THE DEVELOPMENT AND ASSESSMENT OF A PROTOTYPE WATER ACCOUNTING SYSTEM FOR SOUTH AFRICA USING THE *ACRU2000* AND MIKE BASIN MODELS

DB Kime

DISSERTATION

Submitted in partial fulfilment of the requirements
for the degree of MSc in Hydrology

School of Bioresources Engineering and Environmental Hydrology
University of KwaZulu-Natal
Pietermaritzburg
March 2010

As the candidate's Supervisor I have approved this dissertation for submission:

Signed: Name: Date:

FACULTY OF SCIENCE AND AGRICULTURE

DECLARATION 1 - PLAGIARISM

I, ..., declare that

1. The research reported in this thesis, except where otherwise indicated, is my original research.

2. This thesis has not been submitted for any degree or examination at any other university

3. This thesis does not contain other persons' data, pictures, graphs or other information, unless specifically acknowledged as being sourced from other persons.

4. This thesis does not contain other persons' writing, unless specifically acknowledged as being sourced from other researchers. Where other written sources have been quoted, then:

    a. Their words have been re-written but the general information attributed to them has been referenced
    b. Where their exact words have been used, then their writing has been placed in italics and inside quotation marks, and referenced

5. This thesis does not contain text, graphics or tables copied and pasted from the Internet, unless specifically acknowledged, and the source being detailed in the thesis and in the References section.

Signed

....

ABSTRACT

South African water management areas could find themselves without enough water for its users due to new methods of performing water allocation as stipulated in the National Water Act of 1998. A water accounting system would address the need for accurate metering, monitoring and auditing of South Africa's water resources to ensure that users are complying with their allocations. Such a system should be able to provide information such as comparisons between the simulated and observed flow of water at a point, comparisons between the amount of water allocated to a user and the actual water used by that user, and the source and destination of water at a point. This document contains a literature review, an explanation of the methods used to develop a prototype water accounting system and a discussion of the results from testing the system. A literature review was undertaken which covered topics in water resources planning, water resources operations, local legislation for water allocation and new technologies which could be applied to aid the management of water resources in South Africa. The results from the literature review indicated real time water accounting systems can give effect to water allocation rules. The water accounting systen is comprised of two simulation models and a database. The models used for the study were the *ACRU2000* model and the MIKE BASIN model. These models require data as well as a means to automate the transfer of data between the models and thus a database was developed. The database was developed in Microsoft Access and, in addition to the construction of a number of tables required to house the data, a database dashboard was made to control the functions of the database. An assessment of the *ACRU2000* and MIKE BASIN models was performed in order to determine if they are suitable for use as water accounting tools. *ACRU2000* was used for its process based, daily rainfall-runoff modelling capabilities. Due to the process based modelling capabilities of *ACRU2000,* forecasts of rainfall can be used as input to the simulations. Hot starting is the storing of internal model state variables at a particular time and the use of these variables in a different simulation to start the model up again. It was expected that, due to long simulation run times for *ACRU2000,* it would be beneficial to enable *ACRU2000* to be hot started and an attempt to hot start *ACRU2000* is presented. This would have allowed for significantly decreased simulation run times as the model can be warmed up for two years and thereafter hot started to run only for one day at a time. An assessment of the MIKE BASIN network allocation model to be used as a water accounting system was performed by attempting to meet the project objectives through building a fictional water supply network. The network is composed of a small catchment containing six runoff generating regions, a reservoir and ten water users. Three network allocation scenarios were constructed in order to fully test the rule sets and allocation capabilities currently available in the MIKE BASIN model. The study has shown that the tools and models used are capable of forming a rudimentary water accounting system. This is encouraging as it shows that there is the potential to improve the water resources management in South Africa using tools that already exist.

ACKNOWLEDGEMENTS

Prof. J.C. Smithers for his supervision, encouragement and guidance throughout the project.

Mr A.J. Pott for his co-supervision, introduction to industry specialists and creative guidance throughout the project.

Mr D.J. Clark for his assistance with JAVA and internal workings of the *ACRU2000* model.

Mr K.B. Meier for his assistance with database design.

TABLE OF CONTENTS

1. INTRODUCTION

Due to public perception, cost and environmental impacts there are relatively few new dams currently being built in the world compared to the number built during the past (Vogel *et al.*, 2007). The reason for this is that there are fewer suitable dam building sites remaining and the building of dams has a significant negative impact on riverine and other eco-systems (Imhof *et al.*, 2002). This has resulted in the need to manage the existing water resources more efficiently (Labadie, 2005) as opposed to solving the problem by building more dams. The demand for water is increasing in South Africa (DWAF, 2007) due to the increasing population and growth of the economy. Maintaining water supplies for present and future generations while ensuring that the allocations for human, eco-system maintenance and international obligations are met are typical objectives of water resources planning and operations in South Africa (Dube, 2006). Water resources planning is the development of strategies for sustaining and developing water resources by making use of data and predictive tools (Schultz *et al.*, 2000). Water resources operations are the stage in water resources management where decisions are made at a small temporal scale that affects the daily water supply within a catchment (Draper *et al.*, 2004).

The South African National Water Act (NWA) of 1998 (NWA, 1998) has brought about significant changes in the way that water is allocated in South Africa. Prior to 1998 a riparian rights system deemed those properties adjacent to a river to have the right to abstract as much water as necessary. The 1998 NWA introduced a system of authorisation which removed the water right from the property right and requires licenses to be issued to users who have applied and met stipulated criteria. The licenses must specify the exact amount of water that a user is authorised to use and when the water may be used. The conditions specified by the licenses will be derived from system yield modelling and, in order to ensure that water is used equitably, must be monitored to ensure adherence. Due to the 1998 NWA stipulating that users may dispute the allocation method used to determine how much water they may use, it is required that the tools used to generate the allocations must be as accurate, reliable and realistic as possible (Dube, 2006). The NWA also introduced the concept of a Reserve which is water that is prioritised for environmental and basic human needs.

Due to the interaction of processes on a number of different scales in hydrology, the scale at which modelling takes place needs to be carefully considered (Victoria *et al.*, 2005). It has been found that, up to a point, models are likely to be more accurate when they operate at finer time and spatial scales (Victoria *et al.*, 2005). When decisions are required at both fine scales, such as operations required for a run of river system, and large scales, such as for an entire catchment, it is useful to use a multi-scale modelling approach (Victoria *et al.*, 2005).

Smithers (2006) raised a number of scale issues regarding hydrological modelling for planning water resources in South Africa. Where demand for water exceeds supply of water, as it does in more than half of South Africa's water management areas (DWAF, 2004), a detailed and accurate determination of the water resources is required before planning and operations can be undertaken (Smithers, 2006). Further to this, according to Smithers (2006), the Water Resources Yield Model (Mckenzie and Van Rooyen, 1998) is the accepted method for catchment yield determination in South Africa and which has *inter alia*, the following limitations:

- There is limited consideration of the time and space scale as required for water resource management and operations.
- The Water Resources Yield Model (WRYM) is not directly linked to the hydrology of the area.
- There is limited consideration of run-of-river water users with dams being the only water resource systems that are actively modelled.
- There are limitations in the curtailment mechanism used which may promote a use-it-or-lose-it style of water consumption as opposed to using water conservatively.

The Reserve is important in all forms of water resources planning and operations as its needs must be satisfied before any other needs can be considered (Butler, 2001). The determination of the Reserve has been accomplished in a number of catchments in South Africa but the actual implementation has not taken place in most cases due to *inter alia*, the following reasons:

- a lack of tools and methods to implement the Reserve,
- over-allocation of the water-resources in some catchments which would result in the Reserve being allocated water that has already been allocated for other users and which could have negative socio-economic impacts,
- a lack of monitoring and metering of water users, most notably run-of-river irrigators, and
- a lack of monitoring and metering of ecological sites to determine if the ecological requirements are being met (Hughes *et al.*, 2007).

River ecosystems rely on a natural flow sequence that is comprised of high and low flows on a regular basis. This presents a problem for dam operators as they are managing the dam only for its users and the opening and closing of sluice gates is not a trivial matter and may take a number of hours to open and close (Butler, 2001).

An operating rule framework was devised (Butler, 2001) for the *ACRU2000* model (Pike and Schulze, 2000) which aimed to supply demands for water in an equitable and sustainable manner. The framework took basic human needs, industrial needs, environmental needs, and irrigators into account and allowed these users to make requests from either a dam or a river. Requests for basic human needs, industry and irrigators were generated in a simple manner by considering population size, industrial demand and crop water requirements respectively. The requests for the Instream Flow Requirement (IFR) were much more complicated and were divided into a simple and a complex approach. The simple approach used an IFR table (Hughes *et al.*, 1997), which contains a set of flow values for each month for maintenance and drought periods. For low flows the IFR table values were compared to the current inflow to a dam and from this comparison it was determined whether to use either the maintenance or the drought flow. For high flows a dam level was examined to determine if a dam had enough water in storage to release a flood and, if so, the flood was released according to a predefined hydrograph. The complex approach to generating water requests for the environment made use of the Building Block Methodology (BBM) developed by Hughes *et al* (2007), a natural flow time series and the antecedent hydrological conditions in the catchment (Butler, 2001).

The operating rule framework was tested at the Paris Dam, Pongola, and it was noted that it was unlikely that a generic framework could be created due to the unique complexities of each catchment in the country. The framework was shown to work correctly as it supplied a downstream IFR site with the necessary flow regime at reasonable levels of assurance. It was found that, although a single IFR site received its required flow regime, the flow regime below the dam was higher than necessary and the flow regime below the irrigation abstraction point was likely to be lower than required. In terms of the real-time operation of dams, this operating rule framework would be very useful but only if the *ACRU2000* model is capable of storing the internal state variables for the previous day conditions and then simulating for a single day using the stored state variables as starting conditions (Butler, 2001).

A study is currently being undertaken by Hughes *et al* (2007) to operationalise the ecological Reserve through the establishment of a framework of independent tools which can be used at DWAF regional offices. The framework has been applied in the Sabie River Catchment and the Thukela Catchment and a number of important problems have been highlighted from this study including:

- user's licenses are specified with an annual volume which could theoretically allow them to extract their entire allocation over a short space of time which could lead to system failure,
- the framework only determines low flow ecological requirements and it is assumed that floods will occur naturally,
- real-time rainfall data is not reliable which results in inaccurate runoff modelling and,
- without compulsory licensing, there is no point in modelling the operating rules of the system as there is no enforcement of the rules in reality (Hughes *et al.*, 2007).

From the above, it can be concluded that South Africa is a water scarce country with relatively new water management legislation which challenges the current methods used in water resources planning and operations. With water rights being decoupled from property rights there now exists the possibility of trading these rights with other users for economic benefit. This has only become possible since the promulgation of the NWA of 1998.

The tools developed and examined in this study are targeted at multi-stakeholder organisations that are mandated to manage water under the NWA of 1998. At present there are no adequate tools in existence in South Africa which allow water resources managers to audit water users and to easily determine if users are using more water than they are entitled to. The proposed use of MIKE BASIN would facilitate this audit by detailed analysis of water use and water entitlement at a finer spatial and temporal scale than is currently normally practiced in South Africa. With this background in mind there is a clear motivation for research to be undertaken in this field as is detailed in the following section.

Many of South Africa's dams lack a comprehensive system of operating rules, as shown in a recent Department of Water Affairs and Forestry (DWAF) business review (Manqoyi and Nyabeze, 2006). Many of the dams in South Africa are managed using operator experience and rules of thumb and this may lead to problems when staff turnover results when new, inexperienced managers are given the responsibility to manage the dam.

The water resources planning and operations tools that are in currently in use in South Africa may be insufficient to deal with new challenges, such as the 1998 NWA and impacts of climate change, that face hydrology in South Africa. The main tools used in South African for water resources planning and operations are the Water Resources Yield and Planning Models (Mckenzie and Van Rooyen, 2003). These models have been used for many years and operate at spatial and temporal scales that are too coarse to give realistic consideration to individual licenses and the Reserve (Smithers and Pott, 2007). In addition to these factors, there are a number of approaches and models used internationally for water resources planning and operations which implement methods that have not yet been investigated for wide spread application in South Africa. These include using radar-based observations for rainfall forecasting, making streamflow forecasts, trading water use entitlements and operating dams and rivers for the Reserve. Thus with increasing levels of water scarcity, legislation that requires more detailed water resources assessments and improved modelling of water resources operations, and a lack of suitable models available for water resources operations, a need exists in South Africa to develop a system which can address these challenges.

Within this project, it was thus decided to review and select one or more appropriate models and attempt to apply them as part of a prototype water accounting system for South Africa. It is envisaged that the following components will be required before water accounting can be performed adequately:

- Apportionment rules which would determine water ownership in a catchment.
- River flow and dam level monitoring devices at key locations in the catchment such as river confluences and directly above large users.
- Objective decision support systems which are able to simulate a set of outcomes based on current or predicted catchment status.
- Communication systems which broadcast how much water the users are allowed to abstract.
- Water metering devices on the pumps or diversion canals which can report the amount of water that a user abstracts from the system.
- A reconciliation of water used with the entitlement to use that water.

However it must be acknowledged that these components do not all exist in South African catchments and the system will be designed around the assumption that these components do exist.

From a review of river network models it was determined that the RiverWare (Zagona *et al.*, 2001) and MIKE BASIN (DHI, 2007) models were potentially suitable models for application in this study. However, although the RiverWare model is the most suitable for use in this study due to its reported water accounting capabilities, it was not used due to a lack of funding to purchase the model, local expertise and support. MIKE BASIN, which was available for use in the project, is a GIS based network allocation model that is suited to catchment wide water allocation studies. It has been recently applied in the Letaba river catchment (Nyabeze *et al.*, 2007) as well as the Mhlathuze river and Oliphants river catchments (CPHWater, 2007). By enabling the tracking of water through a river system, MIKE BASIN would facilitate visualisation of where water has come from, where it is going, what portion has been allocated and what is unallocated and where it may be lost in a system. The rainfall-runoff component in MIKE BASIN is relatively simple and the *ACRU2000* model (Kiker, 2000), which is a physically based daily rainfall runoff model that has been developed and widely verified for conditions in South Africa and comes packaged with a comprehensive input data and information set for modelling in South Africa, was selected to generate the streamflow time series used as input to MIKE BASIN.

As shown above, there is a need to improve water resources planning and operations in South Africa. The objectives of this study are to assess the capability of *ACRU2000* and MIKE BASIN to perform the following tasks:

- monitor and track water as it moves through a river network thereby facilitating auditing of water availability and use,
- allow individual network segments to be queried for information such as observed streamflow, simulated streamflow, source of water, destination/ownership of water, and
- make use of climate and streamflow forecasts to assist both dam control officers and end water users in making improved water management decisions.

In addition to being outlined in the text below, these objectives are summarised in Figure 1.1. It is proposed that a database be configured to import, store and export rainfall data. The rainfall data will come from both observed rainfall records and rainfall forecasts. The database will need to be configured to export the rainfall data in a format that can be used by *ACRU2000*. Additional features of the database would include the ability to merge observed rainfall data and forecast rainfall information into a continuous time series which can be used as input for *ACRU2000*. Following the use of the database to import, store and export rainfall data, the *ACRU2000* model will be used to generate streamflow time series based on the rainfall data that is supplied from the database. The streamflow time series that are generated from *ACRU2000* will be imported to MIKE BASIN in order to provide the system with streamflow. Following the use of *ACRU2000*, the MIKE BASIN network allocation model will be used to test the affects of allocating water to users under different allocation scenarios. In addition to this MIKE BASIN will be tested for its ability to track and monitor water as it flows through the network, as well as for querying the network for information such as observed streamflow, simulated streamflow, source of water and destination of water. Although observed rainfall data, forecast rainfall information and a real catchment is used in this study, the catchment and its users are configured in a fictitious manner in order to evaluate MIKE BASIN's water allocation and tracking capabilities.

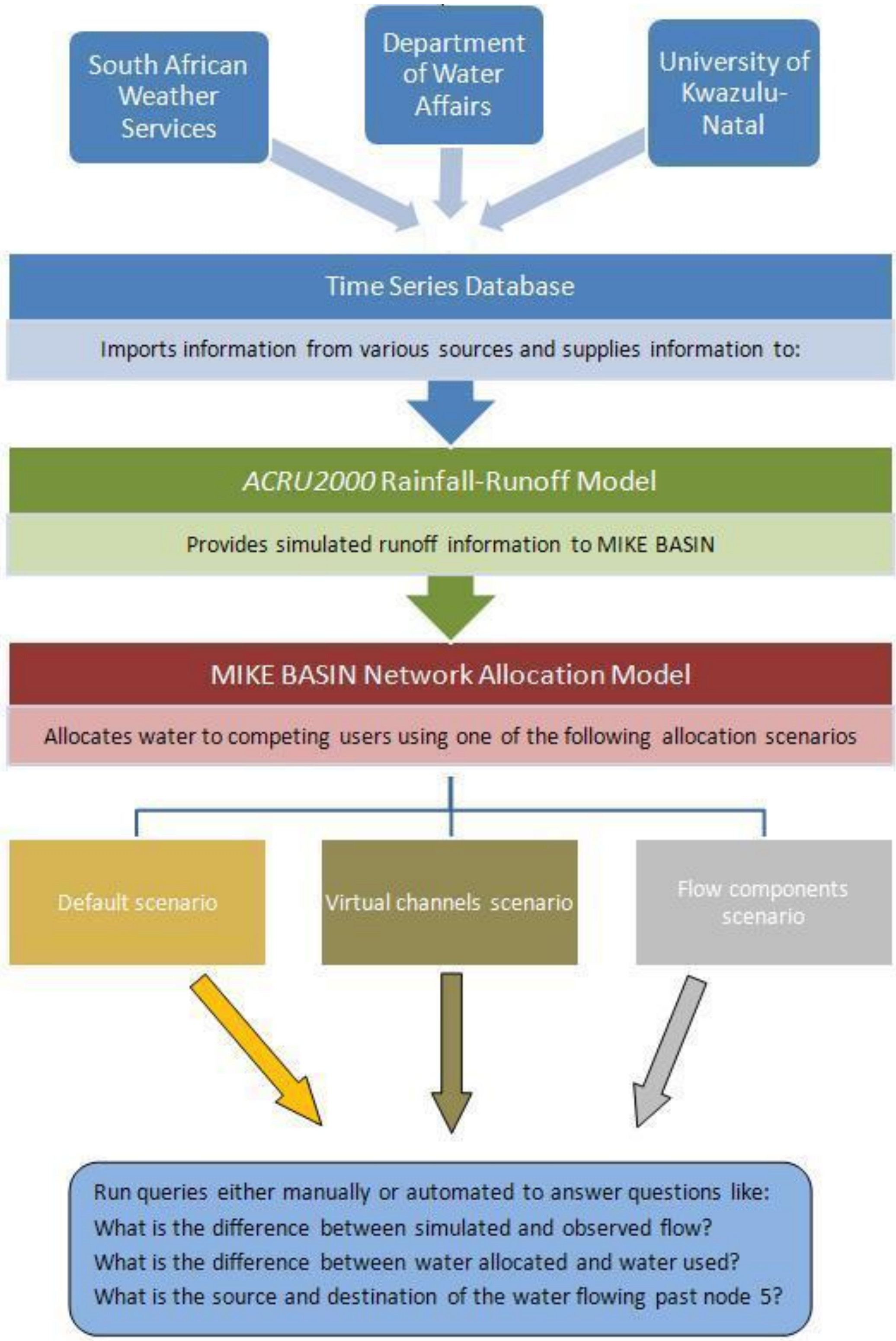

Figure 1.1 Schematic diagram of the components of the project.

A review of international and local literature related to models used for planning and operating water resources is contained in the Chapter 2 of this document. Selected models are reviewed in order to present the state-of-the-art in water resources planning. International approaches to yield determination, water allocation and models are reviewed in Chapter 2 and include CALVIN (Jenkins *et al.*, 2004), MODSIM (Labadie, 2006), RiverWare (Zagona *et al.*, 2001) and a Taiwanese network flow optimisation model (Hsu and Cheng, 2002). The second section of Chapter 2 contains a review of international approaches to water resources operations and contains a review of *inter alia*, two real-time frameworks. The second section of Chapter 2 also contains a review of local approaches to water resources planning and operations. In this section the Water Resources Yield Model (WRYM) (Mckenzie and Van Rooyen, 1998) and the Water Resources Planning Model (WRPM) are reviewed. The findings from a recent Department of Water Affairs and Forestry (DWAF) assessment (Manqoyi and Nyabeze, 2006) of existing operating rules for dams is also presented in this section. Recently developed ideas, technologies and requirements for water resources planning and operations are summarised in Chapter 3. These include using radar-based observations for rainfall forecasting, making streamflow forecasts and trading water use entitlements. This is followed in Chapter 4 by a discussion of the requirements of the system which are anticipated to meet the three objectives outlined at the top of this page. Thereafter the practical investigations with methods and results are presented in Chapters 5, 6 and 7. Chapter 5 contains a review of the method used to construct the time series database for the project. Chapter 6 contains a review of the method used to apply the *ACRU2000* rainfall runoff model. Chapter 7 contains a review of the methods used to assess the MIKE BASIN network allocation model. The results from the assessments are presented in Chapter 8 followed by discussion and conclusions drawn in Chapter 9.

2. REVIEW OF APPROACHES USED FOR WATER RESOURCES PLANNING AND OPERATIONS

This chapter summarises studies from international literature covering the fields of water resources planning and water resources operations. Water resources planning and operations are similar to each other with the primary differences being the frequency that these processes are performed and the time and spatial scales considered. Water resources planning is most often used at the conception of a water resources system or whenever there is a significant change in the system, such as the construction of new infrastructure or significant expansion in demand. Water resources operations are employed at a finer time scale and are used to determine the required operations and typically require shorter time steps ranging from sub-daily up to sub-yearly. Although all related to water resources planning and operations, the literature has been grouped by common themes in this chapter.

2.1. Water Resources Planning

Water resources planning is the development of strategies for sustaining and developing water resources by making use of data and predictive tools (Schultz *et al.*, 2000). According to recently published literature, water resources planning can be performed using a wide variety of techniques (Labadie, 2005). Water resources planning is important as it determines how much water can be reliably extracted from a system, which is termed the yield, and the conditions for using the water. This section contains a review of the yield determination process, allocation of water between competing users and a review of simulation and optimisation models that are applied for water resources planning.

2.1.1. Yield determination

"Firm yield is the draft which will lower the storage in a reservoir or multiple reservoir system to a defined failure level during a hydrologic period-of-record simulation" (Wurbs, 2005). An international and a local approach to yield determination are presented in this section.

The network flow optimisation model (Hsu and Cheng, 2002), was developed as a long-term planning tool for a large-scale water resources system. The model is based on the premise that the statistics of the past flow processes will be repeated in the future. Structurally the model uses a node and arc network to represent reality with nodes representing reservoirs, diversions, public demand points, agricultural demand points, minimum requirement points and source points, while arcs represent river reaches, pipelines, reservoir storage zones and paths to link water use. The model optimisation is performed by minimising the sum of the decision variables multiplied by their cost coefficients. Water is then routed through the system using an embedded generalised network solver (EMNET) (Hsu and Cheng, 2002).

The model was applied to the Tanshui River catchment in Taiwan which comprises of three major river catchments. The dominant water users in the catchment are domestic and agricultural users. Twenty three years of inflow information was available for the project at two reservoirs and four recording stations. The network was simplified to use two demand nodes to represent the domestic water users and four demand nodes for the agricultural water users. When analysing the model results it was found that the model performed well when compared to the RIBSIM model (Delft Hydraulics., 1991) that had previously been used in this catchment as it was able to minimise water shortages while adhering to reservoir operating constraints. Although the model was used for a catchment wide yield analysis in this study, there is potential for the model to be used for defining the reservoir operating rules (Hsu and Cheng, 2002).

In 1983 a water resources evaluation was undertaken by DWAF as a result of water shortages from local supplies to the Gauteng region (Mckenzie and Van Rooyen, 2003). The evaluation found that a systematic approach to the problem was necessary and this prompted the investigation of models and ultimately the development of the Water Resources Yield Model (WRYM) and the Water Resources Planning Model (WRPM), both developed by Mckenzie and Van Rooyen (1998). Currently the WRYM and WRPM make up the primary tools used for managing the regulated water supplies in South Africa (Manqoyi and Nyabeze, 2006). Numerous international models were investigated by DWAF and it was determined that the Canadian Acres Reservoir Simulation Program (ARSP), developed by Sigvaldson (1976), would be adopted and developed and which resulted in the WRYM (Mckenzie and Van Rooyen, 2003). This decision was based on the fact that the model had a flexible structure and a simple input data interface made up of text files (Mckenzie and Van Rooyen, 2003). The ARSP had to be modified for South African conditions in order to allow consideration of South African inter-basin transfer schemes and the highly variable prevailing climate. In order to do this, the use of stochastically generated flow sequences was incorporated in the WRYM which allowed the generation of system yields using a short data record. According to Mckenzie and Van Rooyen, (2003), system yields determined using the WRYM have a relatively high level of confidence. The stochastic series generated are made up of random sequences of streamflow that match the statistical properties of the input monthly streamflow series (Pott and Hallowes, 2001). Input data to the WRYM includes a naturalised streamflow series determined by adding back anthropogenic influences to monthly streamflow generated by a calibrated rainfall-runoff model, point rainfall data, irrigation water use and afforestation data. In addition to this, the system parameters and characteristics are obtained from text files which facilitates quick and easy changing of the water resource system being modelled (Mckenzie and Van Rooyen, 2003).

The WRYM is designed for long-term system analyses under constant operating rules and water demand (Pott and Hallowes, 2001). It is capable of simulating a multi-purpose, multi-reservoir system using a penalty cost structure as a system of prioritising water use. The network solver attempts to satisfy users with the highest cost first from each off take node in the system. A similar method of curtailing water use is used in the storage zones of the reservoirs, as each zone has an associated cost of supplying water and this cost increases as the level of the reservoir drops (Pott and Hallowes, 2001). While the WRYM can simulate the long-term system yield, the WRPM is capable of simulating the impacts of growing demands over time and thereby providing an idea of how much expansion in supply is necessary to meet future demands.

2.1.2. Allocation among competing users

After the yield from a catchment is determined it may be necessary to determine the effects of supplying water to various types of users that may be competing for water from the same source. In addition to requiring water from the same source it is likely that water users will be using the water for different purposes and thus place additional constraints on the methods used to allocate water (Wurbs, 2005). In this section of the document a number of allocation methods used by various hydrological models are presented.

The CALVIN model (Jenkins *et al.*, 2004) simulates surface water, groundwater, water demand and the associated economic costs of supplying urban and agricultural water users. The model consists of two components, first a database containing the physical links, economic costs and constraints and secondly the HEC-PRM (HEC-PRM, 1994) general network flow optimisation solver. When considering how the optimisation routines work in CALVIN, the concepts of "scarcity of quantity" and "scarcity of cost" are introduced. "Scarcity of quantity" represents the difference between deliveries and beneficial use if there are no restrictions and supply was free. "Scarcity of cost" represents the value to users of increasing deliveries until scarcity of quantity is eliminated. CALVIN aims to minimise the sum of water scarcity costs and operating costs in order to bring the highest possible benefit to the entire modelled region (Jenkins *et al.*, 2004).

Owing to spatial and temporal variability of water resources in California, a significant network of hydrological structures now exists and these structures require an integrated management approach so as to satisfy the diverse needs of the users. The CALVIN model has been applied to the state of California and was used to analyse 72 years of hydrological data. Three different scenarios were used, a base case (BC) with current operational policies, a regionally operated case (RWM) and a state wide (SWM) operated case (Jenkins *et al.*, 2004). Among other results, the average total cost for three different water market scenarios was determined and is contained in Table 2.1.

Table 2.1 Comparison of output scenarios from CALVIN for California (Jenkins *et al.*, 2004)

	Average total cost ($M/year)		
Region	BC	RWM	SWM
Upper Sacramento Valley	35	34	29
Lower Sacramento Valley	212	166	166
San Joaquin and Bay Area	394	358	333
Tulare Lake Basin	461	434	415
Southern California	3074	1855	1838
Total	4176	2847	2780

(BC = base case, RWM = regional water markets, SWM = state wide water markets)

With lower values being more desirable, the results in Table 2.1 indicate that both regional and state wide economically driven operations have a significantly lower total cost of operations. This occurs as a result of a series of water exchanges and transfers which satisfy the demand instead of limiting water use to that which originates in the same catchment and which is strictly used for the purpose that it was allocated for. Of particular interest in this study was the observation that many environmental flow requirements have little consequence to other users, especially when considering the fact that instream flows can often be reused downstream. The model does have limitations which include system simplification, as it makes use of a third party network solver, and a lack of capacity for representing hydropower, flood control and recreational use of water (Jenkins *et al.*, 2004).

MODSIM (Labadie, 2006) is a network water quantity simulation model that is capable of modelling systems that have a number of diversions, return flows and reservoirs that are interconnected. MODSIM uses a system of prioritisation to allocate flows and can accommodate reservoir operating rules, in-stream flow requirements, agricultural demands and water allocations (Campbell *et al.*, 2001). MODSIM is designed for use at time steps varying from monthly to daily and can include simulation of water quality and groundwater flows. The network is solved for each individual time step and there is no option to take future reservoir inflows into account for making release decisions. The model has a graphical user interface which allows the river system to be constructed graphically using a set of nodes and links (Wurbs, 2005).

MODSIM was applied in a planning and management exercise in the Lower Arkansas River catchment (Dai and Labadie, 2001). The model was adapted to allow for consideration of surface and groundwater quality using the US Environmental Protection Agency (EPA) QUAL2E model (Brown and Barnwell, 1987) and this adapted version was named MODSIMQ. MODSIMQ was applied to the Lower Arkansas River catchment due to prior inconclusive and incomplete modelling projects such as the interactive accounting model (IAM) (Burns, 1989) and the modelling of sub-sections of the catchment in 1974 (Konikow and Bredehoeft, 1974). After setting up the model to represent the catchment with its dams, rivers and users, the model was calibrated using a year of monthly streamflows and salinity concentrations using data from 1988 to 1989. The calibration period showed that the model performed reasonably well when tracking mean estimates of salinity. Two base runs were performed after the calibration period. The first base run showed that water quantity shortages could be significantly decreased using the optimised MODSIMQ solution which made increased use of groundwater and forced diversion nodes to only supply the actual demand. The second base run included water quality constraints and showed that reduced stream salinity was associated with increased water supply shortages, however these shortages were still less than actual shortages over the same historical time period. This implies that with adherence to regulations, there would be fewer water shortages. A third scenario investigated the effect of increasing irrigation efficiency from 50% to 85% and it was found that again the salinity was reduced, but shortages still occurred (Dai and Labadie, 2001).

RiverWare (Zagona *et al.*, 2001) is a systems planning and operations tool that allows the user to interactively construct a network of rivers and reservoirs. It can be used both as a simulation or optimisation model (Frevert *et al.*, 2006). In addition to the physical network, the user is able to define the operating policies and rules of the system. RiverWare is capable of modelling systems at time steps ranging from one hour up to one year. This range in time steps allows RiverWare to model short term operations, medium-term operational forecasting and long term planning (Frevert *et al.*, 2006).

Water authorities in the western USA are occasionally faced with the challenge of tracking the legal ownership of water as it moves through a catchment (Frevert *et al.*, 2006). As well as tracking ownership, the authorities also need to distinguish between different types of water such as normal streamflow and water that has been transferred from an external system. RiverWare takes this into consideration using its accounting module. This module allows for accounting information from each model object to be included in the model's calculations (Frevert *et al.*, 2006).

RiverWare is currently used in a number of river systems in the USA as part of a framework of technologies. This framework is comprised of RiverWare for simulations and optimisations, the Modular Modelling System (MMS) (Leavesly *et al.*, 2002) for linking models together, estimating uncertainty and analysis of model results, and the Hydrologic Data Base (HDB) (Davidson *et al.*, 2002) for storing hydrological time series data, attribute data, statistical data and other water resources management data. HDB is automatically updated with near real time data and is capable of storing observed, forecasted and stochastically generated data thereby providing a picture of the past, present and future. The framework is used for numerous operating activities such as daily and hourly operating decision for the Hoover Dam, USA. The framework is also used for accurately accounting for water in the Rio Grande river catchment, Colorado where Native American rights and over allocation of water make water management difficult (Frevert *et al.*, 2006).

The MIKE BASIN model (DHI, 2007) is a network based river catchment simulation model. A network is represented by a system of nodes and links and the model performs mass balance accounting for each time step. The model is housed within the ArcMap GIS and is thereby explicitly linked to features on the ground. According to Ershadi *et al.* (2005), the philosophy behind MIKE BASIN is to keep the modelling simple and intuitive while still providing comprehensive planning and management insight. MIKE BASIN can be extended with the purchase of a number of additional modules such as: water quality; groundwater; rainfall-runoff; and soil erosion assessment. Although a monthly time step is commonly used for MIKE BASIN applications, the time step can be specified by the user if a specific need is encountered (Wurbs, 2005). Reservoirs and abstraction points can be used to control the allocation of water through the specification of a set of rules which are capable of simulating riparian rights or prior rights systems (Wurbs, 2005).

The WRPM is an extension of the WRYM and is designed for more complex simulations (Mckenzie and Van Rooyen, 2003). The WRPM is capable of modelling a change in demand over time as well as a change in operating rules over time as opposed to the static modelling approach of the WRYM. It can be used as both a planning and operating tool with planners using it to assess the timing of new water resources which need to be developed while operators use the model on a month to month basis (Pott and Hallowes, 2001). The WRPM can be used as an indicator and early warning system of droughts and thereby assist water resources managers in deciding when to implement water use restrictions (Mckenzie and Van Rooyen, 2003). In a recent survey of dam operating rules used around the country it was found that 65% of the water storage in South Africa is managed using a combination of the WRYM and WRPM (Manqoyi and Nyabeze, 2006) and this system is illustrated in the review of water resource management in the Umgeni Catchment in Section 2.2.6 of the document.

The WEAP (SEI, 2001) model was applied to the Steelport River Catchment in an effort to assess various water demand management scenarios (Levite *et al.*, 2003). The WEAP model is a monthly time step water balance model that represents a water system by means of sources, withdrawals, demands and ecosystem requirements with rivers being represented by sets of nodes and interconnecting reaches. The three water demand management scenarios that were investigated were overall reductions in user demand by 10%, 20% and 30%. It was found that even with a 30% reduction in overall water demand there were still significant shortfalls in water supply indicating that the water in the catchment is over allocated. Although these results are concerning, it was noted that a number of assumptions had been made for this study including the assumed insignificant effect of groundwater and the assumed insignificant effect of changing the river profile through constructing pools or drilling deep boreholes (Levite *et al.*, 2003).

2.2. Water Resources Operations

Water resources operations are the stage in water resources management where decisions are made at a small temporal scale that affects the daily water supply within a catchment (Draper *et al.*, 2004). These decisions include setting dam releases, diverting water into off-channel storage or switching on inter-catchment transfers of water. Many systems are operated according to rules generated by the planning process which do not generally account for daily flow conditions or climate processes.

In the following sections, reviews of two real time water management systems namely the South Platte Water Rights Management System (McCarthy and Light, 1995) and the US Army Corps of Engineers real time water control system (Pabst and Peters, 1983) are presented. After these systems were reviewed it was evident that the objectives for these systems were similar to those of this study. In addition to this, data mining techniques (Bessler *et al.*, 2003), coupled reservoir operation and irrigation scheduling (Teixeira and Marino, 2002) and a Canadian daily reservoir operating system are reviewed (Turgeon, 2005).

2.2.1. The South Platte Water Rights Management System

The South Platte Water Rights Management System (SPWRMS) is a set of computer applications that are used to assist water managers to make decisions and to inform people of the results of their decisions promptly through timely exchange of data (McCarthy and Light, 1995). The South Platte River Catchment is relatively small but 67% of the state of Colorado's population resides in the catchment. The primary water users are agriculture (69%) and municipalities (17%). Demand for water usually exceeds supply during spring, summer and autumn and during these times water users with the most recent water allocations must allow the older users to abstract their rights first. Eleven water commissioners are responsible for the administration of water in the 11 water districts that make up the catchment. The responsibilities of the water commissioners include:

- controlling water distribution,
- maintaining official diversion records,
- measuring flow in rivers, streams and pipes and,
- communicating with water users (McCarthy and Light, 1995).

The SPWRMS was developed by CADSWES (Center for Advanced Decision Support for Water and Environmental Systems), the Colorado Division of Water Resources and a group of the South Platte water users. All data is housed in a single database which allows the water commissioners of the region to all access the same quality controlled data. Previously data pertaining to a particular river section could only be obtained from the water commissioner of that region but now all data is available from the central database allowing commissioners from different river sections to review the hydrological condition in other river sections. The central database is linked to the internet to allow access for the water commissioners to either upload streamflow data or download data for other water districts. The water commissioners are responsible for filling in daily water information sheets which include a list of diversion structures, gauges and inflows in their water district. The information sheets are customised for the intricacies of each water district and the aim is to track water through the system and to monitor key points in a daily basis. Rather than an official water record, the information sheets serve to provide a quick overview of the situation in each water district (McCarthy and Light, 1995).

The first person to use water from the river became a senior water rights holder with all subsequent users classified as junior rights holders. A request for water (river call) can be made by a senior water user if the water user is not getting enough water and junior users above him are using water. This is written into the Colorado water law and the SPWRMS is used to record, delete and update the call status at a particular point on the river. Calls are stored in the central database allowing all districts to investigate the effects of these calls. The SPWRMS is able to translate these effects downstream due to the model being able to trace water upstream and downstream. Curtailment analysis is performed to determine whether a call is requested which allows a senior water user to be satisfied at the expense of a large number of junior users. In this case it is likely that the senior user will not use all the water requested and wastage will occur. The curtailment analysis begins by seeking all upstream junior users from the location of the call. The software then calculates the time it will take for the water to reach the request and lists the junior users that will be affected. The water commissioner aims to choose a curtailment which is near to the call as this will result in the least amount of water being wasted due to river seepage and evaporation losses. An empirically derived table of lag times is used as this saves on model calculation times as well as allowing the commissioners to add values to the table (McCarthy and Light, 1995).

2.2.2. Real-time water control

In 1983 the US Army Corps of Engineers was responsible for the operation of a number of water resource systems in the USA (Pabst and Peters, 1983). Although their primary concern was flood control using reservoirs, the systems also had to be operated for other purposes such as hydropower generation and water supply. Software was developed for real-time data analysis, short-term streamflow forecasting and reservoir system simulation. This system could be employed due to the, then recent, installation of real-time, communication enabled data loggers. The following steps indicate how the system worked on a daily basis, assuming that unprocessed data was available:

i. Data was processed and converted into units that were appropriate for input into the simulation model. This included converting weir level into discharge and performing range validation checks on the data.
ii. Data availability was assessed and it was determined if there was sufficient data to proceed.
iii. A time of forecast was chosen based on the availability of data.
iv. Point precipitation values were used to calculate the catchment average rainfall.
v. An estimation of runoff parameters was performed for the headwaters of the catchment.

vi. Runoff parameters were checked and applied to the remainder of the catchment if suitable.

vii. A set of reservoir inflow hydrographs and hydrographs at downstream control points was generated.

viii. A reservoir system model was used in conjunction with the generated hydrographs to assist in making reservoir release decisions.

ix. Results were displayed and further simulations were performed using alternative precipitation values and operation policies.

The system was, at the time the report was published, operating in the Scioto River Catchment, USA. All of the components of the system were found to perform satisfactorily to assist in making operational decisions. It was noted that the major limitation of the forecasting system was the spatial and temporal estimation of rainfall. It was hoped that with the use of radar this problem would be overcome (Pabst and Peters, 1983).

2.2.3. Real time reservoir operation and irrigation scheduling

A Forward Dynamic Programming (FDP) model was developed by Teixeira and Marino, (2002) for use in optimising reservoir operations and maximising profits to irrigation districts. The model is made up of three modules, namely an inter-seasonal module, an intra-seasonal module and a real-time updating module. The inter-seasonal module uses 6 months of forecasted meteorological and hydrological information to allocate water to irrigation districts. This module is run with the purpose of maximising the net profit from the system taking the maximum irrigated area and the maximum release into consideration. The intra-seasonal module takes the output from the inter-seasonal module and uses it to define an optimum irrigation schedule. The constraints in this case are the capacity of the water conveyance system and the soil-water storage capacity while the objective is to maximise the net profit. The real-time updating model is used for prescribing the timing and quantity of irrigation events and for providing soil-water status information. The real-time module is also updated as soon as actual meteorological information becomes available and water allocation for the day can be refined (Teixeira and Marino, 2002).

The FDP model was tested in northeast Brazil on a system comprised of two reservoirs in parallel with three irrigation districts, two below each reservoir and one at the bottom of the system fed by both reservoirs. The inter-seasonal module was run first and the system was constrained by a minimum release for an urban demand and a maximum release before flooding would occur. Five crops were tested on the irrigation districts which had a total area of 5000 ha. The output of the simulations showed that, of the five crops investigated, rice should be planted and that the area of irrigation could easily be increased as both the reservoirs had surplus water at the end of each season. Alternative scenarios were also evaluated, including expanding the area under irrigation, increasing the cost of water and testing the models sensitivity to evaporation. The intra-seasonal module was then run using the area allocated to specific crops and the total water available during a season. The decision variable in this case was the volume of water to be allocated for irrigation. The optimum irrigation schedule showed that a surplus existed even though some crops experienced stress and this was attributed to a conveyance capacity limitation. The intra-seasonal model was run at a daily time step for a 179 day period. As observed information became available, the model could be updated and the forecasts could become more accurate (Teixeira and Marino, 2002).

2.2.4. Daily reservoir operations

Reasons for operating a reservoir on a daily basis include managing floods and making use of streamflow forecasts which may only be accurate for a few days into the future (Turgeon, 2005). The objective of a recent study, undertaken by Turgeon (2005), was to generate stochastic inflows for a reservoir and use these to determine how the reservoir should be operated for the following day. In addition to being operated for the following day, the reservoir still needed to be operated for longer term goals such as flood management during the spring thaw, storage for the dry winters and minimising reservoir spillage (Turgeon, 2005). The study took place in Quebec, Canada where a new reservoir was proposed. Inflow scenarios were generated using a rainfall-runoff model and historical meteorological data. Supply shortage and flood warning trajectories were plotted which gave the upper and lower bounds for operating the reservoir at each time step. An optimisation process was used to determine the best operating policy of the reservoir between the upper and lower bounds as operating policies for dealing with cases outside the curves were already derived. The optimisation sought to maximise the efficiency of the hydroelectric plants downstream of the reservoir. A dynamic programming technique was used to solve the optimal operating policy for 251 years of inflow data and the results showed that flooding occurred in 4 of the 251 years simulated. It was found that the reservoir could not provide enough water during 105 of the 251 years simulated in the summer months. However, it was shown through simulation that if there were higher reservoir inflows during the Spring, these failures could be greatly reduced (Turgeon, 2005).

2.2.5. Reservoir operation using data mining

Although linear programming and stochastic dynamic programming models are capable of being applied to real-time reservoir control, most reservoirs are operated by a set of predefined rules which are determined from the output of simulation models (Bessler *et al.*, 2003). Most reservoirs are operated by algorithms, look up tables or charts that are designed for reservoir operators in conjunction with the experience of the reservoir operator (Bessler *et al.*, 2003).

One definition of data mining is that it is the "search for relationships and global patterns that exist among parameters, but are hidden among the data" (Bessler *et al.*, 2003). A recent study in the United Kingdom showed that data mining works well for both single and multi-reservoir systems. After an optimisation process using historical data, data mining was used by Bessler *et al.* (2003) to determine a set of rules that resulted in the best operating policy for historical flows. These rules were compared to the rules generated by simulations of the system and it was found that the data mining results came closest to those determined using the optimisation process. A disadvantage of using data mining is that significant processing is required before the technique can be used (Bessler *et al.*, 2003).

2.2.6. Umgeni System Management

The Umgeni Catchment contains four dams which supply the large metropolitan areas of Durban and Pietermaritzburg. In addition to these dams, a transfer of water from the Mooi River into the catchment occurs at the top of the system at the Mearn's Weir transfer. At this stage, the Umgeni system is not operated by making fine adjustments to dam releases on a daily basis. A constant, steady release is used and adjustments, if necessary, would only be made on a weekly basis (Summerton and Gillham, 2007). The catchment is unique in that the dams are operated entirely for domestic and industrial purposes. Decision support in this catchment is complex due to the many types of decisions that need to be made and comprises of numerous software packages and databases. The USAT (Umgeni System Allocation Tool) is based on the WRPM and was developed specifically for Umgeni Water. It is run on a quarter annual basis and creates supply trajectories for all the dams into the near future. The WRPM and WRYM are also employed in managing the system and to assist in creating assurance of supply recommendations as well as for long term system planning. Due to the fact that all water is used for domestic and industrial water use, there are severe economic consequences for curtailing water use and, although the models can generate useful statistics, the final decisions are based heavily on experience and consultation within the Umgeni Water organisation (Summerton and Gillham, 2007).

2.2.7. A Review of Dam Operating Systems in South Africa

A recent report (Manqoyi and Nyabeze, 2006) showed the results of an assessment of operating rules, tools and methods at all existing DWAF dams. A total of 243 DWAF dams with a capacity of over one million cubic meters were assessed by meeting or contacting regional DWAF managers. The decision support systems that were reviewed include, among others, the DWAF system, the Orange River Model, the WRP System and the Vaal System Computer Model. The above-mentioned systems are all derived from the WRPM and WRYM and make up 65% (Manqoyi and Nyabeze, 2006) of the storage of the dams that were reviewed as shown in Table 2.2. It is postulated that there is much efficiency to be gained by reducing the number of dams that make use of rule of thumb as their method of operating the dam.

Table 2.2 Dam operating rules, methods and systems used at DWAF dams after Manqoyi and Nyabeze (2006)

Tool/system used to create operating rule	**Number of dams using tool (% of all dams)**	**Total Storage Capacity (million m^3 [% of all dams])**
Drought Operating Rules System	1 (0.4%)	18 (0.2%)
DWAF System	1 (0.4%)	4 (0.2%)
Kalkfontein Water User Association	1 (0.4%)	256 (1%)
Knight Piesold System	3 (1.3%)	96 (0.3%)
Orange River Model	2 (0.9%)	8521 (32%)
Spreadsheet	3 (1.3%)	495 (2%)
System Model	1 (0.4%)	29 (0.2%)
Vaal System Computer Model	24 (10%)	7090 (26%)
WRP System	5 (2%)	809 (3%)
Rule of Thumb	116 (48%)	5402 (20%)
No Operating Rule	86 (35%)	4184 (16%)
Total	243 (100%)	26904 (100%)

A number of internationally and locally used models for water resources planning and operations were reviewed in this chapter. Selected real time operations systems were reviewed as well as a recent survey which showed that at least 35% of the dams in South Africa had no operating rules. In the following chapter, new approaches and technologies that are being applied to water resources planning and operations and which could potentially be applied in South Africa are reviewed.

3. REVIEW OF RECENT DEVELOPMENTS AND NEW TECHNOLOGIES AVAILABLE FOR WATER RESOURCES PLANNING AND OPERATIONS

In this chapter it is shown that recent developments in personal computer speed, the Internet and radar have allowed new technologies to be applied to the field of water resources planning and management. In addition to this, new approaches to solving hydrological problems such as rainfall-runoff forecasting and trading of water use entitlements have also been developed. A review of a selection of these technologies is presented in this chapter.

3.1. Web-Based Decision Support Systems

The internet is becoming a commonly available communications medium in more and more countries. Applications that can benefit from dynamic updating of data and remote maintenance of systems are well suited to the internet as a platform (Thysen and Detlefsen, 2006). Flood forecasting models have recently been developed for the internet which make use of collaboration between a wide variety of experts in real time and which facilitate the rapid transfer of information to decision makers.

In the recent development of a web-based flood forecasting system for the Shuangpai region in China, a three tier approach was adopted which consists of a presentation tier, an application tier and a data tier (Li *et al.*, 2006). This three tier approach allows for the use of models that already exist simply by developing suitable interfaces between the application, the data and the user display. By housing the applications on central servers, the end users are relieved of installing complex applications and can run the applications directly from their web browsers (Li *et al.*, 2006). Updated models are always available on the central servers and this relieves the administration required for updating an offline model on many users' computers. The use of the models is thus independent of the user's operating system and will always run regardless of the operating system installed on the users' computers, as long as the operating system has a fully functional web browser. Models that require computationally intensive calculations are run on high specification servers which are better equipped for these operations than desktop computers (Dymond *et al.*, 2004). Although, according to (Li *et al.*, 2006), the flood forecasting model only performed satisfactorily, it was found that from a user perspective the system was user friendly, widely accessible, flexible and reusable. Although the system developed in this study was not able to be web based, it is recognised that there are significant benefits from having a web based system and this should be considered for further research.

3.2. Radar-Based Rainfall Observations

Although rainfall gauges are cheap, reliable and reasonably accurate for point measurements they fail to capture the spatial variability of rainfall. Rainfall gauges are also weak in recording rainfall from high intensity storms due to splashing of water out of the gauge and under measurement during windy conditions (Wesson and Pegram, 2006). Weather radars are capable of overcoming most of these problems and a network of weather radars exists in South Africa (Wesson and Pegram, 2006). Additional advantages include very quick data acquisition and low cost of operation when compared with vast arrays of rainfall gauges (Neale, 2008). There are a number of data quality issues that must be overcome when using weather radars which include ground clutter, anomalous propagation and beam blocking. The radars begin measurements at 1 km above the ground surface and further errors are introduced when extrapolating rainfall to the ground surface where it is needed for hydrological applications (Wesson and Pegram, 2006). According to Neale (2008), Thames Water has a number of uses for radar based rainfall data including:

- Analysing historic rainfall events to determine flood risks;
- Presenting information to managers very rapidly as opposed to waiting longer periods for rain gauge data to be downloaded on a weekly basis;
- Verification of rainfall runoff models which can be difficult in large catchments and in highly urbanised areas such as central London and;
- Long term catchment studies which require long data sets are made up of a combination of rain gauges and radar based observations.

A recent South African study aimed to improve ground level estimates of rainfall derived from weather radar (Wesson and Pegram, 2006). Firstly, the rainfall was classified as either stratified or convective which allowed the correct semi-variogram to be fitted to the data. Secondly, the 2 km radar image was examined for a bright band, which occurs when ice crystals melt slightly, producing a water layer around them which causes the radar to incorrectly show very large drops of water. Once the bright band was corrected, Kriging techniques were used to extrapolate the radar image downwards to ground level. The technique was tested using both stratified and convective rainfall events at the Liebenbergsvlei research catchment outside Bethlehem. A comparison was made between weather radar images and tipping bucket rainfall gauges and the results showed that the weather radar corresponds well with the rainfall gauges for moderate and high intensity rainfall events, but only showed a weak correspondence for stratiform rainfall events, which is rainfall that falls from clouds that are stable in comparison to convective rainfall clouds (Wesson and Pegram, 2006).

A paper by Sinclair and Pegram (2004) showed a method that could be used for flood forecasting applications in South Africa. The method was based on conditional merging (Ehret, 2002), which makes use of a combination of rain gauge and radar based rainfall observations to maintain the mean of interpolated rainfall as well as the spatial variability obtainable from radar observations. The conditional merging method was tested using the String of Beads simulation model (Pegram and Clothier, 2001) which is capable of producing sequences of rainfall grids. A number of simulated rainfall sequences were produced and the conditional merging method was applied to these sequences. The merged grids were then compared to the original simulated grids to determine the accuracy of the merging method. It was found that the conditional merging technique performed well when compared to the simulated radar and could thus be recommended as the method used as part of the flood forecasting techniques for application in South Africa (Sinclair and Pegram, 2004). Although radar based observations were not included in the system developed in this study, the system could be adapted to use radar based observations as rainfall input to the *ACRU2000* rainfall-runoff model.

3.3. Streamflow Forecasts

The Columbia River reservoir system relies on snow melt for a large proportion of its inflow. It has been found that there is a direct relationship between the depth of snow pack in the contributing catchment and the streamflow that results from the snow melt in the spring (Hamlet *et al.*, 2002). Due to the fact that the Columbia reservoir generates hydro electric power, it is beneficial for a maximum amount of water to be used in the winter preceding the forecasted runoff. Using climate forecasts based on the El Nino/Southern Oscillation (ENSO) and the Pacific Decadal Oscillation (PDO), the reservoir operators are able to create streamflow forecasts that have a lead time of 12 months. This is highly significant as it provides more lead time to the summer streamflows which constrain the operations of the reservoir. The 12 month lead time is an improvement over the 6 month forecasts that are based purely on the depth of the snow pack. The forecasts are used to create refill curves for reservoir operating policy which allow more water to be used during the winter period in preparation for the increased runoff from the snow melt in the spring and summer (Hamlet *et al.*, 2002).

The ECHAM4.5 Global Circulation Model (GCM) was used in a study in Scandinavia by Nilsson *et al.* (2008) for producing streamflow forecasts. The main driver for this process is the variation of sea surface temperatures (SST) which provide meteorologists with atmospheric predictability on a seasonal time scale (Nilsson *et al.*, 2008). The study used in a canonical correlation analysis (CCA) to determine which GCM parameters were most suitable for streamflow prediction. It was found that the two parameters of zonal wind and moisture were the most suitable parameters. Both a probabilistic and a deterministic forecast model were used and the results were compared with observed streamflow records as well as a climatology model. It was found that there were five stations which showed a good correlation between forecast and observed information but these stations were located near to the coast where prevailing winds influence the local climate. In a nearby region located in the lee of the Scandinavian Mountain Range the models had a lower score (Nilsson *et al.*, 2008).

A similar exercise was carried out in South Africa by Landman et al. (2001). The GCM used in this study was COLA T30 and the comparison between observed streamflow and forecast streamflow was made at the inlet of 12 dams in the Vaal and Tugela river catchments. The GCM produced coarse forecasts which had to be downscaled to a catchment level. The forecast skill was found to be high for 5 of the 12 catchments. However, no relationship could be found between the size of a catchment and the skill of a forecast (Landman *et al.*, 2001). The forecasts were for a three month period and had a lead time of between 1 and 3 months and thus could be very useful for application in a water accounting system. During the time that this research was carried out, in 2007 and 2008, the University of Pretoria had an agreement with the University of KwaZulu-Natal to provide rainfall forecast data in the form of Conformal-Cubic Atmospheric Model (C-CAM) grids. The C-CAM was developed by the CSIRO in Australia (Reason *et al.*, 2006) and is a GCM which is able to provide relatively high levels of detail in areas of interest by using a variable stretched grid. In South Africa, the C-CAM is used by the University of Pretoria to provide daily weather forecasts at a grid resolution of 15 km by 15 km (Rautenbach, 2008).

3.4. Stochastic Rainfall Generation

A recent paper by Srikanthan and Pegram (2006) outlined a method which allowed rainfall information to be stochastically generated at a number of rainfall sites. This is particularly useful when compared to generating rainfall at a single site only because of the spatial dependence of rainfall within a region. Models have been developed for this purpose in the past and include conditional models, extension of Markov chain models, random cascade models and nonparametric models (Srikanthan and Pegram, 2006). An adapted version of Markov chain model was used in this study and applied to three Australian catchments. The model was tested using a log-odds ratio, which is a measure of the pair wise correlation of a pair of sites, and the wet fraction, which is the ratio of rain days to the total number of days (Srikanthan and Pegram, 2006). The model was tested by comparing one hundred stochastically generated sequences of rainfall to the historical record and the results showed that spatial correlation was satisfactorily preserved. Previous methods of correlating pairs of rainfall sites were found to be cumbersome but the root finding method developed in this study was found to be efficient and performed well (Srikanthan and Pegram, 2006). This technique is well suited to the system developed in this study due to the importance of rainfall as the primary input to the *ACRU2000* rainfall runoff model. However its inclusion was beyond the scope of this study and hence was not included.

3.5. Ensemble Streamflow Prediction with Sampling Stochastic Dynamic Programming

The objective of a recent study in Korea (Kim *et al.*, 2007) was to enhance reservoir operations using sampling stochastic dynamic programming (SSDP) and ensemble streamflow prediction (ESP). An investigation of water resources in Korea in 2001 showed that large supply deficits are likely to occur by 2011 and that improving reservoir operation could alleviate this deficit by one third. This prompted investigations into enhancing reservoir operations as there is little opportunity for constructing large dams in the future. A monthly operating policy was investigated which takes the hydrological state of the entire catchment as well as storage levels of many reservoirs into account (Kim *et al.*, 2007).

The first step in the modelling process was to generate ESP scenarios and this was accomplished with the use of a rainfall-runoff model that was configured for the region. Rainfall records for 20 years were used as input and the model provided 20 years of daily runoff values which were summed into monthly values for the study. The optimisation process used the ESP's as input and sought to minimise an objective function which included minimising water shortage at four strategic points and maximising energy production from hydropower reservoirs. The SSDP model could then be developed and tested which was achieved by comparing it with a similar deterministic model. The conclusions of the study showed that stochastic models, which include uncertainty, are superior to those that do not and that monthly updating of the operating policy using ESP was beneficial to this reservoir system (Kim *et al.*, 2007). The use of stochastic modelling would benefit the system developed in this study although was not considered in the practical component of the study as it was beyond the scope of this study.

3.6. Trading Water Entitlements

Recent changes in government policy in Australia have allowed for the definition of comprehensive and consistent water entitlements and the separation of those rights from the land title (Shi, 2006). Due to the fact that the allocation of water rights to users are very clear, including how much water users are entitled to and how transferable the water is, results in the ability for holders of these rights to trade the rights. The Australian government has further facilitated water trading through the establishment of policies based on the assumption that competing water markets are the best method of allocating water in a scarce environment (Shi, 2006). There are two types of water trades in Australia, i.e. permanent trades and temporary trades. Permanently traded water comes from the water entitlement itself while temporary traded water comes from seasonal allocations. An advantage of being able to trade in both temporary and permanent water is that users can manage their own risk by either selling their permanent entitlement and buying water on the temporary market or by using their permanent entitlement and selling water on the temporary market when there is a surplus (Shi, 2006).

It was found that in the 2001/2002 seasons that 92% of all water traded in the Murray-Darling Basin was in the temporary market (Shi, 2006). This occurred for a number of reasons including different tax treatments for temporary and permanent trading, uncertainty in future water supply, and difficulty in conceptually separating water rights with property rights. Temporary markets are easier to administrate and have been successfully implemented in many countries around the world (Shi, 2006).

A study of water markets in South Africa found that water markets exist in the Lower Orange River and the Fish/Sunday's River (Nieuwoudt, 2002). A detailed investigation of the Lower Orange River water markets showed that the market has developed due to a shortage of water and table grape farmers wishing to expand their production for the export market. After operating for some time the market was analysed and it was found that the water had moved to the users who could achieve the most return per unit from its use. Although this is a favourable result, the water being used could still have been applied with greater efficiency. Water markets have not become widespread in South Africa because, up to now, most water trades have occurred between intensive water users and dormant water users. The NWA of 1998 stipulates that dormant rights will fall away in the future and this makes the intensive users unsure of the future market and therefore uneasy (Nieuwoudt, 2002). It is hoped that the trading of water use entitlements would be facilitated by the system developed in this study through the creation of clear, accurate and defendable records and knowledge of the amount and ownership of water.

This chapter contains a review of recently developed technologies for application in water resources management. It is evident that there are new technologies that could be applied to solve the water accounting challenges. The following chapter contains a detailed description of the desired project outcomes thereby allowing the end goal to be considered during the technical review in the three chapters following the next chapter.

4. REQUIREMENTS FOR THE SYSTEM

In order to fulfil the objectives of assessing *ACRU2000* and MIKE BASIN to accommodate water accounting, and to meet the broad objectives outlined in Chapter 1, it is useful to start the process with the outcome clearly defined. In this chapter the outcomes required to meet the objectives of the study are expanded on and detailed.

As stated in Chapter 1, the objective of this study is to assess the capability of the *ACRU2000* and MIKE BASIN models to perform the following analyses:

- Monitor and track water as it moves through a river network, thereby facilitating auditing of water availability and use.
- Enable individual network segments to be queried for information, such as observed streamflow, simulated streamflow, source of water, destination/ownership of water.
- Make use of climate and streamflow forecasts to assist in making improved water management decisions.

This chapter will focus on three components that are required in order to meet the project objectives. The three components are a time series database, the *ACRU2000* rainfall runoff modelling and the MIKE BASIN network allocation model.

4.1. Time Series Database

In order to simulate the hydrological and institutional arrangements of a large catchment in real time, data needs to be collected from various sources, transformed into the correct units and archived in a structure to enable simulation models to access the data. Physically based conceptual rainfall runoff models generally require many types of input data when compared to black box calibration models (Tan *et al.*, 2005) and this data needs to be efficiently managed. Some of these input data do not need to be adjusted on a real-time basis as they do not change rapidly but other data, particularly rainfall, needs to be updated frequently. An application of the Microsoft Access database for the New Jersey water-transfer data system (NJWaTr) was documented by Tessler (2003). The database was required to house information that could support the analysis of water budgets and the development of water management plans. An advantage of using the Microsoft Access database was that it was small and portable and thus accessible to a large number of users. A disadvantage of this is that the database cannot be updated at one central location and a user will need to keep downloading the latest version of the database. Some of the design principles that were used during the design phase of the NJWaTr included:

- using a data-modelling tool to design the database and thereby hide some of the complex yet mundane aspects of database design;
- visualising the database design using entity/relationship diagrams which depict the database entities and the associated links with a series of boxes, arrows and colours;
- normalisation which involves eliminating data redundancy through storing values in only one location and using surrogates for those values in other tables and;
- using a well defined naming convention which allows someone to understand the database structure simply by learning the naming convention (Tessler, 2003).

Although it was not within the scope of the reviewed report to comment on the success of the NJWaTr database, there are many useful and important database design principles that can be applied to this project. According to Maidment (2004), a data model can assist in combining geospatial data that describes a catchment's morphology along with temporal data that describes the dynamics of water resources. For this reason a group of users, coordinated by the Center for Research in Water Resources at the University of Texas at Austin, developed the Arc Hydro data model. The Arc Hydro data model has been applied both to urban hydrology by San Antonio River Authority and to basin hydrology by the Texas Commission for Environmental Quality (Maidment, 2004). Although this data model is well suited to storing hydrological data it was concluded that the model was too complex and time consuming for application to a project of this nature.

It is thus proposed that a database be used for archiving these types of data from their original sources and for deploying the data to the models in the format that is required. The database used for this project is for a smaller, personal computer scale and it is envisaged that a large enterprise database is not necessary. Enterprise databases are capable of storing large amounts of data but are more complex to operate and may require dedicated hardware which is not available for this project. Ideally the database management program will have the capability of being customised. These customizations would include forms, buttons, combination boxes and other user-friendly graphic user interfaces which simplify importing and exporting of data and other database maintenance tasks. In terms of information flow, a desired outcome of the system is a tool, or set of tools, capable of importing, storing, manipulating and exporting rainfall and other times series data in the correct format for use in a rainfall runoff model. This idea is expanded upon in Chapter 5 where the database structure and graphic user interface are further developed. Other information that may be required by the *ACRU2000* and MIKE BASIN models include observed streamflow, monitored water use and user requests for water from a source (i.e. river or dam). User requests for releases from a dam are not a universal feature of catchments in South Africa. However, they are present in the Mhlathuze River catchment which is a water stressed catchment and which is receiving considerable focus. Monitored water use and streamflow at various locations in the catchment will facilitate an audit of water resources in the catchment, as this information can be compared to water allocated by the apportionment rules in the catchment.

4.2. *ACRU2000* Rainfall-Runoff Model

Historical or stochastically generated runoff information is necessary for determining long term system yield in order to allocate water and determine the rules to apply during times of water restrictions (DWAF, 2001). Forecasted runoff information is useful for long term scenario investigations and is generally generated from land use or climate conditions which differ from the current conditions (DWAF, 2001). However, for making daily operational decisions a water manager would benefit from having runoff information that is updated on a daily basis for the near future. Physically based rainfall-runoff models are not typically applied for short term planning and operations and this need is addressed in Chapter 7 where the *ACRU2000* model is reviewed. As a result of this non-typical application of rainfall-runoff models, there are issues such as model "warm-up" time and model simulation time that need to be taken into account. This may be of little consequence in a smaller catchment where a simulation may take a few minutes to run. However, in a large catchment this simulation time could limit the usefulness of the system, and the simulation time needs to be addressed.

The ideal output from a rainfall-runoff model into the system would include a detailed breakdown of runoff into its components. Examples of these components include baseflow, delayed stormflow and quickflow. By having this detailed information on the source of the generated runoff, a water manager is able to better understand where the water in the catchment originated and would be better informed to make decisions regarding the ownership and use of that water.

4.3. MIKE BASIN Network Allocation Model

A network allocation model that is capable of distributing water through a system of rivers, dams and canals to users, while complying with the institutional arrangements of that system, is required to meet the objectives of the system. In addition to this, the branding or partitioning of water according to ownership is required in order to perform an audit of the water use. In the context of this project an audit could be defined as the reconciliation of actual water use with allocated water. A summary of the envisaged auditing requirements are presented in Table 4.1.

Table 4.1 Summary of water audit requirements for the system

Nature of audit	**Location of audit in system**	**Data requirements for audit**
Compare the water requested to the water used	Database query	Water orders, monitored water use (e.g. from flow gauges, user pumps)
Compare the water allocated to the water used	Database query	Water allocation, monitored water use
Compare simulated runoff to observed runoff	Database and network model query	Runoff model output, observed flow data from weirs or other gauging systems
Determine the sources and destination of water packets	Network model query	Water allocation rules for the entire catchment
Determine water losses/ compliance with licences	Network model query	Comparison of simulated runoff to observed runoff at a gauged location within a catchment

The ideal network allocation model would be able to track parcels of water from the point at which ownership is transferred to the user who owns the water. The model should be able to interrogate any section of the network and provide information such as the sources and destinations of the water in the segment, as well as the proportions owned by each user in the catchment. The advantage of this approach is that a water resources manager is able to determine if there is enough water in the system to meet the demands of the users and the environmental reserve while also ensuring that sufficient water is stored in the dams to meet demand during seasons of low rainfall when the dams will be drawn down. Assuming that user requests, entitlements and actual use are available in real time, an audit can be performed to determine if water is being used lawfully. It is anticipated that interactively choosing components of the network and running queries on these components from a GIS will be the most appropriate method for performing an audit.

Apportionment rules are a critical component of this system as they determine the manner in which water is distributed among the users. There are a number of methods of apportioning water and the system needs to be capable of handling the different approaches. The network model is thus required to be flexible in how water is apportioned in the network and may need modifications in order to accurately represent the rights of users in the system. Licences to use water in South Africa at present provide users with an annual volume of water at a specified assurance of supply (DWAF, 2001). There are, however, other schools of thought as to how best a license should be issued to a user. These include the use of fractional water allocation with water banking and a monthly allocated volume as opposed to an annual allocation (Lecler, 2004). The output from the apportionment rule is required for both the network model and the database in this system. The network model needs to know where to send the water and the database needs water allocation information on a daily basis so that an audit of water allocated against water use can be performed.

The three components that have been outlined in this chapter, namely a time series database, the *ACRU2000* rainfall-runoff model and the MIKE BASIN network allocation model, are covered in more depth in the following three chapters. A summary of these components and the links between the components for this study are presented in Figure 1.1 and will be referred to again in the remainder of this document as a guide for the reader.

5. DEVELOPMENT OF A TIME SERIES DATABASE

The database software used in this project is the Microsoft Access database. This database is suited to smaller applications as it only requires a personal computer, but has a capacity limit of two gigabytes (Microsoft, 2006). Another advantage of using this database is the Visual Basic for Applications (VBA) programming language which provides easy access to the internal functions of the database and allows for customisations to be performed. Much of the data that is used in the project either originates from text files or needs to be output in text files and Microsoft Access is capable of dealing with this type of data.

5.1. Role of the Database in the Project

In order to meet the objectives of the study and to interface two hydrological models, each with different functions, a significant amount of data is required. The database has the potential to minimize the exposure of the user to manipulating data directly by providing an easy to use interface to handle these tasks. The role of the database in the project is thus to provide an interface between the input data and the hydrological models, as shown in Figure 1.1. The database is required to be able to import and store time series data, convert areal rainfall forecasts into point rainfall forecasts, present analyses of the data and export the data in the format required by the MIKE BASIN and *ACRU2000* models. The data to be stored in the database for use in this project will be historical, real time and forecast rainfall. The source of the rainfall forecasts is the C-CAM, which is reviewed in Chapter 3. The forecasts are provided daily and contain a daily forecast for the next four days. In this project the development of the database has been taken as far as interfacing rainfall forecasts with the *ACRU2000* model. It is anticipated that in order to provide further value the database should be developed to handle other types of real time data such as observed streamflow and observed water use by water users, however, these tables have not been accommodated into the current design of the database. It is proposed that, should the system capabilities be expanded, increased data requirements may warrant the investigation and application of a data model such as the Arc Hydro data model (Maidment, 2004). This information would not need to be processed by the *ACRU2000* model and would serve as part of the network queries in the MIKE BASIN model.

5.2. Designing the Database Tables

The database is made up of three tables. Two tables store time series data while the third table stores the relationship between a catchment and a rainfall station. The time series data tables implemented in this study hold observed historical and observed real time rainfall data and rainfall forecasts, but could be easily adapted to store user demand and observed water use if required. The observed rainfall table is called "tbl_Observed_Rainfall" and is shown in Table 5.1. The five fields in the table are:

i. "fRecID" is an automatically numbered field that increments with every record added to the table;
ii. "fStationID" is a text field holding the rainfall station identification code;
iii. "fDate_YMD" is a date field holding the date of the rainfall record;
iv. "fRainfall_mm" is a numerical field holding the rainfall value for that record and;
v. "fDataQualityCode" is a text field holding the data quality code for that record.

Table 5.1 Example of "tbl_Observed_Rainfall" from the time series database

fRecID	fStationID	fDate_YMD	fRainfall_mm	fDataQualityCode
750704	0303127W	1991/12/01	2.3	P

The forecast rainfall table is called "tbl_CCAM_rainfall_forecasts" and is shown in Table 5.2. The four fields in the table are:

i. "fRecID" is an automatically numbered field that increments with every record added to the table;
ii. "fDateOfForecast_YMD" is a date field holding the date of the CCAM forecast;
iii. "fCatchmentCode" is a number field holding the catchment code of the forecast and;
iv. "fDay1Forecast_mm" is a number field holding the forecast value for the sub-catchment. This field is repeated three times as each CCAM forecast covers four days into the future.

Table 5.2 Example of "tbl_CCAM_rainfall_forecasts" from the time series database (note table has been drawn on two lines due to long field names)

fRecID	**fDateOfForecast_YMD**	**fCatchmentCode**	**fDay1Forecast_mm**
746	1999/01/01	1	1.2

fDay2Forecast_mm	**fDay3Forecast_mm**	**fDay4Forecast_mm**
0	3.1	5.0

The third table in the database is called "tbl_Forecast_Mappings". This table is required for the data export process and is used to link sub-catchments that have been used to extract data from the CCAM file with an observed weather station. This is required as ACRU2000 uses "driver rainfall stations" as its rainfall input and the database needs the correct file name to export the C-CAM forecast data to. The "driver rainfall station" in *ACRU2000* is the rainfall station that is used as direct input of water into a catchment where one rainfall station may be used for input to many catchments. The table is shown in Table 5.3 and is made up of three fields namely:

i. "fRecID" is an automatically numbered field that increments with every record added to the table;
ii. "fObserved_Station" is a text field holding the observed rainfall station code and;
iii. "fForecast_Catchment" is a text field holding the catchment code of the forecast.

Table 5.3 Example of "tbl_Forecast_Mappings" from the time series database

fRecID	**fObserved_Station**	**fForecast_Catchment**
3	0303127_W.txt	2

5.3. Designing the Database Dashboard

The database dashboard is a Microsoft Access form that has been customised for this database to allow for easy importing and exporting of data. The computer code for the customizations can be found in Appendix A. The database dashboard is divided into four related areas for easy navigation. The four areas are: database management; system status; data import; and data export. The layout of the database dashboard is presented in Figure 5.1.

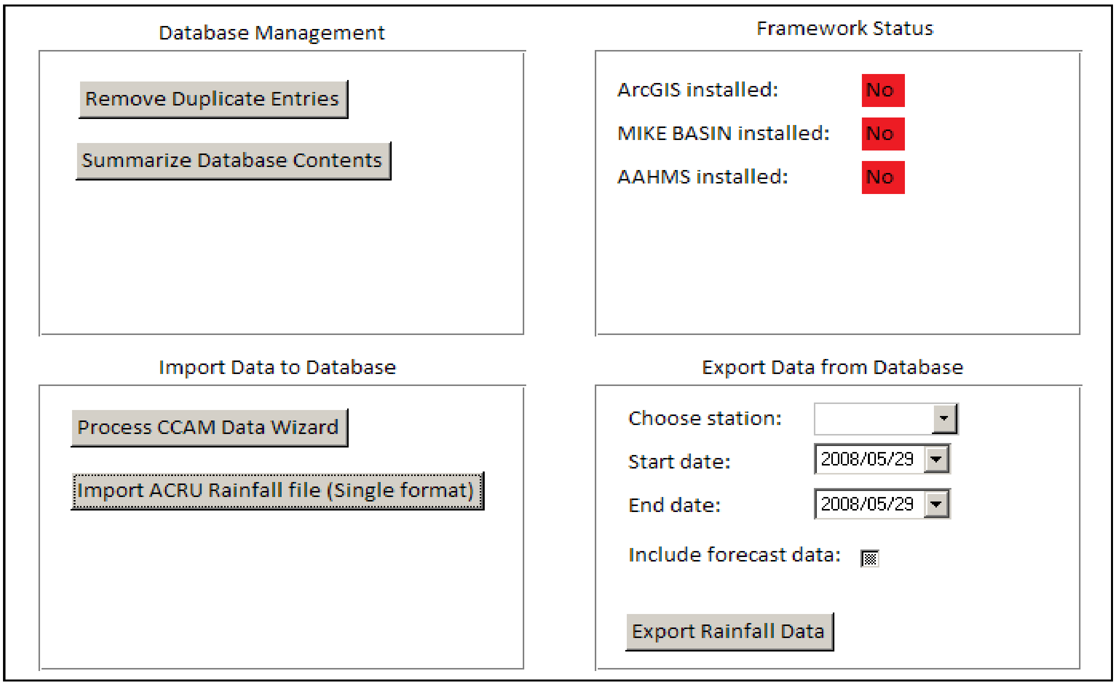

Figure 5.1 Microsoft Access customized form for access to important database functions

The database management section of the dashboard contains two buttons. The remove duplicate entries button searches the database for any duplicate records and removes them. The summarise database contents button presents a new form which provides a brief summary of the time series data that the database contains and is shown in Figure 5.2. The summarised form displays the number of rainfall stations, number of forecast catchments, dates of earliest and most recent data and a graphic indication of the overlap of observed and forecast data. The forecast catchments are derived from a forecast raster layer where the average rainfall for each subcatchment is calculated as detailed further in this section of Chapter 5.

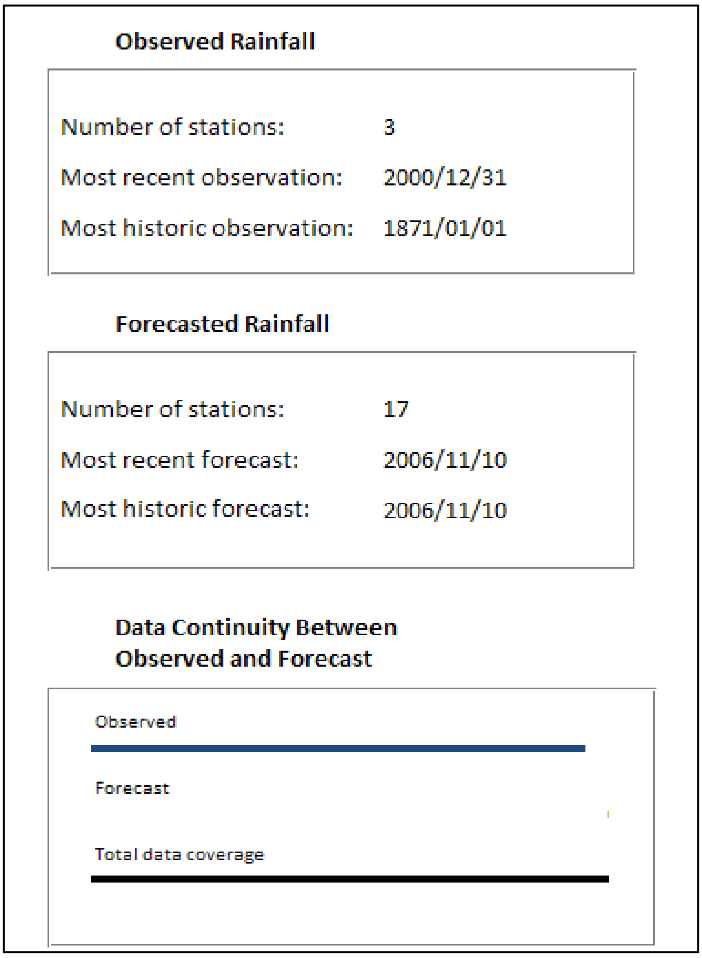

Figure 5.2 Microsoft Access customized form for summarising database contents

The system status section of the database provides an indication of whether the software components needed for the system are present on the computer. When the database dashboard form is first loaded into memory a procedure checks for ArcGIS, MIKE BASIN and the *ACRU2000* on the computer and a green "Yes" or a red "No" are displayed according to the result.

The import data section of the database dashboard is made up of two buttons. The process C-CAM data wizard starts a step wise procedure for converting a raw C-CAM forecast into a catchment rainfall forecast for use in the *ACRU2000* model. The procedure can be outlined as follows:

i. The C-CAM text file is converted to a Microsoft Windows text file format if it is found to be in a Unix text file format. This is performed using a command line application called "todos.exe" (Heng, 2008). This step is performed so that unnecessary characters are removed from the file which is necessary for the following step.

ii. An ArcMap document is launched which uses a macro to open the C-CAM text file which was converted to a Microsoft Windows text file in the previous step. The macro creates a comma separated values (CSV) file from the tab delimited C-CAM file.

iii. The CSV file is imported into ArcMap and displayed as a point grid by the macro. This is done by automating the "Add XY Event Layer" which is a function of ArcMap. The CSV file provides the X coordinate, Y coordinate and four days of C-CAM forecasts.

iv. The macro then automates the conversion of the point grid to a raster. This is performed through automating the interpolation of a raster using Inverse Distance Weighting. A raster is required so that an average value for a an area can be extracted which is not possible using a point grid.

v. A catchment polygon layer is used by the macro to extract the average rainfall value for each subcatchment in the polygon layer. This is performed by extracting a section of the raster based on the shape of a subcatchment. The mean value for this extracted section is determined using the RasterBand Statistics ArcMap object.

vi. The average rainfall values that were extracted from the raster or stored in a CSV text file which is where the ArcMap macro's function ends. From this point a macro in Microsoft Access is used to import the rainfall forecasts into the database.

The other button on the import data section of the database is called "Import *ACRU* Rainfall file (Single format)." This button is used for importing existing *ACRU2000* rainfall files and would typically be used when the database is first set up and does not yet contain any data.

The export data section of the database dashboard contains controls for selecting observed and forecast data and exporting it in an *ACRU2000* single format text file. The controls allow a rainfall station, start date and end date to be specified and includes an option for forecasts to be utilised. If the "include forecasts" option is selected then the output will include any forecast data that is within the start and end dates and does not take preference over any observed information within that period.

A review of the method used to develop the time series database has been presented in this chapter. It is expected that the time series database will prove useful to the water accounting system by eliminating tedious work, reducing errors and increasing the potential for data to be shared by parties involved in the system. The following chapter contains a review of the method used to set up *ACRU2000* as well as the motivation for using *ACRU2000*.

6. RUNOFF SIMULATION USING THE *ACRU2000* MODEL

ACRU2000 was selected for use in this project as it has been widely verified for catchments in South Africa (Pike and Schulze, 2000) and substantial experience with the model was available. In addition, it was desired to test the recent developments which link the *ACRU2000* and MIKE BASIN in a real time context as detailed in Section 6.3. *ACRU2000* is a rainfall-runoff model that has been used for a variety of applications such as water resources assessment, design flood estimation, irrigation water demand and supply and the assessment of the impacts of land use change on water resources (Smithers and Schulze, 1995). These applications typically involve simulating the rainfall-runoff process using many years of data. This is of relevance to the project due to the fact that, in near real time and forecast modes, only a few days of simulated streamflow are required. However, it is acknowledged that before the *ACRU2000* model can be considered to be simulating adequately, at least two years of simulation must be performed. This allows the slowly responding groundwater storages to be accurately accounted for (Schulze, 2008).

6.1. The *ACRU2000* Model

Originally developed in the FORTRAN programming language, a version of the *ACRU* model was programmed in the Java programming language and named *ACRU2000*. The reason for this was to make the model more extensible as Java is an object oriented programming language (Clark *et al.*, 2001). The pre-*ACRU2000* FORTRAN versions of the model had become cumbersome for developers to make changes to the source code and thus a more modular approach was required for the design of the software. It was thus decided to adopt an object oriented approach to programming the *ACRU2000* version so that real world objects, processes and storages could be represented by objects in the source code. The three most important objects in the model are components, processes and data. These objects relate to real world hydrological features, as indicated in the Figure 6.1. Components include vegetation, climate, reach, and segments while processes include surface flow, subsurface flow and groundwater flow while data includes precipitation and reach flow. The interaction between these components can be seen in Figure 6.1 where, after precipitation, surface flow, subsurface flow and groundwater flow move through the land segment. Vegetation and climate have an impact on evaporative use of water and the remaining water ends up in the reach.

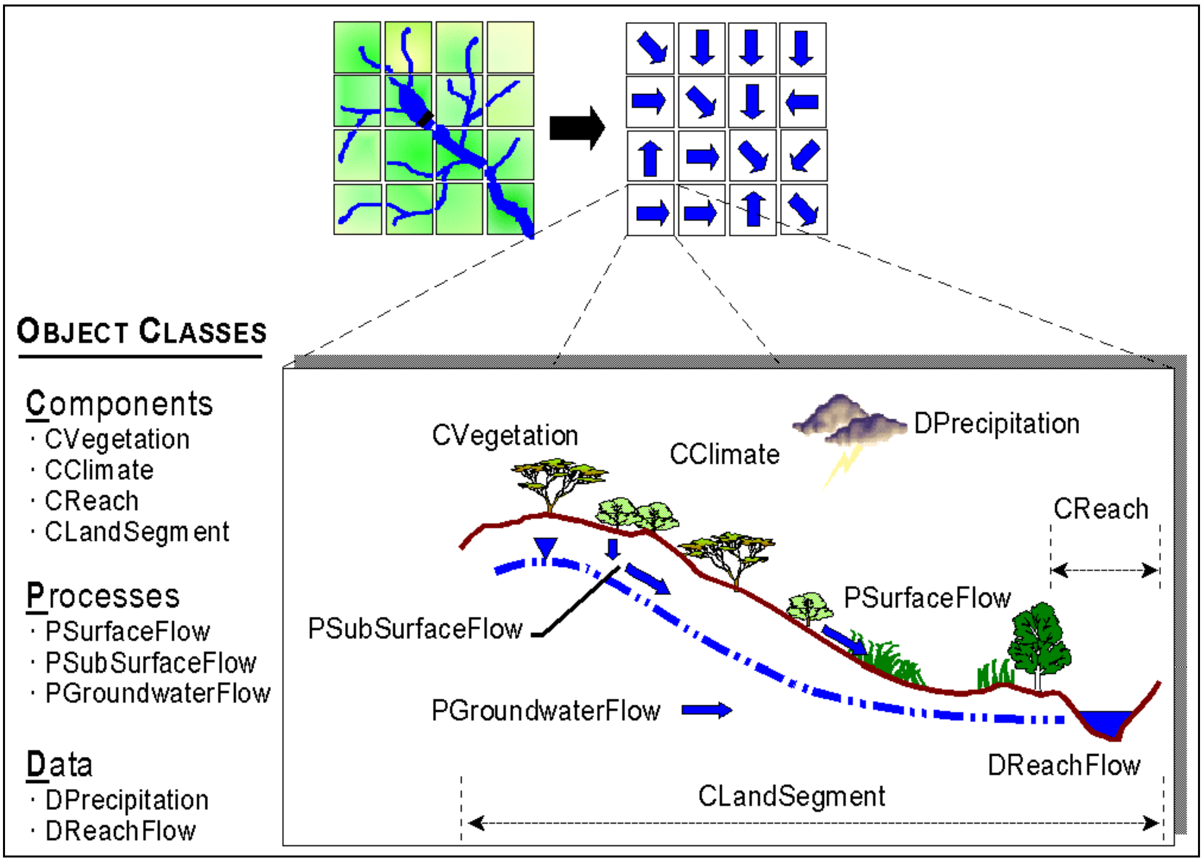

Figure 6.1 Examples of object classes in *ACRU2000* (Clark *et al.*, 2001)

6.2. Hot-Starting the *ACRU2000* Model

In order to operate a large catchment it is anticipated that a rainfall runoff model should be capable of being stopped at the end of a day and then resumed the following day using updated climate and streamflow data. Due to the fact that simulations of at least two years of data should be performed before *ACRU2000* output is considered suitable for use, there was a concern that the extra simulation time would make the system unsuitable for use in an operations environment. An investigation was made to enable the *ACRU2000* model to be "hot-startable". Hot-starting can be described as saving the state variables in the model at the end of a simulation period and then being able to use those state variables again as the starting point for another simulation. This would allow for the simulation of a single day or week to be performed, with results similar to a two year "warm-up" simulation, but many times quicker to perform. This was confirmed by a timing exercise as part of the project investigation whereby the output to the screen from an *ACRU2000* simulation was timed using a stopwatch. The computer used to perform this simulation had a Pentium 4 2.4 gigahertz processor and 512 megabytes of random access memory. It was observed that, for a simulation of 138 subcatchments, it took the model 7 seconds to initialise and thereafter 60 seconds to perform 730 days of simulation. Thus, in this example, hot-starting would save approximately 59 seconds. Due to the fact that numerous *ACRU2000* simulations could be required, based on numerous rainfall forecasts and other scenarios, any time saving would be compounded. After consulting Clark (2007), it was decided to use object serialisation to make the *ACRU2000* model hot-startable. Object serialisation is the process whereby objects in memory are written out to either a binary or a text file on the hard drive such that they may be able to be read back into memory and used again (Evans, 2000).

A number of approaches were evaluated to perform this task. The first approach was to serialise the entire model object into a binary file and reuse that file to start the model again. This approach was taken as it was anticipated that, although a very large file may be produced, serialising the entire model object would save all possible data and this would be the simplest way of achieving hot starting. The "Implements Serialiseable" directive was added to the class file of the model object to allow the class to be serialised. Code was also added to the main loop of the program to write the model object out of memory and into a binary file on the hard disk. A second version of the main program loop was written to read the binary object into memory and to run the model using the serialised object instead of the object created from the *ACRU2000* input data. After the object was successfully read into memory it was found that the model would not run. After investigation, it was found that the reason for this was that the model object contained only a small selection of member variables, and not the entire model as was anticipated. This resulted in a lack of information required for the model to run and the main program loop terminated with errors.

The second approach taken was to serialize the *ACRU2000* data objects at the end of a simulation and then read them back into the model at the beginning of another simulation. The *ACRU2000* data objects contain various types of data that are either read in from input files or adjusted as the model runs and the results are stored for each daily timestep. An attempt was made to use an XML (Extensible Markup Language) file format for the serialised objects. XML files are text files that contain a number of tags which direct the target application on how to process the text that is contained within the tags (Wang, 2002). An example of this is shown in Figure 6.2.

```
<?XML version = "1.0" ?>
<DOCUMENT>
<CUSTOMER>
<NAME>
<LASTNAME>Smith</LASTNAME>
<FIRSTNAME>John</FIRSTNAME>
</NAME>
<PROFESSION>Student</PROFESSION>
<PHONENUMBER>1-800-5412</PHONENUMBER>
</CUSTOMER>
```

Figure 6.2 An example of data stored in the XML format

XML files contain entities and sub entities which form the basis of the organisational structure of the file. In the example shown in Figure 6.2 the customer entity is populated with a number of sub entities such as name, profession and phone number. XML files were anticipated to be useful as they would be human readable and the data stored in the XML files could be adjusted or viewed by an external program. The serialisation of the objects from memory to the hard disk was successful and the XML files that were generated could be opened by a text editor. However, there were problems with this method of serialisation as a consequence of the slow performance and large output file sizes that made this type of serialisation unsuitable for this application. It took approximately thirty seconds to write out each data object and there were a total of 130 objects in memory, resulting in the process taking over half an hour to complete. The example catchment that was used had only a single catchment with a single land use and it was evident that more complex catchments would take far longer for this process to run, thereby negating any benefit obtained from hot-starting the model using this approach.

The final approach to data serialisation was to serialise all data objects into a binary file format and attempt to read these objects back into the model for reuse. Writing out of the data objects was performed by looping through the data objects collection and writing out a binary file for each data object. Each file was named according to the corresponding data object in order to simplify reading the file back in as well as to ensure unique names were used. The speed at which binary files were written out was significantly faster than the XML files. This final approach was the most promising of the three approaches, but was still not successful. The main obstacle to this approach was replacing the in-memory objects with the serialised objects. Although numerous attempts and methods were used to try and accomplish this, it could not be successfully performed and errors were encountered when running the model. According to Clark (2007), a new ACRU2000 menu file is, at the time of writing, planned for development which would see the file format change from text file to XML file. This change in format would theoretically allow for a more structured menu file as well as the storage of model state variables which could be used for hot-starting. It is recommended that further investigation into hot-starting be undertaken once the new XML menu files have been developed.

6.3. Performing the Rainfall Runoff Simulations with the Amalgamation of Agrohydrological Modelling Groups

The Amalgamation of Agrohydrological Groups (AAMG) is an ArcGIS extension that allows *ACRU2000* menus (input files) to be created in a short space of time and the output linked to a MIKE BASIN simulation (Van Der Merwe, 2007). The extension allows a catchment of interest to be chosen and prepares the necessary data and information for generating *ACRU2000* input files in order to run a simulation. With regards to this project, the AAMG is useful as it is capable of quickly generating *ACRU2000* input menus as well as easily converting *ACRU2000* output into a format that can be used in MIKE BASIN. The AAMG is also capable of importing other types of data such as observed streamflow and observed reservoir levels. This information is useful when verifying simulation results. Due to the fact that the AAMG relies on both MIKE BASIN and *ACRU2000*, the use of the AAMG is detailed further in the following chapter in Section 7.3.

A review of the method used to set up *ACRU2000* as part of the water accounting system was presented in this chapter. The *ACRU2000* component of the project is critical for simulating runoff values from either historical, current or forecast rainfall values. The following chapter contains a review of the method used to set up and assess the MIKE BASIN network allocation model for use in a water accounting system.

7. METHOD USED TO SET UP THE MIKE BASIN NETWORK ALLOCATION MODEL

The network allocation model is the most critical component of the project and the motivation for using MIKE BASIN in this project is presented in this chapter. In addition to this the generation of input and the development and testing of a number of network allocation scenarios are presented in this chapter. Figure 1.1 shows the relative location of MIKE BASIN in the project.

7.1. Selection of Model

A number of network allocation models were reviewed in Chapter 2. These include CALVIN, MODSIM, WRPM, WRYM, RiverWare and MIKE BASIN. As mentioned in Chapter 1, RiverWare is the most suitable model for application in this system due to its reported water accounting capabilities. MIKE BASIN is the next most suitable model due to its integration with the ArcMap framework which has facilitated the AAMG, as detailed in Section 7.3. In this project, the MIKE BASIN model was selected for use due to the increasing use of the model in South Africa, the availability of the model to the study and lack of local expertise for the RiverWare software at the time of the study. The MIKE BASIN network allocation model is being increasingly used in South African catchments as discussed in Chapter 1 which referred to studies by CPHWater (2007) and Nyabeze *et al.* (2007).

MIKE BASIN was designed to provide an easy to use interface to river management, water allocation and reservoir operations, among other functions (Ershadi, 2005). In catchments that are regulated by reservoirs, MIKE BASIN is able to model the reservoirs and the demands placed on the reservoirs either by lumping demands and curtailing users based on a rule curve, or by providing each user with their own virtual storage in the reservoir. MIKE BASIN is housed in the ArcGIS framework which allows for easy integration of spatial data with the configuration of the catchment. ArcGIS is well suited to manipulating and presenting data as well as facilitating the development of customized forms and subroutines with the VBA programming language. Although it was decided to use hypothetical data for the rainfall, water use and reservoir properties, the W12 catchment was selected as the test case for use in the project as real data was available for testing should it be required. The location of the W12 catchment is indicated in Figure 7.1 with a blue catchment boundary. As indicated in Figure 7.1, the W12 catchment is located on the East coast of South Africa. The W12 catchment is of interest to the Department of Water and Environmental Affairs due to the current over allocation of water resources in the catchment and a number of water resources research projects have been undertaken in the catchment.

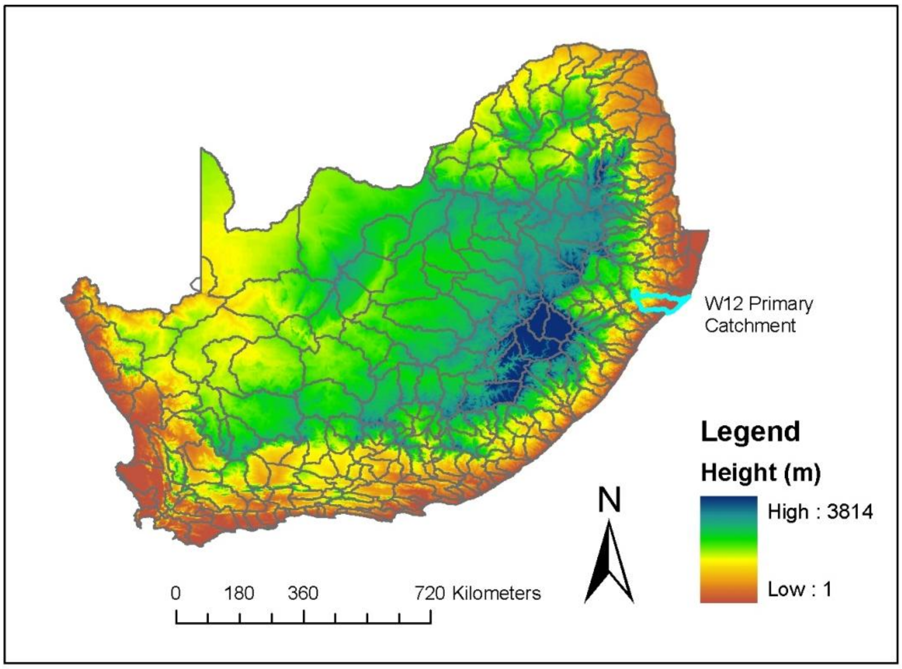

Figure 7.1 Map of South Africa's primary catchments with the location of the W12 catchment indicated

7.2. Apportionment Rules in a Network Allocation Model

Apportionment rules are important in a network allocation model as they define how the water resources of a catchment will be divided up between competing users. Network allocation models have different methods of addressing apportionment rules. Riverware uses a rule based simulation language that provides a run time interpretation of rules (Zagona *et al.*, 2001). Priority ratings are used for these rules to provide an extra layer of control by overriding lower priority rules with higher priority rules (Zagona *et al.*, 2001). Rules are defined using a Riverware-specific rule language and can be based on "if-then-else" statements, looping, mathematical functions or user defined functions (Zagona *et al.*, 2001). The WRYM uses a cost of supply method for determining priority of supply from each node as mentioned in Chapter 2. This rule would result in a high priority user at the base of the catchment receiving allocation before a lower priority user near the top of the catchment. The WEAP model also uses a global priority rule with priorities demand nodes given a priority rating of 1 to 99 (Yates *et al.*, 2005). The demands to priority 1 nodes are fully supplied before other nodes are considered and all nodes with an equal priority will share a deficit if there is not enough water (Yates *et al.*, 2005). The final rule type that has not been discussed is fraction allocation where users are allocated a fraction of the available water. For a reservoir, this would be a fraction of the available storage and, for abstraction directly from a river, users are permitted to abstract a portion of the water flowing past a node.

Ideally the network allocation rules should be derived from the licenses that are issued for water use. The current form of water licenses provide authorization to use an annual volume from a specific location at a given assurance of supply. In this study there are two possible allocation rules that can be analysed. These are local priority rules and fraction allocation. Local priority rules stipulate that each user at an off take node in the river is given a priority of supply. Under this rule set the highest priority user will receive their full allocation before the next priority user is considered. Fraction allocation rules allocate water from an off take node to users by means of a percentage with each user being allocated a percentage of the flow reaching the off take node. These rules only come into effect if there are more than one user at an off take node. The two approaches to water allocation (i.e. local priority and fraction allocation) rules will be evaluated in all the scenarios to determine their effect on water accounting.

In addition to the two rule sets that are available in MIKE BASIN, there are a number of means of joining the water resources to the water users in the model. In order to test these means, three configurations were used in this project namely the default configuration, the virtual channels configuration and the flow components configuration. The default configuration closely mimics reality in that water in the model follows the exact paths that water would follow in reality. The virtual channels scenario shows the effects of providing water to users with a direct connection to the source regardless of where the user is located. The flow components scenario shows how water can be partitioned in the model into the categories of either stormflow or baseflow and how this categorisation is translated downstream. The following sections will present the three methods of setting up MIKE BASIN used in this project and each method will be reviewed against the three main system objectives.

7.3. Constructing the Default Scenario

The first scenario to be reviewed is the application of MIKE BASIN and *ACRU2000* to meet the objectives of the system using the models in their "default" configurations. This exercise will allow the limitations of the default scenario to be determined. The results of the simulation are expected to show that without being able allocate water to higher priority users in the lower portion of the W12 catchment, the lower priority users in the upper portion are able to extract the water first. In the construction of the scenarios, a fictitious catchment is constructed based on the following requirements and assumptions:

i. Accurate historical and real-time data are available for streamflow, rainfall, reservoir releases and levels and user demands.
ii. The catchment should be as simple as possible while still allowing all the issues that are outlined in the project methodology to be investigated.
iii. Synthetic data will be generated so as to test possible effects of different seasons on the reservoirs and users.

Bearing these factors in mind, the W12 catchment was configured in MIKE BASIN using the AAMG to generate an *ACRU2000* menu which can be used for simulating the various components of runoff. The configuration of the catchment was performed in the following manner:

i. The AAMG tool was used to present a map of South Africa's catchments and the W12 catchment was selected, as shown in Figure 7.1. The AAMG tool was then used to clip data grids ready for extraction into *ACRU2000* menus.
ii. A Digital Elevation Model (DEM) was presented for digitisation of the MIKE BASIN network and catchments. The DEM was provided as part of the AAMG and has a resolution of 200m by 200m. MIKE BASIN was used to process the DEM and calculate flow directions of water. A simple network with one main channel and two side channels was created. Catchment nodes were added and the catchment areas were automatically delineated. Six subcatchments were created by virtue of the placement of catchment nodes. The catchment nodes specify an input to the river from a contributing catchment area and are one of the mechanisms in MIKE BASIN for introducing water into the stream.

iii. Rainfall stations were linked to each subcatchment and the AAMG was used to create *ACRU2000* menus based on the MIKE BASIN catchment and rainfall station selection.

iv. Ten water users and one reservoir were added to the network in locations that were anticipated to test the functions of the system and the resulting network is shown in Figure 7.2.

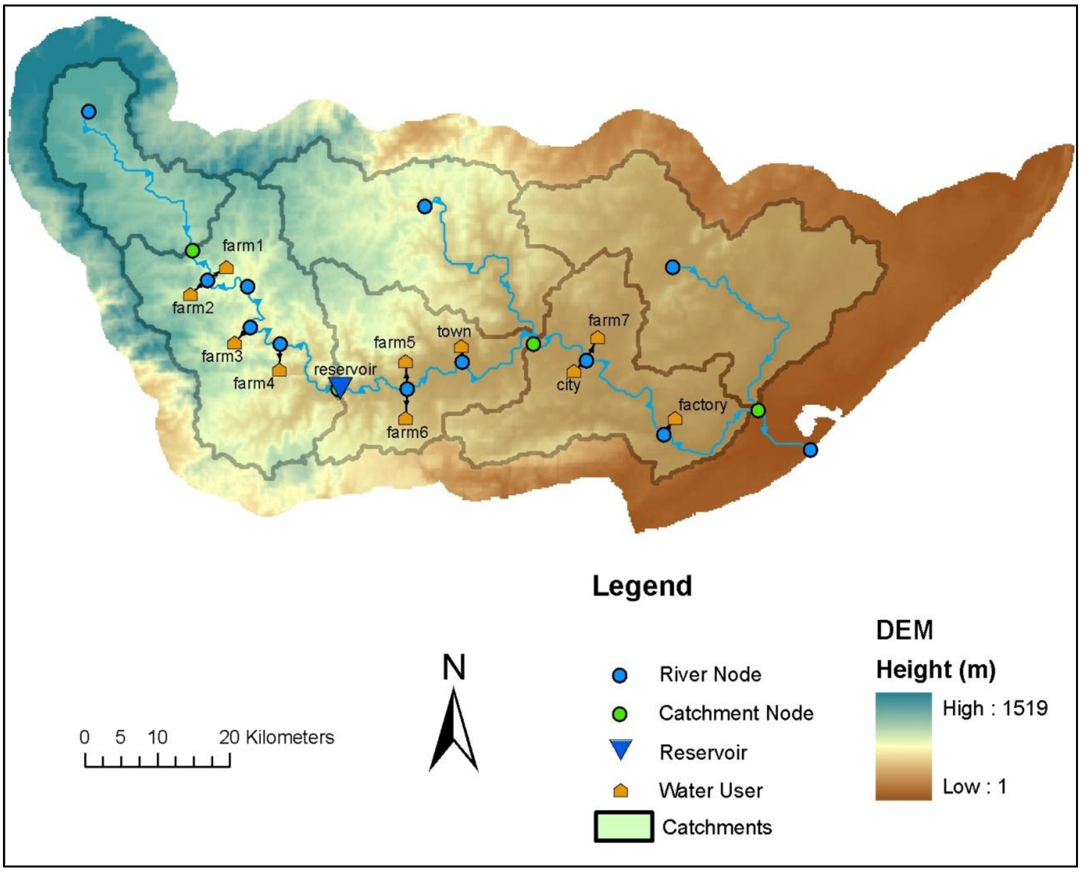

Figure 7.2 Map showing the MIKE BASIN network from the default scenario

As indicated in Figure 7.2 there are a number of implications for water resources management that result simply from the spatial distribution of the water resources and the water users. Farms 1 to 4 receive their water from a single upper catchment area. Farms 5 and 6 and the town receive their water from the reservoir. Farm 7, the city and the factory receive their water from both the reservoir and a catchment area. As indicated in Figure 7.3 the demand values for these users are entered into MIKE BASIN using the DHI Temporal Analyst extension. This ArcMap extension allows information to be entered in a table and thereafter saved for use as a user demand file.

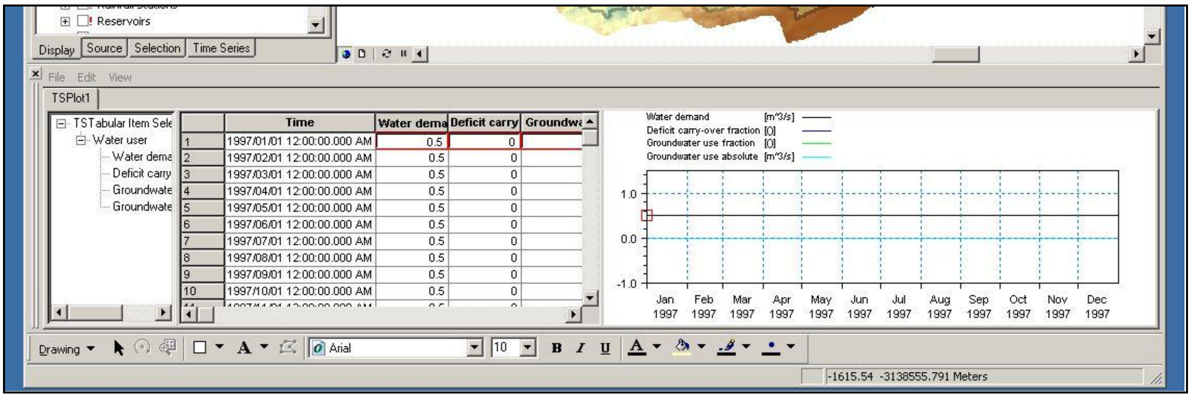

Figure 7.3 Entry of user demand data in a time series table using DHI Temporal Analyst in ArcMap

The final step in setting up the default scenario was to populate the reservoir characteristics and user demands. This required constructing a default reservoir in MIKE BASIN. This was done by using default files for the height-volume-area characteristics, as shown in Figure 7.4, and other characteristics such as bottom level and flood control level, as shown in Table 7.1. The default files are supplied by MIKE BASIN and are usually edited to reflect a dam's true characteristics.

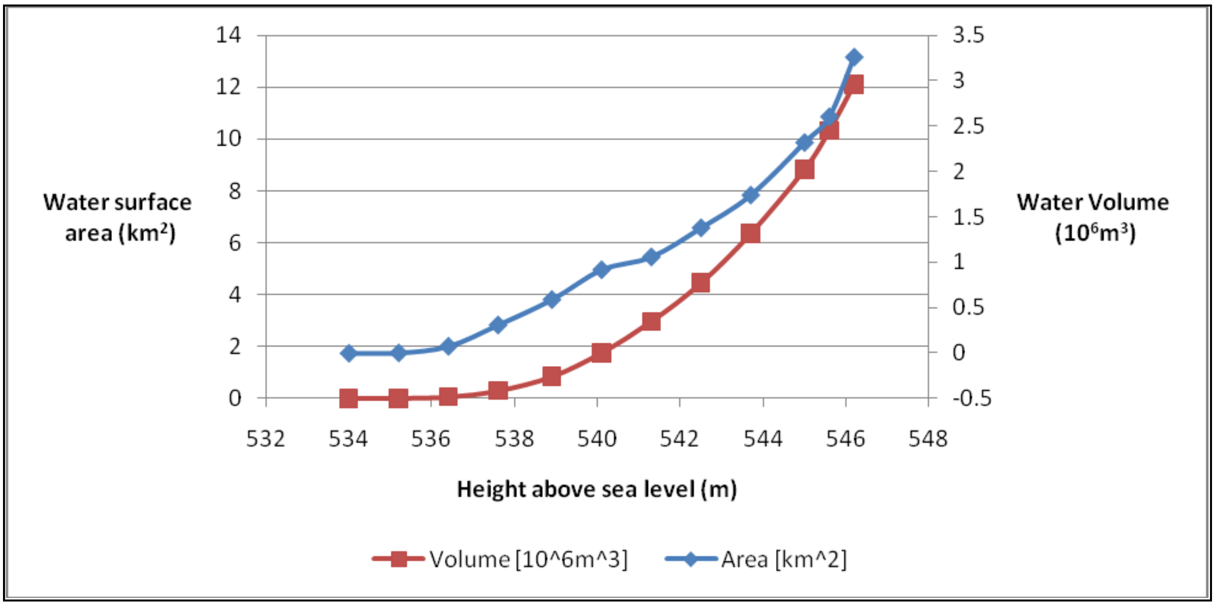

Figure 7.4 Graph showing the height-volume-area relationship for the default reservoir

Table 7.1 Various characteristics of the MIKE BASIN default reservoir

Characteristic name	**Value**
Flood control level	543 m
Bottom level	534 m
Top of dead storage	536 m
Dam crest level	545 m

7.4. Constructing the Virtual Channels Scenario

The same fictitious catchment that has been used and configured in the previous scenarios will be adapted for use in the virtual channels scenario. This scenario is trying to simulate the effect of having an ideal system whereby all water that is allocated from a point is transported from that point directly to the user. By doing this it is possible to determine how much water is theoretically available for allocation should all users only extract what they are entitled to. For this scenario, it was assumed that this catchment has three important supply nodes, two catchment nodes and one reservoir node, which are used to allocate all the water in the catchment. This scenario differs from the previous scenario by the fact that the allocation is performed entirely from the three supply nodes instead of from the closest river node to the location of the users. MIKE BASIN enables this by means of constructing a number of "virtual channels" from the supply nodes to the user nodes as can be seen in Figure 7.5 in the form of the black lines between the supply nodes and the user nodes. The black lines indicate that water is supplied directly from the supply node to the user node and is not transported through the stream. The immediate effect of this is that water can be allocated first to a user that may be downstream of another user. The same runoff information, user demands and reservoir rule curves as the default scenario have been used in this scenario.

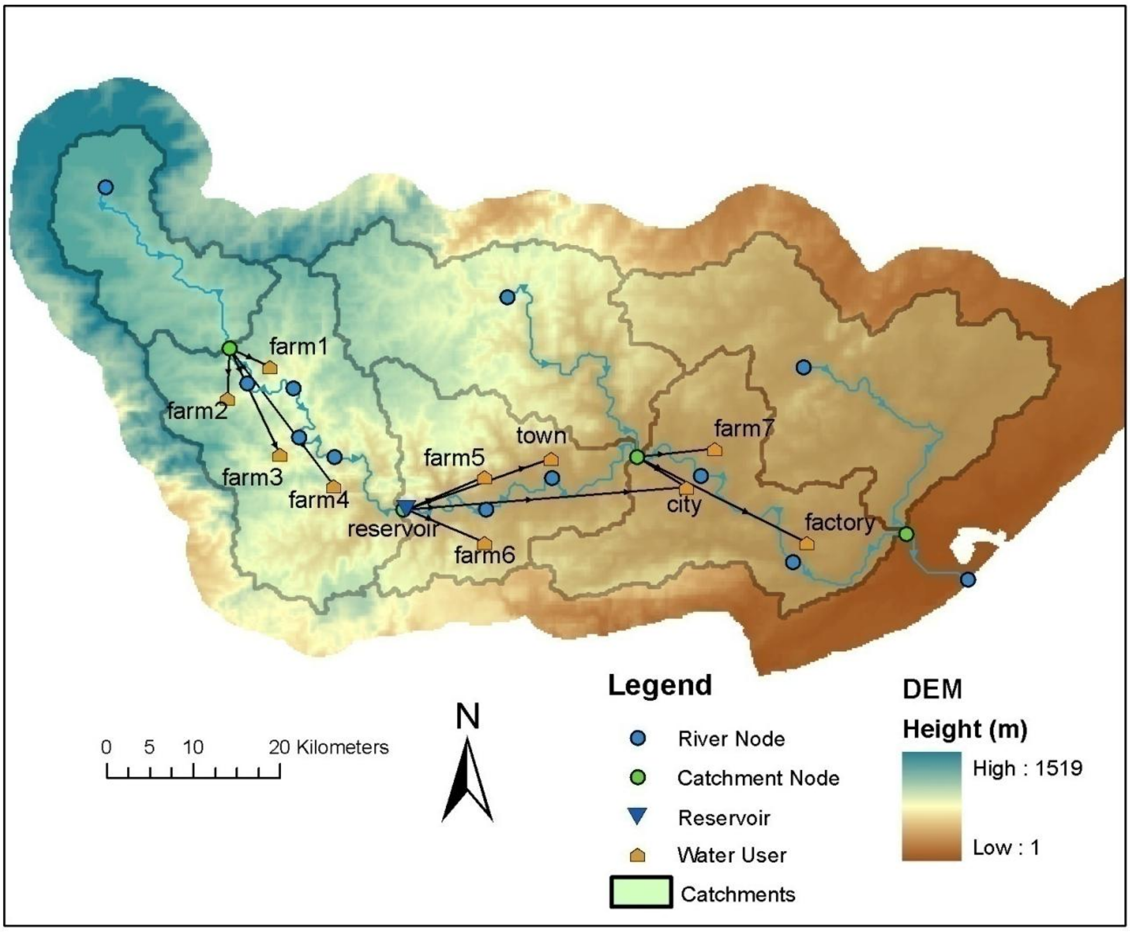

Figure 7.5 MIKE BASIN virtual channels scenario showing water being allocated from three supply nodes

7.5. Constructing the Flow Components Scenario

The *ACRU2000* model is a multi-layer soil water budgeting model and the simulated daily streamflow value for each sub-catchment is the sum of baseflow and quickflow components. Baseflow is defined in the model as water that has originated from the baseflow store which is filled by water percolating through the sub-soil (Schulze, 1995). Quickflow is defined in the *ACRU2000* model as the stormflow response to rainfall which leaves the catchment on the same day, with some of the stormflow response being attenuated to subsequent days according to a quickflow response coefficient (Schulze, 1995). In the event that water use licenses are based not only on quantity of water but also on source of surface water, this scenario could be used to determine the effects of providing water to users based on whether the water is baseflow or quickflow. In order to track the components of streamflow, the approach taken for this scenario was to split each sub-catchment into two pseudo/virtual subcatchments and input the quickflow series into one of these pseudo sub-catchments and input the baseflow series into the other pseudo sub-catchment, as illustrated in Figure 7.6. This approach deviates from reality significantly but should assist in allowing the flow components of runoff to be traced through the river network.

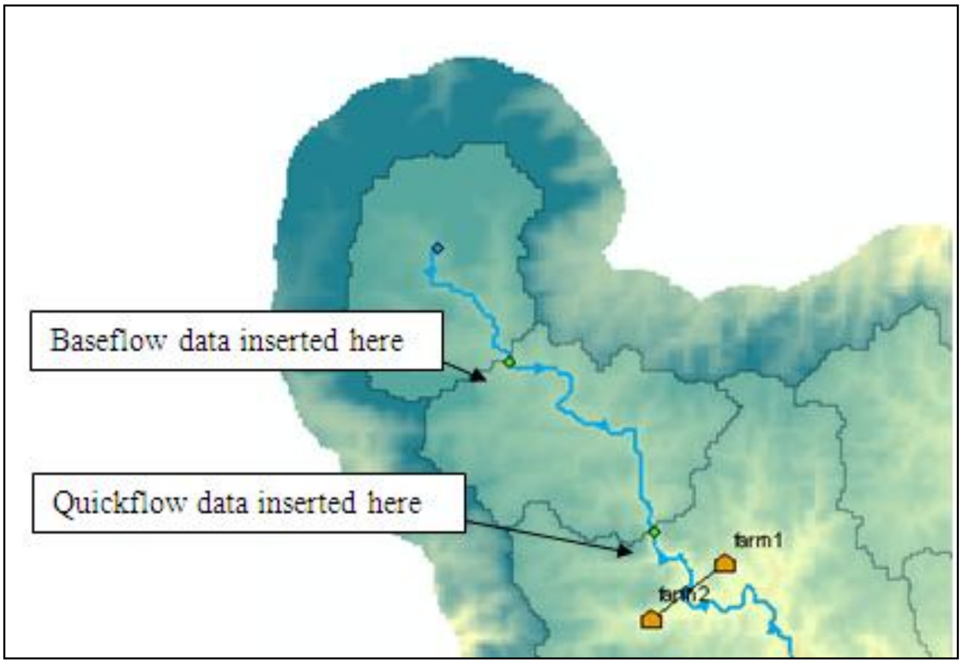

Figure 7.6 Flow components scenario with a sub-catchment split in half to enable tracking of flow components in MIKE BASIN

8. APPLICATION AND EVALUATION OF THE SYSTEM

The methods outlined in Chapters 5, 6 and 7 demonstrated how the three components of the project were designed and implemented. This chapter contains the results from the usage, tests and simulations performed with the time series database and the *ACRU2000* and MIKE BASIN models. Quantitative assessments are presented where possible but, due to the nature of the project, most of the results are qualitative.

8.1. Time Series Database

The time series database was used to import historical rainfall data, generate forecast records and export a combination of this data for use in *ACRU2000*. Historical rainfall data was imported from *ACRU2000* rainfall files using the "Import ACRU Rainfall File" button on the database dashboard. After being prompted to locate the rainfall file the database successfully imported the file and stored the information in the "tbl_Observed_Rainfall" table. The import procedure was validated by performing a visual comparison of the data inside the database and the original data which is located in the *ACRU2000* rainfall file.

The following task to be performed using the database was to generate rainfall forecasts. The rainfall forecasts for this study were received from a File Transfer Protocol (FTP) server which is maintained by the University of Cape Town. In order to generate rainfall forecasts the "Process C-CAM Data Wizard" data button on the database dashboard was clicked to begin the import process. Although the details of what the system is doing in the background have already been detailed in Chapter 5, the process of interaction with the user can be summarized as follows:

i. A dialog box is presented which prompts the user to locate the ArcMap document which contains the code for disaggregating the C-CAM forecast.
ii. The user is prompted to choose the C-CAM data file for the particular forecast date of interest.
iii. Finally the user is prompted to wait for the processing of the data to complete in ArcMap and thereafter close the ArcMap document.

The result of this process is stored in the table called "tbl_CCAM_rainfall_forecasts" which is populated with C-CAM forecast daily rainfall values in mm. This function was validated by making visual comparisons between the C-CAM GIS dataset and the resulting data in the time series database. In Figure 8.1 a diagram is shown indicating the situation, density and point value of a CCAM rainfall forecast. The blue lines indicate a sub catchment that has nearby point rainfall forecast figures ranging from 1.12 mm to 23.2 mm. These values were used to generate a grid where after an average rainfall value of 9.55 mm was calculated. In Figure 8.2 the results of the area weighted average calculation are shown in a text file. It can be seen that the rainfall for the highlighted sub catchment area was 9.55 mm for this particular forecast. This is the expected outcome for this procedure.

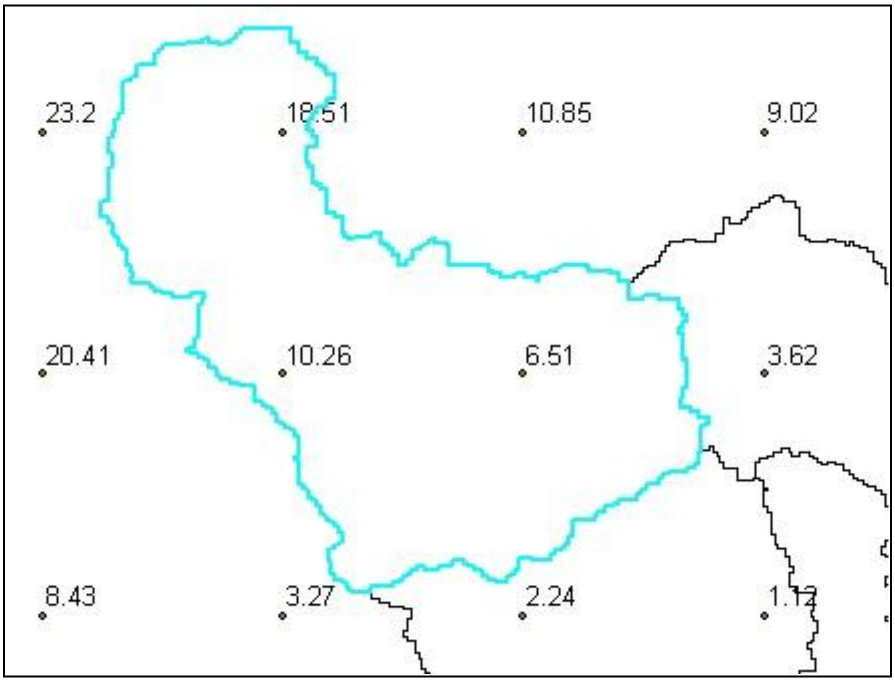

Figure 8.1 Diagram showing a sub catchment and CCAM point rainfall forecast values

```
Catchment,day1,day2,day3,day4
1,0.341734159489473,9.5501823425293,5.26328654289246,6.80359106063843
2,5.18822157755494E-02,1.02649977780323,3.40459843476613,4.99491667747498
3,9.64714059074367E-02,2.60046688653529,3.3914692401886,6.55083531141281
```

Figure 8.2 Results from area weighted average calculations to determine the point rainfall for a single sub catchment

The final use of the time series database was to export a combination of historic and forecast rainfall data. This was achieved using the "Export Rainfall Data" button on the database dashboard. Before clicking on the "Export Rainfall Data" the user is required to enter information into a set of controls. The controls determine the station code to export data from, the start date of the record, the end date of the record and whether or not to include forecast information in the output file. After entering the relevant information and clicking on the "Export Rainfall Data" button the user is informed that the export is complete. This function was validated by performing a visual comparison between the data in the database and the export file.

8.2. *ACRU2000* Rainfall-Runoff Model

After using the AAMG to configure the *ACRU2000* model based on the location of the test catchment, runoff simulations could be performed. Simulation variables and parameters can be adjusted in the *ACRU2000* "Control.men" file which controls aspects of the simulation such as, *inter alia*, the length of the simulation. The "Control.men" file was adjusted to reflect approximately two years worth of rainfall data so that the model would be "warmed up" by the time the forecast rainfall was used in the simulation.

After ensuring that the rainfall data files were named correctly and located in the correct folder, the *ACRU2000* simulation could be run. After the simulation was complete a number of output files with a "dbf" extension were created in the simulation folder. These files contain the results of the simulation and could be imported into MIKE BASIN using the "Convert DBF to DFS0" function of the AAMG. Thus a combination of *ACRU2000* and the AAMG were successfully used to simulate runoff based on rainfall information and convert the results into a format for use by the MIKE BASIN model.

8.3. MIKE BASIN Model

As outlined in Chapter 7, three alternative methods were used to allocate water in MIKE BASIN namely the default scenario, the virtual channels scenario and the flow components scenario. Each of these scenarios are evaluated firstly with local priority rules and secondly with fraction allocation rules. The different rule types are referred to as configurations for clarity. The three methods were investigated based on their ability to meet the project objectives, which are detailed in Chapter 4, and the effect of the rule types on the amount of water received by the users after inputting a constant flow into the system. A quantitative analysis was performed by supplying the users above the reservoir, as indicated in Figure 8.3, with a fixed flow of water for a single day of simulation and thereafter determining which of the users received their required allocation and which of the users were left with a supply deficit.

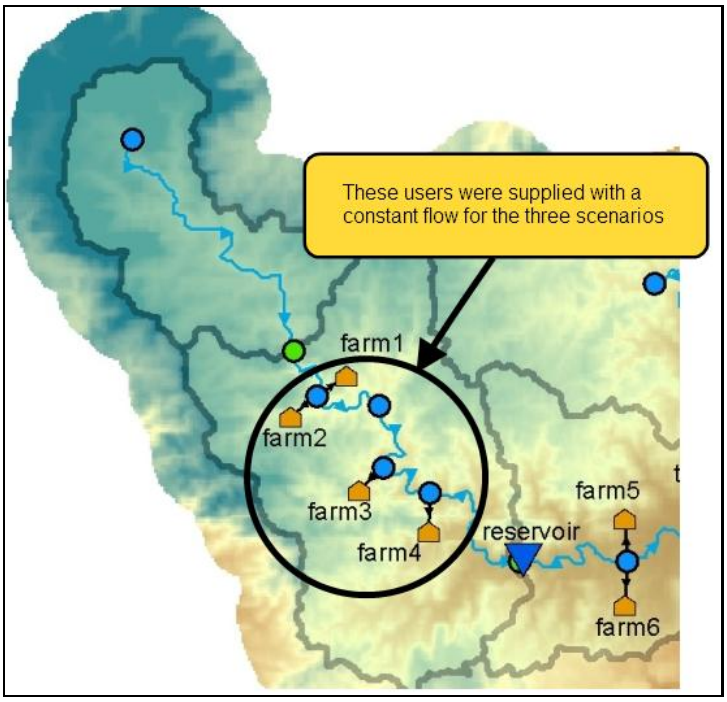

Figure 8.3 Diagram showing the group of users which were supplied with a constant flow of water for comparing the three scenarios

8.3.1. Analysis of the default scenario with a local priority rule configuration

Monitoring under this configuration is made simple by the ability to import observed flow records into the MIKE BASIN using the AAMG. The records are stored in the DHI dfs0 file format which is designed for storing time series information and is the primary input file for the MIKE BASIN model. The AAMG has a function called "Link Observed Flow to MIKE BASIN". This function can be called by clicking a button on the AAMG toolbar and allows a user to click on a point feature in MIKE BASIN and thereafter attempts to locate weir data in DHI dfs0 file format in the AAMG "basedata" folder. This is useful as once the observed data has been imported into MIKE BASIN it can be graphed using the DHI Temporal Analyst Extension, which is installed as part of MIKE BASIN, as illustrated in Figure 8.1.

For the system to be applied on a real-time basis, procedures would need to be developed to automatically add recently available new data to the dfs0 file. This could be easily implemented as DHI provides a programmable interface to manipulate dfs0 files. Although currently only observed streamflow can be imported into MIKE BASIN with the AAMG, future monitoring of user demands and reservoir levels could be incorporated into the system using a very similar function. Additional information could be manually added into MIKE BASIN or a tool could be developed to simplify or automate the process.

The first objective of the study is to be able to monitor and track water as it moves through a river network, thereby facilitating auditing of water availability and use. Tracking water ownership is a more complex task than monitoring what is in the river and what users have pumped from the river or reservoir and is explicitly dependant on the allocation rules that are applied in the system. In this configuration the system is capable of only partly tracking water ownership. The tracking of ownership can only be performed indirectly by examining simulation output, as shown in Figure 8.1, and can only be performed at the point where water is allocated. It is shown in Figure 8.1 that, along with the map of the location of the user nodes and the network, there is a time series table and a time series plot of the flow arriving at the river node and the demand of one of the farms. In this scenario, this point is located at various nodes down the main river of the catchment. After a MIKE BASIN simulation run there are a number of statistics that are available for analysis. Two useful statistics for this exercise are "Net Flow to Node", which is the amount of water in the stream that reaches a node and "Water Demand", which is the amount of water that a user has requested from the system. In the example shown in Figure 8.4 it is necessary to know that the user "farm1" has been assigned a priority of 1 and the user "farm2" a priority of 2. In order to track the ownership of water at the river node that supplies "farm1" and "farm2" the following process was followed:

i. Plot the "Net Flow to Node" for the off take node and the "Water Demand" for both user nodes on the same axis. In this example the "Net Flow to Node" for the date 02/02/1997 was 0.54 m^3/s.
ii. Subtract the "farm1" entire demand from the stream if there is enough water. In this example the demand from "farm1" was 0.4 m^3/s. Due to the fact that there is enough water in the stream it can be calculated that "farm1" owns 0.4 m^3/s.

iii. Subtract the "farm2 demand if there is any water left over in the stream. In this example the demand from "farm2" was 0.3 m^3/s and thus "farm2" only owns 0.1 m^3/s of the water reaching this node.

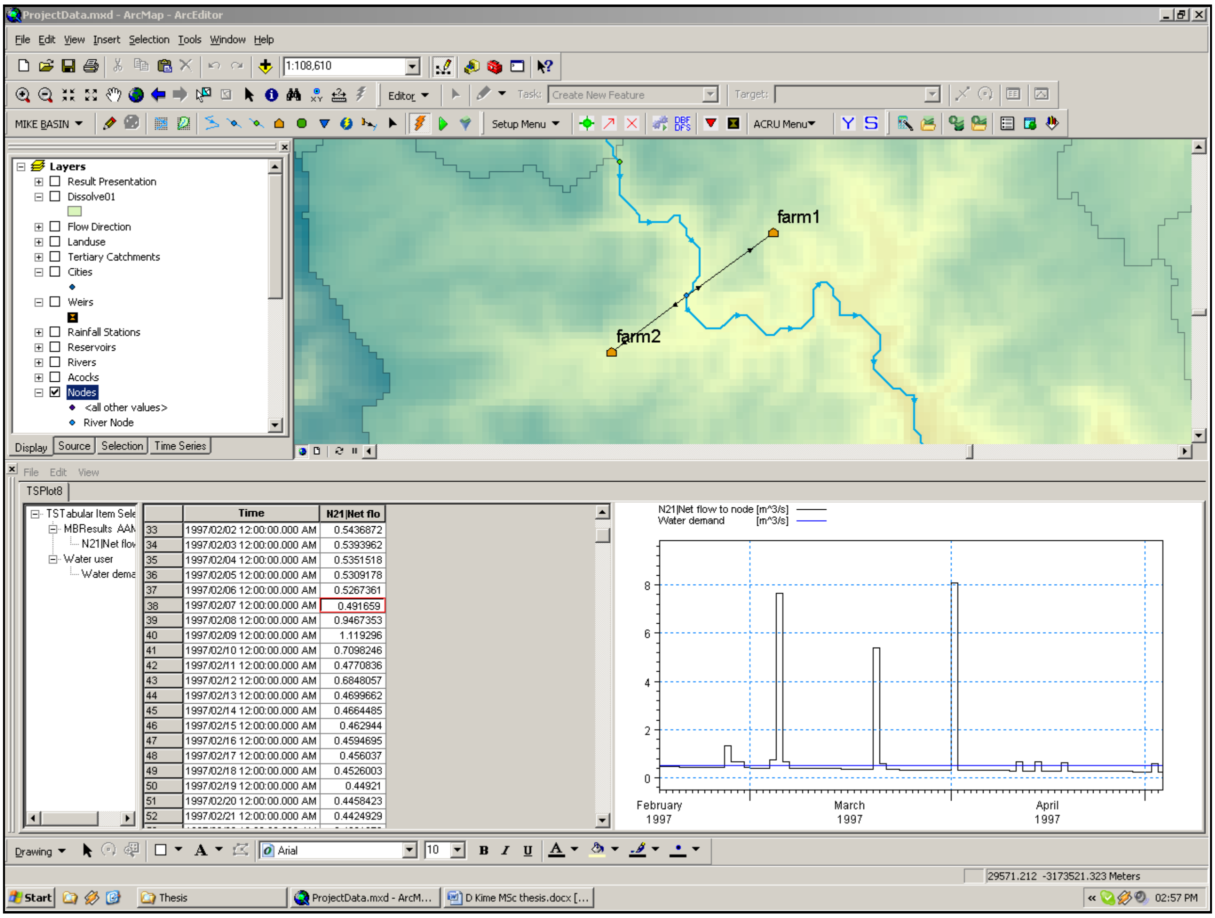

Figure 8.4 Output from the MIKE BASIN model showing time series analysis to track ownership of water

The second objective of the system is to be able to run a number of queries on the network channels and nodes. The first query to be dealt with is how to compare simulated and observed flow at numerous locations in the network. This could be performed provided the following conditions have been met:

i. Observed flow information exists at the point of the query.

ii. *ACRU2000* generated runoff has been imported into MIKE BASIN.

iii. MIKE BASIN has simulated the time step of interest.

When these conditions are met, the DHI Temporal Analyst extension can be used to view the observed and simulated flow at a node on the network. This query works very well for all scenarios where no “virtual channels” are created in MIKE BASIN. The “virtual channels” are a means of representing where a user node receives its water from and thus may not be the closest river node. Examples of this exist where a user node is modelled to receive its water directly from the reservoir despite the fact that the water still has to travel through the river to reach the user. This will result in meaningless observed versus simulated queries as, although water is observed in the river, it may have been simulated to have travelled in a “virtual channel” and thus will not be included in the simulated flow in the river.

Querying the source of water can be performed either for river nodes or for user nodes. For river nodes a procedure such as the following can determine where the water came from:

i. Compile a list of catchment nodes, reservoir nodes and user return flows that lie upstream of the river node of interest.
ii. Disregard all nodes that contribute to a reservoir, as the reservoir impounds these contributions.
iii. Add all the contributions of these nodes together and present a pie graph of the different proportions that each source provides to the river node.

This procedure was followed for the “city” node in order to determine the proportions of the sources that supply the city with water. In Figure 7.2 Node R1 is labelled as “reservoir” and Node N4 is the first green node upstream (West) of the node labelled “city”. A table of catchment nodes and reservoir nodes was compiled and is presented in Table 8.1. Following the populating of the table it is possible to present a pie graph (Figure 8.5) showing the proportional sources that contribute to the city.

Table 8.1 Contributing nodes to “city” and their respective contributions

Node Name	**Node Type**	**Flow Contribution (m3/s)**
R1	Reservoir	0.33
N4	Catchment	44.2

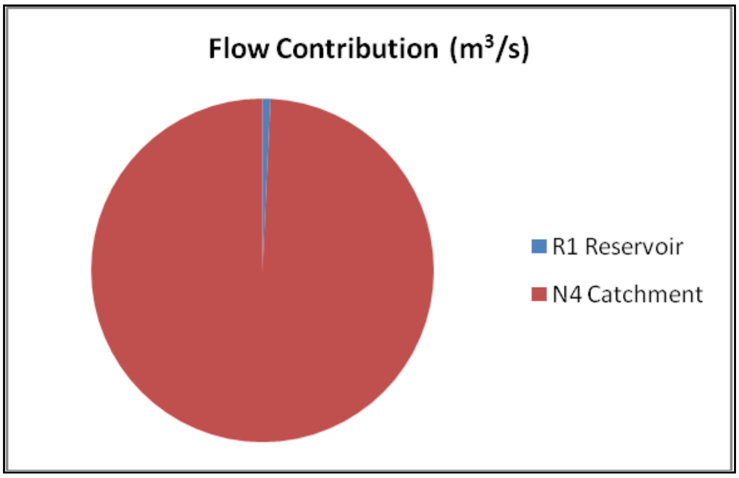

Figure 8.5 Proportional source contributions to the "city" node

A similar process could be performed for a query on a user node. However, the results of this query are closely tied into the allocation rules for that user. The "DHI_MbAllocationRules" table is a MIKE BASIN table that is created by the model to store various allocation rules for the network. Amongst other things the table stores the downstream node, upstream node and allocation rule associated with each user node in the system. In the case of local priority rules a list of the sources that a user node is associated with could be compiled by opening the "DHI_MbAllocationRules" table and searching for all instances of the user node in the "DownstreamNode" column. This would only work if the user node is connected to all possible sources above it and "virtual channels" were in use in order to send water directly from the source of water to the user node.

Querying the destination and/or ownership of water from an upstream node is a reverse process to querying the sources of water from a downstream node. In order to determine where water is going a query would need to determine the routes from an upstream node to a water user node based on the "DHI_MbAllocationRules" table. In the case of the default scenario this would not be useful as, although some users may have an entitlement to a subcatchment at the source of the main river, the supply nodes are not connected directly to the demand nodes and thus no explicit link exists.

The users "farm1" through to "farm4" were configured to have a constant demand of 2 m^3/s The section of the river was configured to have 5 m^3/s flowing in above "farm1". This was done to ensure that there would not be enough water in total and the allocation rules would be enforced by the model. The MIKE BASIN Results Layer Wizard was used to create a layer which shows the results of the simulation as colours on the map as shown in Figure 8.6 for a given simulated day. The criteria for scaling the colours was selected to be the water demand deficit for the water users with a low water demand deficit displayed as a green dot, medium water demand deficit displayed as a yellow dot and high water demand deficit displayed as a red dot. The priorities are, in highest to lowest order, “farm1”, “farm2”, “farm3” then “farm4”.

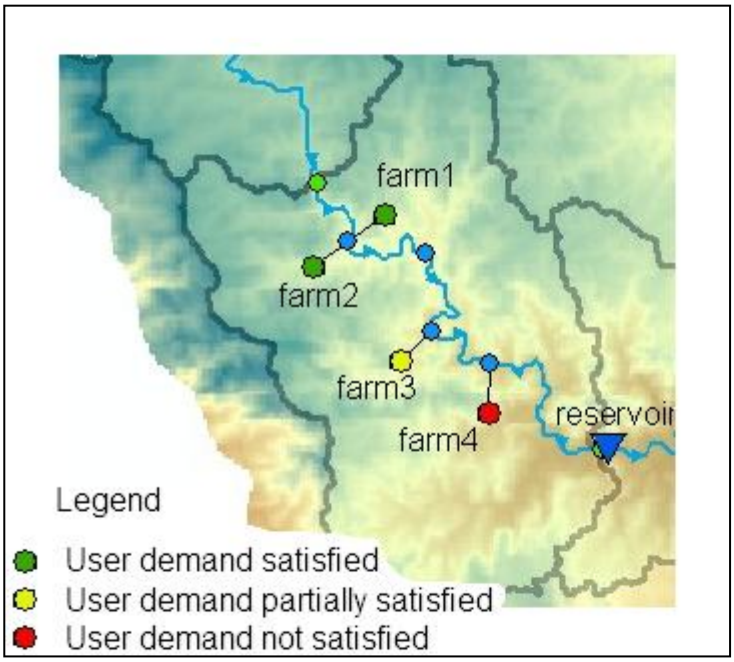

Figure 8.6 Example of results layer for the default scenario in local priority rules configuration for a given day of simulation

It is evident from Figure 8.6 that “farm1” and “farm2” receive their entire water demand. Thereafter “farm3” receives part of its demand and “farm4” receives none to very little water. In order to determine the exact distribution of water the simulation results were viewed and are presented in Table 8.2.

Table 8.2 Simulation results for the default scenario in local priority rules configuration

User node name	**Water available for allocation (m^3/s)**	**Water demanded (m^3/s)**	**Water received (m^3/s)**
farm1	5	2	2
farm2	3	2	2
farm3	1	2	1
farm4	0	2	0

8.3.2. Analysis of the default scenario with a fraction allocation rule configuration

This configuration differs from the previous configuration by the type of allocation rules that are used. The previous configuration used local priority rules while this configuration uses fraction allocation rules. Fraction allocation rules work by allowing a group of users that abstract water from a specific point to be assigned percentages of the water flowing past the point. Each user can thereby only abstract the allocated portion regardless of the flow in the channel and regardless of the user's demand.

Most of the means of meeting the objectives of the system remain the same as the local priority rules and default scenario analysed in Section 8.3.1. The reason for this is that the changes from local priority rule configuration to fraction allocation rule configuration in the default scenario do not affect the entire river system but rather only the allocation at the offtake nodes. The only change is the tracking of water ownership. Tracking water ownership with fraction allocation can be performed in a similar manner to local priority rules and can also only be performed at the point where water is allocated. The fraction for each user is specified in the off take node settings as well as the user node settings which can be accessed by right-clicking on the node in MIKE BASIN and selecting "MIKE BASIN properties" from the menu that appears. In order to track ownership of water on a specified date the following procedure was followed:

i. Plot the "Net Flow to Node" for the off-take node and look up the fractions that each user has been allocated from the off-take node.
ii. For each water user, multiply the "Net Flow to Node" for the off take node by the fraction allocation of the water user and this determines how much water each user owns.

The results from simulating this configuration were exactly the same as the local priority rules configuration and are not presented.

8.3.3. Assessment of the virtual channels scenario with a local priority rule configuration

Monitoring water in the main river channel is affected by the virtual channels as water to meet user demands is removed from the river system at the allocation node. Thus, for a monitoring point just below the first allocation node the simulated flow in the river will not include flows abstracted via the virtual channels and therefore cannot be compared to the observed flow. As shown in Figure 8.7, allocated water is removed at the supply node in this configuration and thus comparisons of simulated and observed flows on the river must be performed with caution. For monitoring purposes, real-time information could still be brought into the model and analysed with the DHI Temporal Analyst extension and this information would be useful at certain points in the river system, such as directly above the reservoir.

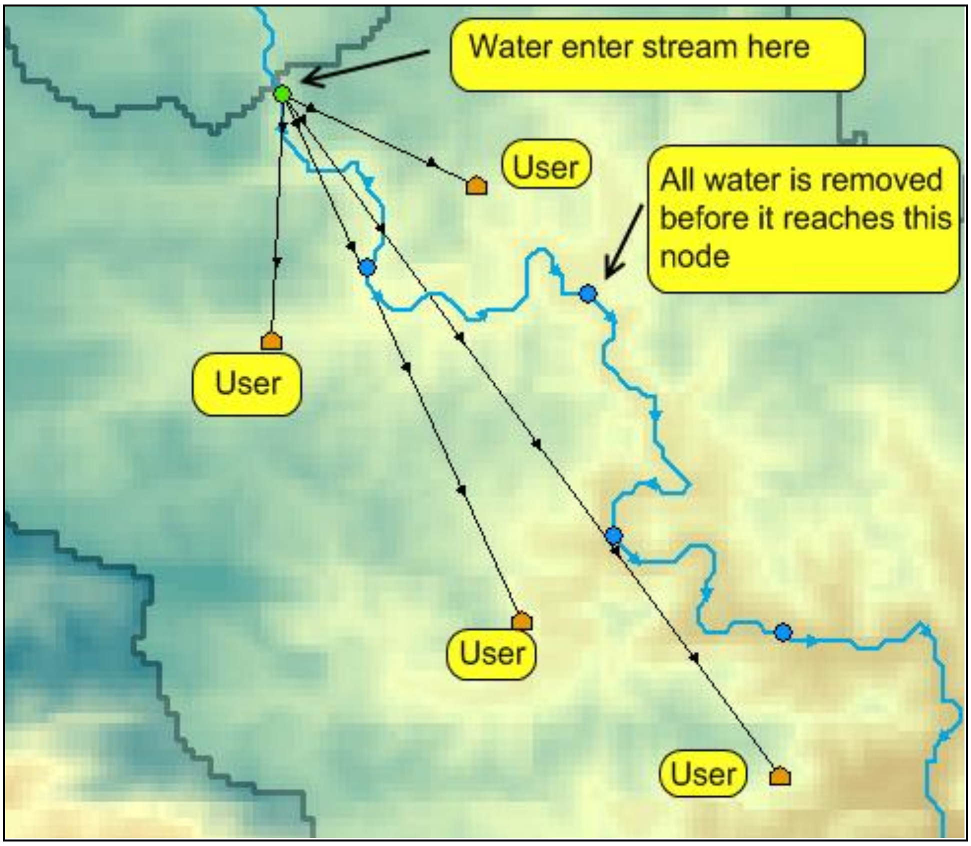

Figure 8.7 Diagram showing how water is conveyed using the virtual channels scenario

Tracking ownership of water with this configuration can be performed at the three water supply nodes in the system. Again this can be done by investigating a combination of the flow reaching a node and the priorities of the users that are allocated water from the node as is performed with the two default scenario configurations. Since tracking ownership of water can only be performed at the allocation nodes, there are fewer locations in this configuration where ownership tracking queries can be performed. The method used to track ownership is the same and involves determining the total flow to the node, determining the combined water demand of the users attached to that node, and finally dividing the water up according to the local priority rules.

The observed versus simulated query that was evaluated to be useful in the previous scenarios will not be useful in this scenario. This is due to the fact that water is moved around the catchment using "virtual channels" and may thus bypass a simulated monitoring point in the catchment. The result of this is that simulated streamflow cannot be compared to observed streamflow at the same point.

Queries related to source and destination/ownership of water are not significantly affected by the configuration of this scenario. Source queries for river nodes can locate all possible sources of water and be able to compile a list. For water users, the process is easier due to the explicit link with water supply nodes whereas in the two default scenario configuration users are simply connected to the nearest channel. In the virtual channel configuration, each user is directly linked to one or more catchment or reservoir nodes and this information can be easily sourced from the "DHI_MbAllocationRules" table. Destination/ownership queries are also made simpler by the explicit link with supply nodes to water users. A supply node can be examined to determine how much water there is at the node and where that water is going. Again this cannot be performed at a simple node in the river due to the fact that there is no allocation information stored either at the node or in the river.

The simulation results for users "farm1" to "farm4" in this scenario and configuration are very similar to the default scenario. The results were viewed both as a results layer and in table format and are presented in Figure 8.7 and Table 8.3 below

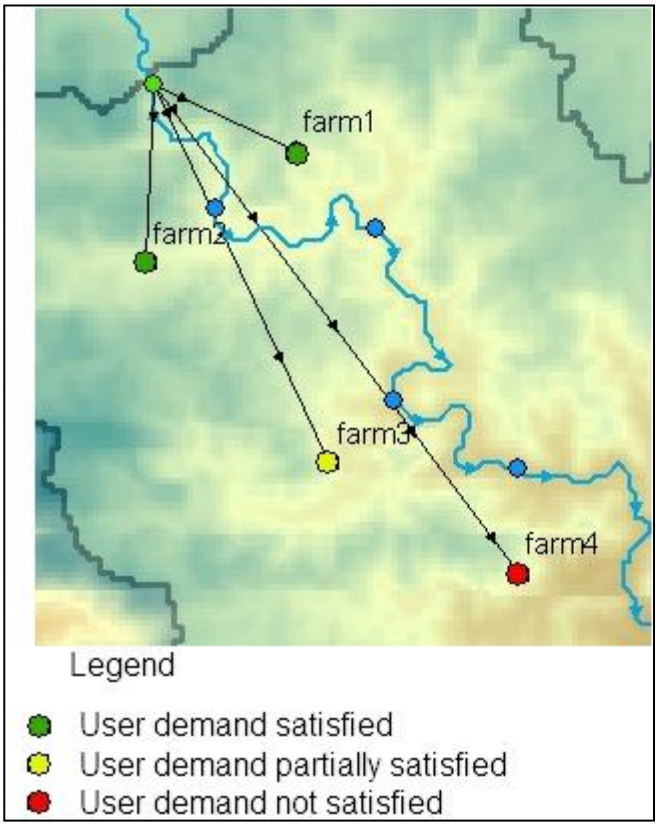

Figure 8.7 Results layer for the virtual channels scenario in local priority rules configuration

Table 8.3 Simulation results for the virtual channels scenario in local priority rules configuration

User node name	**Water available for allocation (m^3/s)**	**Water demanded (m^3/s)**	**Water received (m^3/s)**
farm1	5	2	2
farm2	5	2	2
farm3	5	2	1
farm4	5	2	0

8.3.4. Analysis of the virtual channels scenario with a fraction allocation rule configuration

Fraction allocation rules differ from local priority rules only in the way they allow water to be divided up at the supply nodes. Monitoring water with this configuration suffers from the same problem as the virtual channels scenario with local priority rules configuration in that water is removed from the river at the supply nodes and transported directly to the users.

This results in differences between simulated and observed streamflow that will make this scenario unsuitable for the purpose of monitoring water in the catchment.

Tracking water ownership through the system can again only be performed at the three major supply and allocation nodes as these nodes are the only place where ownership information is stored. The only difference with this configuration is that users receive a portion of the flow at the allocation nodes instead of being assigned water by a priority. Thus tracking of water ownership is not possible at all nodes in the system but is possible at the allocation nodes and therefore allows a more comprehensive breakdown of ownership when compared to the two default scenario configurations where at most two users are supplied from one node due to their proximity to the river nodes.

Simulated versus observed and source and destination/ownership queries are not affected by the change from a local priority rule configuration to a fraction allocation rule configuration in this scenario. This configuration still suffers from the problem of water being removed from the river by “virtual channels” even though the users receiving the water may be further downstream thereby causing difficulty when comparing simulated streamflow to observed streamflow at certain points in the river. Source and destination/ownership queries can still be performed by investigating the “DHI_MbAllocationRules” table and by querying the three major supply nodes in the system where allocation is performed.

The simulation results for this configuration are different to all the previous configurations and scenarios presented because all the nodes receive a percentage of the water arriving at the single supply node and thus it can be ensured that all nodes will at least receive some water. It can be seen in Figure 8.8 that the results layer shows that all nodes have a yellow dot on them which indicates that all nodes are partially satisfied. The reason for this is that each node has been assigned an equal fraction of 0.25 which was entered as part of the node properties during the scenario configuration. This means that the four nodes will each receive one quarter of the water arriving at the supply node if there is less water than the sum of all the nodes’ demands. The actual results for each user node are shown in Table 8.4 and are each one quarter of the amount of water arriving at the supply node as expected.

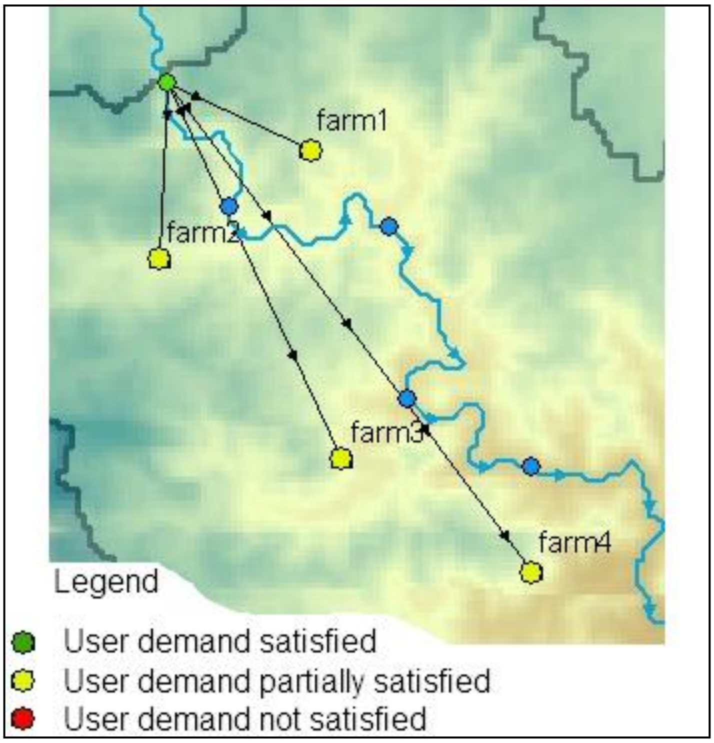

Figure 8.8 Results layer for the virtual channels scenario with fraction allocation rule configuration

Table 8.4 Simulation results for the virtual channels scenario with fraction allocation rule configuration

User node name	Water available for allocation (m^3/s)	Water demanded (m^3/s)	Water received (m^3/s)
farm1	5	2	1.25
farm2	5	2	1.25
farm3	5	2	1.25
farm4	5	2	1.25

8.3.5. Analysis of the flow components scenario with a local priority rule configuration

Monitoring water as it moves through the river network using this configuration suffers from the same problem of the two virtual channel scenario configurations in that water is removed from the stream at the off take nodes and transported to the user outside of the river network. This results in incorrect simulated instream flow values and makes monitoring the flow of water very difficult. It is still possible to import and present observed streamflow values into the system for reference purposes.

As in the previous two virtual channel scenario configurations the tracking of water ownership can only be performed at the off take locations as these locations store the allocation rules. However, as a result of the splitting of each original off take node into one quickflow node and one baseflow node there are now twice as many locations to track water from. In addition to this, the locations provide an increased level of insight into the hydrology as the water is categorized as either baseflow or quickflow. The categorisation of water into either quickflow or baseflow is accurate only in the upper parts of the catchment and the detail is lost in the lower reaches in internal subcatchments. This is due to the fact that along the main river reach a number of quickflow and baseflow catchment nodes contribute to each other. In addition to this the presence of the reservoir adds a third category of water by making releases into the main river reach. As shown in Figure 8.9, the destination and source network queries that can be performed under this configuration and are likely to provide more information than the other two virtual channel scenario configurations due to the increased level of detail of the simulated runoff data.

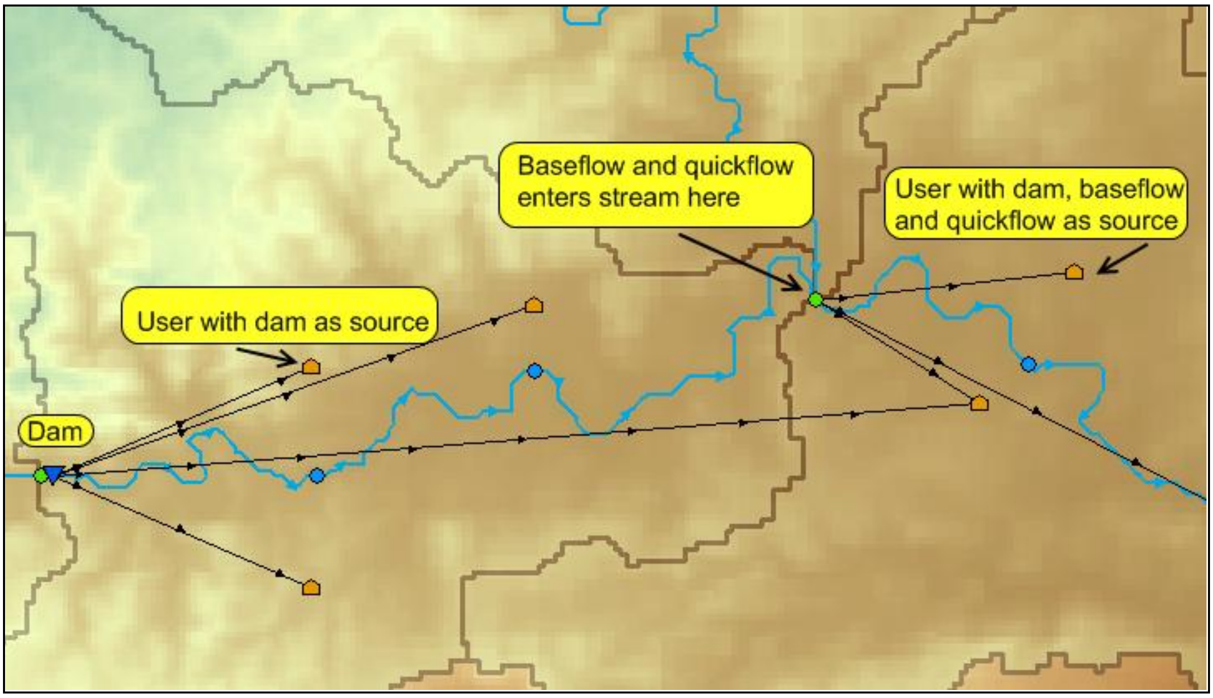

Figure 8.9 Diagram showing increased levels of detail available from the flow components scenario

Tracking ownership of water can be performed at the off take nodes by interrogating the flow arriving at the node and the list of prioritized users that are connected to that node for abstracting water. In this case it possible to determine the quickflow and the baseflow that each user receives from the stream where mixing of water with dam releases or catchments has not yet occurred. Source queries can be performed on the user nodes and the river nodes using the same methods that are highlighted in the previous scenarios.

The simulation results from this scenario are similar to the other scenarios although the increased level of control and detail regarding the source of water, which can be designated as either baseflow or quickflow, are what makes this scenario unique. As shown in Figure 8.10, there is now an extra supply node to this section of the model. This affords extra control because the users have an extra source of water which could be configured to have different priority assignments to each user if required. For this scenario and configuration the highest supply node (baseflow) was configured to input 2 m^3/s into the stream while the second supply node (quickflow) inputs 3 m^3/s.

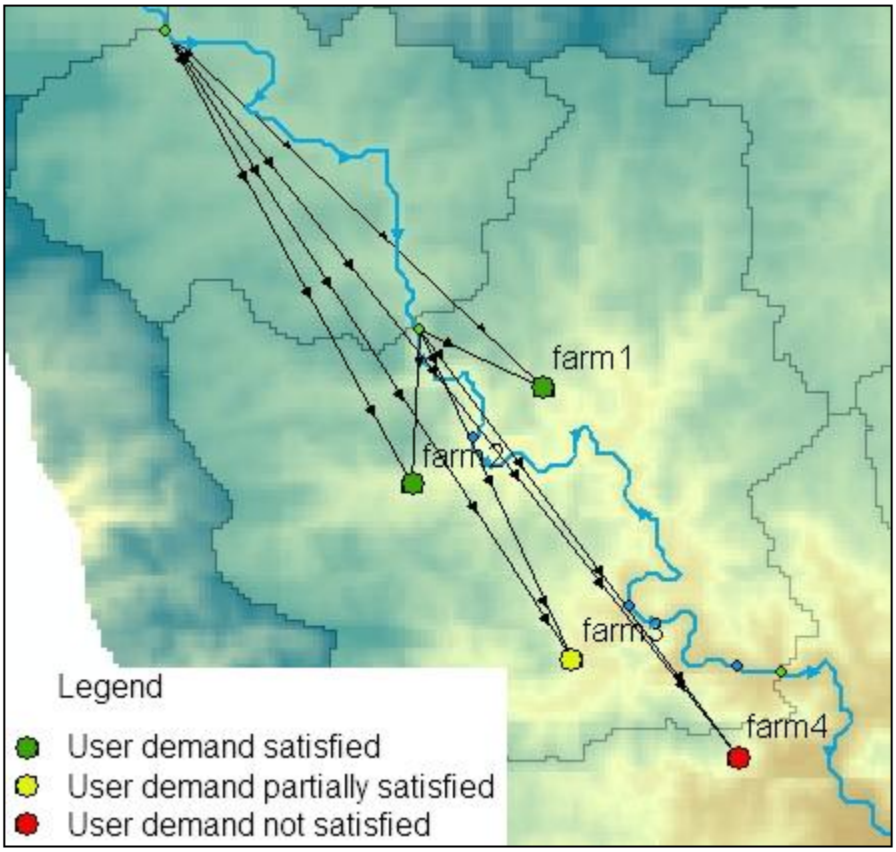

Figure 8.10 Results layer for the flow components scenario with local priority rule configuration.

It is evident from Figure 8.10 that "farm1" and farm2" receive their full allocation while "farm3" receives only a portion of its demand and "farm4" receives none of its demand. Table 8.5 displays a detailed breakdown of the simulation results as well as the source of water for each user node.

Table 8.5 Simulation results for the flow components scenario with local priority rule configuration

User node name	**Water available for allocation (m^3/s)**	**Water demanded (m^3/s)**	**Water received from baseflow supply node (m^3/s)**	**Water received from quickflow supply node (m^3/s)**
farm1	5	2	2	0
farm2	5	2	0	2
farm3	5	2	0	1
farm4	5	2	0	0

As it can be seen from Table 8.5, "farm1" receives its entire allocation first from the baseflow supply node and this leaves no more water available as the baseflow value was set to 2 m^3/s for this simulation. "farm2" receives its entire allocation from the quickflow supply node leaving only 1 m^3/s remaining for use by "farm3". This leaves no water remaining for "farm4".

8.3.6. Results from analysing the flow components scenario with a fraction allocation rule configuration

This configuration is very similar to the flow components scenario with a local priority rule configuration and this discussion will be limited to the differences between the two scenarios.

Monitoring and tracking water as it moves through the river network is performed similarly to the previous configuration. Simulated and observed streamflow are easily imported into the model and can be compared to each other using the DHI Temporal Analyst extension. Care must be taken to account for the fact that water has been removed from the stream and transported in "virtual channels" and this will decrease the simulated streamflow when compared to the observed streamflow. Tracking water ownership can be performed by analysing the streamflow arriving at a water supply node and determining the amount of water that belongs to each user according to the fraction that each user has been assigned. In this case it is possible to assign different fractions of quickflow and baseflow to different users should the need for this extra flexibility arise. Source and destination queries are performed in the same manner as the previous configuration.

The simulation results for users "farm1" to "farm4" in this scenario and configuration share similarities with the other fraction allocation scenarios. The results were viewed both as a results layer and in table format and are presented in Figure 8.11 and Table 8.6 below

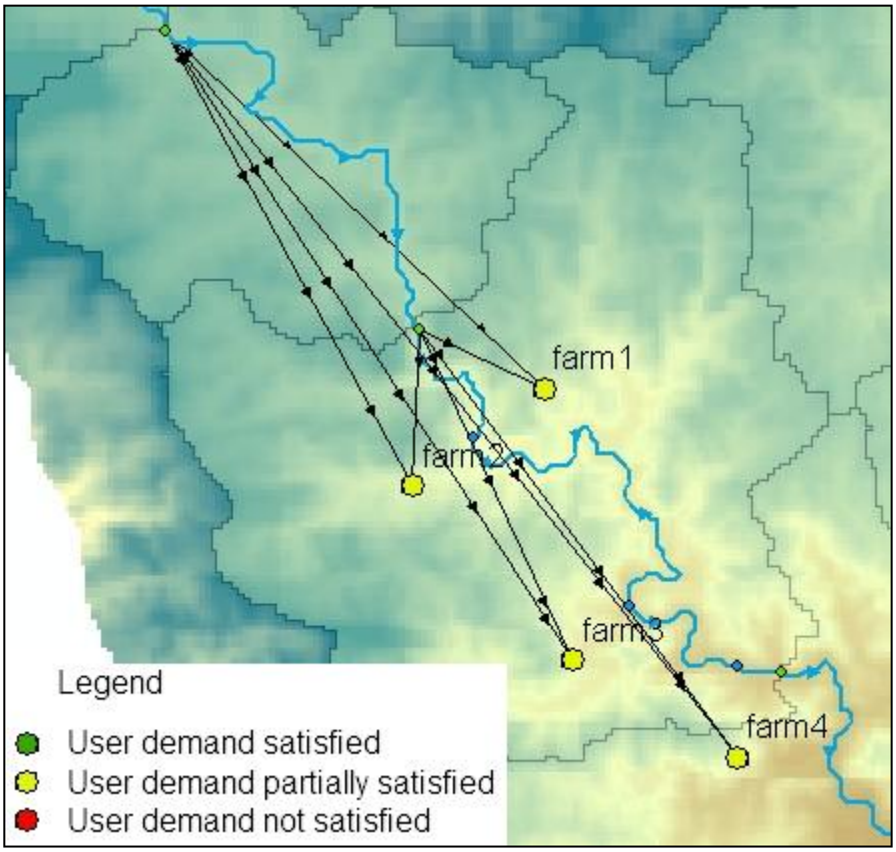

Figure 8.11 Results layer for the flow components scenario with fraction allocation rule configuration

Table 8.6 Simulation results for the flow components scenario with fraction allocation rule configuration

User node name	**Water available for allocation (m^3/s)**	**Water demanded (m^3/s)**	**Water received from baseflow supply node (m^3/s)**	**Water received from quickflow supply node (m^3/s)**
farm1	5	2	0.5	0.75
farm2	5	2	0.5	0.75
farm3	5	2	0.5	0.75
farm4	5	2	0.5	0.75

As it can be seen from Figure 8.11 and from Table 8.6 above, each of the users received the same portion of water. This is due to them all having been configured to receive 0.25 of the amount of water arriving at both the baseflow and quickflow nodes. Table 8.7 summarises the capabilities of all the scenarios that were investigated in this chapter.

Table 8.7 Summary of the capabilities of the scenarios that were investigated.

Scenario name	Ability to monitor flow in real time	Ability to track water ownership in real time	Audit simulated and observed flow	Query the sources of water at a location	Query the destination of water from a location
Default scenario with a local priority rule configuration	Yes	Partial, only at allocation nodes	Yes, at river nodes	Yes, at river and user nodes	Partial, only if direct link from supply to user node exists
Default scenario with a fraction allocation rule configuration	Yes	Partial, only at allocation nodes	Yes, at river nodes	Yes, at river and user nodes	Partial, only if direct link from supply to user node exists
Virtual channel scenario with a local priority rule configuration	No, water removed from main channel at certain nodes	Partial, only at allocation nodes	No, water removed from main channel	Yes, accurate due to explicit link from supply to user	Yes, accurate due to explicit link from supply to user
Virtual channels scenario with a fraction allocation rule configuration	Yes	Partial, only at three allocation nodes	No, water removed from main channel	Yes, accurate due to explicit link from supply to user	Yes, accurate due to explicit link from supply to user
Flow components scenario with a local priority rule configuration	Yes	Partial, baseflow and quickflow information is available	No, water removed from main channel	Yes, accurate due to explicit link from supply to user	Yes, accurate due to explicit link from supply to user
Flow components scenario with a fraction allocation rule configuration	Yes	Partial, baseflow and quickflow information is available	No, water removed from main channel	Yes, accurate due to explicit link from supply to user	Yes, accurate due to explicit link from supply to user

9. DISCUSSION AND CONCLUSIONS

Since the promulgation of the NWA of 1998, users are entitled to query the validity of the methods used to allocate their water. With many of South Africa's catchments being over allocated in terms of water volume, there is a need to reallocate the country's water resources in a manner prescribed by the NWA of 1998. There is thus a need to both allocate water for the licensing process as accurately as possible and to ensure that users comply with the allocation process. A water accounting system could provide information that would assist in determining whether a user has used more than its entitlement and when this has occurred during the year. An accounting system would also assist in accurately determining whether the Reserve is receiving its quota of water. A prototype water accounting system was thus proposed using the *ACRU2000* and MIKE BASIN models. The accounting system should be able to answer a number of questions about the water network being modelled and questions have formed the basis of the project objectives for this dissertation. The objective of this study was to assess the potential of the *ACRU2000* and MIKE BASIN models to perform the following water accounting analyses:

- monitor and track water as it moves through a river network thereby facilitating auditing of water availability and use,
- allow individual network segments to be queried for information such as observed streamflow, simulated streamflow, source of water, destination/ownership of water, and
- make use of climate and streamflow forecasts to assist both dam control officers and end water users in making improved water management decisions.

The first objective was found to be partially achievable in this study. This activity could be partially achieved by importing observed flow at various points into the MIKE BASIN model. This flow can be graphed using the DHI Time Series Analyst extension for ArcMap, which is installed as part of the MIKE BASIN installation, and compared to the simulated flow that is an output of the *ACRU2000* model. Although a manual procedure in this prototype system, it is anticipated that automating the observed data import procedure would enhance the water accounting system. The objective could only be partially achieved due to the fact that queries could only be performed at certain points on the network where allocation rules are stored.

The second objective was partly met in this study. As mentioned in the previous objective, observed and simulated flow can be easily imported into MIKE BASIN and associated with different points on the network. Querying the source of water can be achieved with various degrees of accuracy and depends largely on the model configuration that is used. If "virtual channels" are used to link users to their water source then tracking the source of water to a node is highly accurate as an explicit link exists. Without the virtual channels it is still possible to determine the source of water by investigating the "DHI_MbAllocationRules" table. Tracking the destination of water is not always possible and again depends on the model configuration. If an off-take node has a number of "virtual channels" connecting it as a supply to a number of users then a destination type query is relatively easy. However, querying the destination of water at a normal river node that is not connected to any users will not be able to provide any information. From the six model configurations that were tested, it is recommended that the flow components scenario with either a local priority or fraction allocation configuration be used in a water accounting system. This configuration makes provision for the separation of baseflow and quickflow and the partial tracking of this water as it moves through the river network.

The third objective which entailed making use of climate forecasts to assist in decision making was achieved, although only with one climate parameter in the system developed. C-CAM rainfall forecasts, provided in raster format, were aggregated into point rainfall forecasts which could then be used as an input to the *ACRU2000* model. Due to the modular nature of the system, it is anticipated that using a new forecast method would not cause the rest of the system to malfunction. A new GIS or other routine could be developed to create rainfall time series which could then be stored, cleaned and exported by the time series database and used in *ACRU2000*.

In Chapter 5 the method used to develop a time series database is presented. A time series database was developed to store data for use by the models and to translate the data into different formats if necessary. A Microsoft Access database was used and a database dashboard was designed to house controls for importing and exporting data from the database. A step by step wizard was also designed for converting raster based C-CAM rainfall forecasts into aggregated point rainfall forecasts which could be subsequently used by the *ACRU2000* model. A number of tables were designed to store both forecast and observed daily rainfall values and an additional table was developed for part of the forecast disaggregation process.

The time series database was useful in the real time system as it reduced the effort required to capture, sort, store and export rainfall data. Without the database the rainfall data would be stored in a cumbersome grouping of text files which would need to be opened separately, edited and saved before being used in a rainfall runoff forecast simulation. It is recommended that the time series database should be further developed to house additional data such as observed streamflow and observed water use. This would facilitate an audit directly from the database whereas currently a prototype audit can only be performed from the network allocation model.

In Chapter 6 the method used to set up the ACRU2000 model and an approach to re-program the model to allow for hot-starting is presented. The approach to allow hot-starting was based on object serialisation. This principle involves storing the model objects that are in memory onto storage medium so that they can be read back into memory at a later stage. An XML file format and a binary file format approach were attempted and, although both of these approaches allowed the model objects to be written out from memory, the objects could not be read back into memory and used by the model.

The *ACRU2000* model was not modified for use in this system and performed satisfactorily. The only special use of the model was to modify the input rainfall data files to include four days of forecasted rainfall. The simulations using approximately two years of rainfall input data took two minutes to complete for a 138 *ACRU2000* sub-catchments in the study area. The simulation time is expected to increase for larger catchments and more detailed catchment configurations. It is therefore recommended that the hot starting capability of *ACRU2000* be further investigated if the model is to be used on a daily basis for large catchments and for use in near real time operations. The most promising possibility for hot-starting is the new XML input menu which, at the time of writing, is yet to be developed.

In Chapter 7 the configuration of the MIKE BASIN was presented along with three alternate methods of setting up the model for the prototype water accounting system. The first method used a simple direct attachment of each user node to the nearest point on the river. The second method used virtual channels to connect water resources from relatively long distances to each user node. The third method also used virtual channels but split the water in the stream into either a baseflow or quickflow category based on the flow category supplied from the *ACRU2000* model.

The primary barrier to the accounting system is the fact that individual packets or parcels of water are not branded with ownership from the point of allocation. Ownership thus has to be inferred from the nearest allocation node and this method will not be sufficiently accurate in a typical water supply catchment because the allocation nodes may be located a long distance from the user node. This is particularly the case when considering a reservoir that supplies water to far downstream users. It is recommended that modifications be made to the MIKE BASIN model that would allow individual parcels of water to be tracked and labelled from their source to the destination. An alternative to this may be to investigate other models that are specifically designed for water accounting, or which have water accounting procedures built into the models.

10. REFERENCES

Bessler, F. T., Savic, D. A. and Walters, G. A. (2003). Water Reservoir Control with Data Mining. *Journal of Water Resources Planning and Management* 129(1): 26-34.

Brown, L. and Barnwell, T. 1987. *The enhanced stream water quality models QUAL2E and QUAL2E-UNCAS: Documentation and user manual*. Report No. EPA/600/3-87/007, U.S. Environmental Protection Agency, Athens, USA.

Burns, A. 1989. *Calibration and use of an interactive-accounting model to simulate dissolved solids, streamflow, and water-supply operations in the Arkansas River basin, Colorado*. Report No. 88-4214, U.S. Geological Survey, Denver, USA.

Butler, A. J. E. 2001. The Development and Evaluation of an Operating Rule Framework for the ACRU Agrohydrological Modelling System. MSc Dissertation. School of Bioresources Engineering and Environmental Hydrology, University of Natal, Pietermaritzburg, RSA,

Campbell, S. G., Hanna, R. B., Flug, M. and Scott, J. F. (2001). Modeling Klamath River System Operations for Quantity and Quality. *Journal of Water Resources Planning and Management* 127(5): 284-294.

Clark, D. J. 2007. Personal communication, Pietermaritzburg, South Africa,

Clark, D. J., Kiker, G. A. and Schulze, R. E. (2001). Object-oriented restructuring of the ACRU agrohydrological modelling system. *Tenth South African National Hydrology Symposium*. *SANCIAHS*, Pietermaritzburg, South Africa.

CPHWater 2007. *Technology transfer and integrated implementation of water management models in commercial farming*. Report No. K5/1481/4, Water Research Commission, Pretoria, South Africa.

Dai, T. and Labadie, J. W. (2001). River basin network model for integrated water quantity/quality management. *Journal of Water Resources Planning and Management* 127(5): 295-305.

Davidson, P., Hedrich, R., Leavy, T., Sharp, W. and N., W. (2002). Development techniques and their application to the hydrologic database derivation application. *2nd Federal Interagency Hydrologic Modeling Conf.*, Las Vegas, USA.

DHI 2007. GIS-based water resource management. Internet. Horsholm, Denmark. Available from: http://www.dhigroup.com/Software/WaterResources/MIKEBASIN.aspx. Acessed 1 July 2007.

Draper, A. J., Munevar, A., Arora, S. K., Reyes, E., Parker, N. L., Chung, F. I. and Peterson, L. E. (2004). CalSim: Generalized Model for Reservoir System Analysis. *Journal of Water Resources Planning and Management* 130(6): 480-489.

Dube, R. A. 2006. Appropriate positioning of modelling as a decision support tool for surface water resources planning in South Africa. PhD Thesis. Faculty of Natural and Agricultural Sciences, University of Pretoria, Pretoria, South Africa.

DWAF 2001. *Guidelines for water resources modelling procedures to support water management institutions*. Report No. Edition 1 Draft 4, Department of Water Affairs and Forestry, Pretoria, RSA.

DWAF 2004. *National Water Resources Strategy*. Report No. First Edition, Pretoria, South Africa.

DWAF 2007. *Assessment of stochastic methodologies used in South African water resources planning analyses*. Report No. Phase 3 (Activity 39), Department of Water Affairs and Forestry, Pretoria, RSA.

Dymond, R. L., Regmi, B., Lohani, V. K. and Dietz, R. (2004). Interdisciplinary Web-Enabled Spatial Decision Support System for Watershed Management. *Journal of Water Resources Planning and Management* 130(4): 290-300.

Ehret, U. 2002. Rainfall and flood nowcasting in small catchments using weather radar. University of Stuttgart, Germany,

Ershadi, A., Khiabani, H. and Lorup, J.K. (2005). Applications of remote sensing, GIS and river basin modelling in integrated water resource management of Kabul River Basin. *ICID 21st European Regional Conference*, Frankfurt, Germany and Slubice, Poland.

Evans, H. 2000. *Why object serialization is innappropriate for providing persistence in Java*. Report No. Unknown, The University of Glasgow, Glasgow, UK.

Frevert, D., Fulp, T., Zagona, E., Leavesley, G. and Lins, H. (2006). Watershed and River Systems Management Program: Overview of Capabilities. *Journal of Irrigation and Drainage Engineering* 132(2): 92-97.

Hamlet, A. F., Huppert, D. and Lettenmaier, D. P. (2002). Economic Value of Long-Lead Streamflow Forecasts for Columbia River Hydropower. *Journal of Water Resources Planning and Management* 128(2): 91-101.

Hydrologic Engineering Center's Prescriptive Reservoir Model 1994, HEC-PRM, U.S. Army Corps of Engineers, Hydrologic Engineering Center, Davis, USA.

Heng, C. 2008. Tofrodos Ver 1.7.8. Internet. Available from: http://www.thefreecountry.com/tofrodos/index.shtml. Acessed 29 July 2009.

Hsu, N. and Cheng, K. (2002). Network Flow Optimization Model for Basin-Scale Water Supply Planning. *Journal of Water Resources Planning and Management* 128(2): 102-112.

Hughes, D. A., Mallory, S., Louw, D. and Muller, N. 2007. *Methods and software for the real-time implementation of the ecological reserve - Explanations and user manual.* Report No. K5/1582, Water for Africa, Pretoria, RSA.

Hughes, D. A., O'Keeffe, J., Smakhtin, V. and King, J. (1997). Development of an operating rule model to simulate time series of reservoir releases for instream flow requirements. *Water SA* 23(1): 21-30.

Imhof, A., Wong, S. and Bosshard, P. 2002. *Citizen's Guide to the World Commission on Dams*. Report No. ISBN 0-9662771-9-8, International Rivers Network, Berkeley, USA.

Jenkins, M. W., Lund, J. R., Howitt, R. E., Draper, A. J., Msangi, S. M., Tanaka, S. K., Ritzema, R. S. and Marques, G. F. (2004). Optimization of California's water supply system: results and insights. *Journal of Water Resources Planning and Management* 130(4): 271-280.

Kiker, GA. 2001. *ACRU*2000 Model. In: Lynch, SD and Kiker, GA. *ACRU* Model Development and User Support. Water Research Commission, Pretoria, South Africa, Report 636/1/00.

Kim, Y., Eum, H., Lee, E. and Ko, I. H. (2007). Optimizing Operational Policies of a Korean Multireservoir System Using Sampling Stochastic Dynamic Programming with Ensemble Streamflow Prediction. *Journal of Water Resources Planning and Management* 133(1): 4-14.

Konikow, L. and Bredehoeft, J. (1974). Modelling flow and chemical quality changes in an irrigated stream-aquifer system. *Water Resources Research* 10(3): 1200-1204.

Labadie, J. W. (2005). Optimal Operation of Multireservoir Systems: State-of-the-Art Review. *Journal of Water Resources Planning and Management* 131(5): 407-408.

Labadie, J. W. (2006). River Basin Management Decision Support System. In: ed. V. P. Singh and D. K. Frevert, Watershed Models, 591-569,Taylor and Francis Group, New York, USA.

Landman, W. A., Mason, S. J., Tyson, P. D. and Tennant, W. J. (2001). Statistical downscaling of GCM simulations to streamflow. *Journal of Hydrology* 252: 221-236.

Leavesly, G. H., Markstrom, S. L., Restrepo, P. J. and Viger, R. J. (2002). A modular approach to addressing model design, scale, and parameter estimation issues in distributed hydrological modelling. *Hydrolog. Process.* 16(2): 173-187.

Lecler, N. (2004). Methods, tools and institutional arrangements for water conservation and demand management in irrigated sugarcane. *13th International Soil Conservation Organisation Conference,* Brisbane, Australia.

Levite, H., Sally, H. and Cour, J. (2003). Testting water demand management scenarios in a water-stressed basin in South Africa : Application of the WEAP model. *Physics and Chemistry of the Earth* 28: 779-786.

Li, X., Chau, K. W., Cheng, C. and Li, Y. S. (2006). A Web-based flood forecasting system for Shuangpai region. *Advances in Engineering Software* 37(3): 146-158.

Maidment, D.R. (2004). Arc Hydro data model: A hydrologic integration tool. *Southwest Hydrology* 3(3): 18-19.

Manqoyi, N. and Nyabeze, W. R. 2006. *Situational Assessment of Operating Rules for Existing DWAF Dams*. Report No. Unpublished report, Makgaleng Projects CC, Midrand, RSA.

McCarthy, P. and Light, A. 1995. South Platte Water Rights Management System. Internet. Colorado Water Resources Research Institute, Boulder, USA. Available from: http://cwrri.colostate.edu/pubs/balance/no.4/bal4.html. Acessed 20 July 2007.

Mckenzie, R. and Van Rooyen, P. 1998. *Water Resources Yield Model (WRYM): User Guide 4.1.1*. Report No. Report number P0000/00/001/98, BKS (Pty) Ltd and Department of Water Affairs and Forestry, Pretoria, RSA.

Mckenzie, R. S. and Van Rooyen, P. G. 2003. *Management of large water resources systems*. Report No. E21675a, Water Resources Planning Pty Ltd, Pretoria, RSA.

Microsoft Office Access 2007 - Access Help Getting Started 2006, Microsoft, Redmond, Washington.

Neale, W. (2008). Practical use of radar rainfall data at Thames Water. *WaPUG Autumn Conference*, Blackpool, United Kingdom.

Nieuwoudt, W. L. (2002). Water Market Institutions in South Africa - Lessons from Colorado. *Conference on Irrigation Water Policies: Micro, Macro Consideration*, World Bank, Agadir, Morocco.

Nilsson, P., Uvo, C. B., Landman, W. A. and Nguyen, T. D. (2008). Downscaling of GCM forecasts to streamflow over Scandinavia. *Hydrology Research* 39(1): 17-26.

NWA (1998). National Water Act. 1998. RSA Government Gazette No. 36 of 1998: 26 August 1998.

Nyabeze, W. R., Mallory, S., Hallowes, J. S., Mwaka, B. and Sinha, P. (2007). Determining operating rules for the Letaba river system in South Africa using three models. *Physics and Chemistry of the Earth* 32: 1040-1049.

Pabst, A. F. and Peters, J. C. 1983. *A Software System to Aid in Making Real-Time Water Control Decisions*. Report No. TP-89, US Army Corps of Engineers Hydrologic Engineering Center, Davis, USA.

Pegram, G. G. S. and Clothier, A. N. (2001). High resolution space-time modelling of rainfall: The string of beads model. *Journal of Hydrology* 241: 26-41.

Pike, A. and Schulze, R. E. 2000. *Development of a distributed hydrological modelling to assist in managing the ecological reserve to the Sabie River system within the Kruger National Park*. Report No. K5/884, Water Research Commission, Pretoria, South Africa.

Pott, A. J. and Hallowes, J. S. 2001. *Design of a Decision Support System and Scenario Generator for the Assessement of Land Use Impacts on Water Resources Within a Water Management Area*. Report No. Unknown, CPH Water, Pietermaritzburg, RSA.

Rautenbach, H. 2008. Numerical Weather Predictions - South Africa. Internet. University of South Africa, Pretoria, South Africa. Available from: http://www.up.ac.za/academic/geog/meteo/nwp_intro1.htm. Acessed 19 February 2009.

Reason, C. J. C., Engelbrecht, F., Landman, W. A., Lutjeharms, J. R. E., Piketh, S., Rautenbach, C. J. and Hewitson, B. C. (2006). A review of South African research in atmospheric science and physical oceanography during 2000-2005. *South African Journal of Science* 102: 35-45.

Schultz, C. B., Watson, M. D. and Taviv, I. (2000). An inter regional water resources planning model. *1st WARFSA/WaterNet Symposium: Sustainable Use of Water Resources*, Maputo, Mozambique.

Schulze, R. E. 1995. *Hydrology and Agrohydrology: A text to accompany the ACRU 3.00 agrohydrological modelling system*. Report No. TT69/95, Water Research Commission, Pretoria, RSA.

Schulze, R. E. 2008. Personal communication, Pietermaritzburg, RSA,

SEI 2001. WEAP: User Guide for WEAP21. Internet. Stockholm Environment Institute, Boston, USA. Available from: http:\\www.weap21.org. Acessed 1 August 2009.

Shi, T. (2006). Simplifying complexity: Rationalising water entitlements in the Southern Connected River Murray System, Australia. *Agricultural Water Management* 86(3): 229-239.

Sigvaldson, O. T. (1976). A simulation model for operating a multipurpose multi-reservoir system. *Water Resources Research* 12(2).

Sinclair, S. and Pegram, G. G. S. (2004). Combining radar and rain gauge rainfall estimates for flood forecasting in South Africa. *Sixth International Symposium on Hydrological Applications of Weather Radar*, Melbourne, Australia.

Smithers, J. C. (2006). Modelling Needs in Support of the Implementation of the National Water Act. *WRC Workshop*, Pretoria, RSA.

Smithers, J. C. and Pott, A. J. 2007. Personal communication, Pietermaritzburg, RSA,

Smithers, J. C. and Schulze, R. E. 1995. *ACRU agrohydrological modelling system: User manual version 3.00*. Report No. TT70/95, Water Research Commission, Pretoria, South Africa.

Srikanthan, S. and Pegram, G. G. S. (2006). Stochastic Generation of Multi-Site Rainfall Occurrence. *Asia Oceania Geosciences Society 3rd Annual Meeting*, Singapore, Malaysia.

Summerton, M. and Gillham, S. 2007. Personal communication, Pietermaritzburg, RSA,

Tan, K. S., Chiew, F. H. S., Grayson, R. B., Scanlon, P. J. and Siriwardena, L. (2005). Calibration of a daily rainfall-runoff model to estimate high daily flows. *MODSIM 2005 International Congress on Modelling and Simulation*, Melbourne, Australia.

Teixeira, A. and Marino, M. A. (2002). Coupled Reservoir Operation-Irrigation Scheduling by Dynamic Programming. *Journal of Irrigation and Drainage Engineering* 128(2): 63-73.

Tessler 2003. *Data model and relational database design for the New Jersey water-transfer data system*. Report No. Open-File Report 03-197, U.S. Geological Survey, New Jersey, USA.

Thysen, I. and Detlefsen, N. K. (2006). Online decision support for irrigation for farmers. *Agricultural Water Management* 86(3): 269-276.

Turgeon, A. (2005). Daily Operation of Reservoir Subject to Yearly Probabilistic Constraints. *Journal of Water Resources Planning and Management* 131(5): 342-350.

AAMG - User Manual 2007, Van Der Merwe, R., Johannesburg, South Africa.

Victoria, F. B., Filho, J. S., Pereira, L. S., Teixeira, J. L. and Lanna, A. E. (2005). Multi-scale modeling for water resources planning and management in rural basins. *Agricultural Water Management* 77(1-3): 4-20.

Vogel, R. M., Sieber, J., Archfield, S. A., Smith, M. P., Apse, C. D. and Huber-Lee, A. (2007). Relations among storage, yield, and instream flow. *Water Resources Research* 43: 1-12.

Wang, A. I. 2002. *Experience paper: Using XML to implement a workflow tool*. Report No. Unknown, Norwegian University of Science and Technology, Trondheim, Norway.

Wesson, S. M. and Pegram, G. G. S. (2006). Improved radar estimation at ground level. *Nat. Hazards Earth Syst. Sci.* 6: 323-342.

Wurbs, R. A. 2005. *Comparative Evaluation of Generalized Reservoir/River System Models*. Report No. Unknown, Department of Civil Engineering, Texas University, Texas, USA.

Yates, D., Sieber, J., Purkey, D. and Huber-Lee, A. (2005). WEAP21 - A demand, priority and preference driven water planning model. *Water International* 30(4): 487-500.

Zagona, E. A., Fulp, T. J., Shane, R., Magee, T. and Goranflo, H. M. (2001). RiverWare: A generalized tool for complex reservoir system modeling. *Journal of the American Water Resources Association* 37(4): 913-929.

APPENDIX A – TIME SERIES DATABASE COMPUTER CODE

```
Sub ImportSingleCCAMCSV(FileName As String)

    'imports a csv file that has been processed by the
    'texttogridtodriver mxd

    Dim thisDB As Database
    Set thisDB = CurrentDb
    Dim thisRecord As Recordset

    DoCmd.Close acTable, "tbl_CCAM_rainfall_forecasts", acSavePrompt

    Set thisRecord = thisDB.OpenRecordset("tbl_CCAM_rainfall_forecasts")

    If FileName = "" Then
        Dim fd As FileDialog
        Set fd = Application.FileDialog(msoFileDialogOpen)
        fd.Show
    End If

    Dim strDateOfForecast As String
    Dim strYear As String
    Dim strMonth As String
    Dim strDay As String
    If FileName = "" Then
        strDateOfForecast = fd.SelectedItems(1)
    Else
        strDateOfForecast = FileName
    End If
    strDateOfForecast = Right(strDateOfForecast, 23)
    strDateOfForecast = Left(strDateOfForecast, 8)
    strYear = Left(strDateOfForecast, 4)
    strMonth = Mid(strDateOfForecast, 5, 2)
    strDay = Mid(strDateOfForecast, 7, 2)
    strDateOfForecast = strYear + "/" + strMonth + "/" + strDay

    If FileName = "" Then
        Open fd.SelectedItems(1) For Input As #1
    Else
        Open FileName For Input As #1
    End If
    Dim strTemp As String
    Dim arrSplit() As String
    Line Input #1, strTemp
    Do While Not EOF(1)
        Line Input #1, strTemp
```

```
        arrSplit = Split(strTemp, ",")
        thisRecord.AddNew
        thisRecord!fDateOfForecast_YMD = strDateOfForecast
        thisRecord!fCatchmentCode = arrSplit(0)
        thisRecord!fDay1Forecast_mm = arrSplit(1)
        thisRecord!fDay2Forecast_mm = arrSplit(2)
        thisRecord!fDay3Forecast_mm = arrSplit(3)
        thisRecord!fDay4Forecast_mm = arrSplit(4)
        thisRecord.Update
    Loop

    Close #1

    MsgBox "CCAM CSV imported successfully"

End Sub

Sub ImportACRUSingleRainfall()

    'imports an acru rainfall file (single format)
    'and inserts it into the database

    Dim thisDB As Database
    Set thisDB = CurrentDb
    Dim thisRecord As Recordset
    Dim i As Integer

    DoCmd.Close acTable, "tbl_Observed_Rainfall", acSavePrompt

    Set thisRecord = thisDB.OpenRecordset("tbl_Observed_Rainfall")

    Dim fd As FileDialog
    Set fd = Application.FileDialog(msoFileDialogOpen)
    fd.Show

    Open fd.SelectedItems(1) For Input As #1
    Dim strTemp As String
    Dim strDateTemp As String
    Dim strStationID As String
    Dim strDateOfForecast As String

    Do While Not EOF(1)
        Line Input #1, strStationID
        Line Input #1, strDateOfForecast

        For i = 1 To Mid(strDateOfForecast, 11, 2)
            Line Input #1, strTemp
            thisRecord.AddNew
            thisRecord!fStationID = strStationID
            If i < 10 Then
```

```
            strDateTemp = Left(strDateOfForecast, 4) & "/" & Mid(strDateOfForecast, 7, 2) &
"/0" & i
        Else
            strDateTemp = Left(strDateOfForecast, 4) & "/" & Mid(strDateOfForecast, 7, 2) &
"/" & i
        End If
        thisRecord!fDate_YMD = strDateTemp
        thisRecord!fRainfall_mm = Trim(Mid(strTemp, 6, 5))
        thisRecord!fDataQualityCode = Mid(strTemp, 11, 1)
        thisRecord.Update
      Next i
   Loop

   Close #1

   MsgBox "ACRU rainfall imported successfully"

End Sub

Sub RemoveDuplicates()

   'cleans the database of any duplicate data
   'causes new recid's to be created for all data

   Dim thisDB As Database
   Set thisDB = CurrentDb

   DoCmd.Close acTable, "tbl_CCAM_rainfall_forecasts", acSavePrompt
   DoCmd.Close acTable, "tbl_Observed_Rainfall", acSavePrompt

   thisDB.Execute ("SELECT DISTINCT tbl_Observed_Rainfall.fStationID,
tbl_Observed_Rainfall.fDate_YMD, tbl_Observed_Rainfall.fRainfall_mm,
tbl_Observed_Rainfall.fDataQualityCode INTO temp FROM tbl_Observed_Rainfall;")
   thisDB.Execute ("DELETE * FROM tbl_Observed_Rainfall")
   thisDB.Execute ("INSERT INTO tbl_Observed_Rainfall SELECT * FROM temp")
   thisDB.Execute ("DROP TABLE temp")

   thisDB.Execute ("SELECT DISTINCT
tbl_CCAM_rainfall_forecasts.fDateOfForecast_YMD,
tbl_CCAM_rainfall_forecasts.fCatchmentCode,
tbl_CCAM_rainfall_forecasts.fDay1Forecast_mm,
tbl_CCAM_rainfall_forecasts.fDay2Forecast_mm,
tbl_CCAM_rainfall_forecasts.fDay3Forecast_mm,
tbl_CCAM_rainfall_forecasts.fDay4Forecast_mm INTO temp FROM
tbl_CCAM_rainfall_forecasts;")
   thisDB.Execute ("DELETE * FROM tbl_CCAM_rainfall_forecasts")
   thisDB.Execute ("INSERT INTO tbl_CCAM_rainfall_forecasts SELECT * FROM temp")
   thisDB.Execute ("DROP TABLE temp")

   MsgBox "Duplicates Removed"
```

```
End Sub

Sub ProcessCCAMForecast()

    'presents 4 steps for converting a raw ccam forecast
    'into a useable format for aahms

    'get the path to the arcmap document
    MsgBox "Choose the txtTOgridTOdriver folder"
    Dim fd As FileDialog
    Set fd = Application.FileDialog(msoFileDialogFolderPicker)
    fd.Title = "Choose textTOgridTOdriver folder"
    fd.Show
    Dim strPathToExe As String
    strPathToExe = fd.SelectedItems(1)

    'get the path to the ccam file
    MsgBox "Choose the CCAM forecast file"
    Set fd = Nothing
    Set fd = Application.FileDialog(msoFileDialogFilePicker)
    fd.Filters.Add "CCAM", "*.txt", 1
    fd.Title = "Choose CCAM forecast file"
    fd.Show
    Dim strPathToCCAM As String
    strPathToCCAM = fd.SelectedItems(1)

    'process the ccam file
    FileCopy strPathToCCAM, strPathToExe & "\ccam-forecast.txt"
    ChDir strPathToExe
    Shell "launch.bat"
    MsgBox "ArcMap is now processing the data. Click Ok when you have closed ArcMap"
    FileCopy strPathToExe & "\driver-records.csv", strPathToExe & "\" &
Right(strPathToCCAM, 23)

    'import the ccam file to the database
    ImportSingleCCAMCSV (strPathToExe & "\" & Right(strPathToCCAM, 23))

End Sub

Sub UpdateStatus()

    'this sub sets the values in the framework status box.
    'uncomment the comments below to get a list of all installed
    'programs in a text file

    'Set objFSO = CreateObject("Scripting.FileSystemObject")
    'Set objTextFile = objFSO.CreateTextFile("software.txt", True)
    Dim strComputer As String
    Dim objWMIService As Object
```

```
    Dim colSoftware As Object
    Dim objSoftware As Object

    strComputer = "."
    Set objWMIService = GetObject("winmgmts:" & "[impersonationLevel=impersonate]!\\"
& strComputer & "\root\cimv2")
    Set colSoftware = objWMIService.ExecQuery("SELECT * FROM Win32_Product")
    'objTextFile.WriteLine "Caption" & "Version"
    For Each objSoftware In colSoftware
        If objSoftware.Caption = "ArcGIS Desktop" Then
            Form_Database_Dashboard.Label23.Caption = "Yes"
            Form_Database_Dashboard.Label23.BackColor = RGB(0, 255, 0)
        End If
        If objSoftware.Caption = "DHI GIS Extensions" Then
            Form_Database_Dashboard.Label24.Caption = "Yes"
            Form_Database_Dashboard.Label24.BackColor = RGB(0, 255, 0)
        End If
        If objSoftware.Caption = "AAHMS" Then
           Form_Database_Dashboard.Label25.Caption = "Yes"
           Form_Database_Dashboard.Label25.BackColor = RGB(0, 255, 0)
        End If
    'objTextFile.WriteLine objSoftware.Caption & vbTab & objSoftware.Version
    Next
    'objTextFile.Close

End Sub

Sub UpdateSummary()

    'read the databases and populate the boxes on the
    'database summary form
    DoCmd.Close acTable, "tbl_CCAM_rainfall_forecasts", acSavePrompt
    DoCmd.Close acTable, "tbl_Observed_Rainfall", acSavePrompt
    DoCmd.OpenForm "Database_Summary"

    'observed rainfall
    Dim thisDB As Database
    Set thisDB = CurrentDb
    Dim thisRecord As Recordset
    'number of stations
    Set thisRecord = thisDB.OpenRecordset("SELECT DISTINCT
tbl_Observed_Rainfall.fStationID FROM tbl_Observed_Rainfall")
    thisRecord.MoveLast
    Form_Database_Summary.Label15.Caption = thisRecord.RecordCount
    'most historic data
    Set thisRecord = thisDB.OpenRecordset("SELECT DISTINCT
tbl_Observed_Rainfall.fDate_YMD FROM tbl_Observed_Rainfall ORDER BY
tbl_Observed_Rainfall.fDate_YMD")
    thisRecord.MoveFirst
    Form_Database_Summary.Label28.Caption = thisRecord!fDate_YMD
```

```
    'most recent data
    thisRecord.MoveLast
    Form_Database_Summary.Label16.Caption = thisRecord!fDate_YMD


    'forecasted rainfall
    'number of catchments
    Set thisRecord = thisDB.OpenRecordset("SELECT DISTINCT
tbl_CCAM_rainfall_forecasts.fCatchmentCode FROM tbl_CCAM_rainfall_forecasts")
    thisRecord.MoveLast
    Form_Database_Summary.Label18.Caption = thisRecord.RecordCount
    'most historic data
    Set thisRecord = thisDB.OpenRecordset("SELECT DISTINCT
tbl_CCAM_rainfall_forecasts.fDateOfForecast_YMD FROM tbl_CCAM_rainfall_forecasts
ORDER BY tbl_CCAM_rainfall_forecasts.fDateOfForecast_YMD")
    thisRecord.MoveFirst
    Form_Database_Summary.Label30.Caption = thisRecord!fDateOfForecast_YMD
    'most recent data
    thisRecord.MoveLast
    Form_Database_Summary.Label19.Caption = thisRecord!fDateOfForecast_YMD

    'data continuity
    'find the total span of all data in days
    Dim dtHistoric As Date
    dtHistoric = Form_Database_Summary.Label28.Caption
    If dtHistoric > Form_Database_Summary.Label30.Caption Then
        dtHistoric = Form_Database_Summary.Label28.Caption
    End If
    Dim dtRecent As Date
    dtRecent = Form_Database_Summary.Label16.Caption
    If dtRecent < Form_Database_Summary.Label19.Caption Then
        dtRecent = Form_Database_Summary.Label19.Caption
    End If
    Dim dDateDiffDays As Double
    dDateDiffDays = DateDiff("d", dtHistoric, dtRecent)

    'correctly size and position the observedline
    Dim dObsDays As Double
    Dim dObsLineLength As Double
    dObsDays = DateDiff("d", Form_Database_Summary.Label28.Caption,
Form_Database_Summary.Label16.Caption)
    'size
    dObsLineLength = 7.5 / dDateDiffDays * dObsDays * 567
    Form_Database_Summary.Observedline.Width = dObsLineLength
    'position
    Form_Database_Summary.Observedline.Left = Form_Database_Summary.Baseline.Left

    'correctly size and position the forecastline
    Dim dForDays As Double
    Dim dForLineLength As Double
```

```
    dForDays = DateDiff("d", Form_Database_Summary.Label30.Caption,
Form_Database_Summary.Label19.Caption)
    'size
    dForLineLength = 7.5 / dDateDiffDays * dForDays * 567
    Form_Database_Summary.Forecastline.Width = dForLineLength
    'position
    Form_Database_Summary.Forecastline.Left = 7.5 / dDateDiffDays * DateDiff("d",
dtHistoric, Form_Database_Summary.Label30.Caption) * 567 + 907


End Sub

Sub ExportRainfall(strForecastCatchment As String)

    Dim strStationID As String
    Dim dtStart As Date
    Dim dtEnd As Date
    Dim i As Integer
    Dim j As Integer

    'get user input
    strStationID = Form_Database_Dashboard.Combo45.Value
    dtStart = Left(Form_Database_Dashboard.DTPicker5.Value, 10)
    dtEnd = Left(Form_Database_Dashboard.ActiveXCtl38.Value, 10)
    dtStart = DateAdd("d", -1, dtStart)
    dtEnd = DateAdd("d", 1, dtEnd)

    'build the recordset
    Dim thisDB As Database
    Set thisDB = CurrentDb
    Dim thisRecord As Recordset
    Set thisRecord = thisDB.OpenRecordset("SELECT tbl_Observed_Rainfall.fDate_YMD,
tbl_Observed_Rainfall.fRainfall_mm, tbl_Observed_Rainfall.fDataQualityCode FROM
tbl_Observed_Rainfall WHERE (((tbl_Observed_Rainfall.[fDate_YMD])>#" & dtStart & "#
And (tbl_Observed_Rainfall.[fDate_YMD])<#" & dtEnd & "#) AND
((tbl_Observed_Rainfall.fStationID)='" & strStationID & "'))")

    thisRecord.MoveFirst

    'add the forecast data onto the end of the observed data
    'check if user wants forecasts
    If Form_Database_Dashboard.Check41.Value <> 0 Then
        thisRecord.MoveLast
        dtStart = thisRecord!fDate_YMD
        thisRecord.MoveFirst
        Dim forecastRecord As Recordset
        Set forecastRecord = thisDB.OpenRecordset("SELECT
tbl_CCAM_rainfall_forecasts.fDateOfForecast_YMD,
tbl_CCAM_rainfall_forecasts.fDay1Forecast_mm,
tbl_CCAM_rainfall_forecasts.fCatchmentCode FROM tbl_CCAM_rainfall_forecasts
```

```
WHERE (([tbl_CCAM_rainfall_forecasts]![fDateOfForecast_YMD]>#" & dtStart & "# And
[tbl_CCAM_rainfall_forecasts]![fDateOfForecast_YMD]<#" & dtEnd & "#) AND
((tbl_CCAM_rainfall_forecasts.fCatchmentCode)='" & strForecastCatchment & "'));")
        'check to see if any records are returned
        If forecastRecord.EOF = False Then
            Do
                thisRecord.AddNew
                thisRecord!fDate_YMD = forecastRecord!fDateOfForecast_YMD
                thisRecord!fRainfall_mm = Round(forecastRecord!fDay1Forecast_mm, 1)
                thisRecord!fDataQualityCode = "F"
                thisRecord.Update
                forecastRecord.MoveNext
            Loop Until forecastRecord.EOF = True
        End If
    End If

    'choose the outputfile
    Dim fd As FileDialog
    Set fd = Application.FileDialog(msoFileDialogSaveAs)
    fd.Title = "Save rainfall file as"
    fd.Show
    Dim strOutPath As String
    strOutPath = fd.SelectedItems(1)

    'write the info to the txt file
    Open strOutPath For Output As #1
    Do
        Print #1, strStationID
        Print #1, DatePart("yyyy", thisRecord!fDate_YMD) & "  " & DatePart("m",
thisRecord!fDate_YMD) & "  " & DateAdd("m", 1, thisRecord!fDate_YMD) -
thisRecord!fDate_YMD
        j = DateAdd("m", 1, thisRecord!fDate_YMD) - thisRecord!fDate_YMD - DatePart("d",
thisRecord!fDate_YMD) + 1
        For i = 1 To j
            Print #1, PadDateString(DatePart("d", thisRecord!fDate_YMD)) & "  " &
PadRainfallString(thisRecord!fRainfall_mm) & thisRecord!fDataQualityCode
            thisRecord.MoveNext
            If thisRecord.EOF = True Then
                Exit Do
            End If
        Next i
    Loop Until thisRecord.EOF = True

    'clean up forecast rows from observed table
    If Form_Database_Dashboard.Check41.Value <> 0 Then
        thisRecord.MoveLast
        forecastRecord.MoveFirst
        forecastRecord.MoveLast
        For i = 1 To forecastRecord.RecordCount
            thisRecord.Delete
```

```
        thisRecord.MoveLast
      Next i
   End If

   Close #1

   MsgBox "Export complete"

End Sub

Sub PrepareExportForm()

   Dim thisDB As Database
   Set thisDB = CurrentDb
   Dim thisRecord As Recordset

   'get observed stations
   Set thisRecord = thisDB.OpenRecordset("SELECT DISTINCT
tbl_Observed_Rainfall.fStationID FROM tbl_Observed_Rainfall")
   thisRecord.MoveLast
   Dim i As Integer
   Dim j As Integer
   j = thisRecord.RecordCount
   thisRecord.MoveFirst
   For i = 1 To j
      Form_Database_Dashboard.Combo45.AddItem (thisRecord!fStationID)
      thisRecord.MoveNext
   Next i


End Sub

Function PadRainfallString(strInput As String) As String

   Dim i As Integer
   Dim j As Integer

   If InStr(strInput, ".") = 0 Then
      If strInput < 1 Then
         strInput = "." & strInput
      Else
         strInput = strInput & ".0"
      End If
   End If

   i = 6 - Len(strInput)
   For j = 1 To i
      strInput = " " & strInput
   Next j
```

```
    PadRainfallString = strInput

End Function

Function PadDateString(strInput As String) As String

    If strInput < 10 Then
        strInput = "0" & strInput
    End If

    PadDateString = strInput

End Function
```