, after VGIconsult (2013).

6.2.3 Hazard Rating Map

Hazard rating of any dolomite land parcel is based on the number of events occurring per hectare over a 20-year period. According to Buttrick *et al* (2011), hazard rating is expressed as tolerable where the number of events is ≤ 0.1 and is expressed as intolerable where the number of events is ≥ 0.1 per hectare per 20 years. The assessment of hazard rating is based on the hazard, the inherent risk and socio-economic factors (including type of development, density of development, level of servicing, precautionary/ remedial measures & risk management) at a given time (Buttrick *et al*, 2011). In principle, mitigating measures must be consistently implemented in order to achieve and maintain a tolerable hazard rating for any given area deemed susceptible to damaging dolomite hazard.

Therefore, taking the Buttrick *et al* (2011) expression and using the actual events per hectare values calculated using Method A, a hazard rating for KNT's region over a 20-year period for each of the IHC zones is presented in Figure 54 and Table 17.

Table 17: The distribution and interpretation of events over a 20-year period.

IHC	Surface Area (ha)	No. of Events (45-years)	Events per Ha (Method A)	Inherent Susceptibility in terms of Table 2	Hazard Rating
1 - 2	27	0	0	Low	Tolerable
3 - 4	222	40	0.09	Medium	Marginally Intolerable
5 - 8	252	179	0.31	High	Intolerable

According to Buttrick *et al* (2001), the method of risk mitigation, appropriate development and risk management can on some inherent hazard classes change the hazard rating from “intolerable” to “tolerable”. However, no such mitigation measures have ever been implemented within the research area except some basic awareness and intermittent response measures as and when an event is reported.

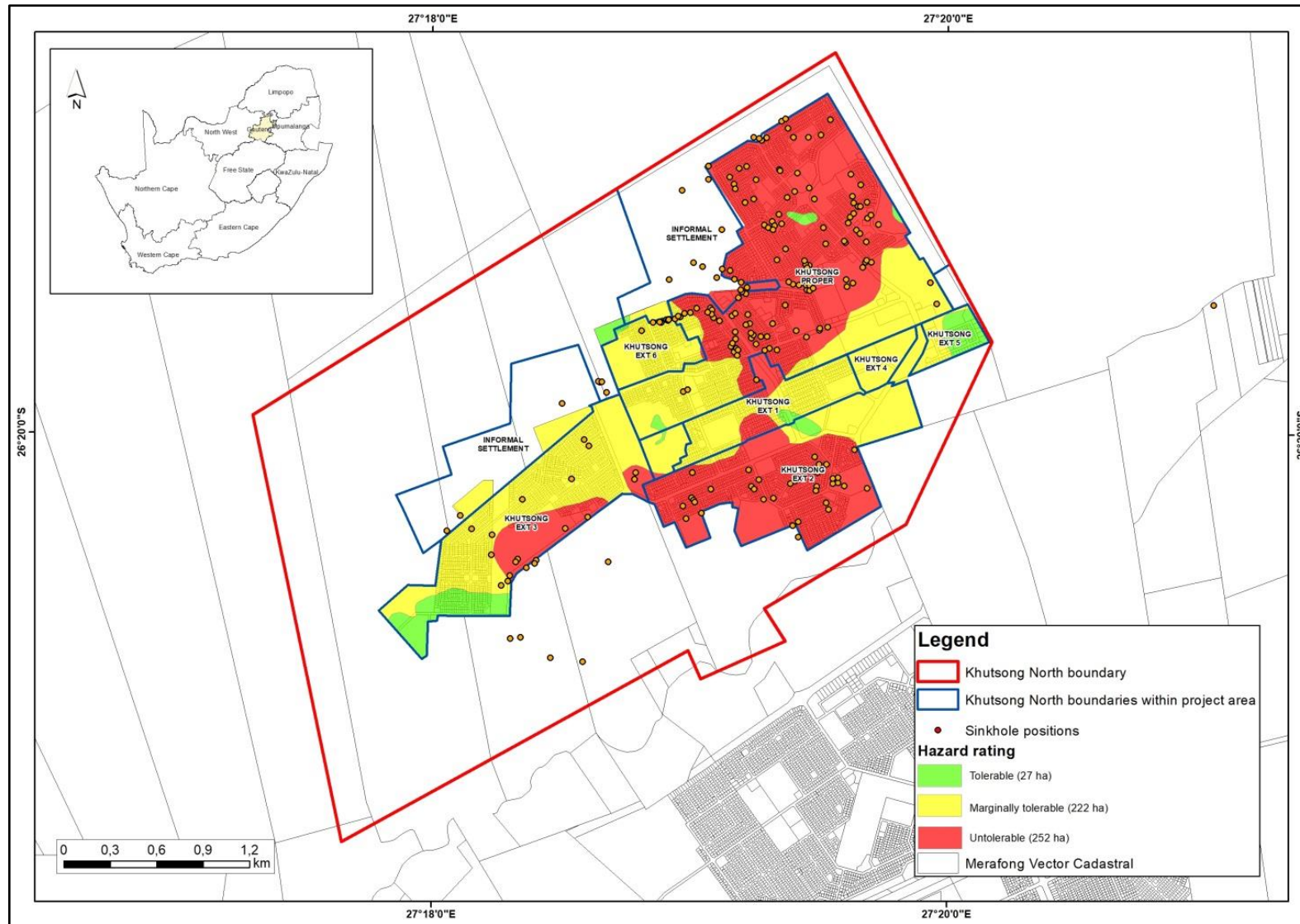


Figure 54: A generalized hazard rating map of the formal townships, Khutsong North.

6.3 VULNERABILITY MAP OF KHUTSONG NORTH

Another major step in effective risk assessment is assessing the area/ region's vulnerability to an identified risk. According to Alcantara (2002), vulnerability can be defined as the propensity of an endangered element due to any kind of natural hazard to suffer different degrees of loss or amount of damage depending on its particular social, economic, cultural, and political weaknesses. The Policy Framework for Disaster Risk Management (South Africa, 2005), defines vulnerability as "a degree to which an individual, household, community or an area may be adversely affected by a disaster".

In line with the above definitions, a dolomite risk assessment shall determine people's, community or infrastructure vulnerability to dolomite related hazards. According to the United Nations International Strategy for Disaster Reduction (UNISDR, 2013), a regional vulnerability is determined by evaluating hazard exposure and coping capacity from which a set of indicators are selected. In general, vulnerability may be defined in terms of those characteristics and circumstances that make an individual household, community or infrastructure susceptible to the damaging effects of a hazard.

For the purpose of effective dolomite risk assessment, the following aspects were considered as indicators for KNT's vulnerability to the prevailing dolomite hazard phenomenon:

- Physical proximity of dwelling houses to existing sinkholes and subsidences
- Sizes of existing erven (reference is made to vulnerability of erven <300m²)
- Impact of the widespread damage to critical wet services infrastructure and response capacity of the MCLM

Therefore, the proximity of households to the measured events, stand sizes and the response capacity of the local authority were used to determine the KNT's vulnerability to the prevailing dolomite hazards, Figure 55.

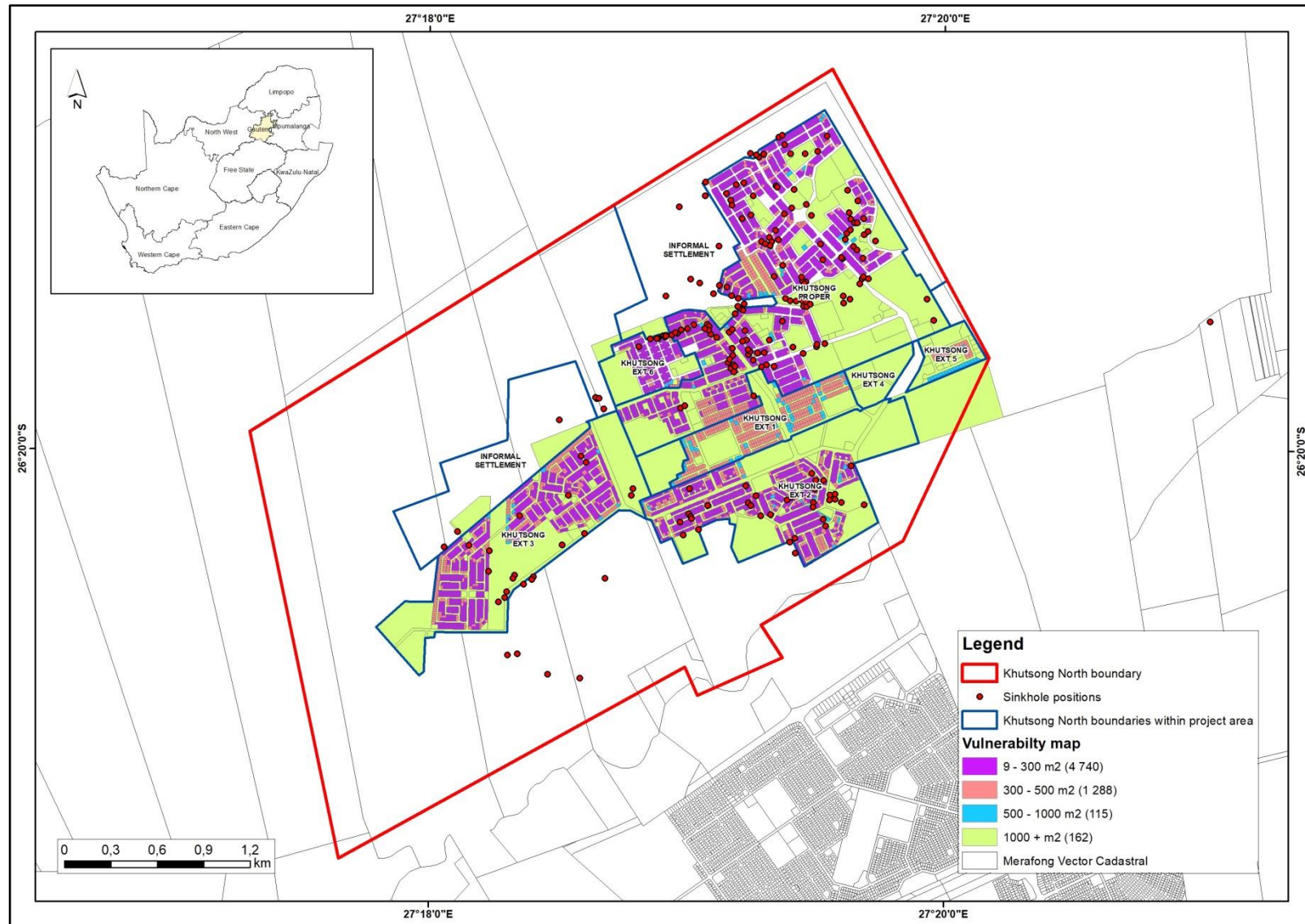


Figure 55: Regional vulnerability map with erven sizes and event positions, Khutsong North.

Therefore, comparing the majority of measured event dimensions (large to very large making up 72% as discussed in Section 4.4) against the majority of stand sizes (4 740 of erven $\leq 300 \text{ m}^2$) and the widespread damage to critical wet services infrastructure against the response capacity, following observations/ conclusions are made:

- 620 of the 6 305 erven (10%) across the formal KNT's were intersected by known ground instability events. As such, several households in the region have been directly affected (damaged) by sinkhole and subsidence events
- 4 740 of the 6 305 erven (75%) are between 9 – 300 m^2 in size
- Based on the measured event dimensions and stand sizes, the majority of the erven (5 360 of the 6 305) are regarded as being vulnerable to ground instability events and non-compliant to the prevailing Code of Practice, i.e. SANS 1936:2012 for Dwelling Houses (RN1-2) and NHBRC 2015 Building Manual requirements for Detached Homes (DH1-2) type land use
- Provision of human settlements comes along with massive infrastructure development needed to deliver critical services such as water borne services and in Khutsong North, these have either been damaged or destroyed
- According to the "Situation Report: Merafong Local Municipality (2017)", compiled by CoGTA Gauteng Province and the Gauteng Provincial Disaster Management Centre, the damage to critical infrastructure due to sinkhole formation runs into over R200 million. Due to the magnitude and the severity of the damage to infrastructure, the report concluded that financial implications of the prevailing problem are beyond the municipality's financial capabilities
- Based on such conclusions clearly indicating lack of coping capacity at the MCLM, the Khutsong North critical infrastructure and housing are vulnerable to damage

6.4 DOLOMITE RISK MAP OF KHUTSONG NORTH

The final step in the effective risk assessment process is compilation of a risk map needed to guide land use planning and safe development of hazard prone areas. As such, available ground instability events record, previous dolomite stability assessments, associated borehole data and Hazard Zonation Maps were reviewed to assess possible influence on safe land use practice in the research area over time.

The available information was used to compile a Dolomite Risk Map (Figure 56) of the KNT's. It must be noted that the risk map is based on the 2013 Hazard Zonation Map (Figure 53), Hazard Rating Map (Figure 54), Vulnerability Map (Figure 55) and the following:

- All erven or undeveloped open land that intersects the surface area extent of known ground instability events are regarded as having a high risk factor (purple in the Risk Map)
- All erven $\leq 300\text{m}^2$ in extent across intolerable hazard rating (based on a number of events per hectare over a 20-year period, calculated using Method A as described in Section 5.4.2) areas are regarded as having a high risk factor (red erven in the Risk Map)
- All erven $\leq 300\text{m}^2$ in extent across marginally tolerable hazard rating (based on a number of events per hectare over a 20-year period, calculated using Method A as described in Section 5.4.2) areas are regarded as having a moderate to high risk factor (light brown erven in the Risk Map). However, these may be regarded as having high risk factor if the problem of damaged wet services infrastructure is not addressed

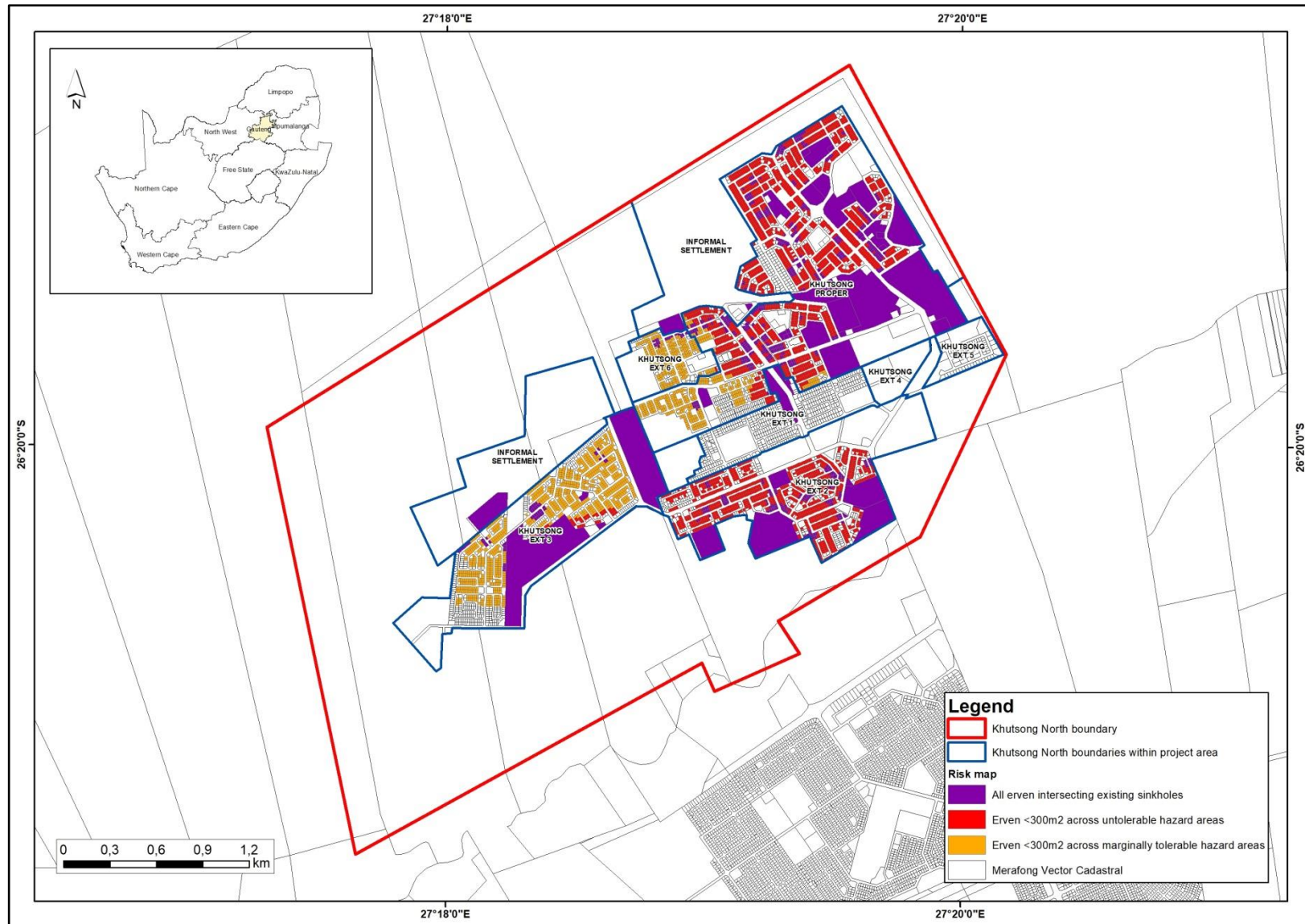


Figure 56: Regional risk map based on the hazard rating, Khutsong North.

6.5 COMPARISON BETWEEN THE 1997 AND 2013 STABILITY ASSESSMENTS

The hazard zonation maps of Khutsong North are presented for 1997 (Figure 52) and 2013 (Figure 53). The 1997 dolomite stability assessment provided a preliminary, composite and broad based zonation of the research area, whereas the 2013 assessment outlined alternative solutions to the already approved relocation proposal, including identification of appropriate development types in areas previously deemed unsuitable for residential land uses.

During the 2013 study additional borehole data were used for stability assessment and this resulted in a significantly improved understanding of the subsurface conditions in KNT's. Achievement of the 2013 zoning and hazard rating of the KNT's calculated during the current research can be attributed to the significant advances made in the science of dolomite hazard and risk assessment since the 1997 study, and the clear guidelines for development of dolomite land as detailed in SANS 1936:2012. The following conclusions can be made from comparing the 1997 and 2013 hazard zonation:

- Increasing the number of boreholes in areas previously deemed “*high risk*” has permitted the compilation of an updated hazard zonation of the area and allowed for infill planning or potential densification in certain areas
- Borehole data and gravity surveys remain critical in hazard assessment, especially on a large (regional scale) site like KNT's. However, these should not be the only guide when determining the zone boundaries, hazard rating and the risk zonation, i.e. acceptable or unacceptable risk status of the study area
- Although more information (borehole data and gravity survey) was available in 2013 to better understand the geology and subsurface conditions, this still does not confirm adequate risk assessment as instability events are also recorded in areas classified as having medium hazard indicative of pockets of high hazard which could not be picked up by recommended ground investigation methods
- It is not possible to pronounce large sites such as KNT's to have been adequately assessed merely on the density of borehole data and gravity interpretation. Therefore, a multi-layered risk assessment including the use of anthropogenic factors, implementation of appropriate DRMS and a detailed events database must be encouraged to determine the site risk status
- In general, the 2013 dolomite hazard zonation is more optimistic in its determination when compared to 1997 zonation. However, the current research has further highlighted the importance of a multi-layered approach, hence the hazard rating calculated in Section 5.4 and Figure 54 of this dissertation.

CHAPTER 7 – CONCLUSION

Upon consideration of the available geo-scientific information across KNT's, it is evident that building without the knowledge of the sub-surface geological conditions, geologically unsuitable areas are often developed thus creating damaging legacies for citizens to bear and the State to address decades after the completion of construction. Geological information from the previous Dolomite Stability Investigations (DSI's) conducted over the last 40 years and historic site zonation, demonstrated that poor subsurface geological conditions exist, but proved insufficient to guide safe development in the research area. This could largely be attributed to a lack of commitment by decision makers and organs of state involved to implement sound building principles including adherence to the pertinent legislation.

Therefore, as part of this research, use of historic geological records, site zonation, enforcement of the dolomite land classification method(s) and the influence of the pertinent legislative framework were analysed in order to determine the latent issues preventing the implementation of sound building principles. After assessing the current accelerated ground instability events situation in the KNT's from a dolomite land risk assessment and legislative framework perspective, the following can be concluded:

- Strict adherence to the Constitutional requirements (the right to a safe environment – Section 24), the National Building Regulations (NBR's) and the SANS 1936 technical requirements is critical in building practice. The promulgation of SANS 1936 in 2012 meant that geotechnical and/ or dolomite stability investigations and implementation of appropriate precautionary measures required to ensure sustainable land use became mandatory on all dolomite land earmarked for development

However, in the context of the current KNT's situation, available geological information, historic site zonation and records of ground instability events have not improved land use planning or an enforcement of dolomite stability investigations for new developments post-SANS 1936

- Extensive research aimed at understanding the peculiar nature of dolomite rock and the latent issues associated with development of dolomite land has taken place. This has led to great scientific advancements at least over the last 40 years characterized by a progressive change in the philosophy from a mere assigning of a code number to a dolomite profile which can be related to its probable stability, to risk characterization for sinkhole formation based on a list of factors and prevailing

scenario, and zonation of dolomite land parcels using the concept of suitable development type and appropriate risk mitigation measures

However, in KNT's a steady densification has occurred in areas previously declared as high risk. The Geological Survey, 1989 report – (now CGS), concluded that development in the then KNT's be halted and Intraconsult, 1997 report revealed that 90% of the existing KNT's residential area falls within the extremely "*High Risk Dolomite Zones*" which are not suitable for human settlement. Therefore, advances made in dolomite land characterization and risk mitigation strategies (from Stephan, 1975 to Buttrick *et al*, 2001 methods) aimed at reducing geologically related effects on development has had minimum or no appreciable influence on the decisions for permissible land use

- Under Section 24 of the Constitution (Act 108 of 1996), the right to a safe environmental and protection thereof has been elevated to a basic human right. In the context of a sound building practice, more particularly post-1994, a series of Acts have been promulgated to provide a regulatory system for building control in South Africa. The National Building Regulations and Building Standards (Act 103 of 1977) as amended, and its Regulations, have been promulgated to promote uniformity in the law relating to the erection of buildings. A key requirement under Section 12 of the Act 103 of 1977 is that if the conditions of the land on which a building was or is being or is to be erected, is showing signs of becoming dangerous to property and/ or life, such conditions must be investigated prior to the approval of the land use application by the relevant local authority. Therefore, a good legislative framework exists in South Africa

However, a review of the legislation applicable to building practice suggests that there are some gaps, which have potentially given rise to implementation issues like silo practice, non-compliance, lack of capacity (fiscal & technical) and division of responsibilities in the building regulatory process between spheres of government. It is imperative therefore, to consider that good legislative framework without consistent implementation serves no purpose

In practice, the current legislative framework has failed to support consistent implementation of the available technical requirements on geologically hazard prone areas. Hence, no material change is observed in the building regulatory process post- the SANS 1936 and the NHBRC 2015 Building Manual

CHAPTER 8 – RECOMMENDATIONS AND FUTURE RESEARCH

Often, development takes place without knowledge of the presence of dolomite land or due consideration of the potential geological hazards. When problems arise years after development has occurred, the state and affected communities must attempt to remedy the effects of latent hazards after the fact, in a reactive fashion. Based on the scientific advances achieved both locally and internationally, and the outcomes of this research in so far as these relate to the current challenges faced by Khutsong North communities, the following considerations are proposed:

- All local authorities in South Africa should establish the extent of dolomite land within their area of jurisdiction and if such a geological terrain is confirmed, SANS 1936 requirements for safe development of dolomite land must be prioritized
- Local authorities shall designate a suitably qualified Dolomite Risk Manager (DRM) with relevant competence to implement municipal Dolomite Risk Management Strategy (DRMS) in accordance with the principles of SANS 1936 Part 4 of 2012
- Potgieter et al (2016), recommended an integration of a Dolomite Risk Management Programme (DRMP) in local governance in South Africa. This is primarily because of the apparent risk that dolomite poses to the people and their assets, and in line with the executive and legislative authority vested in the Local Sphere of Government in terms of Section 155(1) of the Constitution. Therefore, strict implementation of the recommendations made during such research studies is critical to ensure sustainable land use planning including geological disaster management at Local Sphere of Government
- A detailed review of the building regulatory process in South Africa with a primary objective to provide clarity and/ or address potentially contradicting provisions in so far as the law relates to a sphere of government with ultimate approval authority is recommended. This shall include developing a National Plan for each of the hazards identified in terms of the DMA (57 of 2002) guidelines and such plan(s) shall be enforced by the National Disaster Management Centre (NDMC)
- It could be of value to determine the underlying reasons impeding the implementation of sound building practice in South Africa. Good legislation and policies without implementation serves no purpose. Therefore, reasons for silo practice, non-compliance and lack of capacity (fiscal & technical) shall be investigated

- According to Buttrick et al (2011), research in an area south of Pretoria demonstrated that the approach to the mitigation of hazards through risk management can improve the hazard rating of dolomite land. However, the available literature lacks examples of similar successes needed to influence land use regulation and the legislative direction. Therefore, more case studies are needed across the five provinces affected by dolomite land to show improved hazard rating of dolomite land through the mitigation of hazards by introducing risk management strategies and the influence of the current legislative framework on sound building practice

REFERENCES

- ALCANTARA, A., 2002. Geomorphology, natural hazards, vulnerability and prevention of natural disasters in developing countries. *Geomorphology Volume 47*. Elsevier Science (2002), pp. 107-124.
- BEZUIDENHOUT, C. A. and ENSLIN, J. F., 1969. Surface subsidence and sinkholes in the dolomitic area of the Far West Rand, Transvaal, South Africa, *in Proceedings of the First International Symposium on Land Subsidence, Tokyo*. UNESCO Publication No 88, Paris, pp. 482 – 495.
- BRINK, A.B.A., 1979. Engineering Geology of Southern Africa. Volume 1. *Building Publications*, Silverton, 1979.
- BRINK, A.B.A., 1996. Mechanisms of sinkhole and doline formation. *Seminar on the Engineering geology of dolomite areas*, University of Pretoria, Pretoria, 18 January 1996.
- BUTTRICK, D.B. and ROUX, P., 1993. The safety of high density informal settlements on the dolomites of South Africa. *Applied karst geology, Beck (edition) Proceedings*. Balkema, Rotterdam (1993). pp 291-294.
- BUTTRICK, D.B. and VAN SCHALKWYK, A., 1995. The Method of Scenario Supposition for Stability Evaluation of Sites on Dolomitic Land in South Africa. *South African Institution of Civil Engineering Journal*. Fourth Quarter 1995, pp. 9-14.
- BUTTRICK, D.B., and VAN SCHALKWYK, A., 1998. Hazard and risk assessment for sinkhole formation on dolomite land in South Africa. *International Journal of Geosciences. Environmental Geology*, Volume 36 (1-2), November 1998. pp. 170-178.
- BUTTRICK, D.B., VAN SCHALKWYK, A., KLEYWEGT R.J. and WATERMEYER, R., 2001. Proposed method for dolomite land hazard and risk assessment in South Africa. *South African Institution of Civil Engineering Journal*. Volume 43(2) 2001, pp. 27-36.
- BUTTRICK, D.B., TROLLIP, N.Y.G., WATERMEYER, R.B., PIETERSE, N.D. and GERBER, A.G., 2011. A performance based approach to dolomite risk management. *Environmental Earth Sciences*, January 2011. pp 1127-1138.
- COETZEE, C. and VAN NIEKERK, D., 2013. Towards a disaster risk assessment methodology for communities underlain by dolomite. *Disaster prevention and management*. Volume 22 Number 4. 2013, pp. 351-365.
- COUNCIL FOR GEOSCIENCE/ SOUTH AFRICAN INSTITUTE OF ENGINEERING AND ENVIRONMENTAL GEOLOGISTS. 2003. *Guideline for engineering-geological characterisation and development of dolomitic land*. Council for Geoscience Publication.
- COUNCIL FOR GEOSCIENCE., 2007. Consultants Guide: *Approach to Sites on Dolomite Land*. Council for Geoscience Publication, November 2007.
- DE JAGER, C., 2016. Merafong Municipal Spatial Development Framework. *Spatial Planning & Environmental Management Section – Merafong City Local Municipality*, 2016 – 2021.

- FORD, D. and WILLIAMS, P., 2007. Karst hydrogeology and Geomorphology. *John Wiley and Sons, Ltd., Second Edition*. West Sussex, England. 2007.
- GUTIERREZ, F., PARISE, M., DE WAELE, J. and JOURDE, H., 2014. A review on natural and human induced geohazards and impacts. *Earth Science Reviews* 138. August 2014, pp. 61-88.
- HEATH, G.J, TROLLIP, N.Y.G. and VENTER, I.S., 2008. Mandate and powers of the Council for Geoscience in respect of development on dolomite having regards to applicable legislation,
- JENNINGS, J.E., BRINK, A.B.A., LOUW, A. and GOWAN, G.D., 1965. Sinkholes and subsidences in the Transvaal dolomite of South Africa. In; *Proceedings 6th International conference of soil Mechanics and foundation engineering*, Montreal, pp 51-54.
- JENNINGS, J.E., 1966a. Building on Dolomites in the Transvaal, *The Civil Engineer in South Africa*, February 1966.
- JOHNSON, M.R., VAN VUUREN, C.J., VISSER, J.N.J., COLE, D.I., WICKENS, H. DE V., CHISTIE, A.D.M., ROBERTS, D.L. and BRANDL, G., 2006. The Geology of South Africa. Edited 220 by Johnson, M.R., Anhaeusser, C.R. and Thomas, R.J. Published jointly by the Geological Society of South Africa, Johannesburg, and the Council of Geoscience, Pretoria.
- NHBRC, 2015. Home Building Manual and Guide – 2015. *NHBRC Communications*, Sunninghill, Johannesburg.
- OOSTHUIZEN, A.C., 2013. The hazard of sinkhole formation in the Centurion CBD and surrounding areas - Pretoria, Gauteng, South Africa. *Unpublished M. Sc. thesis*, University of Pretoria, Pretoria, 2013.
- OOSTHUIZEN, A.C., AND VAN ROOY, J.L., 2015. Hazard of sinkhole formation in the Centurion CBD using the Simplified Method of Scenario Supposition. *Journal of the South African Institute of Civil Engineering*, Volume 57 No.2, June 2015, pp 69-75.
- POTGIETER, A.S., PRETORIUS, S.J. AND VAN DER WALT, I.J., 2016. Integration of a Dolomite Risk Management Programme in Local Government in South Africa: Tlokwe City Council. *Journal of the Environmental Protection*, 7, pp 1041-1049.
- RICHARDSON, J. J., 2003. Local land use regulation of karst in the United States. In: *Beck BF (edition) Sinkholes and the engineering and environmental impacts of Karst*, Geotechnical Special Publication No. 122, ASCE, pp. 492–501
- RICHARDSON, S., 2013. Sinkhole and subsidence record in the Chuniespoort Group dolomite, Gauteng, South Africa. *Unpublished M. Sc. thesis*, University of Pretoria, Pretoria, 2013.
- SOUTH AFRICA, 1977. National Building Regulations and Building Standards Act – 103 of 1977, *Government Printer*, Pretoria.
- SOUTH AFRICA, 1993. Occupational Health and Safety Act – 85 of 1993, *Government Printer*, Pretoria.
- SOUTH AFRICA, 1996. The Constitution of the Republic of South Africa Act – 108 of 1996, *Government Printer*, Pretoria.

- SOUTH AFRICA, 1998. Housing Consumer Protection Measures Act – 95 of 1998, *Government Printer*, Pretoria.
- SOUTH AFRICA, 1999. Public Finance Management Act – 1 of 1999, *Government Printer*, Pretoria.
- SOUTH AFRICA, 2000. Local Government Municipal Systems Act – 32 of 2000, *Government Printer*, Pretoria.
- SOUTH AFRICA, 2002. Disaster Management Act – 57 of 2002, *Government Printer*, Pretoria.
- SOUTH AFRICA, 2005. Disaster Management Framework, *Government Printer*, Pretoria.
- SOUTH AFRICA, 2005. A Policy Framework for Disaster Risk Management: General Notice 654 of 2005, *Government Gazette, Government publishers*, Pretoria 0001.
- SOUTH AFRICA, 2008. Standards Act – 8 of 2008, *Government Printer*, Pretoria.
- SOUTH AFRICA, 2011. National Development Plan – Vision 2030, *National Planning Commission. The Presidency*, Pretoria.
- SOUTH AFRICA, 2013. Spatial Planning and Land Use Management Act – 16 of 2013, *Government Printer*, Pretoria.
- SOUTH AFRICA, 2014. Infrastructure Development Act – 23 of 2014, *Government Printer*, Pretoria.
- SOUTH AFRICAN NATIONAL STANDARD, 2012. Development of dolomite land – SANS 1936:2012 – PART 1 to 4. *Editions 1 Published by SABS Standards Division*, Pretoria 0001.
- UNITED NATIONS, 2013. Measuring vulnerability to natural hazards: Towards disaster resilient societies (Second Edition). *United Nations University Press*, United Nations University Office, New York, DC2-2062, NY 10017, USA.
- UNITED NATIONS, 2015. Sendai Framework for Disaster Risk Reduction 2015 – 2030: *United Nations Office for Disaster Risk Reduction*, UNISDR/GE/2015 - ICLUX EN5000 1st edition, Geneva Switzerland.
- VAN ROOY, J.L., 1996. Classification systems applied to dolomite terrain: *A review. Seminar on the engineering geology of dolomite areas*. University of Pretoria. Pretoria, 18 January 1996.
- VAN ROOY, J.L. and WITTHUSER, K.T., 2008. Vulnerability and risk in karst terrain. SAICE conference: *Problems Soils in South Africa*. Midrand, 3-4 November 2008.
- VAN SCHALKWYK, A., 1998. Legal aspects of development on dolomite land in South Africa. *Environmental Geology*, 36 (1-2): 167-169.
- WALTHAM, A.C. and FOOKES, P.G., 2003. Engineering classification of karst ground conditions. *Quarterly Journal of Engineering Geology and Hydrogeology*. Volume 36, pp. 101-118.

- WATERMEYER, R.B., BUTTRICK D.B., TROLLIP, N.Y.G., GERBER, A.A. and PIETERSE, N. (2008). A performance based approach to the development of dolomite land. *Proceedings of the Geotechnical Division of SAICE's Conference on Problem Soils in South Africa*. 3-4 November, Midrand.
- WINDE, F. and ERASMUS, E., 2011. Peatlands as filters for polluted mine water? – A case study from a uranium contaminated karst system in South Africa Part 1: Hydrogeological setting and U fluxes. *Water Journal*. Volume 3, pp. 291-322.
- WOLMARANS, J.F., 1996. Sinkholes and subsidences on the Far West rand. *Seminar on the engineering geology of dolomite areas*, university of Pretoria, Pretoria, 18 January 1996.

APPENDIX A:

List of the available Dolomite Stability Reports, Khutsong North

FOLDER NO.	REPORT TITLE	SEGIOLIT NO.	NO. OF BH's	REPORT NO.	REPORT DATE
F1893	Khutsong Stadium: Dolomite Stability and Geotechnical Investigation.	90020346	3	J13-031-CL1	June 2013
F2962	Proposed Police Station at Khutsong.	90108925	6	3/769/9 D/I(at)	April 1987
F2963	Khutsong health care centre.	90568888	4	16/1/5/1/7	December 1987
F2963	An Engineering Geological Investigation of the Site for the proposed community Health centre, Khutsong.	90108912	4	-	July 188
F2964	Report to Fourie & Pretorius Inc. on subsoil investigation for the proposed Khutsong Sewerage Works.	90905948	8	6528/MDC	April 1989
F2965	A report to the town council of Khutsong on a geotechnical investigation and dolomitic risk evaluation of sites immediately south of the admin area.	90568715	5	CG22/GAH/sjh	September 1988
F3023	Khutsong Proper and Extension 1 – 6: Feasibility Stage Dolomite Stability Investigation.	90039630	4	VGI3606	October 2013
F3024	Excavation and further evaluation of stability on Stand 5173 and 5173, Khutsong, Ext 2.	90108860	1		November 1992
F3025	Verslag oor n ondersoek na die geskiktheid vir dorsuitbreiding oor n dolomietgebied van sowat 400ha aangresend aan khutsong.	90108902	76	8099/JFW	March 1987
F3025.1	Khutsong Extension 3: Feasibility Stage Dolomite Stability Investigation.		61	VGI3676	October 2013
F3031	Dolomite Stability Investigation for the proposed extension to Assemblies of God.	90110116			November 1993
F3111	Dolomite Stability of Stand 5706, Khutsong, Carletonville for Commercial development.	90230328	5	-	June 1998
F3908	Gauteng: Merafong City: Stand 2574 Khutsong: Dolomite Stability Investigation.	90584889	2	VGI3325	January 2011
F3909	Merafong City: Khutsong Extension 3: Sewer Pump Station Doline: Hlanganani Primary School.	90584890	5	VGI3201.2	November 2008
F3916	Gauteng: Merafong City: Stand 545, Khutsong: DSI.	90584903	3		January 2011
F3919	Structural inspection: Housing units. Khutsong. Carletonville.	90584918	-		February 2011
F4027	Geotechnical & Dolomite Stability Investigation at Gold Fields West Clinic site (M04) and immediate surroundings, Khutsong Proper Township, Merafong City LM, Gauteng Province.	90584522	8	2011-0201	March 2011
F4055	Inspection report: Stand 5757. Khutsong Ext 2.	90584567	-	CO 2011-5745	January 2012
F4056	Inspection report: Stand 690. Khutsong .	90584568	-	CO 2011-5745	April 2012
F4057	Inspection report: Stand 5034 and 5035.	90584569	-	CO 2011-5745	April 2012
F4060	Dolomite Subsidence Inspection report for Carltenville and Khutsong. Merafong City Local Municipality , Gauteng Province.	90584572	-	CO 2011-5745	February 2012
F4337	Dolomite Stability Investigation for new Ablution Facility situated in the Khutsong Community Park, Johannesburg Metropolitan Municipality.	90624250	1	LM 1021/13	November 2013
F4395	Merafong City LM: Stand 658 to 666 and Stand 848 to 851, Meymbo Street, Khutsong Proper: Dolomite Stability Investigation.	90624347	7	VGI3692	November 2013
F4757	Kamohelo Primary School, Khutsong Geotechnical Investigation.	90251226	6	KHH2256	October 2015
F4815	Proposed New Hlangabeza ETO- 18-0888 Mobile Phone Base Station on: Erf 614, Khutsong, Carletonville District, Merafong City Local Municipality, Gauteng Province.	90251360	2	M16/3575	March 2016
F4838	Dolomite Stability Investigation on Erf 2561, Khutsong for a new MTN Tower, Merafong Local Municipality	90251395	1	GS0414 REV 00	March 2016
F4909	Proposed New Nayaboswa Eto-18-1000 Mobile Phone Base Station on: Stand number 7572, Khutsong Ext 1, Carletonville, Gauteng.	90020429	1	M16/3605	July 2016
F5112	Dolomite Stability and Material Assessment for two Proposed Road Sections, Khutsong North and South.	90251504	3	RS16040	May 2017

FOLDER NO.	REPORT TITTLE	SEGIOLIT NO.	NO. OF BH's	REPORT NO.	REPORT DATE
F5596	Dolomite Stability Investigation: Site SAT0628 Located on Stand 7572 Khutsong Extension 1, Merafong City Local Municipality.	90653117	4	T01904	January 2019
F5615	Dolomite Stability Study: Pipeline, Khutsong, Gauteng Province – Preliminary Report.	90653153	4	MWEM19-02	August 2019

APPENDIX B:

Available percussion boreholes drilled in Khutsong North

CGS FOLDER NO.	BH ID.	X-COORD	Y-COORD	DEPTH TO DOLOMITE BEDROCK (m)	BH DEPTH (m)	GW LEVEL (m)	INHERENT HAZARD CLASS	HAZARD RATING	COMMENTS
F1893	PH001	27.32518	-26.32928	>40	40	dry	7	High	very soft material below 38m
F1893	PH002	27.32484	-26.32915	>40	40	dry	7/8	High	very soft material below 31m
F1893	PH003	27.32479	-26.32907	23	25	dry	4/7	High	
F2962	G/KHU/1	27.32869	-26.32550	15	21	dry	6	High	Wad @ 8m-12m
F2962	G/KHU/2	27.32882	-26.32534	17	22	dry	3	Medium	
F2962	G/KHU/3	27.32897	-26.32512	17	23	dry	3	Medium	
F2963	G/KW/50	27.32602	-26.33060	43	46	dry	7	High	Low density material @ 31m-42m
F2963	G/KW/51	27.32701	-26.33022	27	60	dry	4	Medium	
F2963	G/KW/52	27.32719	-26.33065	38	52	dry	7	High	Low density material @ 27m-38m
F2963	G/KW/53	27.32602	-26.33113	39	59	dry	4	Medium	
F2963	G1	27.32811	-26.32931	34	50	dry	4	Medium	
F2963	G2	27.32789	-26.32886	42	48	dry	4	Medium	
F2963	G3	27.32826	-26.32871	41	48	dry	4	Medium	
F2963	G4	27.32855	-26.32884	48	54	dry	4/7	High	
F2964	BH1	27.31782	-26.34308	>20	20	dry	4/7	High	borehole too shallow to classify
F2964	BH2	27.31787	-26.34379	>30	30	dry	4/7	High	borehole too shallow to classify
F2964	BH3	27.31856	-26.34364	>30	30	dry	4/7	High	borehole too shallow to classify
F2964	BH4	27.31898	-26.34343	>15	15	dry	4/7	High	borehole too shallow to classify
F2964	BH5	27.31919	-26.34429	>20	20	dry	4/6	High	borehole too shallow to classify
F2964	BH6	27.31897	-26.34492	>30	30	dry	4/7	High	borehole too shallow to classify
F2964	BH7	27.31953	-26.34483	>20	20	dry	4/7	High	borehole too shallow to classify
F2964	BH8	27.31939	-26.34532	>15	15	dry	4/7	High	borehole too shallow to classify
F2965	BH1	27.32973	-26.32919	>32	32	dry	4/7	High	
F2965	BH2	27.32763	-26.32890	>34	34	dry	4/7	High	
F2965	BH3	27.33214	-26.32872	30	32	dry	4/4	High	
F2965	BH4	27.33220	-26.32724	35	36	dry	4/7	High	
F2965	BH5	27.33318	-26.32716	13	20	dry	3	Medium	
F3023	1	27.32125	-26.33051	7.5	24	dry	3	Medium	
F3023	10	27.30424	-26.34855	>30	30	dry	6	High	
F3023	11	27.30959	-26.34758	>30	30	dry	6	High	
F3023	12	27.30801	-26.33855	0	15	dry	5	High	
F3023	13	27.30896	-26.34428	1.5	15	dry	5	High	

CGS FOLDER NO.	BH ID.	X-COORD	Y-COORD	DEPTH TO DOLOMITE BEDROCK (m)	BH DEPTH (m)	GW LEVEL (m)	INHERENT HAZARD CLASS	HAZARD RATING	COMMENTS
F3023	14	27.30594	-26.32305	0	21	dry	5	High	
F3023	15	27.30075	-26.32700	13.5	24	dry	6	High	Wad @ 6m-13m
F3023	16	27.30192	-26.32868	>30	30	dry	6	High	Wad @ 9m-13m & 15m-18m
F3023	17	27.30715	-26.33240	>30	30	dry	7	High	Wad @ 17m-30m
F3023	18	27.31229	-26.34132	10.5	21	dry	3	Medium	
F3023	19	27.32625	-26.33466	>30	30	dry	7	High	
F3023	2	27.31765	-26.33204	>30	30	dry	6	High	Wad @ 15m-21m
F3023	20	27.32269	-26.33384	>30	30	dry	4/7	High	
F3023	21	27.32022	-26.34200	>30	30	dry	4/7	High	
F3023	22	27.31930	-26.34032	>30	30	dry	4/7	High	
F3023	23	27.31827	-26.33823	>30	30	dry	4/7	High	
F3023	24	27.31293	-26.33631	>30	30	dry	4/7	High	
F3023	25	27.31309	-26.33683	>30	30	dry	4/7	High	
F3023	26	27.31619	-26.34322	19.5	30	dry	4	Medium	
F3023	27	27.31100	-26.34593	18	30	dry	6	High	Wad @ 6m-18m
F3023	28	27.30659	-26.34863	>30	30	dry	4/7	High	
F3023	29	27.30616	-26.33735	>30	30	dry	4/7	High	
F3023	3	27.31248	-26.33094	>30	30	dry	4/7	High	chert & dolomite residuum
F3023	30	27.30954	-26.33350	>30	30	dry	4/7	High	
F3023	31	27.30010	-26.33354	22.5	30	dry	4	Medium	
F3023	32	27.29194	-26.33588	0	21	dry	5	High	
F3023	33	27.29167	-26.33366	3	18	dry	5	High	
F3023	34	27.29584	-26.33437	1.5	18	dry	5	High	
F3023	35	27.29472	-26.33732	>30	30	dry	8	High	No sample below 21m
F3023	36	27.30202	-26.33839	>30	30	dry	6	High	
F3023	37	27.30139	-26.34152	>30	30	dry	6	High	
F3023	38	27.29974	-26.34958	>30	30	dry	4/7	High	
F3023	39	27.30369	-26.35100	>30	30	dry	4/7	High	
F3023	4	27.31707	-26.33398	>30	30	dry	7/7	High	
F3023	40	27.29773	-26.34920	21	30	dry	4	Medium	
F3023	41	27.29292	-26.34071	>30	30	dry	6	High	
F3023	42	27.30101	-26.34386	18	30	dry	4	Medium	

CGS FOLDER NO.	BH ID.	X-COORD	Y-COORD	DEPTH TO DOLOMITE BEDROCK (m)	BH DEPTH (m)	GW LEVEL (m)	INHERENT HAZARD CLASS	HAZARD RATING	COMMENTS
F3023	43	27.29578	-26.33193	2	21	dry	5	High	
F3023	44	27.29709	-26.34650	105	30	dry	3	Medium	
F3023	5	27.32054	-26.33906	>30	30	dry	6	High	Wad @ 19m-24m
F3023	6	27.31488	-26.33918	>30	30	dry	4/7	High	
F3023	7	27.30397	-26.32973	>30	30	dry	4/7	High	
F3023	7230/2	27.31484	-26.32692	32	36	dry	7/8	High	Low density material @ 6m-26m
F3023	7230/3	27.31462	-26.32692	19	26	dry	3	Medium	
F3023	8	27.30928	-26.32794	10.5	21	dry	3	Medium	
F3023	9	27.30457	-26.32384	0	13.5	dry	5	High	
F3023	A	27.32137	-26.33555	27	30	dry	6	High	Cavity @ 19m-23m
F3023	B	27.32153	-26.33538	28	31	dry	7	High	Cavity @ 17m-20m & 26m-28m
F3023	BH10	27.30613	-26.33990	3	8	dry	5	High	
F3023	BH101	27.31341	-26.33118	10.5	21	dry	3	Medium	
F3023	BH102	27.31432	-26.33242	10	20	dry	5	High	
F3023	BH103	27.31498	-26.33117	46	60	dry	4	Medium	
F3023	BH104	27.31649	-26.33172	>30	30	dry	4	Medium	
F3023	BH105	27.31604	-26.33014	15	25	dry	3	Medium	
F3023	BH11	27.30636	-26.34005	6	10	dry	5	High	
F3023	BH7	27.30578	-26.33997	6	10	dry	5	High	
F3023	BH8	27.30609	-26.34038	4	8	dry	5	High	
F3023	C	27.32116	-26.33511	30	34	dry	6	High	Cavity @ 27m-30m
F3023	EC1	27.32427	-26.31555	5	11	dry	5	High	
F3023	EC2	27.32420	-26.31557	5	11	dry	5	High	
F3023	K01	27.33556	-26.32778	17	23	dry	4	Medium	
F3023	K02	27.32754	-26.33607	30	36	dry	4	Medium	
F3023	K03	27.32771	-26.33752	34	40	dry	7	High	Wad/Cavity @ 12m-15, 21m-25m & 28m-33m
F3023	K05	27.32976	-26.32829	>40	40	dry	4	High	
F3023	K06	27.31663	-26.33844	35	41	dry	4	Medium	
F3023	K07	27.31698	-26.33927	21	27	dry	6	High	Cavity @ 17m-20m
F3023	K08	27.31464	-26.33520	>37	37	dry	4	High	
F3023	K09	27.31610	-26.33353	19	25	dry	6	High	Cavity @ 14m-17m
F3023	K1	27.31515	-26.33612	>30	30	dry	6	High	

CGS FOLDER NO.	BH ID.	X-COORD	Y-COORD	DEPTH TO DOLOMITE BEDROCK (m)	BH DEPTH (m)	GW LEVEL (m)	INHERENT HAZARD CLASS	HAZARD RATING	COMMENTS
F3023	K10	27.31462	-26.33220	20	26	dry	6	High	Low density material @ 11m-16m
F3023	K11	27.31406	-26.33372	27	33	dry	7	High	Low density material @ 18m-21m & 23m-26m
F3023	K13	27.32995	-26.33105	41	47	dry	4	Medium	
F3023	K14	27.31454	-26.33248	12	18	dry	3	Medium	
F3023	K16	27.31762	-26.33378	54	60	dry	4	Medium	
F3023	K18	27.31656	-26.32123	19	21	dry	6	High	Low density material @ 10m-15m
F3023	K19	27.32758	-26.33158	42	48	dry	6	High	Low density material @ 19m-22m
F3023	K2	27.31728	-26.33518	53	57	dry	7	High	Wad @ 31m-39m
F3023	K20	27.33007	-26.33295	24	30	dry	6	High	Low density material @ 15m-21m
F3023	K21	27.32407	-26.33265	56	60	dry	8	High	Wad/Cavity @ 37m-56m
F3023	K22	27.32587	-26.33076	>30	30	dry	4	High	
F3023	K23	27.32696	-26.33030	36	42	dry	4	Medium	
F3023	K24	27.32872	-26.32989	>60	60	dry	6	High	Low density material @ 30m-34m
F3023	K25	27.33047	-26.32692	45	50	dry	4	Medium	
F3023	K26	27.32760	-26.32562	24	30	dry	6	High	Wad @ 14m-23m
F3023	K28	27.32510	-26.32795	24	30	dry	6	High	Wad @ 18m-23m
F3023	K29	27.32796	-26.32765	31	37	dry	4	Medium	
F3023	K3	27.31916	-26.33447	>55	55	dry	4	High	
F3023	K30	27.32624	-26.31724	7	13	dry	3	Medium	
F3023	K31	27.32425	-26.31574	9	15	dry	3	Medium	
F3023	K32	27.32542	-26.31698	8	14	dry	3	Medium	
F3023	K33	27.32536	-26.31810	6	12	dry	5	High	
F3023	K34	27.32755	-26.31919	3	10	dry	5	High	
F3023	K35	27.32811	-26.32018	3	10	dry	5	High	
F3023	K37	27.32499	-26.31999	44	50	dry	7/8	High	Low density material @ 32m-43m
F3023	K38	27.32403	-26.32083	>60	60	dry	4	High	
F3023	K39	27.32934	-26.32306	>60	60	dry	7/8	High	Low density material @ 25m-45m
F3023	K40	27.33224	-26.32514	15	21	dry	4	Medium	
F3023	K41	27.33129	-26.32506	37	43	dry	4	Medium	
F3023	K42	27.32919	-26.32654	>60	60	dry	4	High	Karoo sediments @ 0m-19m
F3023	K43	27.32843	-26.32488	>20	20	dry	7/8	High	Wad @ 5m-20m
F3023	K44	27.32869	-26.32379	5	11	dry	5	High	

CGS FOLDER NO.	BH ID.	X-COORD	Y-COORD	DEPTH TO DOLOMITE BEDROCK (m)	BH DEPTH (m)	GW LEVEL (m)	INHERENT HAZARD CLASS	HAZARD RATING	COMMENTS
F3023	K45	27.32673	-26.32338	5	11	dry	5	High	
F3023	K46	27.32549	-26.32502	16	11	dry	5	High	
F3023	K48	27.32179	-26.32464	11	17	dry	3	Medium	
F3023	K5	27.32476	-26.33629	27	31	dry	4	Medium	
F3023	K50	27.32169	-26.32573	34	40	dry	6	High	Wad @ 26m-30m
F3023	K51	27.31679	-26.32725	38	44	dry	4	Medium	
F3023	K52	27.31652	-26.32772	47	53	dry	4	Medium	
F3023	K53	27.31555	-26.32862	20	26	dry	4	Medium	
F3023	K56	27.31318	-26.32831	27	33	dry	4	Medium	
F3023	K57	27.31155	-26.32990	19	25	dry	4	Medium	
F3023	K59	27.31094	-26.32751	19	25	dry	6	High	Wad @ 8m-15m
F3023	K6	27.32426	-26.33920	>42	42	dry	8	High	Wad @ 23m-42m
F3023	W1	27.32137	-26.33339	27	30	dry	4	Medium	
F3023	W2	27.31864	-26.33442	52	60	51	4	Medium	
F3023	W3	27.31381	-26.33294	22	30	dry	6	High	Wad @ 18m-22m
F3023	W4	27.31929	-26.33221	>30	30	dry	4	High	
F3023	W5	27.32398	-26.33043	>30	30	dry	4	High	
F3023	WC1	27.31538	-26.32639	29	30	dry	4	High	
F3024	G/KC/1	27.32654	-26.33552	35	37	dry	7/8	High	
F3024	G/KC/2	27.32642	-26.33542	25	27	dry	4	Medium	
F3025	45	27.32506	-26.33677	25	35	dry	4	Medium	
F3025	46	27.32132	-26.33436	8	18	dry	3	Medium	
F3025	47	27.32244	-26.33850	15	25	dry	4	Medium	
F3025	48	27.31734	-26.34111	14	24	dry	4	Medium	
F3025	49	27.31363	-26.34058	14	24	dry	4	Medium	
F3025	50	27.31485	-26.34422	35	45	dry	4	Medium	
F3025	51	27.30846	-26.34210	1	11	dry	5	High	
F3025	52	27.30558	-26.34080	0	10	dry	5	High	
F3025	53	27.30506	-26.34674	3	13	dry	5	High	
F3025	54	27.29883	-26.34882	6	16	dry	5	High	
F3025	55	27.29417	-26.35273	1	11	dry	5	High	
F3025	57	27.32353	-26.33459	51	60	dry	4	Medium	

CGS FOLDER NO.	BH ID.	X-COORD	Y-COORD	DEPTH TO DOLOMITE BEDROCK (m)	BH DEPTH (m)	GW LEVEL (m)	INHERENT HAZARD CLASS	HAZARD RATING	COMMENTS
F3025	58	27.32378	-26.33827	>59	59	dry	6	High	Void @ 54m-58m
F3025	59	27.32013	-26.33763	27	36	dry	4	Medium	
F3025	60	27.31759	-26.33683	37	47	dry	6	High	Wad @ 33m-37m
F3025	61	27.31611	-26.33993	44	53	dry	4	Medium	marked in blue on map1
F3025	62	27.31024	-26.33643	50	60	dry	4	Medium	
F3025	63	27.31257	-26.34110	31	40	dry	4	Medium	
F3025	64	27.31324	-26.34259	38	48	dry	6	High	Wad @ 34m-38m
F3025	65	27.31185	-26.34364	12	27	dry	3	Medium	4-12 shear zone
F3025	66	27.30723	-26.34278	20	30	dry	6	High	Wad @ 12m-20
F3025	67	27.30734	-26.34411	3	21	dry	5	High	
F3025	68	27.30594	-26.34183	32	42	dry	4	Medium	
F3025	69	27.30240	-26.33947	64	71	dry	7	High	Wad @ 54m-61m
F3025	70	27.30304	-26.34576	8	21	dry	3	Medium	
F3025	71	27.30235	-26.34824	40	50	dry	4	Medium	
F3025	72	27.30102	-26.35045	38	43	dry	4	Medium	
F3025	74	27.31027	-26.33447	19	30	dry	4	Medium	
F3025	75	27.30753	-26.33600	32	42	dry	4	Medium	
F3025	76	27.30361	-26.34171	32	42	dry	6	High	Low density material @ 20m-31m
F3025	77	27.31203	-26.33985	38	48	dry	4	Medium	
F3025	78	27.31210	-26.33788	44	54	dry	4	Medium	
F3025	79	27.32135	-26.33801	9	19	dry	3	Medium	
F3025	80	27.31400	-26.33840	15	25	dry	3	Medium	
F3025	81	27.32164	-26.33551	39	48	dry	7	High	Low density material @ 14m-34m
F3025.1	KX3-01	27.31062	-26.33535	24	30	dry	4	Medium	
F3025.1	KX3-02	27.31045	-26.33765	19	25	dry	6	High	Low density material @ 5m-9m & 14-16m
F3025.1	KX3-03	27.31303	-26.33376	>29	29	dry	6	High	No sample between 21m-29m
F3025.1	KX3-04	27.30952	-26.33828	22	28	dry	6	High	Low density material @ 5m-10m & 17-20m
F3025.1	KX3-05	27.30988	-26.33795	9	16	dry	3	Medium	
F3025.1	KX3-06	27.30784	-26.33717	>38	38	dry	4	High	
F3025.1	KX3-07	27.30813	-26.33846	6	17	dry	3	Medium	
F3025.1	KX3-08	27.30679	-26.33877	16	22	dry	4	Medium	
F3025.1	KX3-09	27.30709	-26.33981	7	18	dry	5	Medium	

CGS FOLDER NO.	BH ID.	X-COORD	Y-COORD	DEPTH TO DOLOMITE BEDROCK (m)	BH DEPTH (m)	GW LEVEL (m)	INHERENT HAZARD CLASS	HAZARD RATING	COMMENTS
F3025.1	KX3-10	27.30783	-26.33938	3	10	dry	5	High	
F3025.1	KX3-11	27.29935	-26.33717	11	18	dry	5	Medium	
F3025.1	KX3-12	27.29905	-26.34533	13	19	dry	5	Medium	
F3025.1	KX3-13	27.29810	-26.34480	9	20	dry	3	Medium	
F3025.1	KX3-14	27.29781	-26.34424	25	31	dry	3	Medium	
F3025.1	KX3-15	27.29934	-26.34428	15	21	dry	3	Medium	
F3025.1	KX3-16	27.30017	-26.34416	7	13	dry	5	Medium	
F3025.1	KX3-17	27.29838	-26.34343	>30	30	dry	4	High	
F3025.1	KX3-18	27.29995	-26.34346	15	26	dry	3	Medium	
F3025.1	KX3-19	27.29839	-26.34266	17	23	dry	4	Medium	
F3025.1	KX3-20	27.29982	-26.34266	>25	25	dry	4	High	
F3025.1	KX3-21	27.31031	-26.33253	33	39	dry	4	Medium	
F3025.1	KX3-22	27.31062	-26.33309	44	50	dry	4	Medium	
F3025.1	KX3-23	27.31108	-26.33411	47	53	dry	7	High	Cavity @ 39m-46m
F3025.1	KX3-24	27.31143	-26.33511	44	50	dry	4	Medium	
F3025.1	KX3-25	27.31139	-26.33633	33	39	dry	4	Medium	
F3025.1	KX3-26	27.31131	-26.33580	41	47	dry	4	Medium	
F3025.1	KX3-28	27.30617	-26.33810	46	52	dry	4	Medium	
F3025.1	KX3-29	27.31088	-26.33484	27	33	dry	4	Medium	
F3025.1	KX3-30	27.31012	-26.33598	34	40	dry	4	Medium	
F3025.1	KX3-31	27.31024	-26.33650	>60	60	dry	4	High	
F3025.1	KX3-32	27.31162	-26.33677	44	50	dry	4	Medium	
F3025.1	KX3-33	27.30664	-26.33649	44	50	dry	4	Medium	
F3025.1	KX3-34	27.30813	-26.33583	18	24	dry	4	Medium	
F3025.1	KX3-35	27.30852	-26.33718	39	45	dry	4	Medium	
F3025.1	KX3-36	27.30788	-26.33671	41	47	dry	6	High	Low density material @ 36m-40m
F3025.1	KX3-37	27.30675	-26.33689	47	53	dry	4	Medium	
F3025.1	KX3-38	27.31071	-26.33667	37	43	dry	4	Medium	
F3025.1	KX3-39	27.30658	-26.33526	33	39	dry	6	High	Cavity @ 27m-31m
F3025.1	KX3-40	27.30699	-26.33622	16	22	dry	4	Medium	
F3025.1	KX3-41	27.30706	-26.33728	40	46	dry	4	Medium	
F3025.1	KX3-42	27.30588	-26.33707	28	34	dry	4	Medium	

CGS FOLDER NO.	BH ID.	X-COORD	Y-COORD	DEPTH TO DOLOMITE BEDROCK (m)	BH DEPTH (m)	GW LEVEL (m)	INHERENT HAZARD CLASS	HAZARD RATING	COMMENTS
F3025.1	KX3-43	27.30609	-26.33753	44	50	dry	4	Medium	
F3025.1	KX3-44	27.30662	-26.33773	46	52	dry	4	Medium	
F3025.1	KX3-45	27.30523	-26.33756	38	44	dry	4	Medium	
F3025.1	KX3-46	27.30565	-26.33729	35	41	dry	4	Medium	
F3025.1	KX3-47	27.30577	-26.33720	31	37	dry	4	Medium	
F3025.1	KX3-48	27.30206	-26.34198	41	47	dry	4	Medium	
F3025.1	KX3-49	27.30104	-26.33945	41	47	dry	4	Medium	
F3025.1	KX3-50	27.30054	-26.34269	17	23	dry	4	Medium	
F3025.1	KX3-51	27.30192	-26.34148	40	46	dry	4	Medium	
F3025.1	KX3-52	27.30130	-26.34388	11	17	dry	3	Medium	
F3025.1	KX3-53	27.30156	-26.34290	15	21	dry	3	Medium	
F3025.1	KX3-54	27.30354	-26.34270	30	36	dry	4	Medium	
F3025.1	KX3-55	27.30165	-26.34338	11	17	dry	3	Medium	
F3025.1	KX3-56	27.30232	-26.34390	3	9	dry	5	High	
F3025.1	KX3-57	27.30084	-26.34337	16	22	dry	4	Medium	
F3025.1	KX3-58	27.30250	-26.34265	13	19	dry	3	Medium	
F3025.1	KX3-59	27.30326	-26.34154	34	40	dry	4	Medium	
F3025.1	KX3-60	27.30109	-26.34195	33	39	dry	4	Medium	
F3025.1	KX3-61	27.30058	-26.34224	6	12	dry	3	Medium	
F3025.1	KX3-62	27.30118	-26.34244	31	37	dry	4	Medium	
F3025.1	KX3-63	27.30285	-26.34201	26	32	dry	4	Medium	
F3025.1	KX3-64	27.30250	-26.34238	4	10	dry	5	High	
F3025.1	KX3-65	27.30357	-26.34227	31	37	dry	4	Medium	
F3025.1	KX3-66	27.30193	-26.34278	17	23	dry	4	Medium	
F3025.1	KX3-67	27.30302	-26.34284	15	21	dry	4	Medium	
F3025.1	KX3-68	27.30247	-26.34335	32	38	dry	4	Medium	
F3025.1	KX3-69	27.30314	-26.34343	27	33	dry	4	Medium	
F3025.1	KX3-70	27.30287	-26.34390	6	12	dry	3	Medium	
F3025.1	KX3-71	27.30550	-26.33807	29	35	dry	4	Medium	
F3031	BH1	27.32551	-26.32620	23.2	30	dry	6	High	Wad @ 13m-22m
F3031	BH2	27.32592	-26.32648	7.1	13	dry	3	Medium	
F3031	BH3	27.32605	-26.32607	14	20	dry	3	Medium	

CGS FOLDER NO.	BH ID.	X-COORD	Y-COORD	DEPTH TO DOLOMITE BEDROCK (m)	BH DEPTH (m)	GW LEVEL (m)	INHERENT HAZARD CLASS	HAZARD RATING	COMMENTS
F3111	BH1	27.32730	-26.33303	25	30	dry	6	High	Wad @12m-17m
F3111	BH2	27.32727	-26.33206	>30	30	dry	7	High	Wad @ 20m-28m
F3111	BH3	27.32720	-26.33139	>30	30	dry	4	High	
F3111	BH4	27.32791	-26.33114	>30	30	dry	7	High	Wad @ 18m-24m
F3111	BH5	27.32720	-26.33216	49	60	dry	7	High	Wad @ 25m-34m
F3908	3325/1	27.32237	-26.31797	18	24	dry	3	Medium	
F3908	3325/2	27.32243	-26.31801	12	18	dry	3	Medium	
F3909	BH1	27.30551	-26.34056	5	10	dry	5	High	
F3909	BH2	27.30563	-26.34071	5	9	dry	5	High	
F3909	BH3	27.30572	-26.34029	9	13	dry	3	Medium	
F3909	BH4	27.30584	-26.34046	7	11	dry	3	Medium	
F3909	BH5	27.30597	-26.34061	11	15	dry	3	Medium	
F3909	BH9	27.30632	-26.34038	5	8	dry	5	High	
F3909	S1	27.30545	-26.34067	3	18	dry	5	High	
F3909	S2	27.30553	-26.34072	22	30	dry	7	High	Wad @ 7m-22m
F3909	S3	27.30534	-26.34076	10	18	dry	3	Medium	
F3909	S4	27.30546	-26.34076	1.5	18	dry	5	High	
F3909	S5	27.30554	-26.34078	10	18	dry	3	Medium	
F3909	SP1	27.30508	-26.34187	5	11	dry	5	High	
F3909	SP2	27.30514	-26.34168	16	22	dry	4	Medium	
F39099	SP3	27.30521	-26.34151	>39	39	dry	2	Low	Karoo sediments @ 0m-27m
F3909	SP4	27.30510	-26.34150	11	17	dry	3	Medium	
F3909	SP5	27.30518	-26.34129	10	16	dry	3	Medium	
F3916	3327/1	27.32042	-26.32633	30	32	dry	4	High	
F3916	3327/2	27.32052	-26.32644	17	24	dry	6	High	Wad @ 8m-17m
F4027	BH1	27.31537	-26.32669	41	42	dry	6	High	Cavity @ 8m-13m
F4027	BH2	27.31521	-26.32668	>30	30	dry	4	High	
F4027	BH3	27.31521	-26.32678	>30	30	dry	3/4	High	
F4027	BH4	27.31486	-26.32698	28	30	dry	3	High	
F4027	BH5	27.31577	-26.32656	43	45	dry	4/7	High	
F4027	BH6	27.31527	-26.32651	56	60	dry	4	Medium	
F4027	BH7	27.31467	-26.32677	20	60	dry	3/4	Medium	

CGS FOLDER NO.	BH ID.	X-COORD	Y-COORD	DEPTH TO DOLOMITE BEDROCK (m)	BH DEPTH (m)	GW LEVEL (m)	INHERENT HAZARD CLASS	HAZARD RATING	COMMENTS
F4027	BH8	27.31554	-26.32629	>21	21	dry	4	High	
F4337	BH01	27.32106	-26.31921	34	41	dry	4	Medium	
F4395	3692/01	27.31828	-26.32656	66	68	31.6	4	High	Cavity @ 31m-64m
F4395	3692/02	27.31814	-26.32674	45	51	13.4	4	High	Wad @ 12m-16m
F4395	3692/03	27.31854	-26.32686	19	25	11.3	6	High	Wad @ 8m-19m
F4395	3692/06	27.31831	-26.32677	>60	60	dry	8	High	Cavity @ 6m-29m & 48m-51m
F4395	3692/08	27.31830	-26.32669	>60	60	11.9	3	High	Wad @ 15m-27m & 38m-41m
F4395	3692/09	27.31833	-26.32661	>60	60	3.2	3	High	Low density material & Cavities 5m-60m
F4395	3692/10	27.31846	-26.32694	39	35	11.1	3	High	Wad @ 7m-18m & 20m-25m
F4757	BH1	27.32664	-26.31796	13.3	20	dry	6	High	Wad @ 9m-13m
F4757	BH2	27.32708	-26.31909	2.4	10	dry	5	High	
F4757	BH3	27.32724	-26.31937	29.5	36	dry	8	High	Cavity @ 21m-30m
F4757	BH4	27.32751	-26.31892	4.4	11	dry	5	High	
F4757	BH5	27.32648	-26.31883	3	11	dry	5	High	
F4757	BH6	27.32747	-26.31922	1.2	10	dry	5	High	
F4815	HL1	27.32424	-26.32738	18.5	25	dry	4	Medium	
F4838	GS01	27.32068	-26.31906	12	18	dry	3	Medium	
F4909	NB/1	27.31807	-26.33419	>60	60	54	4	High	
F5112	RS01	27.30964	-26.33432	30	36	dry	7	High	Cavity @ 7m-17m
F5112	RS02	27.30875	-26.33519	>36	36	dry	7	High	
F5596	BT7572/1	27.31747	-26.33288	52	58	dry	6	High	Low density material @ 18m-21m & 23m-25m
F5615	KBH1	27.32671	-26.33333	40	48	dry	8	High	Void/cavity between 17m - 35 m
F5615	KBH2	27.32490	-26.33337	>42	42	dry	7	High	Void/cavity between 24m -30 m
F5615	KBH3	27.32133	-26.33470	21	30	dry	6/7	High	Void/cavity between 8m -15 m
F5615	KBH4	27.31986	-26.33407	>60	60	36	4	High	

APPENDIX C:

Available ground instability events recorded in Khutsong North

EVENT ID.	EVENT TYPE	EVENT OCCURRENCE DATE	WIDTH (m)	DEPTH (m)	EVENT SIZE CATEGORY	POSSIBLE CAUSE	COMMENTS
176	Sinkhole	26 October (1991)	30.0	8.0	Very large	Improper water control	Enlarged sinkhole during remedial work.
619	Sinkhole	estimated (2011)	5.0	2.0	Medium	Leaking sewerage pipe	Exposed highly weathered chert material residuum.
1227	Undefined	estimated (1975)			Undefined	Unspecified	Position uncertain, unverified. 1960-1983
1228	Undefined	estimated (1975)			Undefined	Unspecified	Position uncertain, unverified. 1960-1983
1229	Undefined	estimated (1975)			Undefined	Unspecified	Position uncertain, unverified. 1960-1983
1230	Undefined	estimated (1975)			Undefined	Unspecified	Position uncertain, unverified. 1960-1983
1231	Undefined	estimated (1975)			Undefined	Unspecified	Position uncertain, unverified. 1960-1983
1232	Undefined	estimated (1975)			Undefined	Unspecified	Position uncertain, unverified. 1960-1983
1233	Undefined	estimated (1975)			Undefined	Unspecified	Position uncertain, unverified. 1960-1983
1234	Undefined	estimated (1975)			Undefined	Unspecified	Position uncertain, unverified. 1960-1983
1235	Undefined	estimated (1975)			Undefined	Unspecified	Position uncertain, unverified. 1960-1983
1368	Undefined	February (2011)			Undefined	Unspecified	Position uncertain
1369	Undefined	estimated (1995)			Undefined	Unspecified	Position uncertain 1980-2010
1370	Sinkhole	16 December (2009)	1.0	1.0	Small	Unspecified	Position uncertain, dimensions measured from map.
1371	Undefined	February (2011)			Undefined	Unspecified	Position uncertain
1372	Sinkhole	2008	1.0	1.0	Small	Unspecified	Dimensions measured from map.
1373	Undefined	estimated (1995)			Undefined	Unspecified	Position uncertain, 1980-2010
1374	Undefined	estimated (1995)			Undefined	Unspecified	Position uncertain, 1980-2010
1375	Sinkhole	14 May (2011)	0.3	3.0	Small	Leaking pipe	Small but deep sinkhole in front of stand.
1376	Sinkhole	26 October (1991)	30.0	8.0	Very large	Unspecified	Position uncertain
1377	Sinkhole	5 April (1992)	11.0	4.0	Large	Unspecified	Position uncertain, dimensions measured from map
1378	Sinkhole	5 April (1992)	4.5	4.0	Medium	Unspecified	Position uncertain, dimensions measured from map
1379	Sinkhole	1992	8.0	10.0	Large	Unspecified	Position uncertain
1380	Sinkhole	1992	10.0	4.0	Large	Unspecified	Position uncertain
1381	Sinkhole	2002	20.0	5.0	Very large	Stormwater ponding	Position uncertain, dimensions measured from map
1382	Undefined	2002			Undefined	Unspecified	Position uncertain
1383	Undefined	2002			Undefined	Unspecified	Position uncertain
1384	Sinkhole	2002			Small	Unspecified	Position uncertain
1385	Sinkhole	estimated (1995)	40.0	10.0	Very large	Unspecified	Position uncertain, occurred during 1980-2010
1386	Sinkhole	estimated (1995)	22.0	10.0	Very large	Unspecified	Position uncertain, occurred during 1980-2010
1387	Sinkhole	estimated (1995)	13.0	5.0	Large	Unspecified	Position uncertain, occurred during 1980-2010
1388	Sinkhole	estimated (1995)	15.0	5.0	Large	Unspecified	Position uncertain, occurred during 1980-2010
1389	Sinkhole	estimated (1995)	16.0	5.0	Very large	Unspecified	Position uncertain, occurred during 1980-2010

EVENT ID.	EVENT TYPE	EVENT OCCURRENCE DATE	WIDTH (m)	DEPTH (m)	EVENT SIZE CATEGORY	POSSIBLE CAUSE	COMMENTS
1390	Sinkhole	estimated (1995)	19.0	5.0	Very large	Unspecified	Position uncertain, occurred during 1980-2010
1391	Sinkhole	estimated (1995)	15.0	5.0	Large	Unspecified	Position uncertain, occurred during 1980-2010
1392	Sinkhole	estimated (1995)	24.0	10.0	Very large	Unspecified	Position uncertain, occurred during 1980-2010
1393	Sinkhole	estimated (1995)	50.0	10.0	Very large	Unspecified	Position uncertain, occurred during 1980-2010
1394	Subsidence	estimated (1995)	25.0	1.0	Very large	Unspecified	Position uncertain, occurred during 1980-2010
1395	Subsidence	estimated (1995)	17.0	1.0	Very large	Unspecified	Position uncertain, occurred during 1980-2010
1396	Subsidence	estimated (1995)	6.0	1.0	Large	Unspecified	Position uncertain, occurred during 1980-2010
1397	Sinkhole	estimated (1995)	42.0	10.0	Very large	Unspecified	Position uncertain, occurred during 1980-2010
1398	Sinkhole	estimated (1995)	24.0	10.0	Very large	Unspecified	Position uncertain, occurred during 1980-2010
1399	Sinkhole	estimated (1995)	27.0	10.0	Very large	Unspecified	Position uncertain, occurred during 1980-2010
1400	Sinkhole	estimated (1995)	32.0	10.0	Very large	Unspecified	Position uncertain, occurred during 1980-2010
1401	Subsidence	estimated (1995)	20.0	1.0	Very large	Unspecified	Position uncertain, occurred during 1980-2010
1402	Subsidence	estimated (1995)	18.0	1.0	Very large	Unspecified	Position uncertain, occurred during 1980-2010
1403	Subsidence	estimated (1995)	14.0	1.0	Large	Unspecified	Position uncertain, occurred during 1980-2010
1404	Subsidence	estimated (1995)	12.0	1.0	Large	Unspecified	Position uncertain, occurred during 1980-2010
1405	Undefined	estimated (1995)			Undefined	Unspecified	Position uncertain, occurred during 1980-2010
1406	Subsidence	estimated (1995)	14.0	1.0	Large	Unspecified	Position uncertain, occurred during 1980-2010
1407	Subsidence	estimated (1995)	24.0	1.0	Very large	Unspecified	Position uncertain, occurred during 1980-2010
1408	Sinkhole	estimated (1995)	18.0	5.0	Very large	Unspecified	Position uncertain, occurred during 1980-2010
1409	Sinkhole	estimated (1995)	15.0	5.0	Large	Unspecified	Position uncertain, occurred during 1980-2010
1410	Subsidence	estimated (1995)	20.0	1.0	Very large	Unspecified	Position uncertain, occurred during 1980-2010
1411	Subsidence	estimated (1995)	15.0	1.0	Large	Unspecified	Position uncertain, occurred during 1980-2010
1412	Subsidence	estimated (1995)	6.0	1.0	Large	Unspecified	Position uncertain, occurred during 1980-2010
1413	Sinkhole	estimated (1995)	20.0	5.0	Very large	Unspecified	Position uncertain, occurred during 1980-2010
1414	Sinkhole	estimated (1995)	17.0	5.0	Very large	Unspecified	Position uncertain, occurred during 1980-2010
1415	Sinkhole	estimated (1995)	20.0	10.0	Very large	Unspecified	Position uncertain, occurred during 1980-2010
1416	Sinkhole	estimated (1995)	25.0	10.0	Very large	Unspecified	Position uncertain, occurred during 1980-2010
1417	Subsidence	estimated (1995)	18.0	1.0	Very large	Unspecified	Position uncertain, occurred during 1980-2010
1418	Sinkhole	estimated (1995)	15.0	5.0	Large	Unspecified	Position uncertain, occurred during 1980-2010
1419	Sinkhole	estimated (1995)	23.0	5.0	Very large	Unspecified	Position uncertain, occurred during 1980-2010
1420	Sinkhole	estimated (1995)	17.0	5.0	Very large	Unspecified	Position uncertain, occurred during 1980-2010
1421	Sinkhole	estimated (1995)	30.0	10.0	Very large	Unspecified	Position uncertain, occurred during 1980-2010
1422	Sinkhole	estimated (1995)	35.0	10.0	Very large	Unspecified	Position uncertain, occurred during 1980-2010

EVENT ID.	EVENT TYPE	EVENT OCCURRENCE DATE	WIDTH (m)	DEPTH (m)	EVENT SIZE CATEGORY	POSSIBLE CAUSE	COMMENTS
1423	Sinkhole	estimated (1995)	34.0	10.0	Very large	Unspecified	Position uncertain, occurred during 1980-2010
1424	Sinkhole	estimated (1995)	30.0	10.0	Very large	Unspecified	Position uncertain, occurred during 1980-2010
1425	Sinkhole	estimated (1995)	23.0	5.0	Very large	Unspecified	Position uncertain, occurred during 1980-2010
1426	Sinkhole	estimated (1995)	35.0	10.0	Very large	Unspecified	Position uncertain, occurred during 1980-2010
1427	Sinkhole	estimated (1995)	25.0	5.0	Very large	Unspecified	Position uncertain, occurred during 1980-2010
1428	Sinkhole	estimated (1995)	26.0	5.0	Very large	Unspecified	Position uncertain, occurred during 1980-2010
1429	Sinkhole	estimated (1995)	35.0	10.0	Very large	Unspecified	Position uncertain, occurred during 1980-2010
1430	Sinkhole	estimated (1995)	35.0	10.0	Very large	Unspecified	Position uncertain, occurred during 1980-2010
1431	Sinkhole	estimated (1995)	28.0	10.0	Very large	Unspecified	Position uncertain, occurred during 1980-2010
1432	Sinkhole	estimated (1995)	42.0	10.0	Very large	Unspecified	Position uncertain, occurred during 1980-2010
1433	Undefined	estimated (1995)			Undefined	Unspecified	Position uncertain, occurred during 1980-2010
1434	Sinkhole	estimated (1995)	29.0	10.0	Very large	Unspecified	Position uncertain, occurred during 1980-2010
1435	Sinkhole	estimated (1995)	35.0	10.0	Very large	Unspecified	Position uncertain, occurred during 1980-2010
1436	Sinkhole	estimated (1995)	25.0	5.0	Very large	Unspecified	Position uncertain, occurred during 1980-2010
1437	Sinkhole	estimated (1995)	30.0	10.0	Very large	Unspecified	Position uncertain, occurred during 1980-2010
1438	Sinkhole	estimated (1995)	38.0	10.0	Very large	Unspecified	Position uncertain, occurred during 1980-2010
1439	Sinkhole	estimated (1995)	65.0	10.0	Very large	Unspecified	Position uncertain, occurred during 1980-2010
1440	Sinkhole	estimated (1995)	22.0	5.0	Very large	Unspecified	Position uncertain, occurred during 1980-2010
1441	Sinkhole	estimated (1995)	23.0	5.0	Very large	Unspecified	Position uncertain, occurred during 1980-2010
1442	Subsidence	estimated (1995)	36.0	1.0	Very large	Unspecified	Position uncertain, occurred during 1980-2010
1443	Subsidence	estimated (1995)	15.0	1.0	Large	Unspecified	Position uncertain, occurred during 1980-2010
1444	Sinkhole	estimated (1995)	38.0	10.0	Very large	Unspecified	Position uncertain, occurred during 1980-2010
1445	Subsidence	estimated (1995)	26.0	1.0	Very large	Unspecified	Position uncertain, occurred during 1980-2010
1446	Subsidence	2000	5.0	1.0	Medium	Leaking sewer pipe	Position uncertain, dimensions measured from map
1447	Subsidence	2000	10.0	1.0	Large	Leaking sewer pipe	Position uncertain, dimensions measured from map
1448	Undefined	2000			Undefined	Leaking sewer pipe	Position uncertain
1452	Subsidence	estimated (1995)	17.0	1.0	Very large	Unspecified	Position uncertain, occurred during 1980-2010
1453	Subsidence	estimated (1995)	3.0	1.0	Medium	Unspecified	Position uncertain, occurred during 1980-2010
1454	Undefined	estimated (1995)			Undefined	Old sinkhole	Position uncertain, occurred during 1980-2010
1455	Undefined	estimated (1995)			Undefined	Old sinkhole	Position uncertain, occurred during 1980-2010
1456	Undefined	estimated (1995)			Undefined	Old sinkhole	Position uncertain, occurred during 1980-2010
1457	Undefined	estimated (1995)			Undefined	Old sinkhole	Position uncertain, occurred during 1980-2010
1458	Subsidence	estimated (1995)	20.0	1.0	Very large	Unspecified	Position uncertain, occurred during 1980-2010

EVENT ID.	EVENT TYPE	EVENT OCCURRENCE DATE	WIDTH (m)	DEPTH (m)	EVENT SIZE CATEGORY	POSSIBLE CAUSE	COMMENTS
1459	Undefined	estimated (1995)			Undefined	Unspecified	Position uncertain, occurred during 1980-2010
1460	Sinkhole	March (2011)	7.5	3.0	Large	Stormwater ponding	Sinkhole in open stand, former pit latrine site
1461	Subsidence	2009	7.0		Large	Unspecified	Subsidence on property, house demolished
1462	Undefined	estimated (1995)			Undefined	Unspecified	Position uncertain, occurred during 1980-2010
1463	Undefined	estimated (1995)	1.0		Undefined	Unspecified	Position uncertain, occurred during 1980-2010
1464	Subsidence	August (2008)	5.5	1.0	Large	Unspecified	Position uncertain
1465	Subsidence	1988	12.0	1.0	Large	Unspecified	Position uncertain, dimensions measured from map
1466	Subsidence	1993	15.0	1.0	Large	Unspecified	Position uncertain, occurred during 1980-2010
1467	Subsidence	estimated (1995)	10.0	1.0	Large	Unspecified	Position uncertain, occurred during 1980-2010
1468	Subsidence	estimated (1995)	15.0	1.0	Large	Unspecified	Position uncertain, occurred during 1980-2010
1469	Subsidence	November (1995)	20.0	1.0	Very large	Unspecified	Position uncertain, occurred during 1980-2010
1470	Subsidence	estimated (2011)	1.0	0.4	Small	Unspecified	Position uncertain 1980-2010
1471	Subsidence	estimated (2011)	3.1	0.6	Medium	Unspecified	Small hole on side of road near taxi rank
1472	Sinkhole	August (2011)	7.0	2.0	Large	Manhole overflow	Mr. S Manganyi: M LM
1473	Undefined	May (2010)			Undefined	Leaking pipe	Subsidence on corner of house, severe cracking
1481	Sinkhole	May (2013)	1.0	2.0	Small	Unspecified	Small sinkhole, cracks on exterior walls.
1482	Undefined	September (2012)		0.0	Undefined	Leaking pipe	
1483	Sinkhole	12 February (2013)	1.0	1.5	Small	Unspecified	
1484	Undefined	May (2014)			Undefined	Unspecified	Cracks on interior and exterior walls.
1485	Sinkhole	9 January (2011)	3.0	8.0	Medium	Leaking sewer	Sinkhole 1.5m from garage door of Stand 3509
1486	Sinkhole	2011	4.0	1.5	Medium	Manhole overflow	sinkhole opposite communal toilets
1487	Subsidence	October (2014)	14.0	1.0	Large	Leaking sewer	Subsidence in road, aligned with water manholes
1488	Undefined	December (2012)			Undefined	Unspecified	Slight subsidence at back of the house, wall cracks
1489	Sinkhole	May (2013)	3.0	3.0	Medium	Leaking pipe	Subsidence causing severe cracks in walls.
1490	Sinkhole	2011	0.5	0.3	Small	Pump overflow	Small hole in ground
1491	Undefined	2011			Undefined	Unspecified	Cracks to interior walls, bulging tiles in lounge.
1492	Undefined	May (2012)			Undefined	Unspecified	Slight settlement at corner of house, wall cracks
1493	Undefined	August (2011)			Undefined	Possible leaking sewer	Stand 5019 & Stand 5035, severe cracking
1494	Undefined	2012			Undefined	Leaking sewer	Subsidence along sewer line, wall cracks
1495	Undefined	December (2011)			Undefined	Ponding water	Small subsidence at corner of house
1496	Subsidence	28 October (2012)	0.5	1.0	Small	Leaking sewer pipe	Small sinkhole at corner of gate, wall cracking
1530	Sinkhole	December (2014)	7.0	4.0	Large	Leaking sewer	
1531	Sinkhole	December (2014)	3.0	2.0	Medium	Leaking sewer	

EVENT ID.	EVENT TYPE	EVENT OCCURRENCE DATE	WIDTH (m)	DEPTH (m)	EVENT SIZE CATEGORY	POSSIBLE CAUSE	COMMENTS
1532	Sinkhole	2014	8.0	6.0	Large	Leaking pipe	
1533	Subsidence	2014	1.0	0.5	Small	Leaking pipe	
1547	Sinkhole	November (2016)	5.0	3.0	Medium	Unspecified	
1548	Sinkhole	November (2016)	5.0	2.0	Medium	Unspecified	
1549	Sinkhole	November (2016)	7.0	3.0	Large	Sewage pipe?	
3389	Undefined	estimated (2017)			Undefined	Leaking wet service	
3390	Sinkhole	February (2017)	4.0	3.0	Medium	Leaking wet service	
3391	Undefined	estimated (2017)			Undefined	Leaking wet service	
3392	Undefined	estimated (2017)			Undefined	Leaking sewer line	
3393	Subsidence	estimated (2017)	15.0	1.0	Large	Leaking sewer line	Dimensions measured from map F3023
3394	Undefined	estimated (2017)			Undefined	Poor workmanship	
3564	Undefined	2000			Undefined	Stormwater ponding	Visible on Google earth
4511	Undefined	2000			Undefined	Stormwater ponding	Visible on Google earth
4512	Undefined	2000			Undefined	Stormwater ponding	Visible on Google earth
4723	Subsidence	14 April (2019)	13.0	0.5	Large	Leaking sewer line	
4724	Subsidence	21 September (2019)	3.9	0.5	Medium	Leaking pipe	
4736	Sinkhole	14 February (2019)	23.0	4.0	Very large	Leaking pipes	Notified by Eskom
4737	Subsidence	December (2019)	3.0	1.0	Medium	Leaking sewer pipe	Notified by A Ackerman
4738	Sinkhole	December (2019)	20.0	5.0	Very large	Leaking sewage pipe	Notified by A Ackerman
4739	Sinkhole	December (2019)	5.0	2.0	Medium	Leaking sewage pipe	Notified by A Ackerman
4740	Sinkhole	December (2019)	8.0	4.0	Large	Leaking sewage pipe	Notified by A Ackerman
4741	Sinkhole	December (2019)	25.0	2.0	Very large	Leaking sewage pipe	Notified by A Ackerman
4742	Subsidence	December (2019)	12.0	1.0	Large	Leaking sewage pipe	Notified by A Ackerman
4743	Subsidence	December (2019)	3.0	1.0	Medium	Leaking sewage pipe	Notified by A Ackerman
4748	Subsidence	10 May (2020)	4.5	0.5	Medium	Leaking sewer line	Notified by Gerhard Dirker (Merafong Municipality)
4750	Subsidence	3 June (2020)	1.5	0.5	Small	Leaking/broken valves	Notified by Gerhard Dirker (Merafong Municipality)
4755	Sinkhole	July (2020)	9.5	1.5	Large	Burst water pipeline	Notified by Merafong Disaster Group
4756	Subsidence	estimated (1995)	9.0	1.0	Large	Unspecified	Dimensions measured from map F3023.
4757	Subsidence	estimated (1995)	13.0	1.0	Large	Unspecified	Dimensions measured from map F3023.
4758	Subsidence	estimated (1995)	8.0	1.0	Large	Unspecified	Dimensions measured from map F3023.
4759	Subsidence	estimated (1995)	12.0	1.0	Large	Unspecified	Dimensions measured from map F3023.
4760	Subsidence	estimated (1995)	7.0	1.0	Large	Unspecified	Dimensions measured from map F3023.
4761	Subsidence	estimated (1995)	5.0	1.0	Medium	Unspecified	Dimensions measured from map F3023.

EVENT ID.	EVENT TYPE	EVENT OCCURRENCE DATE	WIDTH (m)	DEPTH (m)	EVENT SIZE CATEGORY	POSSIBLE CAUSE	COMMENTS
4762	Subsidence	estimated (1995)	5.0	1.0	Medium	Unspecified	Dimensions measured from map F3023.
4763	Subsidence	estimated (1995)	7.0	1.0	Large	Unspecified	Dimensions measured from map F3023.
4764	Subsidence	estimated (1995)	7.0	1.0	Large	Unspecified	Dimensions measured from map F3023.
4765	Subsidence	estimated (1995)	5.0	1.0	Medium	Unspecified	Dimensions measured from map F3023.
4766	Subsidence	estimated (1995)	6.0	1.0	Large	Unspecified	Dimensions measured from map F3023.
4767	Subsidence	estimated (1995)	5.0	1.0	Medium	Unspecified	Dimensions measured from map F3023.
4768	Subsidence	estimated (1995)	3.0	1.0	Medium	Unspecified	Dimensions measured from map F3023.
4769	Sinkhole	estimated (1995)	50.0	10.0	Very large	Unspecified	Dimensions measured from map F3023.
4770	Subsidence	estimated (1995)	23.0	1.0	Very large	Unspecified	Dimensions measured from map F3023.
4771	Subsidence	estimated (1995)	20.0	1.0	Very large	Unspecified	Dimensions measured from map F3023.
4772	Subsidence	estimated (1995)	45.0	1.0	Very large	Unspecified	Dimensions measured from map F3023.
4773	Subsidence	estimated (1995)	10.0	1.0	Large	Unspecified	Dimensions measured from map F3023.
4774	Subsidence	estimated (1995)	7.0	1.0	Large	Unspecified	Dimensions measured from map F3023.
4775	Subsidence	estimated (1995)	3.0	1.0	Medium	Unspecified	Dimensions measured from map F3023.
4776	Subsidence	estimated (1995)	4.0	1.0	Medium	Unspecified	Dimensions measured from map F3023.
4777	Subsidence	estimated (1995)	3.0	1.0	Medium	Unspecified	Dimensions measured from map F3023.
4782	Subsidence	estimated (1995)	5.0	1.0	Medium	Unspecified	Dimensions measured from map F3023.
4781	Subsidence	estimated (1995)	9.0	1.0	Large	Unspecified	Dimensions measured from map F3023.
4780	Subsidence	estimated (1995)	4.0	1.0	Medium	Unspecified	Dimensions measured from map F3023.
4779	Subsidence	estimated (1995)	9.0	1.0	Large	Unspecified	Dimensions measured from map F3023.
4778	Subsidence	estimated (1995)	3.0	1.0	Medium	Unspecified	Dimensions measured from map F3023.
4783	Subsidence	estimated (1995)	1.0	1.0	Small	Unspecified	Dimensions measured from map F3023.
4784	Sinkhole	estimated (1995)	28.0	10.0	Very large	Unspecified	Dimensions measured from map F3023.
4785	Subsidence	estimated (1995)	4.0	1.0	Medium	Unspecified	Dimensions measured from map F3023.
4786	Subsidence	estimated (1995)	4.0	1.0	Medium	Unspecified	Dimensions measured from map F3023.
4787	Sinkhole	estimated (1995)	27.0	10.0	Very large	Unspecified	Dimensions measured from map F3023.
4788	Subsidence	estimated (1995)	7.0	1.0	Large	Unspecified	Dimensions measured from map F3023.
4789	Subsidence	estimated (1995)	10.0	1.0	Large	Unspecified	Dimensions measured from map F3023.
4790	Subsidence	estimated (1995)	7.0	1.0	Large	Unspecified	Dimensions measured from map F3023.
4791	Subsidence	estimated (1995)	8.0	1.0	Large	Unspecified	Dimensions measured from map F3023.
4792	Subsidence	estimated (1995)	3.0	1.0	Medium	Unspecified	Dimensions measured from map F3023.
4793	Sinkhole	estimated (1995)	34.0	10.0	Very large	Unspecified	Dimensions measured from map F3023.
4794	Subsidence	estimated (1995)	12.0	1.0	Large	Unspecified	Dimensions measured from map F3023.

EVENT ID.	EVENT TYPE	EVENT OCCURRENCE DATE	WIDTH (m)	DEPTH (m)	EVENT SIZE CATEGORY	POSSIBLE CAUSE	COMMENTS
4795	Subsidence	estimated (1995)	7.0	1.0	Large	Unspecified	Dimensions measured from map F3023.
4796	Sinkhole	estimated (1995)	10.0	1.0	Large	Unspecified	Dimensions measured from map F3023.
4797	Subsidence	estimated (1995)	8.0	1.0	Large	Unspecified	Dimensions measured from map F3023.
4798	Subsidence	estimated (1995)	10.0	1.0	Large	Unspecified	Dimensions measured from map F3023.
4799	Subsidence	estimated (1995)	10.0	1.0	Large	Unspecified	Dimensions measured from map F3023.
4800	Sinkhole	estimated (1995)	20.0	5.0	Very large	Unspecified	Dimensions measured from map F3023.
4801	Sinkhole	estimated (1995)	20.0	5.0	Very large	Unspecified	Dimensions measured from map F3023.
4802	Subsidence	estimated (1995)	12.0	1.0	Large	Unspecified	Dimensions measured from map F3023.
4803	Subsidence	estimated (1995)	9.0	1.0	Large	Unspecified	Dimensions measured from map F3023.
4804	Subsidence	estimated (1995)	10.0	1.0	Large	Unspecified	Dimensions measured from map F3023.
4805	Sinkhole	estimated (1995)	25.0	5.0	Very large	Unspecified	Dimensions measured from map F3023.
4806	Subsidence	estimated (1995)	10.0	1.0	Large	Unspecified	Dimensions measured from map F3023.
4826	Undefined	2008			Undefined	Unspecified	
4827	Undefined	2008			Undefined	Unspecified	
4828	Cracks	estimated (2011)	0.4	0.3	Small	Unspecified	small hole in ground
4829	Undefined	4 February (2011)			Undefined	Unspecified	
4830	Subsidence	12 February (2013)	1.5	0.8	Small	Unspecified	
4842	Sinkhole	17 August (2020)	3.1	1.5	Medium	Leaking of water	Notified by Merafong Disaster Group
4843	Undefined	July (2020)		0.0	Undefined	Undefined	Notified by Merafong Disaster Group.
4846	Undefined	June (2020)		0.0	Undefined	Leaking septic tank	Notified by Merafong Disaster Group
255	Sinkhole	31 October (1995)	3.0	1.5	Medium	Storm water ponding	