

Plate 11. The attribute table of the borehole shapefile

5. DATA INTERPRETATION

5.1. Percussion Boreholes

A total of 3437 boreholes are situated within the Centurion CBD and surround areas which covers a surface area of approximately 1657 hectares. This constitute 2,07 boreholes per hectare. A total of 3587 percussion boreholes were used to assess the dolomite stability conditions. Some boreholes just outside the periphery of the demarcated Centurion CBD and surrounds were also included to ensure coverage to the boundary of the Centurion CBD area.

It is obvious that the borehole data is not evenly distributed. Fewer borehole points are present within the area south of the Hennops River (414 boreholes, 0,88 borehole per hectare) compared to north of the Hennops River (3024 boreholes, 2,54 boreholes per hectare) in the Lyttelton Agricultural Holdings, Die Hoewes and the Lyttelton Manor residential area. The boreholes are very densely spaced in the area of the Lyttelton Agricultural Holdings and Die Hoewes. Figure 2 indicates all the boreholes used in the assessment of the Centurion CBD area.

5.1.1. Dolomite Bedrock Depth

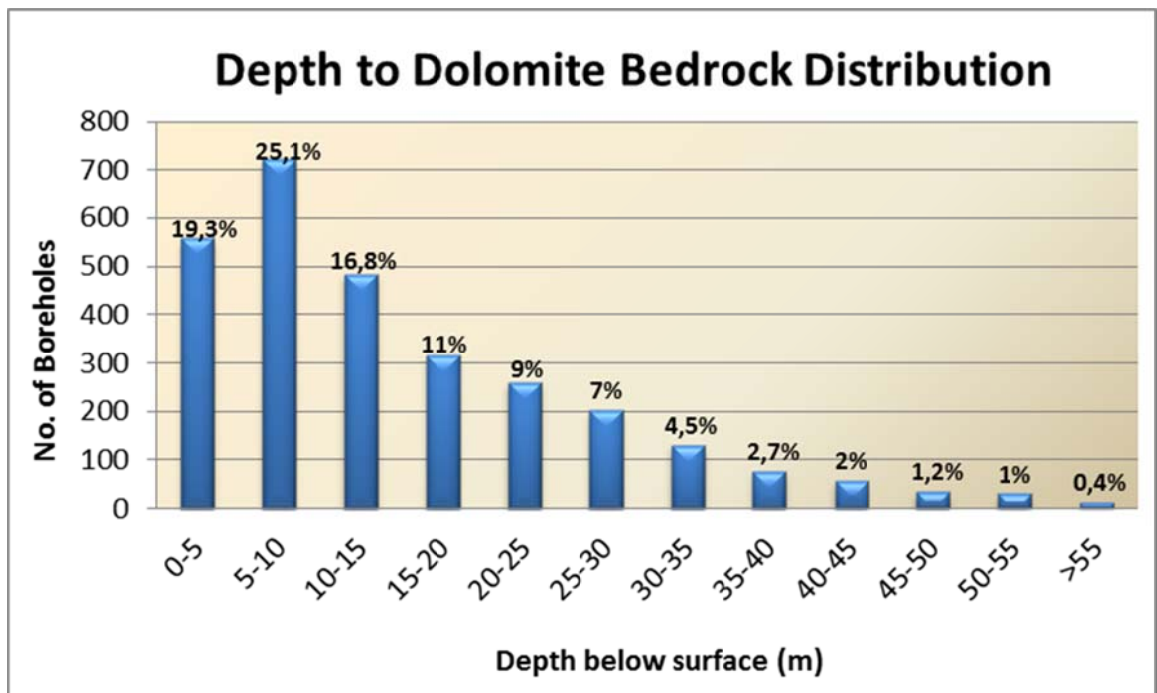
The depth to dolomite bedrock¹⁰ is very irregular with a minimum bedrock depth of 0 m and a maximum of 66 m. Note however that some of the boreholes (21%) were terminated either before solid dolomite bedrock was encountered or within syenite rock. These boreholes were not included in the bedrock statistics (2880 boreholes in and around the Centurion CBD and surrounds area were used for the analysis). The average bedrock depth for the area is 15 m below ground surface. Plate 12, taken in the Lyttelton Quarry situated immediately north of the Centurion CBD area shows the irregularity of the dolomite bedrock where numerous pinnacles are exposed (note the size of the excavator in relation to the dolomite pinnacles).



Plate 12. The variability of dolomite bedrock in the Lyttelton Quarry (I. Venter, 1981)

Graph 1 indicates the distribution of the depth below ground surface at which dolomite bedrock was intersected. The majority of the boreholes, 772 (25,1%) intersected bedrock between 5 m and 10 m. A total of 1763 (61,2%) boreholes intersected dolomite bedrock at a depth of less than 15 m below ground surface.

¹⁰ The dolomite bedrock depth is referred to as the top of dolomite rock head where dolomite rock is referred to as hard, competent rock with a drilling penetration rate of over 3 minutes.

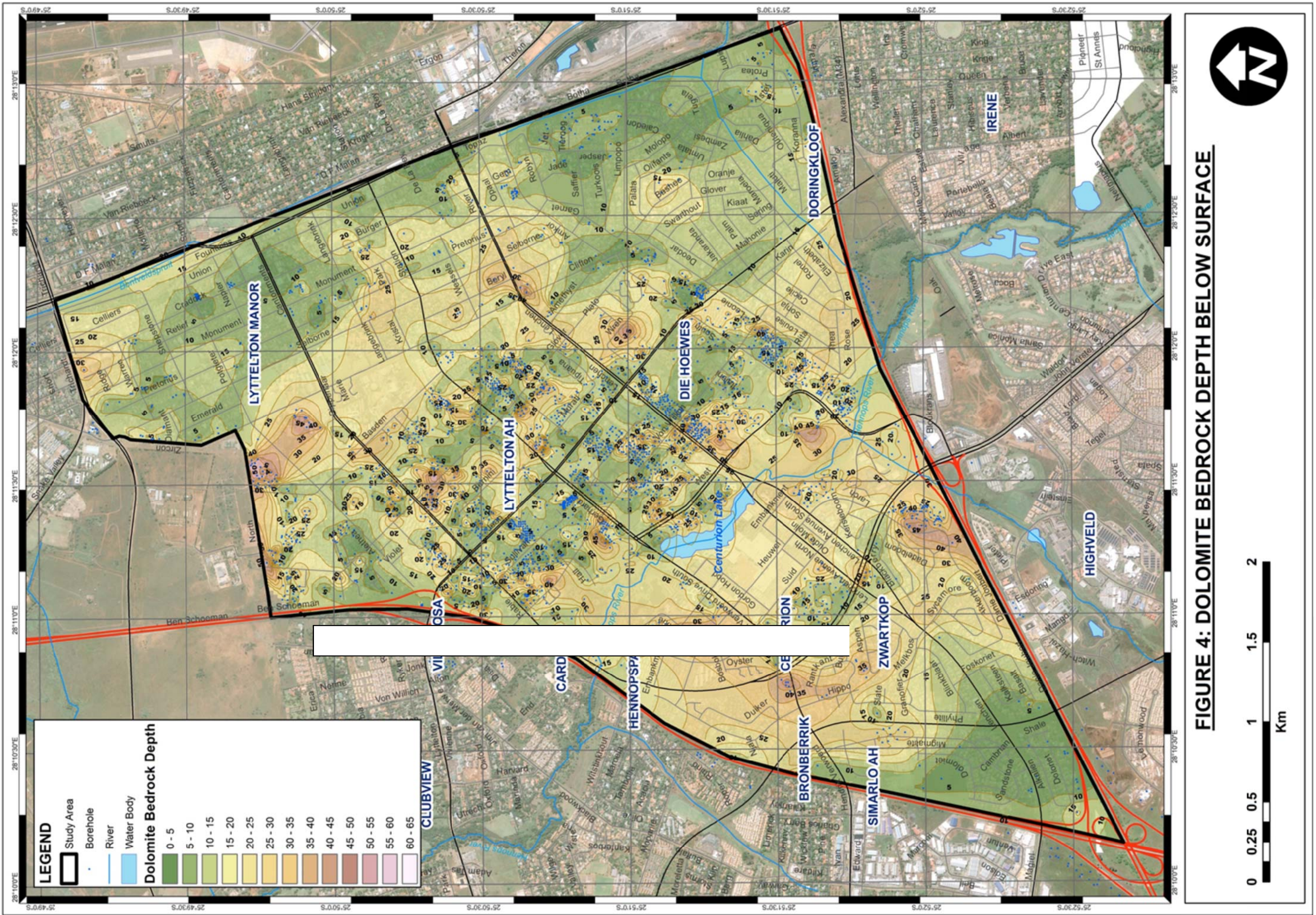


Graph 1. Depth to dolomite bedrock distribution

A map was created in Spatial Analyst® showing the Dolomite Bedrock Depth (Figure 4).

From the Dolomite Bedrock Depth map, the following are noted in the area north of the Hennops River:

- Borehole points are densely spaced over most of this area although some small areas are not covered by any boreholes.
- Shallow dolomite bedrock is present in Lyttelton Manor, extending south-westerly towards Doringkloof. Patches of 0 – 5 m, large areas of 5 – 10 m is present, which correlates well with the type of conditions shown in Plate 12, which is in the Lyttelton Quarry across the road.
- The Lyttelton Agricultural Holdings and Die Hoewes generally represent areas of shallower dolomite bedrock with occasional deeper valleys being present.
- Deeper dolomite bedrock is present in the area of Bernini Street (Lyttelton Agricultural Holdings) and in the area surrounded by Wren and Plato Streets (Die Hoewes).
- Towards the Hennops River the area surrounding Supersport Park and the southern parts of Doringkloof represents deeper dolomite bedrock.
- A large area representing deeper dolomite bedrock is present in the area between the Lyttelton Agricultural Holdings and Lyttelton Manor, running almost parallel to Clifton Street.



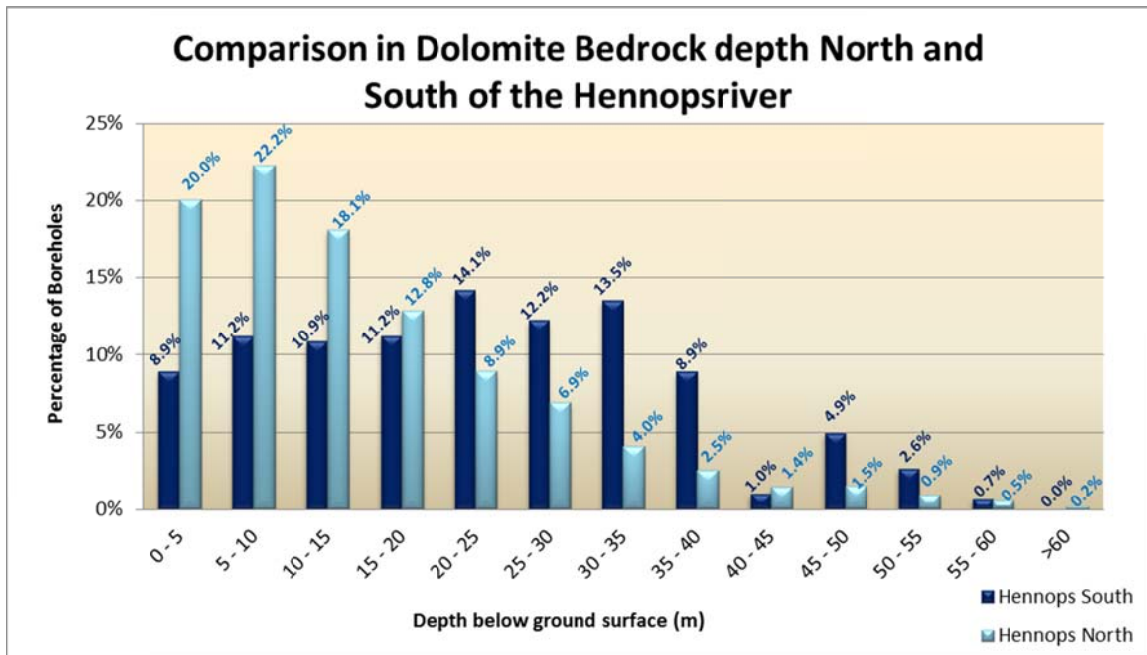
- The average depth to dolomite bedrock for the area north of the Hennops River (Lyttelton Agricultural Holdings, Die Hoewes and Doringkloof) is 14,5 m below ground surface (from 2445 boreholes).

From the Dolomite Bedrock Depth map, the following are noted in the area south of the Hennops River:

- The borehole points are sparsely spaced and large areas are not covered by any boreholes.
- The depth to bedrock map in this area therefore does not give a realistic view of the actual conditions present, but since it is the only data available one can assume that the general depth to bedrock is deeper in the area south of the Hennops River than in the northern part.
- Dolomite bedrock is mostly situated between 20 m and 35 m below ground surface.
- Shallow dolomite bedrock is present in the southern most corner of the Centurion CBD area, towards the intersection between the Ben Schoeman and Danie Joubert Freeways, which correlates well with the Oaktree Formation.
- Areas of deeper dolomite bedrock are present in the area of Kwikkie Street (Hennospark) and Dadelboom Street (Zwartkop).
- The average depth to dolomite bedrock in the area south of the Hennops River is 22,5 m below ground surface (from 304 boreholes).

Graph 2 indicates the difference in dolomite bedrock depth distribution for the areas north (Lyttelton Agricultural Holdings) and south of the Hennops River.

From this graph it is evident that the dolomite bedrock depth in the area north of the Hennops River is generally shallow with 60,4% of the boreholes encountering dolomite bedrock at a depth of less than 15 m below surface. In the area south of the Hennops River, the bedrock is generally at an intermediate depth with 39,8% of the boreholes encountering dolomite bedrock at depths between 20 m and 35 m below surface.



Graph 2. Comparison of the depth to dolomite bedrock between the northern and southern areas of the Hennops River

5.1.2. Dolomite Bedrock Elevation

A dolomite bedrock elevation map was created using Spatial Analyst[®] and is presented in Figure 5. The following are noted from this map:

- The dolomite bedrock generally follows the surface elevation, where a valley is present in the area of the Hennops River with higher slopes on either side of the river.
- In the area south of the Hennops River the average dolomite bedrock elevation is 1420 mamsl with the highest point situated at 1490 mamsl (situated between South and John Vorster Streets, Centurion) and the lowest point at 1364 mamsl (Area of Kwikkie Street, Hennospark).
- In the area north of the Hennops River the average dolomite bedrock elevation is 1436 mamsl with the highest point situated at 1491 mamsl (Corner of Station and Clifton Streets, Lyttelton Agricultural Holdings) and the lowest point at 1366 mamsl (Area of Supersport Park).

It is assumed that the dolomite bedrock elevation will not reflect the actual bedrock topography, as indicated in Figure 5, due to the wide spacing of boreholes and the large scale at which the map was created. For a bedrock elevation map to show the actual undulating dolomite bedrock surface, boreholes need to be drilled at a very close spacing and a site specific map should be created. An example of a 'test' area within the Centurion CBD area is shown below in Plate 13. From this plate it is

evident that pinnacles (marked P on plate) are present with some associated deeper valleys (large area in turquoise colour on plate).

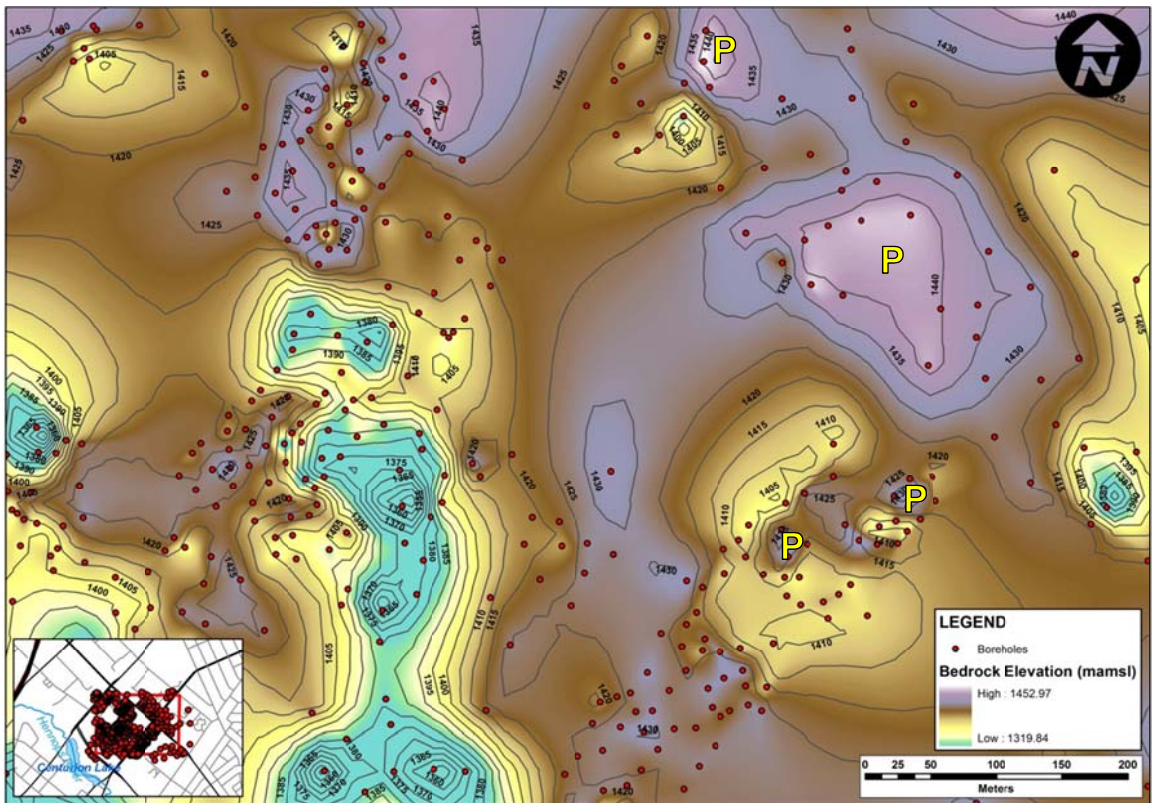


Plate 13. Example of a bedrock elevation map on a small area within the Centurion CBD area

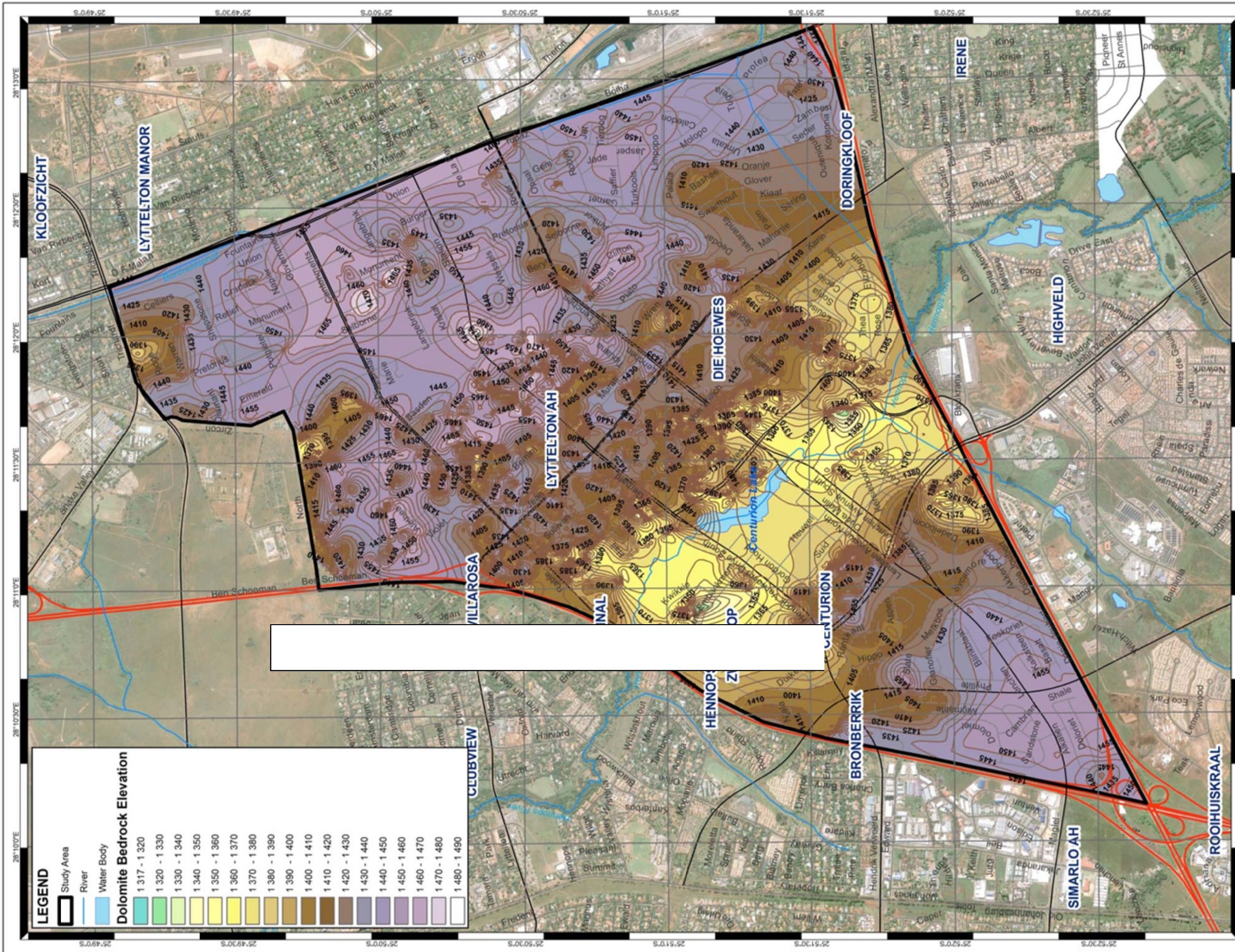


FIGURE 5: DOLOMITE BEDROCK ELEVATION



5.2. Gravity Data

The residual gravity lines, from the Relly investigation (1976) are indicated on Plate 14. Relly has described the pattern of gravity contours to be extremely complicated reflecting complexities in the distribution of subsurface mass and in particular reflecting great variations in the depth of the dolomite sub-surface.

Gravity is used as a tool to indicate areas of low and high density material. A gravity high usually implies an area where high density material is present, i.e. dolomite bedrock is shallow and similarly a gravity low implies an area of lower density material such as a void or thick wad or even dense bedrock but at depth.

In this study the gravity was not used as part of assessing the dolomitic conditions, due to the limited area for which gravity is available.

The residual gravity generally indicates an area of gravity lows and steep gradients, especially in the north-eastern and the eastern corners. A broad gravity low, extending northwest-southeast is present along the western boundary (towards the Hennops River) of the gravity survey area, followed by an area of a broad gravity high in the centre of the gravity survey area, also stretching northwest-southeast in the area of Wren Street in the south to North street in the north. The north-eastern boundary of the gravity survey is mainly characterized by some gravity low areas.

Some of the gravity low areas do correspond to areas of deeper dolomite bedrock, which include:

- The large gravity low feature trending north-south running from Rabie to Von Willich Street (marked 1);
- The smaller gravity low feature immediately east of the intersection between Lenchen and West streets (2);
- Between Rabie and Alethea Streets (3) in the north; and
- The area at the corner of Clifton and Gerhard streets (4).

The only gravity high that corresponds well to an area of shallow bedrock is present at the corner of South and Von Willich Streets (5), and to a lesser extent does the gravity high immediately west of Rabie street (6) correspond with the bedrock depth.

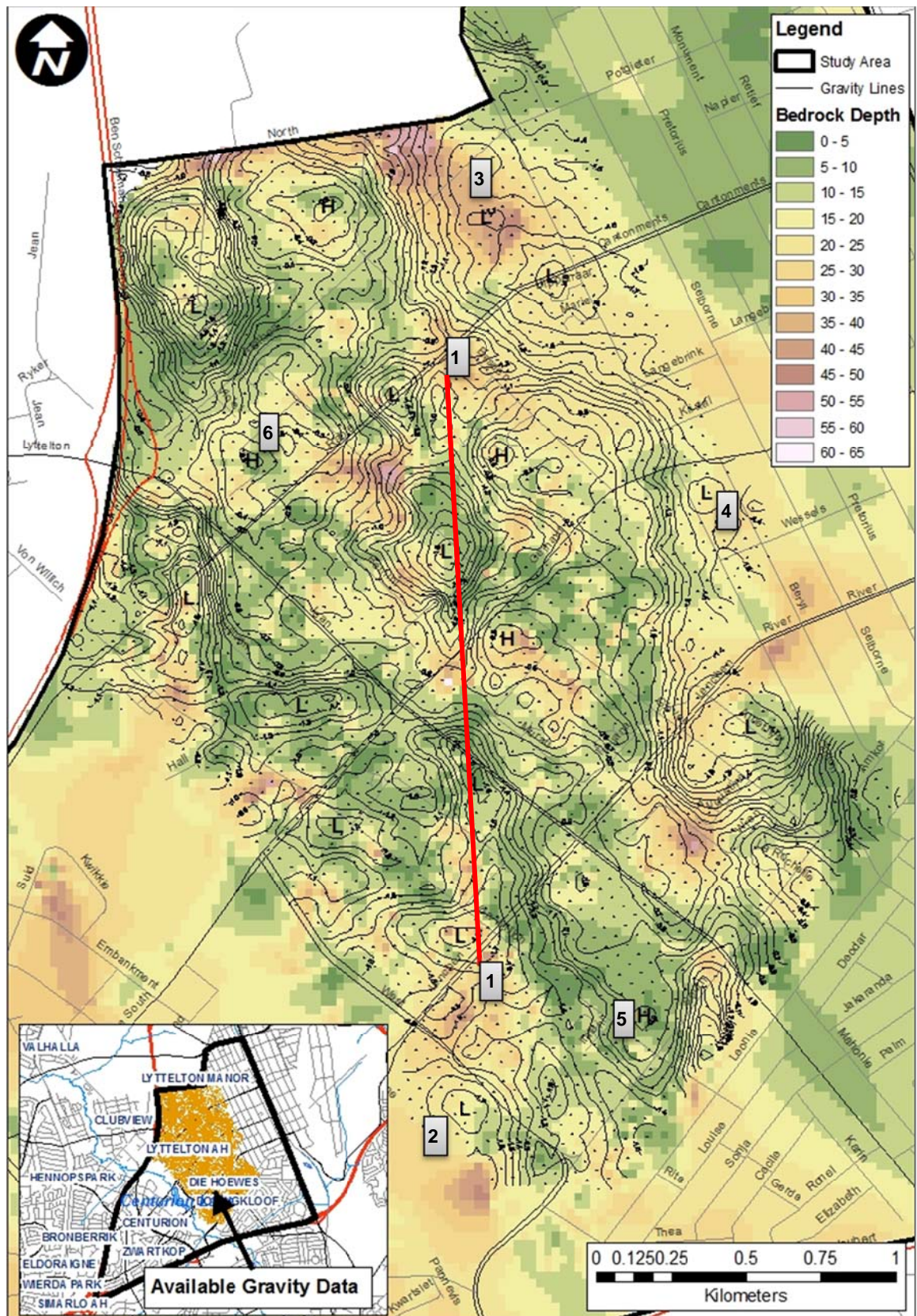


Plate 14. Available gravity data overlain on the dolomite bedrock depth (From Africon (Pty Ltd)

The gravity does not correlate well with the dolomite bedrock map and this could be because the gravity points are widely spaced (45 m), and the borehole points are not equally spaced.

5.3. Sinkhole Database

A total of 119 sinkholes have been recorded in the Centurion CBD area since the early 1970's to date, the positions of which are indicated on Figure 6. The sinkhole record, held by the CGS is still under review and a large number of the sinkholes do not have a complete record. The sinkhole record is presented in Appendix C. It should be noted that the sinkhole database is confidential and not readily accessible to the public. Therefore, limited information is presented in this dissertation on the exact positioning of sinkhole occurrences.

5.3.1. Nature of Sinkhole Occurrences in the Centurion CBD and surrounding areas

The following were derived from the sinkhole database:

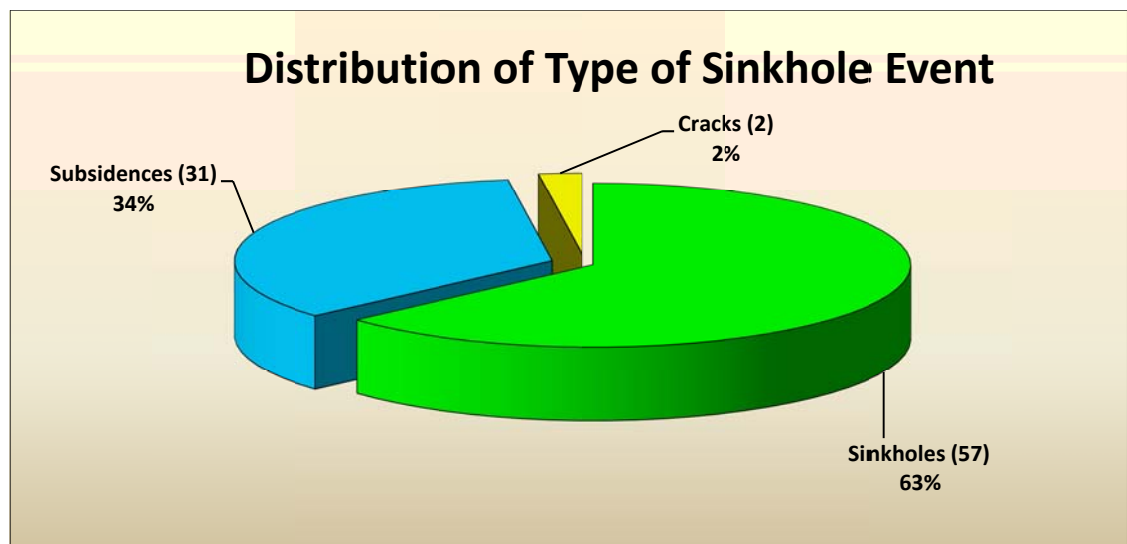
- The largest reported sinkhole is S41, with dimensions of 32 m x 23 m. This sinkhole is situated in Lyttelton and occurred as a result of a broken water pipe.
- The deepest reported sinkhole is S49 that is 10 m deep. This sinkhole occurred as a result of a leaking sewerage pipe.
- Only 1 sinkhole (S45) has occurred through syenite, situated close to the John Vorster and Jean Avenue intersection (No detailed information is available regarding this sinkhole event).
- A total of 110 sinkholes (92%) occurred in the Monte Christo Formation whereas only 8 sinkholes (7%) occurred in the Lyttelton Formation. No sinkholes occurred in the Oaktree Formation. See Table 18 below for the number of sinkhole events that have occurred in each of the geological successions or formations in the Centurion CBD area (from the available unpublished 2528 CC Centurion geology map).
- Only 1 sinkhole (S45) has occurred south of the Hennops River.
- The oldest known sinkhole (S15) occurred on 24 March 1971 and the most recent sinkhole (S109) occurred on 23 September 2011.
- 90 (75,6%) of the database have information regarding the type of the event that occurred. From this available information, 57 (63,3%) of the events were

recorded as sinkholes; 31 (34,4%) were recorded as subsidences¹¹; 2 (2,2%) were recorded as cracks. (29 events (24,37%) did not have available information). Graph 3 indicates the distribution of type of sinkhole events.

- The average sinkhole depth is 3,24 m (data from 47 sinkholes).
- The average sinkhole size is 5,1 m (data from 53 sinkholes).
- 3 lives have been lost as a result of a sinkhole (S19) in the Centurion CBD area. It should be noted that these lives were lost during the rehabilitation of the sinkhole, and not as a result of the event itself.
- 7 Houses or units had to be demolished as a result of sinkholes (S39, S42, S97 & S100) in the area.

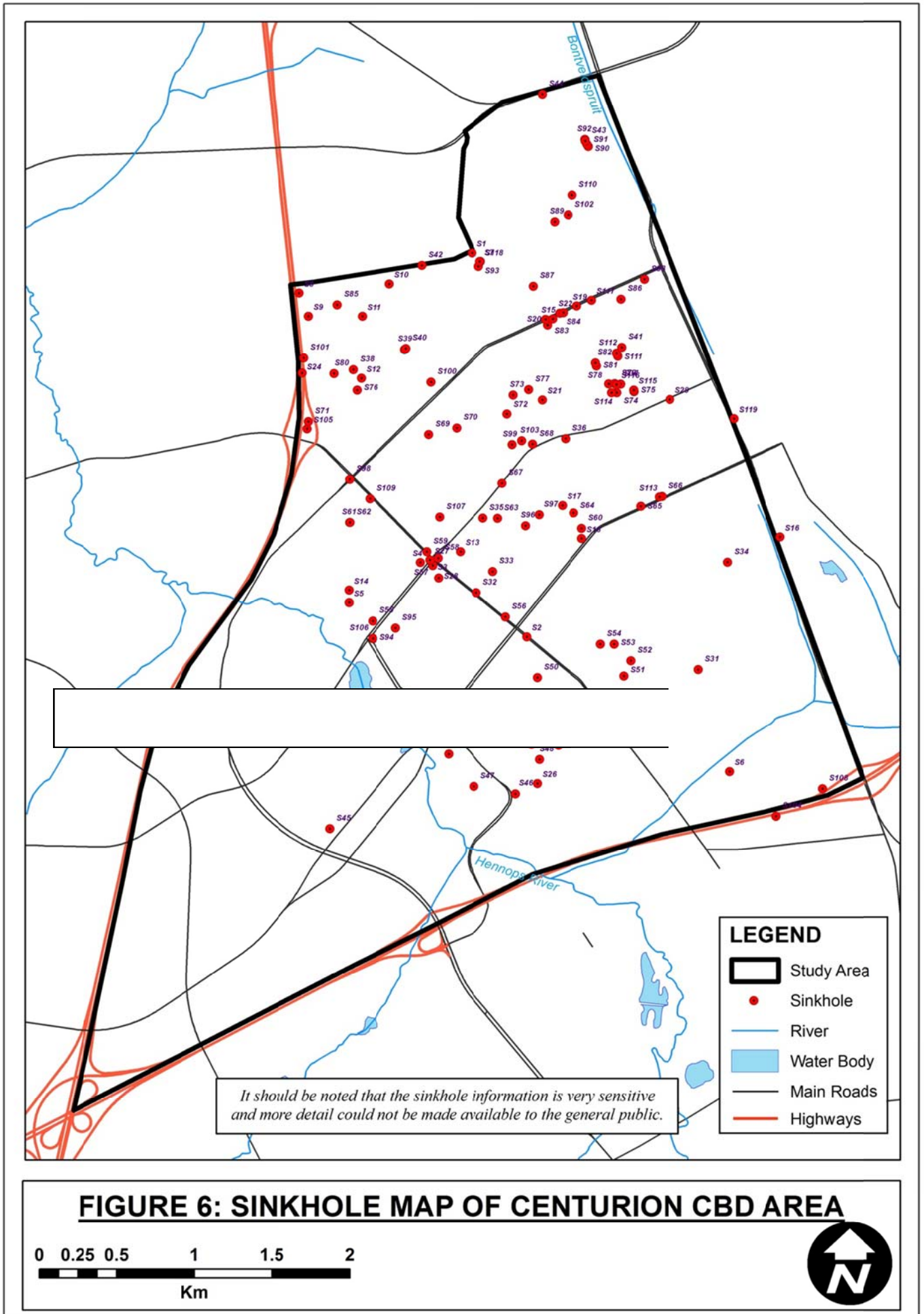
Table 18. Number of sinkholes that have occurred in each geological succession

| Geological Succession / Formation | Area (ha) | No. of Sinkholes Occurred |
|---------------------------------------|-----------|---------------------------|
| Lyttelton Formation | 91,82 | 8 |
| Monte Christo Formation | 1246,61 | 103 |
| Oaktree Formation | 44,80 | 0 |
| Chert Breccia | 9,77 | 0 |
| Dolerite | 35,10 | 1 |
| Quartz – Diorite (Syenite intrusions) | 171,34 | 5 |
| Alluvium | 58,31 | 2 |



Graph 3. Distribution of type of sinkhole events

¹¹ A subsidence is referred to as a shallow earth depression which forms as a result of the compression at depth of low-density dolomite residuum. It is not a catastrophic event and is shallow in nature.

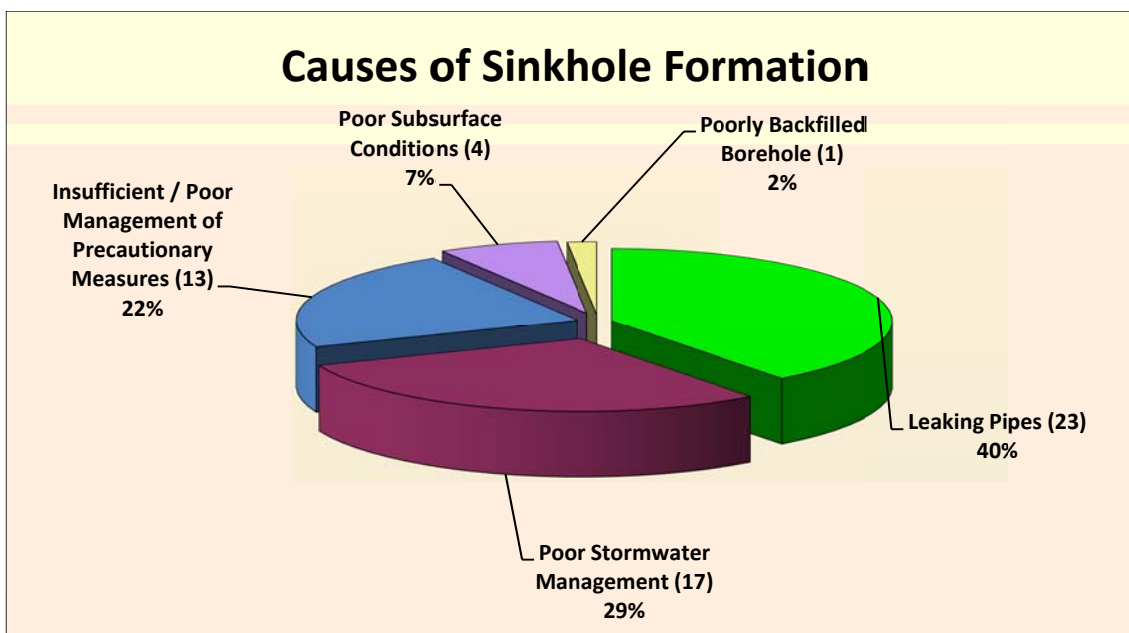


5.3.2. Quality of the Sinkhole Database

The CGS is still in a process to verify all the sinkhole data points with approximately 90% already verified. It should be noted that there could be sinkholes that have not been recorded and more sinkholes could have occurred in the area. Note there is no legal obligation for persons or authorities to record the occurrence of sinkholes, nor to report them to the CGS. It is therefore quite possible that information regarding many events has been lost.

Only 58 of the sinkholes (49%) in the database have information regarding the possible cause of the sinkhole development. According to this information 23 sinkholes or subsidences (40%) formed as a result of leaking water bearing services, 17 events (29%) occurred as a result of poor surface / storm water management and 13 events (22%) occurred as a result of inadequate or poor precautionary measures (e.g. downpipes draining into soil next to foundations, ponding water). Only one sinkhole (2%) occurred as a result of a poorly backfilled borehole whereas a total of 4 sinkholes or subsidences (7%) occurred as a result of poor subsurface conditions. Using this limited information (49% of the database) it is evident that 93% of the events in the Centurion CBD area occurred as a result of man's disturbance of the natural ground conditions, confirming what Buttrick et al (2001) indicated.

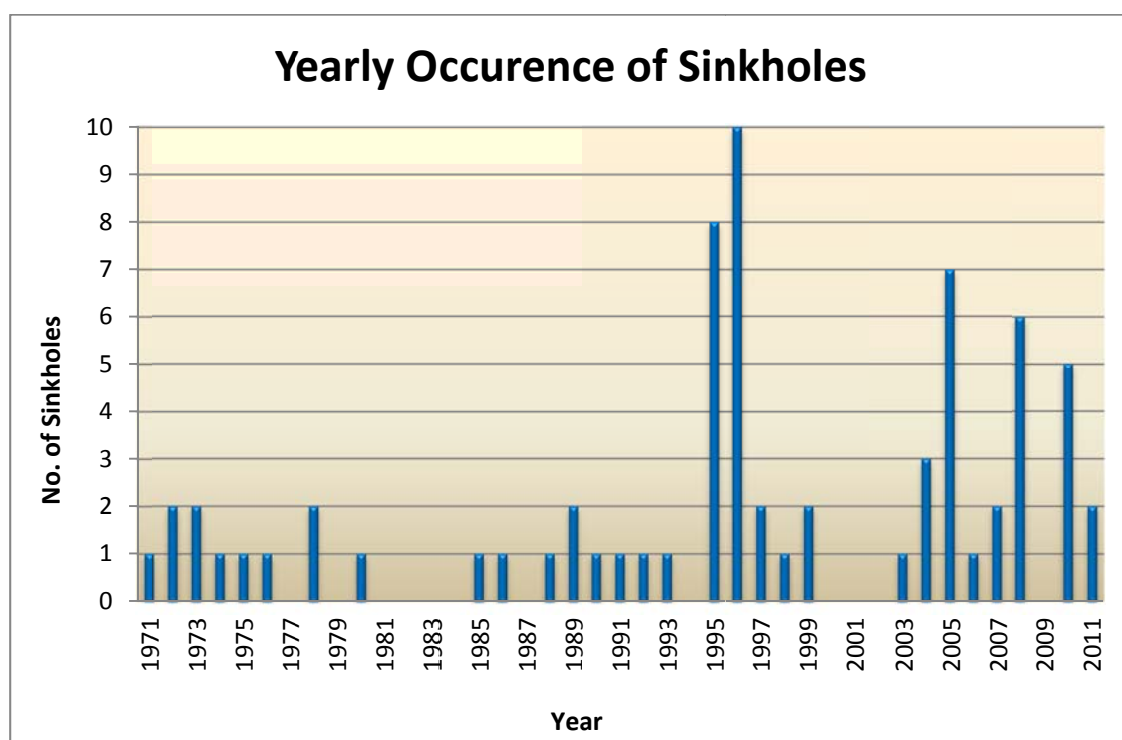
Graph 4 below shows the distribution of the cause of sinkhole occurrence in the Centurion CBD area. Unfortunately, 51% of the database did not have any information regarding the cause of the sinkhole occurrence.



Graph 4. Distribution of cause of sinkhole events

Graph 5 shows the yearly occurrence of sinkholes in the Centurion CBD area. Not all the sinkhole data points have information regarding the date of occurrence, with only 70 sinkholes (58%) having this information. The year where the most sinkholes were recorded is 1996 when 10 sinkholes occurred. This can be ascribed to high rainfall, especially during 1995 and 1996.

For some years (1977, 1979, 1981-1984, 1987, 1994, 2000-2003 and 2009) no sinkholes have been recorded, or none have occurred. It is assumed that all the data has not been recorded, especially in the 1970's and 1980's and 2000 to 2003.



Graph 5. Yearly occurrence of sinkholes in the Centurion CBD area

Only 53 sinkholes (45%) in the database have information regarding the size i.e. the diameter of the sinkhole. The sinkhole size distribution is discussed in Section 5.4 of this dissertation.

5.3.3. Consequence of Sinkhole Occurrence

The consequence of sinkholes occurring has led to the demolishing of houses (7) and other structures which have resulted in a loss of money for property owners in dolomite areas. CTMM attempts to apply more stringent precautionary measures and make the public more aware of the sinkhole problem. In recent years,

developments with improved foundation systems have been implemented in order to prevent damage due to these catastrophic events. The Gautrain route in particular, traversing over the centre of the Centurion CBD area has had to implement foundation systems costing millions of Rands to ensure the safety of the train line.

Below are some pictures showing sinkholes that have occurred in the Centurion CBD and surrounding areas.

Plates 15 and 16 indicate a subsidence (15 m in diameter) that occurred next to the N14 Highway, approximately 100 m north of the Jean Avenue off-ramp (S101). It occurred as a result of surface water run-off from the highway into the adjacent open field. Traffic congestion resulted for a prolonged period during the remediation of this sinkhole.



Plate 15. Sinkhole east of the N14 Highway (S101)



Materialie op die Ben Schoeman-bering in 'n suidelike rigting ry verby die afgesperre sinkgat. Motoriste kan lense vlegs die vlerke baan gebruik en verkeer het gisteroggend agtertoegedruis tussen die Knutsenstraat en die Jaarstraat-afrit. Foto: THERM 06/22

N14 sak in en maak verkeer erge kopseer

Pad herlei weens reusagtige sinkgat

Foto van Pieter van der Merwe

'N Reusagtige gat op die Ben Schoeman-bering (N14) in 'n suidelike rigting naby Lyttelton in Oos-Kaap het die verkeer gisteroggend vroeg tussen Knutsenstraat en herby die Jaarstraat-afrit laat ophang.

Daarom dat die gat nog nie herdoord is, word die verkeer op 'n tydelike omleidingsroete in die suidelike streek van die land weggelei om die verkeer weg te lei van die sinkgat, wat sowat 40 m breed en 10 m diep is. Volgens Pieter van der Merwe, hoofingenieur van die Grondwaaierdepartement van verkeer, pad en water op die pad wat die gat oopgemaak is, is die gat van die pad af herby die Jaarstraat-afrit.

Al begin het met klagen dat daar 'n deuk in die pad is en dat die pad laag is om in te sak. Verder het geen die swaar rulle van die laaste paar weke het waarskynlik versterk dat die sinkgat is, versterk dat die sinkgat is, versterk dat die sinkgat is.

"Dit is moeilik om te sê wat die oorsaak hiervan was, want 'n sinkgat word gewoonlik veroorsaak as byvoorbeeld, daar is geen waterkering nie."

Volgens Van der Merwe is die sinkgat gevorm deur die reuk van die pad.

Hy versterk dat die herdoording van die sinkgat 'n groot deel van die week, ongeveer 'n week of langer, sal duur.

Volgens Van der Merwe is 'n gedeelte van die bering in 'n suidelike rigting oopgemaak word om die tydelike baan in die suidelike streek te laat vloei.

Die oorsaak van die bering is 'n suidelike rigting en terwyl dit is 'n vreesagtige

baan gebruik word. Die bering is alreeds oopgemaak en dit is steeds nie vir laer rulle - van die tydelike baan tot die suidelike.

Die laaste grondwal in die suidelike streek van die bering is 'n afgesperre suidelike afdekking omdat dit nie veilig is vir verkeer nie.

Gister het padwerkers oopgemaak 'n suidelike omleiding op die grondwal. Verkeer sal stadig begin om die suidelike baan te leer.

Volgens Van der Merwe is die sinkgat, oopgemaak van rulle tot in die komende week om die pad te laat vloei. Deur die suidelike bering te oopmaak, word die verkeer weggelei van die sinkgat.

Die tydelike omleiding sal ongeveer 'n week of langer duur, word herby die sinkgat oopgemaak om die suidelike bering te laat vloei.

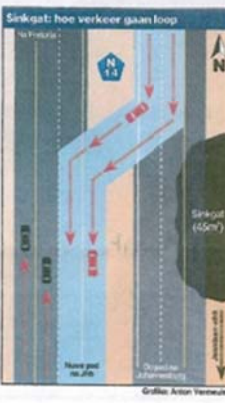


Plate 16. The N14 Highway sinkhole in the newspapers (Beeld, 7 February 2006)

Plate 17 shows cracks in a unit and a broken garden wall in a residential complex in Die Hoewes (S97). Although the damage does not seem very severe, three units have been demolished after a thorough investigation which revealed that poor subsurface conditions are present, and since the foundation systems appear inadequate, substantial repairs are required. The cause of this settlement appears to be poor storm water drainage, where storm water accumulated at the back of the unit against the boundary wall.



Plate 17. A settlement in a residential complex, Die Hoewes (S97)

Plates 18 and 19 below show the sinkholes that have occurred on the embankment of the N1 highway, approximately 300 m south of the Botha Avenue. Plate 17 was taken during September 2010 and Plate 18 during December 2010. The two plates clearly show how these sinkholes have enlarged during this period of three months as a result of continual inflow of rain water.



Plates 18 & 19¹². Sinkholes that occurred on the embankment of the NI Highway (S104)

¹² Plate 19 – Courtesy of Ms. A Sudu from the City of Tshwane Metropolitan Municipality

A large sinkhole (12 m in diameter, 5 m deep) developed in Jean Avenue (S109) during September 2011 as a result of a leaking municipal water service pipe (Plate 20).



Plate 20. A Sinkhole that developed in Jean Avenue (S109)

A large area (approximately 25 m x 15 m) was excavated in order to repair this sinkhole by means of the reverse filter method, which essentially means backfilling the sinkhole by placing coarser grained materials (such as boulders) at depth and finer grained materials nearer to the surface (Plate 21). According to the Tshwane Metropolitan Municipality this sinkhole cost about 6,3 million Rand to repair (pers. Comm., A. Sudu 2013).

This sinkhole was also reported in the local newspaper, The Pretoria News (26-09-2011), see Plate 22. According to the newspaper article water also ponded on the surface before the sinkhole occurred.



Plate 21. Remediation of the sinkhole Jean Avenue (S109)



A sinkhole at the entrance to Jean Village. The earth caved in on Friday afternoon.

PICTURE: YOLANDE DU PREEZ

Sinkhole in Lyttelton causes a hole lot of trouble

YOLANDE DU PREEZ

LYTTELTON residents watched in shock as the entrance to several businesses in Jean Village crumbled, leaving a large sinkhole.

Garvin McGannon, a Lyttelton resident, said he had been told by witnesses that there was a large pool of water on the surface of the road moments before it caved in on Friday.

First little pieces of earth started falling in, but eventually pieces of the tarred road at the entrance to the

Moose Pub and Grill, The Big Six Sports Pub and several other businesses just caved in, he said.

A smaller sinkhole appeared in Jean Avenue itself, one of the busiest roads in the area.

Louise Brits, spokeswoman for the Tshwane Metro Police, said the sinkhole appeared at about 3pm on Friday near the intersection with Rabie Street.

Brits said only one lane of Jean Avenue was open in the vicinity of the sinkhole and barriers and detour signs had been put up.

"Despite our efforts it appears at least two motorists hit the barriers on Saturday night," she said.

Engineers are assessing the problem and have removed some of the soil to determine how deep the hole is and what needs to be done to repair it. Brits could not put a time frame on repairs to the road.

Jacques Visagie, owner of The Big Six Sports Pub, said he was not there when the incident happened, but when he arrived later, dozens of spectators were at the scene, taking photographs.

The sinkhole had cost him business at the weekend.

"Sundays are my busiest days and the place was empty today," he said.

Parts of Centurion are built on dolomite and sinkholes appear from time to time, like the subsidence problems that caused the closure of one of the entrances to the Lyttelton police station.

Engineers took extra precautions on the Gautrain's route through the area, making provision for the dolomitic conditions.

Plate 22. Jean Avenue sinkhole in the Pretoria News Newspaper (26 September 2011)

5.4. Sinkhole Size Distribution

Buttrick and van Schalkwyk (1995) proposed a scale of sinkhole sizes based on the potential development space of a sinkhole, as indicated in Table 11. This table was slightly amended by Buttrick et al. (2001) and has widely been used to refer to a specific sinkhole size. Table 19 below shows the scale sinkhole sizes as proposed by Buttrick et. al. (2001).

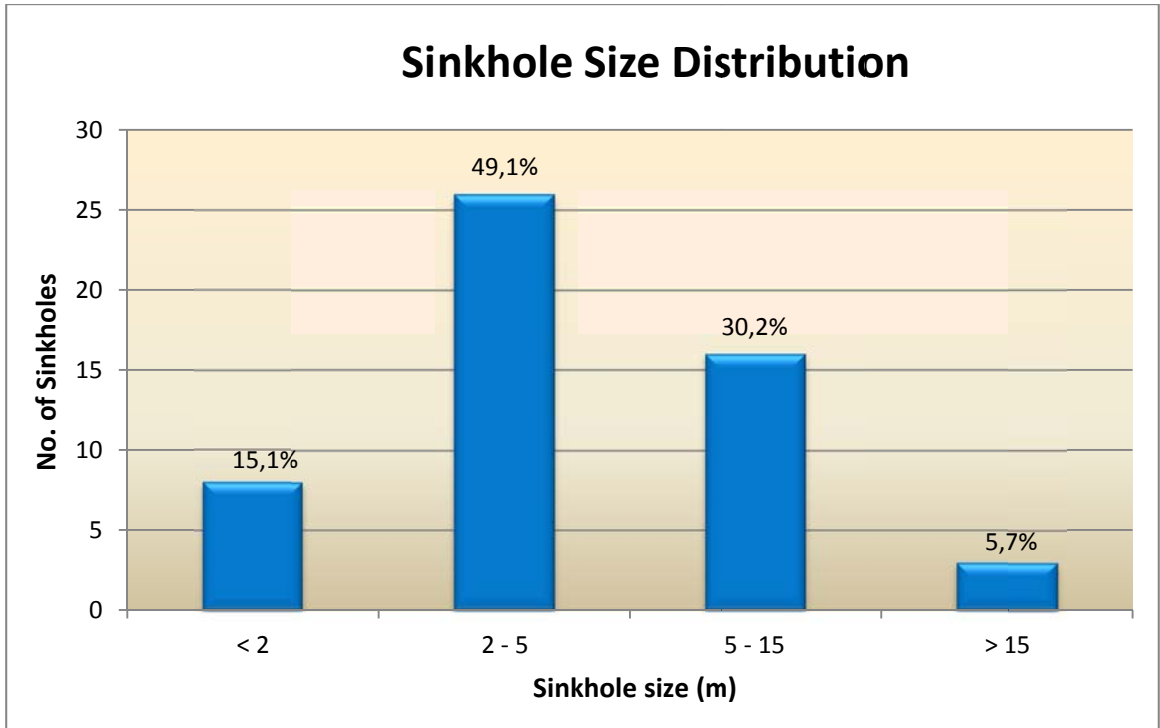
Table 19. Suggested scale of sinkhole sizes (Buttrick et. al, 2001)

| 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 – 15 | Large sinkhole |
| Very large potential development space | > 15 | Very large sinkhole |

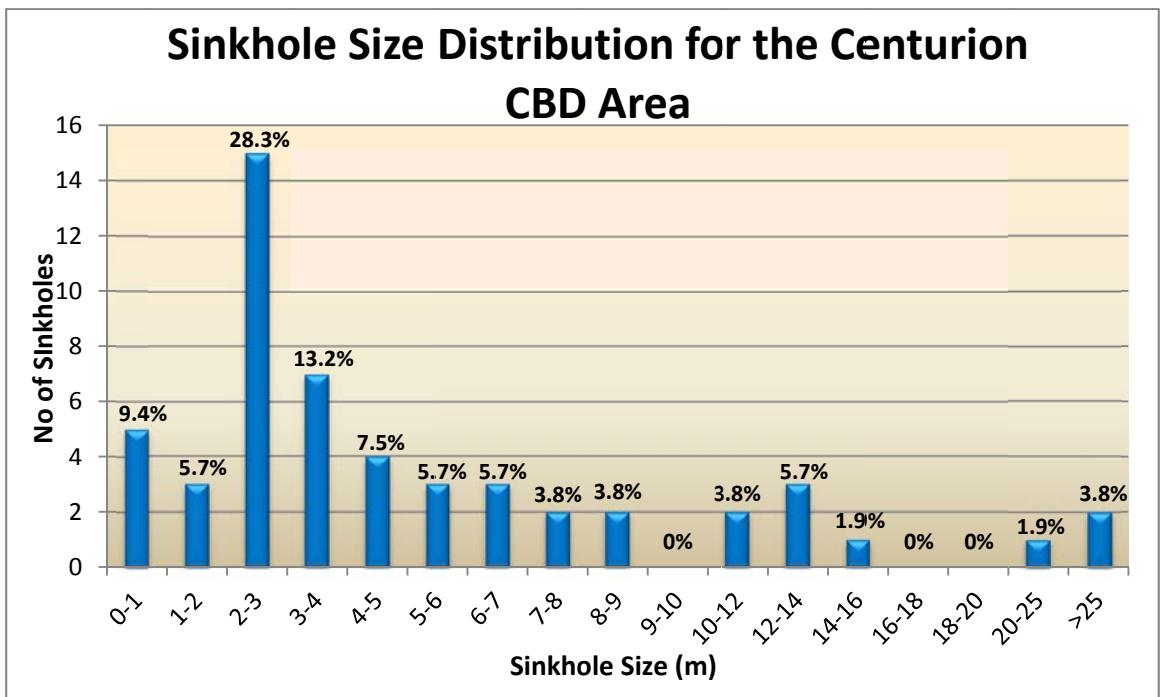
From the available information in the database, Graph 6 shows the size distribution of the sinkholes in the Centurion CBD area, based on the sizes indicated in Table 19. Just less than half of the sinkholes (49,1%) in the area are between 2 m and 5 m in diameter (i.e. medium size sinkholes), followed by large-sized sinkholes being almost a third of the available sinkhole sizes (30,2%). Small sinkholes constitute 15,1 % of the events with only 5,7 % of sinkholes being more than 15 m in diameter, i.e. very large sinkholes.

Graph 7 indicates the sinkhole size distribution using the available sinkhole database of the Centurion CBD. Surprisingly, almost 10% (9,4%) of the sinkholes which occurred were smaller than 1 m in diameter. Almost a third (28,3%) of the sinkholes in the Centurion CBD area are sized between 2 m and 3 m, followed by 13,2% of sinkholes sized between 3 m and 4 m. Only 17% of all sinkholes were larger than 10 m in diameter, whereas 83% of the sinkholes are sized 9 m or less in diameter. This graph confirms that medium sized sinkholes (2 m - 5 m) dominate in the Centurion CBD area.

It should be noted that these graphs only presents the available information (45% of records), using limited information.



Graph 6. The sinkhole size distribution, based on the suggested scale of sinkhole sizes (Buttrick et. al, 2001)



Graph 7. The sinkhole size distribution of the Centurion CBD and surrounding area

5.5. Size of sinkhole occurring compared against depth of dolomite bedrock

One of the most important factors of the proposed '*Modified Method of Scenario Supposition*' is the depth to dolomite bedrock, as it is assumed that the depth to dolomite bedrock has a direct influence on the size of sinkhole that could develop. Table 20 below shows the suggested depth of dolomite bedrock and hence the size of sinkhole that is expected.

Table 20. Suggested depth of dolomite bedrock scale influencing size of sinkhole expected

| Depth of dolomite bedrock below surface (metres) | Expected sinkhole size (metres) (Based on the Suggested scale of sinkhole sizes (Buttrick et. al, 2001)) |
|--|---|
| 0 – 5 | < 2 |
| 5 – 20 | 2 - 5 |
| 20 – 35 | 5 – 15 |
| > 35 | >15 |

Using the proposed sinkhole sizes, as indicated in Table 20 above, the actual data from the Centurion CBD, using only known sinkhole diameters are indicated in Table 21 below.

Table 21. Comparison between dolomite bedrock depth and sinkhole size within the Centurion CBD area

| 1 | 2 | 3 | 4 | 5 |
|--|---|---------------------------------|--|------------|
| Depth of dolomite bedrock below surface (metres) | % of boreholes intersecting dolomite bedrock at depth intervals in Column 1 | Expected sinkhole size (metres) | % of sinkholes at specific size interval in Column 3 | % variance |
| 0 – 5 | 19,3 % | < 2 | 15,1 % | 4,2 % |
| 5 – 20 | 52,9 % | 2 - 5 | 49,1 % | 3,8 % |
| 20 – 35 | 20,5 % | 5 – 15 | 30,2 % | 9,7 % |
| > 35 | 7,3 % | >15 | 5,7 % | 1,6 % |
| <p><i>Column 2: Data obtained from Graph 1</i> <i>Column 4: Recorded sinkhole diameters in the Centurion CBD, as indicated in Graph 6</i></p> | | | | |

In general, the sinkhole size distribution corresponds well with the dolomite bedrock distribution, as indicated in Table 21. The largest variance (9,7%) occurs with large size sinkholes (5 m – 15 m) where not a good correlation exists with the boreholes intersecting dolomite bedrock between 20 m and 35 m. For small size sinkholes (> 2 m), fewer sinkholes occurred than the occurrence of shallow dolomite (> 5 m). The best correlation is for the very large size sinkholes (> 15 m) where a difference of only 1,6% is recorded.

The relative good correlation for all sinkhole sizes except the large size sinkholes as indicated in Table 21, support the fact that the depth of the dolomite bedrock does have an influenced in the size of sinkhole that could develop.

This needs however to be verified with actual data from investigations conducted next to sinkholes that have developed in the past. This was not addressed during this study.

6. HAZARD CLASSIFICATION MAP

A total of 3333 boreholes (93%) were used to compile an Inherent Hazard Class zonation map (Figure 7). Prior to 2004, a 30 m blanketing layer was considered adequate and so it became the norm to drill up to a depth of 30 m even if dolomite bedrock was not encountered (pers. Comm., SP Kok 2012). Some boreholes in the Centurion CBD area were also terminated at very shallow depths, i.e. 10 m. As a result, 7 % of the boreholes could not be used to determine the Inherent Hazard Class. After each of the boreholes was assigned an Inherent Hazard Class, a zonation map was compiled. This map has been compiled using the Spatial Analyst[®] extension of ArcGIS 9.3[®], as explained in Section 4.3 of the dissertation. This method interpolates between data points and if no data exists, nearby data is used to determine the hazard of sinkhole formation in the area.

The hazard map (Figure 7) generally indicates a medium to high hazard for the formation of sinkholes in the Centurion CBD and surround areas with pockets of low hazard areas. The largest area of high hazard conditions, Inherent Hazard Class (IHC) 6 to IHC 8 is present in the area immediately north and east of the Hennops River and Centurion Lake. The largest area of low hazard conditions is present in the area of Zwartkop (south of the Hennops River). The low hazard class areas (IHC 1 and IHC 2) are generally areas where syenite was encountered in the boreholes, and therefore represent syenite dykes or sills of a substantial thickness.

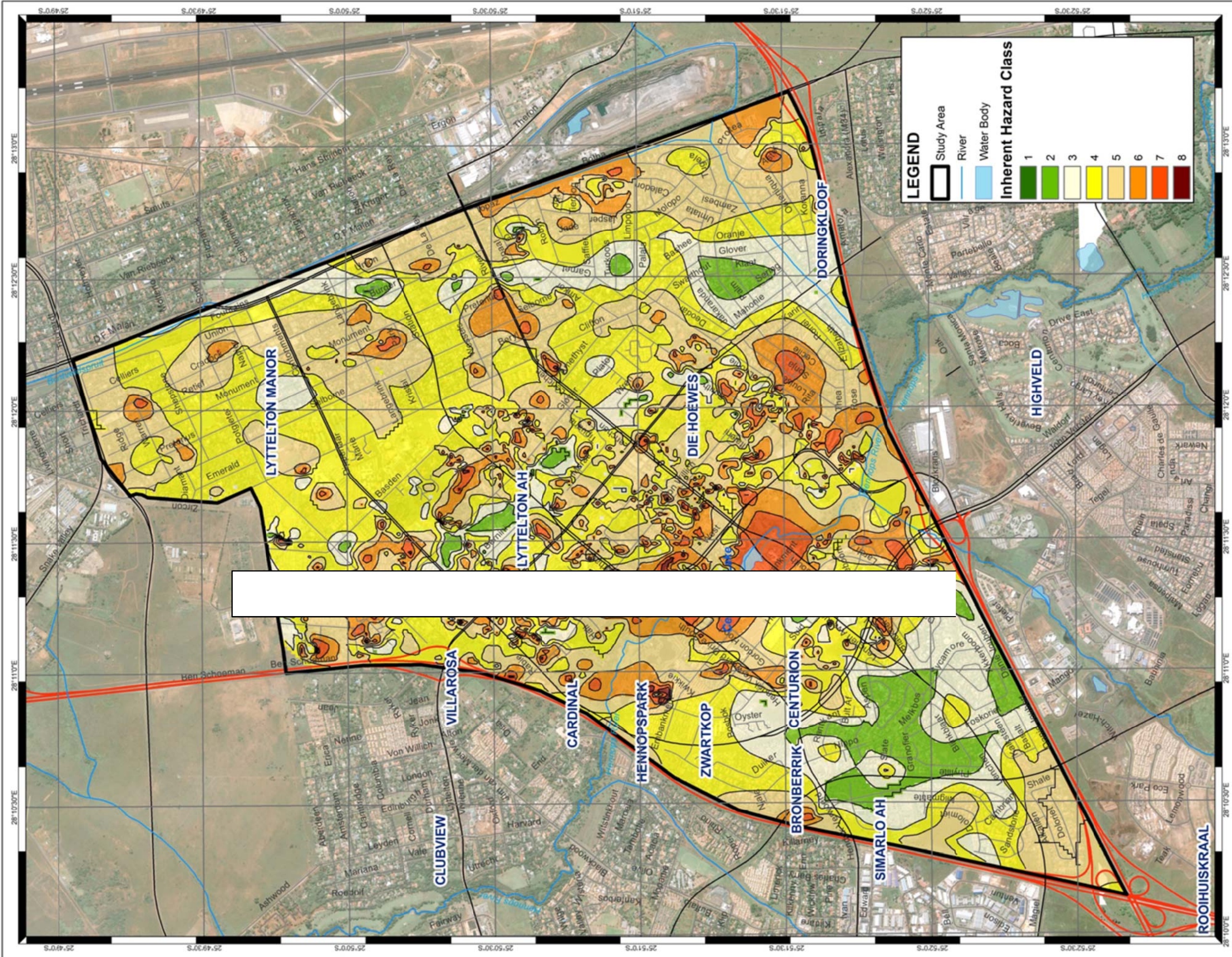
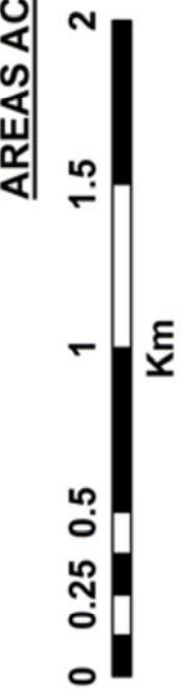


FIGURE 7: INHERENT HAZARD CLASS MAP OF CENTURION CBD AND SURROUNDING AREAS ACCORDING TO TABLE 16 GUIDELINES



From the sinkhole hazard map, the following are noted in the area north of the Hennops River:

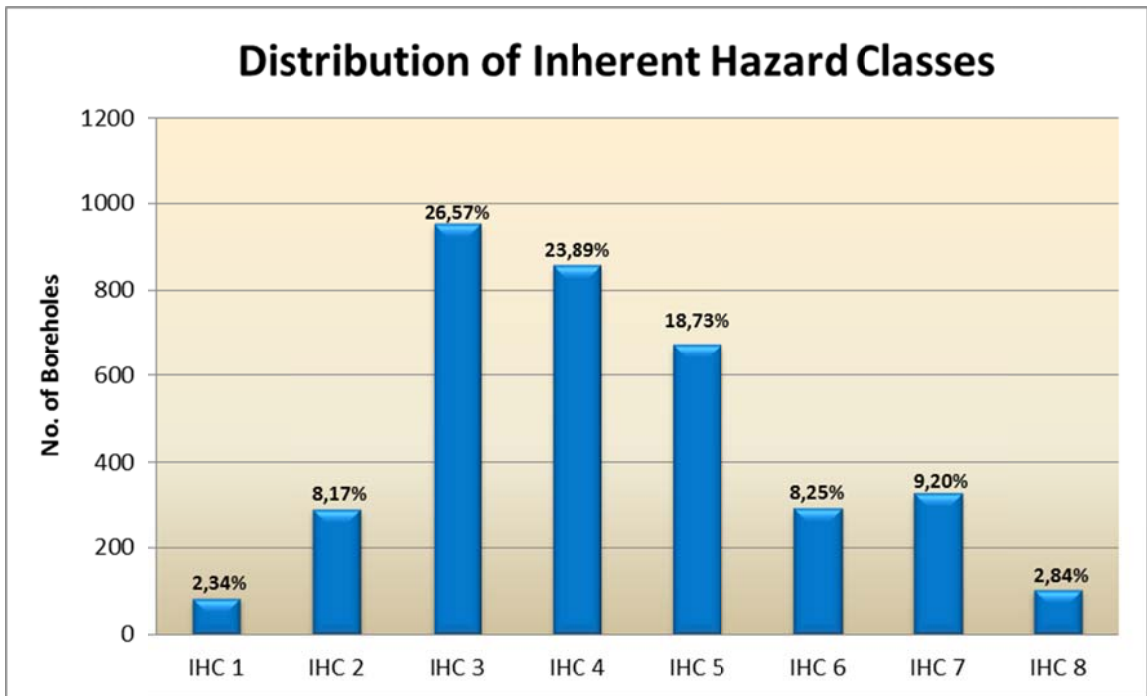
- More data points are available, which explains the variability in this area over smaller distances, i.e. the hazard of sinkhole formation changes over short distances from low to high hazard conditions, and this is especially present in the areas of the Lyttelton Agricultural Holdings and Die Hoewes.
- Towards the north-eastern boundary of the Centurion CBD area low to medium hazard conditions prevail where no IHC 8 conditions are present, though this could be due to a paucity of data or a change in dolomite formation.
- Small patches of low hazard conditions are present in patches across the site with the largest area north of the Hennops River being present in the area of Doringkloof.

From the sinkhole hazard map, the following are noted in the area south of the Hennops River:

- Less data points are available, therefore larger areas represent similar hazard conditions.
- This area generally represents low and medium hazard conditions (IHC 1 to IHC 4) with some areas where IHC 5 and 6 conditions are present.
- Towards the southernmost corner of the Centurion CBD area, towards the intersection between the Ben Schoeman and Danie Joubert Freeways, IHC 5 (i.e. shallow dolomite conditions, high hazard for small size sinkhole) prevail, which correlates well with the Oaktree Formation which is present in this area.
- Only small isolated patches of IHC 7 conditions are present in this area.

Graph 8 and Table 22 indicate the distribution of the hazard classes in the Centurion CBD area. Most of the boreholes (953) were classified as IHC 3 followed by IHC 4 (857) and IHC 5 (672). This corresponds well with the dolomite bedrock distribution that indicates that the most boreholes encountered dolomite bedrock between 5 m and 10 m which is in general classified as IHC 3 or IHC 5.

Table 22 indicates the percentage of each IHC in the Centurion CBD area. The Inherent Hazard Classes are grouped together to indicate Low (IHC 1 and IHC 2), Medium (IHC 3 and IHC 4) and High (IHC 5 to IHC 8) hazardous conditions. Half of the area is classified as having a medium hazard, with 50,46 % of the boreholes representing IHC 3 and IHC 4 conditions, whereas 39,03 % of the area is classified as having a high hazard. Only 10,51 % of all the boreholes indicated a low hazard for sinkhole formation.



Graph 8. The distribution of Inherent Hazard Classes of each borehole in the Centurion CBD and surrounds

Using this distribution of the boreholes, one can make the assumption that the Centurion CBD area generally represents a medium to a high hazard for the formation of sinkholes.

Table 22. Percentages of each Inherent Hazard Class in the Centurion CBD area

| IHC | Total No of Boreholes | Boreholes as Percentage | | |
|-----|-----------------------|-------------------------|---------------|---------|
| 1 | 84 | 2.34% | LOW | 10.51% |
| 2 | 293 | 8.17% | | |
| 3 | 953 | 26.57% | MEDIUM | 50.46 % |
| 4 | 857 | 23.89% | | |
| 5 | 672 | 18.73% | HIGH | 39.03 % |
| 6 | 296 | 8.25% | | |
| 7 | 330 | 9.20% | | |
| 8 | 102 | 2.84% | | |

Figure 8 indicates the Hazard Classification map in terms of the low, medium and high classification. The map confirms the results of the boreholes and shows predominantly medium hazard conditions across the Centurion CBD area. High hazard conditions prevail in the areas surrounding the Centurion Lake and are also present along the south eastern boundary of the Centurion CBD area along Botha

Avenue. Smaller areas of high hazard conditions are present and scattered across the centre of the Centurion CBD area. Only small areas of low hazard are present, mainly in Zwartkop and Doringkloof.

This map has been used to calculate the coverage of each of the Inherent Hazard Classes, and the surface areas of each of the Inherent Hazard Classes and the respective percentage thereof is given below in Table 23:

Table 23. Coverage of each hazard class in the Centurion CBD area

| Inherent Hazard Class | Surface Area (Hectares) | Percentage Cover in Centurion CBD Area |
|-----------------------|-------------------------|--|
| Low | 73 | 4,4 % |
| Medium | 1111 | 67 % |
| High | 473 | 28,6 % |

It is evident that two thirds of the Centurion CBD area represents a medium Inherent Hazard for sinkhole formation. Almost a third of the area can be considered as having a high Inherent Hazard for the formation of sinkholes with only a small portion of the area (4,4%) representing low hazard conditions.

6.1. Comparison between the CBD Hazard Map and Sinkhole Occurrence

The 119 sinkholes that occurred in the Centurion CBD area were plotted on Figure 8 to compare the occurrence of sinkholes against the low, medium and high hazard areas. Table 24 below shows the number of sinkholes in each of the hazard areas.

Table 24. No of sinkholes that have occurred in each of the hazard areas

| Inherent Hazard Class | No of Sinkholes | Sinkholes as Percentage |
|-----------------------|-----------------|-------------------------|
| Low | 0 | 0 % |
| Medium | 83 | 69,7 % |
| High | 36 | 30,3 % |

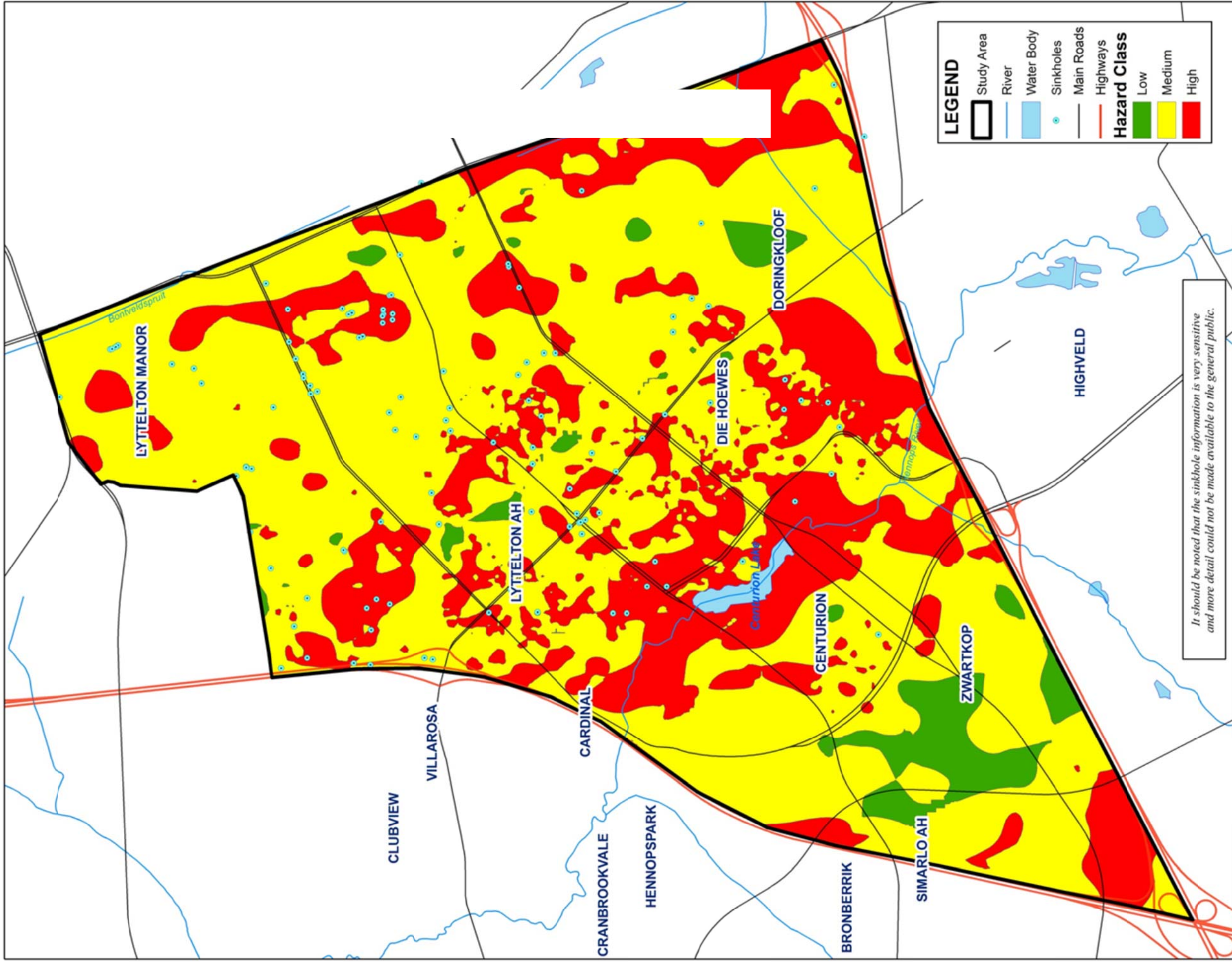
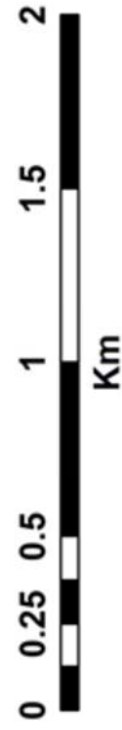


FIGURE 8: SIMPLIFIED INHERENT HAZARD MAP WITH SINKHOLE OCCURRENCES



The comparison between the Hazard map and the previous occurrence of sinkholes does not correlate well. The map does show that no sinkholes occurred in the areas classified as having a low hazard for sinkhole formation, which suggest that the delineation of low hazard areas was accurate and that the classification system define these areas well. Surprisingly, a vast majority (69,7%) of the sinkholes in the Centurion CBD area occurred in areas classified as having a medium hazard for the formation of sinkholes. This could suggest that medium hazard areas are equally vulnerable to sinkhole formation as high hazard areas or that the hazard map does not provide a good indication of the actual hazard conditions. But it must also be borne in mind that two thirds of the Centurion CBD area is considered to have a medium susceptibility for the formation of sinkholes.

6.2. Recommended Development Types

Using the Hazard Classification map, recommendations can also be made to what type of development would be suitable in the Centurion CBD area. The CGS aligns itself with the draft SANS 1936-1:2012 document which indicates permissible land usage that are suitable for the eight Inherent Hazard Classes. Tables 1 and 2 from the draft SANS 1936-1:2012 document is attached in Appendix D of the dissertation. Table 2 from draft SANS 1936-1:2012 specify that the proposed land use is permissible when a Dolomite Area Designation of D2 or D3 is indicated, conditional to the precautionary measures as stipulated in the draft SANS 1936-3:2012. Land uses where a Dolomite Area Designation of D4 is indicated for certain Inherent Hazard Classes, is considered not suitable for development and site specific precautionary measures is required. The definitions of the Dolomite Area Designations of D1 to D4 are indicated in Table 1 of the draft SANS 1936-1:2012, as attached in Appendix D. Table 25 below shows a summary of type of development allowed on each Inherent Hazard Class.

In general, the permissible land uses can be summarized as follows:

- Most Residential development types are allowed on IHC 1 to IHC 5. Some restrictions are placed on IHC 2 to IHC 5.
- Most Commercial development types up to three storeys are allowed on IHC 1 to IHC 6.
- Parking areas and garages are allowed on IHC 1 to IHC 6.
- Roads, railway lines, bulk pipelines, runways and pump stations are allowed up to IHC 6.

Table 25. Permissible land usage as indicated in the draft SANS 1936-1:2012 document

| IHC | Infrastructure Type Allowed (D1 to D3) | Infrastructure Type Not Allowed (D4) |
|---|--|---|
| 1 | C1, C2, C3, C4, C5, C6, C7, C8, RH2, RH3, RL1, RL2, RN1, RN2, RN3, IN1, IN2, IN3, IN4, IN5 | RH1 |
| 2 | C1, C2, C3, C4, C5, C6, C7, C8, RH2, RH3, RL1, RL2, RN1, RN2, RN3, IN1, IN2, IN3, IN5 | RH1, IN4 |
| 3 | C1, C2, C3, C5, C6, C7, C8, RH3, RL2, RN2, RN3, IN1, IN2, IN3, IN5 | C4, RH1, RH2, RL1, RN1, IN4 |
| 4 | C1, C2, C3, C5, C6, C7, C8, RH3, RL2, RN2, RN3, IN1, IN2, IN3, IN5 | C4, RH1, RH2, RL1, RN1, IN4 |
| 5 | C1, C2, C3, C5, C6, C7, C8, RH3, RL2, RN3, IN1, IN2, IN5 | C4, RH1, RH2, RL1, RN1, RN2, IN3, IN4 |
| 6 | C2, C3, C6, C7, C8, IN1, IN5 | C1, C4, C5, RH1, RH2, RH3, RL1, RL2, RN1, RN2, RN3, IN2, IN3, IN4 |
| 7 | C6 | C1, C2, C3, C4, C5, C7, C8, RH1, RH2, RH3, RL1, RL2, RN1, RN2, RN3, IN1, IN2, IN3, IN4, IN5 |
| 8 | None | C1, C2, C3, C4, C5, C6, C7, C8, RH1, RH2, RH3, RL1, RL2, RN1, RN2, RN3, IN1, IN2, IN3, IN4, IN5 |
| <i>Note that only the designation are provided in this table and the full description of each type is available in the complete table in Appendix C</i> | | |

For the purpose of this study Residential and Commercial Land use types are generally present in the Centurion CBD area and are foreseen for the near future. Figures 9(1) and (2) indicates which areas will be suitable for these types of development.

From Figure 9 (1) it is clear that:

- No areas were classified as IHC 1, and therefore no areas in the Centurion CBD area can be developed as such. Small areas are present for the development types proposed for Inherent Hazard Classes 1 and 2 as indicated on Figures 9(1) - 2.
- Large areas are suitable for residential type developments as shown on Figure 9(1) - 3, especially in the Zwartkop, Doringkloof and Lyttelton Manor

suburbs. IHC 4 land is suitable for almost all types of residential development except those of higher densities such as high rise developments, RL1 and RN1.

- Although large areas on Figure 9(1) - 4 is shown as suitable for development, this is mostly for commercial type developments, as several restrictions are placed on IHC 5 land in terms of residential development. IHC 5 land is not suitable for high density type residential developments, and the only residential type developments allowed are RH3, RL2 and RN3.
- All types of commercial developments, except C4 type developments are suitable on Inherent Risk Classes 1 to 5 (Figure 9(1) - 4).
- Figure 9(1) - 4 shows that the area surrounded by the Centurion Lake would be more suitable for commercial type developments, and residential type development would be more suitable towards the outer boundary of the Centurion CBD area.

From Figure 9 (2) it is clear that:

- Most areas in the Centurion CBD area are suitable for Commercial or Industrial type developments.
- No residential type developments are allowed on IHC 6 and higher (Figures 9(2) - 1 and 2). The large areas considered suitable for development in Figures 9(B) - 1 and 2 are mostly for commercial type developments.
- Small scattered areas were classified as IHC 8 (indicated as red on Figure 9(2)-2, where no development would be suitable.

Development is not considered suitable in IHC 8 land and therefore no map was created for IHC 8 land. The reason behind the fact that IHC 8 land is considered not suitable for any type of development is that each hazard class corresponds to a size of sinkhole that can develop, i.e. in IRC 7 areas a sinkhole of up to 15 m in diameter is expected. In IRC 8 areas a sinkhole of up to 40 m in diameter is expected and no foundation system currently exists to ensure safe designs in such areas.

The conclusion can be made that should the Centurion CBD area evolve into a CBD area such as Sandton City, the majority of the CBD (area surrounded by the Centurion Lake) would be suitable for most types of developments, hence high rise commercial type developments is suitable up to IRC 6 land. Residential type developments would be more suitable toward the outskirts of the CBD area, in the areas of Die Hoewes, Lyttelton Manor, Doringkloof and Zwartkop. All areas though require special precautionary measures and special foundation measures to ensure

that sinkhole formation does not occur, and if so, that it does not cause any large scale destruction or loss of life.

The draft SANS 1936-1:2012 does make provision for development on the areas assigned a Dolomite Area Designation D4 (i.e. areas previously considered not suitable for development), but site-specific precautionary measures such as special foundation designs and water precautionary measures are required. All these 'D4' developments are subject to external review by a suitably qualified geo-professional, as stipulated in the draft SANS 1936-1:2012. The conditions for development of 'D4' land are stipulated in Section 4.3.4 in the draft SANS 1936-1:2012 (Attached in Appendix D). A total of 2 developments have been supported by the CGS in the Centurion CBD, which followed the 'D4' process.

FIGURE 9(1) - 1
LAND USAGE: C1, C2, C3, C4, C5, C6, C7, C8, RH2,
Permissible on IHC 1

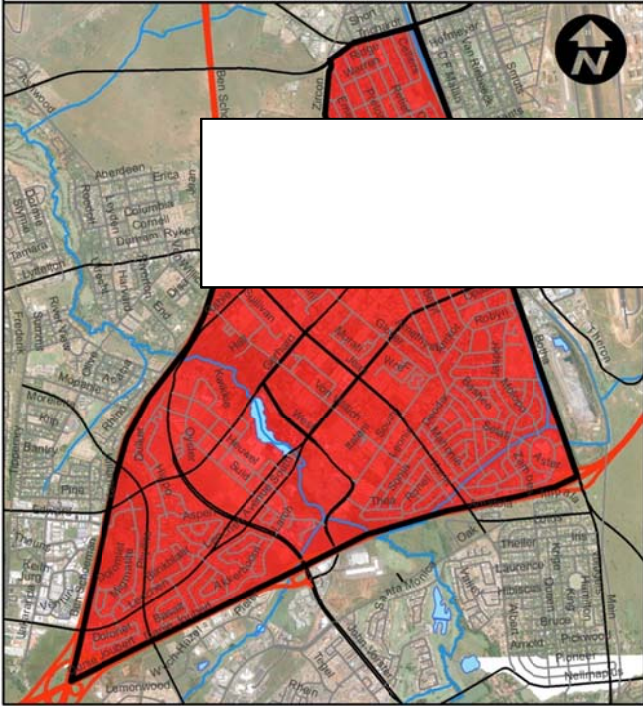


FIGURE 9(1) - 2
LAND USAGE: C1, C2, C3, C4, C5, C6, C7, C8, RH2,
Permissible on IHC 1 and 2

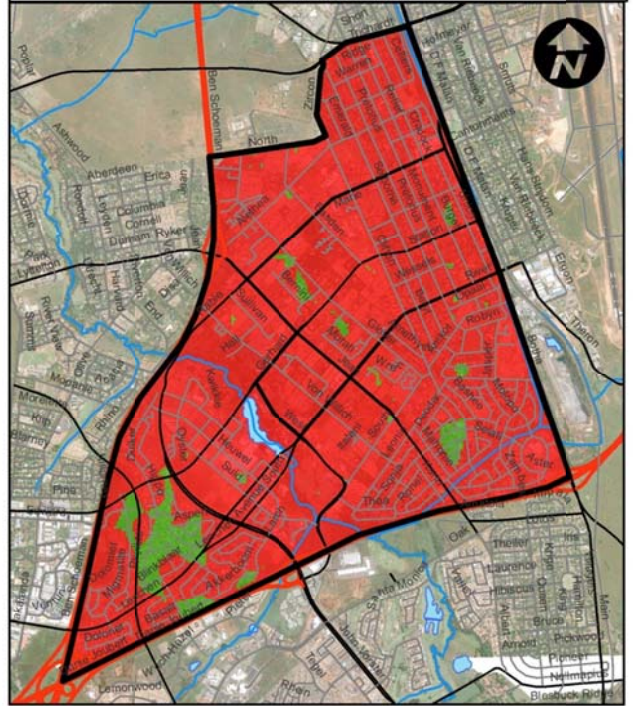


FIGURE 9(1) - 3
LAND USAGE: C1, C2, C3, C5, C6, C7, C8, RH3, RL2,
Permissible on IHC 1 to 4

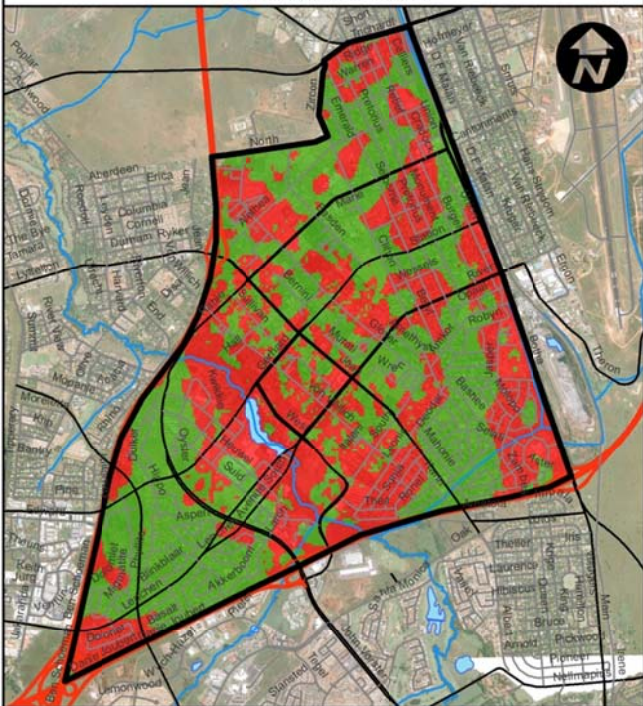
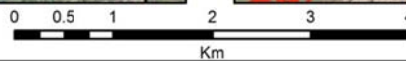
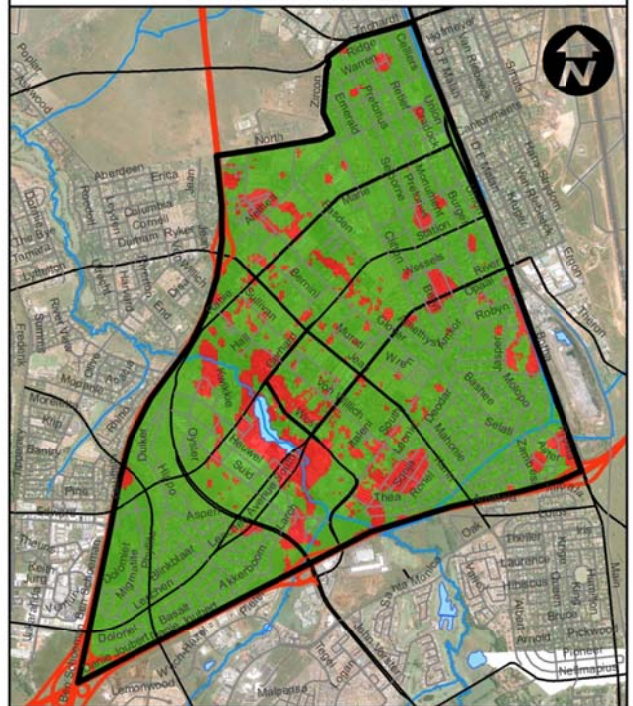


FIGURE 9(1) - 4
LAND USAGE: C1, C2, C3, C5, C6, C7, C8, RH3, RL2,
Permissible on IHC 1 to 5



- LEGEND**
- Study Area
 - River
 - Water Body
 - Inherent Hazard Class**
 - Suitable
 - Not Suitable

FIGURE 9(1): AREAS SUITABLE FOR RESIDENTIAL, COMMERCIAL AND INFRASTRUCTURE LAND USE

FIGURE 9(2) - 1
LAND USAGE: C2, C3, C6, C7, C8, IN1, IN5
 Permissible on IHC 1 to 6

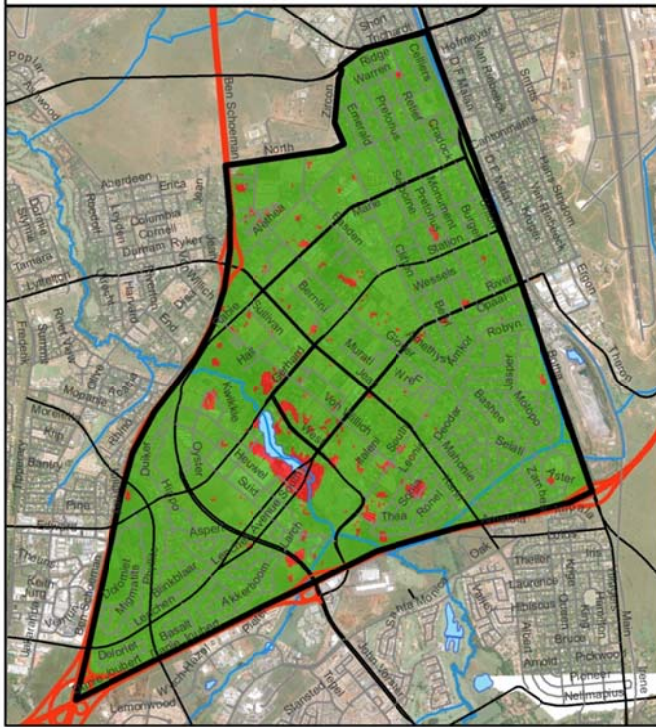
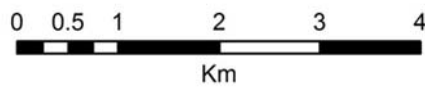
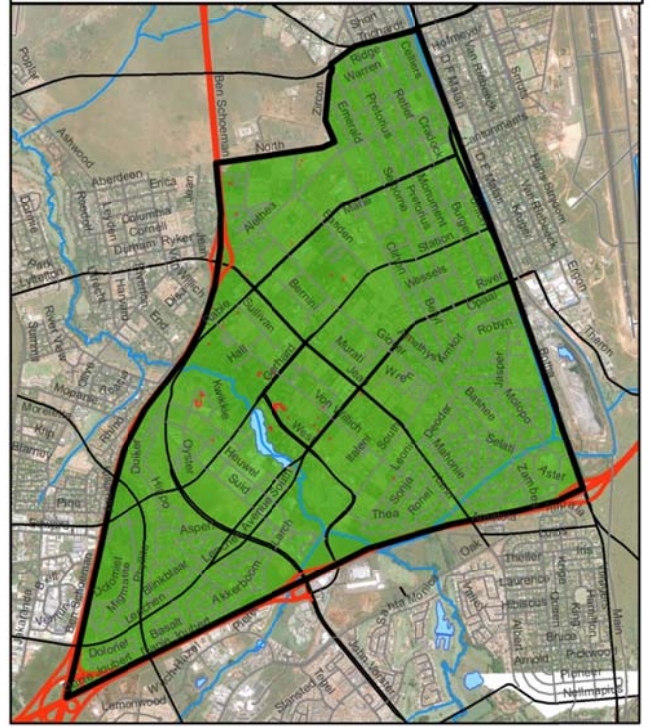


FIGURE 9(2) - 2
LAND USAGE: C6
 Permissible on IHC 1 to 7



LEGEND

Study Area

River

Water Body

Inherent Hazard Class

Suitable

Not Suitable

FIGURE 9(2): AREAS SUITABLE FOR RESIDENTIAL, COMMERCIAL AND INFRASTRUCTURE LAND USE

7. DETERMINATION OF THE HAZARD OF SINKHOLE FORMATION USING VARIOUS METHODS

7.1. Sinkhole Database

Buttrick and van Schalkwyk (1995) indicated that the number of ground-movement events could be predicted based on statistics of inappropriate and poor service design and management over a 20 year period (Table 13). These results were based on data from a limited study area within Pretoria.

The Centurion CBD area is considered to have adequate design parameters and risk management plans in place for most of the area. Therefore, this area is considered not be an 'abused' land use situation which was used in the Buttrick et al. (1995) study, but more controlled and well managed in terms of water bearing services, foundation design and use of land.

In this study, the conventional method proposed by Buttrick et al. (1995) will be used as well as a back analysis method, where the existing sinkhole record is compared with Buttrick and van Schalkwyk's (1995) predicted sinkhole occurrence. Unfortunately, as much of the data does not have dates of occurrence, the outcome is indicative only.

7.1.1. Method Proposed By Buttrick et al. (1995)

By using Table 13, as proposed by Buttrick and van Schalkwyk (1995) the expected number of sinkholes can be predicted in the Centurion CBD area for the low, medium and high hazard classes.

The areas of each of the hazard classes in the Centurion CBD area are as follows (Table 26):

Table 26. Area of the different hazard classes in the Centurion CBD area

| Hazard Class | Area (ha) |
|--------------|-----------|
| Low | 73 |
| Medium | 1111 |
| High | 473 |

Therefore, the actual expected number of sinkholes in each of the hazard classes should be as follows (ha x value in Table 13):

| | | |
|---------------|---|---------------|
| Low Hazard | - | 0 sinkholes |
| Medium Hazard | - | 78 sinkholes |
| High Hazard | - | 331 sinkholes |
| Total | - | 409 sinkholes |

Therefore, this method indicates that a total of 409 sinkholes could have been expected over the last 20 years in the Centurion CBD area. This figure indicates that the expected number of sinkholes predicted per hectare, as proposed by Buttrick and van Schalkwyk (1995), is almost four times more than what was actually recorded. This predicted number of sinkholes, especially for the high hazard areas does therefore not reflect actual conditions encountered in the Centurion CBD area.

According to Table 24 the actual number of sinkholes that have occurred in each of the hazard classes are:

| | | |
|---------------|---|--------------|
| Low Hazard | - | 0 sinkholes |
| Medium Hazard | - | 83 sinkholes |
| High Hazard | - | 36 sinkholes |

There is a relative good correlation between the predicted number of sinkholes against the actual number of sinkholes for the medium hazard areas, 78 predicted vs. the 83 occurred (it should be noted that the predicted number of sinkholes is for a 20 year period, whereas the actual number of sinkholes occurred, occurred over a time period of at least 40 years). In the medium hazard areas, 7 sinkholes have occurred prior to 1990 and 2 post 2010 (those of known the dates). Therefore, 78 were predicted for a 20 year period, against 74 occurrences in 20 years.

There seems to be no correlation between the predicted and actual number of occurrences for the high hazard areas.

It should be noted that since the sinkholes are not evenly distributed across the Centurion CBD area, a 20 hectare test site was not used in order to 'evaluate' the values provided in Table 13. If a 20 hectare site is selected in the Centurion CBD area, it could either have no sinkholes or have several sinkholes, depending on the positioning of the test site and for this reason; this method has not been tested in such a way.

7.1.2. Back Analysis Method

A total of 119 sinkholes have occurred in the entire Centurion CBD area, covering a surface area of 1657 hectares, i.e. 1 sinkhole in every 13,9 hectares or 0,07 events / ha. This occurred over a period of almost 40 years. Only 70 (58%) sinkholes that occurred in the Centurion CBD area have known dates of occurrence. If the time period is ignored, the number of actual events indicates that the Centurion CBD area can be viewed as having a medium hazard for the formation of sinkholes, as per Table 13 (Medium hazard = 0,07 events per hectare).

If a 20 year period is considered, from 1990 to 2010, only 52 sinkholes have occurred in the Centurion CBD area, i.e. 1 sinkhole every 31,86 hectares or 0,03 events / ha. Compared to the Buttrick et al. (1995) table, this indicates that the Centurion CBD area is classified as having a low to medium hazard of sinkhole development.

If it is assumed that the entire database represents a period of 40 years, and 119 sinkholes have occurred during this period a total of 0,04 events per hectare have occurred during a 20 year period (0,07 events per 40 years, i.e. 0,04 events per 20 year period). This confirms that the Centurion CBD area could be classified as having a low to medium hazard in terms of sinkhole development.

To make a rational back analysis of the Buttrick et al (1995) predicted sinkhole occurrence, the sinkhole record needs to be comprehensive. The back analysis method indicates that the Centurion CBD area can generally be classified as having a low hazard for the formation of sinkholes, using two different methods.

The results of the back analysis method do not correlate well with the predicted sinkhole occurrence from Buttrick et al (1995) in the Centurion CBD area. The Centurion CBD area is assumed to have a medium to high hazard for the formation of sinkholes from past experience, but the back analysis method indicates a low to medium hazard of sinkhole formation. The following factors could have an influence on the outcome of the results of the back analysis method:

- The area considered in the current study is too large and does not represent a pragmatic outcome, since sinkholes are not evenly distributed and land uses vary, compared to the area used by Buttrick et al (1995) where only certain portions of military land was used;
- The sinkhole record is not accurate and not all the data has been collected in the Centurion CBD area, compared to the area used by Buttrick et al (1995) where a more reliable sinkhole database was used;

- The Centurion CBD area is situated in an area where dolomite risk management is taking place, i.e. storm water reticulation and improved water bearing services are present compared to the 'abused' area which Buttrick et al (1995) considered.

7.1.3. Using the Hazard Class Areas to Calculate the Actual Number of Sinkholes per Hectare

If the actual number of sinkholes is used to calculate the hazard of sinkhole formation in the Centurion CBD area for each hazard class (areas as per Table 26), it would be as follows:

| | | |
|------------------------------|---|-----------------------------|
| Low Hazard (0 sinkholes) | - | 0 sinkholes per hectare |
| Medium Hazard (83 sinkholes) | - | 0,074 sinkholes per hectare |
| High Hazard (36 sinkholes) | - | 0,076 sinkholes per hectare |

Once again, it should be noted that this is not for a 20 year period, as the data does not have all the dates of occurrence. It is known that 9 sinkholes occurred outside the 20 year time period of 1990 to 2010 in the medium hazard areas. Only two sinkholes occurred prior to 1990 in the high hazard areas. Therefore, if the actual number of sinkholes (assuming all other sinkholes without dates occurred in the 20 year period) is used, the actual occurrence of sinkholes in the Centurion CBD area is as follows:

| | | |
|------------------------------|---|-----------------------------|
| Low Hazard (0 sinkholes) | - | 0 sinkholes per hectare |
| Medium Hazard (74 sinkholes) | - | 0,067 sinkholes per hectare |
| High Hazard (34 sinkholes) | - | 0,076 sinkholes per hectare |

Based on the above calculations, there does not seem to be a substantial difference in the hazard of sinkhole formation in a 'managed area' between medium and high hazard areas. Another influencing factor could be that the high hazard areas are generally not developed, whereas the medium hazard areas are densely developed. Even though municipal water bearing services are installed across the entire Centurion CBD area traversing low, medium and high hazard areas, less water connection points are generally present on the high hazard areas, since less development has taken place on these areas.

7.2. Other factors that have an influence on the outcome of the prediction of the hazard of sinkhole formation

From the above methods it is clear that no “exact” method exists from the Scenario Supposition Method on the classification of land in terms of the hazard of sinkhole formation. Other factors that were noted in the occurrence of sinkholes in the Centurion CBD area are the following:

7.2.1. Geological Succession

As indicated in Table 27, each geological formation has a different hazard for sinkhole formation. This table was derived from the information in Table 18. As expected, the number of events in the dolerite dykes, diorite / syenite intrusions and in the alluvial areas are much lower than those of the Lyttelton and Monte Christo Formations. No sinkholes have occurred on the Oaktree Formation in this area, but this Formation only represents a very small portion of the Centurion CBD area.

Table 27. Number of events per hectare for each geological succession

| Geological Succession / Formation | Events per hectare |
|---------------------------------------|--------------------|
| Lyttelton Formation | 0,09 |
| Monte Christo Formation | 0,08 |
| Oaktree Formation | 0 |
| Chert Breccia | 0 |
| Dolerite | 0,03 |
| Quartz – Diorite (Syenite intrusions) | 0,03 |
| Alluvium | 0,03 |

The areas immediately underlain by ‘non dolomitic’ materials¹³ (i.e. Alluvium, syenite / dolerite) correspond well with Table 13, and can be classified as areas representing a low to medium hazard for the formation of sinkholes. The Lyttelton Formation shows a slightly higher hazard for the formation of sinkholes than the Monte Christo Formation. These two dolomitic formations represent a medium hazard to the formation of sinkholes, as per Table 13.

This method corresponds well with the numbers provided by Buttrick et al (1995) in Table 13, but as shown on Figure 8, these formations cannot be considered to have a single hazard rating, as areas of low to high are present in each of these

¹³ The entire area is underlain by dolomite at depth, and the geology map indicates the geological materials that are encountered at ground surface.

formations. Therefore, although this method seems to provide a more realistic view, dolomite hazard conditions are not uniform for each geological formation and this can only be used as an initial indicative method.

7.2.2. Areas North and South of the Hennops River

As indicated in Section 5.3.1, only one sinkhole have occurred in the area south of the Hennops River, i.e. 1 event per 468 hectares or 0,002 sinkholes per hectare. Therefore this area could be considered as having a very low probability for the formation of sinkholes.

The area north of the Hennops River cover a surface area of 1189 hectares and a total of 118 sinkholes have occurred in this area. Therefore, this area constitutes 1 event for every 10,07 hectares or 0,1 sinkholes per hectare. The area north of the Hennops River can therefore be considered as having a medium to high hazard for the formation of sinkholes.

7.2.3. Water Bearing Services

The largest cause of sinkhole formation is leaking water bearing services. From Graph 4 it is noted that 40% of sinkholes in the Centurion CBD area occurred as a result of leaking services. The following elements could have an influence in the occurrence of sinkholes:

- *The type and age of water bearing services in different townships.* For example, Lyttelton Manor was proclaimed as a township in 1908 (Schöning Msc Notes, 1996) compared to the Doringkloof township which was proclaimed in 1970 (Schöning Msc Notes, 1996). Different types of services were installed as time passed. The current norm in new townships (mostly outside the Centurion CBD) is to install High Density Polyethylene (HDPE) pipes whereas clay pipes were most commonly installed in older townships. Schöning, 1996 indicated that that most sinkholes and dolines occurred in areas which have been in use prior to 1950.
- *Volume and time period of leaking.* If water drips from a pipe over a long period of time, it would generally causes a subsidence or a sinkhole would occur over a prolonged period; whereas if a large diameter pipe burst and vast volumes of water is released, a sinkhole would occur over a short period of time. An example in Centurion CBD of such a sinkhole is S106, which occurred after a main municipal water pipe burst and the sinkhole formed within a couple of hours (pers. Comm., A Sudu, 2010).

- *Higher occurrence of sinkholes in municipal servitude areas.* Although this was not studied in detail in this dissertation, the general trend in the Centurion CBD area is that sinkholes occur along roads, in the servitude area of the water bearing pipes. An example of such a sinkhole is the Jean Avenue sinkhole (S109) discussed in Section 5.3.3 of this dissertation. When studying Figure 6 in detail, it is observed that there seems to be a general trend that some sinkholes occur linearly, i.e. along roads, for example, Sinkholes S2 to S98 in Jean Avenue.

It should be noted that the effect of water bearing services (type, age, location etc.) on sinkhole formation and occurrence is only briefly discussed in this dissertation and more detailed studies could define a more realistic outcome.

7.2.4. Basic Assumptions

Various methods show variable probabilities for the formation of sinkholes in the Centurion CBD area. There seem to be a good correlation between the number of events for the entire Centurion CBD area per hectare if no time period is associated with the data, but this does not give a realistic view (using the back analysis method). There is also a relatively good correlation in the hazard of sinkhole formation per geological succession, as the 'non-dolomitic' areas shows a low hazard and the dolomitic formations show a medium to high hazard. The area south of the Hennops River has a very low hazard for sinkhole formation compared to that of the north of the Hennops River. The reason behind this is not clear.

Different areas within the Centurion CBD area will have different hazard ratings for sinkhole formation. Therefore, it is quite difficult to propose a single rating for areas of low, medium and high hazard, as different factors have an influence. Not all the factors have been considered here, as many more factors such as positioning of water pipes, age of pipes, density of occupancy and type of development (land use) have not been considered.

8. CONCLUSIONS

1. 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.
2. 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. 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.
3. Information for the Centurion CBD area has become available through the dolomite stability reports that are submitted to the CGS for peer review. The availability of substantial data in digital format allowed the analysis and subsequent classification of the Centurion CBD area into the Inherent Hazard Classes, which delineate areas from low to high hazard of sinkhole formation on dolomitic land.
4. The Centurion CBD area is underlain by dolomite and chert of the Malmani Subgroup of the Transvaal Supergroup. The Monte Christo Formation covers the largest area of the Centurion CBD area whereas small areas are underlain by the Oaktree Formation in the south and the Lyttelton Formation in the north. Syenite dykes and sills have intruded the dolomite rock.
5. The Centurion CBD area is situated in two Dolomite Groundwater Compartments. The major portion is situated in the Fountains West Groundwater Compartment where the groundwater level is situated relatively deep (ranging from 48 m to 91 m below ground surface) and it is assumed that it is largely located within dolomite bedrock, as the average depth of dolomite bedrock is 15 m below ground surface. A minor portion of the Centurion CBD area is situated in the Fountains East Groundwater Compartment where the groundwater level is situated relatively close to surface (ranging from 11 m to 20 m below ground surface) and assumed to be situated slightly above or at dolomite bedrock level.

Therefore, the overall hazard of sinkhole formation in terms of a dewatering scenario is generally considered to be low in the Fountains West Groundwater Compartment, and medium in the Fountains East Groundwater Compartment.

6. 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. Each of the classification systems has been well documented, and a summary of each are provided in the dissertation.

Buttrick (1992) proposed the Method of Scenario Supposition and this became an 'accepted method' to classify the risk of sinkhole formation in dolomite land in South Africa.

7. Since there are no numerical limits to the Scenario of Supposition classification system, draft guidelines for allocation of each hazard class, based on experience, has been developed in this study. This is mainly based on the dolomite bedrock depth and the mobilization potential of the overlying horizons. The size of sinkhole that could develop is inter alia a function of the depth of dolomite bedrock. This method is not totally in line with the Method of Scenario Supposition, and therefore it has been referred to as the proposed 'Modified Method of Scenario Supposition'.
8. A total of 3587 boreholes are situated within the Centurion CBD area of approximately 1657 hectares, which constitute 2,16 boreholes per hectare. A total of 3333 percussion boreholes (situated in and in the immediate surrounds of the Centurion CBD area) were used to assess the dolomite stability conditions. These boreholes were each classified in the eight different, Inherent Hazard Classes, using the proposed 'Modified Method of Scenario Supposition'.

The borehole points are not evenly distributed with fewer borehole points present in the area south of the Hennops River compared to north of the Hennops River in the Lyttelton Agricultural Holdings, Die Hoewes and the Lyttelton Manor residential areas.

9. The depth to dolomite bedrock is very irregular in the Centurion CBD area with a minimum bedrock depth of 0 m and a maximum of 66 m. The average bedrock depth of the area is 15 m below ground surface. An assessment of the depth to

dolomite bedrock indicates that dolomite bedrock is generally shallow north of the Hennops River whereas it deepens in the area south of the Hennops River where moderate depth conditions were encountered.

10. A dolomite bedrock elevation map was compiled which shows that the dolomite bedrock elevation generally follows the surface elevation, where a valley is present in the area of the Hennops River with higher gradients on either side of the river. In the area south of the Hennops River the average dolomite bedrock elevation is 1420 mamsl and in the area north of the Hennops River the average dolomite bedrock elevation is 1436 mamsl. It is assumed that the dolomite bedrock elevation will not reflect the actual bedrock topography, due to the wide spacing of boreholes and the large scale at which the map was created.
11. There is a good correlation between the depth to dolomite distribution and the sinkhole size distribution. Buttrick et al. (2001) indicated that the size of sinkhole that could develop is a function of the depth to dolomite bedrock. This is revealed in the Centurion CBD area, where 61,2 % of the boreholes intersected dolomite bedrock at a depth less than 15 m from ground surface and 64,2 % of the sinkholes is smaller than or equal to 5 m in diameter.
12. The residual gravity (Relly, 1976) indicates generally an area of gravity lows and steep gradients, especially in the north-eastern and the eastern corners. A broad gravity low, extending northwest-southeast is present along the western boundary of the gravity survey area, followed by an area of a broad gravity high in the centre of the gravity survey area, also stretching northwest-southeast in the area of Wren Street in the south to North street in the north. The north-eastern boundary of the gravity survey is mainly characterized by some gravity low areas. The gravity does not correlate well with the dolomite bedrock map and this could be because the gravity points are widely spaced (45 m), and the borehole points are not evenly spaced. In this study, the gravity survey was not used in the assessment of the dolomite stability conditions, due to the limited area for which gravity is available.
13. A total of 119 sinkholes have been recorded in the Centurion CBD area since the early 1970's. The average sinkhole depth is 3,3 m for the area whereas the average sinkhole size is 5,1 m. Three lives have been lost as a result of a sinkhole in the area and a total of 7 houses or units had to be demolished.

According to the information in the available databases, 40% sinkholes or subsidences formed as a result of leaking water bearing services, 29% as a result of

poor surface / storm water management and 22% as a result of inadequate or poor precautionary measures. Only one sinkhole (2%) occurred as a result of a poorly backfilled borehole whereas 7% occurred as a result of poor subsurface conditions. Using this limited information (49% of the database) it is evident that 93% of the events in the Centurion CBD area occurred as a result of man's disturbance of the natural ground conditions.

Just less than half of the sinkholes, 49,1% in the area are considered as being medium size sinkholes, with 30,2 % classified as large-sized sinkholes. Small sinkholes constitute 15,1 % of the events with only 5,7 % of sinkholes being more than 15 m in diameter, i.e. very large sinkholes.

14. The hazard map of the Centurion CBD area generally indicates a medium to high susceptibility to sinkhole formation with pockets of low hazard areas. Based on limited information, the following conclusions could be made from the hazard classification of Centurion CBD and surrounding areas:
 - The conditions are not as poor as was always perceived.
 - The largest area of high hazard conditions is present in the area immediately north and east of the Hennops River and Centurion Lake.
 - The largest area of low hazard conditions is present in the area of Zwartkop.
 - The Centurion CBD area is mostly represented by medium hazard conditions (Inherent Hazard Classes 3 and 4), which constitutes 50,5% of the boreholes in the area.
 - Only 2,3% of the boreholes in the Centurion CBD area were classified as Inherent Hazard Class 1, whereas 2,8% of the boreholes were classified as Inherent Hazard Class 8.
 - Almost two thirds of the Centurion CBD area represents a medium hazard for sinkhole formation, with almost a third of the area considered as having a high hazard for the formation of sinkholes and only a small portion of the area (5%) representing low hazard conditions.

15. The comparison between the hazard map and the previous occurrence of sinkholes does not correlate well. The map does show that no sinkholes occurred in the areas classified as having a low susceptibility to the formation of sinkholes, which suggest that the areas of low hazard were delineated well and that the classification system define these areas well.

The vast majority (70%) of the sinkholes in the Centurion CBD area occurred in areas classified as having a medium hazard for the formation of sinkholes, which

could suggest that medium hazard areas are equally vulnerable to sinkhole formation as high hazard areas. Another influencing factor could be that the high hazard areas are generally not developed, whereas the medium hazard areas are densely developed. The position, volume, type and age of wet services also contribute to the type, size and time of sinkhole formation. This is only briefly discussed in this dissertation and not studied in detail.

16. Recommendations regarding the various types of land uses are made. In general, the majority of the Centurion CBD and surrounding areas would be suitable for most types of residential and commercial type developments, with commercial type developments being more suitable in the CBD area, surrounded by the Centurion Lake and residential type developments being more suitable towards the outskirts.
17. Buttrick and van Schalkwyk (1995) indicated that the number of ground-movement events could be predicted based on statistics of inappropriate and poor service design and management over a 20 year period. Using this method, a total of 409 sinkholes should have occurred over the last 20 years in the Centurion CBD area. Compared to actual data, a total of 119 sinkholes have occurred over a period of 40 years in a 'well-managed area' where appropriate foundation and service designs are present.
18. Using the Buttrick et al. (1995) system where the anticipated number of sinkholes in a low, medium and high risk area can be determined, the Centurion CBD area can be classified as a low to a medium hazard area, as 0,03 events per hectare have occurred in the past 40 years in the area. This figure may be unrealistic, since many of the sinkhole data points do not have all the relevant information to make precise comparisons. If no time period is correlated to the sinkhole events, the number of actual events indicates that the Centurion CBD area can be viewed as having a medium hazard for the formation of sinkholes, at 0,07 events per hectare.

Using the actual number of sinkholes that have occurred in the Centurion CBD area, the number of sinkholes per hectare was calculated over a 20 year period. This indicates that 0,067 sinkholes occurred in the medium hazard areas whereas 0,076 sinkholes occurred in the high hazard areas. Therefore, there does not seem to be a substantial difference in the hazard of sinkhole formation in a 'well-managed area' between medium and high hazard areas.

Although there is no substantial difference in sinkhole occurrence between medium and high hazard areas in the Centurion CBD area, it does indicate that there is a

lower probability of sinkhole formation in this area than the area used by Buttrick (1992), referred to as the abused land situation. Centurion CBD and surrounding areas may perhaps not realistically be a 'well-managed' area, but more water precautionary measures and rational foundation designs were implemented in this area than the area used by Buttrick (1992). Therefore, this confirms that less sinkholes occur in areas where appropriate precautionary measures are implemented. Better managed services may need a different approach to correlate the Inherent Hazard Class and events in future.

19. Application of different methods of sinkhole prediction shows that various parameters have an influence on the hazard of sinkhole formation for areas considered as low, medium or high hazard. In the Centurion CBD area, the area south of the Hennops River shows a very low hazard for sinkhole formation, compared to the area north of the Hennops River. Different geological formations also show variable hazard ratings, and the Lyttelton Formation proves to have a slightly higher hazard for sinkhole formation as the Monte Christo Formation, although it is still considered as mainly a medium hazard for sinkhole formation.
20. The hazard classification map shows that the Centurion CBD area can mainly be classified as having a medium to high hazard for sinkhole formation, although calculations using the actual sinkhole events show the area can be classified as a low to medium hazard for sinkhole formation. The reasoning behind this could be explained as follows:
 - a) The method used to classify the boreholes is too conservative, and the actual hazard for sinkhole formation is much lower.
 - b) Not all the sinkhole events were recorded in the Centurion CBD area which causes the calculations to show a lower probability of sinkhole occurrence.
21. Overall, the hazard for sinkhole formation in the Centurion CBD area does not correlate well with the method proposed by Buttrick and van Schalkwyk (1995). According to the anticipated number of events by Buttrick and van Schalkwyk far more sinkholes should have occurred in the high hazard areas. In contrast, the most sinkholes in the Centurion CBD area occurred in the areas classified as having a medium hazard for sinkhole formation. This could be ascribed to the following factors:
 - a) The Scenario Supposition Method by Buttrick and van Schalkwyk (1995) is based on a military area, north of the Centurion CBD area. This military area is mainly situated on the Eccles Formation, whereas the Centurion CBD area is

mainly situated on the Monte Christo Formation and to a lesser extent the Lyttelton and Oaktree Formations.

- b) Development on the high hazard areas are not as common as on the medium and low hazard areas, therefore, not as many services are present on the high hazard areas and the probability of a leaking pipe is lower. This will reduce the probability of a sinkhole occurring.
- c) The probability of sinkhole occurrence is not dependant on the classification of a specific area, but merely the consequence of a certain event happening, such as a leaking pipe. This would imply that a sinkhole will occur on a medium or high hazard area if a leaking pipe and some compressible subsurface material is present.

22. Based on the results of this study, it would seem that there is not a good comparison between a 'well-managed' area and the abused land situation (used by Buttrick, 1995). It seems the hazard for sinkhole formation in medium and high hazard areas is generally the same (0,07 events per hectare in a 20 year period) in the 'well-managed', Centurion CBD area.