1. INTRODUCTION

1.1. Background

The greater part of land in the area south of Pretoria is underlain by dolomite from the Chuniespoort Group of the Transvaal Supergroup. In South Africa dolomite rock has a notorious reputation for the formation of sinkholes and subsidences. Thousands of people reside and work in the Centurion area, where numerous sinkholes have occurred causing damage and in some instances loss of property. Current standard practice is to execute a geotechnical investigation on all dolomitic land earmarked for development, whether it is residential or commercial.

As part of the Council for Geoscience's mandatory role to assist government authorities, the Dolomite Section has been involved in the field of sinkhole risk evaluation since the early 1970's in assisting local authorities such as the City of Tshwane Metropolitan Municipality (CTMM), to ensure safe development on dolomite.

Most of the dolomite stability reports that are produced for residential / commercial development in the Tshwane Municipal area are submitted to the Council for Geoscience (CGS) where they are stored in the National Dolomite Databank. From the available Dolomite Stability Reports that have been submitted to the CGS over the last 30 years, it is apparent that hazardous conditions exist in the Central Business District (CBD) area of Centurion, Pretoria. Centurion has rapidly densified over the last 40 years, as it has become a residential midway between Johannesburg and Pretoria. The Gautrain train route now traverses across the Centurion CBD area, and the Centurion Station being situated in West Street, has attracted high rise developments to this area. This will lead to an increase in the population which results in an increase in road traffic and density of people per hectare in this area. Plate 1 shows the Centurion CBD area, with the Centurion mall, the Gautrain station and commercial developments in this area. Plates 2 and 3 illustrate the densification that has already taken place in the Die Hoewes and Lyttelton residential areas over the past 40 years. CTMM actively supports and propels higher densities in the Centurion CBD area which has required the CGS to evaluate the sinkhole risk associated with this increase in development densities.

The large amount of information available in the Centurion CBD area, particularly in digital formats, meant that a first order sinkhole hazard analysis could be attempted.

Plate 1. The Centurion CBD area (from Google Earth)

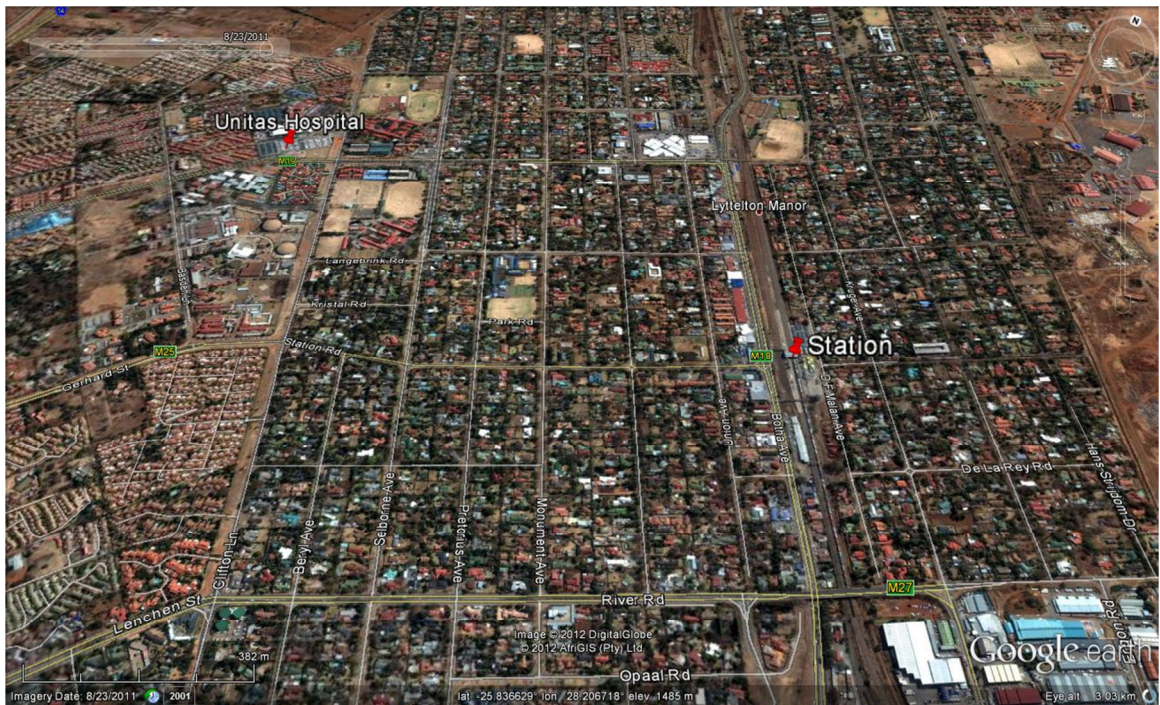*Plate 2. Lyttelton during the 1950's (from the Record Newspaper)*

Plate 3. Lyttelton Manor Extensions during 2012 (from Google Earth)

The current method used in determining the hazard[1] for sinkhole formation in dolomitic areas is the *Method for dolomite land hazard and risk assessment in South Africa*, as described by Buttrick et. al (2001). The methodology and origin of this method will be explained later in Section 3.9 of this dissertation. Buttrick and van Schalkwyk (1998) indicated that this method was developed before the concept of appropriate development and compulsory precautionary measures were introduced and it is therefore assumed in their methodology that the land use is considered as being 'abused'. The Centurion CBD and surrounding areas, on the contrary, cannot be considered as abused land, since precautionary measures and specific foundation designs have been introduced over the majority of the area, and this is therefore considered as 'managed' land.

1.2. Problem Statement

The Centurion area has been known to be vulnerable to sinkhole formation. With the Centurion CBD and surrounding areas being rapidly densified, in terms of commercial and residential development, the Centurion CBD sinkhole occurrence will increase, leading to injury and damage. This could have an adverse effect on the confidence of this area. In order to enable CTMM to guide safe development in Centurion, areas where a high hazard of sinkhole formation exists need to be identified and appropriately managed. However, at present the CGS reviews

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[1] *Hazard is defined as a potential source of danger (Oxford Dictionary).*

development proposals in the Centurion CBD area without having a broad overview of the geological conditions of the area.

This study will be used as a tool for staff of the CGS to make a quick assessment of the type of conditions that are present in the immediate vicinity of the particular site to be developed.

Sinkholes have led to the demolishing of houses, damage to infrastructure and vast amounts of Rands spent on repairing in the Centurion CBD and surrounding areas. Plate 4 shows one of the events that have occurred. This subsidence (S100) affected several units in this residential complex, and access for the residents living in this complex was affected, two units have subsequently had to be demolished.

Plate 4. A 15 m diameter subsidence in a residential complex (S100)

1.3. Study Objective and Aims

The main objectives of the study are as follows:

- To undertake a literature study on dolomite in the Centurion area.

- The classification of the dolomite in terms of low to high hazard (according to Buttrick et. al (2001)) and the occurrence of sinkholes. Provide a map where the

hazard of sinkhole formation is indicated in the Centurion CBD and surrounding areas.

- Compare an 'abused' land use scenario, used in the Buttrick et. al (1995) classification system, against the more controlled, managed Centurion CBD and surrounding areas.

- Make recommendations regarding the suitability of land usage based on the hazard of sinkhole formation, as stipulated in the draft SANS 1936-1:2012.

1.4. Study Area

CTMM demarcated the Centurion CBD area, as John Vorster road in the south, Jean Avenue in the north, the N1 highway in the south-east and South Street in the east (Figure 1). Since development and densification is not only limited to the CBD area the immediate surrounding areas were also included in this study. The study area is thus bounded by Trichardt Road in the north, Botha Avenue in the east, the N1 highway in the south and the N14 highway in the west (Figure 1).

Various suburbs form part of the study area:
- The area south of John Vorster Drive towards the southern corner of the study area is known as Zwartkop;
- The area north-east of John Vorster Drive and the Hennops River is known as Centurion;
- The area north-east of the Hennops River up to North Street in the north, Clifton Street north-east and Leonie Street in the east is known as Die Hoewes or formerly as Lyttelton Agricultural Holdings (some areas are still known as the Lyttelton Agricultural Holdings);
- The area east of Leonie street up to the N1 Highway and bounded by Botha and Limpopo Streets east and north respectively, is known as Doringkloof;
- The area north of Limpopo Street, east of Clifton Street, and south of Trichardt Street up to the boundary of the study area is known as Lyttelton Manor.

In this dissertation the study area as delineated above, will collectively be referred to as the Centurion CBD area.

FIGURE 1: LOCALITY OF THE CENTURION CBD AND SURROUNDING AREAS
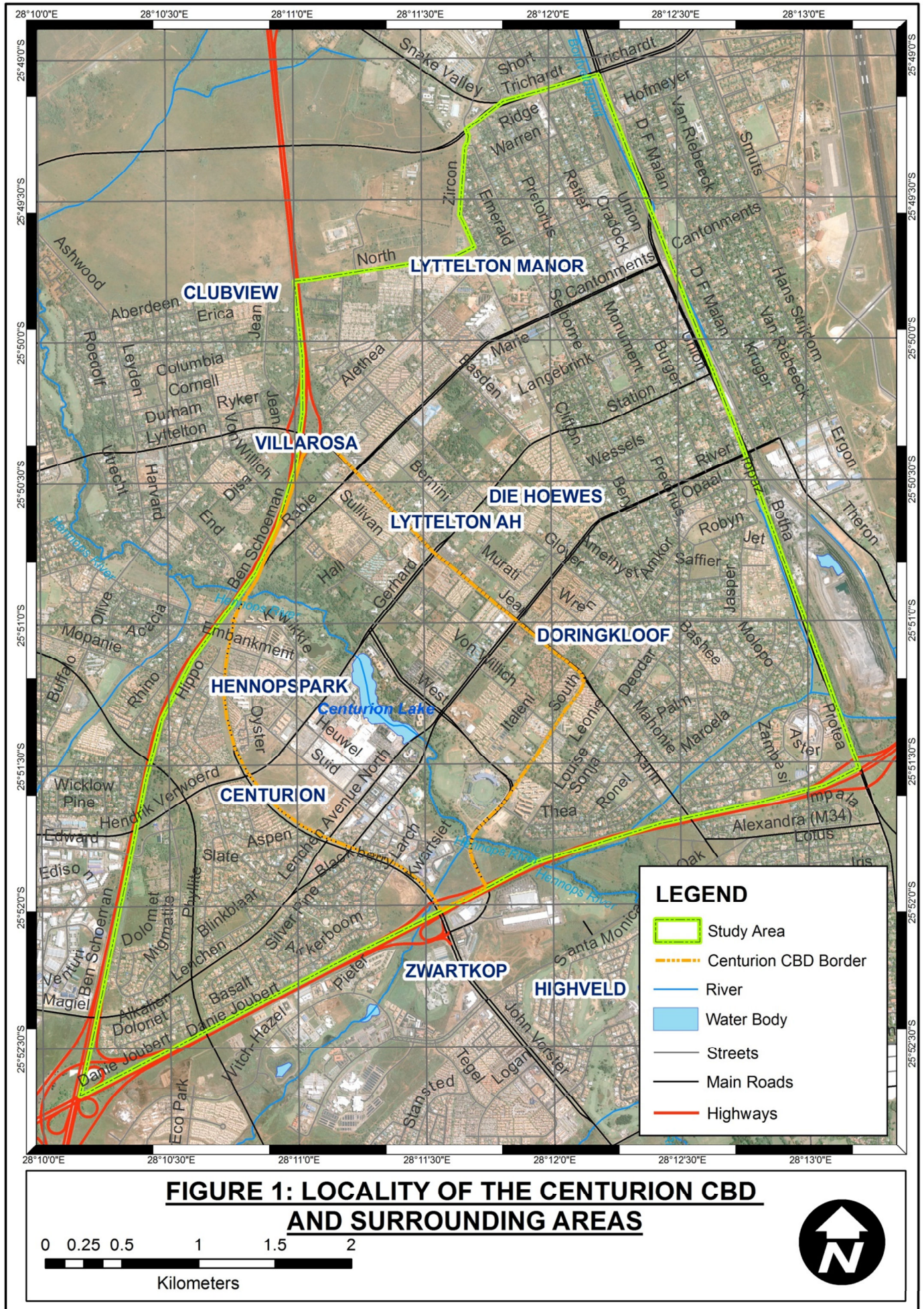
The Centurion CBD and surrounding areas covers a surface area of approximately 1 657 hectares. The area is relatively flat and is gently sloping towards the Hennops River, which cuts thought the middle of the Centurion CBD area. The surface elevation of the area varies between 1410 metres above mean sea level (mamsl) in the area of the Hennops River valley, to 1497 mamsl in the area of Basden Street (Lyttelton Agricultural Holdings) in the north as well as in the area of John Vorster Drive in the south.

The majority of the Centurion CBD and surrounding areas has been developed, with commercial developments dominating the area around the Centurion Lake and residential development present towards the outskirts, as revealed on the aerial photo in Figure 1.

1.5. Available Data

The following data are available within the Centurion CBD area:

- *Dolomite Stability Reports*: The Dolomite Stability Reports, falling within the delineated area, were extracted from the National Dolomite Databank. Their report boundaries and borehole positions had already been plotted on the CGS Geographic Information Systems (GIS) database.

  A total of 555 dolomite stability reports are situated within the Centurion CBD area (Figure 2) and a list of the available Dolomite Stability Reports is attached in Appendix A.

- *Percussion Borehole Logs*: Percussion boreholes are generally drilled as part of the dolomite stability investigations which forms the basis of the Dolomite Stability Reports. A total of 3587 percussion borehole (Figure 2) profiles are available from the Dolomite Stability Reports within the Centurion CBD area and its immediate surrounds. A list of all the boreholes in the Centurion CBD area is provided in Appendix B.

- *Gravity Survey*: The only available usable gravity survey is limited to the Lyttelton Agricultural Holdings i.e. the northern side of the Hennops River and was obtained from a report by Dr. B.H. Relly (Geological Report on the Stability of the Lyttelton Agricultural Holdings – A General Study of a Dolomite Area, 1976). The gravity survey contained in this dissertation is a Bouguer gravity map produced on a 45 m grid which as Dr. Relly indicated, is at 50% of the standard spacing (30 m) for township development projects. This Bouguer gravity information was converted into a Residual gravity layer by Africon (Pty) Ltd as part of the initial

Gautrain investigations, and was made available to the CGS. The map was digitally converted and added as a layer in the GIS (Plate 13).

Gravity surveys are usually conducted as part of the site investigations for each site. Approximately 500 separate gravity surveys were undertaken as part of the dolomite stability investigations available. Due to these gravity maps not being uniform (i.e. different scales, different geophysicists who conducted the study, some in Bouguer format, others in Residual format) and not covering the entire area, these were excluded in this study.

- *Sinkhole Data*[2]: The sinkhole data has been sourced from different sources. The CGS has captured a number of sinkholes in the area. A sinkhole database in the form of an Access database was created by the consultancy firm BKS for CTMM in the early 2000's. CTMM has also recorded a number of sinkholes in the area which was made available. A number of private consultants (engineering geologists) have also reported sinkhole events to the CGS. A record of the sinkhole events are presented in Appendix C.

- *Aerial Photos*: Aerial photos obtained from the Department of Housing, taken during 2004 at a scale of 1:5 000 were used as the background layer in GIS.

All the data is available in ArcGIS®.

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2 It should be noted that the sinkhole information is very sensitive and this could not be made available to the general public.
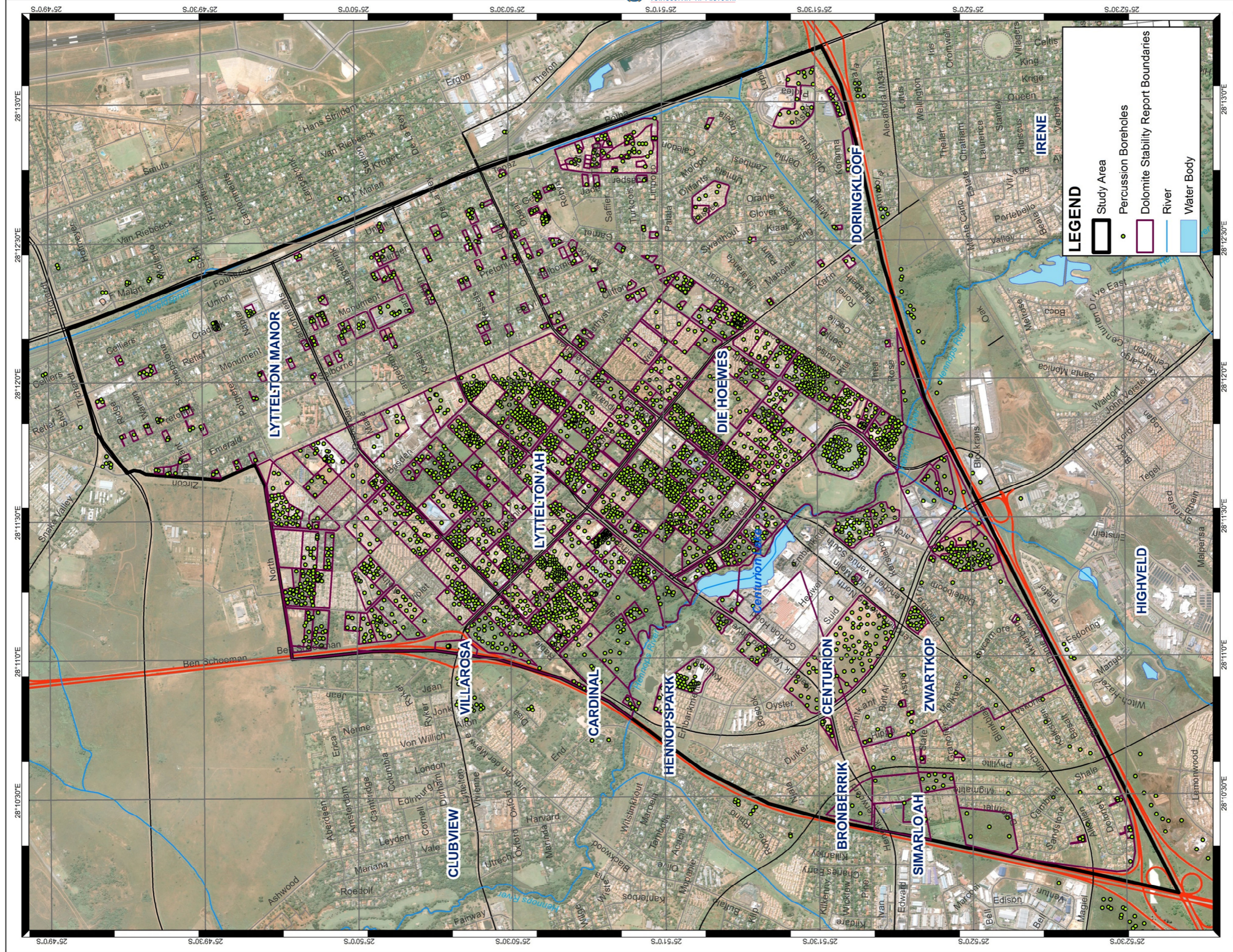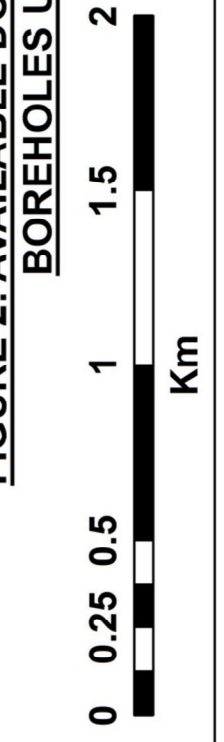
FIGURE 2: AVAILABLE DOLOMITE STABILITY REPORTS AND PERCUSSION BOREHOLES USED FOR THE HAZARD ASSESSMENT

LEGEND

- ☐ Study Area
- • Percussion Boreholes
- ☐ Dolomite Stability Report Boundaries
- — River
- ☐ Water Body

2. GEOLOGY AND GEOHYDROLOGY

2.1. Regional Geology

The Centurion CBD and surrounds are situated in the Malmani Subgroup of the Transvaal Supergroup. The Malmani Subgroup is up to 2 000 m thick and is subdivided into five formations, based on chert content, stromatolite morphology, intercalated shales and erosion surfaces (Button, 1973; Eriksson and Truswell, 1974).

At the base is the Oaktree Formation which is transitional from siliciclastic sedimentation to platform carbonates and consists of 10 – 200 m of carbonaceous shales, stromatolitic dolomites and locally developed quartzites. The Monte Christo Formation, 300 – 500 m thick, overlies the Oaktree Formation and begins with an erosive breccia and continues with stromatolitic and oolitic platformal chert-rich dolomites. The Lyttelton Formation follows the Monte Christo with 100 – 200 m of shales, quartzites and stromatolitic dolomites, and is, in turn, overlain by the chert-rich dolomites of the Eccles Formation, up to 600 m thick, and which includes a series of erosion breccias. The Eccles is overlain by the Frisco Formation comprising mainly stromatolitic dolomites, becomes more shale-rich towards the top and is up to 400 m thick (Johnson, M.R., Anhaeusser, C.R. and Thomas, R.J. 2006).

2.2. Geology of the Centurion CBD Area

The central and larger portion of the Centurion CBD area is underlain by chert and dolomite rocks of the Monte Christo Formation. The Lyttelton Formation is present along the eastern boundary of the area and the Oaktree Formation is present in a small area in the southern corner of the Centurion CBD area. Dolomite from the Lyttelton and Oaktree Formations are generally chert-poor whereas the Monte Christo Formation is chert-rich.

Syenite has intruded the area in the form of sills and dykes and a large syenite sill is present towards the southern boundary of the Centurion CBD area in Zwartkop, as indicated on Figure 3, showing the unpublished 1:50 000 2528CC Centurion Geological Sheet. A prominent north-south trending dyke is present along the eastern boundary of the Centurion CBD area as well as a smaller northwest-southeast trending dyke in the area of the Lyttelton Agricultural Holdings. Alluvial material is present in the center of the Centurion CBD area close to the Hennops

River. A small Karoo outlier (Vryheid Formation) is present in the northwestern boundary of the area. Figure 3 shows the geology map of the area.

2.3. Geohydrology

The Centurion CBD area is situated in the Irene catchment which comprises four sub-catchments or compartments which are hydraulically connected as evidenced by the direction of groundwater flow (Hobbs, 1988). The four sub-catchments are analogous to the Fountains West, Fountains East, Doornkloof West and Doornkloof East compartments described by Vegter (1986).

The majority of the Centurion CBD area is situated in the Fountains West sub-catchment or compartment (Figure 3). Hobbs indicates that an extremely weak groundwater gradient of some 0,2% is manifested from immediately north of the Hennops River in a north-north-easterly direction toward the Fountains West spring, and indicating a high transmissivity of the dolomite aquifer in this sub-catchment. According to a groundwater level contour map by Hobbs the groundwater level of the Fountains West Groundwater Compartment ranges from 1416 mamsl in the south to 1385 mamsl in the north of the Centurion CBD area. This constitutes a range of 48 m below ground surface in the south to 91 m below ground surface in the north.

Along the eastern boundary of the site, the Centurion CBD area is situated in the Fountains East sub-catchment or compartment. This compartment drains in a north-westerly direction to the East Fountain Spring in the north (Hobbs, 1988).

The weak groundwater gradient of some 0,004 again indicates a relatively high aquifer transmissivity. According to Hobbs, the groundwater level of the Fountains East Groundwater Compartment ranges from 1429 mamsl in the south to 1425 mamsl in the north of the Centurion CBD area, indicating a relatively flat groundwater level across this compartment. This level is 16 m below ground surface in the south, to 20 m below ground surface in the north of the Centurion CBD area.

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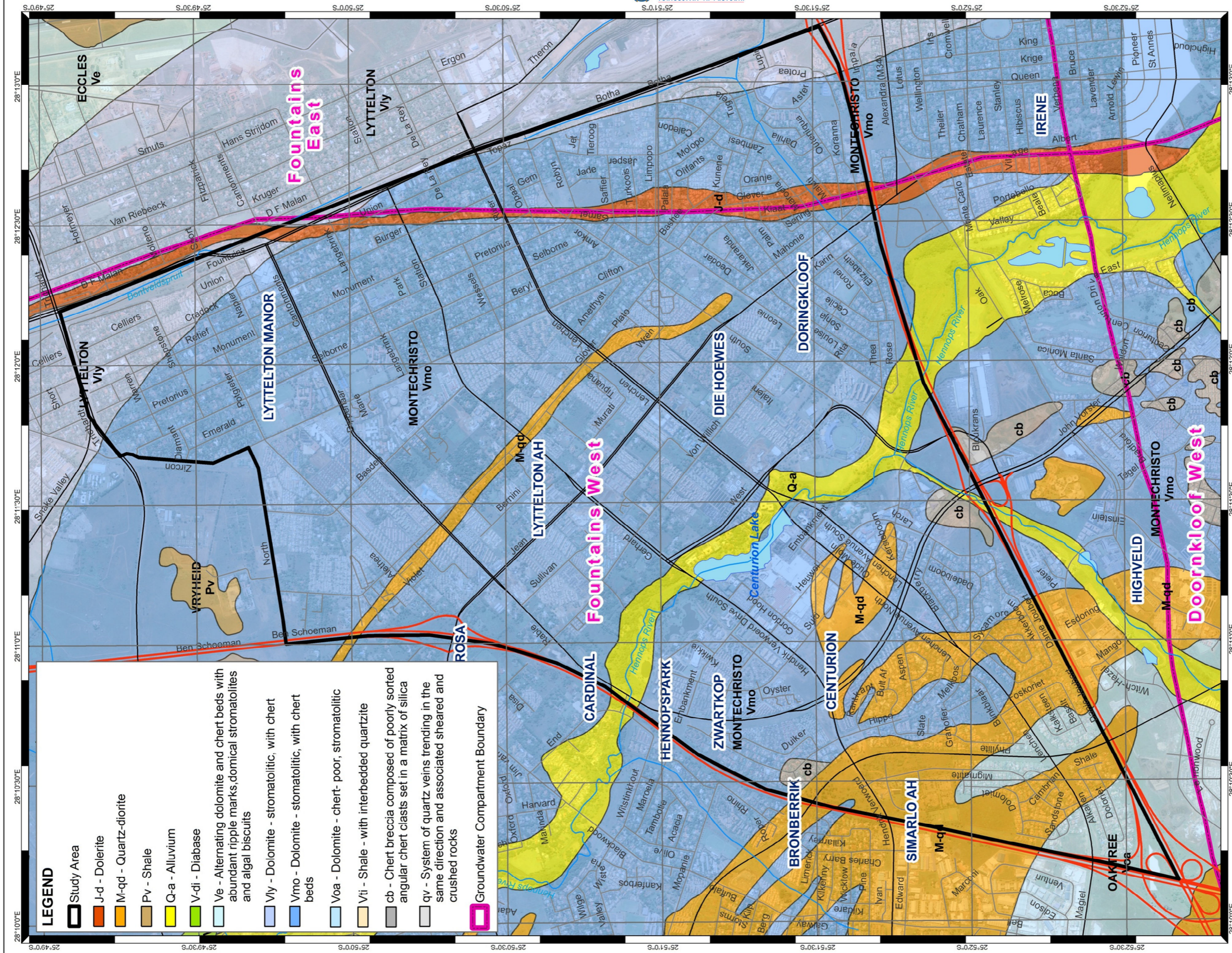
LEGEND

- Study Area
- J-d - Dolerite
- M-qd - Quartz-diorite
- Pv - Shale
- Q-a - Alluvium
- V-di - Diabase
- Ve - Alternating dolomite and chert beds with abundant ripple marks, domical stromatolites and algal biscuits
- Vly - Dolomite - stromatolitic, with chert
- Vmo - Dolomite - stromatolitic, with chert beds
- Voa - Dolomite - chert- poor, stromatolitic
- Vti - Shale - with interbedded quartzite
- cb - Chert breccia composed of poorly sorted angular chert clasts set in a matrix of silica
- qv - System of quartz veins trending in the same direction and associated sheared and crushed rocks
- Groundwater Compartment Boundary

ECCLES Ve
LYTTELTON Vly
Fountains East
LYTTELTON Vly
VRYHEID Pv
LYTTELTON MANOR
MONTECHRISTO Vmo
Fountains West
LYTTELTON AH
M-qd
ROSA
CARDINAL
HENNOPSPARK
ZWARTKOP
MONTECHRISTO Vmo
CENTURION
M-qd
BRONBERRIK
SIMARLO AH
M-qd
OAK TREE
Q-a
Centurion Lake
Q-a
DIE HOEWES
DORINGKLOOF
MONTECHRISTO Vmo
J-d
IRENE
MONTECHRISTO Vmo
HIGHVELD
M-qd
Doornkloof West
cb

FIGURE 3: 1:50 000 GEOLOGY MAP SHOWING GROUNDWATER COMPARTMENT BOUNDARIES

Km
0   0.25 0.5   1   1.5   2
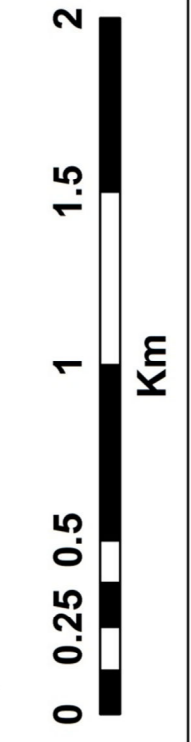
3.   A REVIEW OF CLASSIFICATION SYSTEMS USED FOR THE EVALUATION OF DOLOMITIC LAND

3.1.   Background

Various classification systems have been proposed since the 1970's in an attempt to evaluate the stability of sites on dolomite in South Africa.   The aim of these classification systems was to identify zones or areas of similar geological and geotechnical conditions and to assign a certain risk or hazard value to each zone accordingly.   The advantage of using a classification system is that it provides a standard approach to the problem to be solved which ultimately allows for better communication between parties (Schöning and A'Bear, 1987).

Each of the classification systems has been well documented, and a summary of each are provided in the sections to follow, as prepared by Van Rooy (1996) and Buttrick (1992).

3.2.   A Classification System by Stephan (1975)

Stephan (1975) proposed a classification system based on assigning a code number to each horizon in the dolomitic profile which can be related to its probable stability. The suggested code numbers are as follows:

Code	Number
No sample return above solid rock	5
Wad	4
Wad and little chert	3,5
Wad and chert	3
Chert and wad	2,5
Chert and little wad	2
No sample return in solid dolomite	3
Leached dolomite	2
Unweathered dolomite	1
Terra rosa	1,5
Cemented chert in terra rosa	1,5
Chert, weathered chert and chert breccia	1
Shale, sandstone, quartzite, intrusive	- 4
Weathered shale, weathered intrusive	0

A detailed description of each of the numbers and the conditions to which the numbers can be applied is documented by Stephan (1975).

Each code number is then multiplied by the thickness in metres of the particular layer in the profile. A depth correction is also applied, since the influence of a poor layer at 20 m is not the same as that of a poor layer at 5 m depth. Stephan also proposed that a 1 % reduction in the code number for each 5 m increment of depth.

The reduction factor should not be implemented in the case of stable materials and the following additional limitations should be taken into account:

a) The total thickness of these horizons must exceed 8 m (for horizons less than 8 m thick a code number of 0 is assigned).

b) The upper contact of these horizons must be at a depth of less than 30 m.

The summation of the calculated stability of the various horizons gives the total calculated stability of each profile. These calculated values can be divided into three classes:

Table 1. The outcome of the Classification System by Stephan (1975)

Value	Suitability for development
< 0	Area suitable.
0 – 40	Area suitable for development provided that water precautionary measures are applied.
> 40	Area unsuitable for development.

During the evaluation of this classification system Buttrick (1992) commented as follows:

- The system grossly simplifies the complex dolomite environment.
- The position and interaction of a layer with other layers in a certain geological setting are ignored.
- The system does not include any reference or make any allowance for the context in which the evaluation is being affected, either a dewatering or non-dewatering scenario.
- The use of the term wad and the positive influence on the stability of materials such as chert in terra rosa, weathered chert and unweathered dolomite are not acceptable in view of present terminology and experience.

3.3. X-Factor Classification System by Weaver (1979)

Weaver (1979) proposed that the stability of sites be classified using an empirical method based on information obtained from boreholes that are less than 30 m in depth. The method is based on a comparison between borehole information and the stability history in an area south of Pretoria in the Lyttelton Formation, Chuniespoort Group.

A stability factor, x, is calculated for each borehole. The x factor is the ratio of depth to wad in the profile over the total thickness of wad. Boreholes with no wad present are assigned an x factor value of infinity.

The x values of all the boreholes on the site are determined and contour lines are drawn for the x values between 1 and 4. The three zones are then interpreted as having the following stability evaluation:

Table 2. The stability evaluation of Weaver's X Factor Classification System

Suitability for development	X Factor
Highly Unsuitable	x < 1
Doubtful	1 > x < 4
Suitable	x > 4

During the evaluation of this classification system Buttrick (1992) commented as follows:

▪ This system was one of the first developed to evaluate sites on dolomite. Buttrick (1992) indicates that little was known of wad (residual dolomite) at that time and the material was viewed only having a negative influence on the engineering geological properties.

▪ Buttrick (1986) has concluded a detailed geochemical and geotechnical study of the weathering products of dolomite, i.e. the so called "wad and ferroan soils". He emphasized that the terms "wad and ferroan soils" were merely omnibus expressions describing a range of materials with widely divergent geotechnical characteristics, ranging from poor to very good. Buttrick (1987) indicated that gap graded materials such as chert rubble and fines (clay (wad), silt (wad) or terra rosa), might have a higher erosion potential. Buttrick (1992) indicates that with this classification system the gap graded materials are reviewed in a positive light which implies an enhancement in the stability.

▪ Buttrick (1992) indicates that the following factors were not taken into account with this classification system:

- Groundwater level
- Receptacle development
- Nature of other soil materials in the subsurface profile which may either enhance or detract from the stability characterization.

3.4. A Classification Approach Proposed by Venter (1981)

According to Venter (1981) the classification of dolomite sites should attempt to:
i)   Subdivide the dolomite geology into groups of similar behavior in 3 dimensions.
ii) Create a basis for the understanding of the characteristics of each group.
iii) Provide quantitive data for the design of the foundations of buildings, either precautionary or rehabilitative.
iv) Provide a basis of communication.

A comparison of inducing and inhibiting factors with respect to instability events gives an indication of the suitability of the site for a certain use. Venter (1981) suggests that the degree of suitability of a site will vary according to different proposed usages. The inhibiting and inducing factors are defined as follows:

Inhibiting factors:
▪ The strength of the overburden material. The greater the strength of the overburden material, the greater is the ability of the material to bridge any voids in the residuum.
▪ The erosion resistance of the overburden material. The less erodible the material the less likely is the process of internal erosion to occur.
▪ The thickness of the overburden material. The thinner a layer the less significant it will be. If the overburden is very thin, the characteristics of the bedrock are of importance.

Inducing factors:
The following factors may increase the probability of ground movement:
▪ The bedrock gradient
▪ The pinnacled nature of the bedrock
▪ The degree of cavitation in the bedrock
▪ The degree of void development in the overburden.

Tables 3 and 4 and Plates 5, 6 and 7 give an indication of what values these factors can assume.

Table 3. Factors influencing the strength of geological materials (After Venter, 1981)

Rock Material	Soil Material
1. Type of Material	

2. Degree of Weathering
    Completely weathered
     Highly weathered
     Moderately weathered
     Slightly weathered
	1. Moisture content
	2. Colour
	3. Consistency
	4. Structure
	5. Soil type
	6. Origin

3. Jointing and rock mass strength
    Strong rock
    Average rock mass
    Weak rock mass
    Very weak rock mass
	$\tau = c + \sigma \tan \varphi$

4. Penetration rates
    Very strong
    Strong
    Average
    Weak
    Very weak	

Table 4. Factors influencing the resistance to erosion of geological materials (After Venter, 1981)

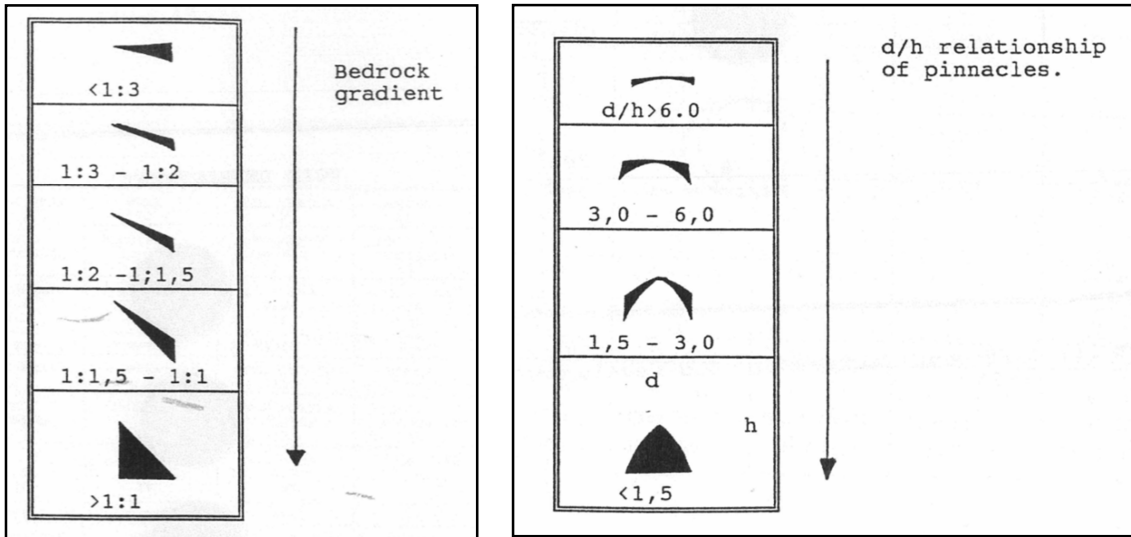| Rock Material	Soil Material
Degree of consolidation and cementing	Grading

Degree of weathering	Wad content
	    High
	    Medium
	    Low

Jointing
    Very closely jointed
    Closely jointed
    Medium jointed
    Widely jointed
    Very widely jointed
	Wad condition
	    Dense
	    Loose

Permeability	Permeability

Plate 5 (left). Different magnitudes of bedrock gradient (After Venter, 1981)

Plate 6 (right). Different magnitudes of pinnacle development (After Venter, 1981)
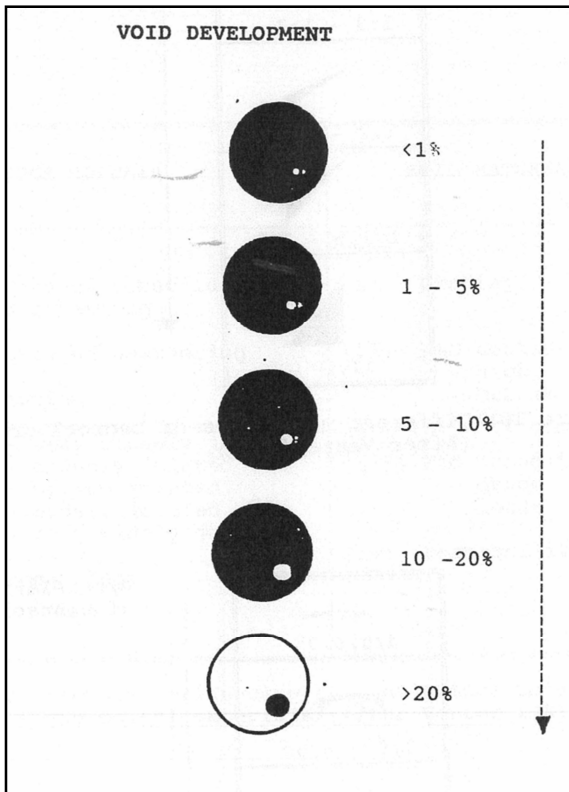
Plate 7. Different degrees of void development (After Venter, 1981)

The position of the groundwater table in the sub-surface profile is also important. It is apparent that the factors will have individual as well as interrelated, combined influence on potential instability events.

Venter (1981) points out that if a single factor were to change in either magnitude or intensity, it is possible that the character of the entire geological setting will change

and consequently the nature of the instability event. Therefore it is necessary prior to classifying a dolomite terrain, to subdivide the area into zones of engineering geological homogeneity.

Each of the factors discussed above are incorporated in Table 5. Each factor is subdivided into five categories where each category is assigned a value depicting its relative importance in terms of the probability that there is a direct correlation between the factor and potential ground movement. Venter (1981) indicates that although the strength and potential erodibility of the overburden material are presently viewed as equal important, this may not necessarily be the case.

Venter (1981) also proposed the use of a value reflecting the ratio of the overburden and the void free residuum A to the thickness of the layer residuum B containing voids or wad. If the ratio is large, the relative importance of such factors as the bedrock gradient, the pinnacled nature of the bedrock etc., is of less importance, whereas with a smaller ratio, the significance of the influence of the bedrock variable increases.

The sum of all factors gives a "grand total". The significance of the total is expressed in terms of the expected number of sinkholes or subsidences that will potentially occur within a twenty year period within an area of one square kilometer (Table 5). Venter (1981) also proposes different development types for the various grades of risk and possible special founding or stabilization methods for high cost / high maintenance developments.

Table 5. Dolomite zonal risk classification (After Venter, 1981)

STRENGH VALUE A	VERY WEAK 7	WEAK 10	MOD. STRONG 12	STRONG 15	VERY STRONG 18
ERODIBILITY VALUE B	HIGHLY ERODIBLE 7	ERODIBLE 10	MODERATELY ERODIBLE 12	LOW ERODIBILITY 14	VERY LOW ERODIBILITY 16
THICKNESS X THICKNESS VALUE C THICKNESS FACTOR T	0 – 3 m 0.6 $\dfrac{3X}{X + Y + Z}$	3 – 12 m 0.7 $\dfrac{3X}{X + Y + Z}$	12 – 30 m 0.8 $\dfrac{3X}{X + Y + Z}$	30 – 60 m 0.9 $\dfrac{3X}{X + Y + Z}$	>60 m 1.0 $\dfrac{3X}{X + Y + Z}$
STRENGH VALUE D	VERY WEAK 7	WEAK 10	MOD. STRONG 12	STRONG 15	VERY STRONG 18
ERODIBILITY VALUE E	HIGHLY ERODIBLE 7	ERODIBLE 10	MODERATELY ERODIBLE 12	LOW ERODIBILITY 14	VERY LOW ERODIBILITY 16

THICKNESS Y **THICKNESS VALUE F** **THICKNESS FACTOR Z**	0 – 3 m 0.6 $\frac{3Y}{X+Y+Z}$	3 – 12 m 0.7 $\frac{3Y}{X+Y+Z}$	12 – 30 m 0.8 $\frac{3Y}{X+Y+Z}$	30 – 60 m 0.9 $\frac{3Y}{X+Y+Z}$	>60 m 1.0 $\frac{3Y}{X+Y+Z}$
STRENGH **VALUE G**	VERY WEAK 7	WEAK 10	MOD. STRONG 12	STRONG 15	VERY STRONG 18
ERODIBILITY **VALUE B**	HIGHLY ERODIBLE 7	ERODIBLE 10	MODERATELY ERODIBLE 12	LOW ERODIBILITY 14	VERY LOW ERODIBILITY 16
THICKNESS I **THICKNESS VALUE R** **THICKNESS FACTOR P**	0 – 3 m 0.6 $\frac{3I}{X+Y+Z}$	3 – 12 m 0.7 $\frac{3I}{X+Y+Z}$	12 – 30 m 0.8 $\frac{3I}{X+Y+Z}$	30 – 60 m 0.9 $\frac{3I}{X+Y+Z}$	>60 m 1.0 $\frac{3I}{X+Y+Z}$
BEDROCK GRADIENT **IF C + F > 0.8** **0.4 – 0.8** **0.4**	> 1:1 -3 -4 -5	1:5 - 1:1 -2 -3 -4	1:2 – 1:5 -1 -2 -3	1:2 – 1:3 0 -1 -2	< 1:3 0 0 0
d/h RATIO **IF C+F > 0.8** **0.4 – 0.8** **0.4**	 -2 -3 -4	< 1:5 -2 -3 -4	1:5 – 3.0 -1 -2 -3	3.0 – 8.0 0 -1 -2	< 8.0 0 0 0
VOID DEVELOPMENT **RESIDUUM B** **IF C+F > 0.8** **0.4 – 0.8** **0.4**	> 20 % -4 -5 -6	10 – 20 % -3 -4 -5	5 – 10 % -2 -3 -4	1 – 5 % -1 -2 -3	< 1 % 0 -1 -2
BEDROCK VOID **DEVELOPMENT** **IF C+F > 0.8** **0.4 – 0.8** **0.4**	> 20 % -4 -5 -6	10 – 20 % -3 -4 -5	5 – 10 % -2 -3 -4	1 – 5 % -1 -2 -3	< 1 % 0 -1 -2
CIRCUMSTANCE FACTOR	12 - 30	31 - 50	51 - 70	71 - 90	91 – 100
GRAND TOTAL OF ASSIGNED VALUES _____ **RISK CATEGORY** _____ **PERMISSABLE DEVELOPMENT**	0 – 20 _____ VERY HIGH _____ NO DEVELOPMENT	20 – 40 _____ HIGH RISK _____ LOW COST	40 – 60 _____ MEDIUM RISK _____ HIGH COST	60 – 80 _____ LOW RISK _____ HIGH COST	80 – 100 _____ VERY LOW _____ HIGH COST

During the evaluation of this classification system Buttrick (1992) commented as follows:

- The system reflects a detailed and thorough consideration of the many complex interrelated factors influencing the stability of a dolomite site and is one of the most comprehensive produced to date.
- Water management, position of the groundwater level and dewatering are not included in the weighting process.

- Buttrick (1992) indicates that to evaluate the resistance to erosion of materials it is necessary to establish the permeability and this assessment is either made directly, or based on laboratory data. In effect, therefore, the materials in the subsurface profile are being evaluated under the influence of head of water simulating what is to be expected when water ingress occurs.
- Void development must be predicted on a scale of <1% to >20% which is not possible by either a geophysical or any other method.
- The pinnacled nature of the bedrock is of particular relevance in areas of shallow bedrock, whereas the importance characteristic diminishes in areas where the bedrock is covered by a substantial blanketing layer.
- This classification system places great emphasis on the bedrock gradient which is particularly important in areas subjected to dewatering. Unfortunately, this system fails to embrace the process of water level drawdown. Based on a study conducted south of Pretoria, Schöning (1990), indicates that there is no preferential occurrence of sinkholes on any particular gravity anomaly.

During the write-up of this dissertation it was also noticed that the classification method by Venter (1981) indicates that on the high risk areas low cost housing are considered suitable. Nowadays, low cost housing are rather placed in low risk areas because the residents can't afford special foundation designs and all the other requirements with developing on high risk dolomite ground.

3.5. A Classification Method Proposed by De Beer (1981)

De Beer (1981) indicates that the evaluation of dolomite areas is affected by assessing certain "influencing factors" that may have had an effect on a site in the past, or that may still affect a site during its development. The "influencing factors" are as follows:
a)   Natural influencing factors
b)   Historical, occupational influencing factors,
c)   Future occupational influencing factors.

De Beer (1981) indicates these factors should be regarded as a checklist of factors to be considered when evaluating dolomite areas.

A rating of 1 to 5 is applied to each of the individual factors within the three main groups of influencing factors, where 1 represents the most favorable condition and 5 the most adverse condition. The individual factors are rated equally compared with each other, but any one factor may emerge as an overriding factor. All the factor ratings are finally added and the total gives a rough guide as to the risk of damage (De Beer 1981).

The proposed subdivision of the influencing factors and the designated ratings are elaborated on below:

a) Natural influencing factors
    i) Watertable
        1   Static and shallow
        3   Static and at bedrock level
        5   Static and at considerable depth below bedrock

    ii) Geology – Depth to bedrock
        1   > 30 m
        3   Around 15 m
        5   Outcropping to less than 10 m

    iii) Geology – Strength and permeability of surface material
        1   Well developed pedocrete of Karoo shale blanket
        3   (No definition given by De Beer (1981))
        5   Wad and waddy dolomite within 1,5 m of ground surface

    iv) Geology – Nature of Intervening residual materials
        1   Mainly chert
        3   Wad and chert
        5   Mainly wad

b) Historical occupational influencing factors
    i) Relative frequency of damage
        1   No known sinkhole / settlement / subsidence occurrence within 10 km of the site. Newly developed area, less than 5 years old.
        3   (No definition given by De Beer (1981))
        5   Sinkhole / settlement / subsidence on site or within 50 m of site. Development in immediate vicinity of site for at least 20 years.

    ii) History of drainage of site
        1   Natural undisturbed gently sloping grassland, no previous development, no ploughing
        3   Gently sloping topography, residential development, no buried storm water reticulation (e.g. Tembisa, Katlehong)
        5   Industrial or residential development with septic tanks, French drains, buried storm water reticulation, well watered gardens (e.g. Valhalla)

c) Future occupational influencing factors
   i) Proposed disturbance of ground surface and natural drainage
      1   None
      3   Removal of pedogenic blanket
      5   Deep cuts exposing wad, pinnacles and voids

   ii) Proposed structure
      1   Railway line
      2   Special residential with shallow foundations
      3   Dairy, brewery factory etc. where quantities of washwater are used
      4   Concrete Reservoir
      5   Unlined dam

   iii) Knowledge of geological conditions
      1   Infra-red photography, gravity, test pits, trial holes, boreholes, shafts
      3   Test pits, trial holes and boreholes
      4   Test pits only
      5   No investigation

The factor ratings are added and grouped into the following broad categories of risk of damage:

      0 – 15   Low
      16 – 30   Moderate
      31 – 45   High

The site is then divided into zones or areas of varying degree of risk of damage.

Once such an evaluation of the site has been completed it has to be related to the Damage Acceptability of the structure which is the soil-structure interaction (De Beer 1981).

d) Damage Acceptability (Soil structure interaction)

   1. *Minor cracking* – filling and repairing of cracks – operation unaffected, inconvenience only
   2. *Damage to walls and finishes requiring extensive repairs* – operation unaffected but major inconvenience
   3. *Major damage to structure* – temporary cessation of operations during repairs
   4. *Major damage to structure or abandonment of parts of structure* – cessation of operations for long periods
   5. *Damage to structure cannot be tolerated, e.g. hospital, nuclear power station etc.*

De Beer (1981) states that the property owner or developer has to be intimately involved in the decisions on damage acceptability of the proposed development related to the final evaluation of the site.

During the evaluation of this classification system Buttrick (1992) commented as follows:

- This detailed and thorough system is particularly aimed at provoking thought and ensuring that the evaluator is considering the key factors influencing the stability of a site.

- <u>Watertable</u>: De Beer (1981) views a static and shallow groundwater table as most favorable situation and the least favorable a watertable which is static and at considerable depth below bedrock.

  Buttrick (1992) indicates that the qualification 'Static' implies that the system does not allow for lowering of the waterlevel and that within the context of a dewatering scenario the shallow groundwater level could represent the most unfavorable situation.

  Buttrick (1992) further indicates that a static watertable at considerable depth below bedrock may present a very unfavorable stability situation if potentially erodible soil materials blanket the bedrock in a non-dewatering and dewatering scenario. In both scenarios, ingress water may cause damage to the subsurface profile.

- <u>Geology – depth of bedrock</u>: Buttrick (1992) indicates that the depth to bedrock is crucial for three reasons:
  - Depth to receptacles in bedrock
  - Depth to an incompressible medium (dewatering scenario)
  - Depth to the bedrock / soil interface where preferential erosion may occur along potential flow paths (non-dewatering scenario)

  Buttrick (1992) further indicates that the location of either receptacles or disseminated receptacles should perhaps be viewed as more important criterion than bedrock depth. Disseminated receptacles, particularly, may be located above bedrock level. Water level is important with respect to receptacle depth in both a dewatering and non-dewatering scenario and with respect to bedrock in the former.

- <u>Geology – strength and permeability of surface material</u>: Buttrick (1992) indicates that it must be noted that the well-developed pedocrete or Karoo shale may be

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favorable in a non-dewatering scenario but may not be adequate to create favorable conditions in a dewatering scenario.

So called wad, may if correctly constituted, enhance stability. Experience indicates that clay (wad) may in fact be less susceptible to subsurface erosion that some of the gap graded materials such as the combinations of chert rubble and fines (Buttrick, 1992).

▪ <u>Geology – nature of intervening residual materials</u>: De Beer (1981) indicates that he views intervening residual materials, mainly of chert, as the most favorable condition, 'wad and chert' as intermediate and 'mainly wad' as the most adverse condition.

According to Buttrick (1992) experience indicates that gap graded materials possess a multitude of potential flow paths which may be exploited by percolating water resulting in subsurface erosion. Clay soil materials (e.g. wad and ferroan soils) may in fact enhance stability if characterized by a low permeability. The nature of the soil material must first be established (Buttrick 1992).

Historical occupational influencing factors are also affected by a change in the dewatering scenario of the site.

▪ The recent past and present state of a site is not necessarily a key to the future stability behavior. The age of surrounding developments, comparison of similar subsurface conditions and man's influence and disturbance all plays a role in revealing its susceptibility to sinkhole and subsidence formation.

3.6. Wagener's (1982) Method of Classes

Wagener (1982) proposed that dolomite sites be classified according to the thickness of the overburden layer. This layer occurs between the soil surface and the average level of dolomite pinnacles and floaters. Evaluation of the thickness of the overburden gives an indication of potential settlement problems. Three types of settlement can be distinguished.

i) Normal settlement – a combination of immediate elastic settlement and consolidation settlement.

ii) Sudden subsidence settlement – the appearance of a sinkhole caused by the collapse of an arch, which is spanned over a cavity in the residuum.

iii)   Gradual subsidence settlement or doline formation – the formation of a slow subsidence over a cavity or weak zone in the residuum, where an arch is not able to form.

Wagener (1982) indicates that a site may be divided into three categories on completion of the filed work and the evaluation.

- Class A: Pinnacle and boulder dolomite either at or near the surface. $0 < C < 3$ m
- Class B: Pinnacle and boulder dolomite overlain by moderately thick soil cover. 3 m $< C < 15$ m
- Class C: Pinnacle and boulder dolomite overlain by thick soil cover. $C > 15$ m

C refers to the average thickness of overburden to the tops of the pinnacles and boulders.

This zonation of the site is executed on the basis of information obtained from remote sensing, gravity surveys, borehole data, test pits and laboratory tests.

Based on the selected category, it is considered possible to quantify the types of settlement and proposed appropriate solutions to withstand expected movements. Wagener (1982) suggests the following solutions in Table 6 in relation to the three classes.

Table 6.   Appropriate foundation solutions according to Wagener's three classes (After Wagener, 1982)

	Foundation Description	Site Categories
i)	Conventional foundations	Class A, B & C
ii)	Mattress of improved earth	Class A, B & C
iii)	Founding on pinnacles	Class A, B & C
iv)	Piling	Class A
v)	Shafts	Class B & C
vi)	Caissons	Class B & C
vii)	Special foundation methods a) Dynamic consolidation b) Reinforced earth	 Class B & C Class B & C
viii)	Special structures a) Reservoirs b) Slimes Dams	 Class A, B & C Class A, B & C

During the evaluation of this classification system Buttrick (1992) commented as follows:
- This system does not include the following factors:
  - groundwater level /s

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- possible movements of the water level or the activities of other mobilizing agencies
- the nature of the materials blanketing the dolomite bedrock
- receptacle development

▪ The system is based on the premise that the selection of an appropriate construction method will preclude stability problems and is an excellent guide to the selection of appropriate construction methods once the stability conditions on the site have been evaluated.

▪ The foundation design of a structure is not the only purpose of conducting a stability investigation. Townships consist of many infrastructural elements, such as roads, walkways, parks etc. and people may be at risk in the open areas around the buildings. The evaluation of the stability of an entire site allows the selection of appropriate township / development design structure and foundation design and water precautionary measures.

3.7. Van Rooy's (1984) MF-Classification System

Van Rooy (1984) developed a classification system based on the data obtained from standard investigation techniques used during dolomite stability site investigations in the early eighties. A so-called Multiple Factor or MF-Classification System was developed. The system encompasses the following factors:
- Drainage history
- Gravity contour feature
- Depth to wad
- Thickness of wad
- Characteristics of the wad
- Type of material above the first appearance of wad
- Type of material below the base of wad
- Damage: Historical record
- Future development

Van Rooy (1984) proposes the use of the following classification parameters:

a) Classification utilizing surface information:
   A site must first be subdivided into similar geological zones due to the great lateral and vertical variation of subsurface conditions in karst areas. This variation makes it difficult to obtain subsurface information through drilling of all the possible conditions on the site. This subdivision is done by using geological maps, air photographs and stratigraphic information.

The following features are delineated: Outcrop areas, chert-gravel zones, areas of similar vegetation, old sinkhole zones, subsidence areas, scattered outcrop areas, different formations and intrusives.

b) <u>Classification utilizing thermal infrared linescan</u>
The following risk characteristics are assigned to tonal variations, on the thermal infrared linescan imagery:

<u>Zone (Tone)</u>	<u>Risk</u>
Black	Very High
Dark Grey	High
Grey	Medium
Light Grey	Low
White Grey	Very low

Terrain data, development density, vegetation, topography and geology influence the imagery. Van Rooy (1984) contends that all these areas of poor drainage may be regarded as high risk areas. Thermal infrared linescan imagery can prove of great value in delineating areas of poor drainage.

c) <u>Classification utilizing gravity information</u>
Features on the gravity contour map permit the identification of four basic zones:
- Gravity "high" anomalies
- Gravity "low" anomalies
- Steep gradient zones
- Gentle gradient zones

Generally this subdivision of the gravity permits the interpretation of the bedrock topography on the site. Confirmation of conditions within these zones by the selective placement of boreholes ultimately limits the amount of drilling required.

d) <u>Classification utilizing borehole data</u>
Borehole information is used to subdivide the following factors into five classes of differing conditions:
- Depth to wad
- Total thickness of wad
- Characteristics of the wad
- Type of soil material overlying the first occurrence of wad
- Type of soil material below the base of the wad

A value of 0,25 to 4 is assigned to each condition ranging from poor to very good. Each factor's value is addressed based on the borehole information (Table 7). These values are then multiplied.

Table 7. Weighting values for boreholes with erodible soil (After Van Rooy, 1984)

Assigned Value	Depth to Wad	Total Thickness of Wad	Properties of Wad	Material Above First Occurrence of Wad	Material Below Last Occurrence of Wad
4	D > 15	A ≤ 1	High penetration resistance Chert with 15% wad	High strength material e.g. dolomite	Unweathered rock
2	12 < D ≤ 15	1 < A ≤ 2	Chert with 30% wad Wad with high penetration resistance	Competent material e.g. leached dolomite with 30% red soil	Leached dolomite Weathered chert
0,75	8 < D ≤ 12	2 < A ≤ 3	Wad with 30% chert	Moderate strong e.g. red soil with 30% chert	Jointed dolomite Chert with red soil
0,5	3 < D ≤ 8	3 < A ≤ 5	Wad with low penetration resistance	Low strength material red soil, shale sand	Red soil with chert
0,25	D ≤ 3	A > 5	Cavity Wad with no penetration resistance	Material with poor strength silt/clay	Cavities in dolomite Pinnacled dolomite

The classification of borehole information is subdivided into two broad categories namely boreholes containing wad and those not. By evaluating the above mentioned factors for each borehole a stability value is calculated.

The following factors must be borne in mind when values are assigned to the various factors:

- Material description in the profile must firstly be grouped into zones of the same characteristics e.g. colour variations in either chert breccia or shale are not distinguished.

- The total thickness of wad is obtained by adding the depth values for all the wad layers if more than one layer of wad occurs in the profile. The properties of the poorest layer are utilized in the assessment of the stability value calculation.
- The depth to wad is taken as the depth to the first layer of wad in the profile.
- The total depth of a borehole also plays a role. A standard depth of 30 m is assumed for this classification system based on the practice of drilling most of the site investigation boreholes on dolomite to only 30 metres. The influence of material deeper than 30 metres is not taken into account.
- An average value is calculated if the material above or below the wad layer have different properties. This average value then serves as the factor for the material above the wad and material under the wad.

Table 7 and 8 represents the proposed values for the subdivision of boreholes with wad and boreholes which do not contain wad respectively.

Table 8. Weighting values for boreholes without highly erodible soil (After Van Rooy, 1984)

Material Type		Value		
		Entire Profile	>10 M	< 10 M
Dolomite:	Unweathered	20	8	4
	Leached	16	5	2
	With chert	16	5	2
Chert:	Unweathered	20	8	4
	Weathered	15	4	2
	With silty clay	0.13	4	2
	With shale	20	8	4
Shale:	Unweathered	20	8	4
	Weathered	15	4	2
	With chert	20	8	4
Igneous Rock:	Unweathered	20	8	4
	Weathered	8	4	2
	Residual clay	0.12	0.25	0.5
Clayey silt (red soil):		0.12	0.5	0.75
	With chert	0.13	0.5	1
Sand		4	2	1
Silt		0.12	0.5	1
Clay		0.12	0.5	1
In general:	Very high strength	16	8	4
	High strength	0.6	4	2
	Medium strength	0.13	0.5	0.75
	Low strength	0.12	0.25	0.5

The borehole stability values are subdivided into intervals relating to designated risk grades with respect to sinkhole formation, as indicated in Table 9.

Table 9. Borehole stability value intervals with corresponding risk classes for sinkhole development (After Van Rooy, 1984)

Borehole Stability Value	Risk
0.0 – 0.0024	Very high
0.0025 – 0.124	High
0.125 – 0.5624	Medium
0.5624 – 15	Low
16 - 256	Very low

e) Classification utilizing damage to structures

Damage to structures existing either on the site or under investigation or on adjacent sites can be utilized to identify poor zones where instability events can be expected. Obviously a distinction must be drawn between damage due to poor construction methods and unstable foundation conditions. Only the latter is considered here (Table 10). Factors such as poor drainage around the building, leaking water bearing services and the utilization of the building, may also play a role.

Table 10. Classification of risk using damage to structures (After Van Rooy, 1984)

Crack Width K (Mm)	Degree of Damage	Risk
k > 10	Severe damage	Very high
5 < k < 10	Moderate damage	High
2.5 < k < 5	Visible damage	Medium
0 < k < 2.5	Little damage	Low
K = 0	No damage	Very low

f) Final stability zoning

All the stability and risk values are depicted on a map of the site according to which the site is subdivided into very high, high, medium, low and very low risk zones.

In summary, the final risk zoning is constituted as follows:
i) Sub-division of the site by means of surface information, drainage history and gravity contour features.
ii) Confirmation of geology, qualification of the variation and risk grade of each zone using borehole information.

iii) The further adaption of the grade of risk by reviewing damage records and property utilization.

In the final risk classification the number of boreholes and the applicability of the factor (e.g., was a gravity survey done?) will determine the proportional contribution made be each parameter.

During the evaluation of this classification system Buttrick (1992) commented as follows:

- This system appears to be designed for application in the context of a non-dewatering scenario. The only agency considered to be operative in the creation of instability events is ingress water. No reference is made to the process of dewatering or other relevant disturbing agencies, water level fluctuation, gravity and ground vibrations.

- The dark zones on the thermal infrared imagery may also depict a moist clay (e.g. residual clay on an intrusive) which may serve as an aquitard in the upper profile giving rise to a cool spot due to dark signature of the moist clay. This aquitard would enhance the stability, in fact warranting a low risk characterization (Buttrick, 1992).

- Gravity usually indicates the bedrock topography on a site and is important in evaluating the stability of an area where dewatering might take place. This system does not take the influence of watertable drawdown into account as it was developed on a site south of Pretoria. The bedrock gradient is not very important in the case of a non-dewatering scenario (Schöning, 1990).

- Van Rooy (1984) has followed the practice of other authors, such as Weaver (1979) in the classification of borehole information, where only a negative connotation to "wad" is attached.

- The classification utilizing damage to structures must be applied with discretion. A lack of damage does not necessarily imply that the site is stable.

3.8. Evaluation of potential instability in Karoo outliers (Jones, 1986)

In the case of Karoo outliers, the inter-related and interdependent influences of lithology, geological structure and hydrology must be taken into account. Jones (1986) proposes that the potential instability in Karoo outliers may be evaluated by:

a) *Ranking the physical or engineering characteristics of individual lithological units in a geological profile according to their potential for instability.*

b) *Expressing the instability potential of a specific geological profile by weighting the engineering or physical characteristics or each lithological unit it contains, according to its apparent thickness.*

c) *Predicting the impact which subsurface water elevation may have on the geological succession.*

d) *Taking the dolomitic bedrock configuration and the presence of any cavities into account.*

e) *Instability potential of lithological units, where this can be regarded as a function of the compressibility, erodibility and inverse of tensile strength or cohesion for either a rock or subsoil.*

The compressibility of unconsolidated subsoils may be quantified in terms of the compression index (C_c) and the co-efficient of consolidation (C_v). In the case of chert gravels and weathered Karoo sedimentary rocks, the above-mentioned laboratory tests are not applicable. Wrench (1984) has shown that relationships exist between Young's modulus, plate bearing capacity and consistency and that these relationships provide an initial estimate of compressibility and bearing capacity in gravels. As far as intact rocks are concerned, Hobbs (in Jones 1984) also suggested that Young's modulus may be applied to determine potential instability. In the case of rock masses the effect of joints and fractures must be taken into account. Coon and Merrit (1978) advocate the use of fracture frequency to quantify rock quality in terms of a mass factor "j".

The erodibility of residual soils and soft rocks is a more difficult parameter to quantify. Any attempt to evaluate potential erodibility should take into account grading (percentage passing 0,075 mm) and permeability as influencing factors.

As far as the tensile strength of residual materials or soft rocks is concerned, the cohesion value "c" is considered a meaningful measure.

To quantify the instability potential it is suggested that the parameters of compressibility, erodibility and inverse of tensile strength be give numerical index values. Low values would indicate low compressibility, low erodibility and high tensile strength or cohesion characteristics whereas high index values would indicate the inverse. The instability ranking of a specific subsoil or stratum 'ind/L' could be derived from the formula:

ind/L = f (a,b,c)

Where 'a', 'b' and 'c' represent the instability index values given to compressibility, erodibility and tensile strength/weakness respectively.

Without explicit information, the contribution of 'a', 'b', and 'c' in the above formula cannot be related. It is essential, therefore, that if valid ranking index values are to be obtained, detailed analysis should be made of each physical characteristic for every individual material in a large number of instability occurrences.

f) *Instability potential of a specific geological profile:*

Jones (1984) proposed that the instability potential of a specific geological profile, 'Rf' may be compiled by weighting the instability index value (ind/L) of each individual material in the succession according to its thickness or apparent thickness. The equation for such an evaluation would therefore be:

$$Rf = \sum_{j=1}^{j=0} \left[\{(tl \times ind/L) + (t_2 \times ind/L_2) + (t_3 \times ind/L_3)....\} / T] \right]$$

In the above equation 'ind/L' and 't' represents the instability ranking index value of an individual material and its thickness respectively, whereas 'T' represents the total thickness of all the materials in a specific geological succession.

g) *Evaluation of risk at a specific site:*

This 'Rf' value only apply to a specific locality (e.g. a borehole) since it does not take other influencing factors such as lithological sequence, subsurface water and the dolomitic bedrock topography into account (Jones 1984).

i) *Lithological sequence:*
   The 'Rf' values should be adjusted where necessary by qualified earth scientist and engineers to take the influence of the lithological order prevalent in the geological succession into account.

ii) *Subsurface water:*
   The movement of subsurface water has probably the most important influence on promoting instability in a geological profile. Jones (1984) argues that in the compilation of an instability risk hazard evaluation for a site, a hydrological factor rated with numerical values to indicate its contribution to instability, must be applied to the 'Rf' value of each individual profile in the area.

iii) *Configuration of the dolomitic bedrock:*
   The configuration of the dolomitic bedrock considerably influences the potential instability of a Karoo outlier. A palaeo-karst subsurface

configuration with closely spaced steep-sided pinnacle, enhances potential sinkhole development providing the infilling materials possess high erodibility and poor tensile strength (Jennings, Brink, Louw and Gowan, 1965). Conversely, a gently undulating dolomitic bedrock profile, in which the span between the shallow sloped abutments is too great to permit the formation of an arch will produce conditions favouring either differential surface settlement or doline development. Jones (1984) also supports the method proposed by Venter (1981) whereby the parameters of abutment slope-gradient, height and width are applied.

iv) *Cavities and voids:*

Jones (1984) advocates that the same approach be followed for voids occurring in either the residual subsoils or Karoo sedimentary rocks as proposed by Venter (1981) for the presence of cavities in dolomitic bedrock.

The compilation of a potentially instability risk evaluation "RH" at any specific point or site can therefore, be derived by the following formula:

$$RH = f (R_f, R_s, R_h, R_d, R_v)$$

In the formula, R_f represents the instability potential of a given geological profile as already discussed, whereas R_s, R_h, R_d and R_v refer to the influences of the lithological sequence, subsurface water movement, the nature of the dolomitic bedrock configuration and the frequency of voids / cavities respectively; each being given numerical values which increase with rising instability potential.

During the evaluation of this classification system Buttrick (1992) commented as follows:

▪ The system is well developed but only applies to a very specific geological setting.
▪ Many of the factors considered may be too difficult to determine, e.g., receptacles. No technique exists to determine either the extent of void development, depth of occurrence or spatial dimensions.

3.9. Buttrick's (1992) Method of Scenario Supposition

Buttrick proposed a single framework of reference for the evaluation of the stability of dolomite land. Many different site investigation methods have been applied and several methods of site classification or characterization have been developed in an effort to accurately predict the risk of ground-surface damage in any given area

(Buttrick, 1992). In response to the identified need for a standardized, functional methodology, Buttrick (1992) formulated a framework of reference for the evaluation of stability.

The 'method of scenario supposition' was developed to characterize the potential stability of dolomitic land. The stability characterization of a site requires hypothesizing the probable impact of man's activities on the dolomitic karst environment during the lifetime of a development. The potential stability of a virgin tract of land must be reviewed in the context of either a dewatering or non-dewatering scenario. The basic supposition in this evaluation process is the selection of the potentially applicable scenario, which provides the framework within which the evaluation procedure may be applied (Buttrick, 1992).

The individual boreholes representing subsurface conditions on the site can only be evaluated and characterized if abstractly subject to the activity of an assumed mobilizing agency within the context of the selected scenario.

3.9.1. Characterization of the Risk of Sinkhole Formation

Buttrick (1992) identified the following factors for the characterization of the risk of sinkhole formation:

a) *Receptacles*: Either the receptacles or disseminated receptacles occurring within the bedrock or within the overburden and can receive mobilized materials. These receptacles may occur as small disseminated and interconnected openings in the overburden or as substantial openings, referred to as cavities, particularly in the bedrock.

b) *Mobilizing agency*: Mobilizing agencies include ingress water, ground vibrations, water level drawdown and any activity or process which includes mobilization of the material in the blanketing layer.

c) *Blanketing Layer*: Overburden refers to any loose, unconsolidated material which rests upon solid rock (Whitten and Brooks, 1972). The overburden is thus the dolomite residuum and other materials found overlying the dolomite bedrock and occurring between the ground surface and the dolomite interface. The term 'blanketing layer' is, however, suggested to denote that component of the overburden which overlies the potential receptacles (Plate 8). The nature of the blanketing layer is crucial to the advancement, retardation or prevention of the process of sinkhole or subsidence formation.
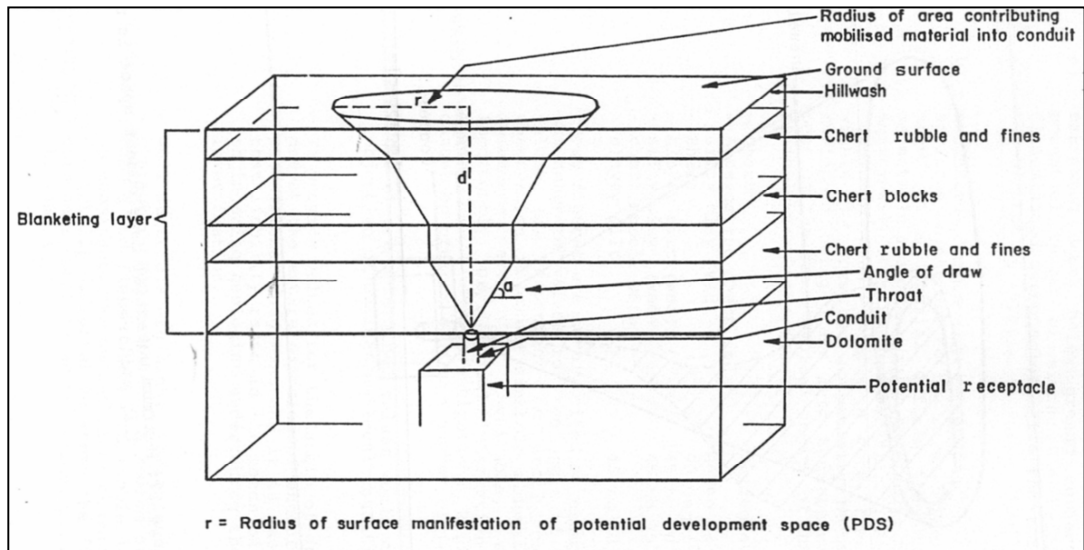
Plate 8. Maximum potential development space (After Buttrick, 1992)

d) *Maximum potential development space*: The 'maximum potential sinkhole development space' is a simplified estimation of the maximum size sinkhole that can be expected to develop in a particular profile, providing that the available space is fully exploited by a mobilizing agency (Plate 9). The potential development space (pds) is associated with either a receptacle or disseminated receptacles and depends on the following factors:

i) Estimated depth below ground surface to the potential throat of either the receptacle or disseminated receptacles (i.e. the thickness of the blanketing layer).

ii) Estimated 'angle of draw' in the various horizons in the blanketing layer. The 'angle of draw' in a material describes a cone and defines the angle of a metastable slope to which a particular mobilizing agency will become operative in that material. The material in the cone within the cone can potentially be mobilized by moved or drawn into the conduit at the base of the cone. Typical angles of draw are defined as follows:

- Chert   90 °
- Alternating chert and silty clay (wad)   80 – 90 °
- Shale   90 °
- Clayey silt (wad)   45 – 60 °
- Silty clay (wad)   45 – 75 °
- Chert rubble with clayey silt   45 – 90 °

Buttrick (1992) indicates that these figures are merely cited as examples of the range of values for the angle of draw. The values are dependent on local

conditions, observation of actual sinkhole sidewalls in the immediate area, if available, and more importantly, geotechnical information gathered during the field investigation.
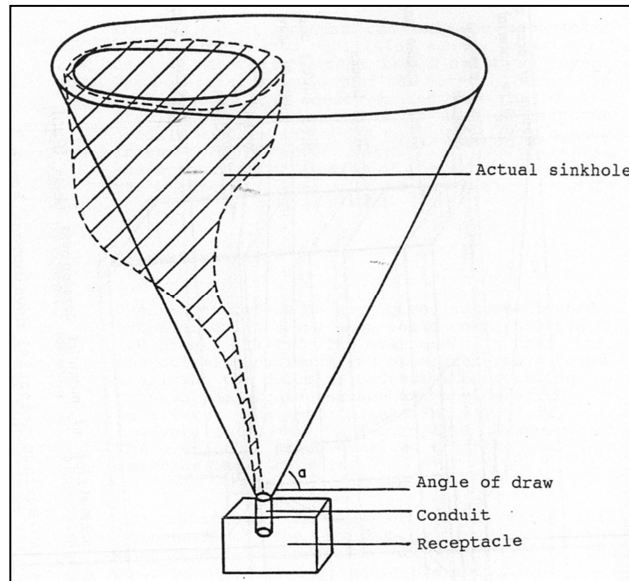

Plate 9. Maximum potential development space is not fully utilized (After Buttrick, 1992)

iii) Thickness of the various horizons constituting the blanketing layer. Plate 8 displays this concept schematically. The depth to the potential receptacle is obtained from borehole information and the radius of the potential development space on surface is obtained by a simplified diagrammic construction. The 'angle of draw' of the various materials and the depth to the receptacle is used to project and estimate the radius.

Realization of the full sinkhole may occur in stages, including an initial catastrophic even when it 'daylights', followed by the growth of the feature owing to slip failures and raveling along the side walls. This process will continue until a metastable state is achieved. The sinkhole could potentially grow until it fully utilizes the limits defined by the potential development space (Plate 10).

Thus, for each receptacle, there is a 'potential development space' that may be fully realized or exploited, creating the maximum size sinkhole, provided that:
- The receptacle is large enough to accommodate all mobilized material from within the 'development space'
- The materials constituting the blanketing layer can be mobilized, and

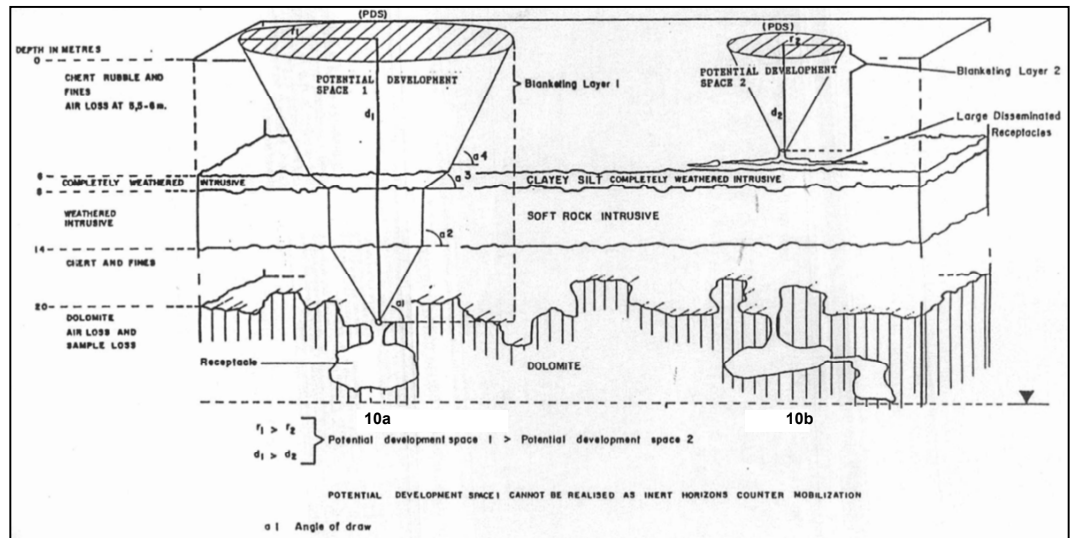-   An adequate and sustained mobilizing agency is present to mobilize all the material.

Plate 10. The influence of horizons with a low mobilization potential on the maximum Potential Development Space (PDS) (After Buttrick, 1992)

In reality, the receptacle may be too small to accommodate the mobilized material and hence the maximum potential development space may not be fully utilized (Plate 9). In such an instance, where a profile is characterized by receptacles of an inadequate volume, the maximum size sinkhole will be smaller than the potential development space. Buttrick (1992) indicates that as there is no efficient technique available at present to ascertain the volume of receptacles, it must be assumed that receptacles of adequate volume are present. It must be emphasized that the potential development space represents the maximum space available in the profile for a sinkhole. Table 11 contains broad categories of 'potential development space' and hence the associated scale of potential maximum size sinkholes.

Table 11. Suggested scale of sinkhole sizes (Buttrick 1992)

Maximum potential development space	Maximum diameter of surface manifestation (dimension: metres)	Suggested terminology
Small potential development space	<2	Small sinkhole
Medium potential development space	2 - 5	Medium-size sinkhole
Large potential development space	5 – 10	Large sinkhole
Very large potential development space	> 10	Very large sinkhole

e) *Mobilization potential of materials in the blanketing layer*: Under the influence of a mobilizing agency, it is the materials within the blanketing layer that determine the potential susceptibility of the development space to exploitation and mobilization. This susceptibility should be expressed in terms of the risk of mobilization. Buttrick (1992) indicates that the materials may reflect a low, medium or high risk of mobilization under the influence of a particular mobilization agency.

The different mobilization risk categories are characterized as follows:
- Low risk of mobilization: The profile displays no voids. No air loss or sample loss is recorded during drilling operations. Either a very shallow water table or a substantial horizon of materials with a low potential susceptibility to mobilization may be present within the blanketing layer (e.g. continuous intrusive features or shale material).

- Medium risk of mobilization: This type of profile is characterized by an absence of a substantial 'protective' horizon and a blanketing layer of materials potentially susceptible to mobilization by extraneous mobilization agencies. The water table is below the blanketing layer.

- High risk of mobilization: The blanketing layer reflects a great susceptibility to mobilization. A void may be present within the potential development space indicating that the process of sinkhole formation has already been affected. Boreholes may register large cavities, sample loss, air loss, etc. The water table is below the blanketing layer. In a dewatering situation, the lowering of a shallow groundwater level would obviously increase the risk of mobilization.

Plate 10(a) indicates a profile with a deep groundwater level situated within the bedrock. The blanketing layer and hence the potential 'development space' are fully exposed to the potential activities of extraneous mobilizing

agencies. This plate also depicts a significant layer of intrusive material with a low mobilization potential. This horizon acts as either an aquitard or an aquiclude that prevents mobilization and movement of materials into receptacle. The material within the 'development space' is thus protected from the mobilizing agency.

Plate 10(b) reveals the presence of potential disseminated receptacles above the intrusive horizon displaying the low mobilization potential. A smaller potential development space is thus available for exploitation by a mobilizing agency.

3.9.2. Characterization of the Risk of Doline[3] Formation

Subsidence as used by Buttrick (1992) refers to a shallow enclosed depression that may have formed as a result of various mechanisms. The factors for the characterization of the risk of subsidence formation are listed below. These factors can be readily identified during the stability investigation.

Buttrick (1992) identified the following factors for the characterization of the risk of subsidence formation:

a) *Receptacles*: Inadequate receptacle size may also result in the premature termination of the process of sinkhole development, resulting in a subsidence.

b) *Nature of the blanketing layer*: The following properties of the blanketing layer must be considered:
- Thickness of the soil material (depth to bedrock)
- Depth to the original water table
- Nature of the soil material above the water table (i.e. type of soil and geotechnical characteristics)
- Nature of the soil material below the water table (i.e. type of soil and geotechnical characteristics)

c) *Mobilization potential*: The influence of the mobilization agency on the profile material is determined by the following:
- Thickness of the overburden
- Depth of the original water table
- Thickness of the soil material above the water table
- Thickness of the soil material below the water table
- Nature of the soil material above the water table
- Nature of the soil material below the water table

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[3] *The term doline has subsequently been replaced by 'subsidence' in the latest South African dolomite literature.*

The susceptibility of the soil material to mobilization i.e., consolidation settlement under the influence of the mobilizing agency (water table drawdown) may be characterized as follows (Buttrick et. al., 1995):

- Low risk of subsidence formation: In this type of profile, the water table can be above the bedrock and at shallow depth (ingress water), in the bedrock (water table drawdown) or in soil material with geotechnical characteristics reflecting a low susceptibility to consolidation settlement, i.e. material with a high density, low void ratio and low compression index (e.g. Karoo shale).

- Medium risk of subsidence formation: This type of profile is characterized by an absence of a substantial 'protective' horizon and has a blanketing layer of materials potentially susceptible to mobilization by ingress water. The water table is within the bedrock or at depth within the blanketing layer. Voids and disseminated voids may be present above the bedrock, indicating the susceptibility to subsidence formation.

- High risk of subsidence formation: The blanketing layer reflects a great susceptibility to mobilization. The water table is above the bedrock in soil material with a low dry density, high void ratio and high compression index. Residual dolomite soils, namely wad and ferroan soils, have a high potential for dramatic ground settlement.

3.9.3. Implementation of the Method of Scenario Supposition

Geophysical surveys and/or relevant remote sensing techniques and field information (geological mapping) are used to subdivide a site into potential (karst) morphological zones (Steps 1 and 2, Table 12).

Boreholes are then drilled to characterize these zones. The normal procedure would be to characterize the profile of each borehole, using the method of scenario supposition (Step 4, Table 12).

The characterizations of the individual boreholes within a potential zone are then pooled (Step 5, Table 12). If several boreholes confirm a particular characterization, that zone will be defined accordingly. If there are marked deviations, the zoning must be modified by the creation of separate zones, always erring in the favour of a conservative assessment.

Table 12. Application of the method of scenario supposition (Buttrick, 1992)

Step 1	Field reconnaissance and desk study of site
Step 2	Preliminary zoning utilizing tools such as air photo interpretation and geophysics
Step 3	Preliminary boreholes to characterize 'preliminary' zonation
Step 4	Characterization process (scenario supposition). *Individual borehole profiles are reviewed within the context of the selected scenarios*

	Evaluation factors	
Step 4	*Sinkhole formation*	*Doline formation*
	Mobilization agency / agencies Receptacle development Potential development space (i.e. potential sinkhole size) Nature of blanketing layer/s Mobilization potential of blanketing layer/s	Mobilization agency Nature of blanketing layer/s Mobilization potential Lateral extent

Step 5	Pooling of individual borehole characterization and amending of preliminary zoning, taking historical information into account
Step 6	Finalized risk zonation characterized in terms of certain risk of certain-sized features forming
Step 7	Selection of appropriate development types and precautionary measures
Step 8	Implementation of appropriate development design and precautionary measures
Step 9	Vigilance and maintenance

3.9.4. Risk Characterization and Recommended Type of Urban Development

An engineering geological stability investigation of an area proposed for development must characterize it in terms of (i) the risk of certain size sinkholes developing and (ii) the risk of doline formation.

Buttrick (1995) defined the denoted hazard[4] to be a reflection of the 'inherent' geotechnical characteristics of the subsurface profile when subject to a postulated scenario or scenarios that reflect the most unfavourable conditions in terms of dewatering and other mobilizing agencies that may be anticipated at that location.

The hazard[5] characterization can be determined only if the profile is assumed to be 'abused'. If the land has a 'high hazard of large sinkholes forming', it retains that characterization irrespective of the recommended or actual development type. What does change with different types of development is the probability of consequence

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[4] The term hazard replaced the initial term 'risk' used by Buttrick (1995)
[5] The term hazard replaced the initial term 'risk' used by Buttrick (1995)

from an event. In order to reduce the probability of the consequence of an event, it is necessary for the development selected for any area to be appropriate in relation to the risk (Buttrick, 1995).

The characterization of the site provides pertinent information for design purposes. Urban development normally results in a disturbance of the metastable conditions prevalent in the dolomitic environment. The particular type of development selected in relation to the risk characterization is critical to the safe and successful long-term viability of a project (Buttrick, 1995).

Table 13 indicates the number of ground movement events anticipated to be generated in low, medium and high risk areas if inappropriate development were to take place.

Table 13. Anticipated Ground-movement events per hectare over a 20-year period (After Buttrick, 1995)

Risk Characterization	Ground-Movement events Per Ha In a 20-Year Period
Low	0,0 events / ha
Medium	0,07 events / ha
High	0,7 events / ha

Buttrick (1992) proposed the use of a zoning system relating the risk characterization of an area and certain suitable or appropriate types of development. Table 14 denotes these suggested types of development, as later adjusted by Buttrick et al (2001), related to the risk characterization. Development design is based on the most conservative assessment for an area, that is on the risk of the most catastrophic event occurring.

Table 14. Characterization: Inherent Risk of subsidence and a specified-size sinkhole forming (After Buttrick et al., 2001)

Inherent Hazard Class	Small sinkhole	Medium sinkhole	Large sinkhole	Very large sinkhole	Risk of doline formation	Recommended type of development in order to maintain acceptable Development Risk
Sinkhole diameter (m)	< 2	2 – 5	5 – 15	> 15	-	
Class 1	Low	Low	Low	Low	Low # NDS or DS	Residential, light industrial and commercial development provided that appropriate water precautionary measures are applied. Other factors affecting economic viability such as excavatability, problem soils, etc. must be evaluated.
Class 2	Medium	Low	Low	Low	Medium #NDS	Residential development with remedial water precautionary measures. No site and service schemes. May consider for commercial or light industrial development
Class 3	Medium	Medium	Low	Low	Medium #NDS	Selected residential development with exceptionally stringent precautionary measures and design criteria. No site and service schemes. May consider for commercial or light (dry) industrial development with appropriate precautionary measures.
Class 4	Medium	Medium	Medium	Low	Medium #NDS	Selected residential development with exceptionally stringent precautionary measures and design criteria may be considered on such land where investigation for individual structures has indicated that conditions are suitable. No site and service schemes. May utilize for commercial or light (dry) industrial development with appropriate stringent precautionary measures.
Class 5	High	Low	Low	Low	High #NDS	These areas are usually not recommended for residential development but under certain circumstances selected residential development (including lower-density residential development, multi-storied complexes, etc.), may be considered, commercial and light industrial development. The risk of sinkhole and doline formation is adjudged to be such that precautionary measures, in addition to those pertaining to the prevention of concentrated ingress of water into the ground are required to permit the construction of housing units.
Class 6	High	High	Low	Low	High #NDS	These areas are usually not recommended for residential development but under certain circumstances high rise structures or gentleman's estates (stands 4 000m2 with 500m2 proven suitable for placing a house) may be considered, commercial or light industrial development. Expensive foundation designs may be necessary. Sealing of surfaces, earth mattresses, water in sleeves or in ducts, etc.
Class 7	High	High	High	Low	High #NDS	No residential development. Special types of commercial or light industrial (dry) development only (e.g. bus or trucking depots, coal yards, parking areas). All surfaces sealed. Suitable for parkland.
Class 8	High	High	High	High	Low-High *NDS or DS	No development, nature reserves or parkland.

* Number of anticipated events per hectare over a period of 20 ears with poor design and management

\# Non-Dewatering Scenario and Dewatering Scenario

The basic philosophy of this zoning system is 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. This table does not deal with all the possible combinations of risks and events but does indicate development type as related to a trend of 'increasing risk of increasingly catastrophic events' (Buttrick, 1995).

Buttrick et. al (2001) explains that the Inherent Risk for sinkhole formation is a reflection of the geotechnical characteristics of the materials in the blanketing layer and depends mainly on the mobilizing potential of the overlying materials to utilization and mobilization under the influence of a mobilizing agency. Buttrick et al. (2001) delineated between low, medium and high Inherent Risk for sinkhole formation based on the susceptibility of the subsurface profile with particular interest to the blanketing layer to mobilization. This table is presented below in Table 15.

Table 15. Guidelines for assessing the risk for mobilization of the blanketing layer (Inherent Risk for sinkholes) (Buttrick et al., 2001)

Inherent Risk	Typical Site Condition
Low	The profile displays no voids. No air loss or sample loss is recorded during drilling operations. Either a very shallow water table or a substantial horizon of materials with a low potential of susceptibility to mobilization may be present within the blanketing layer (e.g. continuous intrusive features or shale material). Depth to potential receptacle is typically great and the nature of the blanketing layer is not conductive to mobilization.
Medium	This type of profile is characterized by an absence of substantial 'protective' horizon and has a blanketing layer of *materials potentially susceptible to mobilization* by extraneous mobilization agents. The water table is below the blanketing layer.
High	The blanketing layer of the high-risk profile reflects a great susceptibility to mobilization. A void may be present and is interpreted to be very likely, within the potential development space, indicating that the process of sinkhole formation has already started. Boreholes may register large cavities, sample loss, air loss, etc. Convincing evidence exists of cavernous subsurface conditions which will act as receptacles. The water table is below the blanketing layer. In dewatering situation, the lowering of a shallow groundwater level would obviously increase the risk of mobilization.

4. METHODOLOGY

4.1. Data Preparation

The Dolomite Stability Report boundaries and percussion borehole positions were captured in GIS as part of the Dolomite Section database activities. The GIS software used by the CGS is Esri ArcMap® Version 9.3.

All the percussion boreholes drilled during dolomite stability site investigations in Centurion were analysed in order to capture groundwater and bedrock depth and later determine the hazard of sinkhole formation at each borehole point. The actual borehole logs (3587 boreholes) are not presented in this dissertation as a summary is provided in Appendix B.

4.2. Classifying the area in terms of the hazard of sinkhole formation

4.2.1. Background

The Buttrick (1992) Scenario Supposition Method was adopted by the CGS as the most acceptable method for evaluation of dolomite sites, in 1994 (pers. Comm., G. Heath 2012). This method has been adjusted by Buttrick et al. in 1995 and 2001 where some factors were refined.

Some of the terms as used in the Scenario Supposition Method were changed in the draft SANS 1936-1:2012 document. The eight classes of the Scenario Supposition Method were known as Inherent Risk Classes, but have subsequently been changed to become Inherent Hazard Classes.

Some definitions from the draft SANS 1936-1:2012 document are:
- *Competent person:* 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, establish 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 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.

Hazard[6]: source of potential harm

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

Inherent Hazard Class: 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)

Risk[7]: potential for realization of some unwanted consequence arising from a hazard

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

Subsidence[8]: shallow, enclosed depression

The draft SANS 1936-1:2012 document does not specify how to derive at the eight hazard classes, and provides the opportunity to the 'competent person' to use any method to derive threat, as long as it can be verified.

4.2.2. Implementation of the Inherent Hazard Zoning System

Since there are no numerical limits to the Scenario Supposition method classification system, draft guidelines for allocation of each hazard class, based on CGS institutional memory and experience has been developed. This approach is mainly based on the dolomite bedrock depth and the mobilization potential of the overlying horizons. The size of sinkhole that could develop is again a function of the depth of dolomite bedrock, i.e. the thinner the overburden the smaller size sinkhole is expected and the thicker the overburden, the larger the size sinkhole expected.

An Inherent Hazard Class is assigned to each borehole, based on the characteristics of the material encountered in that borehole. Table 16 provides these basic guidelines for classifying boreholes in a non-dewatering scenario specific to the Centurion CBD.

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[6] *Hazard is a function of magnitude (of the events), area, and frequency.*
[7] *Risk is a function of the probability of failure and the consequences of failure.*
[8] *Most South African literature previously used the term "doline" when referring to subsidence as defined above. The use of the term "subsidence" is in line with international literature and practice.*

Table 16. Guidelines for determining the Inherent Hazard Class in a non-dewatering scenario, as applied in the Centurion CBD and surrounds

Inherent Hazard Class	Characteristics (Non-Dewatering Scenario)
IHC 1	- Overburden must consist of a competent, non-dolomitic cover (e.g. shale or syenite) of at least 30 m in thickness, overlying dolomite or chert residuum. - No voids (cavities) or low density material (wad) must be present.
IHC 2	- Overburden must consist of a competent, non-dolomitic cover (e.g. shale or syenite) of at least 20 m in thickness, overlying dolomite or chert residuum. - No voids (cavities) or low density material (wad) must be present. OR - A very shallow, static groundwater level exist, i.e. less than 5 m from surface, which forms a solid base
IHC 3	- Dolomite bedrock is situated between a depth of 6 m and 15 m below surface. - No voids (cavities) must be present. - If low density material (wad) is present, no more than 2 m should have recorded penetration rates of less than 15 seconds.
IHC 4	- Dolomite bedrock is situated deeper than 15 m in depth. - No voids (cavities) must be present. - If low density material is present, no more than 2 m should have recorded penetration rates of less than 15 seconds.
IHC 5	- Dolomite bedrock is shallower or situated at 5 m in depth. - Dolomite bedrock is discontinuous i.e. pinnacles and grykes are believed to exist, the latter acting as conduits to the voids below. - It is assumed that the grykes are narrow (i.e. < 1 m) and is present in the bedrock of depths exceeding 5 m. - No voids (cavities) are present in the dolomite bedrock.
IHC 6	- Dolomite bedrock is situated between 6 m and a maximum of 20 m in depth. - Voids and/or low density material (wad) is present. The low density material has recorded penetration rates of less than 15 seconds and is more than 2 m in thickness.
IHC 7	- Dolomite bedrock is situated between 20 m and a maximum of 35 m in depth. - Voids and/or low density material (wad) are present. The low density material has recorded penetration rates of less than 15 seconds and is more than 2 m in thickness.
IHC 8	- Dolomite bedrock is situated deeper than 35 m in depth. - Voids and/or low density material (wad) is present. The low density material has recorded penetration rates of less than 15 seconds and is more than 5 m in thickness.

In a non-dewatering scenario, the base of the erosion level (i.e. the depth to where erosion could occur) is either the head of dolomite bedrock or a static dolomitic groundwater level. Therefore, if the groundwater level is situated at 7 m below surface, and the dolomite bedrock is situated at 18 m below surface, the Inherent

Hazard Rating would be IHC 3, since the groundwater level forms the base of the erosion level and not the dolomite bedrock.

This method does not take the angle of draw, as proposed by Buttrick (1992) into account. It is merely based on the assumption that a larger size sinkhole will develop in deeper dolomite bedrock environments. Since this method is not entirely following the Method of Scenario Supposition, it is proposed as the '*Modified Method of Scenario Supposition'*.

For a dewatering scenario, the following guidelines are suggested, based on experience at the CGS:

Table 17. Suggested guidelines for determining the Inherent Hazard Class in a dewatering scenario, applicable to the Centurion CBD and surrounds

Inherent Hazard Class	Characteristics (Dewatering Scenario)
IHC 1	- Groundwater level is within dolomite bedrock
IHC 2	N/A
IHC 3 & 4	- Groundwater level is situated above dolomite bedrock - No low density material (wad) is present underneath the groundwater level - Should the groundwater level be lowered, no material below should be able to compress (e.g. chert should be present above dolomite bedrock)
IHC 5	N/A
IHC 6	- Groundwater level is situated above dolomite bedrock - If the groundwater level is lowered, the material below will compress which result in subsidence or sinkhole formation - The compressible material below the groundwater level(wad) should not be more than 5 m in thickness - The depth of the groundwater level should be between 5 m and 20 m
IHC 7	- Groundwater level is situated above dolomite bedrock - If the groundwater level is lowered, the material below will compress which result in subsidence or sinkhole formation - The compressible material below the groundwater level(wad) should not be more than 10 m in thickness - The depth of the groundwater level is generally between 20 m and 35 m
IHC 8	- Groundwater level is situated above dolomite bedrock - If the groundwater level is lowered, the material below will compress which result in subsidence or sinkhole formation - The compressible material below the groundwater level(wad) is more than 10 m in thickness - The depth of the groundwater level is generally greater than 35 m

Since dewatering has not had an influence on stability in Centurion, the boreholes were not classified in terms of dewatering classification, and therefore only a non-

dewatering classification was applied. Table 17 was included for information purposes to illustrate that the *'Modified Method of Scenario Supposition'* can be applied in a dewatering scenario.

The table attached in Appendix B indicates the details including the Inherent Hazard Class, of all the boreholes in the Centurion CBD area.

4.3. Creating a Hazard Classification Map

The Inherent Hazard Class of each borehole produced above, was then transferred to the attribute table of the Percussion borehole shapefile[9] in ArcMap®, the GIS software, Plate 11. The attribute table of the shapefile indicates the spatial position of the boreholes and information such as the borehole number, depth of the dolomite bedrock, length of the borehole, etc. were captured in the attribute table.

The Spatial Analyst® extension of ArcMap® was used to create the Hazard Classification Map. In order to create a grid surface in ArcGIS®, the Spatial Analyst® extension makes use of one of several interpolation tools. Interpolation is the process of estimating an unknown value using known values. In the context of the Spatial Analyst® interpolation tools, interpolation is used to determine a value for an empty cell using the nearby sample points, called a z-value. It is based on the principle of spatial autocorrelation which measures the degree of relationship or dependence between near and distant objects.

The method used in the creation of the Inherent Hazard Map is the Natural Neighbor method. The Natural Neighbor interpolator uses the weighted average of surrounding or neighbouring data points. The basic equation used in Natural Neighbor, implements the assumption that things that are close to one another are more alike than those that are further apart.

The input parameter in the Natural Neighbor method is the borehole shapefile. A Z-value is requested, which is the attribute column in the shapefile that contains the values on the Inherent Hazard Class. A cell size can be specified for the output raster, the smaller the value the higher resolution would be the output raster be.

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[9] *A shapefile is a popular geospatial vector data format for GIS software. A shapefile is a digital vector storage format for storing geometric location and associated attribute information. This format lacks the capacity to store topological information. Shapefiles are simple because they store primitive geometrical data types of points, lines, and polygons. These primitives are of limited use without any attributes to specify what they represent. Therefore, a table of records will store properties/attributes for each primitive shape in the shapefile. (Definition from Wikipedia)*