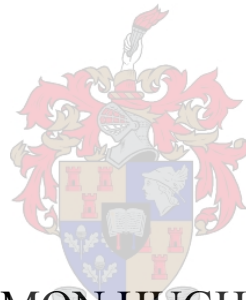# GEOHYDROLOGY DATA MODEL DESIGN:
SOUTH AFRICAN BOREHOLES

SIMON HUGHES

Thesis presented in partial fulfilment of the requirements for the degree of Master of Natural Sciences at the University of Stellenbosch

Supervisor: Mr Adriaan van Niekerk

December 2005

DECLARATION

I, the undersigned, hereby declare that the work contained in this thesis is my own original work and that I have not previously in its entirety or in part submitted it at any university for a degree.

Signature: ....

Date: 24 November 2005
...

ABSTRACT

Since mechanised borehole drilling began in South Africa in the late 1800s, over 1 100 000 boreholes have been drilled. As the country's growing population and the perceived impacts of climate change increase pressure on water surface supplies, attention is turning to groundwater to meet the shortfall in water supply. This will mean even more drilling will take place.

Until the introduction of the Standard Descriptors for Boreholes, published in 2003, South Africa has not had a set of guidelines for borehole information capture. This document provides a detailed description of the basic information requirements needed to describe and characterise the process of drilling, constructing, developing, managing and monitoring a borehole. However, this document stands alone as a specification with little or no implementation or interpretation to date.

Following the development and publishing of the ArcHydro data model for water resource management by the CRWR based at the University of Texas at Austin, there has been a great deal of interest in object-oriented data modelling for natural resource data management.
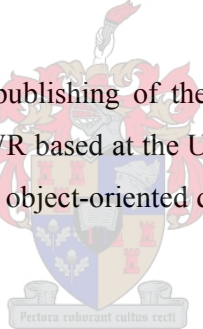
This thesis describes the utilisation of an object oriented data modelling approach using UML CASE tools to design a data model for South African Boreholes, based on the Standard Descriptors for Boreholes. The data model was converted to a geodatabase schema and implemented in ArcGIS.

OPSOMMING

Sedert die aanvang van gemeganiseerde boordery laat in die 19de eeu, is reeds meer as 1 100 000 boorgate gesink. Onder omstandighede waar die land se groeiende bevolking en die impak van klimaatsveranderings toenemende druk op die land se oppervlakte waterbronne plaas, word die aandag al meer gevestig op grondwater om die tekorte in watervoorsiening aan te spreek. Dit beteken dat selfs meer boorwerk sal plaasvind.

Voordat die Standaard Beskrywings vir Boorgate, wat in 2003 gepubliseer is, voorgestel is, het Suid-Afrika geen riglyne gehad vir die vaslê van boorgatinligting nie. Hierdie dokument bied 'n gedetailleerde beskrywing van die basiese inligting wat benodig word om die proses van boor, konstruksie, ontwikkeling, bestuur en monitering van 'n boorgat te beskryf. Hierdie dokument staan egter alleen as 'n spesifikasie met min of geen toepassing of interpretasie tot hede.

Die belangstelling in objek-gerigte modellering vir die bestuur van natuurlike hulpbrondata het in groot mate toegeneem na die ontwikkeling en publikasie van die ArcHydro datamodel vir waterbronbestuur deur die CRWR, verbonde aan die Universiteit van Texas, Austin.
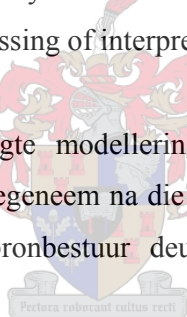
Hierdie verhandeling beskryf die benutting van 'n objek-gerigte data modellerings-benadering wat gebruik maak van UML CASE hulpmiddels om 'n datamodel vir boorgate te ontwerp wat op die Suid-Afrikaanse Standaard Beskrywings vir Boorgate gebaseer is. Die datamodel is omgeskakel in 'n geodatabasisskema en in ArcGIS geïmplementeer.

ACKNOWLEDGEMENTS

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ABBREVIATIONS & ACRONYMS

CAD – Computer Aided Drawing

CASE – Computer Aided Software Engineering

COM – Component Object Model

CRWR – Centre for Research in Water Resources (University of Texas, Austin)

CSIR – Council for Scientific and Industrial Research

CVD – Coded Value Domain

DWAF – Department of Water Affairs and Forestry

ESRI – Environmental Systems Research Institute

GD – Geodatabase Diagrammer

GIS – Geographic Information Systems

IWRM – Integrated Water Resource Management

NGA – National Groundwater Archive

NGDB – National Groundwater Data Bank

NWA – National Water Act

SABS – South African Bureau of Standards

SDB – Standard Descriptors for Boreholes

SDE – Spatial Database Engine

SDG – Standard Descriptors for Geosites

SSD – Static Structure Diagram

SWU – Schema Wizard Utility

TIN – Triangular Irregular Network

TMG – Table Mountain Group

UML – Unified Modelling Language

XML – eXtensible Mark-up Language

XMI – XML Metadata Interchange

CHAPTER 1 : INTRODUCTION

Geographic Information Systems (GIS) use computer technology to link geographic locations and spatial features with a wide variety of information sources (Church 2002; Davis 2003). The ability to link these features with databases of information to perform analysis is truly powerful. Information from GIS can be very useful tools in the hands of decision-makers. However, if information systems are not carefully designed and cognisance is not taken of implementation issues, an organisation may reject them (Sieber 2000). The worlds of GIS and environmental modelling have developed in parallel due to what is described by Sui & Maggio (1999) as a technology driven approach. GIS software developers have not really been addressing the conceptual problems involved in spatial modelling and specifically hydrological resources. They specifically state that the conceptualisation of space and time embedded in the current generation of GIS are not compatible with those of hydrological models.

Vegter (2001) estimates that, since the publication of the first hydrogeological report in 1892, over 1 100 000 water-bearing boreholes have been drilled in South Africa. When a borehole is drilled, a great deal of information is captured: location of the borehole; drilling method; drilling speeds; lithologies, water-strike depths; etc. In addition to its usefulness in determining whether the borehole being drilled is going to be successful or productive, the data collected during the drilling of a borehole can be very useful for regional groundwater management.

With the release of ArcGIS 8, Environmental Scientific Research Institute (ESRI) introduced a new geographic data model, called *geodatabase*, for the storage and management of data. Concurrent with the inclusion of the geodatabase, ESRI further developed existing data models. A data model is a simple method for structuring a set of data to describe a system. "Data models provide an orderly way to classify things and their relationships" (Maidment 2002:16). It can provide a practical template for implementing GIS projects for specific industries and applications.

Normally designed by a consortium of users and ESRI business partners, these models provide ready-to-use frameworks, built on accepted standards, for modelling and capturing

the behaviour of real world objects into a database (ESRI 2003). ESRI data models are available for a variety of industry sectors. Mainly designed and built by and for American industries, the principles of these models remain universal. The ArcHydro Data Model was developed by a consortium called Centre for Research in Water Resources (CRWR), lead by the University of Texas. Work has also begun on groundwater elements of ArcHydro. They are being developed by Strassberg & Maidment (2004) and already have basic schemata and examples available at ESRI (2005).

1.1 PROBLEM FORMULATION

In 2003 the South African Department of Water Affairs and Forestry (DWAF): Directorate Geohydrology published a set of Standard Descriptors for Boreholes (SDB). These standards were developed with stakeholders from throughout the geohydrological community exhaustively describing groundwater attributes related to boreholes. They are aimed at facilitating the standardisation of data captured during the drilling, development and monitoring of a groundwater borehole.

Although there is great interest building around the design and use of data models in South Africa and Southern Africa, very little progress has been made with the implementation of a national scale data model. Furthermore, even though a national standard for borehole information has been defined in the SDB, no schema exists for the standardised capture of borehole data. There is therefore no standard spatial data model or database schema defined for borehole or *geosite* data in South Africa.

1.2 AIMS

The aim of this research is to use CASE tools and an object oriented design methodology to develop a data model that stores borehole information and follows the national standard as laid out by DWAF in the SDB.

To reach this aim, the following objectives were identified:

1. Conduct a literature study of books, journal articles and internet resources;
2. Translate the specifications laid out in the Standard Descriptors for Boreholes (SDB) to a data model design;
3. Implement the data model design through conversion to a database schema;

4. Test the data model with real world borehole data; and

5. Discuss findings and make recommendations.

Chapter 2 will take the form of a literature review. This is required in order to fully understand and appreciate the subject matter necessary to undertake this research. It will cover literature on groundwater related issues raised by the SDB as well as the GIS and object-oriented design principles required to design the data model.

The specifications laid out in the SDB will be translated into a data model design. Chapter 3 will describe the process of translating the standard descriptors into a data model design template. The SDB document holds sufficient detailed information to correctly develop such a schema. The data model specification is created using CASE tools (Microsoft Visio) and result in a diagram that uses the Unified Modelling Language (UML) clearly defining the structure of the model in a visual format. This diagram will also double as an "open-source" document describing the features, the relationships and domains defined in the model.

Chapter 4 will be an account of the implementation of the data model design into a database schema. The UML model will be converted into an empty geodatabase repository. Once finalised, the migration methodology could be re-used to translate other geohydrological feature standards as they are developed. The empty database schema of the data model will then be tested with real world borehole data. This testing phase will be documented with a full description of how the attributes were extracted from borehole logs from live groundwater drilling projects and the database populated, thereby testing the repository in ArcGIS.

Chapter 5 will be a discussion of the findings of the translation and testing phases and will close with a set of concluding remarks and a set of recommendations for future research and work.

1.3 RESEARCH METHODOLOGY

When the development of a new database is undertaken, it is vitally important to fully understand the requirements of the user base. Without this guidance the development is undertaken in a vacuum using only supposition to inform decisions. This research will be investigative and experimental in nature incorporating the design of a data model based upon

needs stated in the SDB document. As this is a standards based document, these requirements are unambiguous and very clearly defined.

This research will see the creation of a new data model for the management of borehole information that conforms to these standards. As the result is a database, the evaluation of the outcomes will be qualitative in nature.

1.4 STUDY AREA

The target for the products of this research will be the wider groundwater community, particularly those concerned with the use or management of borehole data. It is hoped that this work will also inspire the development of other data models from future standard descriptors defined by DWAF.

The geographical area for the testing of the data model will encompass boreholes from several geohydrological studies in the Western Cape region of South Africa; the Langebaan Road Aquifer project (2004), the Botrivier water supply project (1989) and Table Mountain Group (TMG) Feasibility Study (2004). Borehole drilling logs and information in the drilling reports will be used to populate the data model.

The Langebaan Road Aquifer project centres around an area on the edge of the town of Langebaan. The aquifer comprises Langebaan Limestone from the Bredasdorp Formation and Sands/Gravels from the Elandfontein Formation as its major components. It is located between Langebaan Lagoon and Hopefield, see area 1 in Figure 1.1. The study area forms part of a CSIR project investigating the relationships and interactions between surface water and groundwater (Brown et al 2005).
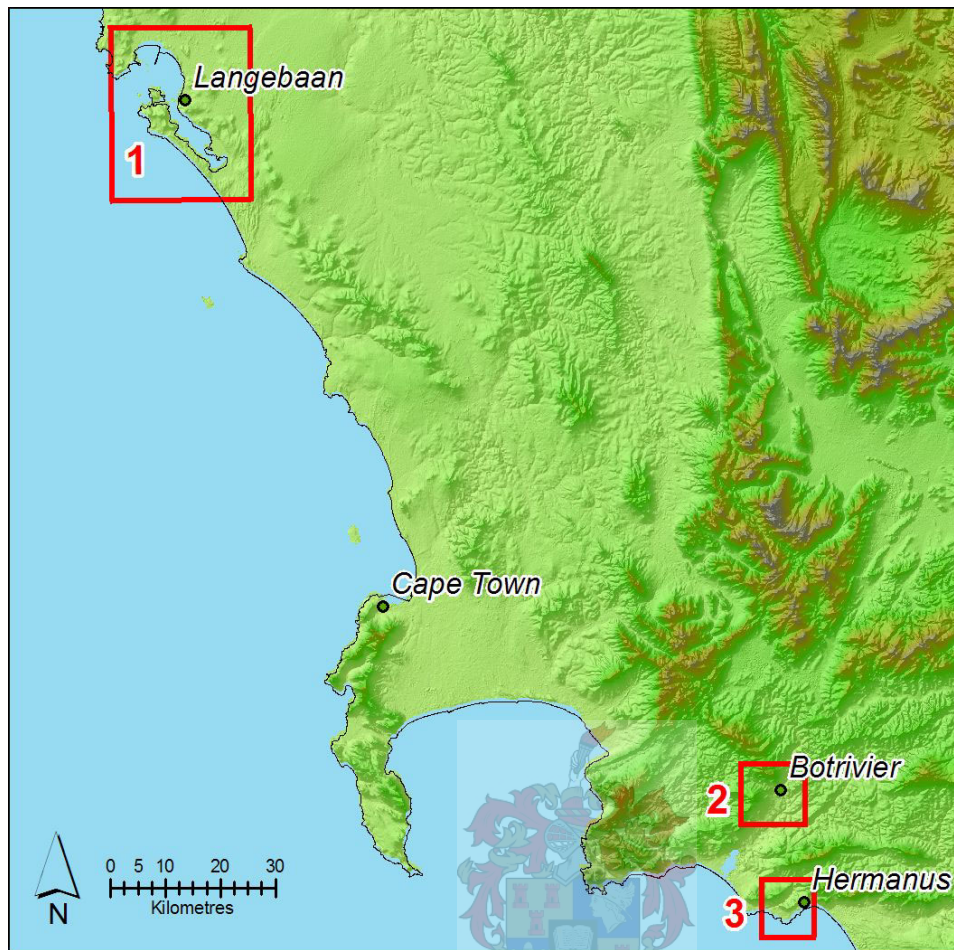
Figure 1.1 – Location of the study areas used in this project

The Botrivier Groundwater Development project study area is located just outside the town of Botrivier (area 2 in Figure 1.1). This project was aimed at enhancing groundwater supplies for the town through the expansion of a small scale groundwater supply scheme. The geology of the area is characterised by sandstones from the Table Mountain Group (TMG) and shales and sandstones from the Bokkeveld Group (CSIR 1989).

The TMG Feasibility Study project is part of a larger project to determine whether or not it is possible to supply bulk water from the TMG aquifer system to augment the struggling City of Cape Town water supply network. This is one of 10 target zones in which boreholes have been drilled to determine whether the aquifer is capable of providing a sustainable resource for bulk water supply from groundwater (area 3 in Figure 1.1). The project is running in parallel to another project that is attempting to quantify the potential impacts to ecosystems

across the TMG if bulk abstraction becomes a reality. This project is targeting the Peninsula Formation sandstones of the TMG.

In order to fully appreciate the subject matter to be researched it is important to make a full and comprehensive search and review of the literature. Chapter 2 covers some key aspects of water and geohydrology, but focuses mainly on the principles of object-oriented data model design.

CHAPTER 2 : OBJECT-ORIENTED DATA MODELLING FOR GROUNDWATER RESOURCES

2.1 INTRODUCTION

Most of the knowledge related to current developments in object-oriented data modelling and GIS lies within the geomatics industry and not within the scientific community. Although probably not intentional, this was mainly driven by ESRI who have been fostering the development of domain specific data models through the Data Model Industry Groups. Each group is a consortium of industry specialists that work with ESRI to develop data models for specific domains such as Hydrology, Facilities Management and Marine Information. The results of this work are posted on the ESRI Data Model Industry Groups website. The finished data model diagrams are stored as Microsoft Visio templates, image files and Microsoft Powerpoint presentation files, often accompanied by database schemata populated with test data. The most high profile developments in this respect are the ArcAM/FM facilities management data model and the ArcHydro data model.

ArcAM/FM is a comprehensive data model that is aimed directly at the management of domestic water, storm water and electricity reticulation facilities. This data model is an exception, in that although it was developed by ESRI in conjunction with industry partners it is not a public domain data model and must be purchased. ArcHydro was developed by a consortium led by Dr. David Maidment of the Centre for Research in Water Resources (CRWR) of the University of Texas in Austin. It is an off-the-shelf surface water data model covering hydrology and hydrography (Maidment 2002). The data model is available through the ESRI Data Model Gateway (ESRI 2005) along with sample database schemata, symbology, map documents, analysis diagrams and UML templates. In addition to the data model diagrams and templates, the book *ArcHydro: GIS for Water Resources* (Maidment 2002) was published in 2002. This is one of the key reference texts of this study as it is the first and, to date, the only book published on one of these public domain specification data models.

Even though the knowledge being created by these consortia is, in one sense, public domain with freely available templates, schemata and some supporting documentation, the groups developing the models are not publishing their work in the literature. Hence, while the

knowledge base of data modelling is in one way expanding through the release of these products, the reality is that the key knowledge – how to develop the data model – remains protected within the consortia. The bulk of documentation supplied with the models concerns the rationale for developing the model and the implementation of the model and associated tools. While this is vital information for someone wanting to implement the data models, it doesn't directly help a reader to understand the analytical and research processes involved in developing the data models.

This study assumes a basic understanding of GIS and Geohydrology and therefore will not cover fundamentals of these disciplines. It will rather focus on the technical elements that directly influence the process of translating the set of standards laid out in the SDB into a workable object-oriented data model and its implementation in a geodatabase. The following section deals specifically with background material concerning groundwater in South Africa. The subsequent sections then briefly describe aspects of boreholes and drilling relevant to the development of a data model for borehole information. A review of the SDB will then be conducted in order to deconstruct the principles that will guide the development of the object-oriented data model for this study. The remainder of the chapter will focus on two main areas, object-oriented data model design and current data model developments.

2.2 GROUNDWATER IN SOUTH AFRICA

The National Water Act (South Africa 1998) (NWA) places the water and forestry resources of South Africa in the custodianship of DWAF along with the responsibility to develop and implement policy governing these two resources (DWAF 2005).

In addition to equitable distribution of natural resources and the change in ownership of water from individual to state custodianship, the NWA recognises a single hydrological cycle and introduces the concept of Integrated Water Resource Management (IWRM) as a fundamental principle of water management in South Africa (South Africa 1998). IWRM is a management approach that attempts to balance the concept of fresh water as a finite resource that experiences pressures to sustain life and support development whilst maintaining the environment (Durham, Rinck-Pfeiffer & Guendert 2002).

2.3 GROUNDWATER

Approximately 70% of rural dwellers in South Africa depend entirely on groundwater (DWAF 2003a).   Recent estimates put groundwater abstraction in South Africa between 1 771Mm³/a and 1 900 Mm³/a (Baron & Seward 2001; DWAF 2004c). However, the actual usage of groundwater is currently largely unknown as there is no formalised groundwater usage data collection in South Africa (CSIR 2004). Figure 2.1 shows the water cycle, clearly illustrating the elements of groundwater systems and their place in the overall cycle (CSIR 2003a).
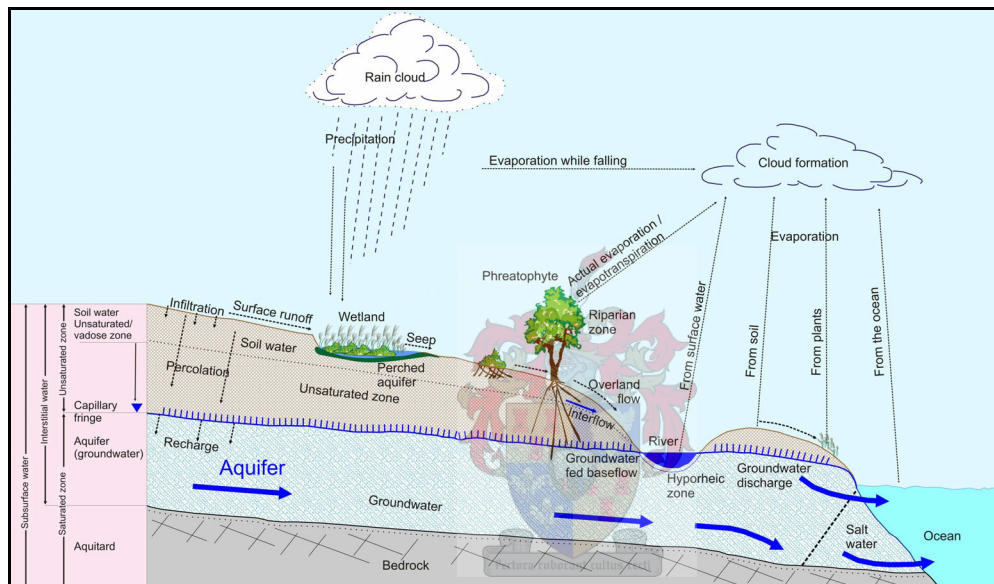
Source: CSIR 2003a

Figure 2.1− Contribution of groundwater to the water cycle

Groundwater contributes significantly to water supplies in many countries around the world, both developed and developing.   However, due to its sub-surface nature, the role of groundwater in society is often undetected and unappreciated (Burke & Moench 2000). As a result, where groundwater is utilised on a production scale it is often over-abstracted, polluted or simply badly managed. Table 2.1 shows the distribution of the world's water resources and the large contribution groundwater makes to freshwater.

Table 2.1 – Contribution of groundwater to global water distribution

Water source	Water volume (km³)	Percent of total water
Oceans	1 338 000 000	96.50%
Ice caps, Glaciers, & Permanent Snow	24 064 000	1.74%
Groundwater	23 400 000	1.7%
Fresh	10 530 000	0.76%
Saline	12 870 000	0.94%
Soil Moisture	16 500	0.001%
Ground Ice & Permafrost	300 000	0.022%
Lakes	176 400	0.013%
Fresh	91 000	00.07%
Saline	85 400	0.006%
Atmosphere	12 900	0.001%
Swamp water	11 470	0.008%
Rivers	2 120	0.0002%
Biological water	1 120	0.0001%
Total water volume	**1 385 984 510**	**100%**

Source: USGS 2005

Groundwater is found in sub-surface geological formations called *aquifers*. Freeze & Cherry (1979) define an aquifer as only those formations that are capable of yielding economic quantities of water. It is widely recognised that there are two types of aquifers; primary and secondary. Primary aquifers allow water to move through primary openings or interstices formed during the formation of the rock (Spitz & Moreno 1996). An aquifer that allows water to move through secondary openings or fractures created after the rock was formed is known as a secondary aquifer (CSIR 2003b; Spitz & Moreno 1996). Only a few of South Africa's aquifers are primary in nature, occurring in coastal areas or associated with alluvial deposits in river systems. The majority, some 98%, are characterised as secondary aquifers (Parsons 2004). The groundwater present in the aquifers described above is most commonly accessed through the drilling of boreholes. The following section will describe boreholes and their uses.

2.4 BOREHOLES

Boreholes, or groundwater wells as they are known in other countries, are holes dug or drilled down from the earth's surface into aquifers to access groundwater stored therein (Rebouças 2004). Boreholes are used for a variety of applications from community water supply to

dewatering in support of mining operations. The main types of boreholes are summarised in Table 2.2.

Table 2.2 – Common Borehole Applications

Description
Exploration
Dewatering of mines, excavations, etc
Monitoring
Production (abstraction):
Bulk water supply
Irrigation
Garden size irrigation
Stock watering
Nature conservation – game watering
Industrial
Mining
Power generation
Recharge – artificial
Waste disposal
Standby – water supply

Source: DWAF 2003a

The majority of boreholes are used for the abstraction water from aquifers for consumption, either for industrial purposes, irrigation or domestic consumption. Dewatering – the drawing down of the water table to protect mine workings from water ingress – is also a very common application in South Africa. Some boreholes are also used for pumping water underground. This is particularly true with respect to artificial recharge projects where water is pumped back into an aquifer during times of surplus to protect a groundwater resource from over-abstraction.

2.4.1   Borehole siting

The identification of a suitable location or site for a new borehole is known as *borehole siting* and is a pursuit that requires a good combined knowledge of geology, geomorphology and geohydrology. As groundwater in secondary aquifer systems is normally associated with fractures and joints (Spitz & Moreno 1996), boreholes generally need to be accurately positioned in order to intersect with these water bearing features (Woodford & Chevalier

2002). The siting is often performed using a combination of the interpretation of geological and hydrogeological reports; structural geology maps; regional knowledge and one or more remote sensing data source (Driscoll 1986). Additional features, such as vegetation, are also used to determine the existence of subsurface water resources. Table 2.3 is a summary of the most common methods for siting boreholes.

Table 2.3 – Common borehole siting methods

Description
Aerial photograph interpretation
Satellite image interpretation
Map interpretation
Resistivity survey
Soundings
Profiling
Magnetic survey
Electromagnetic survey
Time domain
Frequency domain
Seismic survey
Gravity survey
Controlled source audio magnetotelluric surveys
Geological field observation
Other

Source: DWAF 2003a

The first three siting methods are spatial methods, applying either maps or remote sensing imagery, while the following five are geophysical methods. The application of geological field observations is the most traditional method and is usually combined with the other methods.

2.4.2   Borehole data and information

Extensive drilling of boreholes produces vast amounts of data that need to be captured, stored and managed. These data, while varying widely in quality, can often provide a hydrogeologist with considerable information about the regional groundwater context and give insight on past successes and failures in a region (Freeze & Cherry 1979). The successful future management of South Africa's water resources relies on a sound base of

hydrological and hydrogeological information storage, management, monitoring and data capture. With support from databases, GIS software, maps and reports, this information will be the basis upon which decisions will be made in the future (Conrad & Girman 2002).

Burke & Moench (2000) asserted that three types of scientific data collection and analytical activities are required in order to meet the needs of long term groundwater monitoring and assessment. They are:

1. long-term baseline monitoring;
2. targeted research on basic processes; and
3. site-specific analysis of problems and management options at local level.

Long-term baseline hydrogeological monitoring data are essential in order to understand an aquifer system and its response to climatic variability and groundwater abstraction. Through a wide range of work – from basic groundwater research to detailed studies – it will be possible to gain a full understanding of a system, where the system is under pressure, and identify management relevant options (Burke & Moench 2000). Furthermore, Parsons (2004:8-4) underlines the need for good quality monitoring data to support the application of hydrological models: "While modelling may be a useful tool, failure to calibrate models using measured data merely perpetuates our flawed conceptual thinking".

2.4.3   The National Groundwater Archive

Until 2000 groundwater information held by DWAF was captured stored and disseminated through the National Groundwater Data Bank (NGDB) which has been operating since the late 1980s. This is the central repository for groundwater data and information in South Africa. The system followed a standard relational database model and was implemented using a DMSII database. This database has been migrated to an interim database called Open-NGDB, which currently houses records for over 210 000 boreholes across South Africa. A new relational database is currently being developed to take the place of the NGDB databases called the National Groundwater Archive (NGA) (Conrad & Girman 2002). Open NGDB and NGA were implemented using an Informix database system.

2.4.4   Borehole Information for IWRM

The National Water Act (South Africa 1998) (NWA) is based on fundamental principles stating that: water is an indivisible national asset; all elements of the water cycle are

interdependent; the ecological functions of all water is important; and all water is treated consistently in law (South Africa 1998). Chapter 14 of the NWA states that the collection, assessment and dissemination of water resource information are vital for the achievement of the objectives contained within the act itself. With this in mind, it is of great importance that all elements of groundwater data are collected and managed efficiently. Furthermore, now that DWAF, acting as custodians of the water resources of South Africa, are issuing licenses to registered water users, they will require an even greater depth of understanding of water resource availability and quality. DWAF (2003a) asserted that there is a need to advance and facilitate the sharing of groundwater information and to remove the perception that data is a 'bargaining chip'. The SDB aims to play an important and key role in this drive to improve information flow through the definition of standards in addition to enhancing spatial referencing, water level measurement, and the provision of comprehensive metadata.

To construct a borehole it must be drilled, equipped and developed. During the drilling a wide variety of information can also be captured. The following section describes the process of drilling and developing a borehole and the information captured during the process.

2.5 DRILLING

Modern borehole drilling is normally carried out using a drilling rig mounted on the back of a truck. Figure 2.2 shows an example of a truck-mounted rig drilling a borehole in the Limpopo Province.

Source: Colvin 2004, pers com

Figure 2.2 – Truck-mounted drilling rig.

Borehole drilling is carried out using one or more of a range of standard techniques, depending on the circumstances and geology of the site being drilled. Table 2.3 contains a summary of the main drilling methods and their common applications.

Table 2.4 – Common methods used to drill boreholes in South Africa

Methods	Applications
Cable tool	Reliable for a wide range of geological conditions Boulder deposits All rock strata that are highly disturbed, broken, fissured or cavernous Often popular for rehabilitating old boreholes
Direct circulation (mud rotary)	Unconsolidated sands, – coastal quaternary formations
Reverse circulation (mud rotary)	Unconsolidated rock – Mozambique
Rotary air percussion	Semi-consolidated – consolidated materials (hard rock) – used for 90 % of South African drilling
Jetting: Percussion drilling	Commonly used for drilling small-diameter wells in water-bearing sand Also used to penetrate semi-consolidated geological strata that are not too hard.
Well pointing	Sandy riverbeds and the unconsolidated dune-sands along the South African coast
Boring with earth augers: Bucket	Clay formations that stand without caving
Solid stem	Loose soil or drilling below the water table
Hollow stem	Unconsolidated sands Especially useful when important not to contaminate the sub-surface with drilling fluids
Driven wells (well points), i.e. jetting method	
Tube wells	Manual augering into shallow aquifers

Source: DWAF 2003a

Each of the methods listed in the left-hand column is accompanied by an application in the right-hand column. The applications describe the different geological settings in which the method is most effective.

2.5.1 Borehole casings and screens

When a contractor drills a borehole, a tube or *casing* is often inserted into the hole to protect it from collapsing due to substrate instability. Well casings, or screens as they are known in the

United States of America, are required in all unconsolidated and most semi-consolidated geological formations, and occasionally when dealing with consolidated rock (Driscoll 1986). The casings are inserted into the borehole in sections sometimes, but not always, extending to the bottom of the hole. The sections are joined using welding or other forms of bonding suitable for the casing material.

2.5.2 Borehole logs

During the construction of a borehole a drilling technician or logging contractor will compile a log of the details gathered during the drilling exercise. A borehole log usually includes details of drilling speed, diameter of the drill-bits used, depths of water-strikes and the lithology encountered. While the information in a borehole log is useful for understanding how the hole was drilled, it also provides a cross-section of sub-surface conditions. This cross-section includes the lithological composition and stratigraphy of the sub-surface, and when used in combination with logs from other boreholes, can help build a picture of regional lithology and ultimately hydrogeology. Unfortunately, drilling logs are usually only kept by the person contracting the drilling of the borehole. If the contracting agent is DWAF, the log and drilling data is catalogued and stored centrally. However, if the contract is with a farmer or another land owner, the log is submitted with a drilling report to this individual and the information often goes no further.
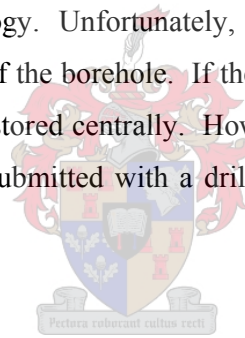
2.5.3 Pump tests

A series of tests known as *Pump Tests* are carried out following the construction and development of a borehole. These tests are undertaken to determine the performance limits and characteristics of both the borehole and aquifer, allowing sustainable use of the borehole (Driscoll 1986). Drilling, developing, pump testing and monitoring of boreholes produces a large volume of data. The SDB aims to put in place standards for the capture and storage of this information. The following section introduces the *Standard Descriptors for Boreholes* and their proposed role in the standardisation of borehole information.

2.6 STANDARD DESCRIPTORS FOR BOREHOLES

2.6.1 The need for standards

Standards are designed to prevent inconsistencies in data captured by an organisation (DWAF 2004b). However, groundwater information capture and management is not restricted to the DWAF. There is also much interaction with a broader community of practitioners. If

information is to be passed rapidly and efficiently between organisations, standards that facilitate the exchange and interoperability of data between these different groups are required (DWAF 2003a). The development and implementation of standards can provide a common language, support best practices and save time and costs (AGI Standards Committee 1989).

DWAF annually invests significant portions of its budget into borehole drilling and groundwater monitoring. Standards will assist DWAF in leveraging the maximum information from these expensive undertakings (DWAF 2003a). Furthermore, it is essential to begin collecting consistent data of a known standard and quality in order to fulfil the requirements of IWRM. This can only be achieved through standardised data capture, management and reporting within DWAF and the broader groundwater community. Through the application of good standards, opportunities for errors, incompatibility of information and time wasting are minimised thereby reducing costs (Cooper 1993, pers com).

In a large government organisation such as DWAF, standards are a *necessary evil* (Cooper 1993, pers com). Good standards promote use and integration of data while reducing costs incurred by unnecessary data conversions and error checking. However, Cooper (1993) warns that the implementation of standards can be expensive, particularly if the standards are either unrealistic or not well thought through. These two factors will drive negative behaviour in the organisation and ultimately lead to a lack of acceptance for the standards.

Braune (2003) clearly stated the need for standards in groundwater and borehole information, linking it to the volume of information that will be created if true IWRM were to be achieved. This is not only geohydrological information, but also hydrology, water quality, land type, use and cover. Furthermore, CSIR (2003a) identify a lack of standards for the capture of spatial, temporal and attribute data in groundwater and borehole information as one of the constraints to the successful implementation of a geohydrological information system for catchment management.

2.6.2   The Standard Descriptors for Boreholes

By the time the lack of standards had been identified by CSIR (2003a) a set of *Standard Descriptors for Boreholes* had already been commissioned by DWAF. The document was published in 2003 as an output of the *Effective Groundwater Management in South Africa programme.* The programme was funded as part of the Norwegian (NORAD) assisted

programme for the *Sustainable Development of Groundwater Sources for the Community Water and Sanitation Programme*, managed by DWAF (DWAF 2003a).

Although the SDB was initially proposed as a South African Bureau of Standards (SABS) approved standards document for borehole information (SABS 2003), institutional problems with regard to the announcement of a national standard were experienced. Hence, the term *Standard Descriptors* was used rather than *National Borehole Standards* (Girman 2005, pers com). The objectives of the SDB document are to provide background information in support of a standard format for describing borehole and other groundwater related items. It includes information on attributes that must be described as well as units of measurement (DWAF 2003a).

The SDB was expanded in 2004 with the release of the Standard Descriptors for Geosites (SDG) (DWAF 2004a). Table 2.5 contains a list of the geosites covered in both sets of descriptors. The SDG expanded the description of the other geosites beyond the simple description that was provided in the SDB.

Table 2.5 – Types of Geosites as described in the Standard Geosites Descriptors

Description
Borehole
Dug well
Well point
Drain
Tunnel
Shaft
Lateral collector
Seepage pond
Spring
Sinkhole
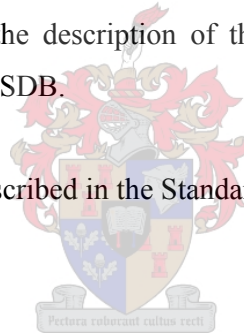
Source: DWAF 2003a

Following the introductory chapter, the SDB document comprises nine other chapters, each focussing on one key area of borehole information. The following sections will briefly describe each key area, outlining the standard elements required to sufficiently describe a borehole.

2.6.2.1   Geosite basic information

This covers the basic information about the physical position of the borehole and how it was located. The required components are: type of geosite, positional information; equipment used to determine the position; accuracy of the position; geomorphological class of the site; the method used to site or determine the location of the borehole; the features targeted by the geosite (fault zones, fractures, etc); purpose of the borehole; status of the borehole; and confidentiality.

2.6.2.2   Borehole drilling details

As the borehole is drilled, details such as drilling contractor; date of the drilling; drilling methods used; drilling fluids used; depth and diameter of drilling; the quality of the drilling data; and drilling penetration rate are captured. How these parameters are to be described are specified.

2.6.2.3   Geological details

This is concerned with the geological description of the borehole specifically its lithology and stratigraphy. This section, and that referring to hydrogeological details, contains important information required to design and construct high-yielding boreholes (DWAF 2003a).

2.6.2.4   Hydrogeological details

The hydrological details of water strike depth, static water level, water quality, and any water samples collected are covered here.

2.6.2.5   Casings, gravel pack and borehole development

Once a borehole has been drilled, certain measures need to be taken in order to protect it from collapsing and to ensure that it is productive and efficient. Casings, gravel packing and borehole development activities are covered. They are: the type of casing; type of screens; screen material; method for creating opening; details of filters and gravel packs; and any borehole development activities.

2.6.2.6   Borehole and aquifer testing details

Following construction, testing of a borehole is an essential part of its life cycle. Aquifer (or pump) tests determine the optimal yield and hydraulic performance of an individual borehole and its operational limits within the larger hydrogeological context of the aquifer (DWAF

2003a). The details of the tests carried out such as: the type of test pumping; duration of the tests; data collected and its analysis are covered.

2.6.2.7   Borehole logging

As described in Section 2.5.2 a borehole log is normally drawn using information collected during the drilling of a borehole. The techniques for collecting the borehole log data are covered here.

2.6.2.8   Borehole – operational management and equipment installed

Once testing of a borehole is completed, it is possible to make recommendations about the management of the borehole – i.e. abstraction rates and monitoring intervals.   These operational management recommendations and the equipment installation specifications are described.

2.6.2.9   Borehole – groundwater monitoring details

Once a borehole has been constructed, developed and tested it can be put into action. As was shown in Table 2.2 a borehole can be utilised for several different applications.   Some boreholes are designed specifically for monitoring groundwater parameters and in many cases can also be used for monitoring. A selection of basic groundwater monitoring parameters are provided, but this list could be extended considerably depending on the purpose of the monitoring being carried out.
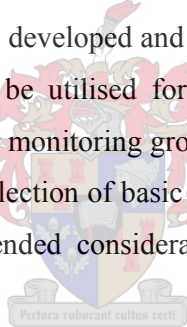
2.6.3   Dissecting the SDB

Much of the information in the document is provided in tabular form, clearly stating a set of desired values that should be used to describe the borehole parameters. To successfully design a database of any kind, a user requirements assessment is essential in order to understand the needs of the user base. Through this document the requirements of the user group in question – DWAF and the groundwater community – are articulated in great detail. The next section will describe the fundamental elements of data modelling in GIS, specifically the object-oriented approach, and illustrate how these user requirements can be translated into a database design.

2.7 GIS AND GISCIENCE

While describing the implications of Tom Siegfried's book, titled *The Bit and the Pendulum* for GIScience, Sui (2001) states that more and more scientists are constructing their research in terms of information and information processing. The analysis of data and information has always played an important role in problem solving. However, the inclusion of spatial elements through GIS tools and techniques will increase the relevance of solutions.

According to Sui & Maggio (1999), problems in the current practices of GIS-based hydrological modelling cannot be resolved if we continue to treat the integration of GIS with hydrological models as essentially a technical issue. They also state that the implicit assumptions behind hydrological models and GIS must be challenged, and that research efforts should be shifted to the fundamental issues of understanding and representation of hydrological processes in the appropriate spatial-temporal framework. What they are proposing is that the conceptual level of GIS and modelling in research should be raised to a more scientific level. Goodchild (1994) in his seminal article *Geographic Information Science*, after describing the pulses of development driving GIS and GIS driving development, also describes the changing emphasis of the 'S' in GIS from Systems to Science. Once again, this is a call to advance the role of science, this time in geomatics, by questioning whether GIS is a legitimate field of scientific study while recognising the role of GIS as a set of tools to support scientific work.

Sound scientific or technical understanding of a domain is required in order to develop an operational data model that will be accepted within the discipline. Without this, the model will not be an accurate representation of the real world.

2.8 GIS AS A MODEL OF REALITY

GIS operators do not commonly think of their work as modelling, but the opposite is true. The simplification of real world elements into discrete spatial entities and linking them to relational databases where attributes and records store information about the entities is simply another kind of modelling. Goodchild (1994) clarifies this by what he refers to as *discretisation*, stating that as data is collected decisions are made through generalisation, abstraction and approximation, thereby affecting the use of the data. Church (2002) similarly refers to the generalisation or abstraction of data which then reduces it to a manageable

quantity, resulting in raster and vector GIS data elements. The degree of abstraction in a model requires a balance between human comprehension of the system and current computing power.

Figure 2.3 shows a hierarchical continuum of abstraction from a real-world situation into abstract spatial objects in a GIS. The real world is simplified by being captured as a remotely sensed image, simplified using image processing software, which is then converted to vector format and integrated into a GIS.
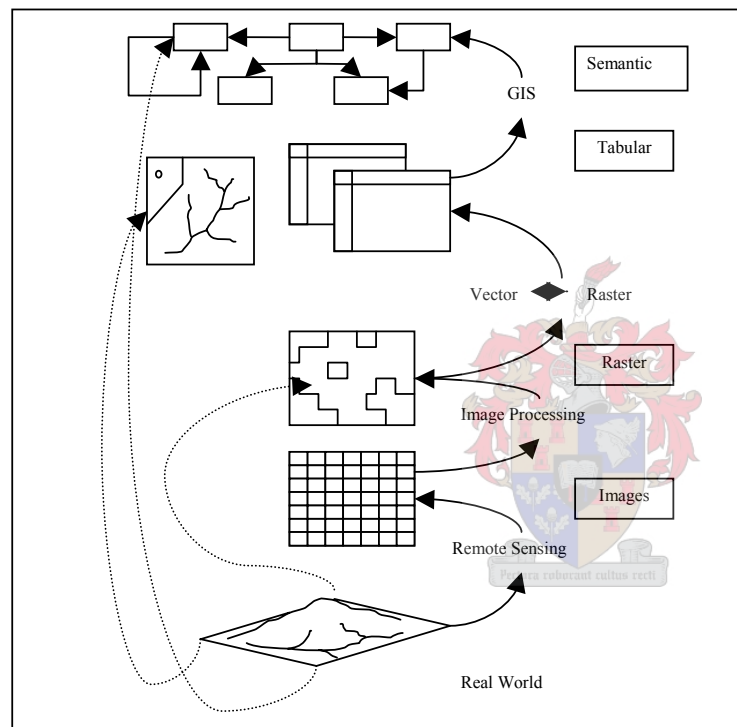
Source: Maidment 1993

Figure 2.3 – Hierarchy of abstraction from the real world to a GIS

The notion of a model is an idealised representation or an abstraction in order to describe the real world in a schematic or less complex form (White, Mottershead & Harrison 1992). In the natural sciences, computational or predictive models are used to describe how systems operate and predict how such systems will react to specific external stimuli. *Descriptive models* are an abstract representation of a real situation whereas *predictive models* develop scenarios based on variables and inputs determined by the modeller (Starfield, Smith & Bleloch 1990).

The research contained in this thesis is concerned with the development of a descriptive model of borehole information.

The conventional descriptive models used to depict geographic variations and features are referred to as *geographic data models* (vector, raster, GRID, TIN). These are discussed briefly in the following section.

2.9 GEOGRAPHIC DATA MODELS

Maidment (1993) recognises three main methods of representing spatial information in a GIS, namely the vector, raster and triangulated geographic data models. The vector model includes features such as points, lines, polygons and geometric networks while the raster model consists of images or grids. The Triangulated Irregular Network (TIN) is an example of a triangulated data model and is used to model surfaces. Each of these types of data models is better suited to represent specific types of data but in most modern GIS software applications, it is often possible to use all three models in an integrated analysis environment. The following sections describe these data models in more detail.

2.9.1 Vector

In contemporary GIS, the most common data model is the vector model that characterises discrete real world spatial features using points, lines and polygons (Zeiler 1999). Points are one-dimensional locations described in a two or three-dimensional space by coordinates, lines are a set of connected points, and polygon boundaries are defined by the beginning point of a line vector coinciding with the end point (Church 2002). Common examples of vector GIS applications are transportation, hydrology and land-parcels/cadastre (Church 2002; Maidment 1993).

2.9.2 Raster

Raster or Grid-based GIS uses a rectangular grid or image composed of equally proportioned cells or pixels (pixel elements) with each cell representing an individual value (Church 2002; Zeiler 1999). It is most often applied to represent features of a continuous or a thematic nature and can be classified according to the following common data types (Zeiler 1999):

1. Nominal data – representing categories of data, such as a vegetation map or a landcover classification.

2. Ordinal data – again representing categories, but usually those ranking values such as low, moderate, high.

3. Interval data – representing a progression of values with a meaningful difference interval such as concentrations.

4. Ratio data – representing a continuous range of values that have a zero point such as precipitation.

Raster GIS can be very useful when calculations incorporating individual layers such as weighting/rating models are required, particularly as most raster GIS software includes some kind of raster calculator that allows the user to apply complex equations in a mathematical expression builder (Zeiler 1999). Most complex spatial analyses are performed using raster data as their processing is more efficient than that of vector data. Land surface features such as elevation, slope and aspect are frequently represented using raster data (Maidment 1993).

2.9.3   Triangulated Irregular Network (TIN)

TINs are surfaces composed of a set of non-overlapping triangles, or faces that completely fill a prescribed area created by connecting three points representing continuous values (Zeiler 1999). The values used to create TINs are usually irregularly spaced points, in contrast to regularly spaced grids. This technology was developed as a more efficient alternative to rasters, for the modelling of volumes and hulls. This is illustrated in Figure 2.4 below.
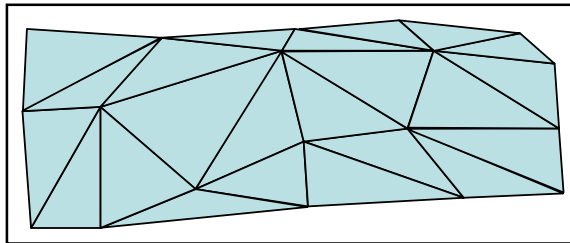
Figure 2.4 – Example of a triangulated surface

The launch of ArcGIS (Version 8) saw the introduction of the geodatabase a new geographic data model that enables the user to store geographic data in a relational database file along with relationships and attribute domains. This enables the development of more complex and realistic object-oriented data models. The next section will discuss geodatabases in more detail.

2.10   THE GEODATABASE

Before data modelling and GIS are explored, it is important to understand the geographic data model that the ESRI geodatabase utilises as the introduction of the geodatabase is fundamental to the application of descriptive data models within the ArcGIS environment. It uses the relational data model as a base, but adapts it in two fundamental ways. Firstly, it allows the geographic coordinates of spatial features to be stored in relational database tables and secondly, it allows relationships to be defined and stored in the database (ESRI 2002; Maidment, Moorehouse & Grise 2002; Zeiler 1999). The incorporation of these object-oriented features in the relational database has resulted in the *object-relational model* (Twumasi 2002).

Geodatabases use existing database formats – Microsoft Jet Access for the personal geodatabases and large enterprise database packages such as Oracle (through ArcSDE) for multi-user geodatabases. Moreover, the geodatabase allows for the inclusion of more behavioural information and paves the way for the development of domain specific data models, encapsulating features and information specific to that discipline.

The geodatabase geographic data model has several advantages over existing models. Firstly, all common types of geographic data (vector, raster, CAD) can be managed in a single database in addition to intelligent features such as rules, domains and relationships (Kaunda 2001; Zeiler 1999). The management of data in a relational database also allows versioning of the database, making multi-user editing possible. Finally, ESRI provide the building blocks of ArcGIS – ArcObjects – with the software, allowing software engineers considerable freedom to develop custom applications (Zeiler 1999). Figure 2.5 illustrates the internal structure of a geodatabase, as seen through the ArcGIS ArcCatalog.
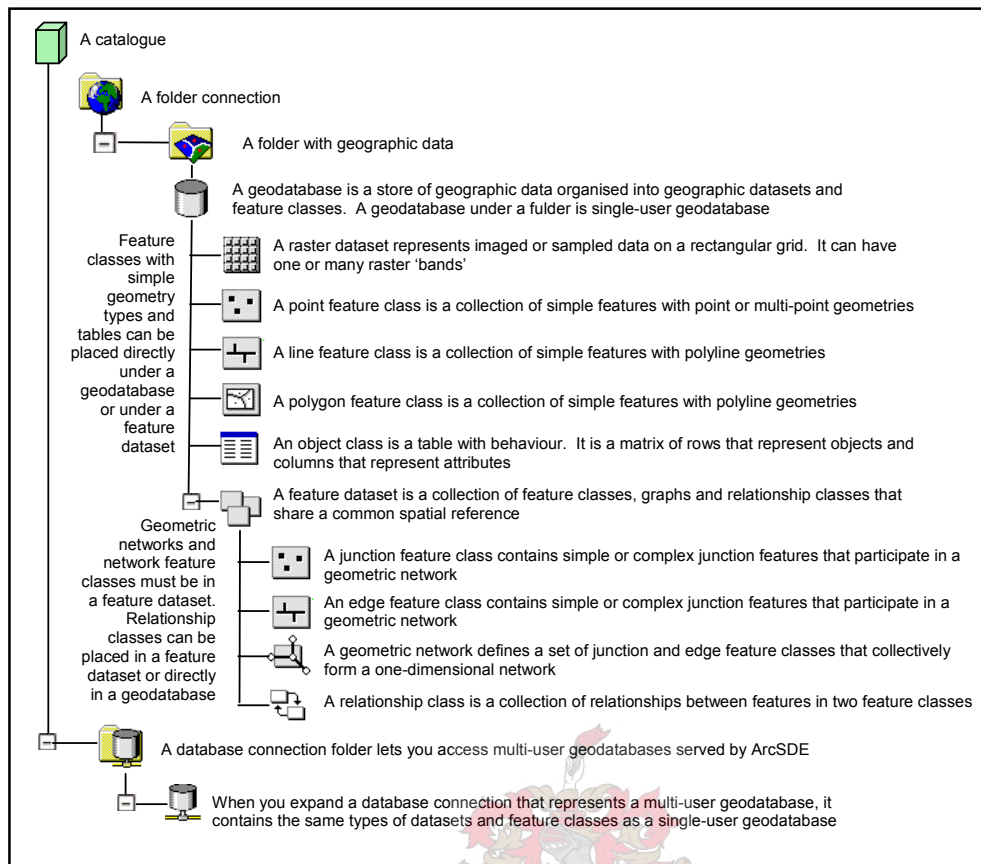
Source: Zeiler 1999

Figure 2.5 – View of a geodatabase through ArcCatalog

Water resource assessment and management are inherently spatial issues, making GIS an ideal tool to contribute to research and decision making in these arena (Wilson, Mitasova & Wright 2000). With the new object-relational technology available within ArcGIS, ArcHydro was developed in order to create a holistic hydrological data model for GIS. ArcHydro was the first complete and fully documented ESRI supported data model to be released. The ArcHydro data model, although dealing mainly with surface water resources, is an important reference for this research, as it assists in the development of understanding of how a natural system can be abstracted into a geodatabase schema. Numerous other data model specifications are in development, many near completion. For a full list of the current projects, please refer to Section 2.15.

2.11   GIS FOR WATER RESOURCES

In the preface for *ArcHydro: GIS for Water Resources* (Maidment 2002) Scott Morehouse offers some of the most salient advice found in the literature on the subject of data model

design. He warns against two great perils – the deserts of oversimplification and the miry swamps of complexity. Whilst these hydrological metaphors are humorous in nature they provide the key to the data model design. In developing a data model a designer must abstract to a level where the objects are efficient representations of the real world environment without filtering out the unique characteristics that make this a natural system. Further to this, he identifies the balance that must be sought between solo design endeavours and what he calls the 'design by committee' paradigm – i.e., it is necessary to broaden ones perspectives with inputs from others whilst avoiding the 'political' approach to the design process.

Although the book is concerned primarily with the development, and most specifically the implementation of the ArcHydro data model, it does elaborate on several key points that should assist anyone developing a data model. This section will draw on the experiences and guidance offered in the text.

2.11.1 Development of a model framework

The ArcHydro team began by defining a *model framework* representing the core of the model to which further improvements can be made. Through this they were able to accurately portray user requirements while remaining as generic as possible and in order to appeal to as broad a segment of the user community as possible (Maidment, Moorehouse & Grise 2002).

2.11.2 Approaches to data modelling

Maidment, Moorehouse & Grise (2002) identify two key approaches to data modelling – *Inventory* and *Behavioural* approaches. The Inventory approach focuses on the individual elements of a system by building a list of its components and describing their location, properties and individual behaviour (Maidment, Moorehouse & Grise 2002). This approach provides a good method for defining individual objects in a system, and is often used for describing hydrological features and their place in a system. The Behavioural approach concentrates on how a system or its components behave. This 'systems oriented' approach leads to a more holistic understanding of a subject (Maidment, Moorehouse & Grise 2002). Reflecting on the apparent benefits of each approach, a hybrid is often applied. This integrates inventory-based analyses used to determine the elements of the system with the behavioural approach which develops a broader picture of the system. This integration is only achievable with knowledge of a system and an understanding of its connectivity (Maidment,

Moorehouse & Grise 2002). Due to the tabular nature of the SDB document, it is likely that a model developed through this research will follow the inventory approach.

Three main success factors were identified by Maidment, Moorehouse & Grise (2002) in the development of ArcHydro – geometric networks, geodatabases and the object modelling process. The latter is the most relevant to this study and its basic principles will be reviewed in the next section.

2.12   OBJECT ORIENTED DATA MODELLING AND GIS

The Microsoft Component Object Model (COM) is a protocol that allows software components to communicate (Microsoft 2005). ESRI used the Visual Basic programming language and ArcObjects to develop ArcGIS which conforms to COM (Maidment, Moorehouse & Grise 2002). This object-oriented approach to software development and databases allows the inter-operability between software packages and data formats. This section aims to explain the basic elements of object-oriented databases and object-oriented design.

2.12.1 The Object

The fundamental building block of object-oriented design is the *object*, the semantics of which are clearly laid out by a number of authors (Hughes 1991; Twumasi 2002; Worboys 1994; Yourdon 1994). It is an abstraction of a tangible, real-world phenomenon or conceptual entity with state, behaviour and identity (Yourdon 1994). Or as Worboys (1994) expresses it:

$$Object = State + Functionality$$

Objects with similar behaviours are organised into *types*, and object *classes* are groupings of objects with corresponding data structures and methods (Worboys 1994; Yourdon 1994). The object-oriented database development methodology relies on three fundamental concepts: *Abstraction, Encapsulation* and *Inheritance* (Yourdon 1994).

2.12.2 Abstraction

The object-oriented method, as with most modelling endeavours, relies heavily on abstraction. As discussed earlier, this is the process of simplifying a real world system to basic elements (Kaunda 2001; Yourdon 1994; Maidment 2002). In ArcGIS these basic elements are referred

to as objects (attribute tables) and features associated (spatial elements). A class is a group of objects with similar attributes or behaviours (Maidment 2002; Demartino & Hrnicek 2001; Zeiler 1999) – i.e. a feature class is a group of features with similar attributes. Through this approach the data model better emulates real world conditions than standard geographic data models. With this technology it is possible to predefine properties unique to that object and *bind* them to that object (Demartino & Hrnicek 2001).

2.12.3 Encapsulation

Most software systems and database designs require functionality, but not necessarily in an explicit manner – i.e. the end user does not see how it functions (Kaunda 2001). Encapsulation is also defined as the object containing both the data and the methods required to determine its behaviour in a unit not accessible other than through a user defined software interface (Davis & Maidment 1999; Evans, Jurday & Lawrence 2002; Twumasi 2002).

2.12.4 Inheritance

In object-oriented database development, a class or feature is able to re-use attributes from other classes or features, thus reducing duplication. This concept is called *inheritance* (Hughes 1991; Twumasi 2002; Yourdon 1994; Zeiler 1999). A feature that shares attributes with a parent class, but also have others specific to it, is known as a sub-class. For example, in a natural system, insects, mammals and birds are all living creatures which share some attributes, but having many other attributes specific to their *sub-class*, as illustrated in Figure 2.6.
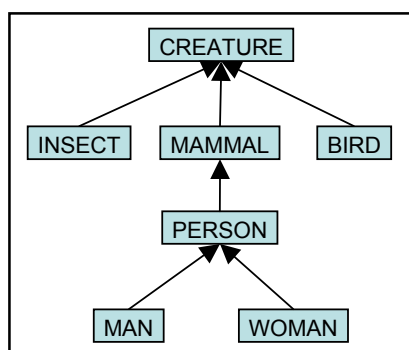
Source: Hughes 1991

Figure 2.6 – Example of an inheritance hierarchy

A more GIS oriented example of inheritance is provided by Twumasi (2002). This can be seen in Figure 2.7 where the spatial object has two subclasses – linear and area. *Linear*

Objects has transportation as a subclass, which in turn has three subclasses, *Road, Railway* and *Canal. Area Objects* has *Hydrography* as a subclass and it in turn has three subclasses, Canal, River and Lake. Note that Canal can be a subclass of *Hydrography* or *Transportation*. This is known as *multiple inheritance*.
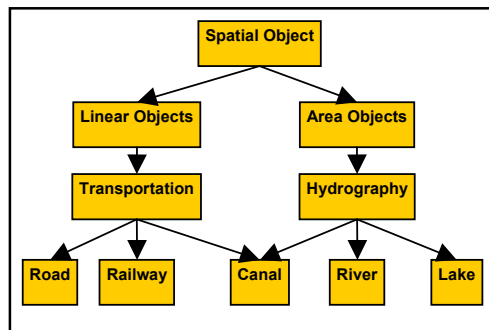
Source: Twumasi 2002

Figure 2.7 – Inheritance of object classes

In addition to the object approach and its three key concepts, the power of the object-relational model is in the application of *Behaviour, Relationships,* and *Data Integrity* to design a richer model of the real world.

2.12.5 Behaviour

The term *Behaviour*, when applied to object-oriented data models, doesn't have the same meaning as behaviour in the real-world sense. It rather refers to a data model designer's ability to tell the database how to react. This is done by defining custom properties for each object through relationships and data integrity routines such as *domains*. Kaunda (2001:13) refers to this as "methods acting on the state of an object upon invocation of commands" – where methods are rules defining behaviour of an object and state is simply defined by the values or attributes of object.

2.12.6 Relationships

In object-oriented data models there are three kinds of relationship: *Associations, Generalisations* and *Aggregations*.

2.12.6.1   Associations

In the real-world, associations between objects provide context and define behaviour. In order to emulate such characteristics in a logical data model, it is necessary to define

relationships between objects and classes. A relationship is a named association between two or more entity types (Hughes 1991). Therefore, these relationships can be defined between two attribute tables, an attribute table and a spatial feature, and between two spatial features. Relationships are usually described by their *cardinality* which is the number of connections or associations it can make (Zeiler 1999). Types of cardinality are defined in Table 2.6 below.

Table 2.6 – Types of cardinality and their role in a database design.

Cardinality	Example	CASE Tools symbology
One to One (1:1)	The relationship HEAD_OF between the entity types MANAGER and DEPARTMENT is 1:1. This means that a department has at most one head and that a manager is head of at most one department.	1 to 1
One to Many (1:N)	The relationship SUPERVISES between the entity types MANAGER and EMPLOYEES is 1:N. This assumes that a manager may supervise any number of different employees but a given employee is supervised by at most one manager.	1 to *
Many to Many (N:M)	The relationship ASSIGNED_TO between the entity types EMPLOYEE and PROJECT is N:M. Thus an employee may be assigned to many different projects and each project may have many employees assigned to it.	* to *

Source: Hughes 1991

As already stated, the geodatabase model allows these associations to be defined and stored in the database as a relationship class (Kaunda 2001) and these become part of the database schema. Relationship classes are important when defining a relationship between two objects that cannot be described through a physical or topological association and can be used in a data model to define how objects behave when related objects are changed (Zeiler 1999).

2.12.6.2 Generalisations

A generalisation is a relationship between a parent class and a subclass in an object-oriented data model (Twumasi 2002), it is also known as an inheritance (see section 2.12.6).

2.12.6.3 Aggregation

A class that is composed of several objects is known as an aggregation (Hughes 1994; Twumasi 2002). The linkages that comprise an aggregation can always be tested using a

notion of lifespan. If a composite object is destroyed, it implies that all of the parts that it is composed of, are also destroyed (Twumasi 2002).

2.12.7 Data Integrity

"No observation of geographic information will ever be perfect" (Duckham *et al* 2001:1), however it is important that data entry errors are minimised. Maintaining correctness and data consistency is another major task that cannot be overlooked (Hughes 1994). Data integrity in object-oriented geodatabase models is achieved through the application of validation rules (Zeiler 1999). The most applicable validation rules in this study are attribute domains as they can control the entry of data to the schema.

2.12.7.1 Attribute domains

In a geodatabase design, different attribute domains – range and coded value domains – can be applied in order to constrain data entered to a specific set of values. A range domain allows the user to enter data between two specified values such as pH, which can only be from 0 to 14 (Zeiler 1999). A coded value domain (CVD) restricts the input of data by providing a set of values that the user must choose from, such as landcover types. This is especially effective in reducing typing errors as the user simply selects a value from a list (Zeiler 1999). Through these interventions at the design stage, the opportunities for error and error propagation are removed.
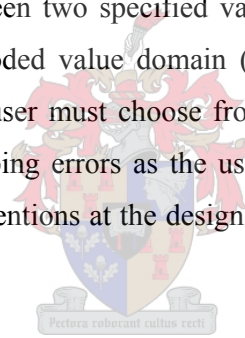
2.12.8 Object-Oriented Design and Development

Hughes (1991) breaks the process of data model design into to two phases: the development of a conceptual model design which involves abstracting real world entities and systems; and creating a database schema from this design with a logical data structure that can be implemented in a 'physical' database. In essence, the first element covers abstraction, encapsulation and inheritance, with the definition of the actual model covered by the design phase.

In Figure 2.8 Worboys (1994) illustrates a simplified lifecycle of system refinement. This diagram shows the progression from real-world phenomena through to the physical computational or data model.
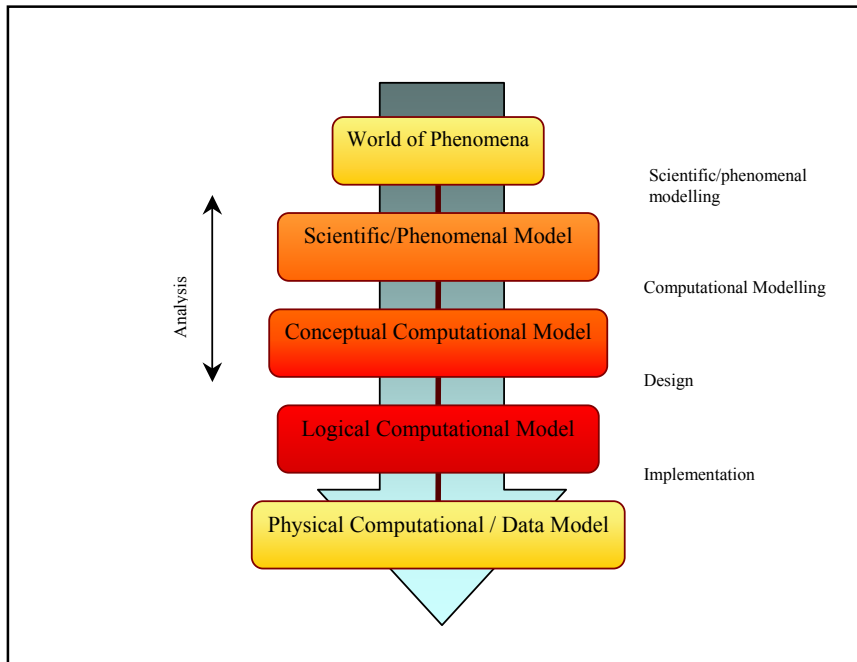
Figure 2.8 – Representation of the lifespan of scientific modelling

Worboys (1994) goes on to describe the inputs to this progression as real-world processes described by appropriate computationally tractable, abstract scientific or phenomenal models, which are independent of any specific computational paradigm. This means that reality is broken down into systems, represented or described using simplified processes and relationships – i.e. an abstraction of reality. Zeiler (1999) captures the same progression in Figure 2.9, showing the deconstruction of reality into a logical data model that is used to develop a database model that can be implemented using GIS.
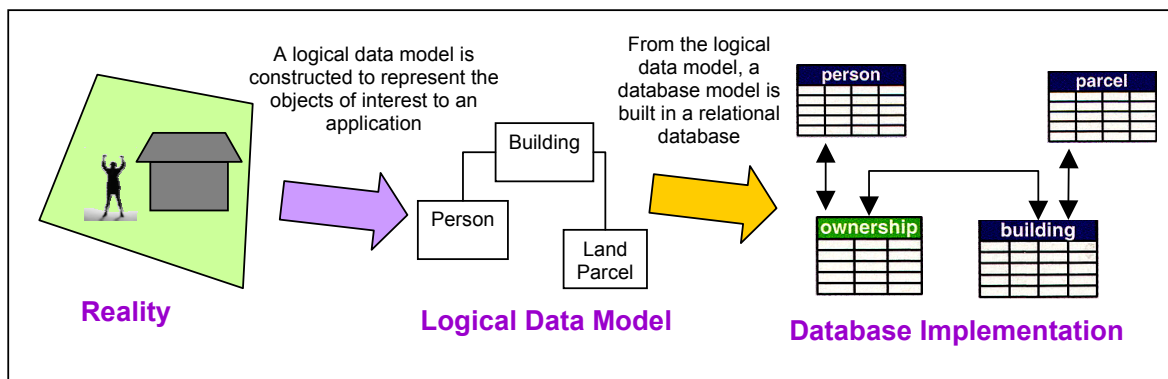
Figure 2.9 – Data model development from reality to implementation.

2.13   CASE TOOLS

There are three approaches to creating geodatabases in ArcGIS: an existing database can be migrated across to a geodatabase using conversion tools; ArcCatalog and ArcToolbox can be used to manually build a geodatabase using tools and routines provided; and finally Unified Modelling Language (UML) and Computer Aided Software Engineering (CASE) Tools can be used to generate a geodatabase schema (Perencsik *et al* 2004b). CASE tools are software packages designed to apply data dictionaries in a graphical user interface to generate, analyse and validate UML diagrams (Hughes 1991; Kaunda 2001). "UML modelling CASE tools enable us to apply the formal object-oriented analysis and design methodology and abstract away from the entanglement of source code, to a level where architecture and design become more apparent and easier to understand and modify" (Zhao 2003:1). Common CASE software applications include *Microsoft Visio* and Rational Software Corporation's *Rational Rose*.

The components required to build a geodatabase using CASE tools are provided with ArcGIS. Visio and Rational Rose template diagrams of the ArcInfo UML model are installed by the installation process of ArcGIS (Perencsik *et al* 2004a). When the drawing template is opened in one of these packages the basic elements required to build a geodatabase are present. These are Logical View, ESRI Classes, ESRI Interfaces, ESRI Network, and a Workspace (Perencsik *et al* 2004a).
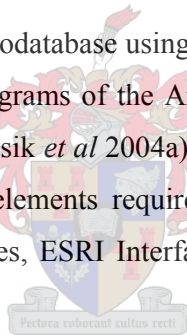
The overall strategy for designing a geodatabase using CASE Tools is illustrated in Figure 2.10 where the UML model is created using the CASE tools, the model is exported to XML Metadata Interchange (XMI) format or a database repository, and the schema is created using tools in ArcGIS ArcCatalog.
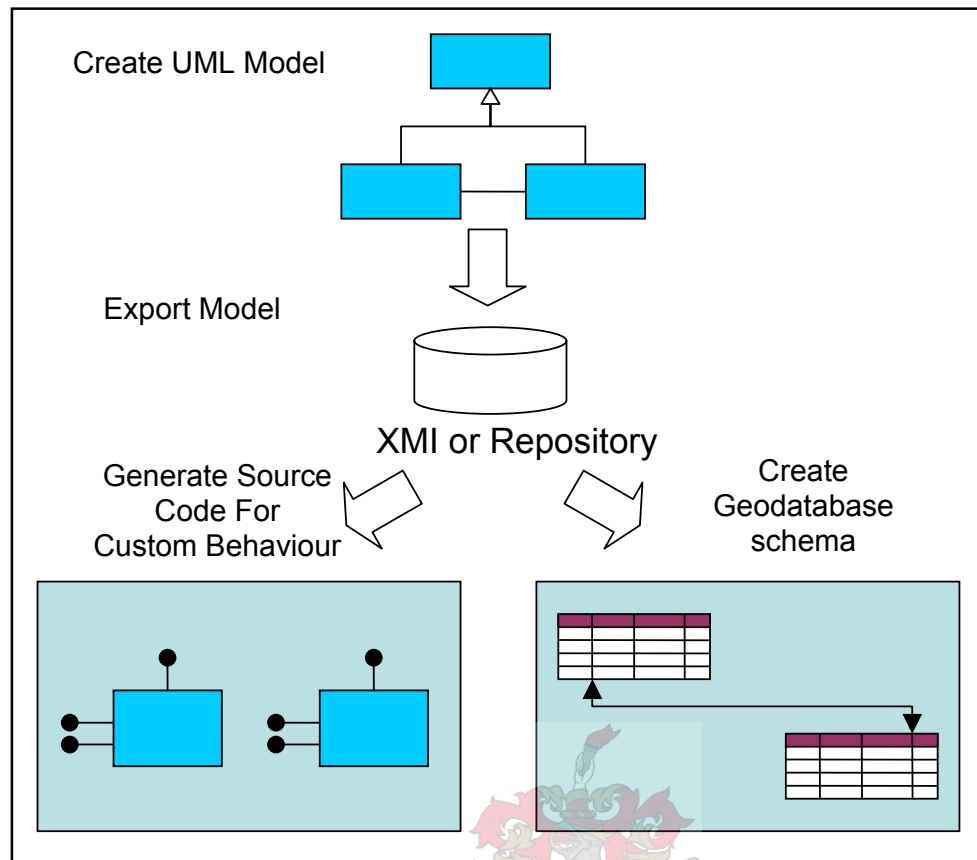
Figure 2.10 – Designing and creating a geodatabase using UML and CASE tools

In addition to the ability to create a database model and schema using easy-to-learn visual methods, there are several other advantages to using CASE tools for database design. The model diagram is easy to share and distribute, is visual in nature and easy to read and interpret, and it can be used to automatically create objects and code (Davis 2000; Perencisk 2004b).

This concludes the background information on object-oriented data model design. The next section will review progress made on the ArcHydro groundwater data model which is relevant to the research objectives of this study.

2.14   ARCHYDRO GROUNDWATER DATA MODEL

The Arc Hydro data model is a conceptualisation of surface water systems and describes features such as river networks, watersheds and channels. The data model can be the basis for

a *hydrologic information* system supporting hydrologic analysis and modelling through the coupling of data sources and data streams (Maidment 2002). This existing implementation of ArcHydro is illustrated in Figure 2.11 and shows the four different surface water components currently defined in the data model, and their link to time-series information.
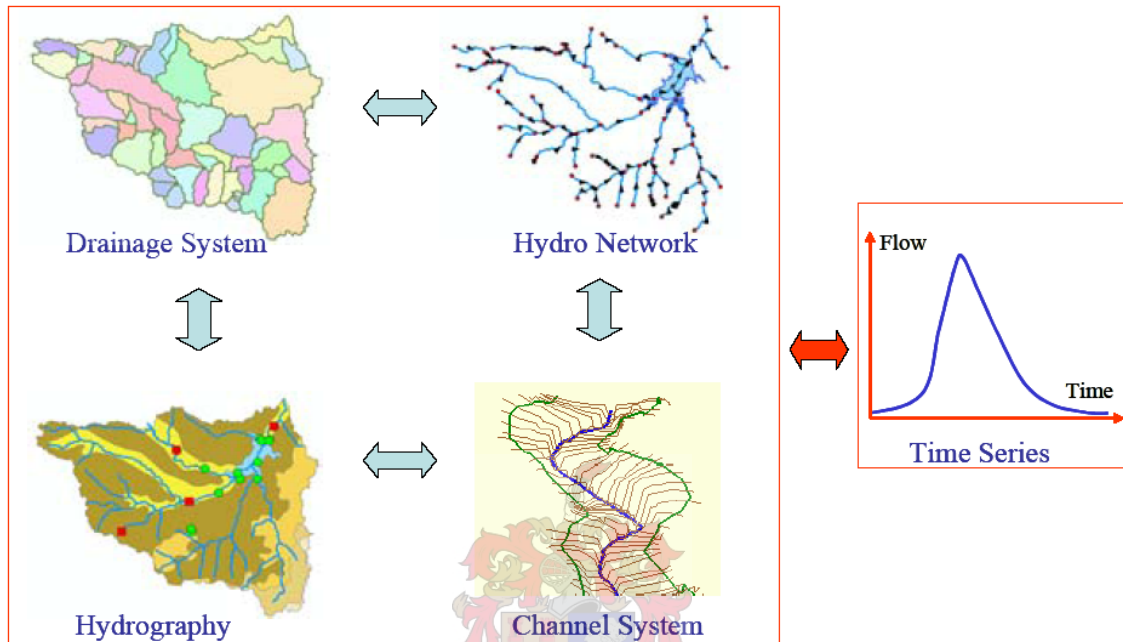
Source: Strassberg & Maidment 2004

Figure 2.11 – ArcHydro surface water components and the link to time series

The groundwater data model adds a new geohydrological dimension to ArcHydro by including subsurface hydrological features such as aquifers, hydrogeologic units, wells and borehole information and is illustrated in Figure 2.12. Although the model appears to be near completion, only one conference paper on it exists in the literature. The material appearing in this section is dependant on this one source (CRWR 2004).
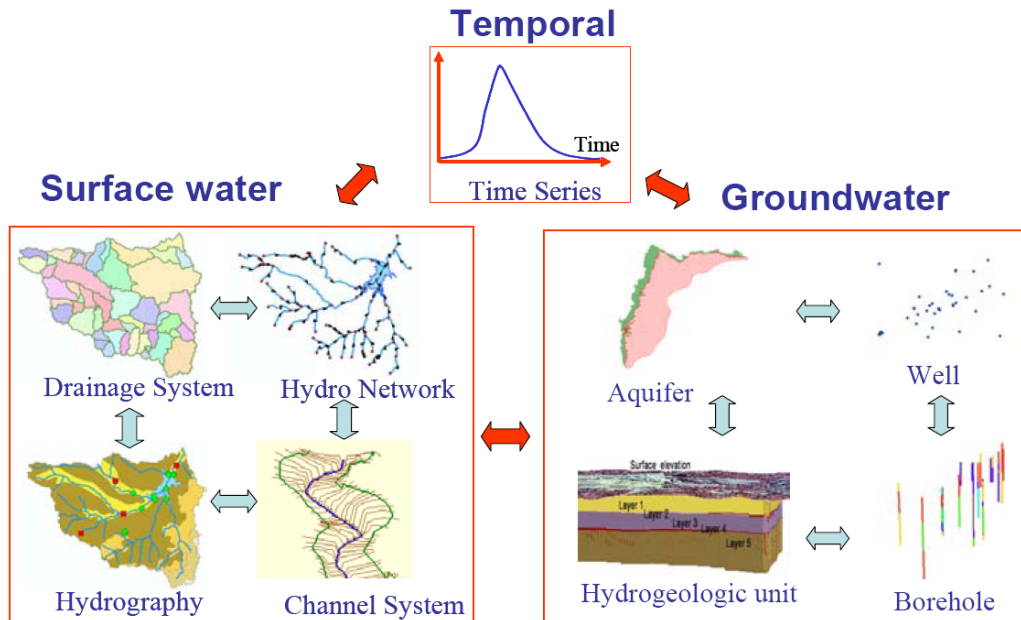
Source: Strassberg & Maidment 2004

Figure 2.12 – Arc Hydro data model with the new groundwater components

This data model describes in some detail the generic subsurface features required for most geohydrological data management and modelling. It combines two-dimensional features such as aquifers extent, three-dimensional features such as *borelines* – 3D lines that follow the sub-surface path of the borehole – and tabular data (see Figure 2.13). All of these are important in the characterisation groundwater of groundwater resources.
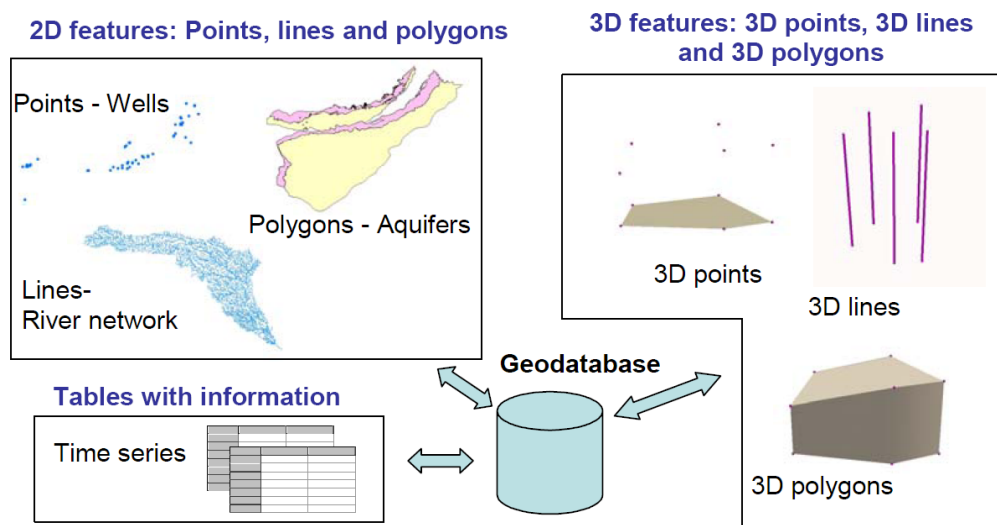
Source: Strassberg & Maidment 2004

Figure 2.13 – 2D and 3D features in the ArcHydro groundwater data model

In addition to the data modelling of generic groundwater components, the ArcHydro groundwater data model includes specific tools for viewing and analysing data stored in the geodatabase schema, and maintaining the data structure in such a way that it can be used directly by the groundwater modelling software package MODFLOW (Strassberg & Maidment 2004; Maidment, Norman & Strassberg 2004). In the same way that the standard ArcHydro model is a functioning but generic data model that should be used as a base upon which a complete model can be developed, the groundwater component is equally generic. Maidment, Moorehouse & Grise (2004) concede that it would be impossible to include all types of groundwater information and that they have tried to cover the basic hydrogeologic components required for groundwater modelling.

A number of other data modelling activities are currently in progress through the Data Model Industry Groups. The following section briefly describes the other domain areas covered in such work.

2.15   APPLICATION OF DATA MODELS

In an effort to promote and support data modelling activities, ESRI have developed Data Model Industry Groups focussed on a variety of industries and disciplines. Academic and industry leaders collaborate with ESRI to design and create data model templates that can be used by other users. The result of these consortia is the existence of a wide variety of data model structures that can be implemented in different industry sectors and scientific disciplines (ESRI 2005). These groups are at different stages of development, from group inception through to full implementation of data models with case studies, templates and supporting documentation. In many cases a final geodatabase schema is available for download.   The existing Data Model Industry Groups are listed in Table 2.7.

Table 2.7 – Current ESRI Data Modelling Groups initiatives

Agriculture	Archiving
Atmospheric	Basemap
Biodiversity	Census-Administrative Boundaries
Defense-Intel	Energy Utilities
Environmental Regulated Facilities	Forestry
Geology	Health
Historic Preservation and Archaeology	Homeland Security
International Hydrographic Organization (IHO) S-57 for ENC	Land Parcels
Local Government	Marine
National Cadastre	Petroleum
Pipeline	Raster
Telecommunications	Transportation and Water Utilities

Source: ESRI 2005

The following chapter presents the method applied to design the data model for boreholes, translating the user requirements presented in the SDB and the process for converting the data model into a finished geodatabase schema.
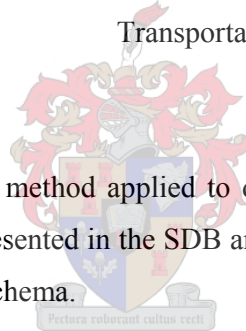
CHAPTER 3 : DESIGNING THE DATA MODEL

3.1 INTRODUCTION

Following an analysis of the literature, it was apparent that the key elements in a successful design process are appreciating the issue being modelled, and successfully translating the user's needs into a clear and efficient logical data model (Hughes 1991; Maidment 1999; Yourdon 1994; Zeiler 1999). The understanding required to achieve this is specifically that of grasping how features relate to each other and how the data model structure effectively represents a system. This chapter presents the methodology and process followed to translate the user requirement specified in the Standard Descriptors for Boreholes (SDB) to a data model design. It then describes how this design was implemented in a GIS environment through conversion to a geodatabase schema.

3.2 THE DESIGN PROCESS

In the book *Modelling Our World*, Zeiler (1999) suggests that the development of a geodatabase data model design should follow the steps highlighted in Figure 3.1, a process followed by Maidment (2002) in the development of ArcHydro. The same design process was applied in this research.
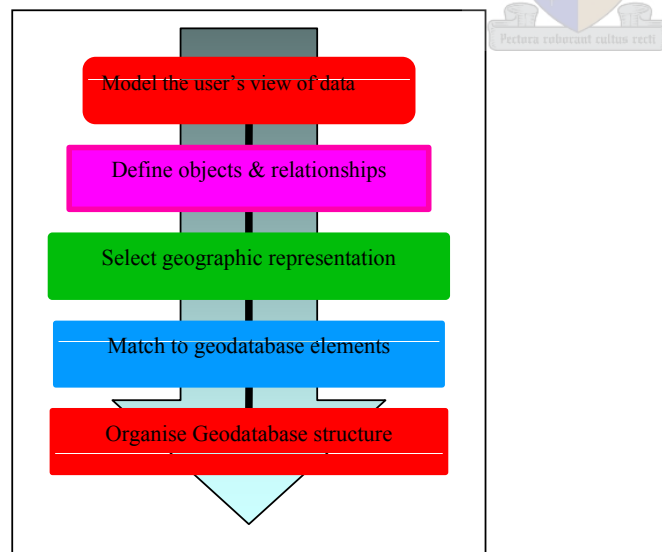
Source: Zeiler 1999

Figure 3.1 – Geodatabase design process steps proposed by Zeiler (1999)

Yourdon (1994) concurred with this approach, stating that software engineers make a clear distinction between the *Analysis* required to build a system and the *Design* of the system itself. Analysis is concerned with what the system must do and design is concerned with how requirements are implemented. The following three sections are an analysis of what the model had to achieve and the subsequent two engage the design process that transformed the conceptual model into a data model design.

3.3 MODEL THE USERS' VIEW OF THE DATA

The first of the five steps in Zeiler's (1999) methodology of designing a data model is to model the users' view of the data. A user requirements analysis is possibly the most important step in the development of any database. If a thorough and detailed user requirements analysis is carried out, it enables the designers to fully appreciate the subject matter informing the design. Fortunately this had, in essence, been covered by the development of the SDB. The SDB document was created as a field guide for capturing borehole data and collecting relevant supporting information (DWAF 2003a). It clearly states the standard attributes that should be captured and alludes to relationships between the different features and elements. The only information that could not be sourced from the SDB document was the list of monitoring parameters. These were obtained from discipline specific options provided in *Integrated water resources management: guidelines for groundwater management in WMAs of RSA* (DWAF 2003b). Table 3.1 below collates the types of data outlined in the SDB that were included in the data model design.

Table 3.1 – Data types identified from the SDB

Types of Data	Data Source
Borehole point data	Contractor /DWAF
Drilling information (geology, waterstrike, equipment installed, gravel/filters installed, development chemicals, etc)	Contractor
Operational management information	Borehole owner/DWAF
Monitoring information	DWAF

Source: DWAF 2003a

In order to build the skeleton of the data model, the data types identified in this section had to be classified as objects and the relationships between them defined.

3.4 DEFINING OBJECTS AND RELATIONSHIPS

The objects required to represent the information stated in the SDB weren't particularly complex. The majority of the data involved in fully describing a borehole were non-spatial in nature and required a tabular structure. Only the location of the borehole and its vertical expressions were spatial. Table 3.2 lists the data types described in Table 3.1 as objects also proposing relationships and identifying which feature they relate to. This is the second step of Zeiler's (1999) design procedure.

Table 3.2 – Objects and relationships determined from the SDB Chapters

Objects	Related to
GeoSite	
Borehole	-
Vertical Expression of Borehole	Borehole
Borehole Vertical Events	Borehole
Drilling Details	Vertical Expression of Borehole
Geological Details	Vertical Expression of Borehole
Water-strike	Vertical Expression of Borehole
Equipment Details	Vertical Expression of Borehole
Gravel/filter Details	Vertical Expression of Borehole
Pump Testing Events	Borehole (location)
Operational Management	Borehole (location)
Monitoring Events	Borehole (location)

As all of the information in the SDB is focussed on the borehole itself, the relationships required to describe a borehole in a GIS environment were similarly focussed on relating information about the borehole with the object representing the borehole location (see Table 3.2). The third step of Zeiler's (1999) process dictates that geographical representations for each of the spatial features described above must be selected.

3.5 SELECT GEOGRAPHIC REPRESENTATIONS

As boreholes are discrete entities, vector types were used to characterise the borehole geometry. A borehole is commonly described as a location and was therefore most appropriately characterised using point geometry. However, in order to add context to the description of the borehole beyond a point, a 3D vertical line was used to represent the downward path of the borehole. This 3D line is referred to as the *boreline* (Strassberg & Maidment 2004). Using this approach allowed segments of the boreline to be classified

according to thematic information such as drill diameter or casing installed, and boreline events such as water-strikes were included as 3D point features. This concept is illustrated in Figure 3.2.
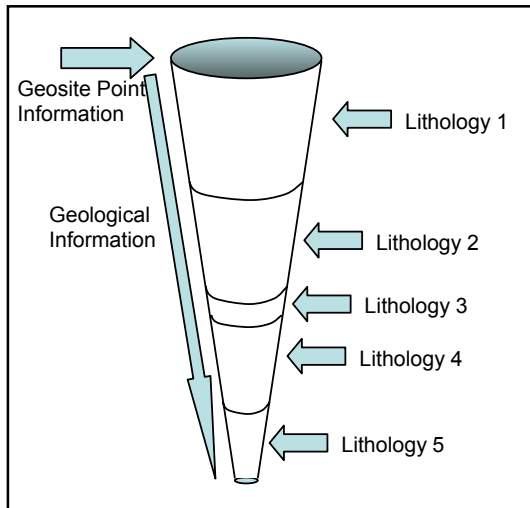
Figure 3.2 – 3D representation of a classified boreline

Appropriately defined relationships between attribute tables and the 2D point feature and 3D features allowed the representation of the more abstract information related to the drilling, construction and management of a borehole.

Expanding on the definitions made in Table 3.2, the *spatial types* of each object were added (see Table 3.3). The spatial features were classified as points or lines and the tabular objects defined solely as *objects*.

Table 3.3 – Spatial representations of data

Objects	Related to	Spatial type
GeoSite		
Borehole	-	Point
Vertical Expression of Borehole	Borehole	Z Line
Borehole Vertical Events	Borehole	Z Point
Drilling Details	Vertical Expression of Borehole	Object (table)
Geological Details	Vertical Expression of Borehole	Object (table)
Water-strike	Vertical Expression of Borehole	Object (table)
Equipment Details	Vertical Expression of Borehole	Object (table)
Gravel/filter Details	Vertical Expression of Borehole	Object (table)
Pump Testing Events	Borehole	Object (table)

| Operational Management | Borehole | Object (table) |
| Monitoring Events | Borehole | Object (table) |

With correctly defined spatial types it was then possible to match these spatial types to geodatabase elements in the final step of the process.

3.6 MATCH TO GEODATABASE ELEMENTS

The five-step design process proposed by Zeiler (1999) further assisted in un-packing the user requirements and the definition of objects, relationships and geographic representations. The analysis of the user needs in the previous three sections, through the expanding table format, facilitated the design of the data model. Using the information from the previous step (Table 3.4), the abstracted spatial elements were assembled in a schematic diagram or *logical data model* of the spatial features. Figure 3.3 shows how these elements were arranged using the object-oriented theory described in the previous chapter. The *feature* was the generic ESRI feature class provided with the ArcInfo Visio CASE tools template. Applying the rule of *inheritance*, all classes below it inherited its attributes which were in this case the generic ArcGIS spatial objects attributes allowing the storage of geometry in a relational database. The attributes common to all geosites were present in the Geosite class such as – positional coordinates, method of siting, accuracy of the position, geomorphology and landcover. The *instances* of Geosite – borehole, dug well, etc – were defined as subtypes of the Geosite class and inherited the above mentioned attributes. Moreover, the borehole subtype had its own specific attributes, such as adherence to drilling standards and pump testing details.
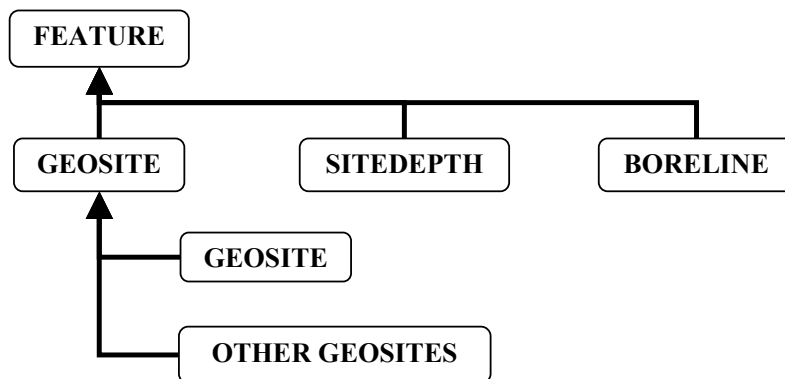
Figure 3.3 – Logical data model

Object types were then defined in Table 3.4 using the ArcInfo geometry nomenclature – point, line, polygon, or table – where the prefix Z associated with certain spatial features denotes a 3D object with altitude (Zeiler 1999).

Table 3.4 – Matching to geodatabase elements

Objects	Related to	Spatial type	ArcInfo Type
GeoSite			
Borehole	-	Point	Point feature
Boreline	Borehole	Z Line	Line feature
Borehole Vertical Events	Borehole	Point	Point feature
Drilling Details	Boreline	Object	Object
Geological Details	Boreline	Object	Relationship
Water-strike	Boreline	Object	Relationship
Equipment Details	Boreline	Object	Relationship
Gravel/filter Details	Boreline	Object	Relationship
Pump Testing Events	Borehole	Object	Relationship
Operational Management	Borehole	Object	Relationship
Monitoring Events	Borehole	Object	Relationship

Deconstructing the SDB in this manner helps the designer understand how the individual features should be represented in the geodatabase. The majority of the information in this data model was in table format related to the borehole and boreline spatial features.

3.7 ORGANISE THE GEODATABASE STRUCTURE

In the final step of the design process (Zeiler 1999) the elements described in Tables 3.1 to 3.4 were assembled as rough geodatabase elements (Figure 3.4).
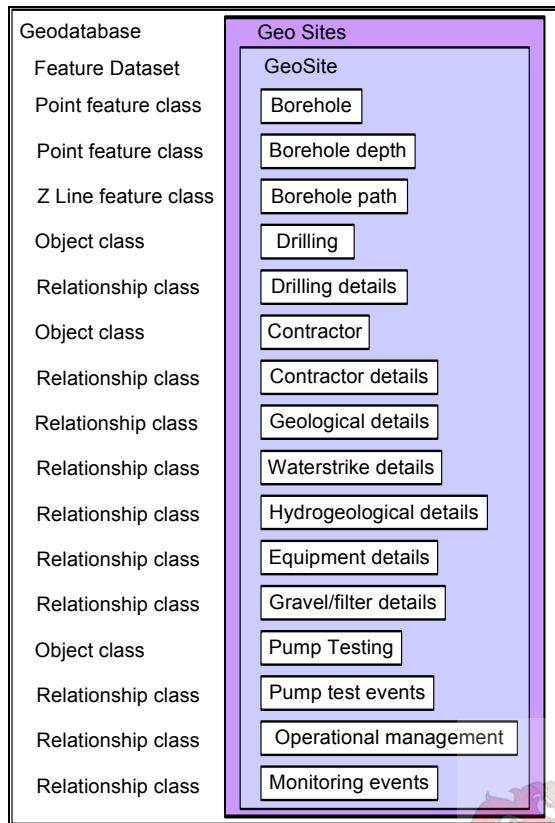
Figure 3.4 – SDB components organised into the geodatabase structural elements

This diagram and the classification used in it categorises the structural elements defined by the individual components used to build the UML data model diagram. The next chapter describes the process that was followed to build this diagram using CASE tools and the method used to convert it into a geodatabase schema.

CHAPTER 4 : PUTTING THE DESIGN INTO PRACTICE – CREATING A GEODATABASE WITH CASE TOOLS

4.1 BUILDING THE DATA MODEL USING CASE TOOLS

This section briefly describes the CASE tools used to build the borehole UML data model diagram, utilising Microsoft Visio 2003 Enterprise edition CASE Tools and the *ArcInfo UML Model* template file provided with ArcGIS[1]. The template provides a *workspace* with *Static Structure Diagrams* (SSDs) where the UML model is developed.

4.1.1   Static Structure Diagrams

In an effort to reduce confusion between the different types of elements within the UML diagram, each of the key elements of the data model – spatial objects, attribute tables, relationships and domains – were constructed on a separate SSD. An example of the use of separate SSDs is given in Figure 4.1a, where each SSD is shown as a new 'folder' in the workspace.
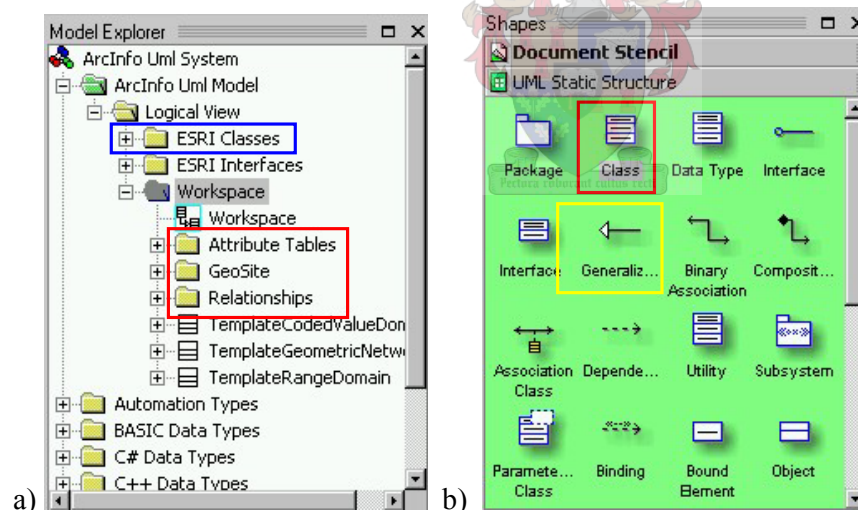
Figure 4.1 – Visio Model Explorer and UML Static Structure stencil
(a) Visio Model Explorer showing the SSDs (red), ESRI Classes Logical Views (blue) and (b) UML Static Structure stencil showing the class object (red) and the generalisation association (yellow).

---

[1] /Arcgis/arcexe83/CaseTools/UML/ArcInfo UML Model (Visio 2000).vst

To begin the construction of the spatial features SSD, a *feature class* was dragged onto the workspace from the ESRI Classes logical view (blue box in Figure 4.1a), followed by a class object from the UML Static Structure Stencil (red box in Figure 4.1b), and joined using a generalisation connector (yellow box in Figure 4.1b). The same process was followed to create the Objects SSD, but the departure point was the *object class* from the ESRI classes logical view. As new classes were created they appeared in the Model Explorer window (Figure 4.1a) and were then placed in the UML diagram to be customised using the class properties dialogue.

4.1.2   Class properties

It was necessary to define the class properties of all UML elements – classes, attributes and relationships – using the UML Class Properties dialogue. The class was given a unique name in the *Class Category* window and attributes *name*, *type* and *initial value* were defined in the *Attributes Category*, as shown in Figure 4.2. The type of attribute was determined by the nature of the data that it had to store – text/string, double precision or integer.
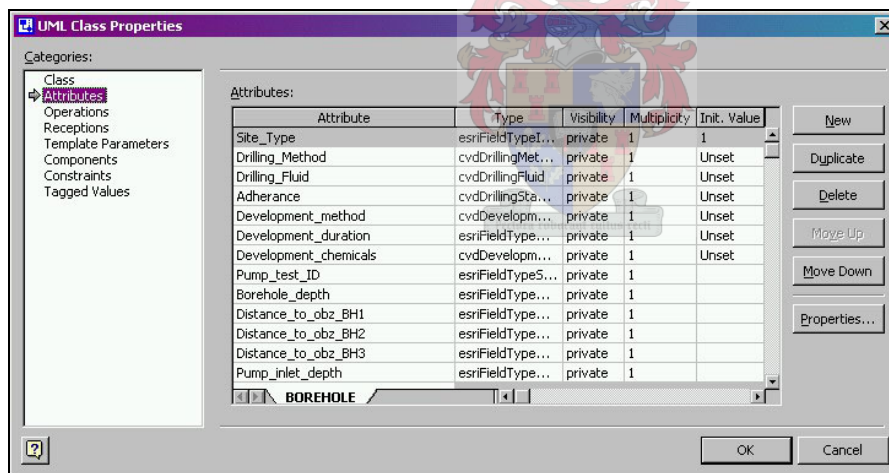
Figure 4.2 – The UML Class Properties dialogue

The initial value that appears as a default during data entry was defined at this stage, forming the first of several data integrity measures implemented in the design, (see section 4.1.4). Each attribute had its own properties that needed to be defined, for example if a text string field was added, *tagged values* defining the length of the field had to be specified.

4.1.3 Tagged values

It was also necessary to define tagged values for the attributes of all UML elements – classes, attributes and relationships – added to the data model. The tagged values are added as new *tags* and then defined in the *tag value window*. The standard tagged value was *length* – where the designer anticipates the longest probable entry for that field in the database. For example, (referring to Figure 4.3) if the tag length is added, then the tag length entered was '15'. The tagged value *scale* was also needed to define the number of decimal places in numeric fields such as *double precision* or f*loating point* data types.
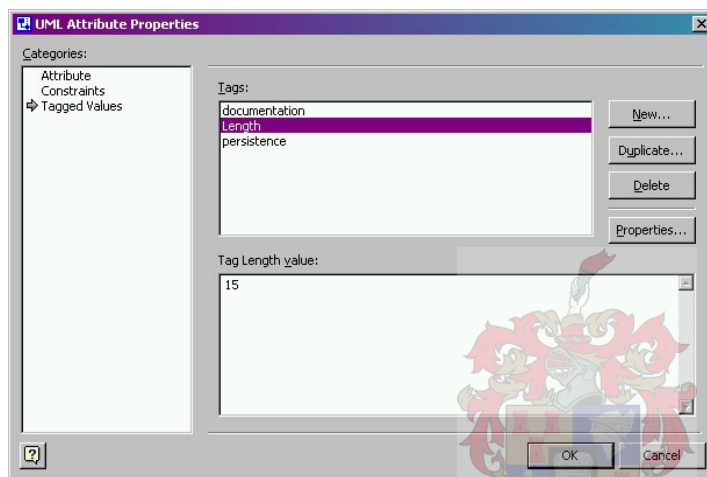
Figure 4.3 – Visio UML attributes properties tagged values dialogue

The second and most widely used data integrity measure that was applied to the data model was the use of *domains* – guiding data entry and removing opportunities for inconsistencies.

4.1.4 Domains

In order to minimise typing errors and variable responses, domains were applied to certain fields limiting how data is added to the database. Two main types of domains were used when developing the data model – *Coded Value Domains* (CVD) and *Range Domains*. For a CVD, the specific values that the end-user must choose from were listed and their attributes defined as described above. The value *undefined* was included in each domain list, so that end-users entering data still had an option when no data was available. Differentiating between *undefined* and *unset* values allows the end-user to determine where values had been overlooked and where there genuinely was no value. Figure 4.4 shows the CVD for *equipment type*, with the options available to the user listed and highlighted in red.

```
                    «CodedValueDomain»
                      cvdEquipmentType
+FieldType : esriFieldType = esriFieldTypeString
+MergePolicy : esriMergePolicyType = esriMPTDefaultValue
+SplitPolicy : esriSplitPolicyType = esriSPTDefaultValue
+Unset : <unspecified> = Unset
+Undefined : <unspecified> = Undefined
+Casing_steel : <unspecified> = Casing_steel
+Casing_stainless_steel : <unspecified> = Casing_stainless_steel
+Casing_uPVC : <unspecified> = Casing_uPVC
+Casing_Fibreglass : <unspecified> = Casing_Fibreglass
+Screen_steel : <unspecified> = Screen_steel
+Screen_stainless_steel : <unspecified> = Screen_stainless_steel
+Screen_uPVC : <unspecified> = Screen_uPVC
-Sump : <unspecified> = Sump
+None : <unspecified> = None
```

Figure 4.4 – CVD for Equipment Type

Instead of specifying a set of entries for an end-user to choose from, a *range domain* provided an upper and lower limit for a range of numeric values. Figure 4.5 shows an example of a range domain in the borehole data model where, as pH could not be lower than 0 or higher than 14, upper and lower limits were placed on the pH field of the *monitoring* attribute table.

```
                    «RangeDomain»
                        rngpH
+FieldType : esriFieldType = esriFieldTypeDouble
+MergePolicy : esriMergePolicyType = esriMPTDefaultValue
+SplitPolicy : esriSplitPolicyType = esriSPTDefaultValue
+MinValue : <unspecified> = 0
+MaxValue : <unspecified> = 14
```
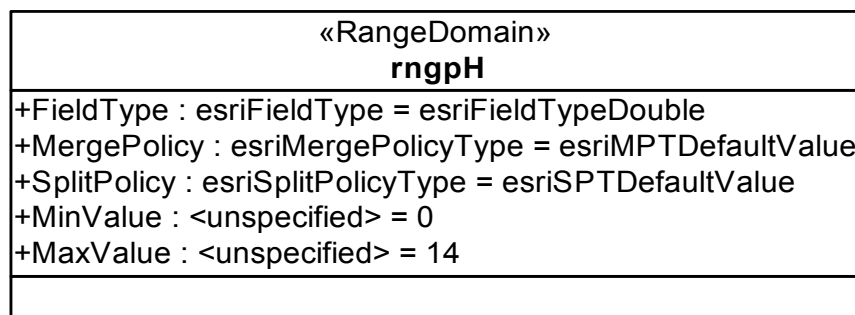
Figure 4.5 – Range domain rngpH

When the range domain had been defined, the field pH referred directly to it – rngpH – instead of an esriFieldTypeDouble data type, as shown in Figure 4.6. Also note that in this case the initial value was set at 7 – the value for neutral pH.
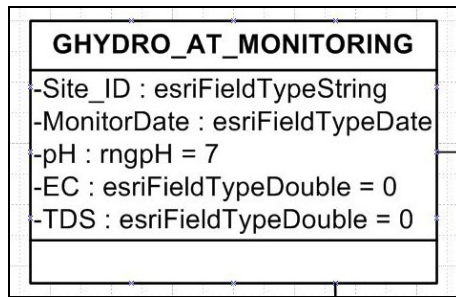
Figure 4.6 – Application of the range domain rngpH in the pH field

Once the data model had been created following the CASE tools methods outlined above, the result was a finished data model which is described in the next section.

4.2 THE DATA MODEL

4.2.1   The UML data model diagrams

The finished UML data model diagram was composed of a series of SSDs, each one describing a different aspect of the data model – Geosite, Attribute tables, Relationships and Domains.   The Geosites SSD described the arrangement and specification of the spatial features of the data model (Figure 4.7).   At the top of the hierarchy was the generic ESRI Feature Class and below this, the three spatial feature classes.   The prefix GHYDRO_* indicated the classes that were part of the data model while the SP denoted the spatial features. The GHYDRO_SP_SITE class contained the descriptive and location-related information for the geosite.   Below this was the subtype GHYDRO_SP_BOREHOLE, a point feature representing borehole geosites that also inherited attributes from the Feature and the GHYDRO_SP_SITE class.   GHYDRO_SP_SITEHOLEPATH represented the boreline and GHYDRO_SP_SITE_WATER STRIKE was a 3D point feature.

Figure 4.7 – GeoSite SSD

The non-spatial elements of the model – *objects* – were located in the *Attribute_Tables* SSD, as seen in Figure 4.8. The AT in each class name denoted an attribute table and the GHYDRO prefix once again indicated that the classes belong to this data model.

ESRI Classes::**Object**
+OBJECTID : esriFieldTypeOID

GHYDRO_AT_WATERSTRIKE
-Site_ID : esriFieldTypeString
-Waterstrike_ID : esriFieldTypeString
-Depth : esriFieldTypeDouble
-Blow_yield_of_strike : esriFieldTypeDouble
-Static_Water_Level : esriFieldTypeDouble
-EC_of_water_strike : esriFieldTypeDouble
-Temperature_of_water_strike : esriFieldTypeDouble

GHYDRO_DEPTH_RANGE
-Site_ID : esriFieldTypeString
-Depth_Start : rngDepth
-Depth_End : rngDepth

GHYDRO_AT_PUMP_TEST_EVENTS
-Test_ID : esriFieldTypeString
-Event_Time : esriFieldTypeDouble
-Pumping_rate : esriFieldTypeDouble
-Drawdown : esriFieldTypeDouble
-Recovery : esriFieldTypeDouble

GHYDRO_AT_OPERATIONAL_MANAGEMENT
-Site_ID : esriFieldTypeString = Unset
-Abstraction_Rate : esriFieldTypeDouble = 0
-Abstraction_duration_hours_per_day : esriFieldTypeDouble = 0
-Pump_installation_depth : esriFieldTypeDouble = 0
-Max_water_level_drawndown : esriFieldTypeDouble = 0
-Target_water_quality_range : esriFieldTypeDouble = 0
-Extent_of_borehole_protection_zone : esriFieldTypeDouble = 0

GHYDRO_AT_CONTRACTOR
-Contractor_ID : esriFieldTypeString
-Contractor_Type : cvdContractorType = Unset
-Contractor_Name : esriFieldTypeString
-Contractor_Postal1 : esriFieldTypeString
-Contractor_Postal2 : esriFieldTypeString
-Contractor_Postal3 : esriFieldTypeString
-Contractor_Post_Code : esriFieldTypeString
-Contractor_Telephone : esriFieldTypeInteger
-Contractor_Fax : esriFieldTypeInteger
-Contractor_Cellphone : esriFieldTypeInteger
-Contractor_Professional_Affiliation : esriFieldTypeString

GHYDRO_AT_DIAMETER
-Diameter : esriFieldTypeDouble
-DrillRate : esriFieldTypeDouble
-DrillMethod : cvdDrillingMethod = Unset
-DrillFluid : cvdDrillingFluid = Unset

GHYDRO_AT_GEOLOGY
-Formation : esriFieldTypeString
-LithCode : esriFieldTypeString
-LithologicalComposition : esriFieldTypeString
-Colour : cvdColour = Unset
-MunselColour : esriFieldTypeString
-Consolidated_Geology_ID : esriFieldTypeString
-UnConsolidated_Geology_ID : esriFieldTypeString

GHYDRO_AT_PUMP_TEST
-Site_ID : esriFieldTypeString
-Pump_test_ID : esriFieldTypeString
-Start_date : esriFieldTypeDate
-Test_method : cvdPumpTestMethod = Unset
-Specific_yield : esriFieldTypeDouble
-Transmissivity : esriFieldTypeDouble

GHYDRO_AT_MONITORING
-Site_ID : esriFieldTypeString
-MonitorDate : esriFieldTypeDate
-pH : rngpH = 7
-EC : esriFieldTypeDouble = 0
-TDS : esriFieldTypeDouble = 0

Additional parameters must be added according to table 7.4 (right), DANCED, (2003)

GHYDRO_AT_EQUIPMENT
-Equipment_Type : cvdEquipmentType = Unset
-Inside_diameter : esriFieldTypeDouble
-Wall_thickness : esriFieldTypeDouble
-Opening_method : esriFieldTypeString

GHYDRO_AT_GRAVEL_FILTER
-Gravel_filter_material : esriFieldTypeString
-Gravel_filter_width : esriFieldTypeDouble
-Particle_size : esriFieldTypeDouble

GHYDRO_AT_CONSOLIDATED_GEOLOGY
-Consolidated_Geology_ID : esriFieldTypeString
-Material_Composition : cvdMaterialComposition = Unset
-Material_Fabric : cvdMaterialFabricConsolidated = Unset
-Material_Colour_Tone : cvdMaterialColourTone = Unset
-Material_Hardness : cvdMaterialHardness = Unset
-Degree_of_Weathering : cvdDegreeWeathering = Unset
-Discontinuity_Spacing : cvdDiscontinuitySpacing = Unset

GHYDRO_AT_UNCONSOLIDATED_GEOLOGY
-Unconsolidated_Geology_ID : esriFieldTypeString
-Particle_Size : cvdParticleSize = Unset
-Particle_Shape : cvdParticleShape = Unset
-Origin_of_Sample : esriFieldTypeString

Table 7.4. Use based selection of groundwater quality monitoring variables

Use	Domestic	Livestock	Irrigation	Industry
Minimum variables Should be included every sampling run	PH EC TDS (calculated) Microbiology	pH EC TDS (calculated) Microbiology	pH EC TDS (calculated)	pH EC TDS (calculated) Alkalinity
Additional variables Should be included for initial sampling to establish background conditions) and may be included selectively or less frequently on later runs	Major ions Nutrients Trace elements Fluoride Iron DOC Cyanide Viruses and parasites Taste Odour Colour Hardness Scaling/corrosion Turbidity (SABS 241:2001)	Major ions Fluoride Nitrate & nitrite Arsenic Copper Molybdenum Selenium Boron Iron	Major ions Scaling/corrosion SAR (calculated) Aluminium Beryllium Boron Chromium Cobalt Copper Fluoride Lithium Iron Manganese Nickel Selenium Zinc	Hardness Scaling/corrosion Chloride Iron Manganese Silica Sulphate Suspended solids COD
Conditional variables Should be included every run if sources are present or problems expected	Nitrate Fluoride Iron Arsenic Uranium Sulphide Cyanide Phenols VOC Pesticides Radioactivity	Trace elements Pesticides	Root crops: Cadmium Lead Faecal coliforms Leaching risk: Inorganic nitrogen (nitrate & nitrite, ammonium)	Depends on requirements for each industrial process

* Requirements for monitoring may be set by Government regulations in future.

Figure 4.8 – Attribute tables SSD

Relationships between the different spatial and non-spatial objects were defined in the *Relationships* SSD. The relationship classes were named – like any other class – and the cardinality[2] was labelled at either end of the connection using the symbols '1' for one and '*' for many, see Figure 4.9. The relationship classes were spared the GHYDRO and SP/AT naming as they already had long names which if extended further would have obscured other elements in the diagram

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[2] one-to-one, one-to-many or many-to-many

Attribute Tables::GHYDRO_AT_CONSOLIDATED_GEOLOGY
- Consolidated_Geology_ID : esriFieldTypeString
- Material_Composition : cvdMaterialComposition = Unset
- Material_Fabric : cvdMaterialFabricConsolidated = Unset
- Material_Colour_Tone : cvdMaterialColourTone = Unset
- Material_Hardness : cvdMaterialHardness = Unset
- Degree_of_Weathering : cvdDegreeWeathering = Unset
- Discontinuity_Spacing : cvdDiscontinuitySpacing = Unset

GEOLOGY_HAS_CONSOLIDATED_GEOLOGY

Attribute Tables::GHYDRO_AT_WATERSTRIKE
- Site_ID : esriFieldTypeString
- Waterstrike_ID : esriFieldTypeString
- Depth : esriFieldTypeDouble
- Blow_yield_of_strike : esriFieldTypeDouble
- Static_Water_Level : esriFieldTypeDouble
- EC_of_water_strike : esriFieldTypeDouble
- Temperature_of_water_strike : esriFieldTypeDouble

Attribute Tables::GHYDRO_AT_GEOLOGY
- Formation : esriFieldTypeString
- LithCode : esriFieldTypeString
- LithologicalComposition : esriFieldTypeString
- Colour : cvdColour = Unset
- MunselColour : esriFieldTypeString
- Consolidated_Geology_ID : esriFieldTypeString
- UnConsolidated_Geology_ID : esriFieldTypeString

GEOLOGY_HAS_UNCONSOLIDATED_GEOLOGY

BOREHOLE_HAS_WATERSTRIKE

BOREHOLE_HAS_GEOLOGY

Attribute Tables::GHYDRO_AT_CONTRACTOR
- Contractor_ID : esriFieldTypeString
- Contractor_Type : cvdContractorType = Unset
- Contractor_Name : esriFieldTypeString
- Contractor_Postal1 : esriFieldTypeString
- Contractor_Postal2 : esriFieldTypeString
- Contractor_Postal3 : esriFieldTypeString
- Contractor_Post_Code : esriFieldTypeInteger
- Contractor_Telephone : esriFieldTypeInteger
- Contractor_Fax : esriFieldTypeInteger
- Contractor_Cellphone : esriFieldTypeInteger
- Contractor_Professional_Affiliation : esriFieldTypeString

Attribute Tables::GHYDRO_AT_UNCONSOLIDATED_GEOLOGY
- Unconsolidated_Geology_ID : esriFieldTypeString
- Particle_Size : cvdParticleSize = Unset
- Particle_Shape : cvdParticleShape = Unset
- Origin_of_Sample : esriFieldTypeString

BOREHOLE_HAS_LOGGING_CONTRACTOR

GeoSite::GHYDRO_SP_BOREHOLE
- Drilling_Method : cvdDrillingMethod = Unset
- Drilling_Fluid : cvdDrillingFluid = Unset
- Adherance : cvdDrillingStandardsAdherence = Unset
- Development_method : cvdDevelopmentMethod = Unset
- Development_duration : esriFieldTypeDouble = 0.0
- Development_chemicals : cvdDevelopmentChemicals = Unset
- Pump_test_ID : esriFieldTypeString
- Borehole_depth : esriFieldTypeDouble = 0
- Distance_to_obz_BH1 : esriFieldTypeDouble = 0
- Distance_to_obz_BH2 : esriFieldTypeDouble = 0
- Distance_to_obz_BH3 : esriFieldTypeDouble = 0
- Pump_inlet_depth : esriFieldTypeDouble = 0

Attribute Tables::GHYDRO_AT_DIAMETER
- Diameter : esriFieldTypeDouble
- DrillRate : esriFieldTypeDouble
- DrillMethod : cvdDrillingMethod = Unset
- DrillFluid : cvdDrillingFluid = Unset

BOREHOLE_HAS_DIAMETER

BOREHOLE_HAS_CONTRACTOR

Attribute Tables::GHYDRO_AT_GRAVEL_FILTER
- Gravel_filter_material : esriFieldTypeString
- Gravel_filter_width : esriFieldTypeDouble
- Particle_size : esriFieldTypeDouble

BOREHOLES_HAS_GRAVEL_FILTER

BOREHOLE_HAS_PUMP_TEST

Attribute Tables::GHYDRO_AT_EQUIPMENT
- Equipment_Type : cvdEquipmentType = Unset
- Inside_diameter : esriFieldTypeDouble
- Wall_thickness : esriFieldTypeDouble
- Opening_method : esriFieldTypeString

BOREHOLE_HAS_EQUIPMENT

BOREHOLE_HAS_MANAGEMENT

Attribute Tables::GHYDRO_AT_PUMP_TEST
- Site_ID : esriFieldTypeString
- Pump_test_ID : esriFieldTypeString
- Start_date : esriFieldTypeDate
- Test_method : cvdPumpTestMethod = Unset
- Specific_yield : esriFieldTypeDouble
- Transmissivity : esriFieldTypeDouble

TEST_HAS_EVENTS

Attribute Tables::GHYDRO_AT_MONITORING
- Site_ID : esriFieldTypeString
- MonitorDate : esriFieldTypeDate
- pH : rngpH = 7
- EC : esriFieldTypeDouble = 0
- TDS : esriFieldTypeDouble = 0

BOREHOLE_HAS_MONITORING

Attribute Tables::GHYDRO_AT_OPERATIONAL_MANAGEMENT
- Site_ID : esriFieldTypeString = Unset
- Abstraction_Rate : esriFieldTypeDouble = 0
- Abstraction_duration_hours_per_day : esriFieldTypeDouble = 0
- Pump_installation_depth : esriFieldTypeDouble = 0
- Max_water_level_drawndown : esriFieldTypeDouble = 0
- Target_water_quality_range : esriFieldTypeDouble = 0
- Extent_of_borehole_protection_zone : esriFieldTypeDouble = 0

Attribute Tables::GHYDRO_AT_PUMP_TEST_EVENTS
- Test_ID : esriFieldTypeString
- Event_Time : esriFieldTypeDouble
- Pumping_rate : esriFieldTypeDouble
- Drawdown : esriFieldTypeDouble
- Recovery : esriFieldTypeDouble

Figure 4.9 – Relationships SSD (cardinality indicated by 1 or *)

The CVDs and range domains were defined in the *Domains* SSD which can be seen in Figure 4.10. A domains SSD was not required for the successful production of the geodatabase schema, but was included to aid interpretation of the data model. The diagram displayed the CVDs and range domains as two separate categories. Also included with *cvdparticleshape* was a graphic of different particle shape examples to assist in the selection of a shape option.

Coded Value Domains

«CodedValueDomain» cvdColour
+FieldType : esriFieldType = esriFieldTypeString
+MergePolicy : esriMergePolicyType = esriMPTDefaultValue
+SplitPolicy : esriSplitPolicyType = esriSPTDefaultValue
+Unset : esriFieldTypeString = Unset
+Undefined : esriFieldTypeString = Undefined
-White : esriFieldTypeString = White
-Grey : esriFieldTypeString = Grey
-Pale Grey : esriFieldTypeString = Pale Grey
-Dark Grey : esriFieldTypeString = Dark Grey
-Brown : esriFieldTypeString = Brown
-Light Brown : esriFieldTypeString = Light Brown
-Dark Brown : esriFieldTypeString = Dark Brown
-Orange Brown : esriFieldTypeString = Orange Brown
-Yellow Brown : esriFieldTypeString = Yellow Brown
-Red Brown : esriFieldTypeString = Red Brown
-Orange : esriFieldTypeString = Orange
-Yellow : esriFieldTypeString = Yellow
-Pale Yellow : esriFieldTypeString = Pale Yellow
-Dark Yellow : esriFieldTypeString = Dark Yellow
-Red : esriFieldTypeString = Red
-Black : esriFieldTypeString = Black
-Other : esriFieldTypeString = Other

«CodedValueDomain» cvdContractorType
+FieldType : esriFieldType = esriFieldTypeString
+MergePolicy : esriMergePolicyType = esriMPTDefaultValue
+SplitPolicy : esriSplitPolicyType = esriSPTDefaultValue
+Unset : <unspecified> = Unset
+Undefined : <unspecified> = Undefined
-Drilling : <unspecified> = Drilling
-Logging : <unspecified> = Logging

«CodedValueDomain» cvdDegreeWeathering
+FieldType : esriFieldType = esriFieldTypeString
+MergePolicy : esriMergePolicyType = esriMPTDefaultValue
+SplitPolicy : esriSplitPolicyType = esriSPTDefaultValue
+Unset : <unspecified> = Unset
+Undefined : <unspecified> = Undefined
-Unweathered : <unspecified> = Unweathered
-Slightly_weathered : <unspecified> = Slightly_weathered
-Medium_weathered : <unspecified> = Medium_weathered
-Highly_weathered : <unspecified> = Highly_weathered
-Completely_weathered : <unspecified> = Completely_weathered

«CodedValueDomain» cvdDevelopmentChemicals
+FieldType : esriFieldType = esriFieldTypeString
+MergePolicy : esriMergePolicyType = esriMPTDefaultValue
+SplitPolicy : esriSplitPolicyType = esriSPTDefaultValue
+Unset : <unspecified> = Unset
+Undefined : <unspecified> = Undefined
-Surfactant : <unspecified> = Surfactant
-Polyphosphates : <unspecified> = Polyphosphates
-Acid_treatment : <unspecified> = Acid_treatment
-Other : <unspecified> = Other

«CodedValueDomain» cvdDevelopmentMethod
+FieldType : esriFieldType = esriFieldTypeString
+MergePolicy : esriMergePolicyType = esriMPTDefaultValue
+SplitPolicy : esriSplitPolicyType = esriSPTDefaultValue
+Unset : <unspecified> = Unset
+Undefined : <unspecified> = Undefined
-Bailing : <unspecified> = Bailing
-Surging : <unspecified> = Surging
-Swabbing : <unspecified> = Swabbing
-Air_lifting : <unspecified> = Air_lifting
-Pumping : <unspecified> = Pumping
-Backwashing_air_surging : <unspecified> = Backwashing_air_surging
-Surging_air_lift_pumping : <unspecified> = Surging_air_lift_pumping
-Jetting_air : <unspecified> = Jetting_air
-Jetting_air_lift_pumping : <unspecified> = Jetting_air_lift_pumping
-Jetting_water : <unspecified> = Jetting_water
-Hydrofracturing : <unspecified> = Hydrofracturing

«CodedValueDomain» cvdDiscontinuitySpacing
+FieldType : esriFieldType = esriFieldTypeString
+MergePolicy : esriMergePolicyType = esriMPTDefaultValue
+SplitPolicy : esriSplitPolicyType = esriSPTDefaultValue
+Unset : <unspecified> = Unset
+Undefined : <unspecified> = Undefined
-Very_highly_fractured : <unspecified> = Very_highly_fractured
-Highly_fractured : <unspecified> = Highly_fractured
-Moderately_fractured : <unspecified> = Moderately_fractured
-Slightly_fractured : <unspecified> = Slightly_fractured

«CodedValueDomain» cvdDrillingFluid
+FieldType : esriFieldType = esriFieldTypeString
+MergePolicy : esriMergePolicyType = esriMPTDefaultValue
+SplitPolicy : esriSplitPolicyType = esriSPTDefaultValue
+Unset : <unspecified> = Unset
+Undefined : <unspecified> = Undefined
-Water_clean : <unspecified> = Water_clean
-Water_clay : <unspecified> = Water_clay
-Water_polymeric : <unspecified> = Water_polymeric
-Water_clay_polymeric : <unspecified> = Water_clay_polymeric
-Air_dry : <unspecified> = Air_dry
-Air_mist : <unspecified> = Air_mist
-Air_foam : <unspecified> = Air_foam
-Air_stiff_foam : <unspecified> = Air_stiff_foam

«CodedValueDomain» cvdDrillingMethod
+FieldType : esriFieldType = esriFieldTypeString
+MergePolicy : esriMergePolicyType = esriMPTDefaultValue
+SplitPolicy : esriSplitPolicyType = esriSPTDefaultValue
+Unset : <unspecified> = Unset
+Undefined : <unspecified> = Undefined
-Cable Tool : <unspecified> = Cable Tool
-Direct circulation : <unspecified> = Direct circulation
-Reverse circulation : <unspecified> = Reverse circulation
-Rotary air percussion : <unspecified> = Rotary air percussion
-Percussing drilling : <unspecified> = Percussing drilling
-Well pointing : <unspecified> = Well pointing
-Bucket auger : <unspecified> = Bucket auger
-Solid stem auger : <unspecified> = Solid stem auger
-Hollow-stem auger : <unspecified> = Hollow-stem auger
-Driven wells : <unspecified> = Driven wells
-Tube wells : <unspecified> = Tube wells

«CodedValueDomain» cvdDrillingStandardsAdherence
+FieldType : esriFieldType = esriFieldTypeString
+MergePolicy : esriMergePolicyType = esriMPTDefaultValue
+SplitPolicy : esriSplitPolicyType = esriSPTDefaultValue
+Unset : <unspecified> = Unset
+Undefined : <unspecified> = Undefined
-Good : <unspecified> = Good
-Moderate : <unspecified> = Moderate
-Poor : <unspecified> = Poor

«CodedValueDomain» cvdEquipmentType
+FieldType : esriFieldType = esriFieldTypeString
+MergePolicy : esriMergePolicyType = esriMPTDefaultValue
+SplitPolicy : esriSplitPolicyType = esriSPTDefaultValue
+Unset : <unspecified> = Unset
+Undefined : <unspecified> = Undefined
-Casing_steel : <unspecified> = Casing_steel
-Casing_stainless_steel : <unspecified> = Casing_stainless_steel
-Casing_uPVC : <unspecified> = Casing_uPVC
-Casing_Fibreglass : <unspecified> = Casing_Fibreglass
-Screen_steel : <unspecified> = Screen_steel
-Screen_stainless_steel : <unspecified> = Screen_stainless_steel
-Screen_uPVC : <unspecified> = Screen_uPVC
-Sump : <unspecified> = Sump
-None : <unspecified> = None

«CodedValueDomain» cvdGeomorphologyClassification
+FieldType : esriFieldType = esriFieldTypeString
+MergePolicy : esriMergePolicyType = esriMPTDefaultValue
+SplitPolicy : esriSplitPolicyType = esriSPTDefaultValue
+Unset : <unspecified> = Unset
+Undefined : <unspecified> = Undefined
-Hill/mountain slope : <unspecified> = Hill/mountain slope
-Steep mountain slope : <unspecified> = Steep mountain slope
-Low gradient hill slope : <unspecified> = Low gradient hill slope
-Raised terrace : <unspecified> = Raised terrace
-Valley floor : <unspecified> = Valley floor
-Riparian zone : <unspecified> = Riparian zone
-Flat/gently undulating surface : <unspecified> = Flat/gently undulating surface
-Waterbody : <unspecified> = Waterbody
-Alluvial fan : <unspecified> = Alluvial fan
-Unvegetated shifting dunes : <unspecified> = Unvegetated shifting dunes
-Vegetated dunes : <unspecified> = Vegetated dunes

«CodedValueDomain» cvdMaterialColourTone
+FieldType : esriFieldType = esriFieldTypeString
+MergePolicy : esriMergePolicyType = esriMPTDefaultValue
+SplitPolicy : esriSplitPolicyType = esriSPTDefaultValue
+Unset : <unspecified> = Unset
+Undefined : <unspecified> = Undefined
-Bright : <unspecified> = Bright
-Dark : <unspecified> = Dark
-Dull : <unspecified> = Dull
-Light : <unspecified> = Light
-Lustrous : <unspecified> = Lustrous

«CodedValueDomain» cvdMaterialComposition
+FieldType : esriFieldType = esriFieldTypeString
+MergePolicy : esriMergePolicyType = esriMPTDefaultValue
+SplitPolicy : esriSplitPolicyType = esriSPTDefaultValue
+Unset : <unspecified> = Unset
+Undefined : <unspecified> = Undefined
-Argillaceous : <unspecified> = Argillaceous
-Arenaceous : <unspecified> = Arenaceous
-Calcareous : <unspecified> = Calcareous
-Cherty : <unspecified> = Cherty
-Chloritic : <unspecified> = Chloritic
-Ferruginous : <unspecified> = Ferruginous
-Feldspacthic : <unspecified> = Feldspacthic
-Glauconitic : <unspecified> = Glauconitic
-Graphitic : <unspecified> = Graphitic
-Micaceous : <unspecified> = Micaceous
-Heavy_mineral_bearing : <unspecified> = Heavy_mineral_bearing
-Phosphorite_bearing : <unspecified> = Phosphorite_bearing
-Peaty : <unspecified> = Peaty
-Pyritic : <unspecified> = Pyritic
-Siliceous : <unspecified> = Siliceous

«CodedValueDomain» cvdLandCoverClass
+FieldType : esriFieldType = esriFieldTypeString
+MergePolicy : esriMergePolicyType = esriMPTDefaultValue
+SplitPolicy : esriSplitPolicyType = esriSPTDefaultValue
+Unset : <unspecified> = Unset
+Undefined : <unspecified> = Undefined
+Natural forest & woodland : <unspecified> = Natural forest & woodland
+Natural forest : <unspecified> = Thicket & bush land (etc)
+Thicket & bush land (etc) : <unspecified> = Low gradient hill slope
+Shrub land and low fynbos : <unspecified> = Shrub land and low fynbos
+Herb land : <unspecified> = Herb land
+Grassland : <unspecified> = Grassland
+Forest plantations : <unspecified> = Forest plantations
+Barren rock : <unspecified> = Barren rock
+Dongas & sheet erosion scars : <unspecified> = Dongas & sheet erosion scars
+Degraded - forest & woodland : <unspecified> = Degraded - forest & woodland
+Degraded - thicket & bush land : <unspecified> = Degraded - thicket & bush land
+Degraded - grassland : <unspecified> = Degraded - grassland
+Degraded - shrub land & low fynbos : <unspecified> = Degraded - shrub land & low fynbos
+Degraded - herb land : <unspecified> = Degraded - herb land
+Cultivated - permanent - commercial irrigated : <unspecified> = Cultivated - permanent - commercial irrigated
+Cultivated - permanent - commercial dryland : <unspecified> = Cultivated - permanent - commercial dryland
+Cultivated - permanent - commercial sugarcane : <unspecified> = Cultivated - permanent - commercial sugarcane
+Cultivated - temporary - commercial irrigated : <unspecified> = Cultivated - temporary - commercial irrigated
+Cultivated - temporary - commercial dryland : <unspecified> = Cultivated - temporary - commercial dryland
+Cultivated - temporary - semi-commercial/subsistence dryland : <unspecified> = Cultivated - temporary - semi-commercial/susbsistence dryland
+Urban/built-up land - residential : <unspecified> = Urban/built-up land - residential
+Urban/built-up land - residential - small holdings/woodland : <unspecified> = Urban/built-up land - residential - small holdings/woodland
+Urban/built-up land - residential - small holdings/bush land : <unspecified> = Urban/built-up land - residential - small holdings/bush land
+Urban/built-up land - residential - small holdings/shrub land : <unspecified> = Urban/built-up land - residential - small holdings/shrub land
+Urban/built-up land - residential - small holdings/grassland : <unspecified> = Urban/built-up land - residential - small holdings/grassland
+Urban/built-up land - commercial : <unspecified> = Urban/built-up land - commercial
+Urban/built-up land - industrial/transport : <unspecified> = Urban/built-up land - industrial/transport
+Mines & transport : <unspecified> = Mines & transport

«CodedValueDomain» cvdMaterialFabricConsolidated
+FieldType : esriFieldType = esriFieldTypeString
+MergePolicy : esriMergePolicyType = esriMPTDefaultValue
+SplitPolicy : esriSplitPolicyType = esriSPTDefaultValue
+Unset : <unspecified> = Unset
+Undefined : <unspecified> = Undefined
-Clayey : <unspecified> = Clayey
-Coarse : <unspecified> = Coarse
-Cobbly : <unspecified> = Cobbly
-Fine : <unspecified> = Fine
-Gravely : <unspecified> = Gravely
-Medium : <unspecified> = Medium
-Muddy : <unspecified> = Muddy
-Pebbly : <unspecified> = Pebbly
-Sandy : <unspecified> = Sandy
-Shaly : <unspecified> = Shaly
-Shelly : <unspecified> = Shelly
-Silty : <unspecified> = Silty

«CodedValueDomain» cvdMaterialHardness
+FieldType : esriFieldType = esriFieldTypeString
+MergePolicy : esriMergePolicyType = esriMPTDefaultValue
+SplitPolicy : esriSplitPolicyType = esriSPTDefaultValue
+Unset : <unspecified> = Unset
+Undefined : <unspecified> = Undefined
-Solid : <unspecified> = Solid
-Hard : <unspecified> = Hard
-Soft : <unspecified> = Soft
-Fresh : <unspecified> = Fresh

«CodedValueDomain» cvdOpeningMethod
+FieldType : esriFieldType = esriFieldTypeString
+MergePolicy : esriMergePolicyType = esriMPTDefaultValue
+SplitPolicy : esriSplitPolicyType = esriSPTDefaultValue
+Unset : <unspecified> = Unset
+Undefined : <unspecified> = Undefined
-Wedge_wire_wound : <unspecified> = Wedge_wire_wound
-Machine_cut : <unspecified> = Machine_cut
-Saw : <unspecified> = Saw
-Drilled : <unspecified> = Drilled
-Cutting_torch : <unspecified> = Cutting_torch
-Punched : <unspecified> = Punched

«CodedValueDomain» cvdParticleSize
+FieldType : esriFieldType = esriFieldTypeString
+MergePolicy : esriMergePolicyType = esriMPTDefaultValue
+SplitPolicy : esriSplitPolicyType = esriSPTDefaultValue
+Unset : <unspecified> = Unset
+Undefined : <unspecified> = Undefined
+Boulder : <unspecified> = Boulder
-Cobble : <unspecified> = Cobble
-Gravel_very_coarse : <unspecified> = Gravel_very_coarse
-Gravel_coarse : <unspecified> = Gravel_coarse
-Gravel_medium : <unspecified> = Gravel_medium
-Gravel_fine : <unspecified> = Gravel_fine
-Gravel_very_fine : <unspecified> = Gravel_very_fine
-Sand_very_coarse : <unspecified> = Sand_very_coarse
-Sand_coarse : <unspecified> = Sand_coarse
-Sand_medium : <unspecified> = Sand_medium
-Sand_fine : <unspecified> = Sand_fine
-Sand_very_fine : <unspecified> = Sand_very_fine
-Silt : <unspecified> = Silt
-Clays : <unspecified> = Clays

«CodedValueDomain» cvdPumpTestMethod
+FieldType : esriFieldType = esriFieldTypeString
+MergePolicy : esriMergePolicyType = esriMPTDefaultValue
+SplitPolicy : esriSplitPolicyType = esriSPTDefaultValue
+Unset : <unspecified> = Unset
+Undefined : <unspecified> = Undefined
+Theis : <unspecified> = Theis
-Cooper-Jacob : <unspecified> = Cooper-Jacob
+FC : <unspecified> = FC
+Other : <unspecified> = Other

«CodedValueDomain» cvdScale
+FieldType : esriFieldType = esriFieldTypeString
+MergePolicy : esriMergePolicyType = esriMPTDefaultValue
+SplitPolicy : esriSplitPolicyType = esriSPTDefaultValue
+Unset : <unspecified> = Unset
+Undefined : <unspecified> = Undefined
+1:10 000 : <unspecified> = 1:10 000
+1:50 000 : <unspecified> = 1:50 000
+1:250 000 : <unspecified> = 1:250 000

«CodedValueDomain» cvdParticleShape
+FieldType : esriFieldType = esriFieldTypeString
+MergePolicy : esriMergePolicyType = esriMPTDefaultValue
+SplitPolicy : esriSplitPolicyType = esriSPTDefaultValue
+Unset : <unspecified> = Unset
+Undefined : <unspecified> = Undefined
-Well Rounded : <unspecified> = Well Rounded
-Rounded : <unspecified> = Rounded
-Sub-rounded : <unspecified> = Sub-rounded
-Sub-angular : <unspecified> = Sub-angular
-Angular : <unspecified> = Angular

Angular   Sub-angular   Sub-rounded   Rounded   Well rounded

Figure 4.1   Sedimentary particle shapes (Bosch, 1999).

Range Domains

«RangeDomain» rngDepth
+FieldType : esriFieldType = esriFieldTypeDouble
+MergePolicy : esriMergePolicyType = esriMPTDefaultValue
+SplitPolicy : esriSplitPolicyType = esriSPTDefaultValue
+MinValue : <unspecified> = 0
+MaxValue : <unspecified> = 2000

«RangeDomain» rngpH
+FieldType : esriFieldType = esriFieldTypeDouble
+MergePolicy : esriMergePolicyType = esriMPTDefaultValue
+SplitPolicy : esriSplitPolicyType = esriSPTDefaultValue
+MinValue : <unspecified> = 0
+MaxValue : <unspecified> = 14

Figure 4.10 – Domains SSD

The following section describes the model in more detail explaining the individual objects and their role in the description of boreholes in the UML data model. Each SSD is described in a separate section with a list of the classes that comprise that part of the model.

4.2.2 Description of the UML data model

As stated above, the UML data model diagram was composed of four SSDs. This section breaks down the diagram into these four components and describes them in more detail. Each sub-section features a listing of the classes in that SSD and a description of the main features of that part of the UML data model diagram.

4.2.2.1 Geosite

The spatial features of the data model were described by the classes in the Geosite SSD which comprised the generic spatial feature and four classes, see Table 4.1 below.

Table 4.1 – Features in the Geosite SSD

Object	Function
Feature	The generic ESRI spatial feature class containing geometry information
GHYDRO_SP_SITE	The geosite feature class with the attributes common to all geosites – Site ID, date of drilling, elevation of the site, scale of information used to determine the position, contractor ID, landcover class and geomorphology at the site.
GHYDRO_SP_BOREHOLE	The borehole subtype of geosite with all of the features specific to the borehole class – drilling method, drilling fluid used, adherence to drilling standards, development method, development duration, development chemicals, borehole depth, distance to observation boreholes and pump inlet depth.
GHYDRO_SP_SITE_DEPTH	The 3D point geometry class that represented water-strikes – depth of the event
GHYDRO_SP_SITE_HOLEPATH	The 3D line geometry class that represented the boreline

As a borehole is a spatially and structurally simple object, all of the spatial elements of the data model were captured in three classes – GHYDRO_SP_BOREHOLE (the sub-type of GHYDRO_SP_SITE), the GHYDRO_SP_SITE_DEPTH and GHYDRO_SP_SITEHOLEPATH. They all had the core attribute *Site_ID* in common, which linked all of the elements of the data model, including most of the attribute tables. This field is a unique identifier for each borehole. With the exception of the *pump inlet depth* and the *distances to observation boreholes*, the attribute

specifics to the borehole point feature in the class GHYDRO_SP_SITE were described by CVDs. The 3D boreline feature GHYDRO_SP_SITEHOLEPATH contained only the attribute Site_ID while the water strike feature GHYDRO_SP_SITE_DEPTH also had the double precision field *depth*.

4.2.2.2 Attribute Tables

The 13 tabular objects in the model were associated directly or indirectly to the generic *object* class. These objects are listed in Table 4.2 below with a brief description of their function.

Table 4.2 – Objects comprising the Attribute Tables SSD

Object	Function
Object	Generic object class containing ObjectID
GHYDRO_LO_CONTRACTOR	Look-up table that captured contact and professional details of logging and drilling contractors
GHYDRO_AT_WATERSTRIKE	Details of individual water-strike events that occurred during the drilling (in the vertical plane)
GHYDRO_AT_DEPTH_RANGE	A parent object for all tables that require range information to describe a phenomenon represented by a classified section of the boreline
GHYDRO_AT_DRILLING	Details of the drilling of the borehole – drill speed, diameter of drill bit used,
GHYDRO_AT_EQUIPMENT	Details of equipment installed in the borehole – casings, screens, size of slots cut in the casing, etc..
GHYDRO_AT_GEOLOGY	Generic geological details that apply to both consolidated and unconsolidated geology
GHYDRO_AT_GRAVEL_FILTER	Information about gravel packs installed in the borehole
GHYDRO_AT_CONSOLIDATED_GEOLOGY	Geological data specific to lithologies that are consolidated in nature
GHYDRO_AT_UNCONSOLIDATED_GEOLOGY	Geological data specific to lithologies that are unconsolidated in nature
GHYDRO_AT_PUMP_TEST	Data collected about a pump test– type of test, date of test, specific yield and transmissivity
GHYDRO_AT_PUMP_TEST_EVENTS	Details of pump testing events captured during a pump test – pumping rate, draw-down, and recover.
GHYDRO_AT_OPERATIONAL_MANAGEMENT	Information relating to the actual management of the borehole – abstraction rate, hours of abstraction per day, pump installation depth, etc.
GHYDRO_AT_MONITORING	Monitoring details including the parameters that were measured in the borehole during monitoring – pH, electric conductivity (EC) and total dissolved solids (TDS).

The objects were assembled in the hierarchy beneath the *generic object class* containing the basic element of an object class for inclusion in a geodatabase – the *ObjectID*, which is in turn inherited by all sub-objects. Nine of the objects were associated directly with this object through a standard generalisation connection. The remaining four objects were specified as generalisations of the depth range class – GHYDRO_AT_DEPTH_RANGE – so that they all inherited the depth-defining properties it provided. This object employed one of only two range domains implemented in this data model. It was located here, defining the minimum and maximum of possible depths that could have been entered into the resulting geodatabase, but it was inherited by the four child objects – GHYDRO_AT_DRILLING, GHYDRO_AT_EQUIPMENT, GHYDRO_AT_GEOLOGY and GHYDRO_AT_GRAVEL_FILTER. This was a good example of the efficient re-use of properties using the inheritance rule. The object GHYDRO_AT_MONITORING only featured basic monitoring parameters, but a table from CSIR (2003a) listing possible monitoring parameters for domestic, livestock, irrigation and industrial use of groundwater was also included in the UML diagram as a graphic. These parameters could be included by users that decided to implement this data model by further customising the properties of the object by adding new attributes and tagged values.

Without the relationships classes that defined the fuller context of the model, these tables would have been floating objects with little or no association to the rest of the data model. The relationships SSD is described in the next section.

4.2.2.3 Relationships

As the majority of the information of this data model was encapsulated in tabular objects rather than spatial descriptions, the definition of relationships and the classes that implemented them was vital to the success of the data model. Table 4.3 below lists the relationship classes and their role in the data model.

Table 4.3 – Relationship classes defined in the data model

Object	Function
BOREHOLE_HAS_WATERSTRIKE	Class associating any water-strike events with the borehole
BOREHOLE_HAS_LOGGING_CONTRACTOR	Class associating the contractor look-up table with the borehole capturing logging contractor details
BOREHOLE_HAS_CONTRACTOR	Class associating the contractor look-up table with the borehole capturing drilling contractor details
BOREHOLE_HAS_GRAVEL_FILTER	Class associating details of a gravel packed section of the

	boreline with the borehole
BOREHOLE_HAS_EQUIPMENT	Class associating details of a casing or screened section of the boreline with the borehole
BOREHOLE_HAS_MONITORING	Class associating details of monitoring activities with the borehole
BOREHOLE_HAS_MANAGEMENT	Class associating details of management activities with the borehole
BOREHOLE_HAS_PUMP_TEST	Class associating details of pump testing activities with the borehole
PUMP_TEST_HAS_EVENTS	Details of any pump test events taking place during a pump test
BOREHOLE_HAS_DRILLING	Class associating details of the drilling of the borehole with the borehole itself
BOREHOLE_HAS_GEOLOGY	Class associating basic geological information captured during the drilling of the borehole.
GEOLOGY_HAS_CONSOLIDATED_GEOLOGY	Class associating consolidated geological information captured during the geology object
GEOLOGY_HAS_UNCONSOLIDATED_GEOLOGY	Class associating unconsolidated geological information captured during the geology object

As can be seen from Table 4.3, with the exception of the objects that described consolidated and unconsolidated geology and pump test events, all of the objects were related directly to the borehole feature class GHYDRO_SP_BOREHOLE through the unique identifier Site_ID. The two additional geology tables are related directly to GHYDRO_AT_GEOLOGY and GHYDRO_AT_PUMP_TEST_EVENTS is related to GHYDRO_AT_PUMP_TESTS. With the exception of the relationship between the geology tables at GHYDRO_AT_GEOLOGY, all of the associations defined in the data model were one-to-many (1.*) relationships meaning that for each borehole there could have been many events in each of the related tables. For example, one borehole could have had utilised several different bits with different diameters to drill down into the earth. These different diameter drill bit sizes would have been captured as depth ranges in GHYDRO_AT_DRILLING as multiple ranges, each with a different diameter.

4.2.2.4 Domains

Domains were utilised extensively throughout the design of the data model in an attempt to facilitate easy entry of data into the geodatabase and reduce opportunities for input errors. Only two range domains were used in the design, in the GHYDRO_AT_DEPTH_RANGE object and in the GHYDRO_AT_MONITORING object. As stated earlier, the GHYDRO_AT_DEPTH_RANGE range domain was recycled in each of the range-based objects

through inheritance. The range domain rngpH was implemented to limit data entry to values from 0 to 14 in a field that captured pH of groundwater. The remainder of the domains used in the model were CVDs, providing a list of possible data entry options for end-users. The domains are too numerous to list here, but can be seen in the UML diagram in Appendix 1.

Once the UML model was completed, it was checked for inconsistencies using the Microsoft Visio semantics checking plug-in.

4.3 EXPORT AND SEMANTICS CHECK

The completed UML data model was exported to an XMI file – a file format developed to allow developers using UML to exchange data models across different software and hardware platforms (XMI 2005). The ESRI Visio plug-in[3], installed when the ESRI template ArcInfo Data Model template was opened, parsed the XMI file checking for inconsistencies and errors which were then displayed as a report that could be exported or printed (see Figure 4.11).

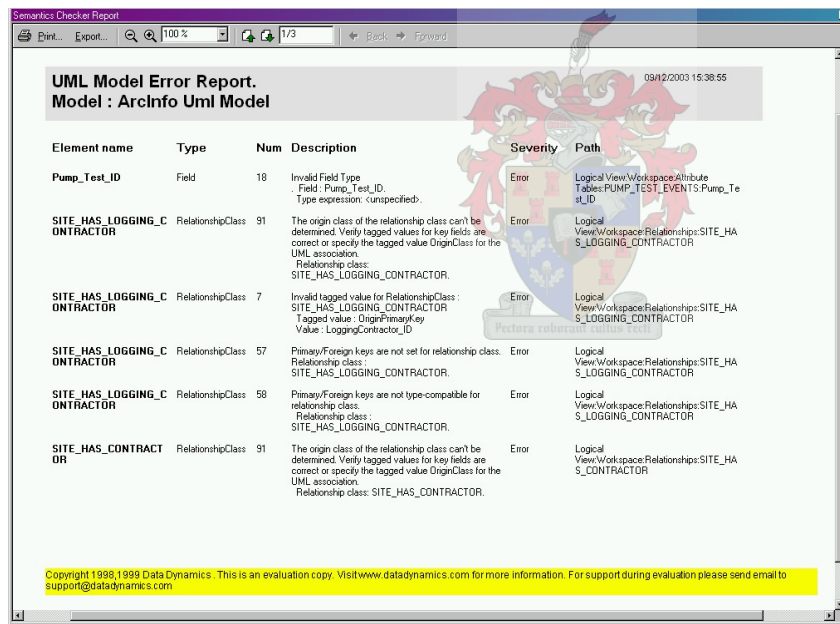Figure 4.11 – ESRI semantics checker report

Using this facility, the data model was checked and unnoticed mistakes were corrected before proceeding.

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[3] The semantics checking macro is found under Tools/Macros/ESRI/ and is called *semantics checker*. The user must have an ArcInfo / ArcEditor license available for this to operate.

4.4 IMPORTING THE SCHEMA INTO ARCCATALOG

Once the errors picked up by the semantics checker had been corrected, the XMI file was imported into ArcCatalog using the *Schema Wizard Utility* (SWU). In order for this utility to work, the format of the XMI file must be specified using a UML.dtd[4] file.

The SWU applied the newly defined schema to a newly created *Personal Geodatabase*. After initiating the SWU, the XMI file was selected and the wizard-driven process translated it into a schema definition. During this process the spatial reference of the personal geodatabase was defined using a set of bounding co-ordinates. This was performed using the minimum and maximum x & y coordinate values and a map projection, selected using the standard projection definition tools provided within ArcGIS.

4.5 THE GEODATABASE SCHEMA

Figure 4.12 shows the resulting geodatabase schema once the model had been exported to XMI format and imported into ArcCatalog using the SWU.
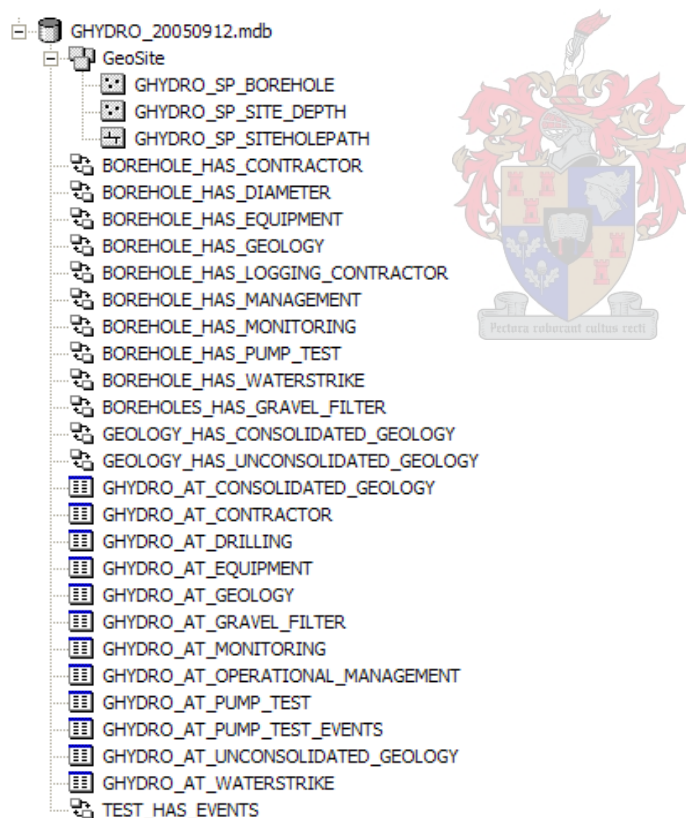

Figure 4.12 – Geodatabase schema once it has been imported into ArcCatalog

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[4] dtd – design template definition

This familiar view of the geodatabase schema shows the different elements with standard ArcGIS icons. The *geosite feature dataset* includes the points and lines of the borehole feature, the site depth z-point, and the boreline z-line. Below this the relationship classes and attribute tables are listed.

The geodatabase schema that was generated by the SWU was not the finished product of the design process, as errors or problems only became apparent when the geodatabase schema had been created. Hence, like the design stage of the data model development, the finalisation of the geodatabase schema was iterative. One of the key tests for the completed geodatabase schema was the entry of test data which, during several iterations highlighted problems and minor issues that required attention. The next section will explain how data was loaded into the geodatabase using the ArcMap interface.

4.6 POPULATING THE GEODATABASE USING ARCMAP

A geodatabase schema can be populated in a number of different ways, including migrating existing databases and spatial coverages to newly designed geodatabases. However, the most direct method, utilising the ArcMap editing interface, was used here. In the case of the GHYDRO schema, a point was placed using the *Create New Feature* editing tool. Once the point had been placed and the point feature was high-lighted, the edit attributes dialog was used to enter data, see Figure 4.13.
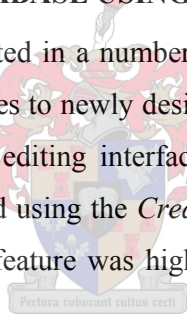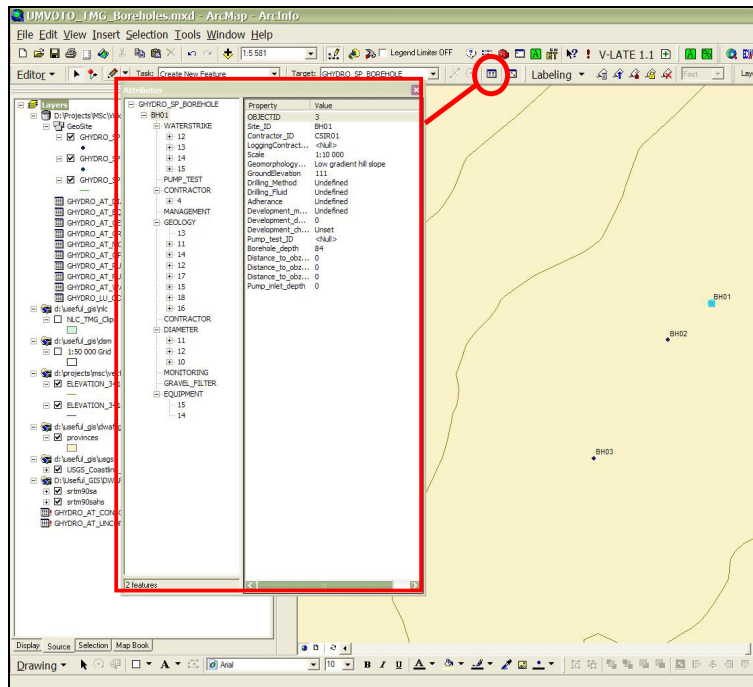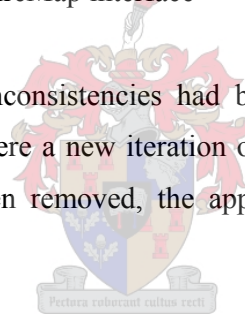
Figure 4.13 – Data entry using the ArcMap interface

Once any further problems and inconsistencies had been identified they were listed and addressed in the UML diagram where a new iteration of the model began. When all of the errors and inconsistencies had been removed, the application of the model was properly tested.

Although the completed data model comprised all of the elements required to appropriately represent boreholes in a GIS environment, the monochromatic UML diagrams produced by CASE Tools did not lend itself to attractive presentation. However, tools have been developed by geodatabase programmers that assist in the development of a data model poster for presentation purposes.

4.7 DATA MODEL POSTER

A script called the Geodatabase Diagrammer[5] (GD) was used to re-export the geodatabase schema from ArcCatalog back into Visio in a presentation format. This created standardised colour-coded presentation format graphics of feature classes, attribute tables, relationship

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[5] ArcGIS 9 version available from http://arcscripts.esri.com/details.asp?dbid=13616 and for ArcGIS 8 at http://arcscripts.esri.com/details.asp?dbid=12616

classes and domains. These were arranged to create a comprehensible poster version of the data model, shown in Figure 4.14. Blue elements with a feature symbol displayed in the top left corner represent spatial feature classes, blue elements with a table symbol in the top left corner are the objects classes, the green elements are relationship classes, and the red boxes are domains.
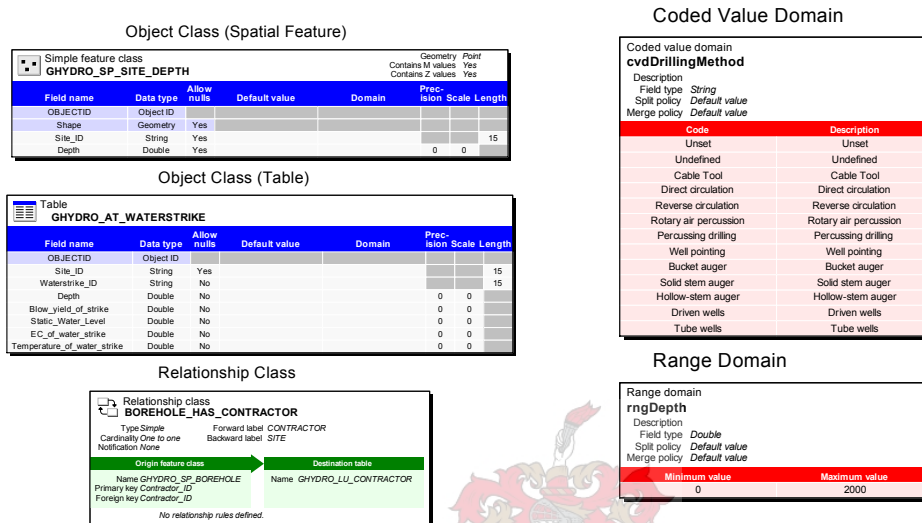

Figure 4.14 – Colour-coded objects generated by the GD

The GD also created a simplified version of the schema that summarise the structural features of the data model with the exception of the domains. Figure 4.15 shows this simplified diagram following the same colour scheme as described above.
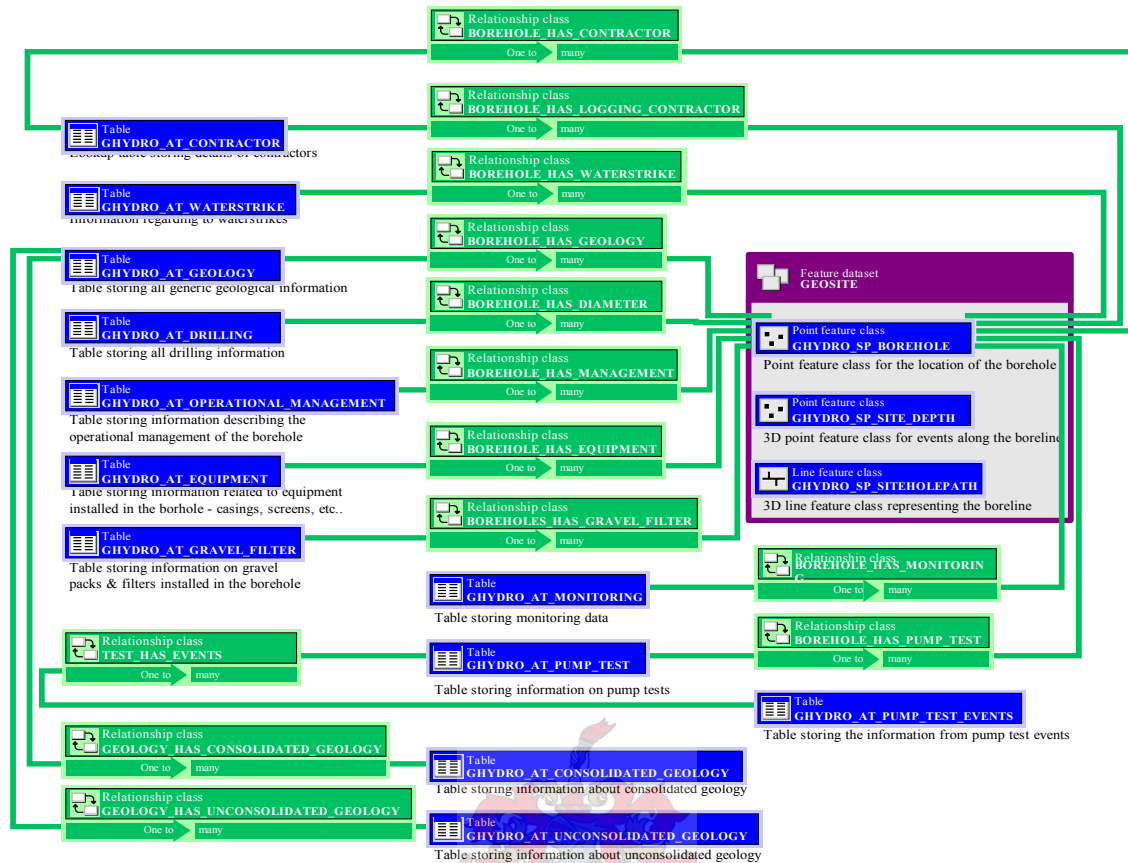
Figure 4.15 – Summary of the geodatabase structure generated by the GD

The feature dataset (outlined in purple) housed the spatial features with the attribute table objects (blue elements) distributed around it. The centre of the geodatabase structure is the borehole class – GHYDRO_SP_BOREHOLE. The icon in the left-hand end of each feature indicates what type of geometry is used to describe that component. All of the objects are directly or indirectly related to the borehole class through relationship classes (green boxes and connections). Appendix 1 contains the detailed UML diagram of the data model developed using the SDB.

4.8 TEST DATA

Beyond the initial iterative corrections and testing phase, the ultimate proof of any database design is through the population of the database with real world data. Moreover, it is important to understand if the data management refinements offered by the design and implementation of a data model have been achieved.

The full specification of the SDB is extremely detailed and it is unlikely that data will meet this standard until the descriptors have been accepted at a national level and by the groundwater community – most specifically the borehole drilling companies. As the design process in this research used the SDB as a user requirements analysis, the data model that was developed was equally detailed and required very detailed borehole data to achieve any level of completeness. This included full site information, with a description of the drilling and construction of the borehole, in the form of a borehole log. Borehole logs are one of the most common types of borehole drilling records and therefore are the most likely media supplied to an end-user populating the geodatabase.

The test data selected for this study encompassed boreholes from several geohydrological studies in the Western Cape region of South Africa – the Langebaan Road Aquifer project (CSIR 2004), the Botrivier water supply project (CSIR 1989) and Table Mountain Group (TMG) Feasibility Study (Brown et al 2003) (see Section 1.4). Borehole drilling logs and drilling reports were used to populate the data model geodatabase schema. These borehole logs and drilling reports are included in Appendix 2.

Figure 4.16 is a borehole log from the TMG Feasibility Study. It illustrates the information captured in borehole logs during the drilling process. The log is separated into five blocks: the three upper boxes and the two lower panels. The upper left box describes the drilling method, date of drilling and the depth to which the hole was drilled. The lower-left panel shows the drill diameter for each part of the hole and the casings, screens and gravel-packs that were used to furnish the borehole. The upper-centre box lists the static water-level and the final blow yield. The co-ordinates of the hole, measured using Global Positioning System (GPS), surface elevation (Z-value) taken from a topographic map, and the method of measurement are listed in the upper-right box. The lower-right panel illustrates the water-strikes and the lithological units encountered as the drilling progressed. All of this information is essential to understand the properties of a borehole and the hydrogeological setting of an area, hence their inclusion in the SDB document.
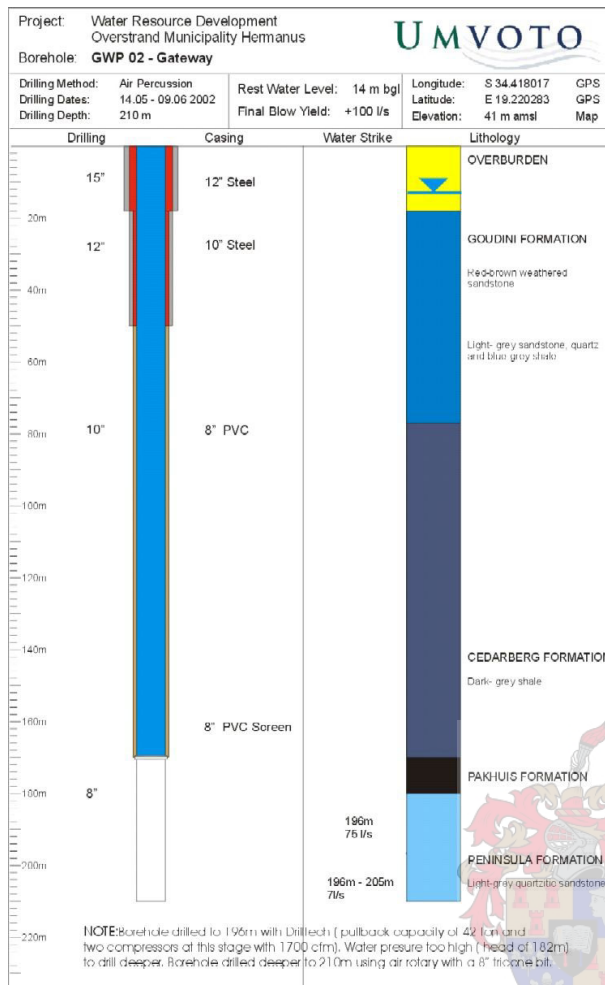
Source: Brown et al 2003

Figure 4.16 – Example of a borehole log used to test the borehole data model

The borehole log is an informally accepted standard for capturing drilling information. Even though Figure 4.17 is an example of an older borehole log from the Botriver area in the Western Cape (CSIR 1989) (also used to test the geodatabase schema), the information captured in this log is essentially identical to that shown in Figure 4.16.
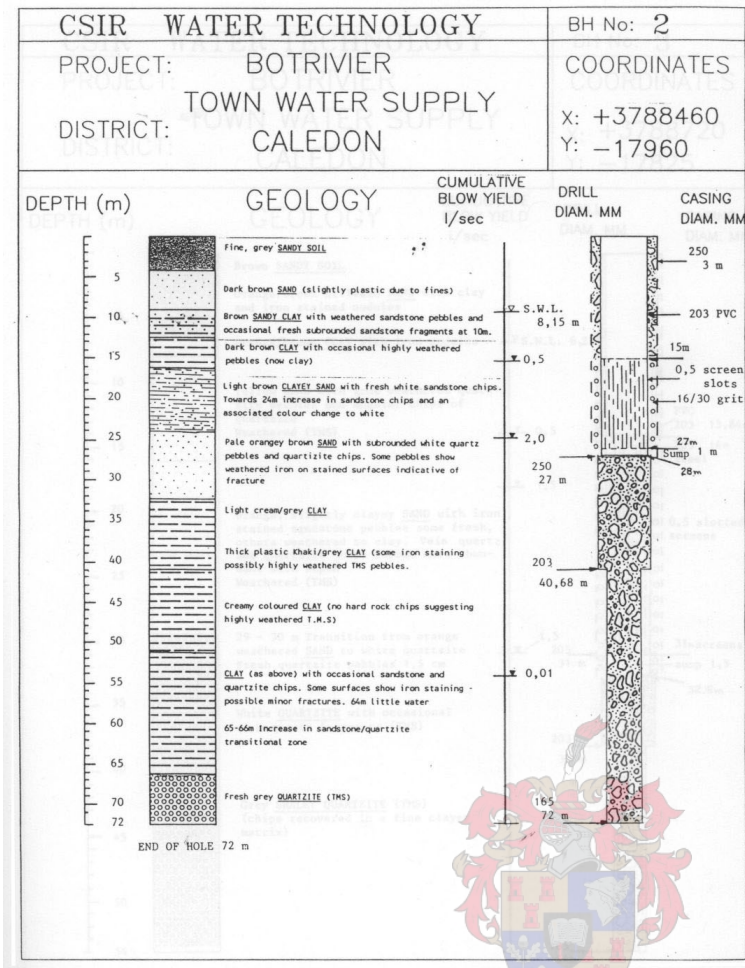
Source: CSIR 1989

Figure 4.17 – Borehole log from a drilling project in 1989

The borehole logs and drilling reports were used as primary data input regarding drilling, lithology, casing/screens and water-strikes. Appendix 2 shows this information source in full. From these logs and reports it can be seen that the information and format of drilling reports varies greatly in style and content.

The development of visualisation tools for the data model was not within the scope of this research. However, a brief effort to visualise the data inside the geodatabase was attempted. The results of this are described in the next section

4.9 VISUALISATION OF THE DATA MODEL DATA

Although the visualisation of data in the model was not a component of this research, it must be remembered that the data in the geodatabase must be accessible to two-dimensional (2D) and three-dimensional (3D) GIS software in order to be visualised and analysed. Due to the 3D nature of the information related to the boreline in the data model, it was preferable to be visualised in a 3D environment. ESRI ArcScene 3D visualisation software was used to display the test data that had been entered with the introduction of some third-party elements.

Two scripts, written by programmers at Geographic Information Management Systems (GIMS), were used to process the data in the data model in such a way that they could be displayed properly. A script that concatenated the depth range data into a single DBF file was used to create a stand-alone table of depth ranges. Then a script written for ArcScene was used to convert the DBF table data into a 3D polygon shapefile which was viewed as a column symbolised according to each of the depth ranges: geology, drilling, equipment range and gravel filter information. Figure 4.18 and Figure 4.19 show the borehole data symbolised using these methods.
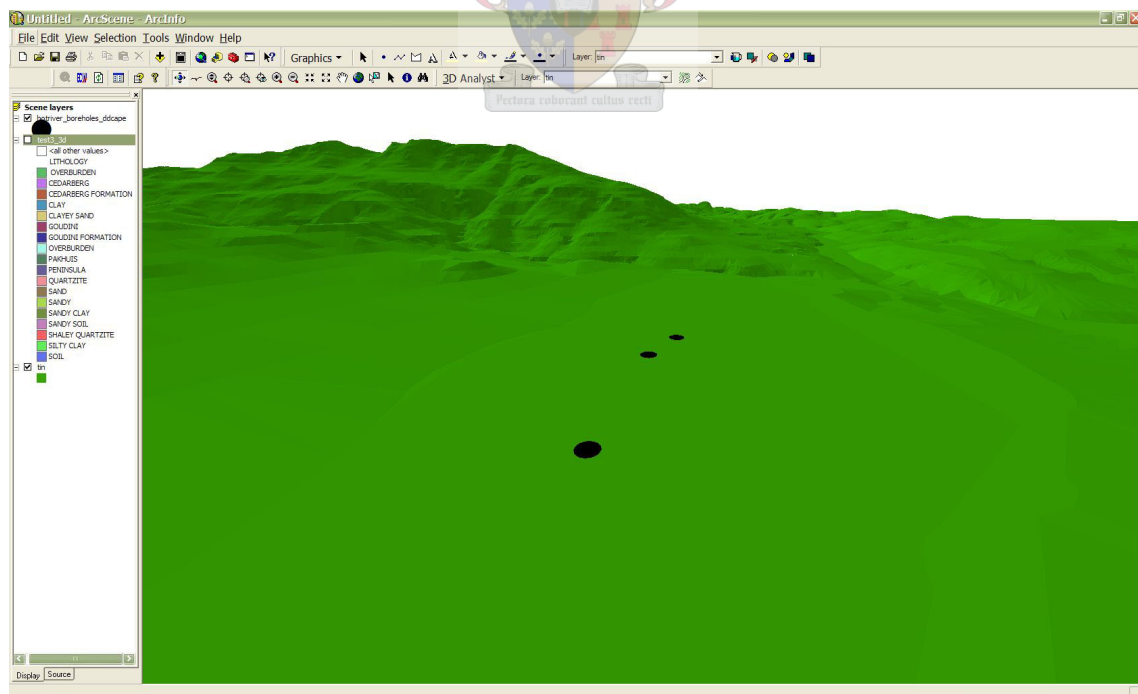
Figure 4.18 – The location of the boreholes in the Botriver valley
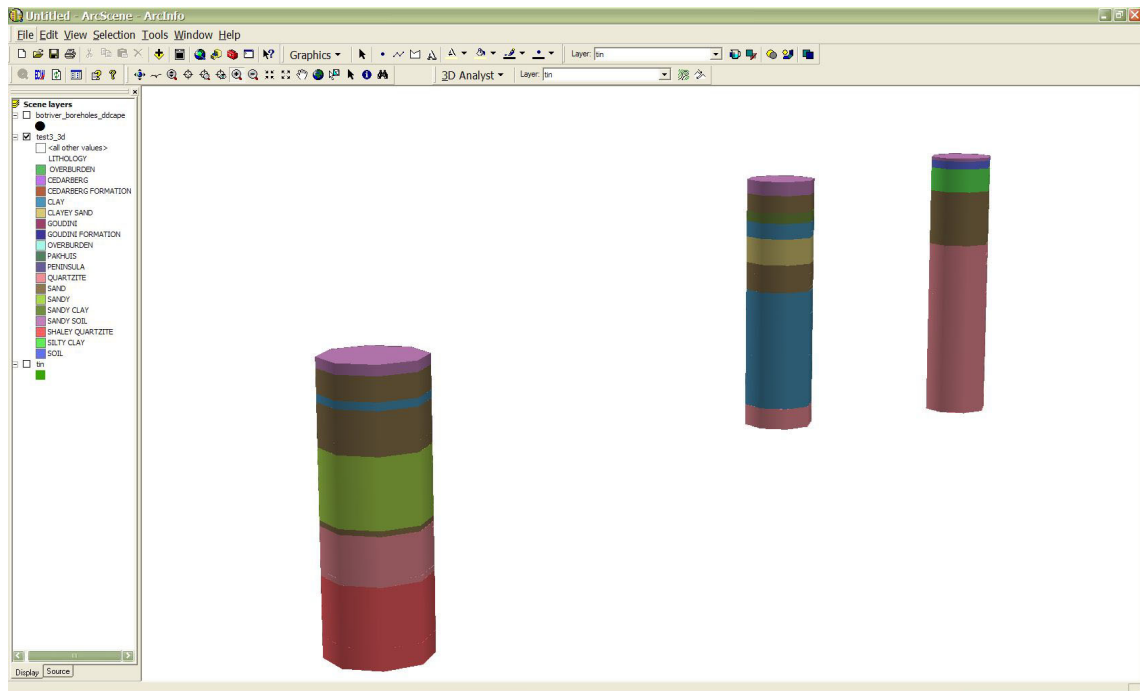
Figure 4.19 – Visualisation of the Botriver boreholes lithology in 3D

The results of this study showed that borehole information could be effectively represented through the application of a data model. The following chapter summarises the findings of this research before presenting some limitations of the methodology followed by recommendations for further research.
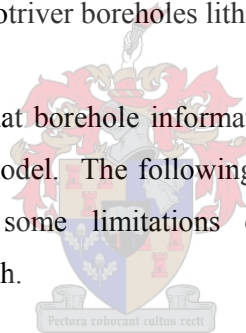
CHAPTER 5 : CONCLUSIONS, LIMITATIONS AND RECOMMENDATIONS

5.1 CONCLUSIONS

The approach presented in this thesis was an effective method for translating a set of user defined standards into a working data model implemented in a geodatabase. Zeiler's (1999) method of deconstructing user requirements into geodatabase elements greatly assisted in the definition of the data model elements and ultimately the geodatabase schema.

The application of CASE tools in the development of the UML diagram is an accepted method in developing data modelling for GIS. While the tools and language employed in the CASE tools method required a paradigm shift for the author, they conformed to database design norms and standards. With a grasp of the object-oriented design principles, such as inheritance and data integrity, and an understanding of how the CASE tools are used to convert a conceptual model of the system to a logical data model it was possible to develop the UML data model diagram. The result was a logical and transparent spatial data model that could be interpreted by the lay person and domain specialist alike. In addition, the result of the data modelling process was the first GIS-based data model developed using the (Standard Borehole Descriptors) SDB in South Africa. Although it is not possible for DWAF to implement a spatial data model such as the one developed in this research within their corporate database structure (Girman 2005, pers com), there could be scope for the application of this model or an adapted version of it in the distribution of DWAF geosite data.

Apart from appreciating the basics of geodatabase design using a UML approach, several key principles need to be understood in order to successfully complete this design process. These were – knowing where to apply sub-types, arranging attribute tables and their contents so that they operated correctly and accurately represented the need, defining relationships, and applying data integrity measures such as *coded value domains* and *range domains*. The most important of these were the data integrity measures as they are vital to the development of databases that require human input, as typing errors and inconsistencies can significantly impact on the quality of data housed in a database and in the long-term, undermine its usefulness.

The development of a geodatabase model to contextualise and manage spatial data is only beneficial if the value of data is associated with long term use or growth, such as a corporate or government database and particularly those with multi-user access requirements. The amount of effort and resources required to develop a data model for geodatabase implementation is such that a cost benefit analysis should be performed before it is conceived. It should balance the benefits offered by this method of database design with the cost of not having this functionality available. For example, it is not worth developing a data model for a small or short duration project unless it forms part of a longer on-going programme. A further example relevant to this research is the case of borehole data in a geohydrology practice. The number of boreholes present in the numerous studies carried out by such a group does not necessarily warrant the implementation of this technology, but as boreholes appear in all (or most) of their projects, the investment in a company or group borehole database with an accompanying data model design, is probably worthwhile.

The SDB document was an ideal source of reference as a user requirements analysis for data model design as the needs of the user community were very clearly stated. This project benefited significantly from the completion of the SDB document prior to the initiation of this research, removing the need for a lengthy and complicated scoping phase, gathering user needs. Without this even the design of a logical phenomena model would have been difficult. This underlines and supports the literature (Sieber 2000; Zeiler 1999) where it states the importance of a clear and well defined set of user needs for any data model development project or initiative.

A drawback to SDB is that two key areas are unfortunately insufficiently complete for this document to be the sole source of information for the data model development. These are the details of monitoring parameters and the way in which geological information is dealt with in the SDB. The lack of information on monitoring parameters was supplemented by literature identified in DWAF (2003b) which provides a comprehensive list of parameters that need to be monitored in boreholes. This list is included as a graphic in the data model diagram (see Appendix 1). Hence, the most significant short-coming of the SDB as a source of specifications for the data model design, is the way in which geological information is handled.

In the SDB geological data is dealt with as either *Unconsolidated* or *Consolidated*. This is a standard and logical division, except that the unique attributes of each kind of geology drives the development of the attribute tables in a direction that does not work as efficiently as the rest of the data model. It necessitates the creation of two separate table objects, one for unconsolidated and the other for consolidated geology, associated with the GHYDRO_AT_GEOLOGY object using a *one to one* relationship.

The process of developing a data model for key data sets could assist in the development of a culture of standards and best practice in an organisation. The analysis of user requirements and development of a method for capture, management and storage of data can drive positive behaviour in data management and adherence to standards and guidelines. The dialogue and participation process necessary to develop a set of user requirements aligns thinking within a user-base and design team and essentially results in a set of standards oriented to that group. If this group can define the requirements within the frame of a national or internationally accepted standard, then the exercise accomplishes two goals at once. It accommodates the needs of the group implementing common naming scheme, standardised feature definitions or other standards.

5.2 EXISTING GROUNDWATER DATA MODELS

The only widely publicised groundwater data model is the ArcHydro Groundwater data model. This model is considerably more complete in its representation of the hydrogeologic system, but it is generic in nature. Although it does utilise a similar approach for modelling borehole data through 'borelines', it is not as detailed as the model presented through this research based on the SDB and does not follow a national borehole construction standard. The published data models, particularly those available through the ESRI support site, are often intended as generic models that can be either customised or re-worked in order to suit individual needs. The borehole data model presented here has been designed specifically to cater for the needs of the South African groundwater community as laid out by the SDB.

The borehole element of the ArcHydro groundwater model provides simple functionality for lithological information and water level recording, but it does not go further. It currently does not include other borehole details such as casing and drilling information, but it does include a link to time series data; a feature that has remained at the core of the ArcHydro project. In

addition, the ArcHydro groundwater data model was developed as part of a PhD and hence afforded a much broader scope to the developer.

5.3 KEY SUCCESS FACTORS

Through experience gained in this research, the key elements to a good geodatabase design appear to be:

1. Understanding user requirements – an appreciation of the application field is fundamental to inform the definition of physical and abstract attributes in the design and how they relate to each other.
2. Simplicity – if the complexity of the data model is such that the user cannot understand the model or that it cannot be adapted or repaired, it is counter-productive and steps should be taken to simplify it. Simplicity is the key to clarity.
3. Clarity – the clarity of the finished data model is paramount if it is to be distributed to a larger user base.

Overall, there is definitely merit in utilising this approach and the technologies presented in the development of GIS databases, particularly those that will be utilised as part of a multi-user framework.

5.4 OPEN SOURCE RESEARCH AND DEVELOPMENT

An additional benefit to the UML CASE approach is that it is open-source in nature. The UML diagram that resulted from this research was a clear and easy to share diagram that could be implemented by others. It illustrated the thinking that was applied to developing the model and demonstrated a tangible link between the user requirements and the finished geodatabase schema. In addition, it also allowed users not using ESRI geodatabases and data model technology to implement the structure using GIS platforms.

5.5 LIMITATIONS IN THE METHODOLOGY

The design presented in this research was developed by one person, whereas both literature and common sense support a more team-oriented approach to design, as working in a group has the benefit of different view points and skill sets. Data modelling is, by nature, normally

a cooperative and multi-discipline effort carried out by a team comprising designers, domain specialists, users and managers. They must draw together their collective experience, knowledge and creativity to create a data model design that has a richer context while meeting the needs of all users, applies good database design principles and can be approved by managers. The process of developing a data model embeds this knowledge and experience in the data model and geodatabase. These teams should also include application specialists to transfer the domain knowledge and make sure that the logical phenomena model is being properly represented in the final database design; people with data modelling skills and experience; and finally programmers with experience in object-oriented programming languages, particularly Visual Basic and preferably including ArcObjects. Perhaps the results of this research can be taken up by DWAF or another group and developed further in a multi-disciplinary team such as the one described above.

Weaknesses in the geodatabase design are often only picked up once the database schema has been created and the geodatabase is being populated. This leads to an iterative process that can waste a great deal of time. Hence, a designer/design team must attempt to be as thorough as possible during the design phase. ArcCatalog does allow a geodatabase to be updated with new schema information, even when the database has been populated, but this process is unpredictable sometimes leading to inconsistencies and corruptions.
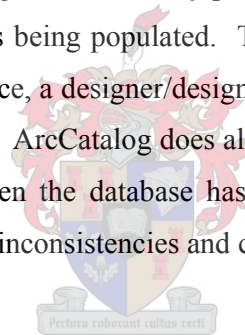
5.6 RECOMMENDATIONS FOR FURTHER RESEARCH

The logical extension of this research is the development of a holistic data model that includes all of the features relevant to the South African geohydrological context. This would of course require the prior development of Standard Descriptors for each of these features. Beyond this, the implementation of data models at a national level inside those government departments dealing with spatial information would go a long way towards supporting both the access to information act and the development of national geospatial information standards. These recommendations are by no means minor tasks and would require extensive scoping and cost benefit analyses. The use of data models could significantly improve the databases managed by DWAF under their mandate as custodians of the national water resources (DWAF 2005).

Beyond the development of this data model, effort needs to be applied to three specific areas to improve data input:

1. A method for porting data across from existing database structures to enable the large scale migration of borehole data from existing databases to a Geodatabase created using this methodology.

2. A data entry form needs to be developed for ArcGIS in order for users to enter data more easily. This input could be developed using the Visual Basic programming language and the COM objects supplied with ArcGIS.

3. The development of a routine to draw borehole logs using data held in the geodatabase schema.

A final element that could improve this research is the development of a graphical user interface for querying and graphing borehole data and custom tools and scripts for processing borehole data held in the geodatabase.

Promotion and mainstreaming is crucial to the further development of object-oriented GIS data models. Without increased awareness of these methods and technologies, GIS data modelling will remain a side discipline of GIS gurus and will not achieve the mainstream impact that it deserves. With increased levels of awareness, communities of practice can develop and data model design and implementation could become part of most GIS projects and data management initiatives in large corporations and government departments.

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APPENDIX 1 : DATA MODEL DIAGRAM

(See data model diagram on CD-ROM included)
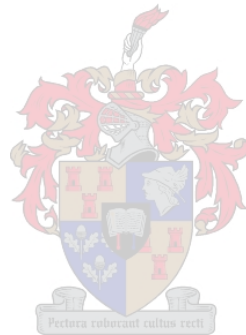
APPENDIX 2 : BOREHOLE LOGS AND DRILLING LOGS

Borehole logs from TMG Feasilbility Study

These borehole logs were drawn up to describe the boreholes drilled as part of the TMG feasibility study project. For more information on this project, please refer to (Brown et al 2003). These borehole log diagrams were not created using complex geohydrological software, but rather using the desktop publishing software, Coreldraw.

Borehole GWP 02 - Gateway

Borehole GWE 04 - Gateway

Borehole GWE 06 Northcliff

Borehole Logs from Botrivier Water Supply Scheme

CSIR WATER TECHNOLOGY — BH No: 1

PROJECT: BOTRIVIER TOWN WATER SUPPLY

DISTRICT: CALEDON

COORDINATES
X: +3788380
Y: −18040

DEPTH (m) / GEOLOGY / CUMULATIVE BLOW YIELD l/sec / DRILL DIAM. MM / CASING DIAM. MM

Surface sandy SOIL
"B" Horizon SOIL
White SILTY CLAY

Orangey red SAND with abundant small angular white quartz chips and quartz pebbles

Yellow SAND with abundant medium sized, rounded, weathered, quartzite pebbles and angular smaller white vein quartz chips, some clay balls – poss.w. Bokkeveld

Weathered QUARTZITE (T.M.S.) Abundant pebbles up to 100 mm

Slightly weathered QUARTZITE (T.M.S.)

Fractures at: 38 m
43 m
79 m

Fresh light grey QUARTZITE (T.M.S.)

S.W.L.6,3
0,5
250 31,97 m
203 35,45 m
2,0
3,5
5,0
165
84 m

203 steel 35,45m
35,7 m
203 PVC

END OF HOLE 84 m

CSIR WATER TECHNOLOGY

BH No: 2

PROJECT: BOTRIVIER
TOWN WATER SUPPLY
DISTRICT: CALEDON

COORDINATES
X: +3788460
Y: −17960

DEPTH (m)	GEOLOGY	CUMULATIVE BLOW YIELD l/sec	DRILL DIAM. MM	CASING DIAM. MM

Fine, grey SANDY SOIL

Dark brown SAND (slightly plastic due to fines)

Brown SANDY CLAY with weathered sandstone pebbles and occasional fresh subrounded sandstone fragments at 10m.

Dark brown CLAY with occasional highly weathered pebbles (now clay)

Light brown CLAYEY SAND with fresh white sandstone chips. Towards 24m increase in sandstone chips and an associated colour change to white

Pale orangey brown SAND with subrounded white quartz pebbles and quartzite chips. Some pebbles show weathered iron on stained surfaces indicative of fracture

Light cream/grey CLAY

Thick plastic Khaki/grey CLAY (some iron staining possibly highly weathered TMS pebbles.

Creamy coloured CLAY (no hard rock chips suggesting highly weathered T.M.S)

CLAY (as above) with occasional sandstone and quartzite chips. Some surfaces show iron staining - possible minor fractures. 64m little water

65-66m Increase in sandstone/quartzite transitional zone

Fresh grey QUARTZITE (TMS)

END OF HOLE 72 m

S.W.L. 8,15 m
0,5
2,0
0,01

250 3 m
203 PVC
15m
0,5 screen slots
16/30 grit
27m
Sump 1 m
28m
250 27 m
203 40,68 m
165 72 m

CSIR WATER TECHNOLOGY	BH No: 3
PROJECT: BOTRIVIER TOWN WATER SUPPLY	COORDINATES
DISTRICT: CALEDON	X: +3788720 Y: −17825

DEPTH (m) — **GEOLOGY** — **CUMULATIVE BLOW YIELD l/sec** — **DRILL DIAM. MM** — **CASING DIAM. MM**

Brown SANDY SOIL

Orange/brown hillwash SAND with clay and iron stained nodules

Orange/brown CLAY with iron nodules — S.W.L. 6,2

Yellow SAND with some weathered quartzite pebbles and angular chips of quartzite
Weathered (TMS) — 0,5

— 1,5

Orange, slightly clayey SAND with iron stained sandstone pebbles some fresh, others weathered to clay. Vein quartz and quartzite chips become more abundant with depth
Weathered (TMS)

29 - 30 m Transition from orange weathered SAND to white quartzite
Fresh quartzite pebbles 1,5 cm — 1,5 — 205 — 31 m

White QUARTZITE with occasional vein quartz fragments (TMS)

— 203 — 38 m

Grey SHALEY QUARTZITE (TMS) (chips recovered in a fine clayey matrix)

— 165 — 54m

PVC 203 13,84m
203 14m steel
0,5 slotted screens
31m screens
sump 1,5
32,5 m

Drilling Report From the Langebaan Road Aquifer Project

Drilling method:

Mud rotary drilling method was used on all boreholes drilled in Langebaan. This method involves the excavation of 2 sumps, roughly 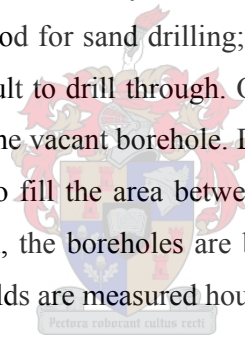1.5 m x 1.5 m x 1.5 m. A mixture of biodegradable Polyflip and water is used in order to stabilise the sand walls of the borehole during drilling and prevent collapsing of the borehole. The pump is placed within the second sump, pumping the Polyflip mixture into the drill rig and consequently the drill head. The area around the borehole is levelled, and sand is placed around the borehole site in order to channel drilling mud into the first pit. During drilling, the mud mixture is pumped down the drill head in order to cool and lubricate the drill bit, and most importantly to stabilise the sand walls. The mud, sand and rock fragments from the borehole flow into the first sump and settle in the sump, allowing a deposit free mixture to flow into the second sump where the pump is located. Waterstrikes are difficult to detect because of the continuous flow of mud out of the borehole, the amount of which is controlled by fissures or factures in the calcrete, etc. Mud rotary drilling is the preferred method for sand drilling; however, hard calcrete layers within the sand are problematic and difficult to drill through. Once drilling is complete, PVC blank pipes and screens are inserted into the vacant borehole. Depending on engineer specifications, sand, gravel, or bentonite is used to fill the area between the borehole wall and the outside PVC pipes. After site rehabilitation, the boreholes are blown with an air compressor for no more than 6 hours, and the blow yields are measured hourly at the v-notch weir.
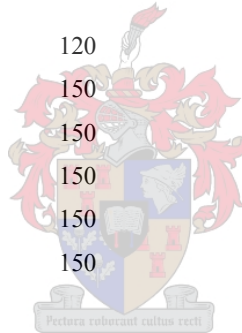
Borehole 1 and 1a

Hole Number	Depth			Description
	From	To	Diff	
	m	m	m	
1				06/09/2004: Moved to site. 07/09/2004: Dug sumps – 6 hours. Drove to fetch water – 15000L (15.6km). 3 Bags of polyflip used.
	0	12	12	08/09/2004: Drilled 0-12 m – 250 mm. Reamed borehole 0-4 m – 300 mm Inserted casing 8 m x 250 mm Polyflip: 4 bags Fetched water 30 000L (31.2km)
				09/09/2004: Waited for 250 mm casing – 6 hours. Reamed borehole 4-12 m – 300 mm. Pulled out 8 m x 250 mm casing. Inserted 12 x 250 mm casing. Fetched 15 000 L water (15.6 km). 4 Bags of polyflip used.
	12	15	3	10/09/2004: Drilled 12-15 m. Pulled out 12 m x 250 mm casing. Inserted 15 m x 250 mm casing. Fetched 30 000L water (31.2 km). 3 bags polyflip used.
	15	23	8	11/09/2004: Drilled 15-23 m x 250 mm. Pulled out 15 m x 250 mm casing. Reamed borehole 15-23 m x 300 mm. Inserted 23 m x 250 mm casing in. Fetched 30 000L water (31.2 km). 6 Bags of Polyflip used.
	23	50	27	13/09/2004: Winch broke. Repaired – 4 hours. Fetched water 15000L. Drilled 23-50 m x 250 mm. 3 bags of polyflip used.
	50	65	15	14/09/2004: Drilled 60-65 m. Fetched water 15 000L. Used 2 bags polyflip.
	65	80	15	15/09/2004: Drilled 65-80 m x 250 mm. Fetched water 15 000L. Used 3 bags polyflip. 16/09/2004: Backfill borehole to 40 m, PVC screens 6 m x 160 mm, PVC blank pipes 36 m x 160 mm, Filter Sand 40 bags, Gravel 13 mm x 5.38 tons.
				17/09/2004 Back fill borehole – 4 hours Moved to borehole No 1a – 4 hours
1a				20/09/2004 Moved caravan from Brackenfell to Langebaan Fetched water 7500L (7.8 km)
	0	13	13	21/09/04

				Fetched water 15000L (15.6 km), 7 bags of Polyflip used, Drilled 0-13 m x 250 mm, PVC Screens 6 m x 160 mm, PVC blank pipes 7 m x 160 mm, Filter sand 31 Bags, Gravel 13 mm 25 bags.
				22/09/2004 Filled sumps up and levelled borehole area for BH1 and BH1a – 7 hours Moved to subsequent site.

Blow test:

Hole Number	Time	Notch height (mm)	Flow Rate (L/s)
1	07h00	60	1.25
08/10/2004	08h00	66	1.58
	09h00	80	2.58
	10h00	80	2.58
	11h00	80	2.58
	12h00	80	2.58
1a	14h00	120	6.96
08/10/2004	15h00	150	12.20
	16h00	150	12.20
	17h00	150	12.20
	18h00	150	12.20
	19h00	150	12.20

GPS Co-ordinates:

Borehole 1: 18°07'54.858 E 33°11'09.690 S

Borehole 1a: 18°07'54.840 E 33°11'09.612 S

Borehole 1 was backfilled with gravel to 41 metres below surface. A 6m sump was placed at the bottom of the backfilled borehole (41 – 35 m), followed by 6 metres of screen (35 – 29 m), and blank pipes to surface. 23 m of 10.5" casing remains in the ground.

Borehole 1a has 6 m of PVC screen (14 – 8 m below surface), followed by 8 m of PVC blank pipes.

Borehole 1/1a

Borehole Log - BH1

Locality - X: 18.13 Y: -33.19 Z: 0.00

Borehole Log - BH1a

Borehole 2 and 2a

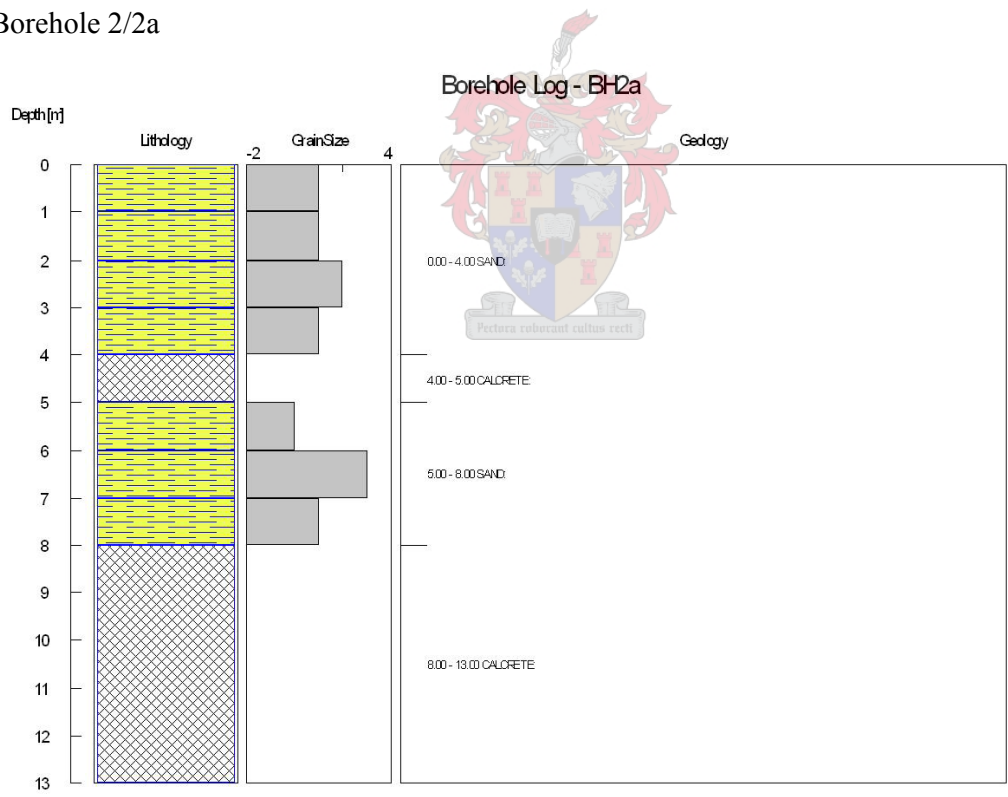| Hole	Depth			Description
Number	From	To	Diff	
	m	m	m	
2	0	27	27	29/09/2004
				Dug Sumps – 2 hours, Fetched water 15 000L (23.7 km), Drilled 0 – 27 m, 5 Bags Polyflip used, Casing inserted 6 m x 160 mm
	27	44	17	30/09/2004
				Drilled 27 – 44 m, PVC Screens 6 m x 160 mm, PVC Blank pipe 38 m x 160 mm, Filter Sand x 39 Bags (± 19 m), Gravel 13 mm x 52 bags (± 25 m), Stand pipe 4 m x 200 mm, Pulled 6 m x 250 mm casing out, Fetched water 15 000L, 6 bags Polyflip used.
2a	0	13	13	30/09/2004
				Drilled 0 – 13 m, Fetched 10 000L water (23.7 km), 3 Bags Polyflip, PVC Screens 6 m x 160 mm, PVC Blank pipe 7 m x 160 mm, Filter Sand x 28 bags (± 6 m), Gravel 13 mm x 33 bags (± 7 m), Stand pipe 4 m x 200 mm
				04/10/2004
				Moved vehicles off site.
				Filled sumps – 2 hours, Borehole site rehabilitation in accordance with nature conservation instructions – 2 hours.

Borehole 2 has a 9 m sump at the bottom of the borehole (44 – 35 m below surface), followed by 6 m of screening (35 – 29 m below surface), and followed by 29 m of blank pipe.

Borehole 2a has a 6 m screen at the base of the borehole (12 – 6 m below surface) followed by 6 m of blank PVC pipe.

Blow Test:

Hole Number	Time	Notch height (mm)	Flow Rate (L/s)
2	06h00	115	6.13
07/10/2004	07h00	126	7.85
	08h00	126	7.85
	09h00	126	7.85
	10h00	126	7.85
	11h00	126	7.85
	12h00	126	7.85
2a	14h00	115	6.13
07/10/2004	15h00	140	10.20
	16h00	146	11.32
	17h00	146	11.32
	18h00	146	11.32
	19h00	146	11.32

Borehole 2/2a

Borehole Log - BH2a

Depth [m]

Lithology   GrainSize   Geology

0.00 - 4.00 SAND

4.00 - 5.00 CALCRETE

5.00 - 8.00 SAND

8.00 - 13.00 CALCRETE

Borehole Log - BH2

Depth [m]

Lithology	GrainSize	Geology

-2   4

0

5

10

15

20

25

30

35

40

45

0.00 - 8.00 SAND:

8.00 - 37.00 CALCRETE

37.00 - 45.00 CLAY:
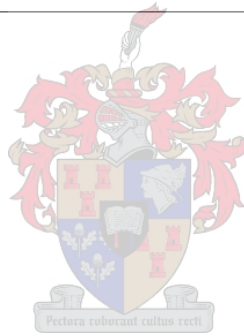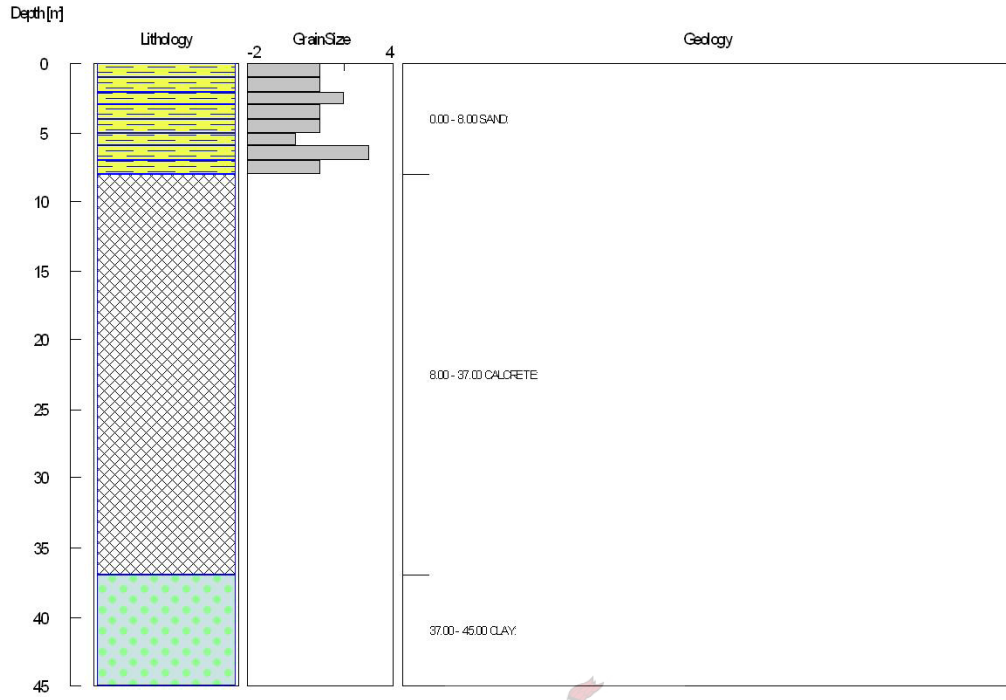
Borehole 3

Hole Number	Depth From M	To m	Diff m	Description
3				23/09/2004
				Dug sums – 3 hours, Fetched water 22500L
	0	20	20	Drilled 0 – 20 m
				3 Bags Polyflip
	20	40	20	24/09/2004
				Drilled 20 – 40 m, Fetched water 15 000L (31.2 km), 7 Bags of Polyflip
	40	47	7	27/09/2004
				Drilled 40 – 47 m, Fetched water 15 000 L(31.2 km), 3 Bags Polyflip
	47	64	17	28/09/2004
				Drilled 47 – 64 m, Fetched water 20 000L (41.6 km), 3 Bags of Polyflip, PVC Screens 9 m x 160 mm, PVC Blank pipes 53 m x 160 mm, Filter sand 40 bags (± 24 m), Gravel 13 mm 67 bags (± 40 m), Stand pipe 4 m x 200 mm
				29/09/2004
				Filled sumps up – 2 hours
				Borehole rehabilitation to requirements of nature conservation – 2 hours

Blow test

Hole Number	Time	Notch height (mm)	Flow Rate (L/s)
3	07h30	98	4.21
06/19/2004	08h30	100	4.43
	09h30	100	4.43
	10h30	100	4.43
	11h30	100	4.43
	12h30	100	4.43

Borehole 4

Hole Number	Depth From m	To m	Diff m	Description
4	0	40	40	05/10/2004
				Moved to site – 5 hours, Dug sumps – 3 hours, Fetched water – 15 000L (6.1 km x 3), 4 bags Polyflip, Drilled 0 – 40 m.
				06/10/2004
				Drilled 40 – 67 m, Fetched water 10 000L (6.1 km x 2), 5 Bags Polyflip, PVC Screens 6 m x 160 mm, PVC Blank Pipe 55 m x 160 mm, Filter sand x 38 bags (± 23 m), Gravel 13 mm x 71 bags (± 44 m), Stand pipe 4 m x 200 mm, Bentonite plug 53 – 48 m (1 bag)
				07/10/2004
				Filled sumps – 2 hours, Borehole site rehabilitation – 2 hours

Borehole 4 has a 1 m sump at the bottom of the borehole (61 – 60 m), followed by 6 m of screen (60 – 54 m) and 54 m of blank pipe (0 – 54 m).

Hole Number	Time	Notch height (mm)	Flow Rate (L/s)
4	08h00	50	0.794
09/10/2004	09h00	50	0.794
	10h00	55	1.05
	11h00	55	1.05
	12h00	55	1.05
	13h00	55	1.05

Borehole Log - BH4

Depth [m]

Lithology | GrainSize | Geology
-1.0 ... 3.0

0.00 - 2.00 SAND

2.00 - 54.00 CALCRETE

54.00 - 60.00 CLAY

60.00 - 66.00 SAND

66.00 - 67.00 GRANITE

0
10
20
30
40
50
60
70