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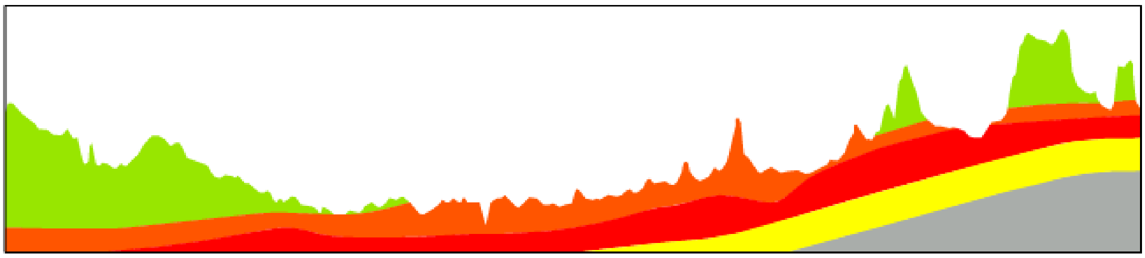
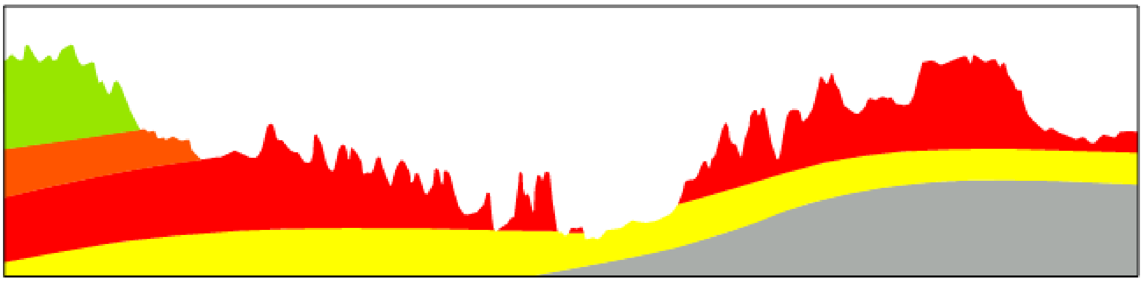
CASE STUDY ON GEOLOCIAL MODELLING LADYSMITH, SOUTH AFRICA





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CASE STUDY ON GEOLOCIAL MODELLING
LADYSMITH, SOUTH AFRICA

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CONTENTS

1. INTRODUCTION

This report provides a description of geologic modelling covering an area near Ladysmith, in the eastern part of South Africa. Geologic modelling includes the development of a conceptual geologic model, a 3D geologic and 3D hydrostratigraphic model. The models are constructed on behalf of the Strategic Water Sector Cooperation (SSC), which is a long-term bilateral cooperation between Denmark and South Africa. Some of the main partners in the SSC are the South African Department of Water and Sanitation (DWS) and the Danish Environmental Protection Agency (EPA).

The objective of the SSC is to contribute to the South African water sector by demonstrating and testing different Danish groundwater mapping methodologies in South Africa, and thereby aiding the South African efforts to obtain a long-term and sustainable utilisation of groundwater as a drinking water resource. One key aspect is to develop a South African groundwater mapping methodology. The methodology is developed by using the South African's specialized knowledge on the South African hydrogeology with the experience and knowledge gained from the Danish Groundwater Mapping Programme. The methodology is tested by conducting case studies, like the current project. In the current project, the Danish approach to geological modelling and groundwater modelling is tested in a South African context by assisting Umgeni Water in locating new potential well fields.

Umgeni Water is appointed by the District Municipality of uThukela, in the KwaZulu-Natal (KZN) province of South Africa, as Water Supply Provider in the area around the city of Ladysmith. The waterwork is looking for possibilities focused on increasing the amount of groundwater in the water supply due to insufficient water yields from the dams in the area. For this purpose, they are siting several new wellfields as well as expanding existing well fields. These well fields must produce enough water to support local water supply, but they should also add a large substantial amount to the bulk water supply. Umgeni Water has appointed the consultancy SRK to do the siting of the well fields. This includes desktop study, hydrocensus, site investigations, and structural analysis and data interpretations in preparation for locating where to establish new well fields as well as expanding existing well fields.

This work has provided 83 primary targets for the establishing of new wells and 21 secondary targets. Before drilling the boreholes, the SSC and Umgeni Water want to verify the proposed locations through geological modelling and groundwater flow modelling.

2. THE DANISH WORK PROCESS IN GEOLOGIC MODELLING

The project solution presented below are based upon the methodology used in the Danish groundwater mapping programme and the guidelines developed during this work in Denmark /1/.

2.1 Workflow process

Geological modelling includes the development of a 3D geological model and a 3D hydrostratigraphic model. The models are developed with the purpose of providing an understanding of the geometry and physical characteristics of the groundwater systems, which forms the basis for a numerical groundwater model. The 3D geological model and 3D hydrostratigraphic model of the Ladysmith area is constructed by following 4 working phases:

Phase 1. Data acquisition
Phase 2. Defining the geological settings
Phase 3. Development of the 3D geological model
Phase 4. Development of the 3D hydrostratigraphic model

A diagram illustrating the workflow is presented in Figure 2-1. Each work step is described in more detail in the following sections.

Figure 2-1: Workflow in geological modelling.

2.2 Problem statement

The first step is to formulate a problem statement, which defines the objectives of the geological modelling, including the expectations to the models' outcome. To determine whether the models' objectives are attainable, it is important to define the area of interest, the amount and quality of the data available as well as whether there are special requirements to the models (*e.g.* geological complexity). These considerations will provide an overview of the model area as well as the challenges to be expected. The problem statement formulated for the current model is presented in Chapter 3.

2.3 Data acquisition and review of previous studies

The second step in geological modelling is the gathering of data. Data are collected and processed, so they can be uploaded to the modelling software GeoScene3D, which is the standard software used for geological modelling in Denmark. Data often used include digital elevation models, geological maps, geophysical surveys (*e.g.* seismic, AEM, gravity and aeromagnetic data), and borehole information (*e.g.* well logs, well screen, water level, water quality and electrical logs). The specific datasets used in the geological modelling process are described in Chapter 4.

2.4 Geological modelling

Geological modelling is a broad term that includes the development of a conceptual geological model, the 3D geological model and the 3D hydrostratigraphic model.

2.4.1 The conceptual geological model

Before constructing the 3D digital models, a review is conducted of the collected data as well as previous studies on the study area's geology and hydrogeology. The object of the review is to obtain an understanding of the area's geological structure, a knowledge that will facilitate in the construction of the 3D geological and hydrostratigraphic models. The review is performed by providing a description of the landscape, the geological units and important structural elements (*e.g.* faults). The text is often accompanied with illustrations (often as cross sections) showing the major architecture of the geological units and geological structures. The geological formations and the known tectonical structures within the study area are described in Chapter 5.

2.4.2 The 3D geological model

Using the conceptual geological model as a template, the 3D geological model is constructed in the modelling software GeoScene3D. In a 3D geological model, lithostratigraphical units (the basic geological units described by physical properties and sequence) are correlated to known geological formations, which are then modelled. The result is a 3D rendering of the thickness and distribution of the individual geological units (*i.e.* geological formations) within the study area. In a 3D geological model, the accuracy and quality of the interpretations are dependent upon the amount of chronostratigraphic information (the relative age of rock strata in relation to time) available. The 3D geological model constructed for the study area is described in Chapter 6.2.

2.4.3 The 3D hydrostratigraphic model

The final step in geological modelling is to construct a 3D hydrostratigraphic model. The 3D geological model subdivides the geological strata into chronostratigraphic units (*i.e.* formations), and as a result the geological units may contain a wide range of lithologies characterised by different hydraulic properties. In a hydrostratigraphic model, the aim is to subdivide the geological strata into hydrostratigraphic units (*i.e.* aquifers and aquitards) using the interpretations from the 3D geological model. It is, thus, the hydrostratigraphic units that define the groundwater system, and the hydrostratigraphic model, therefore, provides the foundation of the groundwater flow model. In addition, the hydrostratigraphic model provides useful information on the location of groundwater recharge areas, and areas where groundwater resources may be most vulnerable to pollution. The 3D hydrostratigraphic model constructed for the Ladysmith study area is described in Chapter 6.3.

3. PROBLEM STATEMENT

The objective of constructing the 3D geological and 3D hydrostratigraphic model is threefold. Firstly, the models are made to identifying the best places to drill new boreholes, and secondly, the models are used as input to a groundwater flow model. The final object is to provide inputs to the development of a South African groundwater mapping approach. The models are constructed using the geological modelling methodologies for the mapping of groundwater resources in Denmark. With the development of the models, the methodologies are tested, thereby providing knowledge on whether the methodologies are usable in mapping the groundwater resources in South Africa.

The models are constructed for an area, wherein Umgeni Water plan to drill the new water wells. Since the models are also used as input to a groundwater flow model, hydrological boundaries such as rivers and groundwater divides are used to define the boundaries of the model area. To determine the hydrological boundaries, an initial and coarse flow model was run for a large area, named the regional study area. The regional study area is shown in Figure 3-1. With the flow model and an assessment of the hydrological conditions, the area of the geological and hydrostratigraphic model is defined. The area is named the local study area and is shown in Figure 3-1, together with the regional study area.

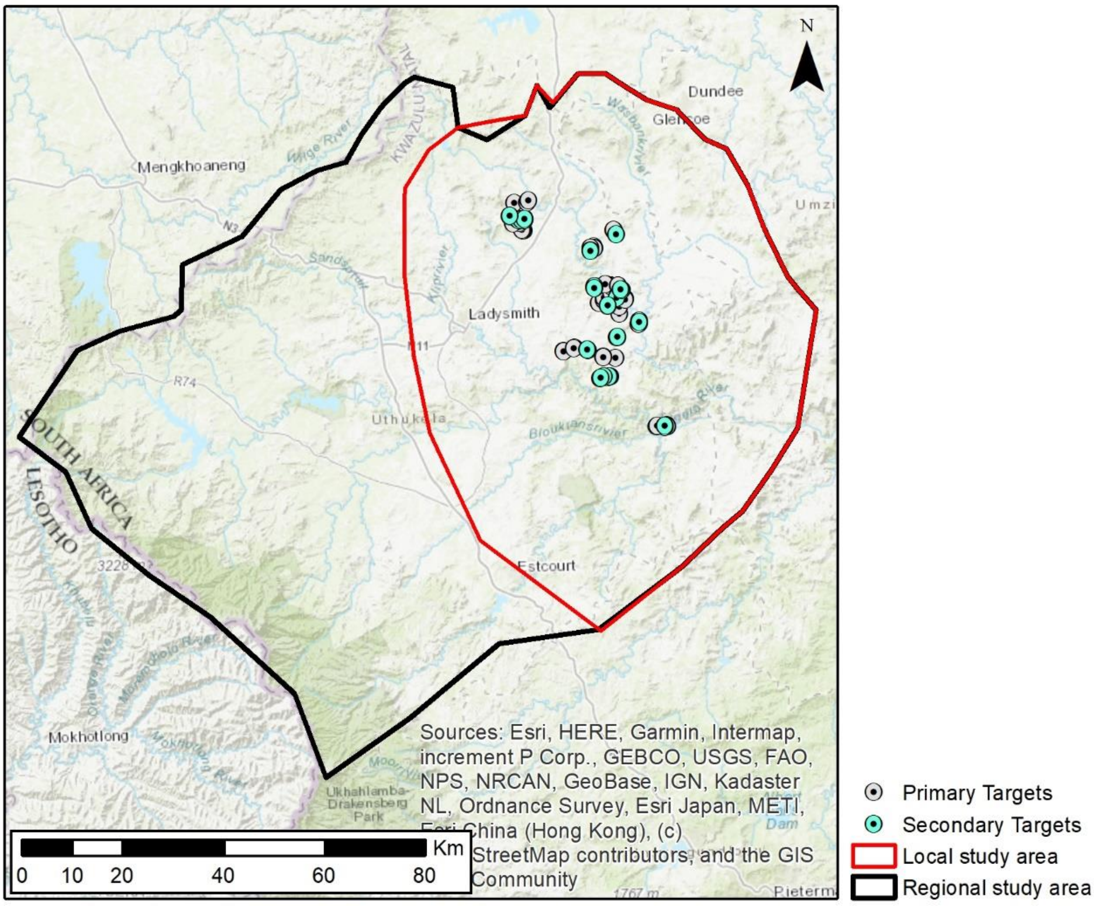

Figure 3-1. Regional and local study area

Before the models are constructed, an initial assessment of the existing data is conducted to determine whether there are sufficient data to construct the models. The data consist mostly of borehole data with a limited amount of geophysical data. It is assessed that data coverage is adequate to construct the models. However, since borehole data do not have the same area coverage as geophysical data, which are only available to a very limited amount, modelling complex geological structures such as faults are considered almost impossible. There are, therefore, limits to the models' accuracy.

The geology in the area's is characterised by vertical or inclined structures such as faults or dolerite intrusions. The models, therefore, need to be able to model these types of structures. In Denmark, the geological and hydrostratigraphic models are commonly constructed as layer models. With layer models it is very difficult to model vertical structures, and it is, therefore, recommended that the models for the Ladysmith area primarily are constructed as voxels models. The two model techniques are described in more detail in chapter 6 in the report.

4. DATA

This chapter provides a description of the data used in the geological modelling process. The data are originally defined by the spatial reference system GCS WGS 1984. To upload data to the modelling software, the data had to be transformed into the spatial reference system WGS 1984 UTM Zone 36S, which is the spatial system working in the GeoScene3D software.

4.1 Digital elevation model (DEM)

A digital elevation model (DEM) of South Africa is used to define the terrain surface in the 3D digital models and is shown in Figure 4-1. The original DEM has a cell size of 93 m. For geological modelling the cell size is changed to 100 m.

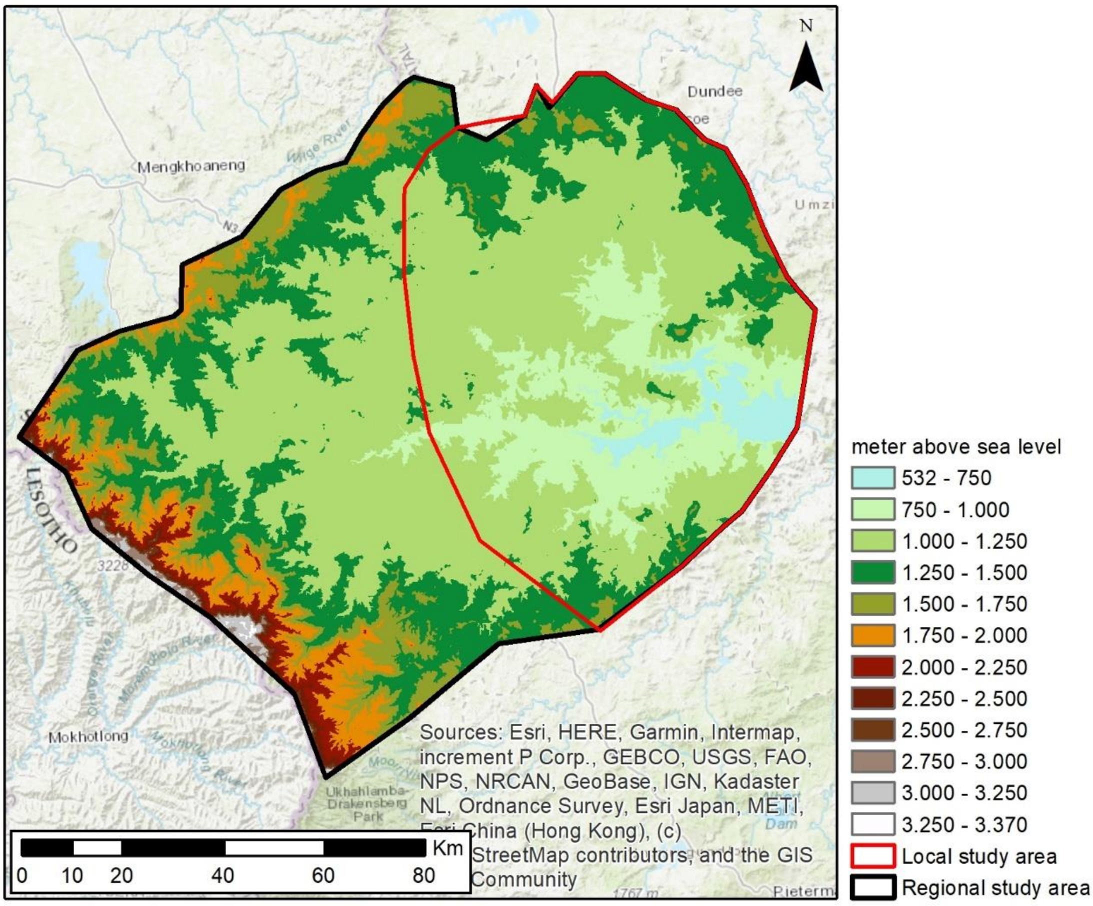

Figure 4-1. Digital elevation model /13/.

4.2 Geologic map

A geological map, scale 1:250.000, showing the geological formations at ground surface, is shown in Figure 4-2, while Table 4-1 provides a lithological description of the geological units shown in Figure 4-2. The map provides both stratigraphical and lithological information on the deposits exposed at ground surface, and the location of dolerite dykes.

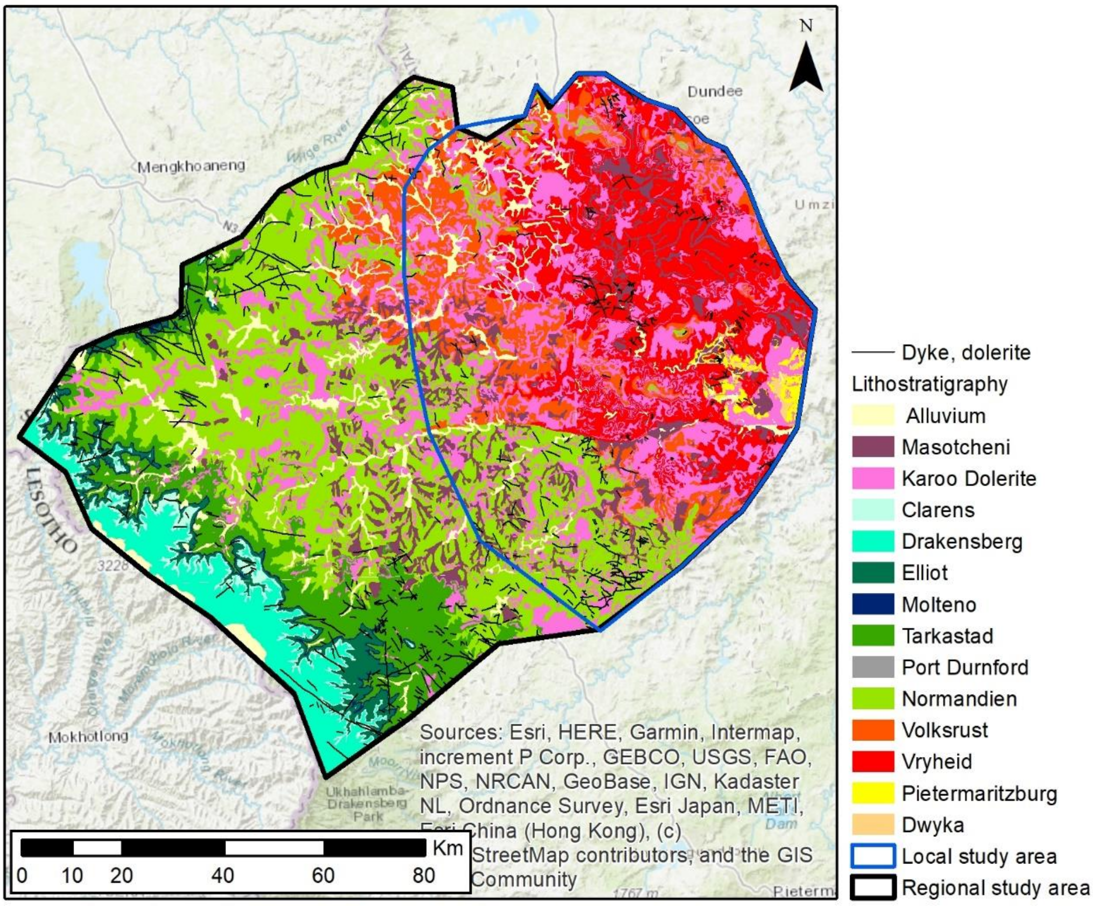

Figure 4-2. Map showing the geological formations at ground surface.

Table 4-1. A lithological description of the geological units shown in Figure 4-2.

Formations	Lithologic description
Alluvium	Alluvium deposits
Clarens	Fine-grained sandstone, siltstone
Drakensberg	Basaltic lava, with minor sandstone, tuff and agglomerate in the lower part of the succession in places
Dwyka	Diamictite (polymictic clasts, set in a poorly sorted, fine-grained matrix) with varved shale, mudstone with dropstones and fluvioglacial gravel common in the north
Elliot	Red and greenish grey mudstone, subordinate sandstone
Karoo dolerite	Network of dolerite sills, sheets, and dykes, mainly intrusive into the Karoo Supergroup
Masotcheni	Sandy or clayey colluvial and alluvial sediments and palaeosols
Molteno	Alternating sandstone (pebbly in places), olive mudstone and dark grey shale (containing plant remains) with coal seams and thin conglomerates in places
Normandien	Green-grey and (at the top) red mudstone and siltstone, grey shale and rhythmite, sandstone
Pietermaritzburg	Shale with thin siltstones and sandstones in the uppermost part
Port Durnford	Fine- to medium-grained sand, clayey sand and silt with a lignite bed up to 2.5 m thick
Tarkastad	Red and greenish-grey mudstone, fine- to medium-grained sandstone
Volksrust	Mudrock
Vryheid	Fine- to coarse-grained sandstone, shale, coal seams

4.3 Borehole data

The primary data input in the development of the models are the existing wells within the study area. Information on the existing wells are obtained from the National Groundwater Archive (NGA) database and from reports provided by Umgeni Water. Since the geological and hydrostratigraphic model are only constructed for the local study area, it is chosen to show data for the local study area and not for the entire regional study area.

4.3.1 NGA borehole database

An extraction of borehole information from the National Groundwater Archive (NGA) database are provided by the DWS. The data are extracted as Excel spreadsheets. From the dataset the following information are extracted and transferred to an Access database to be uploaded to GeoScene3D:

- Borehole location and elevation
- Borehole logs of the geology
- Static water level
- Water strike
- Depth to screen

An initial review of the borehole data showed only a few boreholes containing information on the location of the screens, since the wells in South Africa are constructed as open wells. In open wells, a well casing is often only installed at the top of the well and the boreholes remain open without being filled with grout or a well screen. The borehole remaining open will be filled with water, as groundwater flows into the borehole along one or more fractures in the geological deposits. The location of the fractures is identified by the water strikes, which is the water levels encountered during drilling. To visualise the location of these fractures in GeoScene3D, pseudo screens are defined in the borehole database, which is uploaded to GeoScene3D. The pseudo screens are defined as 1 m long screens and are placed at the centre of each water strike encountered in the borehole as illustrated in the Figure 4-3.

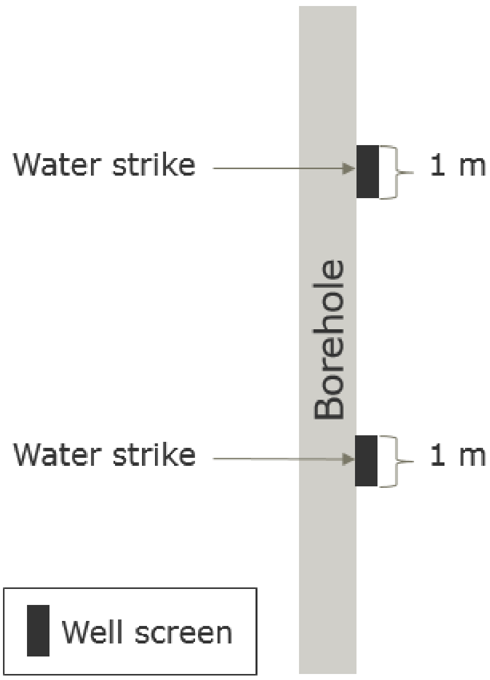

Figure 4-3. Illustration showing how the pseudo screens are defined at the location of the water strikes.

The extraction from the NGA database contains a total of 2598 boreholes of which 1743 are located within the local study area. The distribution of the 1743 boreholes within the area is shown in Figure 4-4. A review of the borehole data shows that of the 1743 boreholes, there are:

- 1178 boreholes having a lithologic description of the geology
- 745 boreholes having information on water strike
- 705 boreholes where the static water level was measured

The static water level is the measured water level in a well under normal, undisturbed, no-pumping conditions.

The NGA boreholes are in Figure 4-4 themed by their drill depth. There are 565 boreholes, with unknown drill depth. These boreholes also have no lithological descriptions. For the rest of the boreholes, 537 boreholes show depths of 0-50 m, 487 boreholes show depths of 50-100 m, while for 154 boreholes the drilling depths are larger than 100 m.

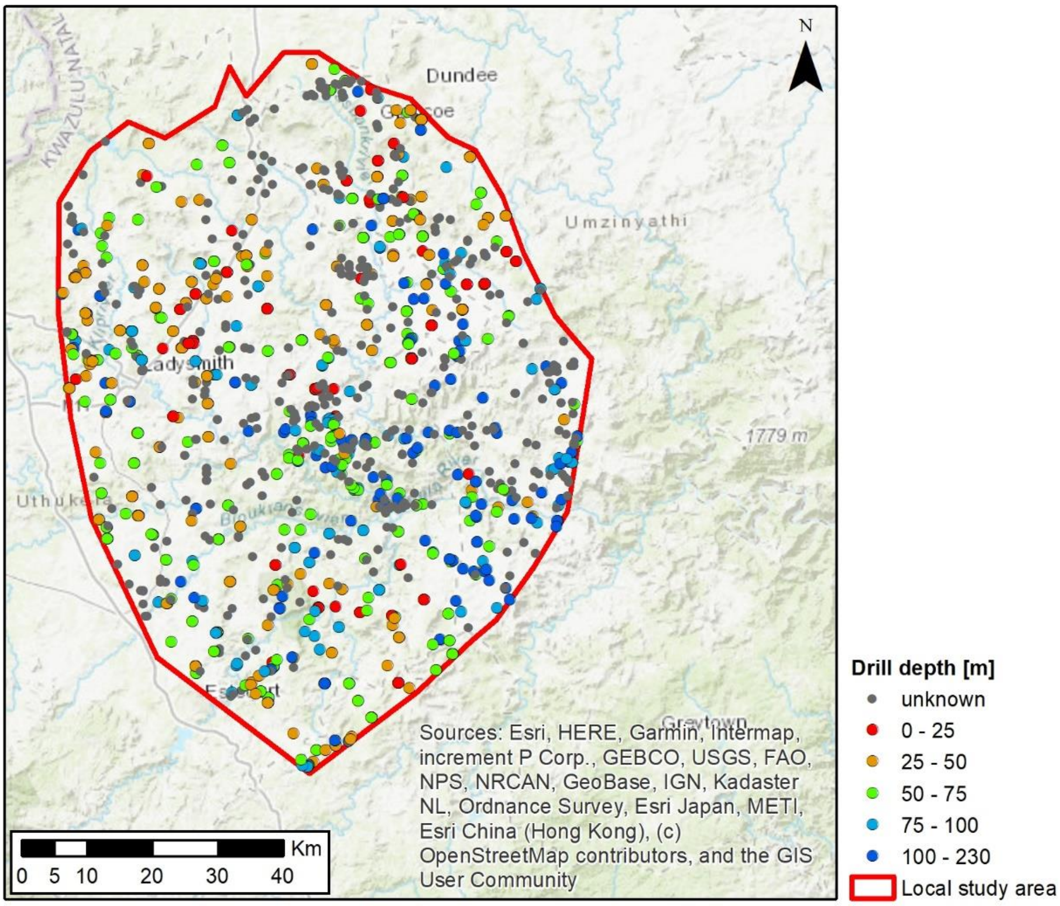

Figure 4-4. The distribution of NGA boreholes within the local study area.

The Access database containing information on lithology, water strike (screen) and water level is uploaded to GeoScene3D. The well lithology descriptions are classified and simplified into basic lithologies (*e.g.* clay, sand, shale and sandstone), which are listed in Table 4-2. The colour-scale used in GeoScene3D to display the different lithologies is presented in Table 4-2.

Table 4-2. Basic descriptors based upon the descriptions from the driller's logs, and the thematic colour-scale for the interpreted lithologies used in the GeoScene3D software. Abbreviations of the lithological descriptions are shown in the parenthesis.

Basic descriptors	Lithological descriptions from driller's logs	Thematic colour
Topsoil	Laterite (lat); overburden (ob); soil (so)	grey
Clay	Boulder clay (bldcl); Boulders, silt and clay (bldcl); clay (cl)	red brown
Silt	Silt (slt)	orange
Sand	Sand (sd); sand and clay (sdcl); sand and silt (sdslt); alluvium (al)	yellow
Gravel and boulders	Gravel (grv); boulders (bld)	light red
Coal	Coal (c)	dark grey
Diamictite	Conglomerate (cgl); diamictite (dia); tillite (tilt)	light brown
Limestone	Dolomite (dol); limestone (ls)	green
Shale	Mudstone (mdst); shale (sh); shale and siltstone (shslst); siltstone (slst)	brown
Sandstone	Sandstone (sst); sandstone and shale (sstsh); flagstone (flst)	red
Quartzite	Quartzite (qtzt)	Dark pink
Schist	Schist (sch); slate (sl)	Dark brown
Dolerite	Diabase (db); Dolerite (db); basalt (bas)	pink
Greenstone	Greenstone (gnst)	light green
Lava	Lava (la); tuff (tf)	Black
Granite	Granite (grt)	Dark purple

4.3.2 NGA borehole quality assessment

The quality of the 3D digital models depends on the quality of the data input. It is, therefore, important to rate the quality of the borehole data, to ensure that boreholes deemed "bad" will have a lesser impact on the quality of the interpretations. Borehole quality is rated according to whether the boreholes contain lithological information and the distance by which the elevation of the boreholes differs from the DEM. The boreholes are subdivided into four quality categories: Good, Medium, Bad and No lithological information. Each of the categories are described in Table 4-3, which also shows the number of boreholes in each category.

Classification	Number of boreholes	Percentage of total boreholes	Description
Good	291	16.7	Boreholes with lithological logs. The boreholes' elevation deviates with a maximum of 3 m from the DEM.
11111Medium	454	26.1	Boreholes with lithological logs. The boreholes' elevation deviates with 3-10 m from the DEM.
Bad	433	24.8	Boreholes with lithological logs. The boreholes' elevation deviates with over 10 m from the DEM.
No litho	565	32.4	Boreholes with no lithological logs

Table 4-3. Classification of NGA boreholes located within the study area.

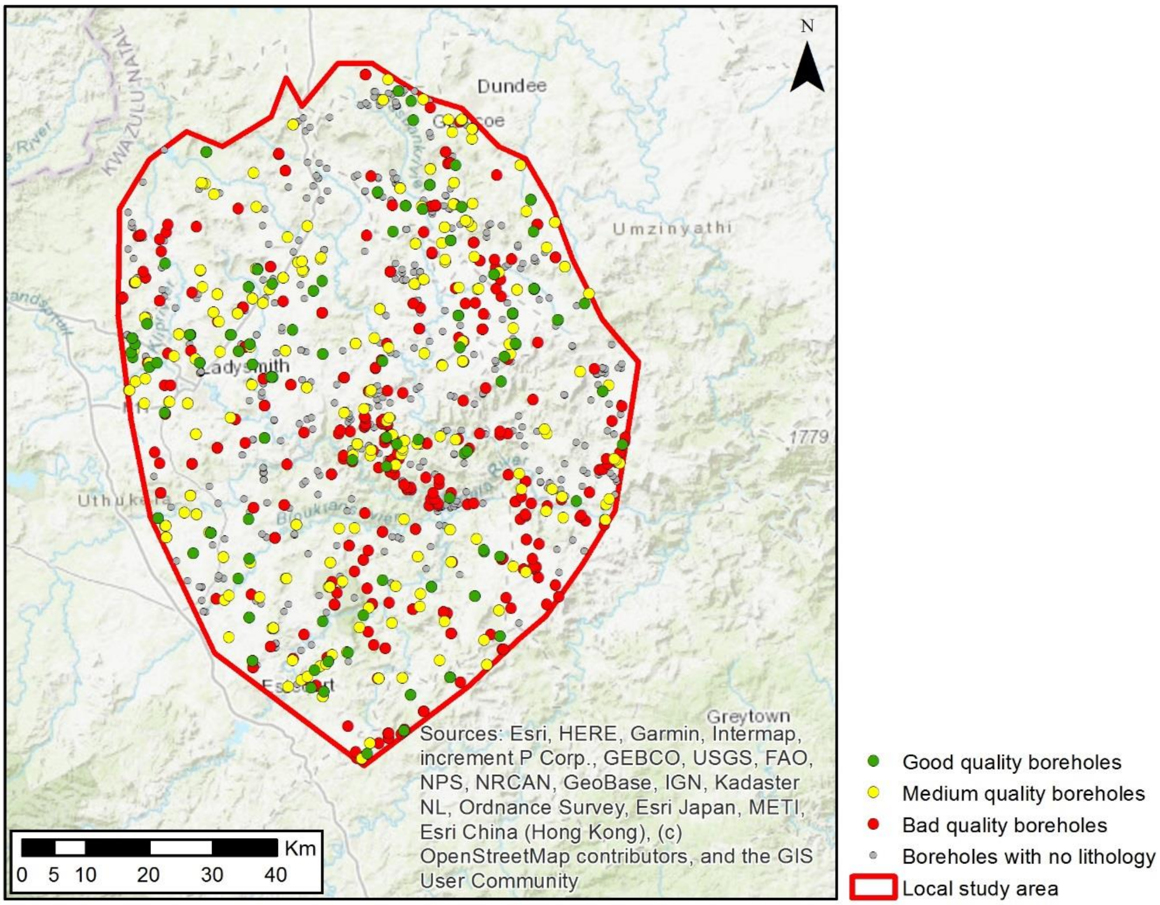

Figure 4-5. Quality rating of the boreholes with a lithological description and boreholes with no lithological description.

The quality analysis shows that from the 1743 boreholes situated in the local study area, a third have no lithological information. These boreholes have no value when developing the 3D models. The lithological descriptions in the remaining boreholes are generally limited to describing one main lithological component such as sandstone, shale, gravel *etc.* with no supplemented descriptions of any secondary components (*i.e.* gravelly, sandy, sand lenses *etc.*) or of the depositional environment and age.

The boreholes with a lithological description are subdivided into three quality categories depending on how much the elevation of the boreholes deviates from the DEM. A high deviation from the DEM suggests that either the registered elevation of the borehole is wrong (z-coordinate) or that the borehole location is wrong (X- and Y-coordinates). Either way, a high deviation means that theses boreholes provide a greater uncertainty to the accuracy of the interpretations within the 3D models.

The quality analysis shows that the elevation of approximately 17 % of the 1743 boreholes has a maximum deviation of 3 m from the DEM. These boreholes are classified as good. Approximately 50 % of the 1743 boreholes have an elevation that deviates more than 3 m from the DEM. These boreholes are grouped in the medium and bad quality categories. The quality analysis, therefore, shows that the interpretations in the 3D models may be affected by the high uncertainty in the accuracy of the borehole information due to the located wellhead offset compared to DEM.

The boreholes' high deviation in elevation compared to DEM is likely due to a registration of the boreholes' location (x- and y-coordinates) or the boreholes' elevation (z-coordinate) which has been carried out imprecisely. Some of the boreholes in the database were captured and recorded in the 1950-1980's, before GPS. Often the boreholes were plotted to be situated in the middle of the farm, and the location of these boreholes has not yet been verified. Furthermore, the boreholes' elevation was often estimated from a map or by using a default value (F. Fourie 2020, personal communication).

4.3.3 Additional boreholes

Umgeni Water provided borehole logs from fourteen wells, which are listed in Table 4-4. The wells were drilled by Umgeni Water, except for the wells AGBH and MBH. These two wells were existing wells, wherein aquifer tests were conducted by Umgeni Water. The fourteen boreholes are not registered in the NGA database.

As shown in Table 4-4, the two existing wells (AGBH and MBH) contain no lithologic descriptions, but they provide information about the boreholes' hydraulic properties determined from the aquifer tests.

The boreholes are digitized in an Access database with the information shown in Table 4-4, which are retrieved from the borehole reports. The boreholes' lithologic descriptions are simplified into basic descriptors defined by Table 4-2. Information on water strike and static water level in the borehole are registered in the database, if present.

Table 4-4. Additional boreholes within the study area.

Borehole Name	X UTM WGS84 zone 36S	Y UTM WGS84 zone 36S	Elevation [mamsl]	Drill Depth [m]	Drill date	Lithologic logs (Y/N)	Reference
KZN120321	185915	6851598.64	1119.49	120	09-10-2012	Yes	/3/
KZN120322	184800.87	6850570.26	1125.76	120	10-10-2012	Yes	/3/
KZN120348	181385.41	6848616.65	1079.42	100	07-11-2012	Yes	/3/
KZN120349	181578.32	6849037.98	1077.8	51	08-11-2012	Yes	/3/
LBH1	187470.86	6844859.43	1114.88	102	17-10-2017	Yes	/4/
LBH2	187305.43	6845621.86	1119.57	140	17-10-2017	Yes	/4/
LBH3	188784.18	6844243.05	1092.52	120	18-10-2017	Yes	/4/
LBH4	192957.49	6848161.83	1113.62	140	20-10-2017	Yes	/4/
LBH5	193335.94	6849034.64	1107.92	140	21-10-2017	Yes	/4/
LBH6	199288.72	6853718.08	1145.37	132	22-10-2017	Yes	/4/
LBH7	197969.21	6855374.07	1192.77	120	23-10-2017	Yes	/4/
DBH1	179802.72	6854910.3	1100.96	92	04-06-2014	Yes	/5/
AGBH	188272.52	6845095.85	1100.3	92	Unknown	No	/4/
MBH	199010.08	6854642.88	1143.08	61	Unknown	No	/4/

The location of the additional fourteen boreholes are shown in Figure 4-6. As seen in the figure, the additional boreholes are all located north of Ladysmith.

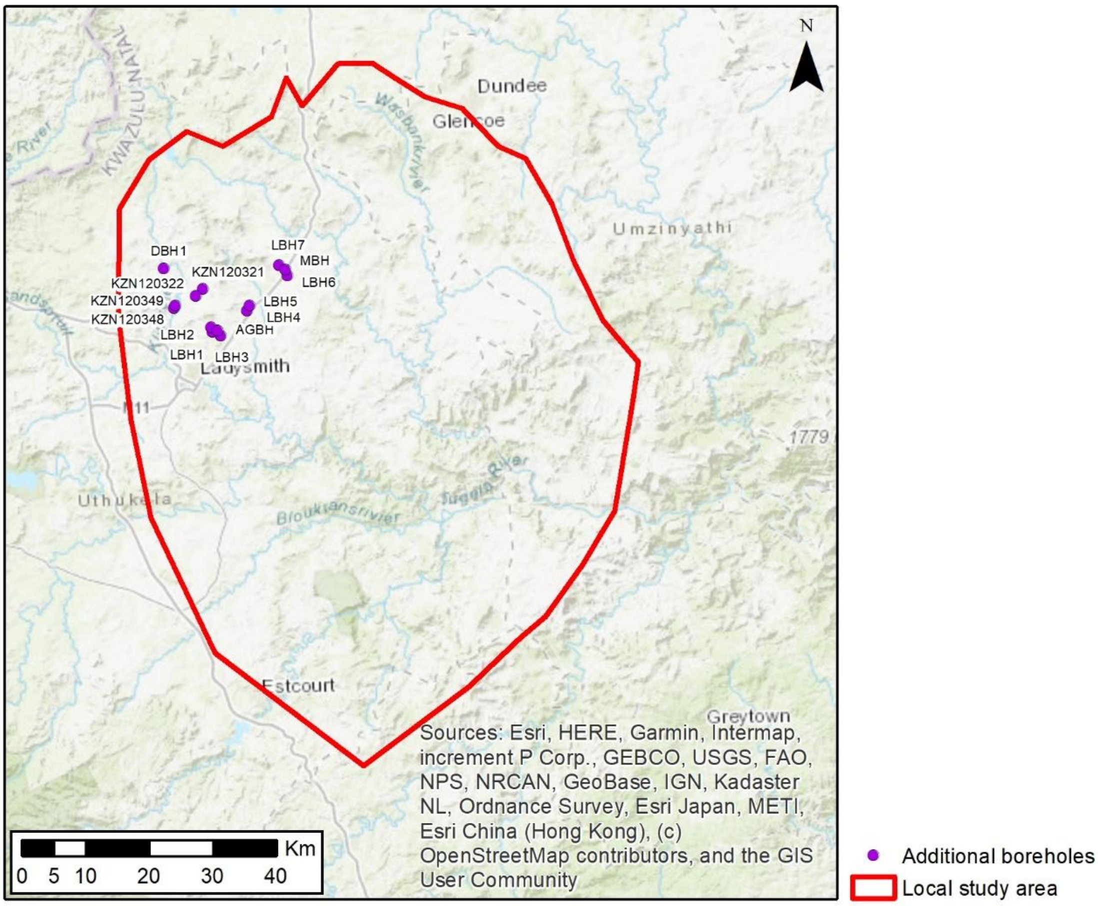

Figure 4-6. The location of the additional boreholes provided by Umgeni Water.

4.4 Geophysical data

Geophysical surveys conducted within the local study area are used as a secondary data input. The geophysical data include tTEM-data collected by Aarhus University in February 2020 /2/ and the measurement of the subsurface resistivity and total magnetic field is provided by Umgeni Water. The location of the geophysical data is shown Figure 4-7. The figure shows that tTEM data is located at two separate locations (Driefontein and Ladysmith) in the western part of the local study area, whereas the geophysical data from Umgeni Water are generally located in the central part. The geophysical data are described in the following two sections.

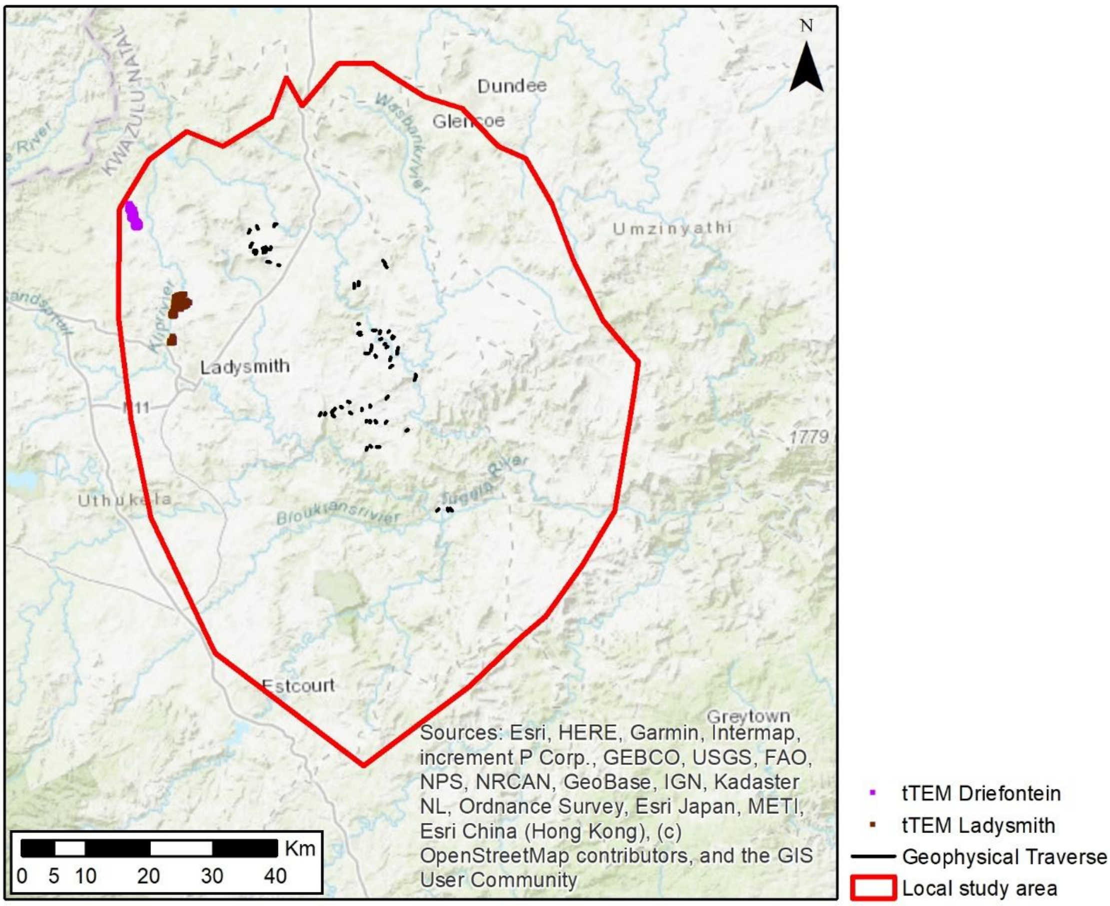

Figure 4-7. The location of tTEM-data and geophysical surveys performed by Umgeni Water within the study area.

4.4.1 tTEM

The tTEM data processed by Aarhus University /2/ are uploaded to GeoScene3D and depictured on the cross sections as 1D geophysical model objects (Figure 4-8). An object is placed at each measuring points, and the object shows the measured resistivity with depth for that specific measuring point. The measured resistivities are illustrated by a user-defined colour-scale. The colour-scale is optimized to heighten resistivity contrasts seen in the geological deposits. From an initial review of the data, it is found that a colour-scale representing the resistivity interval from 1 ohmm to 750 ohmm is well suited for representing the resistivities measured by the tTEM. The colour-scale for the tTEM data is presented in Figure 4-9.

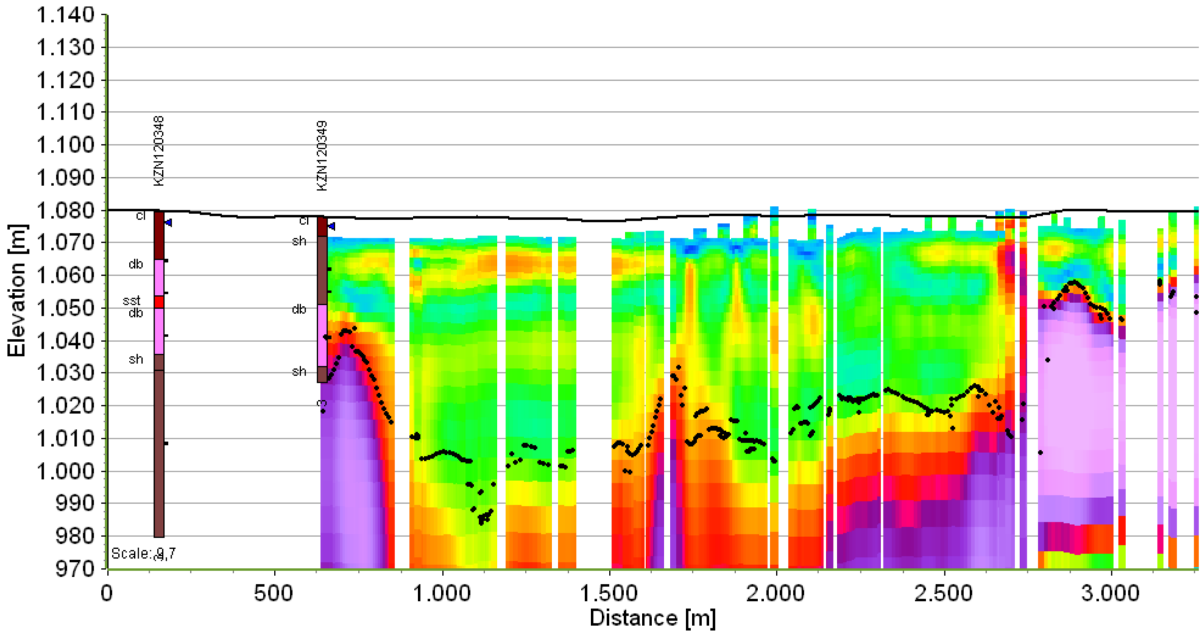

Figure 4-8. Cross section showing the measured resistivities in the tTEM data. The two boreholes (KZN120348 and KZN120349) shown on the cross section are described in section 4.3.3. The black dots on the tTEM-data represent the tTEM's Depth of Investigation (DOI).

On each object in Figure 4-8 a black dot is shown. The black dots represent the tTEM's Depth of Investigation (DOI). The DOI refers to depth below which the geophysical investigation becomes insensitive to the resistivity variations in the subsurface. This means that below this depth, data are unreliable and should therefore be used with care.

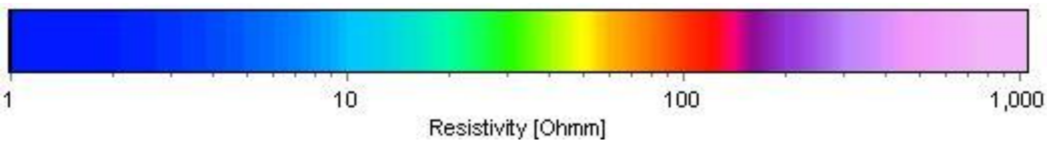

Figure 4-9. Thematic colour-scale for the tTEM data.

4.4.2 Geophysical surveys from Umgeni Water

Umgeni Water has used geophysical surveys to locate potential areas for drilling new boreholes. The geophysical surveys consist of an electric resistivity method and a magnetic method. The two methods measure the electric resistivity (ohm) and magnetic anomalies (nT) in the subsurface. The resistivity measurements were measured using the Wenner Profiling method with a 40 m electrode spacing giving an approximate depth of the profiling around 60 m. The results are plotted as a graph as shown in Figure 4-10. The graphs are uploaded to GeoScene3D as images. The images are plotted on cross-sections that are drawn from the line of the measurement points. It is important to note that the elevation on the cross-sections are not representative of the results on the images.

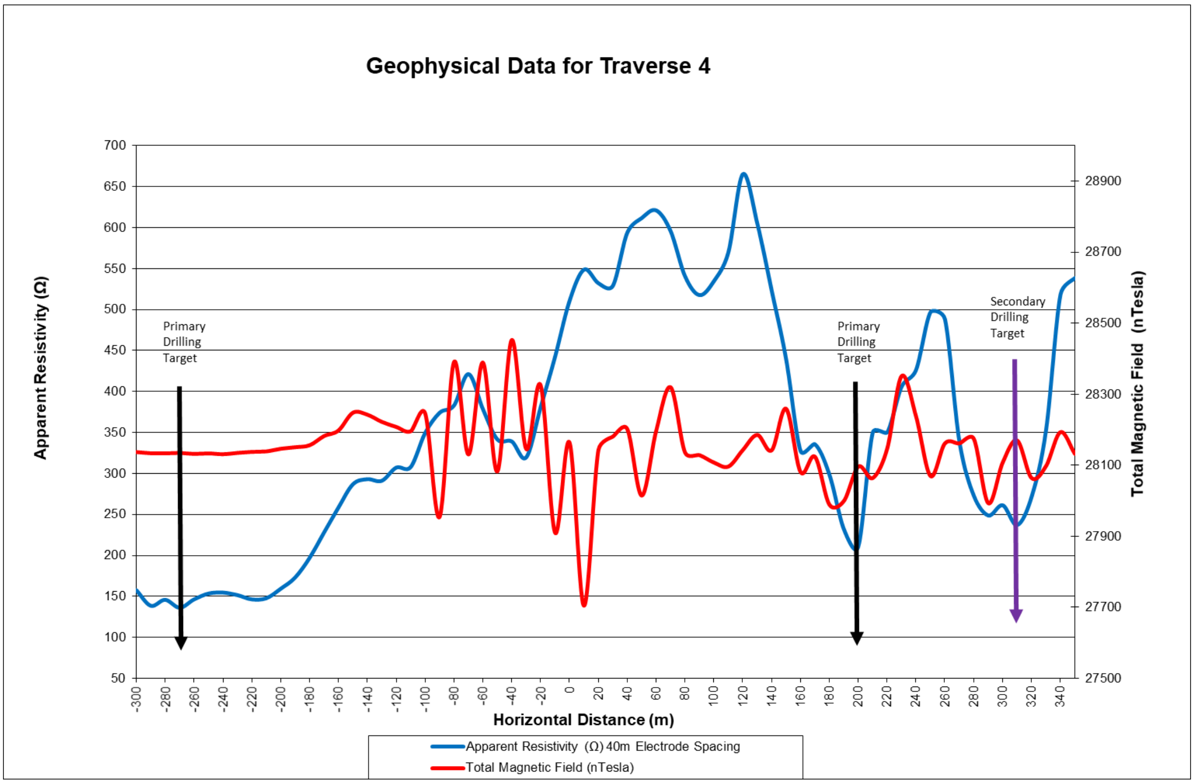

Figure 4-10. An example of the geophysical surveys performed by Umgeni Water.

4.4.3 Resistivity-lithology relationship

Based on a thorough examination of specific boreholes near the tTEM data, a correlation between the tTEM survey resistivity and lithology of the geological formations is established. The correlation is shown in Figure 4-11. The correlation indicates that shale deposits are generally characterized by resistivities below 40 ohmm, while presumable sandstone deposits are characterized by resistivities of 50-200 ohmm. The dolerite intrusions have resistivities over 100 ohmm. These resistivity-lithology correlations are based on limited data, and the correlations should be considered as preliminary.

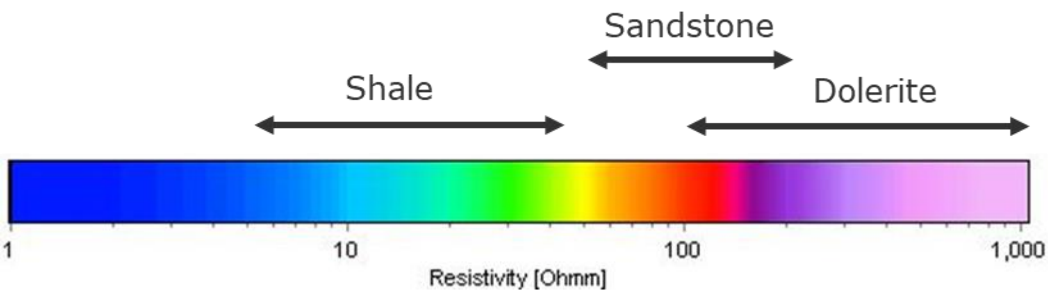

Figure 4-11. The colour key showing the resistivity-lithology correlation in the interpretation of the tTem data.

5. THE CONCEPTUAL GEOLOGICAL MODEL

This chapter provides a review of the regional geology and structural elements within the study area. The review is initiated with a description of the geological formations (section 5.1). This is followed by an overview of the known structural elements (*e.g.* faults) mapped within the study area (section 5.2). Finally, the conceptual geologic model is presented (section 5.3).

5.1 The geological units

The geological setting within study area is composed of lithostratigraphic units from the Karoo Supergroup /6/. The Karoo Supergroup consists of a sequence of different lithostratigraphic units deposited between the Late Carboniferous and Early Jurassic, approximately 323-174 million years ago. The lithostratigraphic units from the Karoo Supergroup present in the study area are listed in Table 5-1. Each of the lithostratigraphic units are described in the following sections.

Supergroup	Group	Formation	Lithology
Karoo		Karoo Dolerite	Dolerite intrusions
	Beaufort	Normandien	Sandstone. shale
	Ecca	Volksrust	Shale
		Vryheid	Shale. siltstone. sandstone and coal seams
		Pietermaritzburg	Silty mudrock or shale
	Dwyka		Tillite. sandstone. rhythmite and mudrock

Table 5-1. The stratigraphic sequence of the depositional units within the study area /6/.

5.1.1 Dwyka group

The deposits in the Dwyka group is mainly composed of tillite and to a lesser extent conglomerate, sandstone, rhythmite and mudrock. The sedimentary rocks were deposited in a glacial environment during late Carboniferous to early Permian. The deposits are unconformable overlying a basement of metamorphic rocks /6/.

5.1.2 Ecca group

The Ecca group consists of 16 different formations that were deposited during the Permian period. Three of the formations are located within the study area and described below.

5.1.2.1 Pietermaritzburg Formation

The Pietermaritzburg Formation comprises dark-grey, blue, or black silty mudrock or shale /6/. It overlies the Dwyka group with a sharp conformable boundary /7/. Near Pietermaritzburg the formation has an average thickness of 150-200 m. The thickness gradually diminishes towards the north, where the formation pinches out against the underlying Dwyka group at around latitude 26° 30’ S. The formation is upward coarsening with streaks of sandstone restricted to the upper 50 m of the formation /8/.

5.1.2.2 Vryheid Formation

The Vryheid Formation comprises shale, siltstone, and sandstone. The contact between Vryheid Formation and the underlying Pietermaritzburg Formation are gradational and conformable. It is also strongly diachronous since the successions of sandstones in the Vryheid Formation shelves out towards the south /6//8/. The Vryheid Formation is composed of regressive cycles of deltaic and fluvial deposits, where the upward-coarsening delta deposits are succeeded by upward-fining fluvial deposits /6//7/. The fluvial deposits contain coal seams formed by the accumulation of peat deposited in a fluvial environment /9/. The formation has the highest thickness in the northeast and east. The thickness pinches out towards the south and southwest /10/.

5.1.2.3 Volksrust Formation

The Volksrust Formation comprises mainly blue-grey and black shale with lenses of siltstone /6//7/. The formation conformably overlies the Vryheid Formation /7/. The contact between the two formation is defined as the top of the topmost sandstone in the Vryheid Formation /7/. The depositional environment is the same as for the Pietermaritzburg Formation. The thickness within the study area varies between 100 and 200 m /7/.

5.1.3 Beaufort

The Beaufort group is composed of the Adelaide subgroup and the Tarkastad subgroup that contain sedimentary rocks deposited between Middle Permian to Early Triassic. The group contains several geological formations, it is only the Normandien Formation that are present in the local study area.

5.1.3.1 Normandien

The Normandien comprises sandy shale and shaly sandstone interbedded with black shale. The formation rest conformably on the Volksrust Formation with a transitional boundary consisting of fine- to coarse grained sandstone. The formation was deposited in fluvial-deltaic environment and is characterised by a thickness of minimum 300 m /7/.

5.1.4 Dolerite intrusions

Dolerite (or diabase) is an intrusive igneous rock. The rock is formed by magma penetrating the overlying sedimentary deposits along joints, cracks, faults, or other weaknesses in the deposits. Depending on the strike of the weakness zones, the magma is injected at an angle, vertically or horizontally into the sedimentary deposits resulting in the formation of dykes and sills. The dykes form when magma solidifies vertically or at a steep angle, while sills form when penetrating along a horizontal plane. Studies have shown that dolerite can have an average sill thickness of 30 m /11/.

5.2 Faults

In South Africa, the aquifers comprise fractured rocks, wherein groundwater storage and flow occur in the structural voids associated with the faults. Faults and fractures are, therefore, very important when looking for localities to extract groundwater. The location of the known faults in South Africa are recorded in the Geoline Database, and Figure 5-1 shows an extraction from the database for the local study area. Most faults are thrust and shear faults with 120 -300m placement. The faults are also intrueded by dolerite dykes /12/.

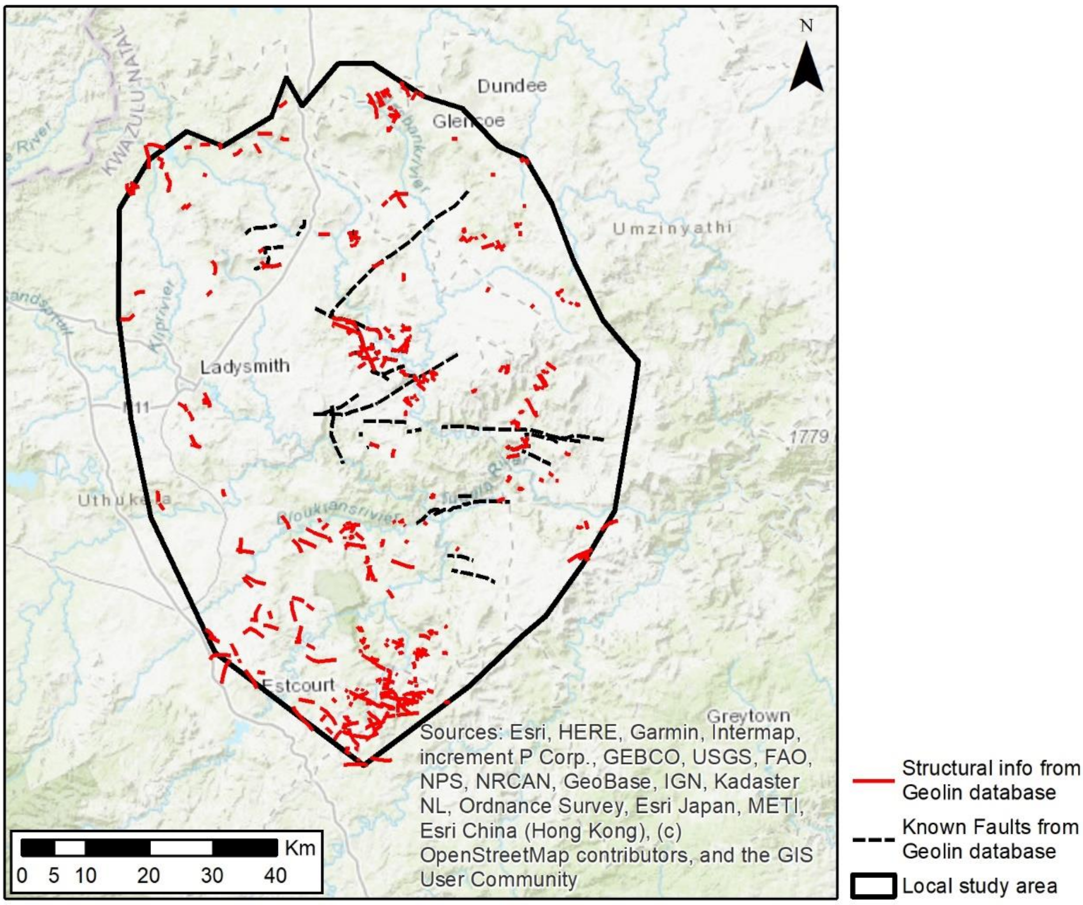

Figure 5-1. Mapped fault structures within the local study area.

5.3 Conceptual geological model

Using the collected data and knowledge from the review of literature, two cross sections are made, which illustrates how the geology is interpreted within the local study area. The location of the two cross sections are shown in Figure 5-2, while the cross sections with the interpreted geology are shown in Figure 5-3. The cross sections show, within the local study area, the upper 200-1200 meter of the geological strata is composed of the formations Normandien, Volksrust, Vryheid, and Pietermaritzburg. The youngest strata, Normandien Formation, is mainly found in the southern and western part of the local study area. The underlying Volksrust Formation is likewise found in the southern and western part of the area, while the Vryheid Formation is interpreted within the whole area. The oldest strata, Pietermaritzburg Formation, is also interpreted to be found within the whole area. However, this interpretation is very uncertain, as there is a general lack of information concerning the deeper geology, which can support the interpretation of Pietermaritzburg Formation. Therefore, the interpretation of Pietermaritzburg Formation in Figure 5-3 is drawn with several question marks.

On both cross sections, it is interpreted that the strata slightly incline towards the south.

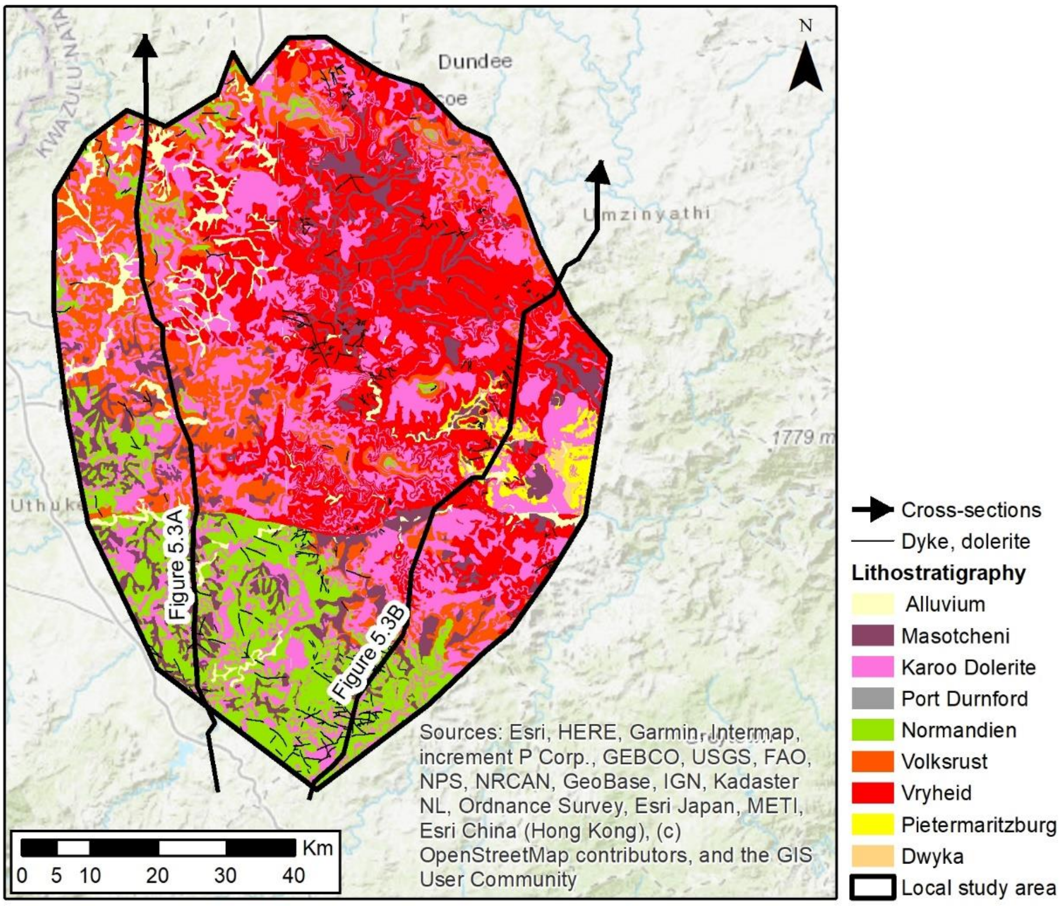

Figure 5-2. Map showing the geological formations at ground surface and the location of the two geological cross sections shown in Figure 5-3.

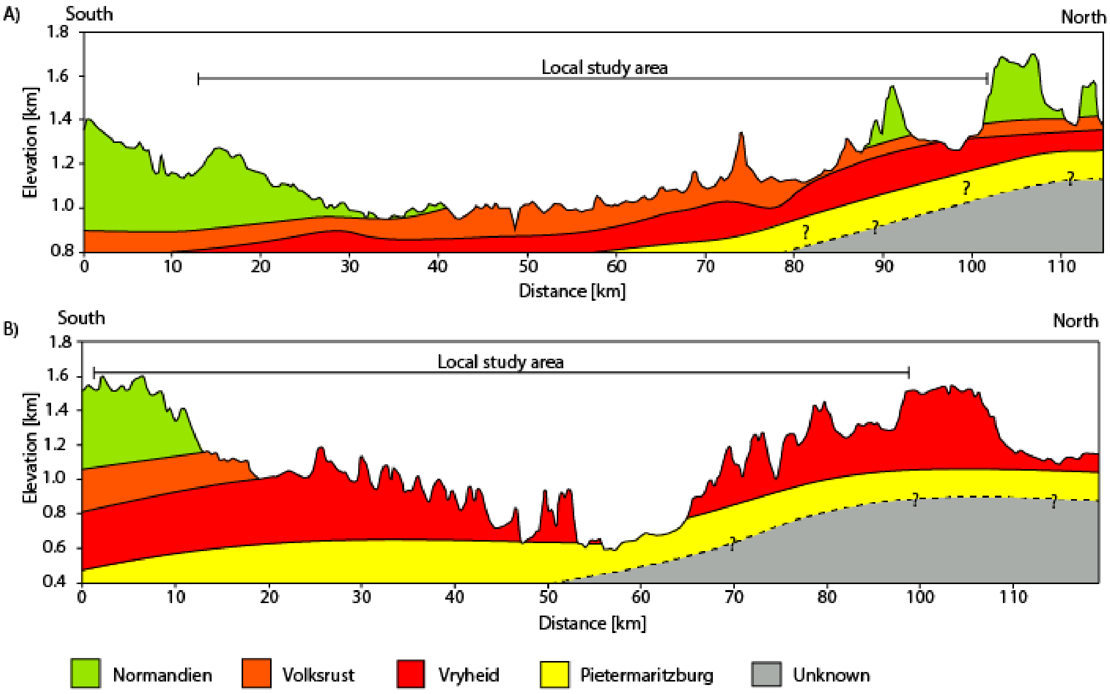

Figure 5-3. Cross section (A) and (B) show a conceptual illustration of the geological strata in the western and eastern part of the local study area, respectively.

6. 3D DIGITAL MODELS

The 3D models for the study area is developed using a combination of a digital layer model and a voxel model. This chapter provides a description of the model's setup and the results from the modelling work.

6.1 Model setup

The modelling software GeoScene3D developed by I·GIS is used to construct the 3D geological model, as well as the 3D hydrostratigraphic model. The models are constructed using the spatial reference WGS 1984 UTM Zone 36S. All data (*i.e.* databases, GIS-files etc.) are imported using this coordinate system.

To construct the models, all available data described in Chapter 4 are uploaded to the software and visualized within a rectangular area, called Scene Extent. The Scene extent is specified by the modeler and is defined by the coordinates:

X_{min}=172,600; Y_{min}=6,772,300; and
X_{max}=255,600; Y_{max}=6,890,500.

The GeoScene 3D software offers two building modules to construct a 3D model: a layer builder and a voxel builder. With the layer builder the geological or hydrostratigraphic units are interpreted as layers (grids) generated from XYZ points placed along cross sections by the modeller. When using the voxel builder, the modeller creates a regular 3D grids, where each grid cell is defined as a voxel. Each of the voxels is then assigned a specific lithology. When deciding which of the builder modules to use, the modeller need to consider the type, quality, and density of data as well as the complexity of the area's geology. The layer builder is generally suited for modelling geological units that have a large regional extent, whereas the voxel builder is preferred when the geology is complex (*i.e.* with significant faults or intrusions), showing significant lateral and vertical variations.

The 3D geological model is constructed as a layer model, because the geological formations are composed of mostly horizontal or shallowly inclined bedded strata that have a large regional extent within the local study area. It is chosen not to include the dolerite intrusions in the 3D geological model, because these structures are frequently steeply inclined or vertical, and are, therefore, difficult to model in a layer model. To include dolerite intrusions in the 3D hydrostratigraphic model, this model is constructed as a voxel model.

The interpretation of the geologic and hydrostratigraphic units is assisted of a network of cross sections drawn across the local study area. Data located within a user-defined distance orthogonal to the cross-section plane, called the buffer-zone, are projected onto the cross sections. The buffer-zone is set to 500 m, which means that borehole data and tTEM-data are projected onto the cross-sections if they are located within 500 m from the cross section.

A total of 40 stationary cross sections are constructed across the local study area. Of the 40 cross sections, 21 are drawn in a southwest-northeast direction, while the last 19 are drawn in a southeast-northwest direction. The 40 cross sections are shown in Figure 6-1.

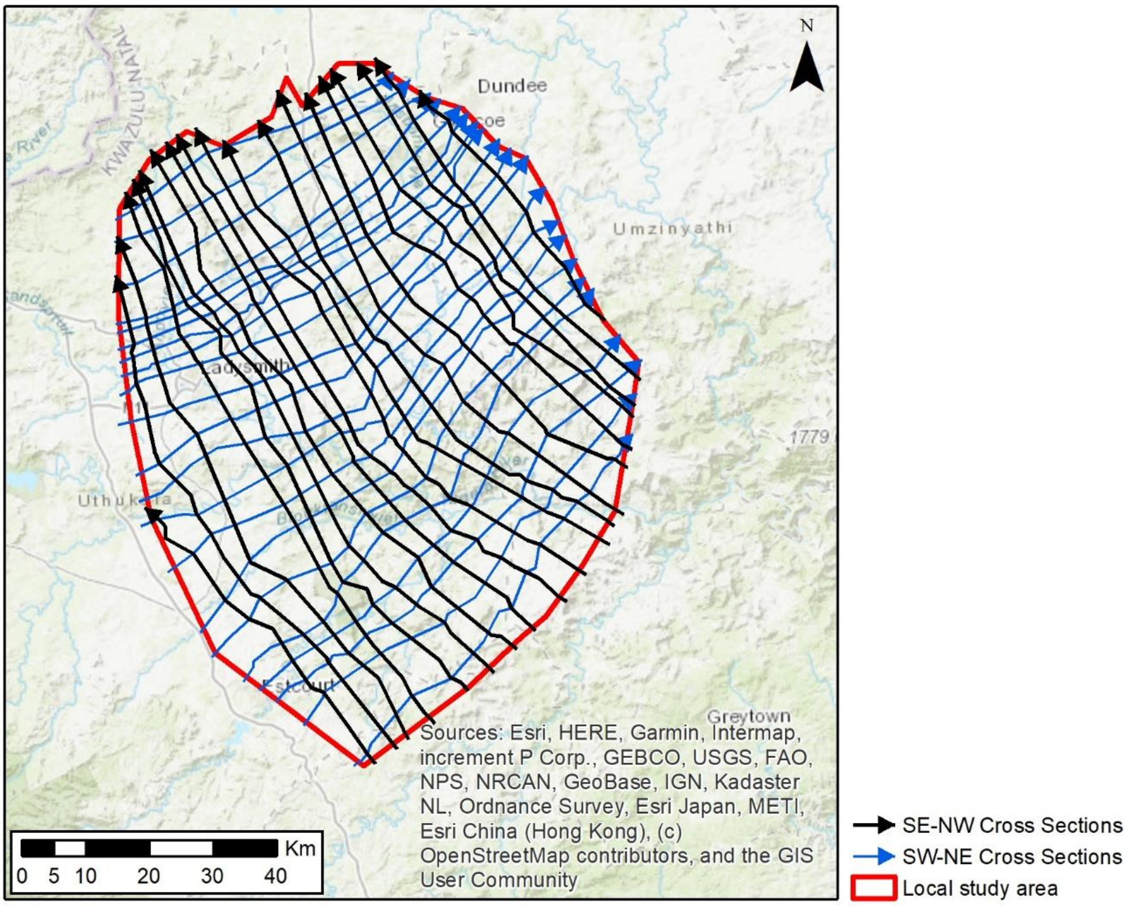

Figure 6-1. The forty stationary cross sections drawn across the local study area.

The southwest-northeast cross sections are sequentially named from south to north, starting with SW-NE Cross Section 1 and ending with SW-NE Cross Section 21 in the northern part of the local study area. Likewise, the southeast-northwest cross sections are sequentially named from south to north, starting with SE-NW Cross Section 1 and ending with SE-NW Cross Section 19. The name of the individual cross sections is shown in Appendix 1.

In addition to the stationary cross sections, several moveable cross sections are drawn across the local study area. The moveable cross sections are used to interpret the areas not covered by stationary cross sections. Furthermore, they are used to quality check the interpretations by moving the cross sections across the local study area from a different direction than the stationary cross sections (*e.g.* west-east or south-north).

6.2 3D geological model

The 3D geological model is constructed as a layer model. In a layer model, the boundaries between different layers are defined, where the DEM represents the uppermost boundary. Each layer represents a geological formation. In GeoScene3D, the lower or upper boundary of a layer is defined by a series of interpretation points (XYZ points), which are stored in a standard Microsoft-Access database.

This section describes the geological framework, modelling process, and results from the 3D geological model.

6.2.1 The geological framework

The 3D geological model is constructed by first defining a conceptual framework for the model, which again is determined from the conceptual geological model. The framework defines the number of geological units, which are to be modelled within the study area. The framework of the 3D geological model is determined from the geological map (see Figure 5-2) and existing borehole information. The geological framework for the 3D geological model is defined in a downward sequence by the following geological units:

A. Normadien Formation
B. Volksrust Formation
C. Vryheid Formation
D. Pietermaritzburg Formation

The individual units are described in section 5.1. The dolerite intrusions are not represented in the 3D geological model.

6.2.2 Modelling method

The individual layers are defined by placing so called control points, based on interpretation, along the cross sections. When a layer boundary is identified in the geophysical data or well logs, the control points are snapped to data. This means the control points in the MS-Access database will contain the ID number of the geophysical data or the borehole number. In areas with no data available, the control points are placed on the cross sections based on the modeler's understanding of the geology. These points are often referred to as 'support-points', since they are placed on the cross sections to ensure that the layer boundaries are defined within the whole study area.

For each of the defined layers, the control points are used to create a 2D surface grid (Surfer® grid format by Golden Software), which depicts the spatial geometry of the individual boundaries. To create the surface grids, an interpolation algorithm for each of the layers is selected and configured in GeoScene3D. During the modelling process, the control points are continually gridded, so the modeler visually can inspect the results from the interpretations. In the 3D geological model, the interpolation algorithm 'inverse distance weighting' is used to create the 2D surface grids.

To avoid surface grids overlapping each other, a grid adjustment routine is configured in Geo-Scene3D. For example, if a boundary surface crosses the terrain grid (DEM) (*i.e.* the boundary surface grid is located higher than the terrain grid), the routine ensures that the boundary surface grid is adjusted below ground surface, and will follow the terrain grid instead. All the surface grids are adjusted in the same way, so no surface grids overlap each other. The terrain grid is the only surface grid that is fixed, and is, therefore, not adjusted by the other surface grids.

Grid interpolation and adjustment are performed continuously during interpretation. This is done to check how well the interpolated, adjusted surfaces match the data in the model.

The quality check of the interpolated surfaces is done on the southwest-northeast and southeast-northwest trending stationary cross sections, but also by using movable cross sections. Quality control using the moveable cross sections is particularly important since it ensures no significant offset in the interpolated surfaces in the areas between the stationary cross sections. This improves the interpretation of the geological unit boundaries.

When the interpolated surfaces do not fit the data, the surfaces are manually edited by either adding additional interpretation points or through a re-interpretation of the surface (*i.e.* moving interpreted points higher or lower). Once the manual editing of the interpretation points is complete, the surfaces are re-interpolated and checked. This is an iterative process, repeated until a reasonable fit between the data and the interpolated surfaces is achieved.

6.2.3 Extent and thickness of the geological units

Maps showing the extent and thickness of the four geological units are created from the adjusted surface grids interpreted in GeosScene3D. These maps are described in more detail in the following subsections.

The extent and thickness are interpreted using a geological surface map (Figure 5-2) and existing borehole information. The boreholes do not contain any stratigraphic information, which can be used to subdivide the lithological units into geological formations. The only stratigraphical information available originate from the geological surface map (Figure 5-2). The interpretation of the geological units is, therefore, very uncertain and the results should be used with care. The borehole information is primarily used to distinguish whether the subsurface is primarily composed of sandstone or shale. If there are a dominance of shale, it is assumed that these deposits either represent the Volksrust Formation or the Pietermaritzburg Formation, whereas a dominance of sandstone may suggest the Normadien Formation or the Vryheid Formation.

Normandien Formation

The Normandien Formation is interpreted mainly in the south and south-eastern part of the local study area. The formation has an interpreted thickness between 100-800 m (Figure 6-2). In the southern part of the local study area, the interpretations are especially uncertain since the boreholes are not deeper than approximately 200 m. No data are available to determine the lower boundary of the Normandien Formation in the area. This issue occurs likewise for the other formations in the southern part of the local study area.

The formation is described to contain sandstone interbedded with shale.

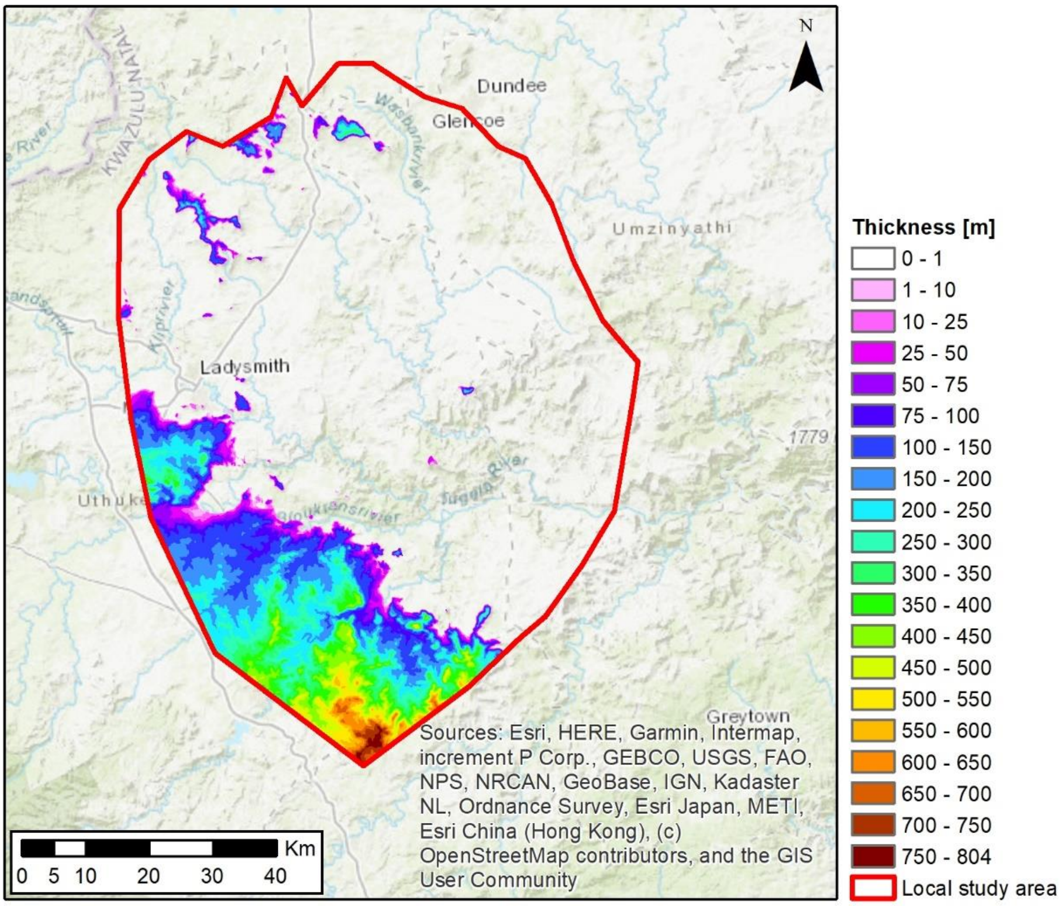

Figure 6-2. The interpreted thickness of the Normandien Formation.

Volksrust Formation

The Volksrust Formation, which consists mostly of shale, is primarily interpreted in the eastern and southern part of the local study area (Figure 6-3). In the 3D geological model, the formation has an interpreted thickness of 25-400 m. Thickness above 350 m is generally seen in the south-eastern part of the local study area.

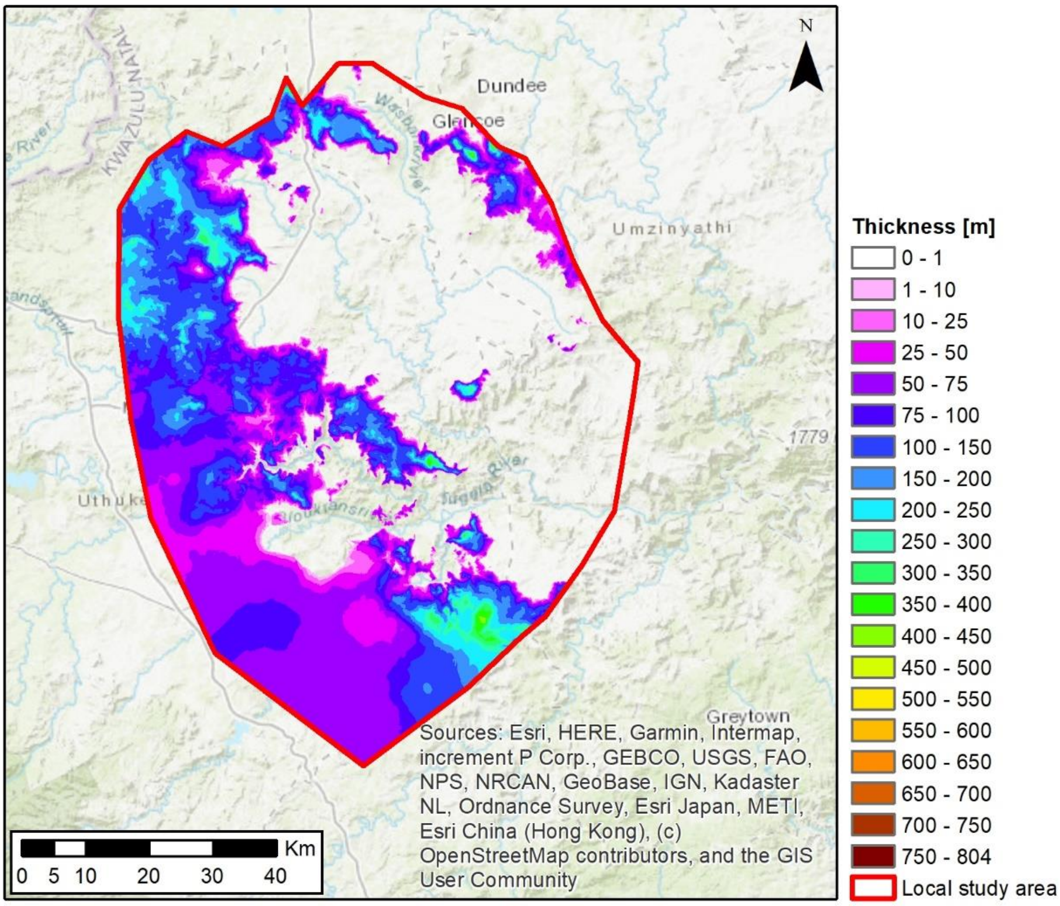

Figure 6-3. The interpreted thickness of the Volksrust Formation.

Vryheid Formation

The Vryheid Formation mainly consists of sandstone. It is interpreted to be present in most of the local study area (Figure 6-4) except for a small area in the eastern part of the study area. The formation has an interpreted thickness of 25-550 m. The maximum thickness is generally seen in the eastern part of the local study area.

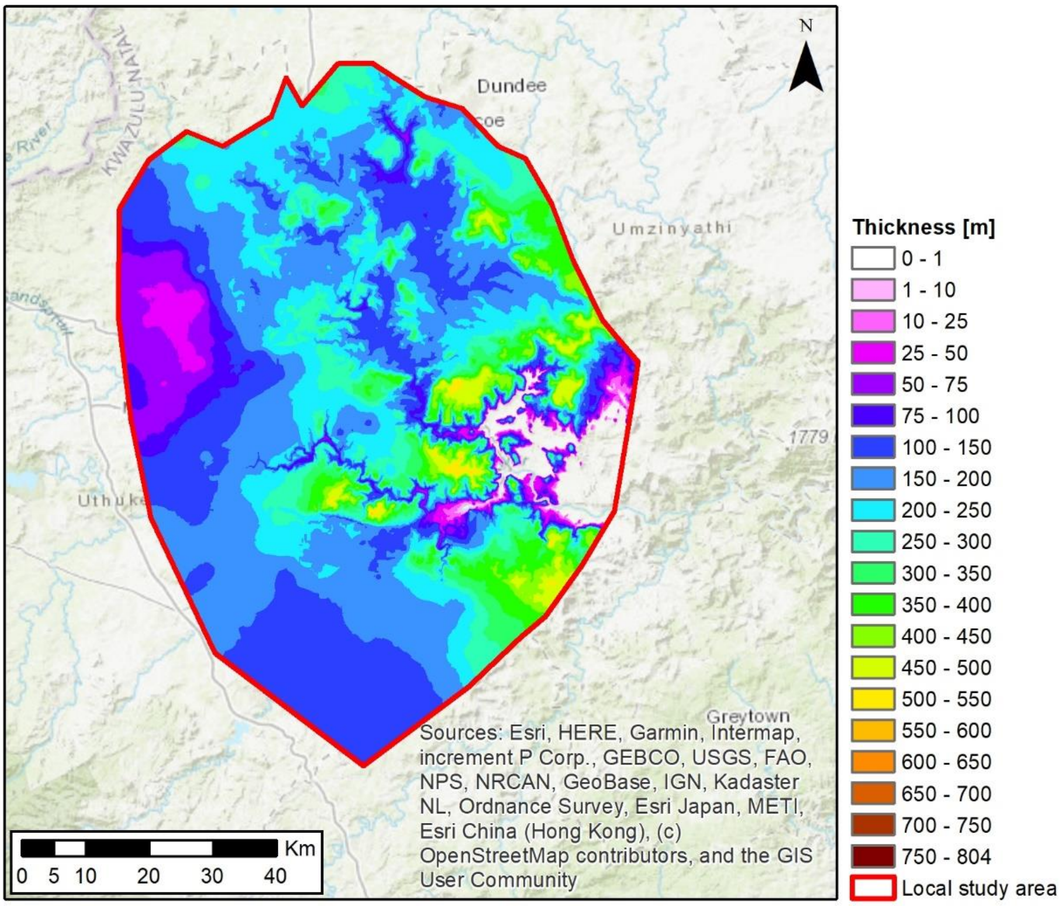

Figure 6-4. The interpreted thickness of the Vryheid Formation.

Pietermaritzburg Formation

The Pietermaritzburg Formation is composed of mainly shale. In the 3D geologic model, the Pietermaritzburg Formation is interpreted to be limited to the eastern part of the local study. Based on the geological understanding and the conceptual geological model, this is most likely not correct. It is believed that the formation has a more widespread distribution in the local study area. However, there are no data in the remaining part of the study area to support the interpretation. It is, therefore, chosen to only model the Pietermaritzburg Formation in the eastern part of the local study area, where data can verify the interpretations. The Pietermaritzburg Formation has an interpreted thickness of 100-450 m.

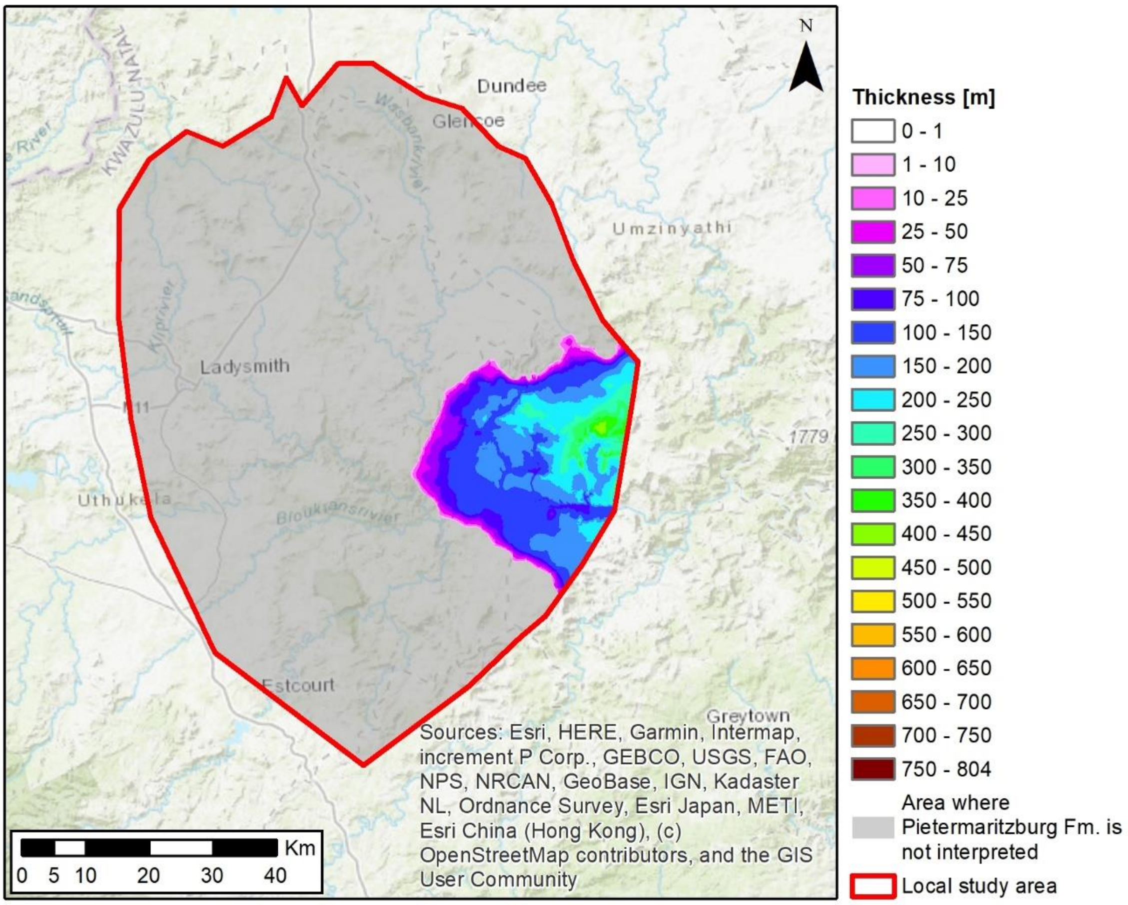

Figure 6-5. The interpreted thickness of the Pietermaritzburg Formation. The grey area is the area, where it is chosen not to model Pietermaritzburg Formation due to a lack of data.

6.3 3D hydrostratigraphic model

The 3D hydrostratigraphic model is constructed as a voxel model. The voxel model consists of a regular 3D voxel grid. The 3D voxel grid has a discretisation of 250 × 250 m in the X–Y direction and 10 m in the Z direction. This gives a 3D voxel grid composed of approximately 19.6 million voxels organised in 131 voxel layers. These layers are defined within the elevation interval 500 m to 1800 m above sea level.

This section describes the hydrostratigraphic framework, the modelling process, and the results from the 3D hydrostratigraphic model.

6.3.1 The hydrostratigraphic framework

The hydrostratigraphic framework conceptualizes the number of hydrogeological zones (aquifers and aquitards) observed within the study area. The framework of the 3D hydrostratigraphic model is determined from the 3D geological model and existing borehole information. It is defined by the following hydrostratigraphic units:

A. Shale
B. Sandstone
C. Dolerite
D. Dummy

The hydrostratigraphic unit "dummy" is assigned to voxels that are located outside the area of interest. The voxels are assigned the value "dummy" to illustrate that these voxels are not part of the 3D hydrostratigraphic model.

6.3.2 Modelling method

The 3D hydrostratigraphic model is constructed by assigning a specific lithology to each voxel. First, the voxels are assigned a lithology using the DEM, surface grids from the 3D geological model and the local study area polygon. The surface grids and the polygon are used as limits during assignment. All voxels located outside the local study area polygon are assigned the value "dummy" to show that these voxels are not part of the hydrostratigraphic model. Likewise, voxels located above the DEM surface grid and below the surface grid to the Pietermaritzburg Formation are assigned the "dummy" value. The "dummy" voxels are shown on cross sections with a grey colour.

The rest of the voxels are assigned a value as either shale or sandstone. This is done by using the surface grids from the 3D geological model, which define the upper and lower boundary of the geological formations. Voxels limited to the Normandien Formation and the Vryheid Formation are assigned sandstone, while voxels limited to the Volksrust Formation and Pietermaritzburg Formation are assigned shale as value.

After the initial assignment, the voxels are manually edited using the 'profile polygon' tool. The tool is used to select voxels along a cross-section. The voxels are selected by drawing a polygon on the cross-section window. The polygon defines the area of selection, while the cross-section's user-defined buffer distances determines the length of the selection. When using the 'profile polygon' tool, it is important to choose a proper buffer distance with respect to data density and size of the study area. If the buffer distance is too high (*e.g.* 1000-2000 m), there is a greater risk of overwritten previous interpretations by mistake. On the other hand, if the buffer distance is too low (*e.g.* 10-50 m), the modelling process may be very time consuming. In the modelling process it is chosen to use a buffer distance of 250-500 m.

The voxels are manually edited because the initial interpretations as an example do not include sandstone layers within the Volksrust Formation or shale layers within the Vryheid Formation, which are seen in the borehole data. Also, dolerite intrusions are not included. These additions to the interpretations are added with the 'profile polygon' tool along mobile cross-sections, which are incrementally moved through the local study area (250 m per move). The interpretations are mainly conducted using the mobile cross-sections, while the stationary cross-sections are used to check the quality of the interpretations.

6.3.3 Thickness

Maps showing the extent and accumulated thickness for each of the three hydrostratigraphic units, shale, sandstone, and dolerite, are created and are shown in Figure 6-6, Figure 6-7, and Figure 6-8.

6.3.3.1 Shale

The extent and accumulated thickness of the hydrostratigraphic unit shale is shown in Figure 6-6. The map shows that shale is present in most of the local study area except in the northern and north-western part. In this area, the shale has a more sporadic distribution and a general thickness of around 10-100 m. In the rest of the local study area, the shale thickness is between 100-900 m. The maximum thickness (300-900 m) is observed in the southern part, but here the interpretations are especially uncertain, since the boreholes are not deeper than approximately 200 m.

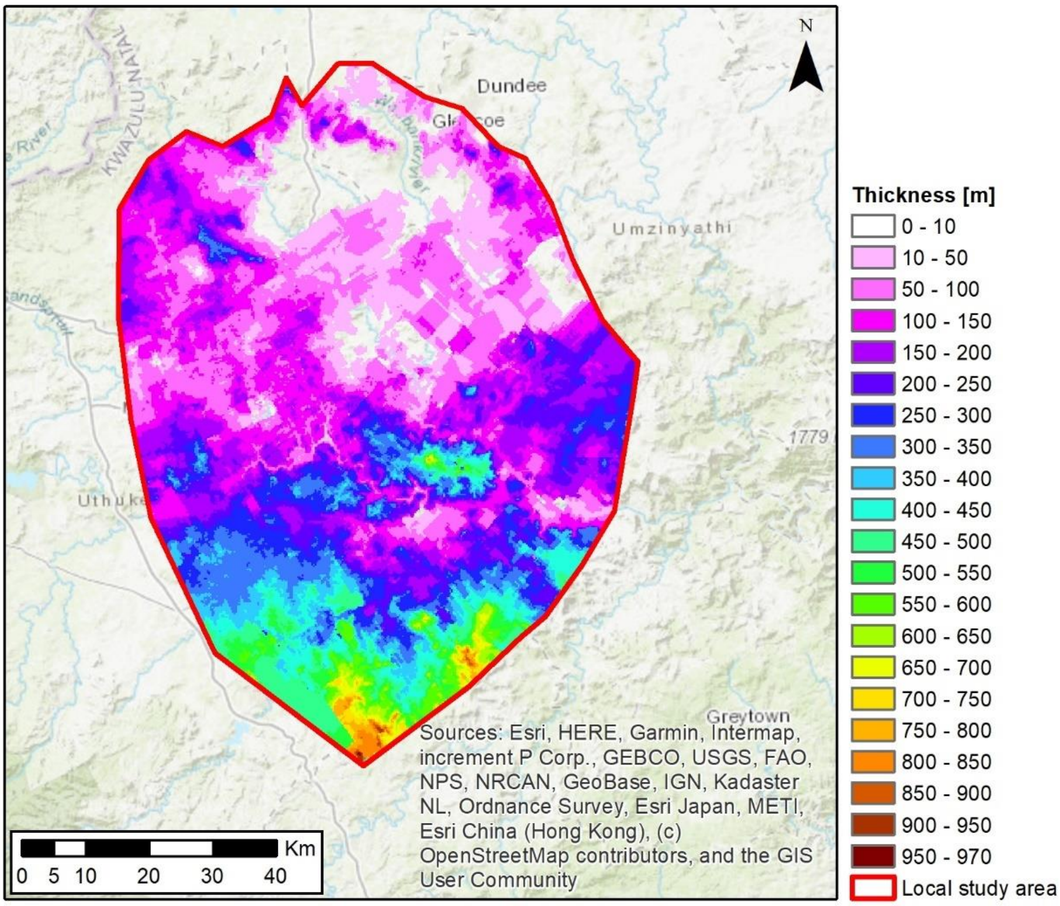

Figure 6-6. The interpreted thickness of shale within the local study area as defined in the 3D hydrostratigrahic model.

6.3.3.2 Sandstone

The extent and accumulated thickness of the hydrostratigraphic unit sandstone is shown in Figure 6-7. The map shows that sandstone is primarily present in northern part of local study area. Here, the sandstone has an accumulated thickness of around 100-500 m. In the southern part of the local study area, the sandstone has a more sporadic distribution with a thickness of around 10-200 m.

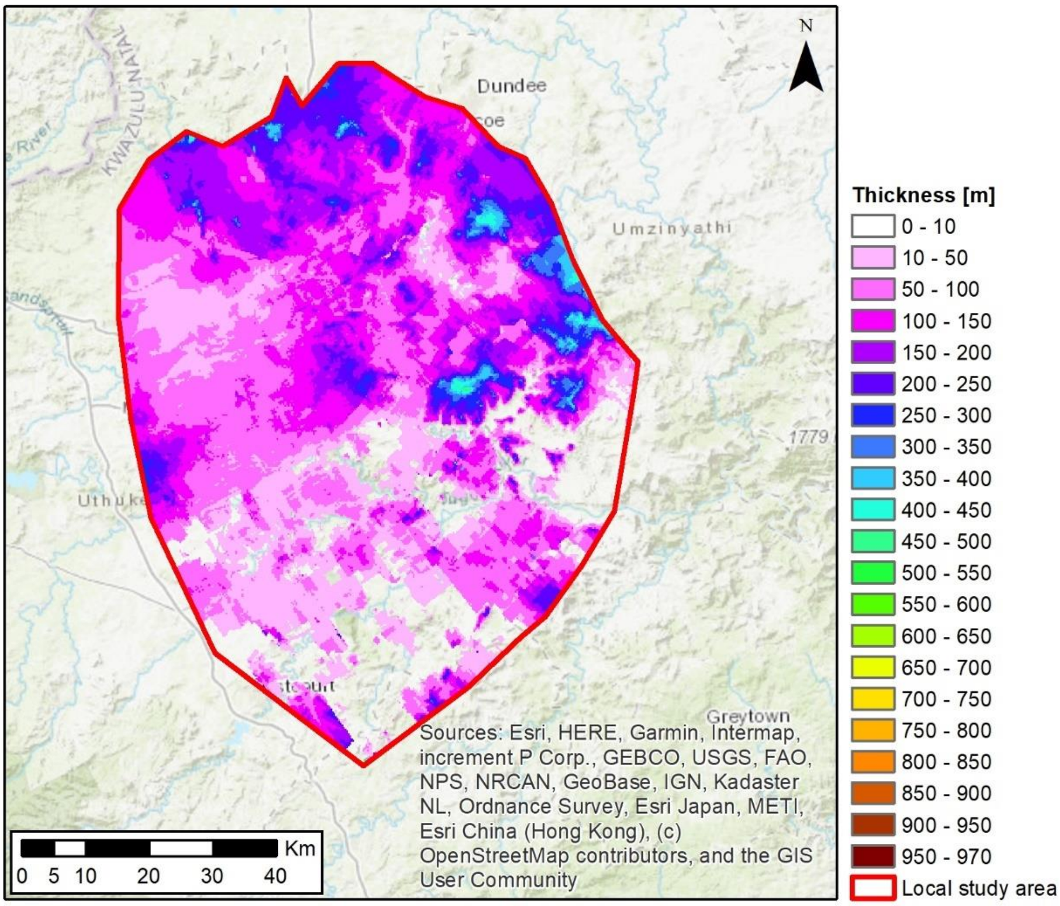

Figure 6-7. The interpreted thickness of sandstone within the local study area as defined in the 3D hydrostratigrahic model.

6.3.3.3 Dolerite

The extent and accumulated thickness of the hydrostratigraphic unit dolerite is shown in Figure 6-8. The map shows that dolerite generally is sporadic distributed in the local study area. The thickness generally varies between 10 m and 100 m, but locally the accumulated thickness reaches 250 m. It is assessed that the thickness of the dolerite is likely overestimated in some places due to the large size of the voxels.

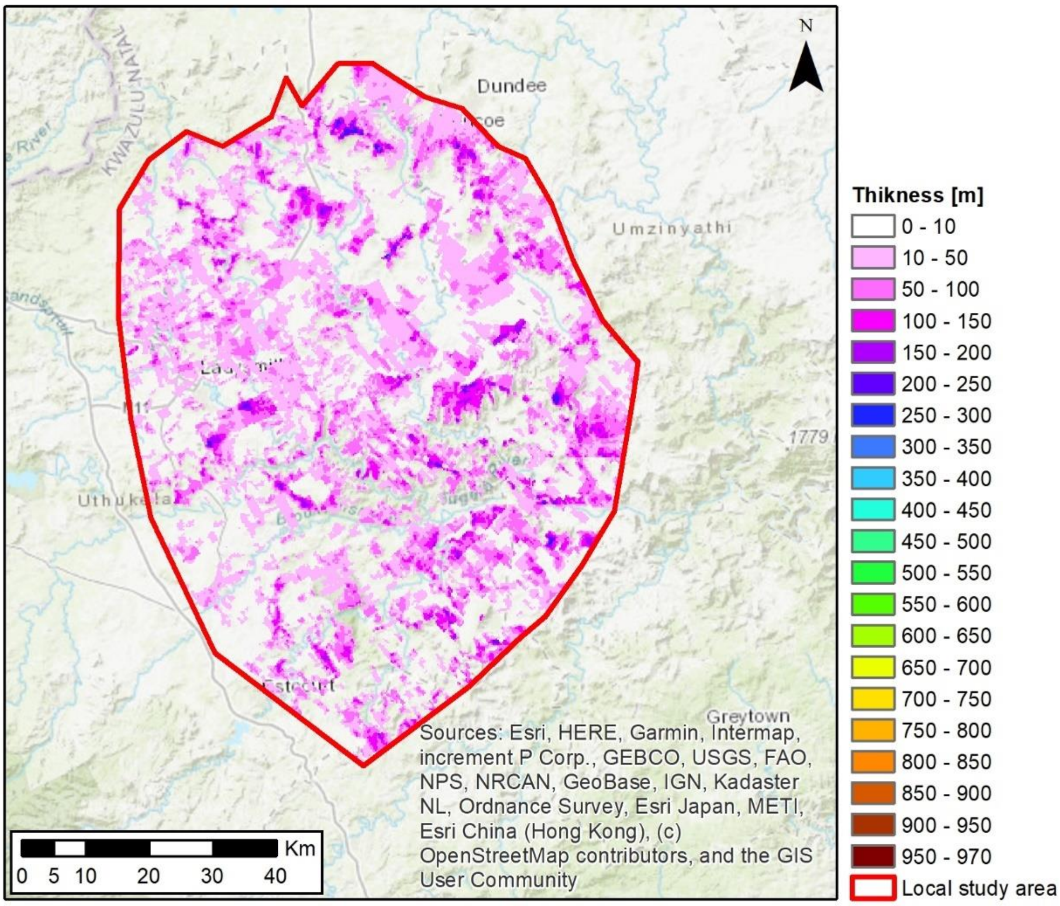

Figure 6-8. The interpreted thickness of dolerite within the local study area as defined in the 3D hydrostratigrahic model.

6.3.4 Hydrogeological zones

The interpretations from the 3D hydrostratigraphic model suggests that the local study area can be subdivided into two main hydrogeological zones. The local study area can be subdivided into:

- a northern zone with primarily sandstone
- a southern zone with primarily shale

The two hydrogeological zones represent deposits to a depth of around 700 m. In the southern part of the local study area, the hydrogeological zone represents deposits to a depth of 900 m, though the interpretations are very uncertain.

7. CONCLUSION AND RECOMMENDATIONS FOR FUTURE UPDATE

Geological modelling includes the development of a 3D geological model and a 3D hydrostratigraphic model. The models are developed with the purpose of providing an understanding of the geometry and physical characteristics of the groundwater systems, which forms the basis for a numerical groundwater model. The construction of these models for the Ladysmith area has resulted in some key learnings and recommendations, which are listed in the following:

-The accuracy of the models depends on the modeller's experience and knowledge, but also to a high degree on the quantity and quality of the data input. The primary data input are boreholes from the National Groundwater Archive (NGA) database. The database contains information on the boreholes' location and elevation, water level and water strike measured in the boreholes, and borehole logs with the lithologic descriptions of the geology. The information is extracted from the database as Excel spreadsheet. The data structure in the spreadsheets are logical and simple, and data are, therefore, easily extracted from the spreadsheet and transferred to an Access database, which again is uploaded to the modelling software. There are, though, one problem with the borehole data, which affects the quality of the models. Approximately 50 % of the boreholes, with a lithologic description of the geology, have an elevation that deviates more than three meters from the digital elevation model. The deviation likely originates in an imprecise registration of borehole location or borehole elevation. This uncertainty in the boreholes' location and/or elevation affects the validity of the geological interpretations as well as the simulated hydraulic heads in the groundwater flow model. It is, therefore, recommended to locate the boreholes registered in the National Groundwater Archive (NGA) database with the purpose of measuring the exact location and elevation of the boreholes using GPS (*i.e.* borehole registration - see Table 2-2).

-A 3D geological model was constructed for the Ladysmith area. The model was constructed as a layer model using information from a geological surface map and the lithological descriptions (sandstone and shale) in the boreholes. Normally, a 3D geological model is constructed using stratigraphic information to correlate sedimentary rocks to specific geological formations, but the boreholes in the National Groundwater Archive (NGA) database do not contain any stratigraphical information. In Denmark, 3D geological models are seldom constructed in connection with groundwater mapping, mainly because there is limited stratigraphic information available. Over the years, there has also been a debate on whether it is necessary to construct a 3D geological model before constructing a 3D hydrostratigraphic model. However, there has recently been a greater focus on incorporating stratigraphic information during hydrostratigraphic modelling of Miocene aquifers and aquitards in Denmark. Experience has shown, by utilising stratigraphic information in the modelling of the Miocene aquifers and aquitards, a higher interpretation quality is ensured. This may likewise be the case for the South African sedimentary rocks (*i.e.* shale and sandstone), as they have been deposited under a similar depositional environment as the Miocene sediments in Denmark. It is, therefore, recommended that future survey drillings include stratigraphic analysis of the lithostratigraphic units.

-It was chosen to construct the 3D hydrostratigraphic model as a voxel model because the South African geology is characterised by both horizontal structures (*i.e.* sedimentary strata and dolerite sills) and inclined/vertical structures (*i.e.* faults and dolerite dykes). A voxel model consists of a regular 3D voxel grid, where the individual voxel cells are assigned a lithology during modelling. Modelling the geology using voxel worked well, but the large size of the model area posed a challenge. The model area covers approximately 6300 km^2, and with this large size there was a lower limit on the size of the voxel cells, as a too small cell-size affected the modelling software's capacity. In the end, a voxel cell size of 250×250 m in the X–Y direction and 10 m in the Z direction was chosen. This means, though, that the interpretations do not always fit with the boreholes' lithological descriptions, because the lithological strata may have a thickness below 10 m. It is, therefore, recommended to construct hydrostratigraphic models for a smaller area than the Ladysmith model area. In Denmark, the models generally cover an area between 200 and 1000 km^2.

-During modelling it was very difficult to discern major fault systems from the available borehole data, and these structures were, therefore, not modelled in the hydrostratigraphic model. As a result, information about these structures (as lines) was added in the groundwater flow model. To identify fault structures in the subsurface, it requires data that cover a large area, like geophysical surveys, and not just point-data like boreholes. A case study in California, USA has shown that geophysical surveys like SkyTEM is capable of mapping major fault systems. In the case study, the geophysical survey was conducted in an area, where the geological structure mainly consists of shale and sandstone deposits. The sedimentary rocks are truncated by large-scale strike-slip, normal and thrust faults because of the tectonic activity associated with the San Andreas fault. Thrust faults and normal faults were generally most properly identified in the SkyTEM-data due to high resistivity contrast, but from the SkyTEM data it was also possible to identify strike-slip faults. SkyTEM-data can, though, only map the geological structure to a depth of around 200 m. This can be an issue in areas with high altitude because the method won't provide information on the deeper geology. This lack of information beneath areas with high altitude was a problem during modelling because the existing borehole data only provide information to depths of 100-200 m. Below this depth, no data could support the interpretations. Seismic investigations might be used in mapping the deeper geology in these areas.

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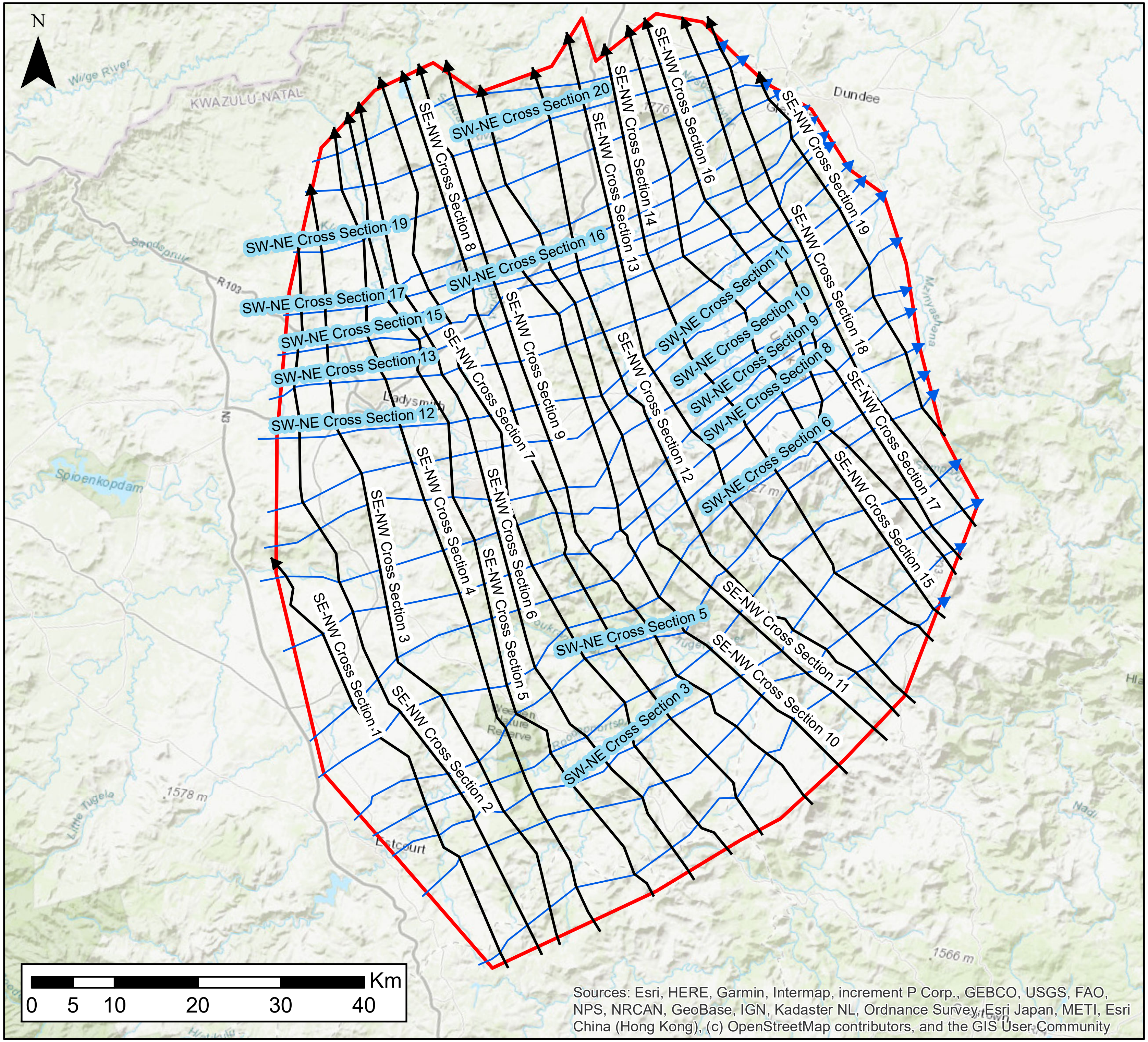
APPENDIX 1
THE LOCATION AND NAME OF FORTY CROSS SECTIONS



Legend

- SE-NW Cross Sections
- SW-NE Cross Sections
- Local study area

Date:	Drawn:	Control:	Approved:
2021-12-01	TLM	XXX	TLM
Sag: 1100042354		Version: 1	

Ladysmith - geologic modelling

The location and name of 40 cross-sections

Appendix 1