# CREATION OF A HYDROLOGICAL MODELLING ENVIRONMENT TO ASSIST IN THE DECISION MAKING OF WATER-RELATED ACTIVITIES

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# DECLARATION

I, **SAREL JOHANNES VILJOEN**, with identity number ▬▬▬▬▬▬▬▬, and student number **9504974**, do hereby declare that the research project which has been submitted to the Central University of Technology, Free State for the degree **MAGISTER TECHNOLOGIAE: INFORMATION TECHNOLOGY**, is my own intellectual work; and complies with the *Code of Academic Integrity*, as well as other related guidelines, procedures, rules and regulations as stipulated by the Central University of Technology, Free State; and has not been submitted before by any other person in fulfilment (or partial fulfilment) of the requirements for the attainment of any qualification.

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SJ VILJOEN                                            DATE

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- the National Research Foundation (NRF), for supporting this research project and for enabling me to attend conferences to gather much needed information.
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# S U M M A R Y

In South Africa, water is a scarce resource and it has become very important to manage this resource effectively. The State developed a regulating framework, under the hospice of the Minister of Water Affairs and Forestry, which protects the country's water resources from over-exploitation by ensuring that it is protected, used, developed, conserved, and managed, in a sustainable and equitable manner. The laws and policies governing the use of water resources are contained in the National Water Act (South Africa, 1998), the National Water Policy (South Africa, 1997a), the National Water Resource Strategy, and the Water Services Act (South Africa, 1997b). In addition some water-related functions were transferred to Catchment Management Agencies and Water Users' Associations, and it is their task to ensure that the strategies, laws and policies are implemented.

Effective water management can only be performed by making use of hydroinformatics which assists with simulations and estimations. As a result input data will be collected, added to a Relational Database Management System and output results generated. A Geographic Information System with the support of a geodatabase will allow users to store spatial and temporal data.

The research project investigated different water-related data models (ArcHydro, Hydstra, GML, HYMOS, and WinHSPF), as well as hydrological modelling frameworks (BASINS, OMS, OpenMI, SPATSIM, and TIME) to determine whether they were adequate to assist with the decision making of water-related activities.

It was found that these data models and hydrological modelling frameworks did not allow users to add new datasets to their existing data structures and in many cases only had a limited set of functions. For these reasons it was

decided to develop a comprehensive, modifiable, geodatabase that will function in a modelling environment which will allow users to save their data in a centralised database. Additionally the functionality provided by other data models and modelling frameworks may be linked and used in the new modelling environment.

A methodology that has been followed was to first establish the objectives of the research project, gather the necessary data, investigate various data models and hydrological modelling frameworks, determine the requirements for the modelling environment, design and create the modelling environment, design and create the geodatabase, and finally selecting the study area which will provide the research project with the necessary data.

The following findings were made concerning the research project: firstly, that ArcHydro will be used as example data model to assist in designing the geodatabase. Secondly, that UML will be used as a development tool to assist with the development of the geodatabase. Thirdly, that the geodatabase will be generated from the XML schema and be made available to ArcCatalog. Fourthly, that data from different users/providers (Hydstra, Stats SA, Weather Bureau, Department of Water Affairs and Forestry, etc.) be inserted into the geodatabase. Fifthly, that any other hydrological modelling framework may make use of the data stored in the geodatabase. Finally, ArcGIS was selected as GIS application and Microsoft Access as a storage area.

# OPSOMMING

Water is „n skaars hulpbron in Suid-Afrika en dit het baie belangrik geword om die hulpbron effektief te bestuur. Die Staat het „n reguleringsraamwerk ontwikkel, onder leiding van die Minister van Waterwese en Bosbou, wat die land se waterhulpbronne beskerm teen oor-ontgunning deur te verseker dat dit beskerm, gebruik, ontwikkel, bewaar, en bestuur word op „n volhoubare en regverdige wyse. Die wette en beleide wat die gebruik van waterhulpbronne reguleer, word vervat binne die Nasionale Waterwet (South Africa, 1998), die Nasionale Waterbeleid (South Africa, 1997a), die Nasionale Waterhulpbronstrategie en die Waterdienstewet (South Africa, 1997b). Daarbenewens word sekere waterverwante funksies oorgedra na die Opvangbestuur Agentskappe en Watergebruikersverenigings en dit is hulle taak om te verseker dat die strategieë, wette, en beleide, soos hierbo vervat, uitgevoer word.

Effektiewe waterbestuur kan slegs uitgevoer word deur gebruik te maak van hidro-informatika wat simulasies en skattings ondersteun. Gevolglik sal invoerdata versamel word, by die Relasionele Databasisbestuurstelsel gevoeg word, en afvoerresultate gegenereer word. „n Geografiese Inligtingstelsel, wat ondersteun word deur „n geodatabasis, sal gebruikers toelaat om ruimtelike en temporele data te berg.

Die navorsingsprojek het verskeie waterverwante datamodelle (ArcHydro, Hydstra, GML, HYMOS en WinHSPF) asook hidrologiese modelleringsraamwerke (BASINS, OMS, OpenMI, SPATSIM en TIME) ondersoek om vas te stel of hulle voldoende is vir besluitneming met betrekking tot waterverwante aktiwiteite.

Daar is vasgestel dat die datamodelle en hidrologiese modelleringsraamwerke nie die gebruiker toelaat om nuwe datastelle by die bestaande datastrukture te

voeg nie en in baie gevalle slegs „n beperkte stel funksies bevat. Weens hierdie redes is daar besluit om „n omvattende, veranderbare geodatabasis te ontwikkel wat sal funksioneer binne „n modelleringsomgewing wat gebruikers sal toelaat om hulle data te berg in „n gesentraliseerde databasis. Daarbenewens sal die funksionaliteit wat deur ander datamodelle en hidrologiese modelleringsraamwerke verskaf word, gekoppel en gebruik kan word binne die nuwe modelleringsomgewing.

„n Metodologie is gevolg waar die doelwitte van die navorsingsprojek eerstens bepaal is, die nodige data versamel is, verskeie datamodelle en hidrologiese modelleringsraamwerke ondersoek is, en die behoeftes vir die modelleringsomgewing bepaal is. Daarna is die modelleringsomgewing en geodatabasis ontwerp en geskep, en laastens is die studiegebied gekies wat die navorsingsprojek van data sal voorsien.

Die volgende bevindinge is gemaak rakende die navorsingsprojek: eerstens, dat ArcHydro gebruik word as voorbeeld datamodel om ondersteuning te bied met die ontwerp van die geodatabasis. Tweedens, dat UML gebruik word as ontwikkelingshulpmiddel met die ontwikkeling van die geodatabasis. Derdens, dat die geodatabasis geskep word uit die XML Skema en beskikbaar gestel word vir ArcCatalog. Vierdens, dat die data van die verskillende gebruikers/verskaffers (Hydstra, Stats SA, Weerburo, Departement van Waterwese en Bosbou, ens.) bygevoeg word by die geodatabasis. Vyfdens, dat enige ander modelleringsraamwerk gebruik kan maak van die data binne die geodatabasis, en laastens dat ArcGIS gebruik word as GIS toepassing en Microsoft Access as bergingsarea.

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# LIST OF ABBREVIATIONS

ArcIMS – Arc Internet Map Server

BASINS – Better Assessment Science Integrating Point & Nonpoint Sources

CASE – Computer Aided Software Engineering

CMA – Catchment Management Agency

CMIS – Catchment Management Information System

CMS – Catchment Management Strategy

DDL – Dynamic Link Library

DEM – Digital Elevation Model

DWAF – Department of Water Affairs and Forestry

ER-diagram – Entity Relationship diagram

ERM – Extended Relationship Model

ESRI – Environmental Systems Research Institute

HSPF – Hydrologic Simulation Program, FORTRAN

GIS – Geographic Information Systems

GML – Geographic Markup Language

GUI – Graphical User Interface

ICT – Information and Communication Technology

IS – Information System

IT – Information Technology

IWMI – International Water Management Institute

IWR – Institute for Water Research

KML – Keyhole Markup Language

NWA – National Water Act of South Africa, Act 36 of 1998

NWP – National Water Policy of 1997

NWRS – National Water Resource Strategy

OGC – Open Geospatial Consortium

OpenMI – Open Modelling Interface

OMS – Object Modelling System

OS – Operating System

RDMS – Relational Database Management System

SDE – Spatial Database Engine

SPATSIM – Spatial and Time Series Information Modelling Software

SQL – Structured Query Language

SWAT – The Soil and Water Assessment Tool

TCP/IP – Transmission Control Protocol / Internet Protocol

UML – Unified Modelling Language

USEPA – United States Environmental Protection Agency

USGS – United States Geological Survey

WMA – Water Management Area

WRC – Water Research Commission of South Africa

WRM – Water Resources Management

WRSM – Water Resources Simulation Model

WRYM – Water Resources Yield Model

WSA –Water Services Act of South Africa, Act 108 of 1997

WUA –Water Users Associations

XMI – XML Metadata Interchange

XML – Extensible Markup Language

# CHAPTER 1- INTRODUCTION AND PURPOSE OF THE RESEARCH

## 1.1  BACKGROUND

Water is a scarce resource in South Africa and is characterised by frequent droughts, floods and erratic, unevenly distributed rainfall (Ashton, 2001).  It has become very important to manage the water resources and their quality in a sustainable and efficient way.  According to Thompson (2006:7), South Africa is on the threshold of water stress.  He states that within the next few years the population growth, developing economy, and urgent need to supply water to the millions of people will take the water resources beneath the water stress level, which indicates that more water will be needed than could be delivered at any given time and place.  The International Water Management Institute (IWMI) has conducted a research project to determine the water demand and supply needs for countries around the world, and according to their projections South Africa will face a physical water scarcity in 2025 (refer to Figure 1.1) (IWMI, 2000).

Figure 1.1 Projected Water Scarcity in 2025 (IWMI, 2006).

Thompson states that: firstly, South Africa is lacking in the effective provision of water for certain sectors (agricultural, domestic, industrial and environmental). Secondly, many people are still without access to adequate services, and those that have access expect them to be supplied in a sustainable manner. Thirdly, there is a conflict of interests between the different uses and users of water in and between catchments. Fourthly, the present generation need to consider the needs of the future generation. Fifthly, the application of human and capital resources for water resource development is relative to other investments. Finally, the economic prosperity and preservation of ecosystems should be kept in consideration. For this reason any conflicts of interest should be resolved through interventions to ensure that the water resources are protected, used, developed, conserved, managed, and controlled, in such a way as to achieve long-term sustainability (Thompson, 2006:7-22). A regulating framework has been developed and is currently in a process of being implemented to address some of the above-

mentioned aspects.  Different regulating frameworks (planning, environmental, disaster management, minerals, land, agriculture and provision of essential services) should take the needs of each other into consideration to ensure that no one is affected in a negative way.   The regulating framework developed for water resources is aimed at the management of absolute water scarcity as well as the provision of water services with significant participation by all role-players.  Government has realised the importance of this regulating framework and has created the necessary legislation of which the National Water Act (NWA) 36 of 1998 and the Water Services Act (WSA) 108 of 1997 are the most important.   These Acts are enabling laws, empowering government to manage the water resources (mainly with the measures as contained in the NWA) and to provide potable water and sanitation services (mainly with the measures as contained in the WSA).   These Acts are therefore mechanisms (together with other tools) to implement the water-related policies.  Below are extracts from the Constitution and the NWA, which highlight the importance of the newly created regulating framework.

The Constitution of South Africa states, in Sections 27 (1.b) and 24 (a), that:

"Everyone has the right to have access to sufficient food and water" and "an environment that is not harmful to their health or well-being" (South Africa, 1996).

and secondly, Act 36 of the NWA (South Africa, 1998) states that:

"Water is a national resource, owned by the people of South Africa and held in custodianship by the State".

The purpose of the NWA (South Africa, 1998) is to provide a framework to protect water resources against over-exploitation.   Furthermore the NWA indicates that water is essentially a tool to transform society towards social and environmental justice and poverty eradication.  Moreover it is supposed to

ensure that there is enough, good quality, water for social and economic development now and in the future.  Many factors have an impact on the available water resources and a balance should be struck between the interests of property holders (persons with entitlements to water) and the interests of the general public (Thompson, 2006:64-76).  It is clear that the scope and scale of the water resources policy and management is enormous and difficult to put into practice (Theron *et al.*, 2006:298).

The organisational framework is one of the most important aspects of water management, because it determines the effectiveness of policy implementation.  Various organisations are involved and it is important that their respective roles and responsibilities are clearly defined to minimise overlapping mandates (Figure 1.2 gives a schematic layout of the different role-players involved in water management).

The organisational framework should be flexible with respect to scale of function and the type of organisation.  This flexibility recognises the diverse realities of water issues and management in South Africa.  The organisations/parties involved in water management may be grouped into (Thompson, 2006:117-125; South Africa, 1997a):
* custodians of the water resources;
* water resource developers;
* regulators, which could be divided into:
  o those regulating the use of water resources;
  o regulating activities that may affect the water resources;
  o regulating land uses; and
  o providing frameworks for the provision of water services;
* water services providers;
* conflict resolvers;
* users of water; and
* interested and affected persons and groups.

# CUSTODIANS OF THE WATER RESOURCES
## Minister of Water Affairs and Forestry
## Department of Water Affairs and Forestry (DWAF)

### REGULATORS | WATER RESOURCES DEVELOPERS

| REGULATING LAND USES | REGULATING ACTIVITIES THAT MAY AFFECT THE RESOURCES | REGULATING WATER USES | PROVIDING FRAMEWORK FOR SERVICE PROVISION | WATER RESOURCES DEVELOPERS |
|---|---|---|---|---|
| National<br>- Department of Land Affairs<br>- Department of Housing<br>- Department of Environmental Affairs | National<br>- Department of Environmental Affairs<br>- Department of Minerals and Energy<br>- Department of Agriculture | National<br>- Department of Water Affairs and Forestry | National<br>- Department of Water Affairs and Forestry<br>- Department of Provincial and Local Government | National<br>- Department of Water Affairs and Forestry |
| Provincial<br>- Departments Local Government<br>- Departments of Housing<br>- Departments of Environment<br>- Departments of Land Administration | Provincial<br>- Departments of Environment<br>- Departments of Agriculture | Provincial | Provincial<br>- Departments of Local Government | Provincial |
| Local<br>- Local Authorities | Local | Local | Local | Local |
| Other | Other<br>- Catchment Management Agencies (CMAs) | Other<br>- Catchment Management Agencies (CMAs) | Other | Other<br>- Catchment Management Agencies (CMAs)<br>- Bodies to implement International Agreements |

### LAND USES
Settlements
- Urban
- Rural, formal and informal

Agriculture
- Dryland
- Irrigation
- Cattle
- Concentration of live stock

Infrastructure development
- Civil
- Water
- Waste disposal sites and areas

Industrial
- Power generation
- Factories
- Business
- Forestry

Mining
- Open cast
- Underground
- Beneficiary plants

Recreation
- Boating
- Angling
- Camping
- Picnicking

Environmental

Tourism

Other
- Religious
- Medicinal

### CONFLICT RESOLVERS
Water Tribunal
Mediators
Courts

### AFFECTED PERSONS
- Other water users
- Owner of adjoining land
- Person using product

### WATER USERS
Persons undertaking the following activities:
- taking water from a water resource
- storing water
- impeding the flow of water in a watercourse
- diverting the flow of water in a watercourse
- engaging in a stream flow reduction activity
- engaging in a controlled activity
- discharging waste into a water resource
- disposing of waste impacting on a resource
- disposing of water from industrial process
- altering the bed and banks of a watercourse
- removing and discharging ground water
- using water for recreational purposes

### SERVICES PROVIDERS
Providing the following services:
- treat, convey and distribute water
- collect water-related waste
- remove water-related waste
- treat water-related waste
- services necessary to use water
- water resource management services
- provide resources and assistance
- provide information

National
- Department of Water Affairs and Forestry

Provincial

Local
- Metropolitan municipalities
- Some district municipalities
- Authorised local authorities

Other
- Water boards
- Water service committees
- Water user associations
- Private water services providers

### INTERESTED PERSONS
National
- Department of Public works
- Department of Health
- National Treasury
- Department of Education

Provincial
- Departments of Education

Local

Other
- Provincial liaison committees
- South African Local Government Association
- Traditional leaders
- Water committees
- NGOs
- CBOs
- Agri SA
- Transvaal Agricultural Union
- National African Farmers Union
- Chambers of Mines
- Financiers
- Investors
- Developers
- Aid agencies
- Forums
- Conservation and environmental interest groups
- Human rights activists
- Manufactures and suppliers
- Consultants
- Researchers

Legend:
- Co-operative government and intergovernmental relationship
- Monitor and regulate activities and remedy effects of activities
- Intervention
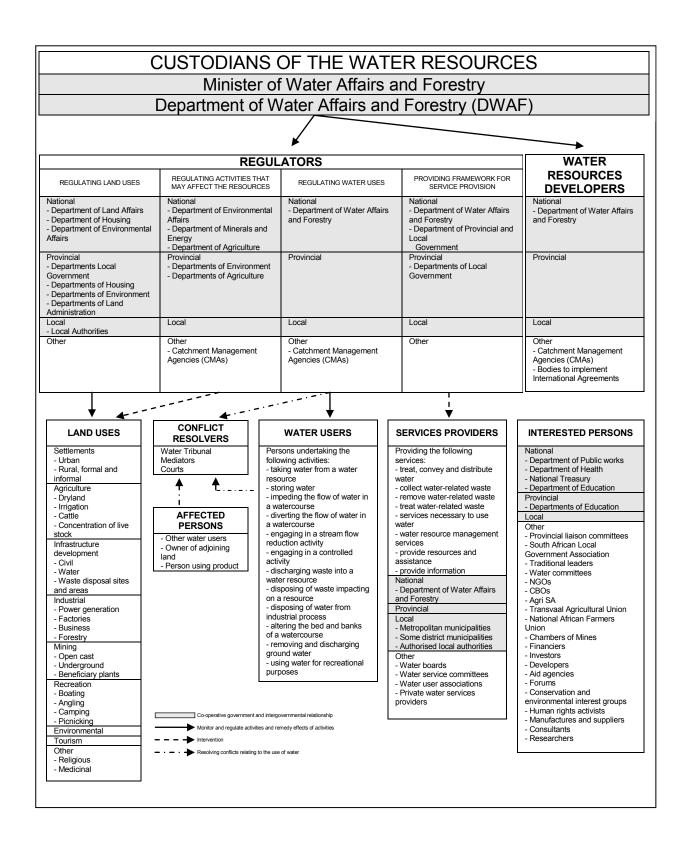- Resolving conflicts relating to the use of water

Figure 1.2  Different organisations/parties involved in water management
(Thompson, 2006:218-219)

The NWA, 1998 (Act No. 36 of 1998) requires that the National Government, acting through the Minister of Water Affairs and Forestry, must ensure that the water is protected, used, developed, conserved, managed, and controlled, in a sustainable and equitable manner, for the benefit of all persons. To do this, the Minister must not only ensure the equitable distribution of water to all South Africans, but also protect the water resources for future generations. This requires both the protection of the water resources from over-exploitation as well as the quality of resources. The Department of Water Affairs and Forestry (DWAF) is in the process of implementing the NWA of 1998 (South Africa, 1998). The NWA creates the legislative framework for implementing the National Water Policy of 1997 (South Africa, 1997a). Due to time, manpower, funding, and technical know-how constraints, DWAF follows a phased process to implement the policy. This is done within a stable and transparent institutional, administrative, and financial framework. The entitlements to use water are not contained in the NWA (South Africa, 1998), as the Act only contains the mechanisms for determining and obtaining rights. Rights to use water are contained in various documents, including notices in the *Government Gazette*, licenses, purchase contracts, deeds of servitudes, etc. The following strategies will be developed in a progressive and phased manner to help with the implementation of the Policy:

- National Water Resource Strategy (NWRS). The Minister must, after consultation with society at large, establish a NWRS. This strategy provides a framework for the protection, use, development, conservation, management, and control, of the water resources of the country as a whole. It also provides the framework within which water will be managed at regional and catchment level (DWAF, 2004b).

- Catchment Management Strategies (CMS). An area of concern was the collection and provision of information for water resource managers and development planners wherever water-related planning takes place (Theron *et al.*, 2006:298-305). The Minister will create the necessary institutional capacity through the establishment of Catchment

Management Agencies (CMAs). These CMAs share the responsibility for managing water resources with the State (DWAF, 1999). Their initial functions being for example, performing water-related investigations and providing advice to interested persons on the management of the water resources. Certain water resource management functions will be delegated or assigned to these agencies, depending on their capacity, the availability of resources, and the relevant water resource aspects to be managed within their management areas will be addressed. CMAs will be required to develop a CMS for the water resources within their management areas. This strategy must be in harmony with the NWRS (DWAF, 2004b) and should, among others, set out the objectives and plans of the CMAs for the protection, use, development, conservation, management, and control, of the water resources. In the process of developing the strategy, the CMA's must seek co-operation and agreement in water-related matters from various stakeholders (South Africa, 1997a; Schreiner and Van Koppen, 2002:394&398-399).

Figure 1.3 provides a visual layout indicating how the strategies and frameworks mentioned-above, relate to one another.

Figure 1.3  Layout of the strategies/frameworks that relate to water management.

These strategies are binding on the Minister, Departments of State, and all water management institutions, when exercising powers or performing duties under the NWA of 1998 (South Africa, 1998), and they must give effect to it.

The Minister may also establish Water Users' Associations (WUAs).  These associations operate at a restricted localised level as co-operative associations of individual water users who wish to undertake water-related activities for their mutual benefit.  The functions of a specific WUA depend on the approved Constitution of that association, and guidelines are specified in Chapter 8 of the NWA of 1998 (South Africa, 1998).

In addition a Water Tribunal, an independent body, may be established and it hears the appeals against certain decisions on the use of water made by water management institutions and CMA's. The functions of the Water Tribunal are explained in Chapter 15 of the NWA of 1998 (South Africa, 1998).

## 1.2  RATIONALE AND MOTIVATION FOR THE RESEARCH

As mentioned previously, CMA's share the responsibility for managing water resources with the State (Schreiner and Van Koppen, 2002:398).  In order to manage the water resources effectively each CMA needs to look at large collections of variables (data), for example, environmental attributes (soil type, rainfall, evaporation, geology, temperature, and water quality), and water supply attributes (industrial needs, human consumption, water demand, water leakage, and purification plants).

According to Clark and Smithers (2006a), many CMA's have spent huge amounts to determine what is needed in order to create the perfect management solution.  This has led to the creation of many water Catchment Management Information Systems (CMIS).  They continue by indicating that some information systems were developed out of research projects, but that only a few of them were implemented, and even a smaller number is active to this day.  Water Resources Management (WRM) requires an in-depth understanding of complex hydrological systems.  Since the 1980's advances in computer science, combined with an improved understanding of hydrological processes, have resulted in the development of computer simulation models that aid our understanding of hydrological systems.  The problem that currently exists with many of these models is the fact that they were designed and developed for a particular domain within the hydrological system, such as surface water, groundwater, and ecology, etc.  In addition

these data models use specific datasets and don't allow users to add their own, custom-made, datasets. WRM requires that these different models be integrated, and that experts from different fields may collaborate in the overall assessment of water resources. Clark and Smithers (2006b: 465) also feel that there is a need to integrate different models. They continue and indicate that this need for integration has led to the trend of developing modelling frameworks and environments. Before the development of modelling frameworks, models run within their own modelling systems, each consisting of similar tools to prepare model input data, writes model input files, and analyse model output. To move data from one model to another became tedious, caused a lot of duplication, and could only be solved by creating a modelling framework that would reduce the duplication of effort and make the model easy to work with by providing common data preparation and post-processing tools. Today, there are many legacy models in existence, and it is not financially practical to restructure all of these models into a common modern programming language to ensure that they may work together in one large framework (Clark & Smithers, 2006a:1).

Due to the fact that many models had their own data structures which were not compatible with one another and did not easily allow users to customise them, it was decided that a CMIS should be designed for the Upper Orange Catchment Area which should contain a relational database (which will later be converted into a geodatabase) with all the relevant data (water oriented, environmental, social, and political). A new modelling environment will be developed, to act as CMIS, which will allow the geodatabase to interact with existing geographic information system (GIS) applications and hydrologic modelling frameworks, which in turn will allow CMA's to extract both alphanumerical data as well as spatial data to allow for fact-based decision-making.

This study will first evaluate and investigate existing data models and hydrological modelling frameworks (information systems) to determine what

management features they provide.  Secondly, a new modelling environment will be developed (according to the latest modelling standards) to work with the data of the study area and subsequently assist with decision-making.


## 1.3  OBJECTIVES AND HYPOTHESIS


The primary objective of this research project is to create a modelling environment that will make use of a multi-user geodatabase (Maidment, 2002:21) that contain as much hydrological data from the last 20 years as possible.  The framework will connect the geodatabase to the GIS software and hydrological models.  This connection will allow stakeholders to perform simulations and estimations directly, causing them to make more knowledgeable decisions when it comes to the distribution and use of water.

These decisions are important because they need to comply with the Catchment Management Strategy (CMS) set out for each Water Management Area (WMA) as stipulated in Chapter 2 - Water Management Strategies of the NWA of 1998 (South Africa, 1998).  The strategy specifies that the following goals should be pursued:

- Principles for the allocation of water must be set.
- The provision of a framework for the management of water resources in a WMA.
- The preservation that water resources are protected, conserved, developed, managed and controlled.


The objective of this study is to integrate the functionality of both hydrological- and simulation models into a new modelling environment (framework).  Clark and Smithers (2006a: 1; 2006b: 466) define a modelling framework as an open modelling environment in which existing models (or modules);

databases, and user interfaces, may be linked or organised in a consistent manner.

The modelling environment will not only be important for the outcome of this study but also for its beneficial use by water resources managers (e.g. within CMA's) and other research projects.

The formulation of the first objective of the study resulted from the above-mentioned realisation and may be stated as follows:

### 1.3.1 Objective 1

*To determine whether existing data models and frameworks will provide decision makers (within CMA's and WMA's) with the necessary management and data tools to allow them (the decision makers), to do estimations and simulations in order to make informative decisions.*

A second objective of the research project, which flows out of the first objective, is:

### 1.3.2 Objective 2

*If the existing data models and frameworks do not provide the necessary management and data tools, a new modelling environment (framework) will be developed that will allow decision makers (within CMA's and WMA's) to make more informative decisions by implementing this newly created set of management and data tools.*

The formulation of the hypothesis was based on the objectives of the study, and states that:

### 1.3.3 Hypothesis

*Existing data models and frameworks do not fulfil in the needs of managers (within CMA's and WMA's) of the new management process to manage*

*catchments according to the NWRS, and it is therefore necessary to develop a new modelling environment (framework) that complies with the stipulations in the NWRS.*

## 1.4  STUDY AREA

The study area, the C5 secondary catchment, is located in the Upper Orange WMA.  This WMA is primarily situated in the Free State, but also occupies portions of the Eastern and Northern Cape provinces.  Figures 1.4, 1.5 and 1.6 indicate the geographical location of the study area in relation to the Free State province and Bloemfontein, one of the provincial capitals of South Africa.  The C5 secondary catchment contains 5 sub-catchments: Riet, Riet/Modder, Krugersdrift, Rustfontein and Kalkfontein.  The study area is discussed in more detail in Chapter 3, Section 3.2 of this dissertation.

The study area was selected because the newly developed modelling environment will make use of the data, from the C5 secondary catchment, to conduct thorough simulation and estimation processes.  Additional projects will also make use of the modelling environment to test the validity of their findings with that of the modelling environment's outputs.  One such project is currently being investigated by DWAF and the Central University of Technology, Free State.  Changes are currently being made to hydrological and water resource system analyses models.  These include the Water Resources Simulation Model (WRSM) and the Water Resources Yield Model (WRYM).  By changing these models, new licensing procedures identified by DWAF will be better implemented and supported.
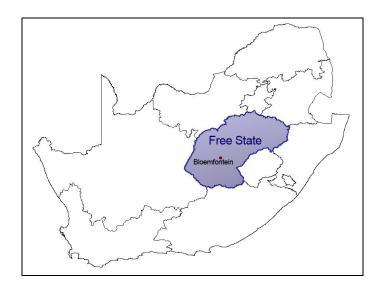
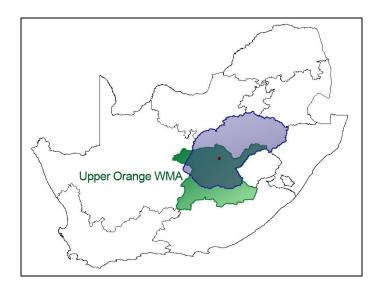Figure 1.4  Relation of the Free State Province to South Africa.



Figure 1.5  Relation of the Upper Orange Water Management Area to the
Free State Province.

Figure 1.6  Relation of the Secondary Catchment C5 to the Upper Orange WMA/Free State Province.

## 1.5  STRUCTURE OF THE RESEARCH PROJECT

Water managers and authorities urgently need support systems to assist them with decision making when it comes to managing water resources.  In order for a water authority to function properly it requires information.   This information is derived from data that has been collected, processed, and interpreted, via Information Systems (IS) and Information Technology (IT) (Johnson, 2002).

A few IS's (frameworks) have been developed in the past or are currently being developed by different research groups.   An in-depth investigation launched at existing data models and hydrological modelling frameworks will determine whether they currently fulfil the needs of CMA's and whether they could accommodate the data available from the WMA's.  If the existing data models or hydrological modelling frameworks do not provide for effective water management, a new modelling environment needs to be developed to

handle the data in an organised manner. The modelling environment should assist with data management as well as allow for the creation of output results. This modelling environment will consist of a comprehensive geodatabase (that contain complex datasets that record the actual environmental and managerial data in the form of topological relationships, implicit spatial relationships, or other general relationships) which should be linked to existing hydrological data models (WinHSPF, HYDSTRA, and ArcHydro) and hydrological modelling frameworks (BASINS).

Information about various data models and hydrological modelling frameworks were collected from Internet sources, published articles, GIS workshops, and conference proceedings. A poster was presented at the 2006 Water Institute of Southern Africa (WISA) Biennial Conference, with the title: Creating a catchment management information system – Moving from a database to a geodatabase (Viljoen, 2006). This interaction with industry ensured that important contacts could be established and that discussions could take place.

Data gathered from various systems (HYDSTRA, Weather Bureau, Stats SA, DWAF, etc.), will be analysed, interpreted and incorporated into the newly created geodatabase.

The proposed modelling environment should:
  ✦ Allow for the management of modelling projects and scenarios.
  ✦ Support a GIS interface that will display spatial input and output data by making use of an established GIS application. ArcGIS will be used because it is established in the GIS world and is the most widely used GIS application to date (GISJobs.com, s.a.).
  ✦ Make use of a well designed extensible multi-user geodatabase that will store the spatial and temporal data. This geodatabase will form the backbone of the study, and will store all the relevant model input and

output data.  Microsoft Access will initially be used to create a personal geodatabase.

- Make use of the Unified Modelling Language (UML) which will be used to design the geodatabase and subsequently be responsible for the generation of the geodatabase.
- Facilitate the use of example data from ArcHydro and HYDSTRA.

The flow diagram in Figure 1.7 illustrates the framework that will be followed for the research project and the different tasks conducted during the project. Each of the tasks will be explained in more detail in Chapter 4 of this dissertation.
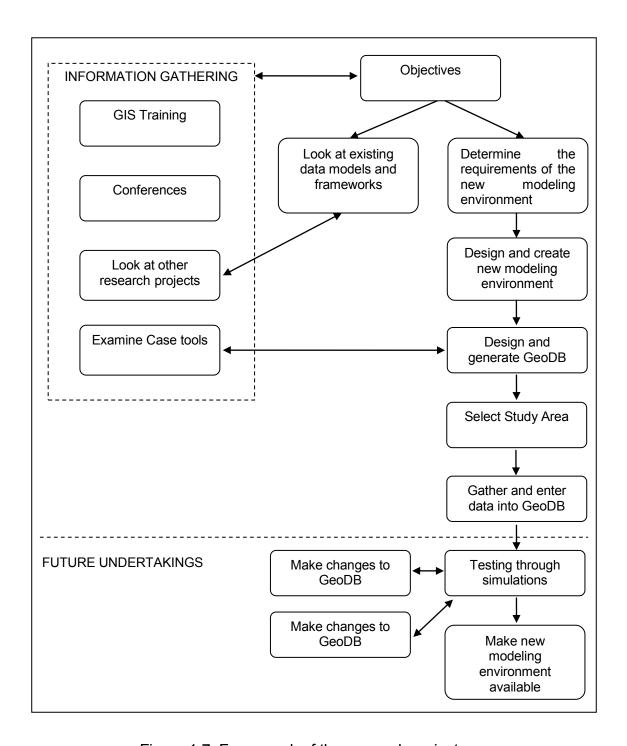
Figure 1.7  Framework of the research project.

## 1.6  DISSERTATION OUTLINE

The dissertation is divided into 6 chapters.  Chapter 1 provides a background, placing the study in the context of Water Management and Hydrologic modelling.  The second chapter takes a closer look at some of the current data models and hydrological modelling frameworks, and indicates whether these data models and hydrological modelling frameworks would be sufficient with the effective management of water resources and assist with the decision making purposes.  In Chapter 3, the methodology that was followed for the research study is discussed and an explanation is given why the C5 secondary catchment (which is situated in the Upper Orange WMA) was selected.

Chapter 4 starts by discussing the proposed modelling environment. Secondly, it is explained how data was gathered, how the proposed geodatabase (by making use of UML) was designed, how the Schema was created, and eventually how the geodatabase was generated.

Chapter 5 concludes the research study by revisiting the objectives and hypothesis set by the study.  Future expansions on the study are also discussed, and suggestions are made for further research projects.

Chapter 6 gives a list of references that were used in this study.

# CHAPTER 2 - LITERATURE STUDY

Hydrology may be defined as the study of the movement, distribution, and quality of water throughout the earth, and addresses both the hydrologic cycle and water resources. In broad terms hydrology is the movement of water throughout the earth through different pathways and at different rates, for example; water evaporates from oceans, forms clouds which drift over the land and produce rain which flows into lakes, rivers, and aquifers, evaporates or flows back into the ocean, thus completing the cycle (Microsoft Encarta Online Encyclopaedia, 2007b).

There are different branches of hydrology, namely; chemical hydrology, ecohydrology, hydrogeology, hydroinformatics, hydrometeorology, isotope hydrology, and surface hydrology (Microsoft Encarta Online Encyclopaedia, 2007b). Hydroinformatics is used in this study, and concentrates on the application of information and communication technologies (ICT's) in addressing the serious problems relating to the allocation, efficient use, and distribution of water (Hydroinformatics Community, 2007).

Over the last few years it has become more and more important to analyse the statistical properties of hydrologic records, such as rainfall or river flow, so that hydrologists may estimate future hydrologic phenomena and needs, and make informed decisions when it comes to hydrology (Microsoft Encarta Online Encyclopaedia, 2007b).

Chapter 1 of this dissertation iterates the importance of managing water resources, and directs users to look at hydrologically-based data models and modelling frameworks in order to estimate the current and future water needs. It is clear from this discussion that if the effective management of water resources does not take place many countries, including South Africa, will be faced with devastating water shortages. It is due to this reason that the South

African government has committed itself to manage all water resources in a sustainable manner.

Water (catchment) management still tends to suffer from a continuous failure to establish meaningful programme objectives due to the lack of data and a comprehensive information system to aid decision-making by making use of Geographic Information Systems (GIS). A water authority is dependent upon this information to carry out its scientific, engineering, and operational functions (Clarke, 2005).

For example, DWAF (Directorate Hydrology) uses various data models to manage and edit raw meteorological data as part of their decision-making efforts. Each of these models has its own data specifications and storage methods and does not necessarily allow for the transfer of data from one model to another.

## 2.1 CMIS

To achieve effective water management, an CMIS should be put into place to handle data in an organised manner (Viljoen *et al*., 2006). This system will ultimately assist with decision-making and ensure that water resources are used in a sustainable manner (Figure 2.1).

Figure 2.1  The movement of data in a CMIS

The flow of data in a CMIS will be conducted in the following manner.  Data will first be inserted, simulations and estimations will be performed, and output results will be generated, which will be used for decision-making.  The data, required for water management, may be categorised into three broad categories, namely: commercial data, network data, and mission-specific data. Commercial data are defined as all the data describing a consumer connection.  Network data being all the data representing the infrastructure that conveys water from source to consumer including bulk conveyance and storage, distribution pipes and reservoirs, pump stations, and valves. Mission-specific data as all peripheral data is required to solve a specific

mission or goal. Data about water quality, return flow, effluent characteristics, cadastral and other GIS based datasets, may also be included (Gumbo *et al.*, 2003).

The system itself may provide storage facilities in the form of a Relational Database Management System (RDMS), where data is stored in a set of tables linked by relationships, flat files where data is listed in text form, SQL functions or a GIS-based database also known as geodatabase (Maidment, 2002:21). In addition to the storage facilities, management information system (MIS) modules (for analysis, water management, and presenting and reporting information), and decision support tools (which allow for the execution of simulations and estimations), are usually also provided. Finally output results (in the form of time-based results, presentations, and reports) will be presented that will be used for strategic planning. From the output results users may provide feedback with ideas to improve the system, which will indirectly mean that better input data will be created and better results will be delivered (Gumbo *et al.*, 2003).

This study looks at current systems (data models and hydrological modelling frameworks) and how they are used to effectively manage water resources. The data models and hydrological modelling frameworks work on the same principle as is illustrated in Figure 2.1. The data models (collection of datasets and data management functions), and hydrological modelling frameworks (containing data models and decision-making tools specifically formulated to assist with simulation and estimation purposes), will fit into the CMIS section (Maidment, 2002:16).

## 2.2 GIS

According to Johnson (2002), Maidment (2002:18), Clarke (2005) and the web site GIS.com (2006), the interactions between objects in the real world are linked to their physical proximity with one another and the fact that they have a physical representation of their location. This gives a better understanding of how objects relate to one another. Spatial data that provides information about the precise location of objects in the environment has proven extremely useful for the study of environmentally-based processes, and are referred to as geospatial information (Clarke, 2005). Specifically to the field of hydrology, an accurate spatial representation of object characteristics such as the length of a river, the slope of the land contributing to that river, and the physical proximity of specific areas of land to the river, are all extremely important to understand the processes of water movement in the environment (Microsoft Encarta Online Encyclopaedia, 2007b).

In the past, spatial information was stored almost exclusively on paper maps. Paper maps are helpful for observing spatial relationships between objects, but performing any sort of complex spatial analysis by hand is tedious and time consuming. Hydrologic parameters such as slope, distance, and direction may be measured on a paper-based map, but cannot be extracted quickly or automatically (McGlamery, 1999).

In order to interpret and understand the interaction (relationship) between the various objects, new and innovative techniques may be used by making use of computers. Since the creation and acceptance of GIS, many paper maps have been reproduced into a digital form (Maidment, 2002:14). The following definitions will provide a better understanding as to the way in which information will be handled in these digital formats. First of all an IS will be needed and is defined by The Alliance for Telecommunications Industry Solutions (ATIS) as; "a system, whether automated or manual, that comprises

people, machines, and/or methods organised to collect, process, transmit, and disseminate data that represent user information" (ATIS, 2001). An adaptation from an IS, is a Geographic Information System (GIS). Environmental Systems Research Institute (ESRI) (GIS.com, 2006) describes a GIS as follows: "GIS is a computer technology that uses a geographic information system (computer software, hardware and data) as an analytic framework for managing and integrating data; solving a problem; or understanding a past, present, or future situation".

In other words, GIS is a geographic database management system (DBMS) that extends the capabilities of a normal relational database to allow for the storage, viewing, editing, and analysis of geographic (spatial) information. GIS may be used to create paper maps, analyse the interaction between different objects, or calculate parameters for environmental analyses.

## 2.2.1 GIS Applications

A range of GIS applications is available and may be categorised under open source software or commercial/proprietary software. Table 2.1 provides a list and short description of some of these GIS applications and tools that are currently being used around the world (Wikipedia Contributors, 2007).

Table 2.1  List of GIS applications and tools

| CATEGORY | NAME OF GIS APPLICATION | DESCRIPTION |
|---|---|---|
| Open source software | GRASS | Originally developed by the U.S. Army Corps of Engineers (complete GIS). |
| | MapServer | Web-based mapping server developed by the University of Minnesota. |
| | Chameleon | Environments for building applications with WebServer. |
| | GeoTools | GIS toolkit written in Java using the Open Geospatial Consortium (OGC) specifications. |
| | gvSIG | GIS written in Java. |
| | JUMP GIS | Java Unified Mapping Platform. |
| | MapWindow GIS | GIS desktop application and programming content. |
| | PostGIS | Spatial extensions for the open source |

| | | PostgreSQL database. |
|---|---|---|
| | Quantum GIS | User friendly GIS that runs on Linux, Unix, Mac OSX, and Windows. |
| | TerraView | Handles vector and raster data stored in a RDMS or Geodatabase, including ACCESS, PostgreSQL, MySQL and Oracle Spatial. |
| | LandSerf | Written in Java. Source available but not strictly open source. |
| | SPRING | Developed at INPE (Instituto Nacional de Pesquisas Espaciais). |
| | TerraLib | GIS class and functions library allowing for the development of GIS tools. |
| | SavGIS | Developed by the Development Research French Institute and are available in French, English and Spanish. |
| Commercial/Proprietary software | Autodesk | Products include MapGuide and other products that interface with its flagship AutoCAD software package. |
| | CadCorp | Developers of GIS and OpenGIS standard. |
| | ESRI | Developed products like ArcView 3.x, ArcGIS, ArcSDE, ArcIMS, and ArcWeb services. |
| | IDRISI | GIS developed by Clark Labs. |
| | ILWIS | Integrated Land and Water Information System integrate image, vector and thematic data. |
| | Intergraph | Include products like GeoMedia GIS as well as photogrammetry and other mapping-related software. |
| | MapInfo | Products include MapInfo Professional and MapXtreme. Integrates GIS, data and services. |
| | MapPoint | Developed by Microsoft. |
| | Calipher | Products include Mapitude, TransCAD and TransModeler. |
| | axpand | GIS Cartography software developed by Axes Systems |
| | CartaVista | Geographic Information Visualisation (GIV) product development by A3Dt. |
| | DeLorme | Developer of XMap and other GIS tools, data and GPS hardware. |
| | GMS | Three-dimensional environment for building geologic and groundwater models. |
| | Maria | A Windows-based product developed by Teleplan Globe AS. |
| | Manifold System | Low-cost GIS software package. |
| | Map Maker | Low-cost Windows-based GIS software. |
| | Oracle Spatial | A product that allows the user to perform basic geographic operations and store common spatial data types in a native Oracle environment. |
| | Safe Software | Spatial ETL products including FME, SpatialDirect and the ArcGIS Data Interoperability Extension. |
| | Smallworld | Developed in Cambridge, England and purchased by General Electric in 2000. Used |

| | | |
|---|---|---|
| | | primarily by public utilities and other related industries. |
| | TatukGIS | Products include: TatukGIS Developer Kernel, Internet Map Server, GIS Editor, free GIS Viewer, and Aerial Imagery Corrector. |
| | GeoBase | Geospatial platform developed by Telogis. The focus was placed on real-time processing for reverse-geocoding and geofencing. |
| | Panorama | Russian GIS for military purposes. |
| | TNTMips | Geospatial analysis system which provides a GIS, RDMS, and automated image processing system with CAD, TIN, surface modelling, and data publishing tools. |

## 2.2.2  ArcGIS

ArcInfo and ArcView systems, developed by ESRI in Redlands (California), are considered to be the GIS software applications that are used most widely around the world.  ArcInfo was originally developed in 1980 and allows the user to perform activities related to data manipulation, editing, and analysis (ESRI, 2007).  ArcInfo uses a combination of vector data (points, lines, and areas) with tabular attributes, and was later extended to include surface modelling using square-cell raster grids and triangulated irregular networks (TINs).  ArcView was developed in the early 1990's, initially as a sample viewing application for GIS data, the creation of maps, and then later expanded to support spatial analysis and modelling.  Special programming languages, ARC Macro Language (AML) for ArcInfo and Avenue for ArcView, were used to allow for the customisation of the GIS for particular applications (ESRI, 2007).

ESRI recently re-engineered its entire GIS software system to construct a new GIS more closely following current IT and software engineering standards. This new product, ArcGIS, is presently distributed as ESRI GIS software package.  ArcGIS comes in several variants depending on the degree of functionality required by the user, with ArcView remaining the entry-level version of ArcGIS for data viewing, querying, and analysis, and ArcInfo as the high-end version of ArcGIS for data creation and sophisticated operations

(ESRI, 2007).  One major difference is the programming languages available to customise and extend the capability of the software.  ESRI decided to stop providing support for the Avenue and AML languages and instead focuses on Visual Basic for Applications (VBA).  ESRI also decided to provide open access to the ArcGIS components through the Microsoft Component Object Model (COM) standards (ESRI, 2007).

Additional applications are available from ESRI, for example; ArcReader (allows the user to view and query maps created with other Arc products) and ArcEditor (includes the functionality of ArcView but also includes more advanced tools for manipulating shape files and geodatabases) (ESRI, 2007).

The ArcGIS 9 release includes a geoprocessing environment that may be used through traditional GIS processing tools, or by making use of any scripting language that supports COM standards.  ArcGIS 9 also includes a visual programming environment called ModelBuilder that allows users to graphically link geoprocessing tools into new tools called models.  These models may be executed directly or exported to scripting languages which may then execute them (models) in batch mode, or allow further editing in which case additional functionality may be added.  Due too many of these changes a large number of the previously developed user add-ons or third-party software that was used in previous versions cannot be used with ArcGIS 9.  This has led to many users still using the previous versions, these are still available for purchase from ESRI with support provided (ESRI, 2007).

According to 35525 participants who participated in a survey conducted by GISjobs.com, 77% of GIS professionals around the world make use of ESRI's products.  Some of the other most used GIS packages include: Autodesk (AutoCAD) with 27%, MapInfo with 19%, and Intergraph with 15%.  In South Africa (259 participants) ESRI is still the most popular application and is used by 67% of GIS professionals, MapInfo with 22% and AutoCAD with 18% (GISJobs.com, s.a.).

Figure 2.2 presents an overview of the ArcGIS range of applications developed by ESRI.



Figure 2.2  The ArcGIS framework developed by ESRI (2007).

ArcGIS Desktop GIS (more specifically ArcInfo and ArcCatalog) is used as GIS software package in this research project.


## 2.3  EXISTING DATA MODELS


One of the major advantages of GIS is the fact that it represents data in both a spatial and tabular form, which further motivates the need for data management and modelling.  Modelling presents two problems: firstly, the need to represent the natural world, and secondly, the need to represent the

man-made world. GIS technology can manage this aspect by making use of two basic data models (Goodchild & Kemp, 1990; Klinkenberg, 2006). GIS has started by creating and implementing the ESRI geodatabase model. Many of the new models, today, are based on the ESRI geodatabase model.

According to Klinkenberg (2006) and Goodchild & Kemp (1990), two basic data models are used, namely; the field model and the object model. The field model represents the spatial variation of a single variable using a continuous surface. This model represents continuous space and is often used to display natural distributions. There are five commonly used field models: irregular point sampling, regular point sampling, contours, cell grid, and triangular nets. A Digital Elevation Model (DEM) is an example of regular and irregular point sampling that is derived from topographic data and has been converted into a continuous surface. The contour model is comprised of contour lines on maps and contour polygons which represent irregular shaped areas with similar elevation values. A Triangulated Irregular Network (TIN) is an example of a triangular net model, and remotely sensed imagery is an example of the cell grid model because a single value is attached to each grid cell (Goodchild & Kemp, 1990; Klinkenberg, 2006).

According to Maidment (2001), the object model represents discrete space using points, lines, or areas (polygons). He states that object models often represent man-made creations like buildings, monuments, etc. and that these models also provide a mechanism for the depiction of scientific categorisation such as the geomorphologic representation of the land surface.

An extension of the object model is the network model that allows for the representation of continuous variable data. Networks form a framework layout that allows different locations to be connected by sets of lines joined at points (Maidment, 2001).

The latest data model that has been created is the geodatabase data model. ESRI created this object-oriented model and introduced it with the new GIS software available from them, namely ArcGIS (Zeiler, 1999:5). The geodatabase model, according to Zeiler (1999:64) and Davis (2000:20-21), combines the field, object and network models that where previously used in ArcGIS. They continue and indicate that the basic form of the geodatabase model contains; feature datasets (i.e. group of monitoring stations), feature classes (i.e. rain gauge station locations), and object classes (i.e. yearly rainfall data collected at the different stations). The model is packaged in a geodatabase, which contains the feature datasets, which in turn contains all the feature classes. Zeiler (1999:64) indicates that the relationships between these feature datasets and classes are then contained within a common co-ordinate system. An object class is a non-spatial entity like a data table, and a feature class an object with spatial information (co-ordinates). Figure 2.3 illustrates the basic framework of the geodatabase model.
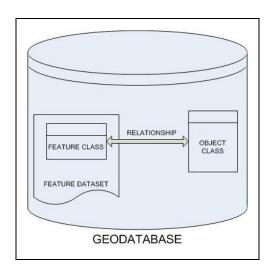


Figure 2.3  Basic Geodatabase Model

The new way of packaging information in the geodatabase model allows users to modify the model according to their specific needs or to create their own formalised geodatabase data models. These models may then be

applied to standard geodatabases, allowing for almost automatic data standardisation (Schneider, 2002: 20-21). The principles used in the geodatabase model will be applied to this research project.

## 2.3.1 ArcHydro and ArcHydro framework

### 2.3.1.1 Introduction

As part of the ArcGIS development effort, ESRI initiated efforts to show how ArcGIS may be customised for particular applications of GIS using specially designed data models. The water resources data-modelling effort was undertaken in association with the Centre for Research in Water Resources (CRWR) at the University of Texas (Austin). Together the CRWR and ESRI formed a GIS in Water Resources Consortium to involve representatives from industry, government, and academia to participate in the development of the water resources data model. After many prototypes were built and tested, the current form was reached and is called ArcGIS Hydro or in short ArcHydro (ESRI, 2001).

ArcHydro is a geospatial and temporal data model for water resources that operate within ArcGIS. ArcHydro has an associated set of tools, built jointly by ESRI and CRWR (Centre for Research in Water Resources) that populate the attributes of the features in the data framework, interconnect features in different data layers, and support hydrologic analysis. ArcHydro is a data structure that supports hydrologic simulation models, but it is not itself a simulation model. Hydrologic simulation is accomplished by exchanging data between ArcHydro and an independent hydrologic model, by constructing a simulation model attached to ArcHydro using a dynamic linked library, or by customising the behaviour of ArcHydro objects (ESRI, 2001).

The developers suggest that it is best to begin with the scaled down version of ArcHydro called the ArcHydro framework data model, then to add additional classes and attributes to the framework model as the need dictates. ArcHydro

is based on concepts and ideas that may be adapted and developed to suit individual applications. ArcHydro supports basic information management tasks for water resources, and serves as a point of departure for further expansion to fit particular circumstances (ESRI, 1990; Maidment, 2002:179).

As mentioned before the ArcHydro framework data model is a simplified version of ArcHydro. The framework data model stores information about river networks, watersheds, water bodies, and monitoring points. Additional components may be assembled around the framework data model to form a more complete ArcHydro data model. A data model is simply a method for describing a system using a structured set of data or as put by Answers.com (LearnThat, 2004); "a model that describes how data is represented and used". For example, the set of variables used in a computer program is the data model for the program. Data models provide an orderly way to classify objects and their relationships to one another and how these objects interact with one another. According to Maidment (2002:18), geographic data models define a vocabulary for describing and reasoning about things located on earth.

A behavioural approach to data modelling will be followed in this study. In a behavioural approach a system of behaviour may be defined by looking for pertinent features to describe the behaviour, and then defining how the behaviour of individual features interact with others, which in turn defines the behaviour of the whole system (Maidment, 2002:18).

ArcHydro is a connected set of objects and features built on top of a generic set of objects and features called ArcObjects that is delivered to the user as part of ArcGIS. To understand this environment it is important to define some basic terms. An ArcGIS database is called a geodatabase because it stores data describing geospatial objects in a relational database format. The term "class" denotes a group of objects with similarly defined attributes and behaviours where an object is one member of an object class. Attributes of

an object are its descriptive properties, stored as numbers or text fields in columns of an attribute table, which has one row for each object. The behaviour of an object describes how it interacts with other objects; the most important kind of behaviour is the object's interface, which contains the protocol for passing information to and from the object (Maidment, 2002: 22-23).

For this study the existing ArcHydro framework data model will be investigated, and similar information (classes) will be created in a custom-designed geodatabase so that it better fits the management needs of the study area.

### 2.3.1.2 Features / Functionality

ArcHydro comes with a set of tools that provide the functionality to perform many tasks that are common to hydrologic model preparation. Delineating drainage areas and streams, calculating lengths, areas, and slopes, and defining connectivity between system components, are all tasks that are supported with the ArcHydro tools (Johnson, 2005: 15).

According to Nathan Johnson (Johnson, 2005: 17-18), ArcHydro has proved to be very helpful to the process of linking GIS data with hydrologic models for two reasons. Firstly, ArcHydro contains a toolset that may be used to calculate hydrologic parameters that are used by many different models. These tools make use of ArcGIS to perform spatial analysis with an interface that was designed specifically for hydrological applications. Secondly, ArcHydro helps in preparing data for use with hydrological models by providing a framework for organising and managing the data. The ArcHydro data model stores data in a general format that was designed to be independent of individual models, types of models, or applications. The data framework does not make assumptions about the scale of the data, where it came from, or what it will be used for. An attempt was made to capture essential relationships amongst hydrologic elements in the environment.

Various tools to aid in organising and managing data were designed to operate in this hydrological GIS data framework.

According to ESRI (2002) and Johnson (2005: 16), ArcHydro provides Terrain Preprocessing Tools, Watershed Processing Tools, Attribute Tools, Network Tools and ApUtility Tools (ESRI, 2002). Below is a list of these tools and their related sub categories.

Terrain Pre-processing Tools (deal primarily with the processing of the DEM – to prepare spatial information for later use)

- DEM Reconditioning
- Fill Sinks
- Flow Direction
- Flow Accumulation
- Stream Definition
- Stream Segmentation
- Catchment Grid Delineation
- Catchment Polygon Processing
- Drainage Line Processing
- Adjoint Catchment Processing
- Drainage Point Processing

Watershed Processing Tools (deal with watershed and sub watershed delineation and basin characteristic determination)

- Batch Watershed Processing
- Batch Sub watershed Processing
- Drainage Area Centroid
- Longest Flow Path

Attribute Tools (provide functionality for the generation of some of the key attributes/fields in the ArcHydro data model)

- Assign HydroID
- Generate From/To Node for lines
- Find Next Downstream Line
- Calculate Length Downstream for Edges
- Calculate Length Downstream for Junctions
- Find Next Downstream Junction
- Store Area Outlets
- Consolidate Attributes
- Accumulate Attributes

Network Tools (deal with the generation and manipulation of properties of the geometric/hydro network)
- Hydro Network Generation
- Node/Link Schema Generation
- Store Flow Direction
- Set Flow Direction

ApUtility Tools (deal with the management of ArcHydro project properties)
- Flow Path Tracing (traces the downstream path from a user specified point to the edge of the DEM)
- Point Delineation (delineates a watershed for a user specified point based on the pre-processed DEM)
- Batch Point Generation (allows the user to specify a point to a batch point feature class)
- Assign Related Identifier (assigns a value of a field in a source feature to a field in the target feature)
- Global Point Delineation (delineates a watershed for a user specified point based on a set of pre-processed geographic units tied together by a geometric network)

◆ Trace By NextDownID Attribute (by using the attribute relationship established through the NextDownID field allows for tracing upstream, downstream, or in both directions)

### 2.3.1.3 User interface

ArcHydro does not have its own interface and provides merely an extension to the ArcGIS interface developed by ESRI.
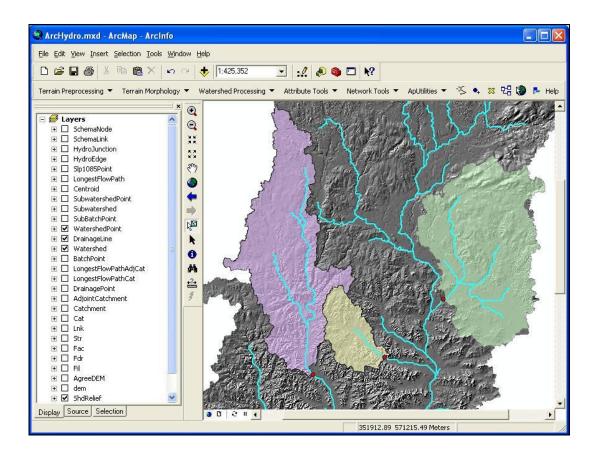


Figure 2.4  ArcGIS interface with ArcHydro Toolset (retrieved from ESRI web site)

### 2.3.1.4 Data handling

ArcObjects, a set of generic ArcGIS object classes, were used for creating the ArcHydro data model which is arranged according to a class hierarchy.  Due

to the class hierarchy all objects lower in the hierarchy inherit the attributes and behaviours associated with the objects above them. This hierarchy is defined using UML, a standard language for describing objects developed in the software industry and adopted by ESRI as the platform for the design of ArcGIS (Maidment, 2002:24; Schneider, 2002: 33-34). UML is described in more detail in Chapter 4 of this dissertation.

The ArcHydro framework data model provides a simple, compact, data structure for storing the most important geospatial data describing a water resources system. The framework data model contains information organised in several levels (Maidment, 2002:24; ESRI, 2001), as depicted in Figure 2.4. Below is a description of some of the keywords used in this data model (Maidment, 2002: 27-28; Herrington, 2004).

- Geodatabase – Either a personal geodatabase or enterprise database may be used (Maidment, 2002:21).
- Feature dataset – A folder where feature classes are stored within the geodatabase. The feature data set has a defined map projection, co-ordinate system, and spatial reference.
- Geometric network – Information that topologically connects hydro edges and hydro junctions are stored here.
- Feature class – Information on individual geographic features are stored here, for example, watershed or stream segment information. Five feature classes may be found: firstly, a HydroEdge (a network of "blue lines" describing map streams and water body centrelines), secondly, a HydroJunction (a set of junctions located at the ends of flow segments and at other strategic locations on the flow network), thirdly, a waterbody (these include ponds, lakes, and bays in the water system), fourthly, a watershed (the drainage areas contributing flow from the land surface to the system), and finally, a MonitoringPoint (a set of points representing gauge locations where water is measured). HydroEdges and

HydroJunctions are topologically connected in an ArcGIS geometric network, called the hydro network.

  ◆ Relationship – An indication how different features from different classes relate to one another. For example, each watershed, water body, and monitoring point is related to a hydro junction on the network.

Since HydroJunctions are topologically linked to HydroEdges in the hydro network, the combination of this network and the other relationships indicate that the classes are linked into an integrated data structure. This allows the user to trace the movement of water from one feature to another through the landscape.
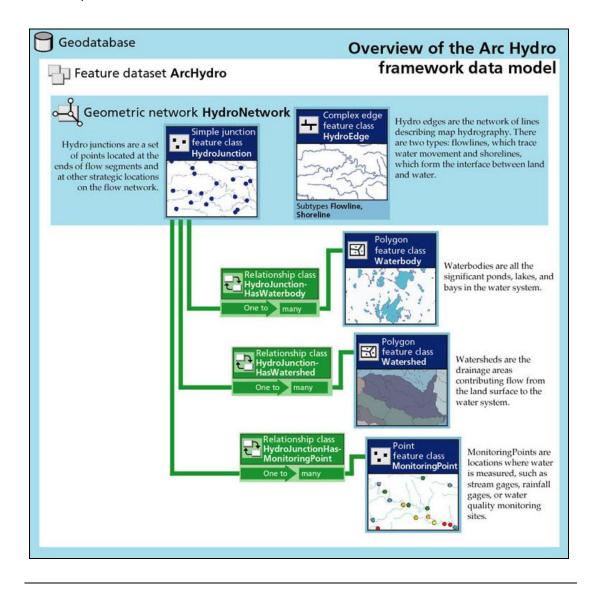
Figure 2.5  ArcHydro Framework Data Model (Maidment, 2002:178)

The ArcHydro framework data model has been extended and customised to fit the needs of several hydrologic models.  There are a few common parameters that are used by almost all hydrologic simulation models, such as area, slope, and distance, but each individual model naturally relies on many additional parameters that are specific to the model algorithms.  It was therefore unpractical to attempt to fit all of these model parameters into the ArcHydro database structure (Johnson, 2005: 19).

All hydrologic modelling efforts are built upon some representation of the physical landscape through which water moves.  However, model requirements and assumptions vary widely, and maintaining a consistent representation of the physical environment across modelling efforts is not simple.  Maintaining a consistent set of GIS data in the ArcHydro framework data model allows each model linked to the GIS data to have the same representation of the physical environment, such as a river channel geometry, watershed lengths, distances, areas, and landcover distributions (Johnson, 2005: 19).

2.3.1.5  System requirements

The following software and hardware requirements are listed by the CRWR (2003) and ESRI (2006):

Software:
* ArcGIS Desktop 8.1 or later with ArcEditor or ArcInfo license
* ArcGIS Spatial Analyst extension (If geoprocessing a DEM)
* Arc Hydro Tool Set
* Database Schema
* ArcHydroFrameworkSchema, Simplified data model version without time series

- FrameworkWithTimeSeriesSchema, Simplified data model version with time series
- ArcHydroSchema, Full version of the data model

Hardware:
- Minimum of 256 MB RAM for ArcHydro
- Minimum of 512 MB RAM for ArcView, 1 GB or higher recommended
- Intel Pentium or Xeon Processor with 1 GHz or higher is recommended
- A screen resolution of 1024x768 or higher is recommended
- A minimum of 1.2 GB disk space
- Internet explorer 6.0/7.0
- .NET framework 2.0

### 2.3.2 Hydstra

2.3.2.1 Introduction

The Hydstra database system (or sometimes called Hydsys) may be described as an integrated suite of software functions and services for the management and analysis of large amounts of hydrological, geo-hydrological and water quality data (Kisters, 2005). In addition to the data management part, Hydstra also has a wide variety of statistical programs and a modelling platform for the generation of specific models for the different data types (Keuris, 2004).

Hydstra is a commercial off-the-shelf product that was originally developed by two Australian companies (Hydsys Pty Ltd and Hydro Tasmania). The subsidiary company created by the above-mentioned companies was sold in 2004 to Kisters in Germany. Kisters indicates in its marketing documents that there are approximately 150 installations of Hydstra installed in 22 countries around the world (Kisters, 2005).

After the acquisition by Kisters, various changes have been made to Hydstra. According to the Kisters group the new software allows for the management of large amounts of time-series data in the hydro power, water resources, and wastewater industries. Hydstra offers capability in; data acquisition, data management, data analysis, modelling and simulation, and automated task scheduling (Kisters, 2007c).

2.3.2.2 Features / Functionality

Editing facilities enable the user to manipulate the data according to their specific needs. Various techniques are available to edit and evaluate data at a gauging station and against other gauging stations. A number of reporting and graphical programs are available to evaluate and generate reports for the user, of which statistical programs form a major part. These generated reports may be viewed in different formats such as Word Documents, Excel Spreadsheets, text files, CSV files, etc (Keuris, 2004).

Hydstra includes specialised modules and the following may be found in the latest version (Hydstra/TS v9.01.08 or Hydstra/TSM v4.1.1.13) (Kisters, 2007i) the following modules are available: Hydstra/TS Time-series Data Management, Hydstra/MO Network Modelling, Hydstra/MA Mapping Interface, Hydstra/WQ Water Quality Management and Hydstra/GW Ground Water Bore Management (Kisters, 2007c).

According to Kisters (2007g), the Hydstra Time-series Data Management Suite provides a complete solution to environmental data management, incorporating components to manage time-series data, groundwater bore information and water quality, as well as providing a mapping interface and modelling tools. These include: data acquisition, data importing and exporting, data management, data analysis, modelling and simulation, automated task scheduling and processing, integration with the water quality and groundwater databases, integration with GIS functionality, integration with modelling packages, and is fully user configurable.

The Hydstra/MO Network Modelling module may be applied for: flow forecasting, yield analysis, data manipulation, data comparison, regression, analysis, design assessment of infrastructure, and catchment modelling (Kisters, 2007f).

Hydstra/WQ Water Quality Management module provides features like: the ability to keep a water quality archive, the analysis of sample data, the ability to be integrated with Hydstra/Time series, the ability to import and export data from spreadsheets, allows for the manual entry of data, and other functions associated with other segments available in Hydstra (Kisters, 2007h).

The Hydstra/GW Ground Water Bore Management module contains functionality to work with ground water, well construction, and well production (Kisters, 2007d).

## 2.3.2.3 User interface

The Hydstra/MA Mapping Interface makes the data available to other users. Kisters states that the mapping capability was not designed to replace corporate GIS systems like ArcInfo or MapInfo but was created to allow users to get simple access to time-series data (Kisters, 2007e).
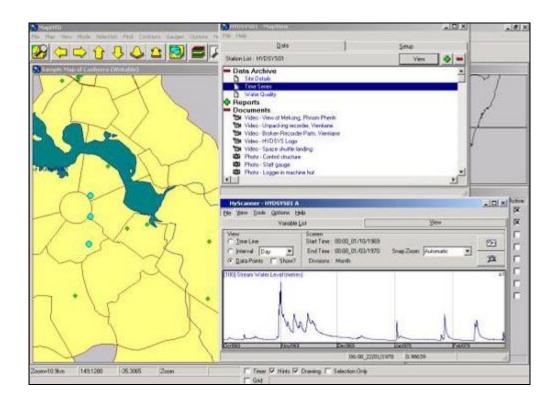
Figure 2.6  Hydstra/MA Mapping Interface

## 2.3.2.4  Data handling

The database system is designed as a complete solution including acquisition, management, and analysis of engineering and environmental data.  Hydstra may be used for the scheduling and acquisition of data from remote measuring stations using telemetry (Kisters, 2005; Keuris, 2004).

The management component makes use of different tables for the creation and registration of gauging points, hydrological data (height vs. time) and calibration data (rating tables) to store the relevant data.  Provision is made for different types of data such as continuous data that is measured at 12 minute intervals for flow records, or rainfall data that has a daily reading.  All data types and their subsequent data qualities are assigned unique codes to identify and describe the data.  One of the biggest advantages of Hydstra is the speed at which data is processed and analysed.  The fast processing

speed is mainly due to the way in which the data is compressed and stored (Keuris, 2004).

Data may be imported in one of two ways, either through the Internet or by accessing dedicated folders on a computer or network. The import process may be set up to allow data to be retrieved automatically or manually from various sources. Hydstra allows for data to be imported according to a standard data format (SDF), or allows the user to specify the data structure that might be needed (Keuris, 2004; Kisters, 2007i).

Data may be exported through the Internet or through dedicated folders on a computer or network. Again this process may be automatic or handed manually by the user. An advantage that Hydstra offers over other data management tools is the ability to export data in such a way that it may be used by other modelling software programs (Keuris, 2004). Data may be saved as CSV files for use in Excel or may be imported into other DBMS like dBaseIII (Kisters, 2007j).

2.3.2.5  System requirements

The following system requirements are needed (Kisters, 2007a; Kisters, 2007b):
  * Intel Pentium, AMD Athlon or equivalent processor
  * Microsoft Windows 95, 98, NT or 2000; Windows 2000 recommended
  * Display capable of at least 800x600 pixels and 256 colours

### 2.3.3  Geography Markup Language (GML)

2.3.3.1  Introduction

The Geographic Markup Language (GML) was written according to the XML (Extensible Markup Language) Schema to allow for the modelling, transport, and storage of geographic information including the spatial and non-spatial properties of geographic features.  GML was developed and are currently being maintained by the OGC, an international voluntary consensus standards organisation.  GML is in the process of being adopted as an ISO (International Standards Organisation) standard (ISO 19136) to be released in 2007 (OGC, 2004).  GML is the XML data standard for the GeoWeb-infrastructure which enables devices with Internet connectivity to get access to geographical information (Lake, s.a.).

GML defines a set of entities that may be used for describing geography including features, co-ordinate reference systems, geometry, topology, time, and units of measure.  GML defines these entities using a hierarchy of classes as shown in Figure 2.7 (OGC, 2004; Lake, s.a.).
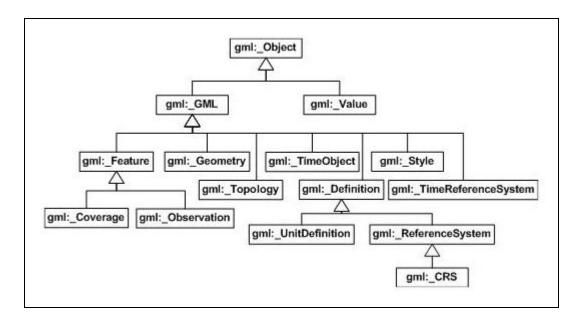


Figure 2.7  UML class diagram of GML class hierarchy.

The full GML Schema consists of a set of sub-schemas describing the GML hierarchy of classes. These include; the Feature Schema, the Geometry Schema, the Co-ordinate Reference System Schema, the Time Schema, the Dynamic Feature Schema, the Coverage Schema, the Temporal Information Schema, and the Units, Measurements and Values Schema (OGC, 2004; Lake, s.a.).

2.3.3.2 Features / Functionality

According to the developers, GML defines a comprehensive set of elements and properties, each with its associated relationships. These elements, properties and relationships are used to fully describe the geographic system. In some situations, the full functionality of GML is not needed and only the required functionality to represent certain application domains such as hydrology (GML may be extended or restricted to suit the requirements of particular applications) may be used (ESRI, 2003).

GML contains smaller subsets which are known as profiles, which may be expressed as a document, a XML schema, or both. The profiles are intended to simplify the adoption of GML and to facilitate rapid adoption of the standard. The following profiles are available and are proposed for public use: a Point Profile (used for applications with point geometric data but without the need for the full GML grammar), a GML Simple Features Profile (which supports vector feature requests and transactions), a GML Profile for GMJP2 (GML in JPEG 2000), and a GML Profile for RSS (Really Simple Syndication). The GML specification provides a subset tool that allows users to generate GML profiles each containing a user-specified list of components (Lake, s.a.).

In order to expose an application's geographic data with GML, users create an XML schema specific to the application domain of interest (for example, hydrology, ecology, water quality, etc.). This schema describes the object types (whose data the users are interested in) and user applications which should be opened for processing (Lake, s.a.).

A complimentary language, KML (Keyhole Markup Language), was developed by Google to assist GML with the visualisation of the geographic information (Lake, s.a.; Google, 2007). KML is an XML-based language that manages the display of three-dimensional geospatial data in programs like Google Earth, Google Maps, Google Mobile and WorldWind (Google, 2007).

2.3.3.3 User interface

A user interface is not present, as GML is a pure data model presented as a newly developed ISO standard that stores geographical data in XML-based files.

2.3.3.4 Data handling

GML text files (XML-based files) are used for the storage of geographical data, especially large datasets. Users are, however, allowed to use other storage formats and use GML as a transport format and the GML Schema as a data model (OGC, 2004).

2.3.3.5 System requirements

GML is not explicit software and does not have specific hardware requirements like other data models. Storage space will, however, be needed to store the geographical data.

**2.3.4 HYMOS**

2.3.4.1 Introduction

WL | Delft Hydraulics (2007a) describes HYMOS as an information system that is used for the storage, processing, analysis and presentation of data related to water resources management, surface and groundwater hydrology, meteorology, water quality, and environmental assessment. After 30 years of communicating with users WL | Delft feels that they have developed an efficient, flexible and multi-functional information system (WL | Delft Hydraulics, 2007a; WL | Delft Hydraulics, 2007c).

### 2.3.4.2  Features / Functionality

According to WL | Delft Hydraulics (2005a; 2005b; 2007a) HYMOS 4.5 offers a multitude of features including: database management, time series storage, time series analysis, tools that allow for the storage and processing of measurements and simulation data, as well as capabilities to exchange data between other databases.  Below is a more detailed list of these features:

Solid database management
  * Multiple users for the same database
  * Easy user access administration
  * Standard fast binary his-database
  * Connection with your own database, also in Oracle and SQL-server

Time series storage
  * Unlimited amount of stations per database
  * Unlimited amount of data values per station
  * Data time step free
  * Equidistant and non-equidistant data

Time series analysis
  * Time series validation and completion
  * Water quality tests
  * Extreme value analysis
  * Intensity duration and frequency analysis
  * Comprehensive statistics

Tools: storage and processing of
  * Flow measurements
  * Stage-discharge measurements
  * Rainfall-runoff simulation
  * Meteorological data

Data Exchange

- ◆ Periodical reports

- ◆ Import and export to other software

- ◆ Import and export to clipboard

- ◆ HTML reports

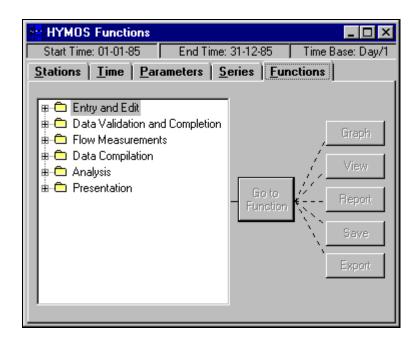Figure 2.8 shows a dialog box with some of the functions presented in HYMOS.



Figure 2.8  HYMOS Functions

2.3.4.3  User interface

HYMOS has a graphical and map-based user interface (refer to Figure 2.9) which includes modules for the production of graphics, maps and tables (WL | Delft Hydraulics, 2007a).    HYMOS currently uses the Netter software developed by WL | Delft Hydraulics as a mapping interface, and information is exchanged using an OLE (Object Linking and Embedding) connection. Provision is made for other GIS systems such as ArcView and MapInfo. HYMOS provides standard graphing templates and also allows users to

change graph layouts according to their requirements. HYMOS is compatible with several other software products from WL | Delft Hydraulics and is OpenMI compliant (WL | Delft Hydraulics, 2005a; WL | Delft Hydraulics, 2007b). The IS offers three interface languages (English, Spanish, and Dutch), but other languages may be supported by placing a request to the company (WL | Delft Hydraulics, 2007a).
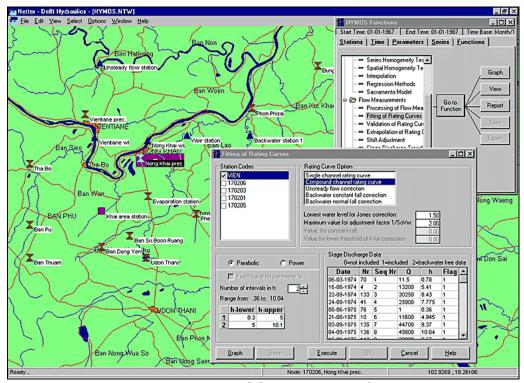


Figure 2.9  HYMOS 4.5 User Interface.

2.3.4.4  Data handling

HYMOS is time-series data oriented with common facilities for spatial data analysis (WL | Delft Hydraulics, 2007a). The open data structure enables interaction and data transfer with other compatible database and modelling systems like Oracle and SQL-Server (WL | Delft Hydraulics, 2005a; WL | Delft Hydraulics, 2007a). In addition, import and export functions exist to allow for the interchange of data between other databases (dbase and FoxPro), as well as the ability to save data in different formats (CSV, text and the Delft

standard format) (WL | Delft Hydraulics, 2007a).  HYMOS uses two data types: matrix data and metadata.  Equidistant and non-equidistant time-series data is stored in a three dimensional matrix of location, time, and parameter values.  Metadata includes details regarding locations, parameters, time, and relationships (WL | Delft Hydraulics, 2007c).

According to the developers many data-related functions (entry, editing, validation, and completion) have been improved in the latest version of the data model.  Additional functionality like the analysis of meteorological data, flow measurements and stage-discharge analysis, rainfall-runoff simulation, statistical and time series analysis, and various reports and graphs, are supported (WL | Delft Hydraulics, 2007c).

### 2.3.4.5  System requirements

HYMOS 4.5 requires the following hardware configuration (WL | Delft Hydraulics, 2007d):

- Intel Pentium, AMD Athlon or equivalent processor; 2.4 GHz or faster recommended
- Microsoft Windows 98 or better; XP or 2003 Server recommended
- 256 MB RAM; 512 MB or more recommended
- At least 110 MB of free disk space, depending on use
- Display capable of at least 800x600 pixels and 256 colours; 1024 * 768 true colour recommended

### 2.3.5  WinHSPF (Hydrologic Simulation Program, FORTRAN) Model

### 2.3.5.1  Introduction

HSPF has been remodelled to work in the Windows operating system environment and is now called WinHSPF.  The development of the new data model was undertaken by the AQUA TERRA Consultants, and forms part of BASINS 3.0 of the United States Environmental Protection Agency (USEPA). This newly created software (WinHSPF) provides a windows-based interface

to assist with the entering of input data (Duda, *et al.*, 2001:4). HSPF will mainly be discussed in this section to explain the core functionality of this data model. Additional changes that were made to the Windows-based version will also be discussed.

WinHSPF was mainly developed to make the development and modification of HSPF input sequences easier. WinHSPF provides an advanced interaction with the HSPF input sequence and provides a graphical illustration to represent the model (USEPA, s.a.; Duda, *et al.*, 2001:4-5).

### 2.3.5.2 Features / Functionality

HSPF is a comprehensive package that allows for the simulation of watershed hydrology and water quality for both conventional and toxic organic pollutants (Bicknell *et al.*, 1993; Donigian *et al.*, 1984). Nathan Johnson (2004) of the CRWR defines HSPF as "a set of computer codes that can simulate the hydrologic and associated water quality processes on pervious and impervious land surfaces, streams and well-mixed impoundments". The simulation done by HSPF, delivers a time history of the runoff flow rate, sediment load, and nutrient and pesticide concentrations, along with a time history of water quantity and quality at any point in a watershed (USEPA, s.a.).

USEPA (2001a) indicates that the following functions/sections is available in WinHSPF 2.0, namely: Edit Operations (which provides a powerful interface to HSPF operations), Reach Editor (that allows the user to edit selected properties of each reach), Simulating Time (that allows the user to edit the simulation starting and ending dates and times, as well as the met segments used in this HSPF project.), Landuse Editor (which allows the user to edit the amount of each land use contributing to each reach), Control Cards (which prompts the user to choose between the HSPF Activity Edit window or the old NPSM Control Card Editor.), Point Sources (which is used to view and manage the point sources that may be included in the simulation), Input

Manager (which contains a tree diagram of the blocks and tables of HSPF), Output Manager (which contains a set of radio buttons and a list of output locations), Run (which is used to perform the HSPF simulation), View Output (which is used to start the program GenScn for viewing timeseries output), and Best Management Practices (BMP) (which is an advanced feature for assisting users in adding BMPs to a simulation).

## 2.3.5.3 User interface

The majority of the user interface consists of standard Windows components like; a varying number of menus, toolbars, buttons, lists, check boxes, radio buttons, command buttons, picture boxes and text boxes (Duda, *et al.*, 2001:5).

Interaction with WinHSPF takes place through interacting with a graphical user interface (GUI). Screens are organised in a logical manner to minimise both the user learning time and user mouse/keystroke effort. Information is organised in layers, with the most basic important information being readily available, and very detailed and less frequently used information only accessible through additional menus or buttons. The way in which the information is layered is through the use of overlaid tabs, with the most frequently used tabs on top of the stack. In addition the user is assisted by means of labels (descriptions of the tasks) to keep track of where they are in the system (Duda, *et al.*, 2001:5).

Keyboard shortcuts have been created for all functions of WinHSPF to make the interaction with the data model easy. Toolbars are used to provide quick access to the most frequently used functions and are located in close proximity to the controls with which certain functions are associated. The toolbar buttons contain graphical images and tool tips which further enhance the user interface (Duda, *et al.*, 2001:5).
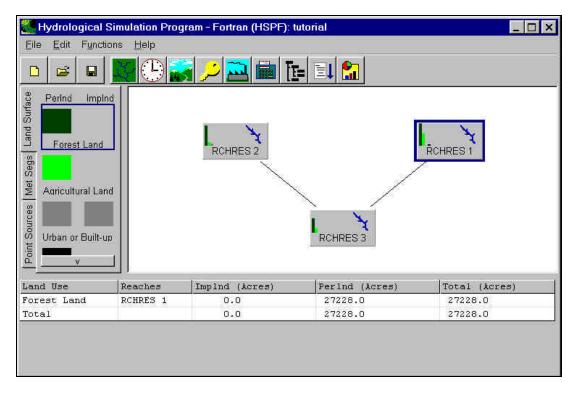
Figure 2.10  WinHSPF GUI (USEPA, 2001a)

## 2.3.5.4  Data handling

The data needs for HSPF are extensive and requires continuous data to drive the simulations. At a minimum, continuous rainfall records are required to drive the runoff model and additional records required for evapotranspiration, temperature, and solar intensity. A large number of model parameters may be specified although default values are present. HSPF is a general-purpose program and special attention has been paid to cases where input parameters are omitted. In addition, option flags allow for the bypassing of whole sections of the program where data are not available (USEPA, s.a.).

Simulation results may be processed through a frequency and duration analysis routine that produces output compatible with conventional toxicological measures (USEPA, s.a.).

2.3.5.5  System requirements

WinHSPF requires:

- Windows 95/98, Windows NT 4.0 or higher or Windows 2000.
- Pentium or equivalent processor (at least 200 MHz).  Pentium II, 400 MHz processor recommended.
- At least 64 MB of memory.  128 MB or more recommended.
- At least 100 MB of storage space.
- A display resolution of at least 1024x768.  1280x1024 screen resolution recommended.
- For printing purposes a good quality colour printer is recommended.

## 2.3.6  Comparison of the different data models

After investigating the different data models it became clear that there were some major differences between them.  The most noticeable difference being the cost (licensing fees) associated with some of these data models.  GML and WinHSPF are available free of charge and may be downloaded from the Internet.  The most expensive data model is the ArcHydro model, not due to the cost of the model itself but mainly because of the GIS requirements in which the model functions (ArcHydro requires ArcGIS which is very expensive).

The hardware requirements are fairly similar with regards to the Platform (Intel, AMD, etc.), the operating system (mainly Windows-based), and the screen resolution recommended to be 1024x768.  The main difference between the models is the amount of storage space needed (as much as 1.2 GB for ArcGIS - ArcHydro) and the amount of memory needed.

It should be noted that many of the system requirements; indicated, are the minimum requirements that are needed for the data model or related environment to function properly.  For peak performance it is generally recommended that a computer with a fast processor, a large amount of

memory, a large amount of storage space and a screen with a high screen resolution be used.

Table 2.2 provides a summary of all the models discussed and the system requirements associated with each.

Table 2.2  Comparison of Data Models

| Hydstra | GML | HYMOS | WinHSPF |
|---|---|---|---|
| Intel Pentium, AMD Athlon or equivalent processor | Not Applicable | Intel Pentium, AMD Athlon or equivalent processor; 2.4 GHz or faster recommended | Pentium or equivalent processor (at least 200 MHz). Pentium II, 400 MHz processor recommended. |
| Microsoft Windows 95, 98, NT or 2000. Windows 2000 are recommended | Not Applicable | Microsoft Windows 98 or better; XP or 2003 Server recommended | Windows 95/98, Windows NT 4.0 or higher or Windows 2000. |
| At least 32 MB | Not Applicable | 256 MB RAM; 512 MB or more recommended | At least 64 MB of memory.  128 MB or more recommended. |
| - | Determined by amount of data | At least 100 MB of free disk space, depending on use | At least 100 MB of storage space. |
| Screen display of at least 800x600 | Not Applicable | Display capable of 800x600 pixels and 256 colours 1024x768 true colours recommended | A display resolution of 1024x768.  1280x1024 screen resolution recommended. |
| Viewer build-in (Mapping interface) | None. Use KML in conjunction with Google Earth, Google Maps, Google Mobile and WorldWind | - | - |
| Hydstra Basic script language (similar to Microsoft Visual Basic) | - | - | - |
| Hydstra/TS v9.01.08 or Hydstra/TSM v4.1.1.13 | 3.1.1 | 4.50.065 | 2.0 |
| Licence for limited number of users.  Any additional functionality or DBMS support require additional licensing. | - | - | Free. Download from the USEPA's BASINS website. |
| - | - | - | - |
| Kisters | Open Geospatial Consortium | WL | Delft Hydraulics | - |
| Provided | - | Provided | - |

| ArcHydro | |
|---|---|
| **System** | Intel Pentium or Xeon processor. 1 GHz or higher |
| **Operating System (OS)** | -Windows XP (Professional or Home) - Windows Server 2000 or 2003 |
| **Memory** | - At least 256 MB for ArcHydro - At least 512 MB for ArcView |
| **Disk Space** | 1.2 GB |
| **Other requirements** | - At least 500 MB swap space - Internet explorer 6/7 - .NET Framework 2.0 |
| **GIS Requirements** | - ArcGIS Desktop 8.1 + - ArcGIS Spatial Analyst - Arc Hydro Tool Set |
| **Programming Language** | - .NET - Visual Basic for Applications (VBA) |
| **Current Version** | 9.2 |
| **Licensing** | Licences required for ArcGIS and Spatial Analyst |
| **Cost** | - |
| **Supplier** | ESRI |
| **Support** | Provided |

## 2.4  EXISTING HYDROLOGICAL MODELLING FRAMEWORKS

According to Clark and Smithers (2006b: 466; 2006a: 1), a modelling framework may be defined as "an open modelling environment in which existing models, databases and user interfaces can be linked or organised in a consistent manner".

The modelling framework will include one or more data models or databases. Some of the modelling frameworks that are used in the South African environment are discussed in the following section of this dissertation.

### 2.4.1  BASINS (Better Assessment Science Integrating Point & Nonpoint Sources)

2.4.1.1  Introduction

Basins may be described as a multipurpose environmental analysis system. BASINS were originally designed for use by regional, state and local agencies in the United States of America (USA) to perform catchment and water quality based studies.  Other countries may, however, still make use of BASINS by creating their own databases that will be used by the framework.  According to

USEPA (2001b:8), the developers of BASINS, the objectives of BASINS are to: facilitate in the examination of environmental information, provide support analysis of environmental systems, and provide a framework for examining management alternatives.

BASINS integrate GIS, data analysis, and modelling into a single system and is designed to assist with the estimation of total maximum daily loads (TMDLs), using both point and non-point sources for a variety of pollutants (various scales may be specified).  The aim is to make catchment and water quality studies easier by integrating key data and analytical components into one system (USEPA, 2001b:1).

A major advantage of the BASINS system is its flexible architecture that allows other models to be added without making changes to the core BASINS software (Duda *et al.*, 2003).  According to Duda *et al.* (2003) the next version of BASINS (version 4) is easy to work with.

The release of BASINS 4 has marked a significant shift in the core GIS software underlying the BASINS system.  BASINS 4 operate using an open source GIS platform called MapWindow to provide the GIS capabilities.  With the new release users will no longer be required to purchase any GIS software to use BASINS.  MapWindow can perform most of the same operations on shape files, database files, and grids that that were available to users in the previous versions of BASINS with ArcView as GIS application (MapWindow GIS, 2005).  As mentioned, BASINS 4 will not be dependent upon any proprietary GIS platform, the core of the system is designed to complement and interoperate with enterprise and full-featured GIS systems. BASINS 4 will interoperate with ArcView and ArcGIS so that users that use those packages will be able to transfer files to and from BASINS 4.  The interoperability allows users who wish to transfer files into ArcView/ArcGIS to perform more advanced GIS operations (USEPA, 2005).

Version 4 will implement models through generic interfaces by making use of classes that contain codes specific to each particular model. Each of these models will make use of standard properties and methods that are used by the newly developed BASINS System Application and other related components. Models that are added to BASINS would still, however, be able to read input from and write output to files in WDM format (Duda *et al.,* 2003). The only watershed model available through the first release of the BASINS 4 MapWindow interface will be HSPF (Johnson, 2004); the AGWA and SWAT models that were available in version 3.1 are currently not available in version 4 (USEPA, 2004). The main functionality that was available in BASINS 3.1 is still available in BASINS 4. BASINS 4 is currently available, for free, from the EPA website (USEPA, 2005).

2.4.1.2 Functioning of the framework

According to USEPA (2001b: 6, 14; 2004) the BASINS GIS environment includes three geographically based analytical tools, namely TARGET, ASSESS and Data Mining (Figure 2.11 System overview of Basins). These are used to perform regional and site-specific analysis. TARGET may be used for broad-based evaluations of a catchment's water quality and point source loadings. This is done by integrating and processing large amounts of detailed, site-specific data. Summaries on a catchment basis are also provided. ASSESS uses the same data as TARGET but is used for watershed-based evaluations of specific water quality sites or discharge facilities and their proximity to water bodies. Finally, Data Mining is a tool that provides more detailed analysis at station level by dynamically linking different data elements, using a combination of maps and tables, and allowing geographic and historical data to be visually interpreted.
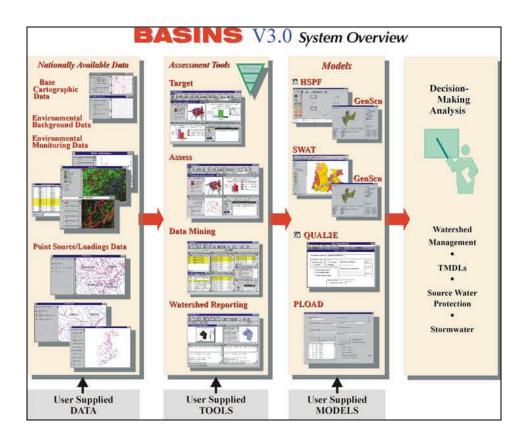
Figure 2.11  System overview of BASINS.

BASINS also includes several utilities for importing, storing, manipulating and managing data.   Included in these utilities are tools for the manual and automatic delineation (based on DEMs) of watersheds.   GenScn, originally developed by the USGS, is a post-processing tool that assists with the display and interpretation of observed water quality and other time-series data. Included in GenScn is model output data from the HSPF and SWAT models. GenScn allows users to do statistical analysis and data comparisons by creating tables and graphs from the selected data of specific geographic areas and specific time periods.

The Watershed Characterisation Reporting tools allow users to summarise watershed information in standard reports, using tables, charts, or map layouts.

## 2.4.1.3. User interface

BASINS 3.1 use ArcView to provide a customised user interface which contains the standard ArcView features. Other tools and menus which are specific to BASINS are accessed through the BASINS extension Manager and include: assessment tools, utilities, catchment characterisations reports, water quality models, and catchment hydrology models (USEPA, 2001b:7; USEPA, 2004).
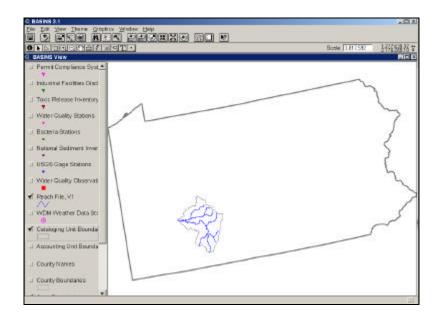


Figure 2.12  BASINS 3.1 Interface in ArcView 3.x (Duda *et al.*, 2003).

BASINS 4 may, however, make use of the MapWindow GIS which is an open source system (USEPA, 2005; MapWindow GIS, 2005), refer to Figure 2.13 for an example, or ESRI's ArcGIS 8.x (Figure 2.14) (Duda *et al.,* 2003).
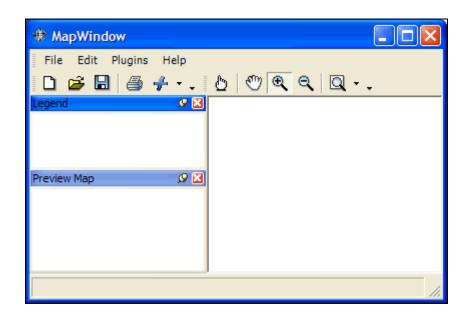
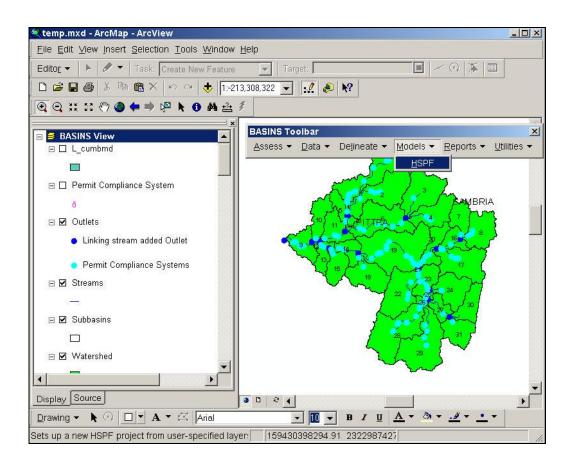Figure 2.13  Basic MapWindow Graphical User Interface.



Figure 2.14  BASINS 4.0 Toolbar in ArcMap (Duda *et al.*, 2003).

2.4.1.4  Support provided for other models

Various data models were included in BASINS to allow users to simulate in-stream behaviour of toxic chemicals, conventional pollutants, and nutrients, at various levels of complexity.  The use of these models is facilitated by tools that allow for input data preparation and the ability to display model output results (USEPA, 2001b:5-7).  These models include:

✦ HSPF.  The Hydrologic Simulation Program, FORTRAN (HSPF) is a watershed model used to simulate non-point source runoff and pollutant loadings for watersheds, and performs flow and water quality routing in reaches (USEPA, 2001b:6, 20).  WINHSPF is described in more detail on page 52 of this dissertation.

✦ QUAL2K.  The QUAL2E model is a one-dimensional water quality model allowing analysis of pollutant fate and transport through selected stream systems (USEPA, 2001b:5, 20).  The QUAL2E model has, however, been replaced by QUAL2K due to operating system compatibility issues. QUAL2K works with Excel under the Windows XP platform (USEPA, 2005).

✦ SWAT.  The Soil and Water Assessment Tool (SWAT) is a physically based, watershed, scale model used to predict the impacts of land management practices on water, sediment, and agricultural chemical yields in watersheds with varying soil, land use, and management conditions (USEPA, 2001b:6, 20).

✦ PLOAD.  Is an ArcView extension used to calculate non-point source pollutant loads for watersheds (USEPA, 2001b:7, 21).

2.4.1.5  Data handling / Data models

According to USEPA (2006:8), BASINS includes a set of custom databases to facilitate catchment-based analysis and modelling.  These databases contain data compiled from a wide variety of federal sources in the USA including national databases at the USEPA, USGS (United States Geological Survey) and other databases that are available for download through the Internet.

These custom BASINS databases are distributed on CD's or may be accessed over the Internet through the extraction tool that is provided in BASINS. Additional data is stored in Water Data Management (WDM) and DBF (database) files which may be accessed by BASINS models and tools. The data is intended as a starting point for areas where there is limited site-specific data available. Users are encouraged to import more accurate locally derived data if such data is available. Some of the datasets used in BASINS include: catchment boundaries, administrative boundaries, roads, eco-regions, soils information, river networks, DEM's, land use, land cover dams, water quality and flow monitoring stations, water quality, flow, and climate data. BASINS was not explicitly designed for use outside the borders of the USA (USEPA, 2001b:8).

Figure 2.15 Indicates how data will flow in the BASINS system and interact with the models and tools mentioned previously.
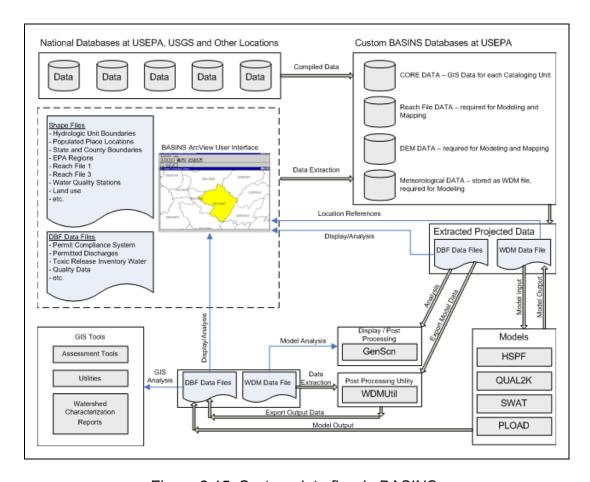
Figure 2.15  System data flow in BASINS.

Data are collected from the national databases at USEPA or from the BASINS system, compiled or extracted and stored in the custom BASINS databases at USEPA.  The extracted project data will then be sent to either DBF Data Files or WDM Data Files.  The DBF Data Files are subsequently used by BASINS for display and analysis purposes, whereas the WDM Data Files are used for model analysis through GenScn, the exportation of model data through the WDMUtil post-processing utility, or as model input to the various models (HSPF, QUAL2K, SWAT, and PLOAD).  After processing by the model(s) and the WDMUtil post-processing tool, the model output (exported output data) is stored in a DBF Data File.  This data file may then either be used by BASINS for display/analysis purposes or by GIS tools for further processing (Assessment Tools, Utilities, or Watershed Characterisation Reports).

2.4.1.6. Programming languages supported

Visual Basic classes will be used to implement interfaces to the BASINS Watersheds.

2.4.1.7.  System requirements

The following requirements are needed to run the BASINS framework (USEPA, 2001b:23):

- 166 MHz Pentium processor, 400 MHz Pentium II processor or higher recommended
- A minimum of 550 MB (watershed, BASINS environmental data and operating space) is needed, 3 GB or more is recommended
- 256 MB minimum required, 512 MB recommended
- Screen resolution of 1024x768 with 16 colours needed, 1024x768 with 256 colours recommended
- Windows 95, 98 or NT required (Take note that QUAL2E cannot function on NT)
- ArcView 3+ and Spatial Analyst 1+ required as GIS software extensions

**2.4.2  OMS (Object Modelling System)**

2.4.2.1  Introduction

The developers of the Object Modelling System (OMS) describe it as a Java-based modelling framework that consists of a library of science, control, and database components, which facilitates the assembly of selected components into a modelling package suited to the problem, data constraints, and scale of application.  OMS is supported by a GUI and utility components, including a data dictionary, data retrieval and storage tools, a GIS, a graphical visualisation section, and statistical analysis tools (OMS, 2005).

According to David *et al.* (2004) the OMS is a modelling framework that facilitates simulation model development, evaluation, and deployment.  He

further explains that a model may be considered to be a collection of components, where each component represents a single unique concept (such as runoff or evaporation hydrological processes).

## 2.4.2.2. Functioning of the framework

Kralisch *et al.* (2004) indicates that the concept behind OMS is to create a system that allows all system and model tools to be self-governing re-usable components. These components may be linked together, using standardised software interfaces to create an application specific modelling package.
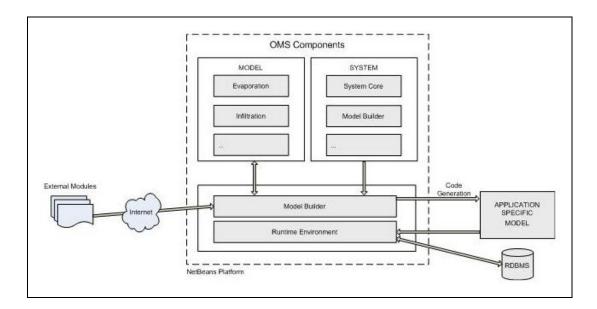


Figure 2.16  Conceptual layout of OMS (Kralisch *et al*., 2004).

The conceptual layout of OMS (Figure 2.16) demonstrates that two types of OMS components are available: model components (the building blocks from which models are created within OMS), and system components (used to assemble and execute the model components). After using the model and system components to create a new model the required model components are selected and assembled by the Model Builder to create an application specific model. This newly created application specific model is then

populated with suitable data and may be executed by the OMS system (Kralisch *et al.*, 2004).

Some of the main system components are the System Core, the Model Builder, the Update Centre, and the User Interface. The System Core provides the basic functionality required by the other components and forms the runtime environment required for the development and execution of components and models. A set of base classes are implemented by this model component, and these classes act as a container to which component developers may add code specific to the component they are developing. These classes contain standardised methods which facilitate the linking and communication between different components. The model builder has a GUI that allows for the linking of single model components to form more complex models. Input and output parameters for each model are available to allow different models to communicate with one another. Furthermore, the model builder provides tools for the storage and management of different model configurations, which in turn allow users to create and store custom model sets. The update centre is a standard NetBeans component which allows a collection of OMS components to be bundled together to form NetBeans modules. These may be easily updated and downloaded over the Internet. The OMS NetBean modules contain both the model components and implementation data (parameter sets and component documentation). The update centre also allows users to share components with one another via the Internet. The user interface component contains a set of components that are available to developers to create visual tools such as maps and graphs to display modelling results (Kralisch *et al.*, 2004).

According to the OMS website (OMS, 2005), the following functionality is available or currently under development:

* automatic generation of model input forms based on the components selected for a model;

- user interfaces for data validation, external data source input, model output variable selection, and statistical analysis of model output data;
- the ability to display model output data through tables, graphs and GIS.

### 2.4.2.3. User interface

Figure 2.17 Illustrates how OMS is applied in practice. Various users work with OMS through interacting with the OMS Toolbox. The OMS Toolbox contains a Model Interface, Model Engine, Database (Repository) and specific modules. Various models may be linked together in the Model Engine and supply the user with information through the Model Interface (Kralisch *et al.*, 2004).
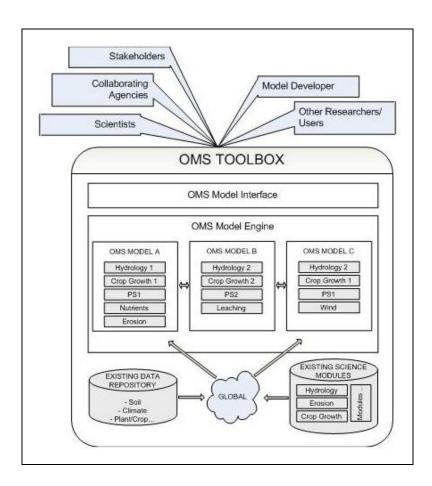


Figure 2.17  Schematic diagram illustrating the application of OMS (Ahuja *et al.*, 2004).

### 2.4.2.4. Data handling / Data models

The OMS uses a dictionary framework which Ahuja *et al.* (2004) describes as the "knowledge backbone" of OMS. The data dictionaries are used to specify parameter sets, model control information, and details regarding component connectivity. OMS uses XML to create these data dictionaries.

### 2.4.3 OpenMI (Open Modelling Interface)

#### 2.4.3.1. Introduction

Gijsbers (2003) and the writers of the OpenMI website (OpenMI, 2007a; OpenMI, 2007b) describe the Open Modelling Interface (OpenMI) as a generic interface (standard) that allows models simulating different water-related processes to be linked on a temporal and spatial basis, allowing for the simulation of process interactions.

The OpenMI has been developed by a team consisting of 14 organisations and seven countries, co-funded through the European Commission's Fifth Framework programme. The HarmonIT project, as it was called, was led by the Centre for Ecology and Hydrology and comprised of; the Institute for Inland Water Management and Waste Water Treatment RIZA, DHI Water and Environment, WL Delft Hydraulics, HR Wallingford Group, Universitat Dortmund, Instituto di Ricerca Sulle Acque, the National Technical University of Athens, WRc plc, DHI Hydroinform a.s., Povodi Labe s.p., Hydroprojekt a.s., Alterra B.V. and the Centre National du Machinisme Agricole, du Genie Rural, des Eaux et des Forets. Design and development has been led by the three major commercial model developers, DHI Water and Environment, Delft Hydraulics and HR Wallingford. The role of the other organisations has been to manage the project, to support the design and development, and to test the standard and environment rigorously (Moore *et al.*, 2005:9).

According to the HarmonIT group (the developers of OpenMI) (OpenMI, 2007a); the modelling framework enables Water Managers to save time and

money when building integrated models, enables Modellers to select and easily combine the most appropriate modelling tools available, enables Researchers to conduct sensitivity analyses more easily as models may be swapped, and enables Model developers to commercialise their models more easily.

OpenMI was created to simplify the linking of models that run parallel. In many instances these models operate at different spatial and temporal scales, and the need exists to transfer data between models without writing to or reading from intermediate text files (Gijsbers, 2003).

### 2.4.3.2. Functioning of the framework

The objectives of the OpenMI model were to resolve or improve several complicated model linking issues, including: the difference in spatial and temporal scales, feedback loops, differences in spatial and temporal concepts, different units and naming of variables, and distributed computing (Blind & Gregersen, 2004). OpenMI simplifies the linking of models from a computer science point of view, allowing modellers to concentrate on the complexities of linking models from a hydrological point of view (Gijsbers, 2003).

The following list gives an overview of the functionality of OpenMI (OpenMI, 2007a; Moore *et al.*, 2005:10):

- Link models from different domains (hydraulics, hydrology, ecology, water quality, economics etc.) and environments (atmospheric, freshwater, marine, terrestrial, urban, rural etc.);
- Link models based on different modelling concepts (deterministic, stochastic etc.);
- Link models of different dimensionality (0, 1, 2, 3D);
- Link models working at different scales (e.g. a regional climate model to a catchment runoff model);
- Link models operating at different temporal resolutions (e.g. hourly to monthly or even annually);

- Link models operating with different spatial representations (e.g. networks, grids, polygons);

- Link models using different projections, units and categorisations;

- Link models to other data sources (e.g. databases, user interfaces, instruments);

- Link new and existing (legacy) models with the minimum of re-engineering and without requiring an unreasonably high level of IT skills;

- Not impair performance, especially of large models;

- Be based on proven and available technologies (and, in particular, the architecture must be component based and multilayered);

- Link models running on different platforms (e.g. Windows, Unix and Linux);

- Be „open' (the interface specification should be placed in the public domain);

- Allow components to be developed using at least the following programming languages: C/C++, C#, FORTRAN, Delphi/Pascal, Java and Visual Basic.

A typical system consists of a user interface and an engine. The engine is a generic representation of a process. All the calculations for the simulation or modelling of the process take place in the engine. The user supplies information through the user interface which is then converted into input data for the engine. After the user has initiated the processes to be performed in the engine, the engine reads the inputs, performs the calculations, and outputs the results to files or visual displays. When an engine has read its inputs it becomes a model. Refer to Figure 2.18 for a visual layout of the above-mentioned process (Moore *et al*., 2005:11-12).
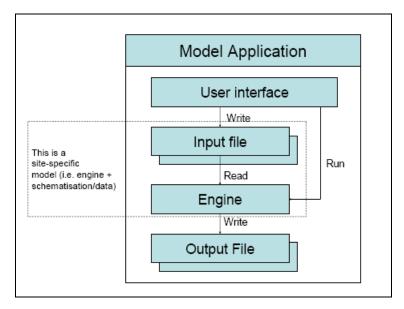
Figure 2.18 The general structure of a model application

## 2.4.3.3. User interface

The OpenMI defines a standard interface that has three functions: namely, Model definition (to allow other linkable components to find out what items this model may exchange in terms of quantities simulated and the locations at which the quantities are simulated), Configuration (to define what will be exchanged when two models have been linked for a specific purpose), and Runtime operation (to enable the model to accept or provide data at run time) (Moore *et al.*, 2005:12).

Figure 2.19 shows two model applications whose engines have been made OpenMI-compliant. Their overall structure remains unchanged but each engine is now a component with an OpenMI interface and one component may now get values from another (Moore *et al.*, 2005:13).
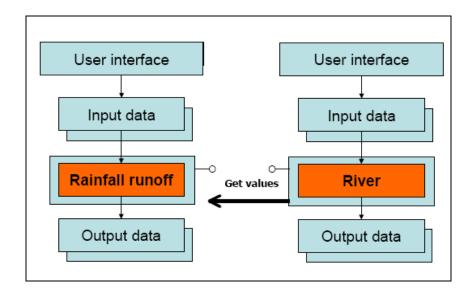
Figure 2.19  Two applications after migration to the OpenMI standard

## 2.4.3.4.  Support provided for other models

A wide variety of domain- (hydraulics, hydrology, ecology, water quality, economics etc.) and environmental-based (atmospheric, freshwater, marine, terrestrial, urban, rural etc.) models are supported (OpenMI, 2007a; Moore *et al.*, 2005:10).

## 2.4.3.5.  Data handling / Data models

The system makes use of OMI files which are XML files that contain the functionality of the model (Gijsbers and Gregersen, 2005: 2).

## 2.4.3.6.  Programming languages supported

The development of new components is available for OpenMI but should be developed in one of the following languages; C/C++, C#, FORTRAN, Delphi/Pascal, Java, or Visual Basic (OpenMI, 2001).

## 2.4.3.7.  System requirements

The OpenMI model functions on a range of platforms.  These include Windows, Unix and Linux (OpenMI, 2001).

## 2.4.4 SPATSIM (Spatial and Time Series Information Modelling Software)

### 2.4.4.1. Introduction

The Spatial and Time Series Information Modelling Software (SPATSIM) has been developed by the Institute for Water Research (IWR) at the Rhodes University in Grahamstown, with financial support provided by the Water Research Commission of South Africa (WRC) as well as guidance provided by DWAF (IWR, 2004a).

According to the developers (IWR, 2004c) of SPATSIM the system may be defined as an integrated hydrology and water resource information management and modelling system. The system makes use of ESRI Map Objects and the Delphi programming language to create a data management environment that uses a spatial information front end and a relational database structure (Paradox) at the back end.

### 2.4.4.2. Functioning of the framework

The main menu of SPATSIM includes information that assists with the running of a SPATSIM application, as well as decision support information that provides support for a range of water resource applications (IWR, 2004a).

SPATSIM has been designed in such a way that new models may easily be added without changing the application itself. SPATSIM provides an extensible and efficient storage structure for data. Provision has been made for the inclusion of time series data. SPATSIM together with TSOFT provides some useful tools for the management, manipulation, and visualisation of data. The current model does, however, only allow one GIS feature layer to be used when linking model parameters to SPATSIM attributes, and there is no facility for storing relationships between features in different layers. For a model to be able to run in SPATSIM it will require that codes are added to the model so that it may access a SPATSIM project database to obtain model

input parameters and write model output parameter values (Hughes, 2002:43-49).

The main window of SPATSIM displays the spatial feature layers of the project as well as the attributes that may be set for that particular project. Other components are available and may be accessed through the menu and toolbar components (data manipulation, visualisation and data management) of the application.   These tools include features such as: creating and removing attributes, loading attribute data from different data sources, displaying and editing attribute data, exporting data, the analysis of time series data, and the transformation of time series values (Hughes, 2002:43-49).

SPATSIM also facilitates access to TSOFT, an external application designed to display and analyse time series data (Hughes, 2002:43-49).

### 2.4.4.3.  User interface

The GIS functionality provided in SPATSIM only includes what is required for setting up and storing the attribute data required by the models to be run. SPATSIM provides GIS related functionality, which includes: handling of shape files, changing the colours of features and labels, creation of maps (print or write to file), rendering of features using attribute values, generation of attribute data, and the interpolation of point data values (Hughes, 2002:43-49).
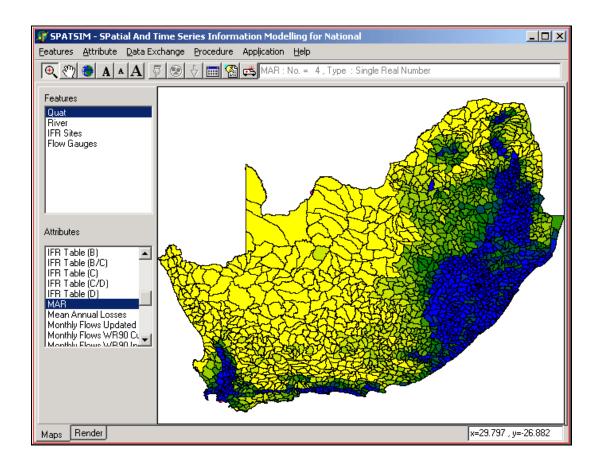
Figure 2.20  User interface window for SPATSIM.

### 2.4.4.4.  Support provided for other models

The following external model and data analysis tools are available in SPATSIM (IWR, 2004c; IWR, 2004b):

* General Hydrology Data Analysis Models
    * Baseflow Separation Calibration Model
    * Patching Model (Flow Data)
    * Patching Model (Using Rain Data)
    * Tributary Inflow Analysis Model
    * Residual flow diagrams generation Model
* Catchment Rainfall-Runoff Models
    * Pitman Monthly Model
    * Ground Water Pitman Monthly Model

- o Ground Water Pitman (parameter exploration)
- o VTI Model Requirements
- ✦ Flood Models
  - o Design Flood Model
- ✦ Water Resources Systems Models
  - o Rapid Simulation Model
- ✦ Ecological Reserve Models
  - o Reserve Method DSS
  - o Present Day Hydrological Class Model
  - o Desktop Reserve Model
  - o Desktop Parameter Calibration Model
  - o Daily IFR Design Model
  - o Stress/Flow & Risk Indicator Model
  - o Flood Stress/Event Model
  - o Hydraulic Model
  - o Reserve Licensing Model linked to the Desktop Model
  - o Water Quality Data Analysis Model

## 2.4.4.5. Data handling / Data models

Support is provided for the importing of all types of data, as well as the viewing, editing, displaying, and sharing of data. In addition, access is provided to a wide range of linked models and data analysis procedures that are used in water resource assessments and ecological water requirement assessments (IWR, 2004c).

Paradox is used as RDMS for the SPATSIM system (IWR, 2004c).

## 2.4.4.6. Programming languages supported

SPATSIM was written with the Delphi programming language and ESRI Map Objects was used to provide the GIS component (IWR, 2004c).

### 2.4.5 TIME (The Invisible Modelling Environment) and the Catchment Modelling Toolkit

#### 2.4.5.1. Introduction

Murray *et al.* (2004:1) and eWater (2007c) describe the Invisible Modelling Environment (TIME) as a modelling and programming system that is used for developing, applying, and deploying environmental models. Marston *et al.* (2002:1) highlights that the aim of the Catchment Modelling Toolkit is to provide land and water managers, researchers, and educators with an integrated collection of software tools and components to simulate catchment response to management and climate variability at a range of scales, and by allowing them to make use of a range of approaches. Rahman *et al.* (2003) reiterates this fact and indicates that the objective of the Catchment Modelling Toolkit project is to produce a cohesive suite of environmental modelling applications. This is achieved by making use of a modelling framework that allows new models to be developed and integrated quickly and consistently. The explanations given by the above-mentioned researchers are further substantiated by eWater CRC (2007c), the developers of TIME, who specify that TIME provides support for the representation, management, and visualisation, of a variety of data types, as well as support for testing, integrating and calibrating simulation models. The developers continue and specify that TIME may be used by application developers to produce standalone and integrated modelling applications (i.e. Rainfall Runoff Library).

Most of the modelling frameworks simplify the task of creating models, by providing re-usable components for data handling, visualisation, and model execution, but TIME further simplifies the process by providing a high level, metadata driven environment for automating common tasks, such as creating user interfaces for models, or optimising model parameters. eWater CRC believes that this reduces the learning curve for new model developers. The use of commercial programming languages (languages supported by the

.NET platform) (Murray *et al.*, 2007:3) further assists more advanced users with the development of these new models (eWater, 2007c).

TIME supports the deployment of models as graphical applications, command line applications, and active web pages.

### 2.4.5.2. Functioning of the framework

TIME supports programmers and modellers who wish to (eWater, 2007c):
- Create, test, and calibrate model components;
- Design integrated system models that combine model components;
- Develop highly visual, customised user interfaces for applications that are used by users.

TIME includes support for a number of advanced tools that are used for the visual integration of models, calibration of models using automatic optimisers, and the pre and post processing of data. In addition TIME has a wide range of statistical and data visualisation tools, data export capabilities for common GIS and time series formats, and a statistical library that provides access to common summary and comparison statistics on the data sets (eWater, 2007b).

### 2.4.5.3. Data handling / Data models

A variety of types of data are supported by TIME for example, Grid, TIME Series, Points, Lines, Polygons, Node Link Networks, and Images. Each one of these may be loaded and saved into a variety of file formats that is available for use by the system. New formats may, however, be developed by more advanced users to fit their custom environments (eWater, 2007a).

### 2.4.5.4. Programming languages supported

According to Murray *et al* (Murray *et al.*, 2007:2), .NET provides a solid foundation for developing environmental modelling applications. The writers

indicate that the .NET Common Language Runtime (CLR) co-ordinates the integration of programs and components written in different languages (VB.NET, C#, Delphi.NET, Visual J#, Python, and Lahey FORTRAN 95.NET) (eWater, 2007d; Murray *et al.*, 2007:3-5).  By making use of the .NET Metadata standard, modelling components may be distributed as self-describing and contained units.  TIME uses the Metadata facilities to extract information about a model and perform generic model processing functions, such as generating user interfaces (Murray *et al.*, 2007).  Development may, however, still take place by making use of older languages like C++ and Java (eWater, 2007c; eWater, 2007d).

## 2.4.5.5.  System requirements

The following requirements are needed in order to develop models for TIME, to work with the Visual Studio environment, or to run models developed for TIME (eWater, 2007d).

Software:
- Microsoft Visual Studio .NET
- The .NET Runtime (downloadable at no cost)
- Appropriate language plug-in to Visual Studio (such as C# or Fortran 95.NET)

Hardware:
- Microsoft Windows 98, ME, NT4, 2000 or XP
- 128-256 Mb of RAM
- 1.5 Gb of available disk space
- 1 GHz processor

eWater CRC (2007c; 2007d) specifies that specific TIME models will require additional hardware and software requirements.  These include better processing capabilities, more memory, and more disk space.

## 2.4.6  Comparison of the different modelling frameworks

It is evident from the investigation on the different hydrological modelling frameworks that there were similarities between them.  Specifications, requirements and pricing information could be found for all the modelling frameworks except for OMS (due to this reason OMS was excluded from table 2.3).  Most of the modelling frameworks are provided free of charge to users. If costs were associated with a modelling framework it was mainly due to GIS software needed by that particular modelling framework.  Online support and documentation are provided for many of the modelling frameworks.  Further support is provided in the form of discussion groups (Internet-based) which allow users with specific problems to communicate with other users, which in turn might assist them in solving their problems.

The operating system platforms used are similar to those used with the different data models.  Microsoft Windows was most frequently used but support was also provided for UNIX and Linux.  Visual Basic, the .Net-related languages (C#, VB.NET, Delphi.Net and Visual J#), C, C++, Delphi, Pascal, Java, FORTRAN and Python are used by the different modelling frameworks as programming languages.

No clear hardware requirements were indicated for any of the modelling frameworks.

Table 2.3 presents a list of the modelling frameworks discussed, and a gives a summary of their system requirements.

Table 2.3  Comparison of Hydrological Modelling Frameworks

| | Basins | OPENMI | SPATSIM | TIME & Catchment Modelling Toolkit |
|---|---|---|---|---|
| Operating System | Windows 95, 98 or NT | Windows, Unix and Linux | | Windows 98, ME, NT4, 2000 or XP |
| GIS Requirements | ArcView 3+ and Spatial Analyst 1+ | - | | |
| Programming Languages Supported | Visual Basic classes | C/C++, C#, FORTRAN, Delphi/Pascal, Java or Visual Basic | | VB.NET, C#, Delphi.NET, Visual J#, Python, Lahey Fortran 95.NET, C++ and Java |
| Current Version | 4.0 | OpenMI 1.4 September 2007 | 2.0.0.9 (IWR, 2007) | |
| Licensing | | Open source (free) | | |
| Cost | Free | Free (Open source) | R1200 which covers the application distribution cost for ESRI Map Objects. | |
| Supplier | USEPA | OpenMI (Centre for Ecology and Hydrology, Wallingford, UK) | | |
| Models Supported | HSPF, SWAT, QUAL2K, and PLOAD | Support models from different domains and environments | General Hydrology Analysis, Catchment Rainfall-Runoff, Flood, Water Resources Systems and Ecological Reserve | |
| Support | FAQ provided on USEPA site as well as training | A full description is given of the interface, including a full range of documentation | | |

## 2.5  THE NEED FOR A NEW MODELLING ENVIRONMENT

After investigating the different data models and hydrological modelling frameworks it became evident that these models and frameworks were restrictive and could only be used for specific purposes and only functioned with limited, restrictive datasets.  Valuable functionality is provided, but in many cases these data models and hydrological modelling frameworks only provided information (simulations/estimations) for specific water-related domains.  This was a major concern and needed to be addressed.  In many cases users found it difficult or impossible to add new datasets to the existing data structures.  The sharing of data between these data models and hydrological modelling frameworks was in most cases not allowed, and users had to export data to basic file formats, restructure the data to fit the next environment, and once changed, import the data into the data model or hydrological modelling framework.  Many users, however, did not do this because it was a long and tedious process and many of them did not have the data manipulation/programming skills to do so.

At the same time the NWA (South Africa, 1998) states that water resources should be managed in a sustainable manner, and because many role-players (people, domains, etc.) are involved, quick and accurate decisions should be taken to ensure that none of them are negatively affected and that water resources are effectively managed.  The need exists for users to record as much data about water-related (and possibly other) activities as possible, share the data amongst one another and carry out various simulations and estimations, in relative short time frames, to effectively manage the country's water resources.

Therefore a new modelling environment with an extensive, adaptable geodatabase should be created to allow users/role players to record as much data as possible (to allow for more accurate decisions) and to share this data

between themselves, the different data models, and hydrological modelling frameworks.

The modelling environment and geodatabase is discussed in more detail in Chapter 4 of this dissertation.

# CHAPTER 3 - METHODOLOGY AND STUDY AREA

## 3.1 METHODOLOGY

The theoretical background with regard to existing data models and hydrological modelling frameworks given in Chapter 2, and the proposed new modelling environment in Chapter 4, form the basis on which the study was developed. This chapter outlines the methodology, which was followed in the research project. The rationale for selecting the study area and the approach which was followed in creating the new modelling environment is explained. The different tasks conducted during the study are illustrated in the flow diagram in Figure 1.7 of Chapter 1. The first undertaking was to understand the NWA (South Africa, 1998) and NWRS (DWAF, 2004b) by looking at the strategies and requirements they place on decision makers and how data models and hydrological modelling frameworks may assist in the decision making so that these strategies can be met (Chapter 1). The next step involved examining existing data models and hydrological modelling frameworks in order to establish how they assist and handle water management, and whether they may be used for the effective management of data (Chapter 2). From the analysis of the existing data models and hydrological modelling frameworks the new modelling environment was designed and created (Chapter 4). After establishing the requirements of the new modelling environment the geodatabase was designed and created by making use of object oriented design methods (UML). The geodatabase will form the basis of the modelling environment and should be created in such a way that it would be easy to extend its capabilities for future projects. The next step involved gathering the data from the different sources. Information (data) was gathered from DWAF, the Weather Bureau, StatsSA, Bloem

Water, as well as data that might have been created (generated) by previous projects, research undertakings, and systems (for example, HYDSTRA). The gathered data were then interpreted, assessed, altered, and entered into the geodatabase.

### 3.1.1 Establishing the objectives of the research project

To understand the objectives of the study it was important to understand why the effective management of water resources is needed, and who the stakeholders are that would manage these water resources. It was furthermore important to understand whether the effective management of water resources would ensure that adequate water would be available to the citizens of South Africa in future.

Information was then gathered from books, journals, Internet sources, Government White Papers, conference proceedings, and personal correspondence, to determine the current and projected future state of water resources in South Africa. It was important to understand the importance of water to people and how the usage of water is specified in the Bill of rights (South Africa, 1996), the NWA (South Africa, 1998), the WSA (South Africa, 1997b), the NWRS (DWAF, 2004b), and the NWP (South Africa, 1997a).

A closer look was then undertaken to understand how the above-mentioned Acts, Policies and Strategies relate to one another (Figure 1.3 Chapter 1), as well as who the different organisations and parties are that should accept responsibility for the distribution and protection of water resources (Figure 1.2, Chapter 1).

The objectives and hypothesis were then determined and it became evident that a closer look should be taken at current data models as well as hydrological modelling frameworks. It was important to understand how these models and modelling frameworks might assist with the effective management of water resources and thus satisfy the strategies and goals set out by the

State in order to ensure that the country has adequate water resources for the future.

### 3.1.2 Gathering the data

From the beginning of the research project, meetings were held with various participants ranging from employees from Bloem Water, employees from DWAF, and employees from other government departments. From these meetings the data requirements were established for the geodatabase and the task of collecting data began. Various amounts of data were gathered from different sources (DWAF, the Weather Bureau, StatsSA, Bloem Water, and HYDSTRA). The data was then interpreted and tables, fields, and relationships were determined. It must, however, be mentioned that some data was missing or incomplete and could not be incorporated into the geodatabase.

By making use of ArcGIS data was entered into the geodatabase. Chapter 4 explains how data was entered into the geodatabase.

### 3.1.3 Evaluating existing data models and hydrological modelling frameworks

The next step of the research process was to conduct a literature review (Chapter 2) by looking at some of the more recent developments related to GIS, data models and modelling frameworks. This was primarily conducted by referencing books, journals, Internet sources, as well as conference proceedings. Through discussions with various specialists at the Central University of Technology, Free State many thoughts and ideas were shared and the certain directions were investigated.

GIS packages were investigated as a geographic DBMS that would assist in the storage and management of data that would provide a medium for

decision makers to carry out simulations, by making use of the gathered data, in order to make more informed decisions.

After looking at the most prominent GIS system (ArcGIS) it became clear that different prominent types of data models should first be investigated. Four data models that form part of the GIS system were looked at, these include; the field model, the object model, the network model, and the geodatabase model (this is a newer technology that has been developed to follow current trends and developments in GIS and IT and was developed by ESRI).

The geodatabase model is an object-oriented model which contains a geodatabase, feature datasets, feature classes, as well as object classes. This particular data model was used in the creation of the ArcHydro framework which may be used and customised to provide management tasks for water resource management. The ArcHydro framework forms the basis of ArcHydro (a data structure that supports hydrologic simulation models) and was used as starting point after working through the book of David Maidment (2002), where he explains the working of ArcHydro as well and how the ArcHydro framework may be used to create a custom made data model.

Through using the Internet as main source, other data models were investigated and compared, these include; Hydstra, GML, HYMOS, and WINHSPF.

Near the end of the study additional data models were identified for possible inclusion in the research project. The WRSM, WRYM, and SAPWAT models were identified, and need to be considered for future investigations because of the level of functionality they provide to modelling environments.

In addition to the data models, the following hydrological modelling frameworks were looked at and compared to one another: Basins, OMS,

OPENMI, SPATSIM, and TIME. Again the Internet proved to be a valuable resource in obtaining information about the different modelling frameworks.

### 3.1.4 Establishing the requirements for the proposed modelling environment

It was evident from the comparison of the data models and hydrological modelling frameworks (Chapter 2) that a new modelling environment was needed, or that an existing modelling framework should be changed to support the needs identified. This framework/environment should be capable of handling large amounts of data, include data management features, contain a geodatabase (the geodatabase should be designed in such a manner that it may be easily changed and generated), and provide users with output results in order to make decisions.

The new modelling framework/environment should facilitate the interaction between the geodatabase, different data models (ArcHydro, HYDSTRA and WINHSPF), as well as one or more hydrological modelling frameworks (Basins). This new modelling framework/environment should ultimately assist in performing simulations and estimations for the study area identified.

The following were identified as requirements for the proposed modelling framework/environment. The proposed modelling framework/environment should:
- allow for the management of modelling projects and scenarios;
- support a GIS interface that will display spatial input and output data by making use of an established GIS application;
- make use of a well designed customisable geodatabase that will store spatial and temporal data;
- make use of the functionality provided by Basins, WINHSPF, ArcHydro, HYDSTRA, WRSM, WRYM, and SAPWAT;

- be customisable and allow additional or new technologies (data models, hydrological frameworks, and other databases) to be added in future research projects.

### 3.1.5  Designing and creating the proposed modelling environment

After discussions with various specialists and other stakeholders it was decided to create a new modelling environment that would allow for the interaction between the ArcHydro, WINHSPF, HYDSTRA, WRSM and WRYM data models as well as the Basins modelling framework.  The core of this new modelling environment will be a newly created geodatabase that was created after investigating the ArcHydro framework.   A flowchart was created to illustrate the flow of information within the new modelling environment (Figure 4.1 of Chapter 4).

### 3.1.6  Designing and creating the geodatabase

From the objectives (Chapter 1) and literature review (Chapter 2) it was clear that a new geodatabase should be designed and created for the proposed modelling environment and that the ArcHydro framework should be used as starting point.  The necessary hydrological and environmental entities, that form part of the study area, were identified, created, and implemented in the new geodatabase design.   An ER-diagram designed and developed previously for the research project, was used as basis to establish which entities and fields should be used for the geodatabase.   This design is available in Appendix A of this dissertation.   The design of the new geodatabase was created by making use of Microsoft Visio Professional a Computer Aided Software Engineering (CASE) development tool with UML as object-oriented design platform.   The full design of the geodatabase with corresponding UML diagram may be found in Chapter 4, Section 4.3.4.

The generated geodatabase (from the UML design) will be available as an Access database.  Access was chosen as DBMS due to its popularity around

the world. According to a survey conducted by GISJobs.com (s.a.) Access is most widely used by GIS professionals around the world (60%). Other DBMS that might be considered for future research projects, include; Oracle with 26% usage, or dBase and MS SQL each with 24% usage. The statistics gathered from the South African professionals present a similar picture. Access has 62% of the market, MS SQL with 35%, dBase with 31% and Oracle with 24% usage.

### 3.1.7 Selecting the study area

The C5 secondary catchment area was selected because it falls in the Upper Orange WMA, and is central to Bloemfontein, and has a fair amount of stakeholders that are responsible for the management of water resources. Another important consideration was that enough data has been gathered about the hydrological and environmental entities of this particular secondary catchment, which could be entered into the newly created geodatabase. This study area is also used by other research projects which might make use of the gathered data and proposed modelling environment. The study area is explained in more detail in Section 3.2 of this chapter.

## 3.2 STUDY AREA

The country has been divided into 19 WMA's. The delegation of water resource management from central government to catchment level is achieved by establishing CMA's at WMA level (Schreiner and Van Koppen, 2002:398). Each CMA will gradually develop a Catchment Management Strategy (CMS) for the protection, use, development, conservation, management, and control of water resources within its WMA (DWAF, 1999).

DWAF eventually aims to hand over certain water resource management functions to CMA's. Until such time the Regional Offices (RO's) of DWAF will

continue to manage the water resources in the areas of their jurisdiction. Furthermore, the way in which the resources are protected, used, developed, conserved, managed, and controlled, needs to form an integral part of other planning initiatives at provincial, district, and local authority level (DWAF, 2004a).

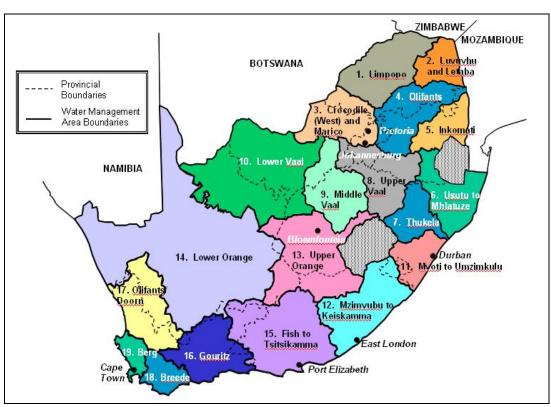In this study the focus will be on the Upper Orange WMA, secondary catchment C5. Figure 3.1 shows the location of the Upper Orange WMA in relation to South Africa (DWAF, 2004a; DWAF, 1999).



Figure 3.1 WMA's in South Africa

### 3.2.1 Current study area – Upper Orange WMA (Secondary Catchment C5)

#### 3.2.1.1 Overview

The Upper Orange water management area lies mainly within the Free State, but also occupies portions of the Eastern and Northern Cape provinces.  It borders on Lesotho in the east, as well as on six other water management areas.  The Orange River, which rises in the eastern highlands of Lesotho where it is known as the Senqu River, is the main river in the water management area and is also the largest and longest river in South Africa (DWAF, 2004a).

From the Upper Orange water management area, the river flows through the Lower Orange WMA and discharges into the Atlantic Ocean some 2 300 km from its origin in Lesotho.  The Caledon River, which forms the border between South Africa and Lesotho over most of its length, is the largest tributary to the Orange River within the Upper Orange water management area.  Other sizeable tributaries are the Kraai and Riet Rivers.  The Riet River, however, first flows into the Vaal River, which then joins the Orange River a short distance further downstream. Refer to Figure 3.2 for the location and general layout of the Upper Orange WMA (DWAF, 2004a).
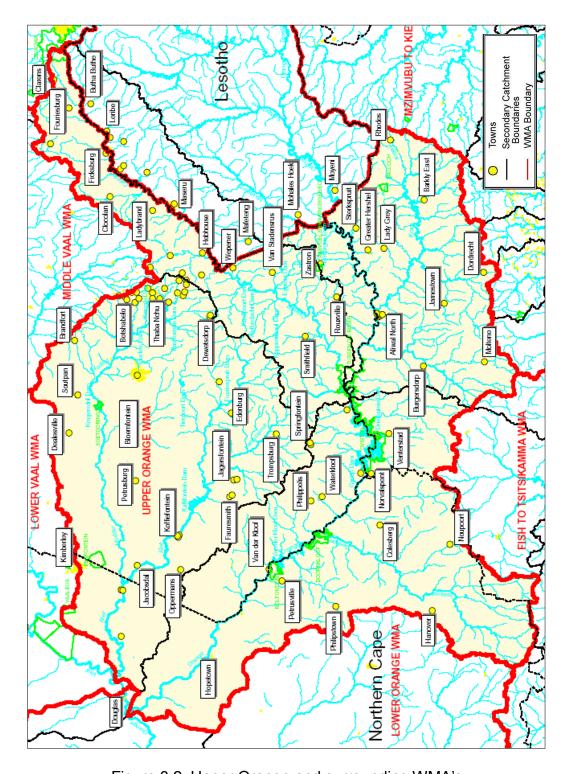
Figure 3.2  Upper Orange and surrounding WMA's

Climate over the water management area is cool to temperate and ranges from semi-arid to arid.  Rainfall mainly occurs as summer thundershowers,

and reduces dramatically from as high as 1 000 mm per year in South Africa at locations in the east to about 200 mm per year in the west. In Lesotho (the source of most of the water in the Upper Orange water management area), rainfall varies between 600 mm per year to about 1 500 mm per year. Potential evaporation over most of the WMA is well in excess of the rainfall (DWAF, 2004a). The temperatures in the Free State are between an average minimum of 12 ➡C and an average maximum of 30 ➡C in summer, and an average minimum of 3 ➡C and an average maximum of 18 ➡C during winter. The winters in this area are dry (Theron *et al.*, 2006:298-305).

The study area reaches an average height of 1200m above mean sea level (MSL). The highest point is at around 2100m and the lowest at 1100m. 99% of the catchment lies at a height between 1200m and 1400m above MSL (Theron *et al.*, 2006:298-305).

Savannah grassland covers the eastern part of the water management area, with Karoo shrub land towards the south and west. From the foothills of the Maluti Mountains at the border of Lesotho, the topography opens into wide plains in the west, with characteristic flat topped hills (DWAF, 2004a).

### 3.2.1.2 Land use and development

The history of human presence in the water management area may be traced back to at least 40 000 years through, the Florisbad skull, which was discovered near Dealesville in the 1930's. The major movement toward modern economic development has occurred after the discovery of the first diamond in June 1870 near a fountain frequented by early transport riders. This prompted a diamond rush (about 3 years before Kimberley) and led to the establishment of the towns Koffiefontein and Jagersfontein. Bloemfontein (the judicial capital of South Africa), the capital of one of the former Boer Republics which was founded in 1846 (Microsoft Encarta Online Encyclopaedia, 2007a), later developed into the only city in the water management area. Irrigation development was stimulated by the construction

of several dams in the water management area, the most recent and notable being the Gariep and Vanderkloof Dams in the Orange River (DWAF, 2004a).

Livestock farming (sheep, cattle and some game) is the main economic activity in the WMA, much of which is still naturally vegetated. Extensive areas under dry land cultivation, mostly for the production of grain, are found to the north-east. Large areas under irrigation for the growing of grain and food crops have been developed along the main rivers, mostly downstream of the irrigation dams. There is no afforestation in the water management area (DWAF, 2004a).

Bloemfontein and Thaba ‚Nchu represent the main urban and industrial development areas in the water management area. Two large hydropower stations were constructed at Gariep and Vanderkloof Dams. Mining activities have significantly declined and currently mainly relate to salt works and small diamond mining operations (DWAF, 2003).

From a water resource management perspective this is a very important WMA, as some of the largest dams in Africa have been built on the rivers of the Senqu catchment in Lesotho and on the main stem of the Orange River in South Africa. The Orange River in this area is characterised by the transfer of large quantities of water both within and out of the WMA. Transfers out of the Upper Orange include transfers to the Upper Vaal WMA (Lesotho Highlands Water Project), to the Fish/Tsitsikamma WMA (Orange-Fish Transfer), to the Lower Vaal WMA (Orange-Vaal Transfer) and downstream releases to the Lower Orange WMA as well as for use by Namibia. Transfers within the WMA occur from the Orange and Caledon Rivers to the adjacent Modder/Riet catchment (DWAF, 2004a).

Through its interdependence with other water management areas, it is essential that water resource management in the Upper Orange WMA should be well co-ordinated with these WMAs, particularly in the Orange/Vaal Basin,

and that water resources management is viewed in an integrated systems context. Management of water resources in the basin should also be within the framework of the Orange-Senqu River Commission recently established by South Africa, Lesotho, Namibia and Botswana (DWAF, 2004a).

### 3.2.1.3 *Economic Characterisation of the WMA*

Approximately 5% of the Gross Domestic Product (GDP) of South Africa originates from the Upper Orange WMA. The largest economic sectors (in 1997) in terms of GDP are:

- Government 24,6%
- Finance 16,0%
- Trade 15,7%
- Transport 14,4%

Geographically, nearly 64% of the GDP is produced in Bloemfontein, with the second largest district contribution being 4,2% from the Thaba ‚Nchu decentralised development zone, approximately 60km east of Bloemfontein (DWAF, 2004a).

Bloemfontein, as the capital of the Free State, and one of three capital cities (along with Pretoria and Cape Town) in South Africa (Microsoft Encarta Online Encyclopaedia, 2007a), fulfils an important government function with many provincial government departments located in this area. The activities of the University of the Free State, the Central University of Technology, Free State, the Appeal Court, and the major hospitals, further enhance the role of this sector. Bloemfontein also serves as a regional centre with close links to economic activities, such as those generated by the agricultural sector, in the surrounding rural areas (DWAF, 2004a).

The importance of the transport sector is attributable to transport companies taking advantage of the fact that Bloemfontein is a major model interchange and stopover for cargo travelling on the routes from Gauteng or Durban to

Cape Town or Port Elizabeth. The transport sector is also supported by the Bloemfontein airport and national rail network, with a railway line built as early as 1890 between Bloemfontein and Cape Town (DWAF, 2004a; Microsoft Encarta Online Encyclopaedia, 2007a).

The strength of the finance and trade sectors is largely as a result of the other economic activities in the region. Manufacturing occurs mainly in Bloemfontein, while manufacturing activities at Thaba ‚Nchu have seriously declined since the cancellation of the previous government's decentralisation policy. This may be reversed through the establishment of the Thaba ‚Nchu Industrial Development Zone (DWAF, 2004a).

Of the work force of 376 000 people in the water management area in 1994, 59% were active in the formal economy, 31% were unemployed, which is close to the national average of 29%. The remaining 10% participated in the informal economy. Of those formally employed, 33% were in the government sector, 17% in agriculture, and 12% in trade. (DWAF, 2003)

There are no distinct strong primary drivers to stimulate economic growth in the water management area. Potential for growth may be found in the agricultural sector converting to higher value products, such as from grain to orchard crops and cut flowers. Growth in the transport sector, given the strategic central location of Bloemfontein, is likely to be stimulated by increasing economic activity elsewhere in the country (DWAF, 2003).

Demographic projections show a population growth in the Bloemfontein area, whereas the rural population slightly decreases (Theron *et al.*, 2006:298-305).

### 3.2.1.4 Relation of the WMA to other countries
The Upper Orange WMA is part of the Orange River Basin, with South Africa, Lesotho, Botswana, and Namibia, as co-basin countries.

Bilateral arrangements on water issues by South Africa and Lesotho are addressed through the Lesotho Highlands Water Commission, and in terms of the treaty between the countries on the Lesotho Highlands Water Project. Co-operation amongst the Orange River Basin countries is facilitated through the Orange-Senqu River Commission (ORASECOM), with membership by the basin countries (DWAF, 2004a).

### 3.2.1.5 Sub-catchments of the Upper Orange water management area

The WMA shows significant spatial variations in climate, water availability, level, and the nature of economic development and growth, and is therefore divided into smaller catchments. This results in an improved representation of the water resource situation, and allows for the better use of information for strategic management purposes (DWAF, 2004a).

Delineation of the smaller catchments was based on practical considerations such as the size and location of these smaller catchments, homogeneity of natural characteristics, location of pertinent water infrastructure (e.g. dams), and economic development. These smaller catchments have no administrative weighting, and the catchment management agency may later introduce smaller or alternative subdivisions (DWAF, 2004a).

According to DWAF the Upper Orange water management area was divided into secondary catchments comprising the following catchments as used in the NWRS (DWAF, 2004b):
- Catchment of the Caledon River in South Africa (Caledon RSA);
- Catchment of the Kraai River together with that of Orange River between the Lesotho border and the Caledon River confluence (Kraai);
- Orange River catchment between the Caledon confluence and the Vaal River confluence (Vanderkloof);
- Catchment of the Riet River together with Modder tributary (Riet/Modder).

The secondary catchments have been further divided into quaternary catchments. The hydrological sub-catchments showing numbered quaternary sub-catchments, sub-catchment boundaries, rivers, dams, and major towns, are illustrated in Figure 3.3.
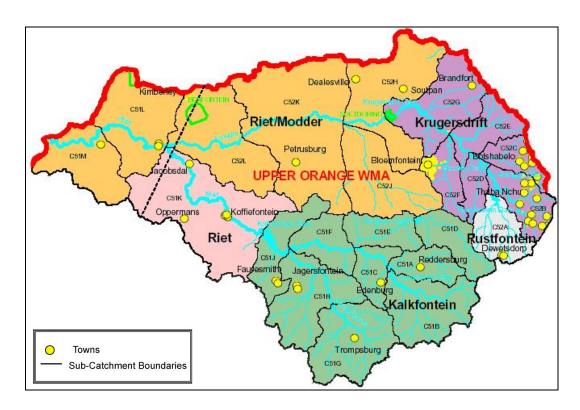


Figure 3.3  Secondary Catchment C5 (Includes the Riet, Riet/Modder, Krugersdrift, Rustfontein and Kalkfontein Sub-Catchments)

To summarise, DWAF (1999:4) defines a catchment as; "an area from which any rainfall will drain into the watercourse or watercourses or part of a watercourse, through surface flow to a common point or points". Catchments are categorised as primary, secondary, tertiary, and quaternary. For example, the Upper Orange water management mainly contains the C5 secondary catchment which in turn contains two tertiary catchments (C51 and C52). The two tertiary catchments in turn contain quaternary catchments. The C51 tertiary catchment contains the C51A, C51B, C51C, C51D, C51E, C51F, C51G, C51H, C51J, C51K, C51L, and C51M quaternary catchments and the

C51 tertiary catchment the C52A, C52B, C52C, C52D, C52E, C52F, C52G, C52H, C52J, C52K, C52L quaternary catchments. The reason behind the smaller catchments is to ensure that water resources are more manageable.

### 3.2.1.6 Secondary Catchment C5

Data (environmental and non-environmental) that has an influence on the secondary catchment C5 will be gathered from different sources and systems and will be entered into the newly created geodatabase for simulation and estimation purposes.

### 3.2.1.7 Water Resources used by the Secondary Catchment C5

All the sub-catchments have different water requirements with water being supplied by one or more water resources. These sub-catchments may get their water from water bodies (Bloem Water), pipelines, boreholes, groundwater, dams and canals. Table 3.1 gives a summary of the towns/districts with adequate water resources in the sub-catchments (with their corresponding quaternary catchments) of the secondary catchment C5 (DWAF, 2004a).

Table 3.1  Summary of sub-catchments and towns with adequate water

resources

| NAME OF TOWN | QUARTERNARY CATCHMENT | KEY NOTES |
|---|---|---|
| **Kalkfontein Sub-catchment** | | |
| Reddersburg/Matoporong | C51A | Caledon/Modder system Bloem Water & supplemented from boreholes |
| Edenburg/Ha-rasebei | C51C | Caledon/Modder system Bloem Water & supplemented from groundwater |
| Trompsburg/Madikgetla | C51G | Pipeline from Gariep Dame operated by Bloem Water & supplemented by groundwater |
| **Riet Sub-catchment** | | |
| Koffiefontein/Ditlhake | C51K | Vanderkloof Dam via Orange Riet Canal & supplemented from groundwater |
| Jacobsdal/Ratanang | C51K | Vanderkloof Dam via Orange Riet Canal & supplemented from boreholes |

| Oppermansgronde | C51K | Boreholes, bulk supply from Orange-Riet Canal |
|---|---|---|
| **Riet/Moddel Sub-catchment** | | |
| Ritchie/Motswedimosa | C51L | Vanderkloof Dam via Orange-Riet Canal |
| Bloemspruit/Bainsvlei | C52H | Caledon/Modder system Bloem Water |
| Soutpan/Ikgomotseng | C52H | Located about 15km North of Krugersdrift Dam no major tributary or river nearby.  Bulk supply from Krugersdrift Dam |
| **Rustfontein Sub-catchment** | | |
| Dewetsdorp/Morojaneng | C52A | Caledon/Modder system Bloem Water |
| **Krugersdrift Sub-catchment** | | |
| Botshabelo | C52B | Caledon/Modder system Bloem Water |
| Thaba „Nchu | C52B | Caledon/Modder system Bloem Water & Groothoek Dam |
| Bloemfontein/Mangaung | C52F | Caledon/Modder system Bloem Water |
| Brandfort/Majwemasweu | C52G | Sand-Vet GWS |

## 3.2.2  Future study area

After the successful creation, testing, and implementation, of the new geodatabase and modelling framework environment the rest of the WMAs data will be systematically entered into the geodatabase.  Decision making scenarios, simulations, and estimations, may then be conducted for the rest of the WMAs.

Data will be gathered and entered in the following order:
  * the rest of the secondary catchments that fall within the Upper Orange WMA;
  * all the secondary catchments that form part of the Middle Vaal WMA;
  * and eventually the catchment data of the 18 remaining WMAs.

# CHAPTER 4 – RESULTS & DISCUSSION

After the literature review on the data models and hydrological modelling frameworks, the following requirements for to the new modelling environment and geodatabase were identified:

- ArcHydro would be used as example data model to assist in the design of the new geodatabase;
- UML would be used as design tool to design the proposed geodatabase;
- a personal geodatabase would be created in ArcCatalog from the generated XML Schema (this database is limited to 4 GB in size with up to 4 concurrent users);
- data would be collected from HYDSTRA and other providers for the geodatabase;
- some of the hydrological processes available in Basins and ArcHydro should be used with the data from the geodatabase;
- future changes or additions, to entities and attributes inside the geodatabase, should be possible.

## 4.1 HYDROLOGICAL MODELLING ENVIRONMENT

An environment should be created to facilitate the transfer of data between data models and hydrological modelling frameworks. Data from different sources (DWAF, Weather SA, Hydstra, etc.) should be stored in a central location (geodatabase), and should allow users to perform general simulations or allow other modelling processes (Basins and ArcHydro) to perform simulations on the data.

Figure 4.1 presents an illustrative diagram of the modelling environment.

Figure 4.1  Modelling environment

The core of the hydrological environment consists of a geodatabase that contains information from various sources, ranging from DWAF, Stats SA, the Weather Bureau and various other sources.  The recorded information should be accessible in a suitable GIS package and allow different hydrological modelling frameworks (BASINS) to have access to this data.   These hydrological modelling frameworks may then perform hydrological processes, specific to them, by making use of the data.

After discussion with various specialists, changes were suggested for the modelling environment.  The changes were mainly made due to new projects currently undertaken by DWAF and other stakeholders.  Figure 4.2 presents an illustrative diagram of the changed modelling environment.

Figure 4.2  Changed modelling environment

BASINS was originally considered as a hydrological modelling framework to assist in performing hydrologic functions, but after discussions with various specialists it was decided to rather consider the WRSM and WRYM models. The WRSM and WRYM models were not originally included in the research project and further investigation into the working of these models should be performed in order to determine whether additional features or object classes should be added to the geodatabase.  Section 4.3.2 of this Chapter explains the process of adding features and object classes to the geodatabase.

## 4.2 GEODATABASE DESIGN

### 4.2.1 Identifying the datasets

Traditionally, data was stored in spreadsheet programs. Although spreadsheets operate in a manner that is relatively straightforward and easy to comprehend, they were not intended as a storage tool for large amounts of data. To keep data organised in a spreadsheet, separate files were often created by users to keep the data from various locations (places), years, and types of data (e.g., catchments, stations, rivers, and dams). This resulted in an ever-increasing number of files, each of which had to be individually managed when new data was added or when new calculations were performed and the results were saved. The use of a RDMS will provide for a more flexible and locally manageable system to solve these data management problems. If suitable table structures and database design techniques are used, decreased data storage size, decreased data retrieval times, and inclusion of new data is easily achieved. This increases data accuracy by providing one central data source, thereby eliminating the need for error prone cutting and pasting operations done by multiple users (Carleton *et al.*, 2005: 394).

Different data (Temperature, Evaporation, Rainfall, Dams, Catchments, WMAs, etc.) has been identified by the different specialists and will be included in the new modelling environment to assist with decision making. Appendix B includes a list of the entities that has been identified. Included are the names for the different entities, their fields, a short description of each, as well as decisions, taken by the specialists, which might affect the characteristics of a particular entity.

For this study, only the entities that are specified in Appendix C will be implemented in the newly created modelling environment. The additional entities will be added at a later stage.

## 4.2.2  Use the previously created ER-Diagram

An Extended Relationship Model (ERM) was created to represent the conceptual database schema (Rob and Coronel, 2004: 549).  This was done by creating an Entity-Relationship Diagram (ERD) that depicts the standardised graphical notation of the database (Rob and Coronel, 2004: 45).  The idea behind the ERM is the representation of real world objects through entities and relationships between these entities.  An entity is either a physical or an abstract object of the real world that may be clearly identified by its attribute values (Rob and Coronel, 2004: 549).

After the data was gathered from the different sources (DWAF, Stats SA, the Weather Bureau, etc.) it was grouped into entity types, and given descriptive names to identify them later.  An analysis of .dbf files gave an indication of possible attributes that belong to each entity type.

It was evident, from the start, that the names given to attributes and entity types were not always meaningful, due to missing metadata.  This had to be solved by communicating with specialists from different organisations.  Feedback was slow, and in some cases took up to five weeks.  Approximately only half of the gathered attributes could be clarified in this manner.

Meetings were held with the different specialists to discuss which entities and attributes to include, and what the relationships between these entities should be.

The full ER-Diagram created from discussions during these meetings is presented in Appendix A of this dissertation.

## 4.3 GEODATABASE CREATION

A geodatabase may be created in various ways, for example; by creating a UML design of it or by creating it directly in ESRI's ArcCatalog application. One of the requirements specified by specialists was that changes should be easily made to the geodatabase, and for this reason it was decided to use the first approach.

### 4.3.1 Understanding UML

UML may be defined as a non-proprietary specification language for object modelling. UML is a general-purpose modelling language that includes a standardised graphical notation used to create an abstract model of a system, referred to as a UML model. UML is extendable as it offers a profile mechanism for customisation. UML is officially defined at the Object Management Group (OMG) by the UML metamodel – a Meta-Object Facility metamodel (MOF). Like other MOF-based specifications, the UML metamodel and UML models may be serialised in XMI (XML Metadata Interchange). While UML was designed to specify, visualise, construct, and document, software-intensive systems, UML is not restricted to modelling software. UML is also used for business process modelling, systems engineering modelling, and representing organisational structures (Bell, 2003).

In 1994, the authors of the three dominant systems (James Rumbaugh's OMT – Object Modelling Technique, Grady Booch's Booch method and Ivar Jacobson's OOSE – Object-oriented Software Engineering) came together and unified their models to collectively refer to their methodologies as the *Three Amigos*. In 1996 they decided that a Unified Modelling Language was more viable than a Unified Method, and redirected their efforts to respond to the OMG Request for Proposal (RFP) for an object modelling language (Bell,

2003). In 1997 the Unified Modelling Language (UML) specification was released (Bell, 2003; Davis, 2000: 29). UML is a standard language for writing software blueprints using object-oriented techniques (Booch *et al.*, 1999).

UML provides the user with nine different types of diagrams, ranging from class diagrams to deployment diagrams (Bezivin & Muller, 1998). ArcGIS uses class diagrams to create custom features. For example, a combination of UML's class and package diagrams were used to create the features of the ArcHydro data model. A class diagram describes the static structure of a model, and a package diagram, which is a collection of class diagrams, brings together related groups to minimise dependences (Smartdraw, 2006). Custom Features and Object Classes are presented as nodes in the static structure diagram, and arcs exhibit the relationships between classes (Maidment, 2002:27). The package diagrams create the Feature Datasets of the geodatabase by bringing together related Features.

The class diagram allows for the object model to be specified, but it does not create the code that will inform ArcGIS which classes possess certain attributes or methods. An add-on tool within the CASE program provides a mechanism to export the UML design into a Microsoft Repository format, which is an industry wide standard. ArcCatalog reads the Microsoft Repository format, using the Schema Creation Wizard, and generates the corresponding geodatabase (Maidment, 2002:179-186).

## 4.3.2  Creating the Geodatabase in Microsoft Visio Professional 2003 (Case Tool)

The following steps were followed in order to create the Geodatabase for the C5 secondary catchment by making use of Microsoft Visio Professional 2003.

Step 1 :  Creating an empty geodatabase in ArcInfo

The geodatabase will contain one or more feature datasets (which contain feature classes to capture the spatial data) and object classes (which contain non-spatial data).   The geodatabase will be generated from the XMI file through the Schema Wizard in ArcCatalog.
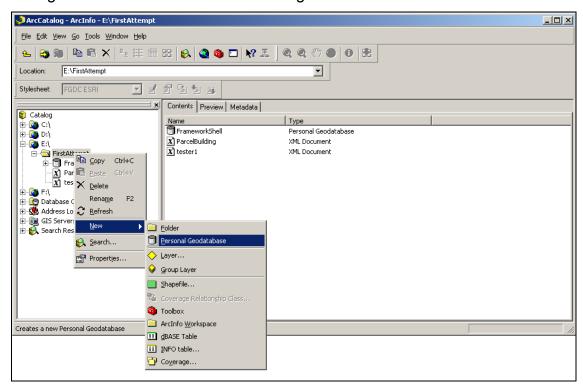


Figure 4.3  Creating the geodatabase in ArcCatalog

Step 2 : Using the ArcInfo UML Model (2003) as starting point.

ESRI provides a template UML model that contains the necessary ESRI classes and interfaces needed in order to create a custom geodatabase.  This UML model template may be obtained from the ESRI website.  Figure 4.4 shows the UML model when it is opened in Microsoft Visio Professional 2003. In the Model Explorer structure the ESRI classes and data types may clearly be seen.  These are used in order to create the UML design for the new geodatabase.

Figure 4.4  ArcInfo UML Model (2003) opened in Visio Professional 2003

Step 3 : Creating class packages

Create a feature dataset package and user-defined (object) package that will
contain all the spatial (feature classes) and non-spatial entities (user-defined)
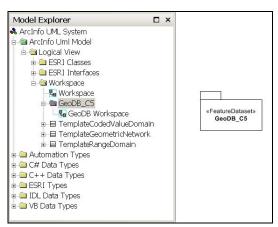for the geodatabase.



Figure 4.5  GeoDB_C5 Package (Feature Dataset)

Step 4 : Creating the necessary entities and associate them with the appropriate ESRI classes.

Entities were created for the information (entities) identified previously. A list of entities may be seen in Appendix B and C of this dissertation. Entities were associated with the following ESRI classes; Simple Feature Classes, Network Feature Classes, and Object Classes. Figures 4.6 and 4.7 present the entities with their respective associations to the different ESRI classes. Enlarged representations of both figures are available in Appendices F and G of this dissertation.



Figure 4.6  Subset of simple feature and network feature classes as created in the Feature Dataset Package

Figure 4.7  Subset of object classes (user-defined entities)

It should be noted that difficulties were encountered during the semantics checking of the Network Feature Classes, and only Simple Feature and Object Classes were subsequently used.  Difficulties experienced with some of the ESRI classes are discussed in more detail in Section 4.3.3.

Step 5 : Creating the relationships between the entities (associations).

After the creation of the entities, the necessary relationships (binary associations) between entities were created.  These relationships indicate how entities with their related information relate to each other.

Figure 4.8 shows a small subset of entities (Catchments, Rivers and Contours) and how they relate to one another.  Additional information is also indicated with the relationship, for example, a Catchment may have zero or many Rivers (0..*) and a River has one or many Catchments (1..*).
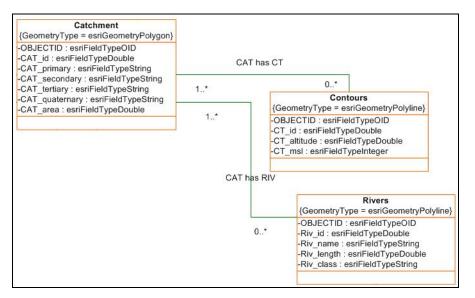
Figure 4.8  Relationships between different entities

Step 6 : Generating the XMI (XML-based) file to create a schema to generate the geodatabase in ArcCatalog

An ESRI XMI file should be created from the UML design of the geodatabase. This XML-based file will then be used to generate the geodatabase in ArcCatalog.  This add-on tool is available after installing the ESRI suite of applications or may be downloaded and installed from Microsoft's website.
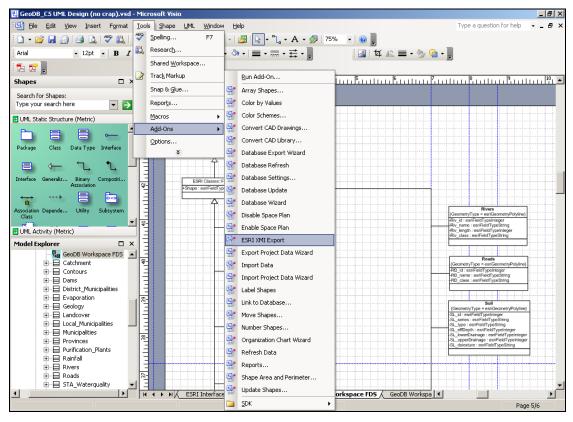
Figure 4.9  Generating the XMI file

Step 7 : Testing the UML model by using the Semantics Checker

After the generation of the XMI file it is recommended to check the UML design to ensure that all entities, class associations and relationships will be created successfully when the geodatabase is generated in ArcCatalog.  This may be done by running the ESRI Semantics Checker macro in Microsoft Visio Professional 2003.
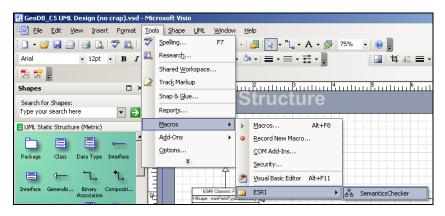


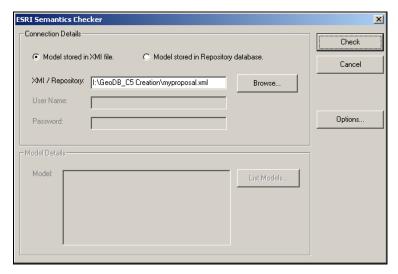Figure 4.10  Performing the Semantics Checker

Figure 4.11  Selecting the previously generated XMI file

Step 8 : Ensuring that the new geodatabase was generated without problems

The log file created from the schema generation and Visio Professional Semantics Checker indicates whether model errors occurred.  During the first few attempts errors were reported due to invalid tagged values, as well for entities that were created as Edge and Junction Feature classes.  The errors have been fixed by making changes to the UML design.  Section 4.3.3 provides a summary of some of the problems/errors encountered, and how they were solved.



Figure 4.12  Summary of Semantics Checking

A complete generation report is available in Appendix E of this dissertation.

## 4.3.3  Difficulties encountered during the generation of the Geodatabase

A number of changes had to be made to the geodatabase UML design due to the following reasons:

ESRI class types

It has been indicated by the specialists that certain entities should be associated with specific ESRI class types.  For example, the Rivers, Roads, and Soil type entities, should be associated with the ESRI Simple Edge Feature class type, Contours should be associated with the ESRI Complex Edge Feature class type, and Towns should be associated with the ESRI Complex Junction Feature class type.  These class types were originally associated with the entities in the UML design.  They generated various errors indicating that OBJECTID's should be specified for each of these entities, and when they were added the Checker complained and indicated that duplicate OBJECTID's existed.  Other errors indicated that geometric networks should be specified for the entities.

After consideration it was decided to change the entities to basic Feature Classes.  No errors were generated and the UML design allowed for the successful creation of the geodatabase.

Relationships between entities

Another problem that was encountered was the creation of relationships between the different entities located in different packages.  Entities were either categorised as a Feature or Object class.  Each of these types was contained in a separate package, and establishing the relationships between these entities was difficult and could not clearly be indicated in the original UML design.

A new UML design was created and the Objects classes were copied to the package that contained the Feature classes.  The necessary entity relationships were then created and the geodatabase was created successfully.

## 4.3.4  Geodatabase – Final UML Diagram

Figure 4.13 shows the final UML diagram that was used to generate the geodatabase.  An enlarged representation is available in Appendix D of this dissertation.

The orange blocks indicate Feature Classes with a generalisation link to its parent class (ESRI Classes: Feature), the grey blocks indicate Object Classes with a generalisation link to its parent class (ESRI Classes: Object).  Finally the green lines indicate binary associations which indicate inter-relationships between entities.
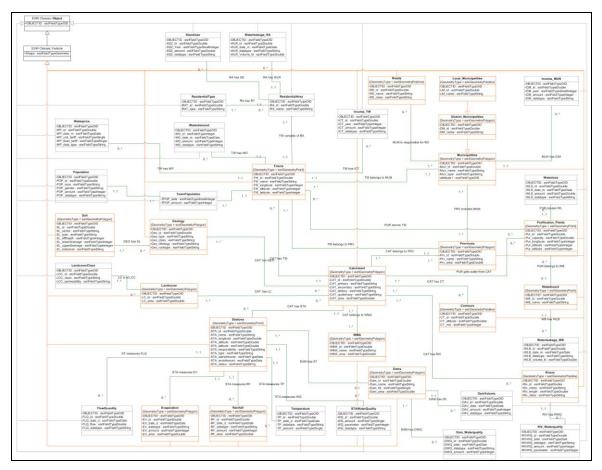


Figure 4.13  Final UML design (geodatabase)

### 4.3.5 Geodatabase – Implemented in ArcGIS

Figure 4.14 represent the entities (feature and object classes) as they appear in ArcCatalog. From Figure 4.14, the name of the entity may be clearly identified, as well as an icon that indicates whether the entity has a geometry type of polyline, polygon, or point.
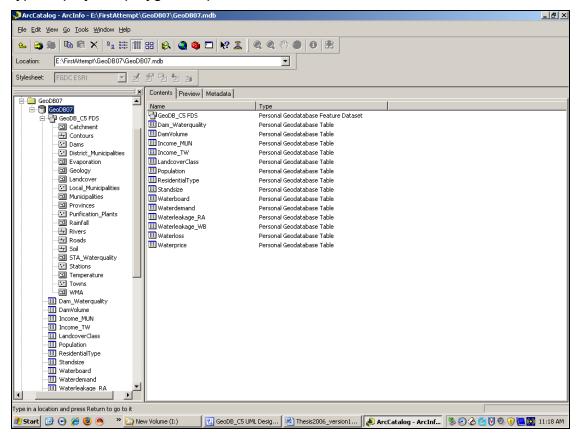


Figure 4.14  Entities represented in ArcCatalog

## 4.4  GEODATABASE DATA

None of the data was on hand in the beginning, and it had to be requested from several organisations and other sources. The focus of the geodatabase is to capture data about the C5 catchment area and how information relates to this catchment; for example, soil, land cover, contour lines, WMA's, etc. Additional information was also recorded, for example, data gathered from

monitoring stations; which include data about rainfall, evaporation, temperature, and water and flow quality.

It is important to realise that the gathering of data is an ongoing process which will never be fully completed. The environment is constantly changing and so also the parameters of the hydrological environment. As mentioned in Chapter 3, information was gathered from the South African Weather Bureau, DWAF, the Mangaung Municipality in Bloemfontein, and Bloem Water (waterboard). Data was gathered for many of the entities but for some entities data is still outstanding; for example, purification plants, water boards, residential areas, stand size of residential areas, gauging stations, water leakage in residential areas, water leakage in water boards, water loss, water demand, water price, income of towns, income of municipalities, flow quantity, water quality of dams, and the water quality measured at measuring stations.

A major concern with the data that was collected, is the fact that important segments of the data is missing or that attributes are not clearly specified and provides little or no meaning. This resulted in sets of data that could not be used.

Most of the gathered data was in ArcGIS file format. ArcGIS uses five different files for storing geographical data: .dbf, .sbn, .sbx, .shp and .shx. A .dbf-file is basically a table that contains columns for the attributes and different rows for the single object entries. Some .dbf-files contain spatial information and may be categorised as feature classes. The rest of the spatial data is placed in different tables (object classes) that were created by ArcCatalog during the creation of the Geodatabase.

The most extensive data source was the Census 2001 database of Space-Time- Research Pty Ltd. Although a small segment of the census data was needed, it was necessary to install all 12 CD's worth of information about the

South African population.   The files on these CD's are also in the ArcGIS shape file format and may be used in ArcGIS.

## 4.5  LINK BETWEEN THE GEODATABASE AND THE MODELLING ENVIRONMENT

In order to link the geodatabase to the proposed modelling environment certain applications, hydrological modelling frameworks, and data models, should be in place (refer to Figure 4.1 for a graphical representation of the modelling environment).   The data from the geodatabase will be viewable through ESRI's application suite (ArcView is the recommended minimum application needed).    Additional hydrological processing tasks may be performed, but will require that additional applications or modules are installed like ArcHydro or BASINS.   Data may also be imported or exported to the Hydstra data model.   This will, however, require additional data manipulation to ensure that data is in the correct format and layout before such interchange may take place.

# CHAPTER 5 – CONCLUSION & RECOMMENDATIONS

With the geodatabase and hydrological modelling environment in place, testing may take place to ensure that the correct results are delivered to users. Participants of other projects and stakeholders (those that are responsible for water resources management) should work closely with the modelling environment to ensure that it meets the needs originally specified (those needs identified by the research project and those indicated by the Minister of Water Affairs and Forestry).

The literature review regarding current data models, hydrological modelling frameworks, GIS technologies, and ICT developments, provided much needed information about the current technologies available for water management around the world, and in South Africa. By corresponding with other academia (other people in South Africa and abroad), and attending conferences, it became clear that an IS/CMIS should be put in place to assist with the effective management of water resources. The current data models and hydrological modelling frameworks do provide assistance to decision makers but are limited to certain mission specific domains. It also became clear that people around South Africa have certain preferences when it comes to data models and hydrological modelling frameworks, and frequently jump between these data models and hydrological modelling frameworks to solve specific problems.

## 5.1 REVISITING THE OBJECTIVES AND HYPOTHESIS

The objectives and hypothesis set out in Chapter 1 are revisited and an explanation is given to indicate whether these objectives and hypothesis were met.

### 5.1.1 Revisiting objective 1

*To determine whether existing data models and frameworks will provide decision makers (within CMA's and WMA's) with the necessary management and data tools to allow them (the decision makers), to do estimations and simulations in order to make informative decisions.*

From the literature review it became clear that each of these data models and hydrological modelling frameworks do provide mechanisms to assist with the management of data and provide functions that assist with model specific simulations and functions. These data models and hydrological modelling frameworks only partially fulfil the needs of decision makers, and in many instances decision makers will move between different systems in order to gather information (through simulations and estimations) and make more informed decisions.

### 5.1.2 Revisiting objective 2

*If the existing data models and frameworks do not provide the necessary management and data tools, a new modelling environment (framework) will be developed that will allow decision makers (within CMA's and WMA's) to make more informative decisions by implementing this newly created set of management and data tools.*

A modelling environment (CMIS) was designed and developed to ensure that data may be easily transferred between different data models and hydrological modelling frameworks. In addition a geodatabase has been

created to assist the modelling environment and to act as storage medium for the large amounts of data needed in order to perform simulations and estimations, and to subsequently make informed decisions.

### 5.1.3 Revisiting the hypothesis

*Existing data models and frameworks do not fulfil in the needs of managers (within CMA's and WMA's) of the new management process to manage catchments according to the NWRS, and it is therefore necessary to develop a new modelling environment (framework) that complies with the stipulations in the NWRS.*

The hypothesis was met by investigating the data models and hydrological modelling frameworks and identifying certain concerns and problems with them.  This has led to the design and development of the modelling environment.  From the early stages it was evident that the modelling environment needed a centralised storage area, which led to the design and creation of a database (geodatabase).  The geodatabase will, eventually, contain large amounts of information about the various aspects involved in water resources management and other activities that might influence the use and allocation of water (decision making).

## 5.2  RECOMMENDATIONS FOR FUTURE RESEARCH

The following activities should be considered for future research projects:
- The data currently available should be systematically entered into the geodatabase.  Missing data should be gathered, analysed, and entered into the geodatabase.  This process will never be fully completed as data changes on a consistent basis.
- The WRSM, WRYM and SAPWAT models should be further investigated and linked to the modelling environment.  The data needs

of these models should be investigated, and gaps in the geodatabase should be filled by creating new entities, attributes, and relationships.

* The modelling environment and geodatabase should be thoroughly tested to ensure that the design is 100% correct. This testing should be performed by stakeholders that are responsible for water resources management.

* Refinements should be made to the modelling environment (geodatabase) where inconsistencies exist. The UML design should be taken, altered, and an improved geodatabase should be generated.

* The modelling framework should be released to the specialists at the CUT and other stake holders that might be interested to use it.

* A web-based interface should be developed to allow outside members to have access to the geodatabase. The web-based interface should allow users to import and export data in various file formats so that it may be used in other data models and hydrological modelling frameworks.

* The current geodatabase will allow access for a limited number of users and provide storage space of up to 4 GB; if more storage space and simultaneous requests are needed the UML design may be taken and a multi-user geodatabase may be generated. Oracle or any relevant RDBMS may be used for this purpose.

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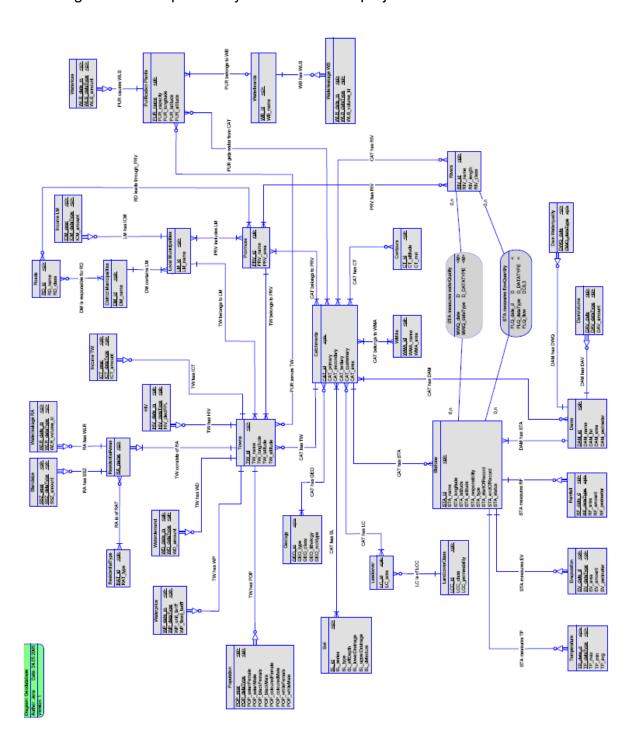WL | DELFT HYDRAULICS.  2005a.  HYMOS – Hydrological Database System.  Netherlands: WL | Delft Hydraulics.  [PowerPoint presentation]. http://www.wldelft.nl/soft/hymos/doc/index.html  Date of access: March 2005.

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# A P P E N D I X   A

ER-Diagram created previously for the research project.

# APPENDIX B

Below is a list of the original data entities and corresponding attributes as identified by specialists for the new geodatabase.

| Name of entity | Fields | | | Description | Decisions taken about this entity |
|---|---|---|---|---|---|
| Catchment | CAT_id<br>CAT_primary<br>CAT_secondary<br>CAT_tertiary<br>CAT_quaternary<br>CAT_area | VARCHAR2(4)<br>CHAR(1)<br>CHAR(1)<br>CHAR(1)<br>CHAR(1)<br>NUMBER(8,5) | \<pk> | A catchment is an area of land that collects water, which drains to the lowest point in that area. A primary catchment consists of many secondary catchments, they consist of many tertiary catchments and they again include quaternaries. Consequently a quaternary catchment is the smallest type of a catchment and a primary the biggest. | The name of a catchment depends on the fact whether it is a quaternary, tertiary, secondary or a primary catchment. The quaternary C52A is located within the tertiary C52, the secondary C5 and the primary C. The value for the attribute quaternary is not set for a tertiary catchment, but the values for primary, secondary and tertiary are. Therefore the CAT_id was introduced to identify the single entities. That means, each catchment entity can be recognised and linked to an entity of another entity-type. Thus, it was not necessary to create four different catchment types. |
| Contours | CT_id<br>CT_altitude<br>CT_msl | INTEGER<br>INTEGER<br>INTEGER | \<pk> | Contours show the elevation changes of the land. Many contour lines indicate an abrupt increase/decrease in height while no contour lines point at a constant level. | A contour line cannot be an attribute of another entity-type in this model. It is an entity-type itself. Contour lines can have the same values. Therefore CT_id had to be added. |
| Dams | DAM_id<br>DAM_name<br>DAM_fsl<br>DAM_area<br>DAM_perimeter | INTEGER<br>VARCHAR2(100)<br>NUMBER(3,2)<br>NUMBER(8,5)<br>NUMBER(9,5) | \<pk> | A dam stores an amount of water. A scale for the maximum amount of water is the full supply level (FSL). | A dam is a geographic object which must be saved as entitytype. Each dam already has an id that can serve as key. |

| DamVolume | DAM_id | INTEGER | <pk,fk> | This table stores the amount of water in a dam. Measurements are taken weekly or monthly (not certain). The data can be based on measurements or on calculations. | The volume of a dam must be stored in a constant period of time, whereas other data on dams stay the same. It would Creation of a Geographic Database for Water Management and Water Harvesting A.15 not is very efficient to store both data within the same entity-type. The attribute dataType determines whether the data are based on measurements or calculations. The key is DAV_date in combination with DAV_dataType and the DAM_id. This is necessary because there can be more entities with the same values for DAV_date and DAV_dataType. |
|---|---|---|---|---|---|
| | DAV_date | DATE | | | |
| | DAV_dataType | CHAR(11) | | | |
| | DAV_amount | INTEGER | | | |
| Dam_Waterquality | DAM_id | INTEGER | <pk,fk> | Different attributes indicate the daily water quality of a dam. The data can be based on measurements or on calculations. | The reason for the existence of this entity-type is basically the same than it is for DamVolume. The attributes for the water quality that have to be stored were unknown until the finishing of this report. |
| | DWQ_date | DATE | <pk> | | |
| | DWQ_dataType | CHAR(11) | <pk> | | |
| District_Municipalities | DM_id | VARCHAR2(5) | <pk> | A district municipality is a large administrative district within one of the provinces. | In this model are district municipalities and local municipalities. The first thought was putting them together and categorise them by means of an attribute. Later on this approach was skipped because of the fact that two single entity-types are easier to model and to implement. The name of District_Municipalities was not chosen as a key, because even the names of provinces were changed in the last years in South Africa. So, if there are any name changes in future, then an ID number is less costly to administer. |
| | DM_name | VARCHAR2(100) | | | |

| Evaporation | STA_id INTEGER <pk,fk><br>EV_date_d DATE <pk><br>EV_dataType CHAR(11) <pk><br>EV_area NUMBER(8,5)<br>EV_amount NUMBER(4,3)<br>EV_perimeter NUMBER(9,5) | Stores the daily amount of evaporation in a certain area measured by an evaporation station. The data can be based on measurements or on calculations. | Evaporation stores data that should be stored separated from the station data. It has its own attributes and the values change in a short period of time, while those of Stations constantly stay the same. The key consists of the Creation of a Geographic Database for Water Management and Water Harvesting A.16<br>date to which EV_amount refers and the attribute dataType. Additionally the station ID is needed, because more entities could be measured or calculated for the same day. |
|---|---|---|---|
| Geology | GEO_id INTEGER <pk><br>GEO_type VARCHAR2(15)<br>GEO_class VARCHAR2(15)<br>GEO_lithology VARCHAR2(250)<br>GEO_rocktype VARCHAR2(100) | Stores data on the geology of a catchment respectively of parts of a catchment. Geology is not limited by the boundaries of a catchment. The number of different geology entities is limited. | A geology entity could also be identified by the combination of all four of its attributes. Instead GEO_id was created to make the management of this entity-type more efficient. |
| Income_LM | LM_id VARCHAR2(5) <pk,fk><br>ICM_year INTEGER <pk><br>ICM_dataType CHAR(11) <pk><br>ICM_amount INTEGER | There are different income data available. Early data refer to towns (Income_TW), whilst newer data refer to local municipalities (Income_LM). The data are yearly and can be based on measurements or on calculations. | One possibility was to put the different income data together in one entity-type and then categorise them with an attribute. This solution is more complex and thus faultprone. For this reason two entity-types were formed. |
| Income_TW | TW_id INTEGER <pk,fk><br>ICT_year INTEGER <pk><br>ICT_dataType CHAR(11) <pk><br>ICT_amount INTEGER | There are different income data available. Early data refer to towns (Income_TW), whilst newer data refer to local municipalities (Income_LM). The data are yearly and can be based on measurements or on calculations. | One possibility was to put the different income data together in one entity-type and then categorise them with an attribute. This solution is more complex and thus faultprone. For this reason two entity-types were formed. |
| Landcover | LC_id INTEGER <pk><br>LCC_id NUMBER(2) <fk><br>LC_area NUMBER(8,5) | The land cover describes the surface of a catchment respectively of parts of a catchment. Landcover is not limited by the boundaries of a catchment. This entity-type is linked to the LandcoverClass. | A catchment can have more than one land cover type. For this reason it was decided to store it as its own entity-type. |

| LandcoverClass | LCC_id NUMBER(2) <pk><br>LCC_class VARCHAR2(30)<br>LCC_permeability VARCHAR2(10) | The LandcoverClass stores the class of the land cover and its permeability. | There are only a limited number of different land cover classes. Therefore it was outsourced from the Landcover entity-type. Since the Landcover entity-type will have thousands of entities, less disc space will be needed storing the landcover class like this. |
|---|---|---|---|
| Local_Municipalities | LM_id VARCHAR2(5) <pk><br>DM_id VARCHAR2(5) <fk><br>LM_name VARCHAR2(100) | A local municipality is a small administrative district within a district municipality. | In this model are district municipalities and local municipalities. The first thought was putting them together and categorise them with help of an attribute. Later on this approach was skipped because of the fact that two single entity-types are easier to model and to implement. The name of Local_Municipalities was not chosen as a key, because even the names of provinces were changed in the last years in South Africa. So, if there are any name changes in future, then an ID number is less costly to administer. |
| Population | TW_id INTEGER <pk,fk><br>POP_year NUMBER(4) <pk><br>POP_dataType CHAR(11) <pk><br>POP_asianFemale VARCHAR2(15)<br>POP_asianMale INTEGER<br>POP_blackFemale INTEGER<br>POP_blackMale INTEGER<br>POP_colouredFemale INTEGER<br>POP_colouredMale INTEGER<br>POP_whiteFemale INTEGER<br>POP_whiteMale INTEGER | This table gives information about the number of people of different races and genders that populated a town in a certain year. | The population and the towns should not be saved together within one entity-type. The reason is that the population changes yearly, while the data for the town stay the same. |
| Provinces | PRV_id VARCHAR2(2) <pk><br>PRV_name VARCHAR2(25)<br>PRV_area NUMBER(8,5) | South Africa is sub-divided into nine provinces. | The names of some provinces in South Africa were changed lately. Therefore PRV_id was chosen as primary key. If the name was the identifier then a change of the name would cause a substantial administration effort. All tables that were linked to this entity-type had to change their foreign key. |
| Purification_Plants | PUR_name VARCHAR2(60) <pk><br>WB_id NUMBER(11) <fk><br>PUR_capacity INTEGER<br>PUR_longitude NUMBER(7,5)<br>PUR_latitude NUMBER(7,5)<br>PUR_altitude INTEGER | A purification plant is responsible for the water treatment. It belongs either to a water board or to a town. | Purification plants have their own attributes and thus their own entity-type. |

| | | | | |
|---|---|---|---|---|
| Rainfall | STA_id      INTEGER    \<pk,fk\><br>RF_date_d    DATE       \<pk\><br>RF_dataType   CHAR(11)    \<pk\><br>RF_area     NUMBER(8,5)<br>RF_amount    NUMBER(4,3)<br>RF_perimeter   NUMBER(9,5) | Stores the daily amount of precipitation in a certain area measured by a rainfall station. The data can be based on measurements or on calculations. | The same reasons that speak for an Evaporation entity-type, do also speak for a Rainfall entity-type. |
| ResidentialAreas | TW_id       INTEGER    \<pk,fk\><br>RA_name     VARCHAR2(80)\<pk\> | A town can consist of residential areas, e.g. industrial area. Each of those can be of one or more types. This entity-type is linked to the ResidentialType entity-type. | The primary identifier for a residential area is its name and the town where it is part of. The fact that the town ID has to be used as part of the key is marked by the type of the relationship between the two entity-types (dependent). |
| ResidentialType | RAT_id      NUMBER(2)     \<pk\><br>RAT_type    VARCHAR2(50) | Stores the different types of residential areas. The single values for RAT_type were not clear until the finishing of this document. | There are only a limited number of different residential area types. Therefore it was outsourced from the ResidentialArea entity-type. Since the ResidentialArea entity-type will have thousands of entities, less disc space will be needed storing the types of the residential areas like this. |
| Rivers | RIV_id       INTEGER      \<pk\><br>RIV_name    VARCHAR2(50)<br>RIV_length    NUMBER(5,2)<br>RIV_class     VARCHAR2(12) | Rivers are categorised into two classes: perennial rivers and non-perennial rivers. | The name is not qualified to identify a river. Therefore RIV_id was created. |
| Roads | RD_id        INTEGER    \<pk\><br>RD_name     VARCHAR2(50)<br>RD_class     CHAR(1) | Roads can be categorised into national roads like the N1, primary roads like R310 and secondary roads. | The name is not qualified to identify a road. Therefore RD_id was created. |
| Soil | SL_id         INTEGER    \<pk\><br>SL_series     VARCHAR2(30)<br>SL_type      VARCHAR2(30)<br>SL_effDepth    INTEGER<br>SL_lowerDrainage   INTEGER<br>SL_upperDrainage   INTEGER<br>SL_dstexture    VARCHAR2(30) | This entity-type stores information about the soil of a catchment respectively of parts of a catchment. Soil is not limited by the boundaries of a catchment. | SL_id was chosen as a key for Soil. Otherwise four attributes were necessary to identify an entity. |
| Standsize | TW_id       INTEGER      \<pk,fk\><br>RA_name     VARCHAR2(80) \<pk,fk\><br>SSZ_year     INTEGER      \<pk\><br>SSZ_dataType   CHAR(11)     \<pk\><br>SSZ_amount   NUMBER(5,3) | Each residential area has a yearly average stand size. The data can be based on measurements or on calculations. | Standsize stores data that change annually whereas the residential areas stay the same. For this reason the entitytype Standsize was created. |

| Station | STA_id | INTEGER | \<pk\> | A station can either be a rainfall station, an evaporation station, a weather station or a flow gauging station. Dependent on the type of the station they measure the daily amount of precipitation, evaporation, average temperature, or water quality and flow quantity of a river. They fall within the responsibility of a certain organisation. | The decision to create only one station entity-type instead of four was made, because all station types have the same attributes except one, the flow gauging stations. The only difference here is STA_status. This attribute is thought to categorise flow gauging stations into temporary measuring points or permanent stations. |
|---|---|---|---|---|---|
| | DAM_id | INTEGER | \<fk2\> | | |
| | CAT_id | VARCHAR2(4) | \<fk1\> | | |
| | STA_name | VARCHAR2(100) | | | |
| | STA_longitude | NUMBER(7,5) | | | |
| | STA_latitude | NUMBER(7,5) | | | |
| | STA_altitude | INTEGER | | | |
| | STA_responsibility | VARCHAR2(30) | | | |
| | STA_type | VARCHAR2(20) | | | |
| | STA_startOfRecord | DATE | | | |
| | STA_endOfRecord | DATE | | | |
| | STA_status | CHAR(9) | | | |
| Temperature | STA_id | INTEGER | \<pk,fk\> | Stores the daily average of the temperature in a certain area measured by a weather station. The data can be based on measurements or on calculations. | The same reasons that speak for an Evaporation entity-type, do also speak for a Temperature entity-type. |
| | TP_date_d | DATE | \<pk\> | | |
| | TP_dataType | CHAR(11) | \<pk\> | | |
| | TP_amount | DC2, 1 | | | |
| Towns | TW_id | INTEGER | \<pk\> | All towns must be stored in the database. | The name of Towns is not a unique identifier. This is why TW_id was created. |
| | PRV_id | VARCHAR2(2) | \<fk3\> | | |
| | LM_id | VARCHAR2(5) | \<fk2\> | | |
| | CAT_id | VARCHAR2(4) | \<fk1\> | | |
| | TW_name | VARCHAR2(80) | | | |
| | TW_longitude | NUMBER(7,5) | | | |
| | TW_latitude | NUMBER(7,5) | | | |
| | TW_altitude | INTEGER | | | |
| Waterboards | WB_id | NUMBER(11) | \<pk\> | A water board is a company that provides towns and local municipalities with water. | Waterboards forms its own entity, because it has its own attributes. As identifier serves an ID number instead of the name. |
| | WB_name | VARCHAR2(60) | | | |
| Waterdemand | TW_id | INTEGER | \<pk,fk\> | Each town has a certain monthly demand of water. The data can be based measurements or on calculations. | The data which is stored in Waterdemand change monthly, whereas the data for the towns stay the same. For this reason the entity-type Waterdemand was created. |
| | WD_date_m | DATE | \<pk\> | | |
| | WD_dataType | CHAR(11) | \<pk\> | | |
| | WD_amount | INTEGER | | | |
| Waterleakage_RA | TW_id | INTEGER | \<pk,fk\> | The pipelines in a residential area can cause water leakage. The data are monthly and can be either based on measurements or on calculations. | Waterleakage_RA stores data that change monthly whereas the residential areas stay the same. For this reason the entity-type Waterleakage_RA was created. |
| | RA_name | VARCHAR2(80) | \<pk,fk\> | | |
| | WLR_date_m | DATE | \<pk\> | | |
| | WLR_dataType | CHAR(11) | \<pk\> | | |
| | WLR_volume_kl | INTEGER | | | |
| Waterleakage_WB | WB_id | NUMBER(11) | \<pk,fk\> | A water board must deal with water leakage in its pipelines. The data are monthly and can be either based on measurements or on calculations. | Waterleakage_WB stores data that changes monthly whereas the water boards stay the same. For this reason the entity-type Waterleakage_WB was created. |
| | WLB_date_m | DATE | \<pk\> | | |
| | WLB_dataType | CHAR(11) | \<pk\> | | |
| | WLB_volume_kl | INTEGER | | | |

| Waterloss | PUR_name VARCHAR2(60) <pk,fk><br>WLS_date_m DATE <pk><br>WLS_dataType CHAR(11) <pk><br>WLS_amount INTEGER | A purification plant loses water during the purification process. This monthly amount is stored in the water loss table. The data can be based on measurements or on calculations. | Waterloss stores data that change monthly whereas the purification plants stay the same. For this reason the entitytype Waterloss was created. |
|---|---|---|---|
| Waterprice | TW_id INTEGER <pk,fk><br>WP_date_m DATE <pk><br>WP_dataType CHAR(11) <pk><br>WP_unit_tariff NUMBER(2,2)<br>WP_fixed_tariff NUMBER(8,2) | The monthly price for water can differ from town to town. The data can be based on measurements or on calculations. | The data which are stored in Waterprice changes monthly, whereas the data for the towns stay the same. For this reason the entity-type Waterprice was created. |
| WMAs | WMA_id INTEGER <pk><br>WMA_name VARCHAR2(80)<br>WMA_area NUMBER(8,5) | South Africa is divided into 19 Water Management Areas (WMA). | WMA already provides an ID number, so it was used as primary identifier rather than the name. |

# A P P E N D I X   C

List of the data entities identified for the new geodatabase/new modelling framework (spatial type and corresponding ArcGIS type).

| Entity | Spatial Type | ArcGIS type |
| --- | --- | --- |
| Catchments | area | polygon feature (planar topology) |
| Contours | line | complex edge feature |
| DAM Waterquality | object | object |
| Dams | point | point feature |
| DamVolume | object | object |
| District Municipality | area | polygon feature (planar topology) |
| Evaporation | area | polygon feature (planar topology) |
| Geology | surface | raster |
| Income MUN | object | object |
| Income TW | object | object |
| Landcover | surface | raster |
| LandcoverClass | object | object |
| Local Municipality | area | polygon feature (planar topology) |
| Population | object | object |
| Provinces | area | polygon feature (planar topology) |
| Purification Plant | point | point feature |
| Rainfall | area | polygon feature (planar topology) |
| ResidentialArea | area | polygon feature (planar topology) |
| ResidentialType | object | object |
| Rivers | line | simple edge feature |
| Roads | line | simple edge feature |
| Soil | surface | raster |
| Standsize | object | object |
| Stations | point | point feature |
| Temperature | object | object |
| Towns | point | complex junction feature |
| Waterboard | object | object |
| Waterdemand | object | object |
| Waterleakage RA | object | object |
| Waterleakage WB | object | object |
| Waterloss | object | object |
| Waterprice | object | object |
| WMA | area | polygon feature (planar topology) |
| WQ Measuring Sites | point | point feature |

# APPENDIX D

Completed UML design for proposed Geodatabase (Divided into two segments).

Diagram — ESRI geodatabase entity-relationship model

**Roads**
{GeometryType = esriGeometryPolyline}
-OBJECTID : esriFieldTypeOID
-RD_id : esriFieldTypeDouble
-RD_name : esriFieldTypeString
-RD_class : esriFieldTypeString

**Local_Municipalities**
{GeometryType = esriGeometryPolyline}
-OBJECTID : esriFieldTypeOID
-LM_id : esriFieldTypeDouble
-LM_name : esriFieldTypeString

**Income_MUN**
-OBJECTID : esriFieldTypeOID
-ICM_id : esriFieldTypeDouble
-ICM_year : esriFieldTypeSmallInteger
-ICM_amount : esriFieldTypeInteger
-ICM_datatype : esriFieldTypeString

**...ialArea**
...FieldTypeOID
...TypeDouble
...FieldTypeString

**Income_TW**
-OBJECTID : esriFieldTypeOID
-ICT_id : esriFieldTypeDouble
-ICT_year : esriFieldTypeInteger
-ICT_amount : esriFieldTypeInteger
-ICT_datatype : esriFieldTypeString

**District_Municipalities**
{GeometryType = esriGeometryPolygon}
-OBJECTID : esriFieldTypeOID
-DM_id : esriFieldTypeDouble
-DM_name : esriFieldTypeString

**Municipalities**
{GeometryType = esriGeometryPolygon}
-OBJECTID : esriFieldTypeOID
-Mun_id : esriFieldTypeDouble
-Mun_name : esriFieldTypeString
-Mun_type : esriFieldTypeString
-attribute1 : esriFieldTypeOiD

**Waterloss**
-OBJECTID : esriFieldTypeOID
-WLS_id : esriFieldTypeDouble
-WLS_date_m : esriFieldTypeDate
-WLS_amount : esriFieldTypeDouble
-WLS_datatype : esriFieldTypeString

**Purification_Plants**
{GeometryType = esriGeometryPoint}
-OBJECTID : esriFieldTypeOID
-Pur_id : esriFieldTypeDouble
-Pur_capacity : esriFieldTypeDouble
-Pur_longitude : esriFieldTypeInteger
-Pur_altitude : esriFieldTypeInteger
-Pur_latitude : esriFieldTypeInteger

**Provinces**
{GeometryType = esriGeometryPolygon}
-OBJECTID : esriFieldTypeOID
-Prv_id : esriFieldTypeDouble
-Prv_name : esriFieldTypeString
-Prv_area : esriFieldTypeDouble

**Catchment**
{GeometryType = esriGeometryPolygon}
-OBJECTID : esriFieldTypeOID
-CAT_id : esriFieldTypeDouble
-CAT_primary : esriFieldTypeString
-CAT_secondary : esriFieldTypeString
-CAT_tertiary : esriFieldTypeString
-CAT_quaternary : esriFieldTypeString
-CAT_area : esriFieldTypeDouble

**Waterboard**
{GeometryType = esriGeometryPoint}
-OBJECTID : esriFieldTypeOID
-WB_id : esriFieldTypeDouble
-WB_name : esriFieldTypeString

**Contours**
{GeometryType = esriGeometryPolyline}
-OBJECTID : esriFieldTypeOID
-CT_id : esriFieldTypeDouble
-CT_altitude : esriFieldTypeDouble
-CT_msl : esriFieldTypeInteger

**WMA**
{GeometryType = esriGeometryPolygon}
-OBJECTID : esriFieldTypeOID
-WMA_id : esriFieldTypeDouble
-WMA_name : esriFieldTypeString
-WMA_area : esriFieldTypeDouble

**Waterleakage_WB**
-OBJECTID : esriFieldTypeOID
-WLB_id : esriFieldTypeDouble
-WLB_date_m : esriFieldTypeDate
-WLB_datatype : esriFieldTypeString
-WLB_volume_kl : esriFieldTypeDouble

**Dams**
{GeometryType = esriGeometryPolygon}
-OBJECTID : esriFieldTypeOID
-Dam_id : esriFieldTypeDouble
-Dam_name : esriFieldTypeString
-Dam_fsl : esriFieldTypeSingle
-Dam_area : esriFieldTypeDouble

**Rivers**
{GeometryType = esriGeometryPolyline}
-OBJECTID : esriFieldTypeOID
-Riv_id : esriFieldTypeDouble
-Riv_name : esriFieldTypeString
-Riv_length : esriFieldTypeDouble
-Riv_class : esriFieldTypeString

**DamVolume**
-OBJECTID : esriFieldTypeOID
-DAV_id : esriFieldTypeDouble
-DAV_date : esriFieldTypeDate
-DAV_amount : esriFieldTypeInteger
-DAV_datatype : esriFieldTypeString

**...Temperature**
...FieldTypeOID
...FieldTypeDouble
... : esriFieldTypeDate
...e : esriFieldTypeString
...t : esriFieldTypeSingle

**STAWaterQuality**
-OBJECTID : esriFieldTypeOID
-WQ_id : esriFieldTypeDouble
-WQ_amount : esriFieldTypeSingle
-WQ_parameter : esriFieldTypeInteger
-WQ_datatype : esriFieldTypeString

**Dam_Waterquality**
-OBJECTID : esriFieldTypeOID
-DWQ_id : esriFieldTypeDouble
-DWQ_date : esriFieldTypeDate
-DWQ_datatype : esriFieldTypeString
-DWQ_amount : esriFieldTypeInteger

**RIV_Waterquality**
-OBJECTID : esriFieldTypeOID
-RIVWQ_id : esriFieldTypeDouble
-RIVWQ_date : esriFieldTypeDate
-RIVWQ_datatype : esriFieldTypeString
-RIVWQ_amount : esriFieldTypeInteger
-RIVWQ_parameter : esriFieldTypeInteger

Relationship labels:
- MUN is responsible for RD
- MUN has ICM
- TW has ICT
- TW belongs to MUN
- ...sts of RA
- PRV includes MUN
- PUR causes WL
- PUR serves TW
- TW belongs to PRV
- CAT belongs to PRV
- PUR gets water from CAT
- PUR belongs to WB
- CAT has CT
- WB has WLB
- ...T has STA
- CAT belongs to WMA
- DAM has ST
- CAT has RIV
- DAM has DV
- ...s WQ
- DAM has DWQ
- RIV has RWQ

# APPENDIX E

Report Generated by ArcCatalog during the creation of the geodatabase.

```
Target database:
E:\FirstAttempt\GeoDB07\GeoDB07.mdb

-----------------------------------
Objects created at the workspace
level.
-----------------------------------


   ---------------
   Feature classes

  Feature class: ResidentialType
    ResidentialType is an object
class (table)
    Behavior class:
esriGeoDatabase.Object

     ------
     Fields
       Field: OBJECTID
         Type: Object ID
         Is Nullable: No
       Field: RAT_id
         Type: Float
         Is Nullable: Yes
         Precision: 0
         Scale: 0
       Field: RAT_type
         Type: String
         Is Nullable: Yes
         Length: 0

  Feature class: Dam_Waterquality
    Dam_Waterquality is an object
class (table)
    Behavior class:
esriGeoDatabase.Object

     ------
     Fields
       Field: OBJECTID
         Type: Object ID
         Is Nullable: No
       Field: DWQ_id
         Type: Long Integer
         Is Nullable: Yes
         Precision: 0
       Field: DWQ_date
         Type: Date
         Is Nullable: Yes
       Field: DWQ_datatype
         Type: String
         Is Nullable: Yes
         Length: 0
       Field: DWQ_amount
         Type: Long Integer
         Is Nullable: Yes
```

```
         Precision: 0

  Feature class: Income_TW
    Income_TW is an object class
(table)
    Behavior class:
esriGeoDatabase.Object

     ------
     Fields
       Field: OBJECTID
         Type: Object ID
         Is Nullable: No
       Field: ICT_id
         Type: Long Integer
         Is Nullable: Yes
         Precision: 0
       Field: ICT_year
         Type: Long Integer
         Is Nullable: Yes
         Precision: 0
       Field: ICT_amount
         Type: Long Integer
         Is Nullable: Yes
         Precision: 0
       Field: ICT_datatype
         Type: String
         Is Nullable: Yes
         Length: 0

  Feature class: Waterdemand
    Waterdemand is an object class
(table)
    Behavior class:
esriGeoDatabase.Object

     ------
     Fields
       Field: OBJECTID
         Type: Object ID
         Is Nullable: No
       Field: WD_id
         Type: Long Integer
         Is Nullable: Yes
         Precision: 0
       Field: WD_date_m
         Type: Date
         Is Nullable: Yes
       Field: WD_amount
         Type: Long Integer
         Is Nullable: Yes
         Precision: 0
       Field: WD_datatype
         Type: String
         Is Nullable: Yes
         Length: 0

Feature class: LandcoverClass
```

```
    LandcoverClass is an object          Field: WLS_date_m
class (table)                              Type: Date
    Behavior class:                        Is Nullable: Yes
esriGeoDatabase.Object                 Field: WLS_amount
                                           Type: Long Integer
    ------                                 Is Nullable: Yes
    Fields                                 Precision: 0
      Field: OBJECTID                    Field: WLS_datatype
        Type: Object ID                    Type: String
        Is Nullable: No                    Is Nullable: Yes
      Field: LCC_id                        Length: 0
        Type: Long Integer
        Is Nullable: Yes
        Precision: 0                 Feature class: Waterboard
      Field: LCC_class                   Waterboard is an object class
        Type: String                 (table)
        Is Nullable: Yes                 Behavior class:
        Length: 0                    esriGeoDatabase.Object
      Field: LCC_permeability
        Type: String                      ------
        Is Nullable: Yes                  Fields
        Length: 0                         Field: OBJECTID
                                            Type: Object ID
                                            Is Nullable: No
  Feature class: Income_MUN               Field: WB_id
    Income_MUN is an object class           Type: Long Integer
(table)                                     Is Nullable: Yes
    Behavior class:                         Precision: 0
esriGeoDatabase.Object                    Field: WB_name
                                            Type: String
    ------                                  Is Nullable: Yes
    Fields                                  Length: 0
      Field: OBJECTID
        Type: Object ID             Feature class: Waterleakage_RA
        Is Nullable: No                 Waterleakage_RA is an object
      Field: ICM_id                 class (table)
        Type: Long Integer             Behavior class:
        Is Nullable: Yes            esriGeoDatabase.Object
        Precision: 0
      Field: ICM_year                     ------
        Type: Long Integer                Fields
        Is Nullable: Yes                  Field: OBJECTID
        Precision: 0                        Type: Object ID
      Field: ICM_amount                     Is Nullable: No
        Type: Long Integer                Field: WLR_id
        Is Nullable: Yes                    Type: Long Integer
        Precision: 0                        Is Nullable: Yes
      Field: ICM_datatype                   Precision: 0
        Type: String                      Field: WLR_date_m
        Is Nullable: Yes                    Type: Date
        Length: 0                           Is Nullable: Yes
                                          Field: WLR_datatype
  Feature class: Waterloss                  Type: String
    Waterloss is an object class            Is Nullable: Yes
(table)                                     Length: 0
    Behavior class:                       Field: WLR_Volume_kl
esriGeoDatabase.Object                      Type: Long Integer
                                            Is Nullable: Yes
    ------                                  Precision: 0
    Fields
      Field: OBJECTID             Feature class: Population
        Type: Object ID               Population is an object class
        Is Nullable: No           (table)
      Field: WLS_id                   Behavior class:
        Type: Long Integer        esriGeoDatabase.Object
        Is Nullable: Yes
        Precision: 0                      ------
```

```
    Fields                              Precision: 0
      Field: OBJECTID                 Field: SSZ_Year
        Type: Object ID                 Type: Long Integer
        Is Nullable: No                 Is Nullable: Yes
      Field: POP_id                     Precision: 0
        Type: Long Integer            Field: SSZ_amount
        Is Nullable: Yes                Type: Long Integer
        Precision: 0                    Is Nullable: Yes
      Field: POP_race                   Precision: 0
        Type: String                  Field: SSZ_datatype
        Is Nullable: Yes                Type: String
        Length: 0                       Is Nullable: Yes
      Field: POP_gender                 Length: 0
        Type: String
        Is Nullable: Yes          Feature class: Waterprice
        Length: 0                   Waterprice is an object class
      Field: POP_amount           (table)
        Type: Long Integer          Behavior class:
        Is Nullable: Yes          esriGeoDatabase.Object
        Precision: 0
      Field: POP_datatype               ------
        Type: String                  Fields
        Is Nullable: Yes                Field: OBJECTID
        Length: 0                         Type: Object ID
                                          Is Nullable: No
  Feature class: Waterleakage_WB        Field: WP_id
    Waterleakage_WB is an object          Type: Long Integer
class (table)                             Is Nullable: Yes
    Behavior class:                       Precision: 0
esriGeoDatabase.Object                  Field: WP_date_m
                                          Type: Date
    ------                                Is Nullable: Yes
    Fields                            Field: WP_unit_tariff
      Field: OBJECTID                     Type: Double
        Type: Object ID                   Is Nullable: Yes
        Is Nullable: No                   Precision: 0
      Field: WLB_id                       Scale: 0
        Type: Long Integer            Field: WP_fixed_tariff
        Is Nullable: Yes                  Type: Double
        Precision: 0                      Is Nullable: Yes
      Field: WLB_date_m                   Precision: 0
        Type: Date                        Scale: 0
        Is Nullable: Yes              Field: WP_data_type
      Field: WLB_datatype                 Type: String
        Type: String                      Is Nullable: Yes
        Is Nullable: Yes                  Length: 0
        Length: 0
      Field: WLB_volume_kl        Feature class: DamVolume
        Type: Long Integer          DamVolume is an object class
        Is Nullable: Yes          (table)
        Precision: 0                Behavior class:
                                  esriGeoDatabase.Object
  Feature class: Standsize
    Standsize is an object class        ------
(table)                               Fields
    Behavior class:                   Field: OBJECTID
esriGeoDatabase.Object                  Type: Object ID
                                        Is Nullable: No
    ------                          Field: DAV_id
    Fields                            Type: Long Integer
      Field: OBJECTID                   Is Nullable: Yes
        Type: Object ID                 Precision: 0
        Is Nullable: No             Field: DAV_date
      Field: SSZ_id                     Type: Date
        Type: Long Integer              Is Nullable: Yes
        Is Nullable: Yes            Field: DAV_amount
```

```
        Type: Long Integer                    Behavior class:
        Is Nullable: Yes                   esriGeoDatabase.Feature
        Precision: 0
      Field: DAV_datatype                      ------
        Type: String                           Fields
        Is Nullable: Yes                         Field: OBJECTID
        Length: 0                                  Type: Object ID
                                                   Is Nullable: No
-----------------                              Field: Shape
Feature datasets                                 Type: Geometry
-----------------                                Geometry type: Point
                                                 Has Measures: No
                                                 Has Z Values: No
   ---------------------------------                  Num of grids: 1
   Feature dataset name: GeoDB_C5 FDS              Grid(0) = 1000
   ---------------------------------
                                               Field: Dam_id
   Spatial reference name: Unknown               Type: Long Integer
                                                 Is Nullable: Yes
   ---------------                               Precision: 0
   Feature classes                             Field: Dam_name
   Feature class: Catchment                       Type: String
     Feature type: FEATURE                        Is Nullable: Yes
     Behavior class:                              Length: 0
   esriGeoDatabase.Feature                     Field: Dam_fsl
                                                 Type: Long Integer
                                                 Is Nullable: Yes
     ------                                      Precision: 0
     Fields                                    Field: Dam_area
       Field: OBJECTID                           Type: Long Integer
         Type: Object ID                         Is Nullable: Yes
         Is Nullable: No                         Precision: 0
       Field: Shape
         Type: Geometry                     Feature class: Soil
         Geometry type: Polygon               Feature type: FEATURE
         Has Measures: No                     Behavior class:
         Has Z Values: No                   esriGeoDatabase.Feature
               Num of grids: 1
           Grid(0) = 1000                      ------
                                               Fields
       Field: CAT_id                             Field: OBJECTID
         Type: Long Integer                        Type: Object ID
         Is Nullable: Yes                          Is Nullable: No
         Precision: 0                            Field: Shape
       Field: CAT_primary                          Type: Geometry
         Type: String                              Geometry type: Polyline
         Is Nullable: Yes                          Has Measures: No
         Length: 0                                 Has Z Values: No
       Field: CAT_secondary                              Num of grids: 1
         Type: String                            Grid(0) = 1000
         Is Nullable: Yes
         Length: 0                             Field: SL_id
       Field: CAT_tertiary                        Type: Long Integer
         Type: String                            Is Nullable: Yes
         Is Nullable: Yes                         Precision: 0
         Length: 0                             Field: SL_series
       Field: CAT_quaternary                     Type: String
         Type: String                            Is Nullable: Yes
         Is Nullable: Yes                         Length: 0
         Length: 0                             Field: SL_type
       Field: CAT_area                           Type: String
         Type: Double                            Is Nullable: Yes
         Is Nullable: Yes                         Length: 0
         Precision: 0                           Field: SL_effDepth
         Scale: 0                                 Type: Long Integer
                                                  Is Nullable: Yes
   Feature class: Dams
     Feature type: FEATURE
```

```
        Precision: 0                              Precision: 0
      Field: SL_lowerDrainage              Field: Mun_name
        Type: Long Integer                    Type: String
        Is Nullable: Yes                      Is Nullable: Yes
        Precision: 0                          Length: 0
      Field: SL_upperDrainage              Field: Mun_type
        Type: Long Integer                    Type: String
        Is Nullable: Yes                      Is Nullable: Yes
        Precision: 0                          Length: 0
      Field: SL_dstexture
        Type: String                     Feature class:
        Is Nullable: Yes                 District_Municipalities
        Length: 0                          Feature type: FEATURE
                                           Behavior class:
  Feature class: Contours                  esriGeoDatabase.Feature
    Feature type: FEATURE
    Behavior class:                          ------
esriGeoDatabase.Feature                      Fields
                                             Field: Shape
      ------                                   Type: Geometry
      Fields                                   Geometry type: Point
      Field: OBJECTID                          Has Measures: No
        Type: Object ID                        Has Z Values: No
        Is Nullable: No                            Num of grids: 1
      Field: Shape                             Grid(0) = 1000
        Type: Geometry
        Geometry type: Polyline              Field: OBJECTID
        Has Measures: No                       Type: Object ID
        Has Z Values: No                       Is Nullable: No
            Num of grids: 1                  Field: Mun_id
        Grid(0) = 1000                         Type: Long Integer
                                               Is Nullable: Yes
      Field: CT_id                             Precision: 0
        Type: Long Integer                   Field: Mun_name
        Is Nullable: Yes                       Type: String
        Precision: 0                           Is Nullable: Yes
      Field: CT_altitude                       Length: 0
        Type: Long Integer                   Field: Mun_type
        Is Nullable: Yes                       Type: String
        Precision: 0                           Is Nullable: Yes
      Field: CT_msl                            Length: 0
        Type: Long Integer                   Field: DM_id
        Is Nullable: Yes                       Type: Long Integer
        Precision: 0                           Is Nullable: Yes
                                               Precision: 0
  Feature class: Municipalities            Field: DM_name
    Feature type: FEATURE                    Type: String
    Behavior class:                          Is Nullable: Yes
esriGeoDatabase.Feature                      Length: 0

      ------                             Feature class:
      Fields                             Local_Municipalities
      Field: OBJECTID                      Feature type: FEATURE
        Type: Object ID                    Behavior class:
        Is Nullable: No                  esriGeoDatabase.Feature
      Field: Shape
        Type: Geometry                       ------
        Geometry type: Polygon               Fields
        Has Measures: No                     Field: OBJECTID
        Has Z Values: No                       Type: Object ID
            Num of grids: 1                    Is Nullable: No
        Grid(0) = 1000                       Field: Shape
                                               Type: Geometry
      Field: Mun_id                            Geometry type: Point
        Type: Long Integer                     Has Measures: No
        Is Nullable: Yes                       Has Z Values: No
```

```
        Num of grids: 1                      Behavior class:
      Grid(0) = 1000                    esriGeoDatabase.Feature

   Field: Mun_id                           ------
     Type: Long Integer                    Fields
     Is Nullable: Yes                        Field: OBJECTID
     Precision: 0                              Type: Object ID
   Field: Mun_name                            Is Nullable: No
     Type: String                           Field: Shape
     Is Nullable: Yes                         Type: Geometry
     Length: 0                                Geometry type: Polyline
   Field: Mun_type                            Has Measures: No
     Type: String                             Has Z Values: No
     Is Nullable: Yes                              Num of grids: 1
     Length: 0                                  Grid(0) = 1000
   Field: DM_id
     Type: Long Integer                     Field: RD_id
     Is Nullable: Yes                         Type: Long Integer
     Precision: 0                             Is Nullable: Yes
   Field: DM_name                             Precision: 0
     Type: String                           Field: RD_name
     Is Nullable: Yes                         Type: String
     Length: 0                                Is Nullable: Yes
   Field: LM_id                               Length: 0
     Type: Long Integer                     Field: RD_class
     Is Nullable: Yes                         Type: String
     Precision: 0                             Is Nullable: Yes
   Field: LM_name                             Length: 0
     Type: String
     Is Nullable: Yes              Feature class: Landcover
     Length: 0                       Feature type: FEATURE
                                     Behavior class:
 Feature class: Provinces          esriGeoDatabase.Feature
   Feature type: FEATURE
   Behavior class:                         ------
 esriGeoDatabase.Feature                   Fields
                                             Field: OBJECTID
                                               Type: Object ID
     ------                                    Is Nullable: No
     Fields                                  Field: Shape
       Field: OBJECTID                         Type: Geometry
         Type: Object ID                       Geometry type: Polygon
         Is Nullable: No                       Has Measures: No
       Field: Shape                            Has Z Values: No
         Type: Geometry                             Num of grids: 1
         Geometry type: Polygon                  Grid(0) = 1000
         Has Measures: No
         Has Z Values: No                     Field: LC_id
              Num of grids: 1                   Type: Long Integer
            Grid(0) = 1000                      Is Nullable: Yes
                                                Precision: 0
       Field: Prv_id                         Field: LC_area
         Type: Long Integer                    Type: Long Integer
         Is Nullable: Yes                      Is Nullable: Yes
         Precision: 0                          Precision: 0
       Field: Prv_name
         Type: String                 Feature class: Rivers
         Is Nullable: Yes               Feature type: FEATURE
         Length: 0                      Behavior class:
       Field: Prv_area               esriGeoDatabase.Feature
         Type: Double
         Is Nullable: Yes                    ------
         Precision: 0                        Fields
         Scale: 0                              Field: OBJECTID
                                                 Type: Object ID
 Feature class: Roads                            Is Nullable: No
   Feature type: FEATURE
```

```
      Field: Shape                              Behavior class:
        Type: Geometry                        esriGeoDatabase.Feature
        Geometry type: Polyline
        Has Measures: No                          ------
        Has Z Values: No                        Fields
              Num of grids: 1                     Field: OBJECTID
          Grid(0) = 1000                            Type: Object ID
                                                    Is Nullable: No
      Field: Riv_id                             Field: Shape
        Type: Long Integer                        Type: Geometry
        Is Nullable: Yes                          Geometry type: Polygon
        Precision: 0                              Has Measures: No
      Field: Riv_name                           Has Z Values: No
        Type: String                                  Num of grids: 1
        Is Nullable: Yes                          Grid(0) = 1000
        Length: 0
      Field: Riv_length                         Field: Geo_id
        Type: Long Integer                        Type: Long Integer
        Is Nullable: Yes                          Is Nullable: Yes
        Precision: 0                              Precision: 0
      Field: Riv_class                          Field: Geo_type
        Type: String                              Type: String
        Is Nullable: Yes                          Is Nullable: Yes
        Length: 0                                 Length: 0
                                                Field: Geo_class
  Feature class: Rainfall                         Type: String
    Feature type: FEATURE                         Is Nullable: Yes
    Behavior class:                               Length: 0
esriGeoDatabase.Feature                         Field: Geo_lithology
                                                  Type: String
      ------                                      Is Nullable: Yes
    Fields                                        Length: 0
      Field: OBJECTID                           Field: Geo_rocktype
        Type: Object ID                           Type: String
        Is Nullable: No                           Is Nullable: Yes
      Field: Shape                                Length: 0
        Type: Geometry
        Geometry type: Polygon              Feature class: Towns
        Has Measures: No                        Feature type: FEATURE
        Has Z Values: No                        Behavior class:
              Num of grids: 1               esriGeoDatabase.Feature
          Grid(0) = 1000
                                                  ------
      Field: RF_id                              Fields
        Type: Long Integer                        Field: OBJECTID
        Is Nullable: Yes                            Type: Object ID
        Precision: 0                                Is Nullable: No
      Field: RF_date_d                          Field: Shape
        Type: Date                                Type: Geometry
        Is Nullable: Yes                          Geometry type: Point
      Field: RF_datatype                        Has Measures: No
        Type: String                             Has Z Values: No
        Is Nullable: Yes                              Num of grids: 1
        Length: 0                                 Grid(0) = 1000
      Field: RF_amount
        Type: Long Integer                      Field: TW_id
        Is Nullable: Yes                          Type: Long Integer
        Precision: 0                              Is Nullable: Yes
      Field: RF_area                            Precision: 0
        Type: Long Integer                      Field: TW_name
        Is Nullable: Yes                          Type: String
        Precision: 0                              Is Nullable: Yes
                                                  Length: 0
  Feature class: Geology                        Field: TW_longitude
    Feature type: FEATURE                         Type: Long Integer
                                                  Is Nullable: Yes
```
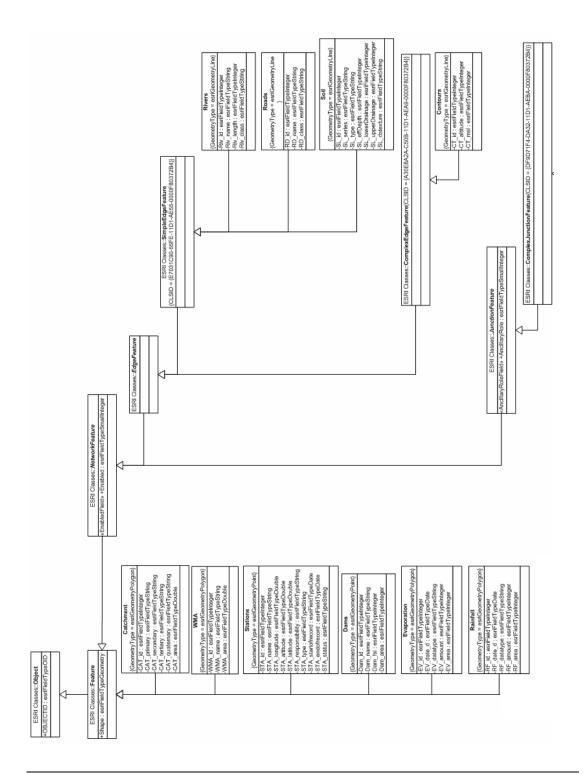
```
        Precision: 0                              Field: Pur_capacity
      Field: TW_altitude                            Type: Long Integer
        Type: Long Integer                          Is Nullable: Yes
        Is Nullable: Yes                            Precision: 0
        Precision: 0                              Field: Pur_longitude
      Field: TW_latitude                            Type: Long Integer
        Type: Long Integer                          Is Nullable: Yes
        Is Nullable: Yes                            Precision: 0
        Precision: 0                              Field: Pur_altitude
                                                    Type: Long Integer
  Feature class: Temperature                        Is Nullable: Yes
    Feature type: FEATURE                           Precision: 0
    Behavior class:                              Field: Pur_latitude
esriGeoDatabase.Feature                            Type: Long Integer
                                                    Is Nullable: Yes
      ------                                        Precision: 0
      Fields
      Field: OBJECTID                        Feature class: STA_Waterquality
        Type: Object ID                        Feature type: FEATURE
        Is Nullable: No                        Behavior class:
      Field: Shape                           esriGeoDatabase.Feature
        Type: Geometry
        Geometry type: Polygon                   ------
        Has Measures: No                         Fields
        Has Z Values: No                         Field: OBJECTID
            Num of grids: 1                        Type: Object ID
          Grid(0) = 1000                           Is Nullable: No
                                                 Field: Shape
      Field: TP_id                               Type: Geometry
        Type: Long Integer                        Geometry type: Polygon
        Is Nullable: Yes                          Has Measures: No
        Precision: 0                              Has Z Values: No
      Field: TP_date_d                                Num of grids: 1
        Type: Date                                  Grid(0) = 1000
        Is Nullable: Yes
      Field: TP_datatype                         Field: STAWQ_id
        Type: String                              Type: Long Integer
        Is Nullable: Yes                          Is Nullable: Yes
        Length: 0                                 Precision: 0
      Field: TP_amount                          Field: STAWQ_date
        Type: Long Integer                        Type: Date
        Is Nullable: Yes                          Is Nullable: Yes
        Precision: 0                            Field: STAWQ_datatype
                                                  Type: String
  Feature class: Purification_Plants              Is Nullable: Yes
    Feature type: FEATURE                         Length: 0
    Behavior class:                            Field: STAWQ_amount
esriGeoDatabase.Feature                          Type: Long Integer
                                                  Is Nullable: Yes
      ------                                      Precision: 0
      Fields                                   Field: STAWQ_parameter
      Field: OBJECTID                            Type: Long Integer
        Type: Object ID                          Is Nullable: Yes
        Is Nullable: No                          Precision: 0
      Field: Shape
        Type: Geometry                     Feature class: Evaporation
        Geometry type: Point                   Feature type: FEATURE
        Has Measures: No                       Behavior class:
        Has Z Values: No                     esriGeoDatabase.Feature
            Num of grids: 1
          Grid(0) = 1000                         ------
                                                 Fields
      Field: Pur_id                            Field: OBJECTID
        Type: Long Integer                       Type: Object ID
        Is Nullable: Yes                         Is Nullable: No
        Precision: 0                           Field: Shape
```

```
        Type: Geometry                              Type: Double
        Geometry type: Polygon                      Is Nullable: Yes
        Has Measures: No                            Precision: 0
        Has Z Values: No                            Scale: 0
              Num of grids: 1                 Field: STA_latitude
          Grid(0) = 1000                            Type: Double
                                                    Is Nullable: Yes
      Field: EV_id                                  Precision: 0
        Type: Long Integer                          Scale: 0
        Is Nullable: Yes                      Field: STA_responsibility
        Precision: 0                                Type: String
      Field: EV_date_d                              Is Nullable: Yes
        Type: Date                                  Length: 0
        Is Nullable: Yes                      Field: STA_type
      Field: EV_datatype                            Type: String
        Type: String                                Is Nullable: Yes
        Is Nullable: Yes                            Length: 0
        Length: 0                             Field: STA_startofrecord
      Field: EV_amount                              Type: Date
        Type: Long Integer                          Is Nullable: Yes
        Is Nullable: Yes                      Field: STA_endofrecord
        Precision: 0                                Type: Date
      Field: EV_area                                Is Nullable: Yes
        Type: Long Integer                    Field: STA_status
        Is Nullable: Yes                            Type: String
        Precision: 0                                Is Nullable: Yes
                                                    Length: 0
  Feature class: Stations
    Feature type: FEATURE                 Feature class: WMA
    Behavior class:                         Feature type: FEATURE
esriGeoDatabase.Feature                     Behavior class:
                                        esriGeoDatabase.Feature
    ------
    Fields                                  ------
      Field: OBJECTID                       Fields
        Type: Object ID                       Field: OBJECTID
        Is Nullable: No                         Type: Object ID
      Field: Shape                              Is Nullable: No
        Type: Geometry                        Field: Shape
        Geometry type: Point                    Type: Geometry
        Has Measures: No                        Geometry type: Polygon
        Has Z Values: No                        Has Measures: No
              Num of grids: 1                   Has Z Values: No
          Grid(0) = 1000                              Num of grids: 1
                                                  Grid(0) = 1000
      Field: STA_id
        Type: Long Integer                    Field: WMA_id
        Is Nullable: Yes                        Type: Long Integer
        Precision: 0                            Is Nullable: Yes
      Field: STA_name                           Precision: 0
        Type: String                          Field: WMA_name
        Is Nullable: Yes                        Type: String
        Length: 0                               Is Nullable: Yes
      Field: STA_longitude                      Length: 0
        Type: Double                          Field: WMA_area
        Is Nullable: Yes                        Type: Double
        Precision: 0                            Is Nullable: Yes
        Scale: 0                                Precision: 0
      Field: STA_altitude                       Scale: 0
```

# A P P E N D I X  F

Subset of simple feature and network feature classes as created in the
Feature Dataset Package.

# A P P E N D I X   G

Subset of object classes (user-defined entities).