THE DEVELOPMENT OF A COMPUTERIZED SYSTEM FOR AUDITING REAL TIME OR HISTORICAL WATER USE FROM LARGE RESERVOIRS IN ORDER TO PROMOTE THE EFFICIENCY OF WATER USE

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Water Research Commission

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Report to the

Water Research Commission

by

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EXECUTIVE SUMMARY

Introduction

South Africa is a water scarce country. The water situation reports contained in the National Water Resources Strategy (NWRS, First Edition 2004) indicate that an alarming number (more than 50%) of South Africa's water resources are considered to be either fully-allocated or over-allocated. The statistic is concerning given the fact that few economically viable water augmentation options (e.g. the building of dams and inter-basin transfers) exist, as most viable sites have already been developed. Given the limited potential to address the situation with a supply-side solution, focus has shifted to the improvement of water use efficiencies and water resource management. Improved levels of water use efficiency may liberate water with little to no reductions in the production levels associated with the use of the water. However, it has been documented that improved levels of water use efficiency may in fact reduce the water available to downstream water users as a result of reduced return flows associated with gains in water use efficiency (Grové, 1997).

The efficient operation of large dams is particularly important as dams increase the yield of catchments by retaining water during periods of water abundance for use during periods of scarcity. The underlying objective of this research project was to assess options with which efficiencies related to the use of water could be improved, with particular reference to the efficiency of water use from large dams. The original thinking was that water use efficiencies would be improved by the introduction of the water audit system for the following reasons:

- The intensified monitoring of water releases from the dam (associated with the water audit system) would potentially reveal inefficiencies associated with water releases from dams,
- The monitoring of actual water use by downstream users could reveal over-use by water users
- The monitoring of river flows downstream of the dam could reveal the presence of unauthorised water use upstream of the monitoring point. In this way unauthorised users could be prosecuted by water managers.

Clearly, improved monitoring networks and a system (auditing procedures) of reconciling actual water use against the entitlements of the water users to the use the water were central to the originally envisaged water audit system. In the course of the project however, it was discovered that a "use-it-or-lose-it" principle is generally adopted for the management of water use from large dams in South Africa. The implication of the principle is that if a given water user does not use his water use entitlement in a certain time-period (generally a year), the entitlement is lost in that time-period. An investigation of the potential impact of this principle on water use efficiency revealed that the principle does not promote improved water use efficiency.

In contrast, the principle may in fact induce the inefficient use of water. The reasoning relates to the fact that different categories of water users are identified in South Africa (e.g. high, medium and low assurance users). Irrigators, who are responsible for over 50% of South Africa's water use (NWRS, First Edition 2004), are generally awarded lower levels of assurance than industrial and domestic water users. Low assurance water users pay lower water use charges than users with higher water use charges. The assurance levels influence (i) priority levels with which water users are to receive water in times of water scarcity, and (ii) the level of water restrictions faced by the respective categories of water users during periods of water restrictions.

The inefficiency results from the fact that water users do not have incentive to use water more efficiently. The low assurance users in particular have every incentive to use all the water they can, particularly when dams levels start dropping and the impostion of restrictions starts being discussed by water resource managers and stakeholders. These water users will try to use as much water as they can before restrictions are imposed. This action paradoxically leads to dam levels which draw down quicker than they would have if no restrictions were imminent. The quick draw down in dam levels as restriction levels are neared then results in the imposition of restriction levels. Bear in mind that there may be several dam restriction levels, with restrictions becoming more severe as the dam levels lower.

The realisation of the potential negative impact of the use-it-or-lose-it principle of water use from dams on water use efficiency changed the course of the project to a large extent, as an alternative "use-it-or-bank-it" principle was explored, as this was believed have a number of benefits over the existing system, including:

- A water management system based on the "use-it-or-bank it" principle would promote the adoption of water use efficiency by water users. Irrigators for example may adopt irrigations systems and scheduling practices which are more water use efficient, thus requiring less water. The liberated water could then be banked by the irrigator, which could be used at a later stage, or could be traded with other water users.
- The definition of water use entitlements is far clearer under a system based on the "use-it-or-bank-it" principle as opposed to a system based on the "use-it-or-lose-it" principle. One is thus more able to successfully implement a water audit system, which reconciles water use against the entitlements to use the water by various individuals, based on a "use-it-or-bank-it" management system as opposed to the "use-it-or-lose-it" system.

The focus of the project thus shifted away from a purely "operational water audit system", to an understanding of what would be required to implement the new water management system for large dams based on the "use-it-or-bank-it-principle". The management system based on the "use-it-or-bank-it principle" has been referred to as a Fractional Water Allocation and Capacity Sharing (FWA-CS) water management system in this document, whereas the management system based on the "use-it-or-bank it" principle is referred to as a Priority-based River and Reservoir Operating Rule (PRROR) system. The assessment of the FWA-CS arrangement included an assessment of the National Water Resources Strategy (NWRS, First Edition 2004) and 1998 National Water Act to ensure that it would be legally possible to adopt this new water resource management approach. It was found that nothing in the 1998 National Water Act or National Water Resources Strategy (NWRS, First Edition 2004) disallowed the adoption of the new FWA-CS water management approach. Secondly, it was necessary to assess if the computer models currently used by the Department of Water Affairs and Forestry (DWAF) could in fact support the new water resource management approach. It was found that the Water Resources Yield and Water Resources Planning models used by the DWAF could not in their current form support the FWA-CS water management approach. A model was sourced which could support the FWA-CS water management report. The model, the Mike Basin model, was developed by the Danish Hydraulic Institute. The authors tailored the Mike Basin model to include some functionality required for South African conditions, such as the development of an In-stream Flow Requirement (IFR) module, as well as a module to derive yield curves for water resources.

The project research area

The Mhlathuze Catchment was chosen as the research project area, as it is one of the first catchments in the country in which the Compulsory Licensing process has been initiated, as the catchment is currently deemed to be over-allocated. Furthermore, the catchment is heavily dependent on water stored in a large dam located in the upper reaches of the catchment, i.e. the Goedertrouw Dam. The Mhlathuze Catchment was a suitable research area given the reliance on the Goedertrouw Dam, as well as the fact that the Mhlathuze Catchment is one of the first catchments to undergo the compulsory licensing process in South Africa, as a key objective of the project was to share with the stakeholders and water resource managers involved in the Compulsory Licensing process any relevant findings from this research.

Project objectives and activities undertaken

Objective 1: To develop a water audit system for large dams.

The scope of the deliverable was increased to include the development of an audit system for a catchment. The option to use the WRYM supporting the PRROR institutional arrangement for the further development of the audit system was not pursued as the WRYM was unable to support the FWA-CS institutional arrangement, and was unable to operate on a near-real-time basis (which would be required to calculate water use entitlements during times of water scarcity). Instead, the decision was taken to purchase the Mike Basin planning model (for approximately R40,000), as the model can support the FWA-CS as well as the PRROR institutional arrangements, and can operate on a daily, weekly or monthly time step. The model was tailored in order to meet the requirements of water resource planners, as the IFR and Yield modules were developed to interact with the Mike Basin model via the COM interface.

Objective 2: To increase the understanding and knowledge of the practicalities, strengths and weaknesses, and potential costs and benefits of developing and implementing a "water audit system" for use by CMAs. Although a fully operational water auditing system was not developed in the course of this project, largely as a result of the increased project scope and assessment and accommodation of the FWA-CS institutional arrangement, the requirements of this aim are discussed within this document. Furthermore, persons in DWAF were consulted on a few occasions to assess if and how the FWA-CS institutional arrangement could be integrated into the operational management of water resources. Stakeholders were also consulted to assess their interest in the institutional arrangement, and the benefits, strengths and weaknesses of the FWA-CS institutional arrangement.

Objective 3: To transfer knowledge/technology to decision makers and stakeholders.
A number of presentations of the FWA-CS institutional arrangement were held with DWAF: Head Office, DWAF: Regional Office as well as stakeholders in the Mhlathuze Catchment. The Mike Basin software has been demonstrated within DWAF.

Objective 4: To assess the feasibility of implementing the water audit system for the management of South Africa's water resources.
Consideration has been given to the 1998 National Water Act, NWRS (First Edition, 2004) and discussions have been held with DWAF:HO, DWAF:RO and Mhlathuze stakeholders in order to report on the feasibility of (i) introducing the FWA-CS institutional arrangement in order to promote water use efficiency from large dams, and (ii) the feasibility of developing and implementing a water audit system.

Project outcomes

The following are notable outcomes of the project:

- It has been recommended to the DWAF by Prof A. Görgens as part of a User Requirements Survey related to the modelling needs to support the Compulsory Licensing process in the Mhlathuze Catchment, that a pilot project be undertaken in which the concept of FWA-CS be further explored.
- In the course of the project the Mike Basin model has been declared an "emerging model" in the DWAF "Guidelines for models to be used for Water Resources Evaluation", Version 2, Nov 2003.

- A few Directorates in DWAF have shown an interest in the use of the Mike Basin model, and other range of Mike models, resulting from the exposure given to the model as a result of this project.
- The earlier version of the Mike Basin model did not accommodate for the fractional allocation of run-of-river flows very well. As a result of the project and communication with the DHI, the Mike Basin model is being modified to better accommodate FWA-CS.
- Modules have been developed which enable the Mike Basin model to be used by water resource planners. Although stochastic hydrology has not been included in this development, it is believed that this will be achievable.
- Stakeholders have been exposed to the concept of FWA-CS, as well as to the PRROR institutional arrangement.
- The monitoring equipment installed in the Mhlathuze Catchment will remain there for the improved management of water resources.

Capacity building

During the course of the project the capacity of a number of individuals and organisations was developed. Details of these are provided in Appendix A of this report.

Conclusions

The following conclusions can be drawn from this research

- Due to the water scarcity in South Africa, the efficient use of the water resources we have available to us is vital.
- The Priority-based River and Reservoir Operating Rule (PRROR) is the currently adopted water management system in South Africa. The PRROR system is founded upon the "use-it-or-lose-it" principle for water use from large dams. This water management system is believed to result in the inefficient use of water from dams. A new water management system, which is based on a "use-it-or-bank-it" principle for water use from large dams was explored, upon which an a water audit system can be developed to promote further water use efficiency.
- The NWRS (First Edition, 2004) and 1998 National Water Act do not prohibit the adoption of an institutional arrangement such as FWA-CS. The FWA-CS institutional arrangement is however a new potential management option, and one which can not be supported by the Water Resources Yield Model (WRYM) and Water Resources Planning Model (WRPM) in their current form.
- The Mike Basin model was purchased and further developed in order to accommodate for FWA-CS in a manner suitable for water resources planning purposes. Without this development the FWA-CS institutional arrangement

would be of little value to stakeholders in the Mhlathuze, as water resources planning is a key component of the Compulsory Licensing process.

- The Mike Basin model was not fully developed into a water auditing system in the course of this project, for either the FWA-CS or the PRROR institutional arrangements, however details of how the auditing system could be developed were discussed.
- Many of the stakeholders in the Mhlathuze Catchment showed an interest in the FWA-CS institutional arrangement, and the Sugar Association of South Africa (SASA), recently renamed to the South African Sugar Research Institute (SASRI), has formally requested that the institutional arrangement be further explored in the course of the Compulsory Licensing process.
- It may be the case that due to the newness of the FWA-CS institutional arrangement, and also due to the pressure to complete the Compulsory Licensing process, particularly in stressed catchments in South Africa, that the FWA-CS institutional arrangement is not initially adopted. However, as the value of water increases in catchments and monitoring systems are improved, and the CMAs become operational and established it is believed that the FWA-CS institutional arrangement will become increasingly more attractive to implement.
- The FWA-CS institutional arrangement is viable in relatively small catchments where water users receive the bulk of their water from dam releases (and not from tributary flows). The flows from tributaries complicate the FWA-CS institutional arrangement in that more monitoring is required, and the apportionment of flows from the tributary flows will be important as water users will want to use as much tributary flow as possible in order to maximise the banking of water in dams.
- It must be highlighted that water banking has been undertaken in the Mhlathuze Catchment during the drought experienced in the 1990's. Furthermore the Catchment is one of the only catchments where water users pay for actual water use, as opposed to paying for their full entitlements. This, combined with a monthly and six monthly water management report related to the water usage in the catchment have resulted in high water use efficiency within the Mhlathuze Catchment.

Recommendations

The following recommendations, resulting form this project, are made:

- Weather data collected using the Automatic Weather Station installed at the Goedertrouw Dam as part of this project showed a very poor correlation with DWAF recorded data. Details for this poor correlation are not clear, and it may be appropriate for this to be further investigated.
- The 1998 National Water Act and NWRS (First Edition, 2004) make very little mention of the exact details in which water resources are managed, i.e.

how the rules that govern the apportionment of water amongst competing water users are reflected in computer models, and how the results are used in the licensing process. Although this is a very technical discussion, it may be one which is required in order to build the capacity of stakeholders in catchments, so that they can better understand how their entitlements are influenced by upstream water users, and how their activities influence downstream water users.

- Accurate weather forecasts could improve the water use efficiency from large dams in that water users may require less water to be released from dams if they know with a suitably high level of confidence that rainfall is expected in the near-future. Due to the travel time associated with water released from the Goedertrouw Dam, it can take up to 2.5 days for the released water to reach water users. In the Mhlathuze Catchment water users will thus require high confidence 3 day forecasts.
- The Mike Basin model makes use of a different solver to the WRYM. A recommendation is that further research be undertaken related to the solvers used for various node and channel hydrological models used locally and internationally, and that the advantages and disadvantages of the respective solvers be compared.
- It is recommended that the ACRU model be integrated via the COM interface with the Mike Basin model. This link will enable ACRU to gain the functionality of a multi-user, multi-reservoir planning model (such as Mike Basin), which even be used on an operational level, as the Mike Basin model can operate at on a daily time-step, and can be hot-started.
- It is recommended that a more detailed legal review be undertaken regarding FWA-CS to assess if slight amendments may be required to the wording of clauses in the 1998 National Water Act to better accommodate FWA-CS.
- It is recommended that the full link between Mike Flood Watch and Mike Basin be explored in order to complete a fully functional water auditing system for catchments, for both PRROR and FWA-CS institutional arrangements. This development will enable the water resource planning model to be operated at an operational (i.e. near real time level). This functionality is required for water audits to be undertaken on a near-real time basis, which is often required during very dry periods.

ACKNOWLEDGEMENTS

This research report is the result of a project funded by the Water Research Commission (WRC). The WRC is thanked for this financial assistance, and guidance given in the course of the project.

The Steering Committee members (now referred to as Reference Group Members) consisted of the following persons:

Dr. GR Backeberg	: Water Research Commission (Chairman)
Mr. JC Perkins	: DWAF
Mr. B Grové	: University of the Free State
Mr. DB Versfeld	: Independent consultant
Adv. H Thompson	: Independent consultant
Mr. JA van Rooyen / Mr. NJ Van Wyk	: DWAF
Prof. PJT Roberts	: Forestry SA
Mr. EJ Schmidt / Mr. NL Lecler	: South African Sugarcane Research Institute

Note:

- Mr. Schmidt moved to Australia in the course of the project. His position was replaced by Mr. Lecler from the same organisation.
- Mr. van Rooyen attended a few of the reference group meetings. Where he was not able to attend, Mr. N. Van Wyk attended in his place.

The steering committee provided valuable inputs in giving direction to the research project. Many members of the committee willingly shared their expertise with the project team, and their contributions are acknowledged and appreciated.

The project was a joint project between CPH Water (the lead contractor), and the CSIR. CPH Water would like to acknowledge the contribution made by the CSIR to this project. In particular the contributions made by Dr. C. Everson are acknowledged.

The monitoring component of this research project partially dove-tailed with another WRC project related to water metering (WRC project no. K5/1265//4). Ms. Van der Stoep and Mr. Y. Tsehave participated in the joint testing of metering equipment at one location in KwaZulu Natal. Their contribution is acknowledged. The owner of the Umlaas farm on which the metering assessment was undertaken is thanked for his willingness to participate in the project.

Officials from the Department of Water Affairs and Forestry were very helpful. Special attention must be made of Mr. Perkins, Mr. J.C. Bouwer, Mr. P. Vorster, Mr R. Fakeer, Miss N. Wasmuth, Mrs E. van Heerden.

Stakeholders in the Mhlathuze Catchment that were very helpful, and deserve a sincere word of thanks include in particular Mr. M. Easton and Mr. B. Nelson.

The Danish Hydraulic Institute (DHI) has further developed the Mike Basin model as a result of suggestions put forward during the course of this project. Their support and contributions are acknowledged.

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LIST OF ACRONYMS

AOS	Assurance Of Supply (of water)
AWS	Automatic Weather Station
BMP	Best Management Practice
DHI	Danish Hydraulic Institute
DWAF:HO	Department of Water Affairs and Forestry : Head Office
DWAF:RO	Department of Water Affairs and Forestry : Regional Office
CMA	Catchment Management Agency
CMS	Catchment Management Strategy
CS	Capacity Sharing
CSIR	Counsel for Scientific and Industrial Research
EFR	Ecological Flow Requirement
FWA-CS	Fractional Water Allocation and Capacity Sharing
IA	Institutional Arrangement
IFR	In-stream Flow Requirement
ISP	Internal Strategic Perspective
IWRM	Integrated Water Resources Management
NWA	National Water Act (Act No 36 of 1998 as amended)
NWRS	National Water Resources Strategy (First Edition, 2004)
PRROR	Priority-based River and Reservoir Operating Rules
RDM	Resource Directed Measures
RQO	Resource Quality Objectives
SASRI	South African Sugarcane Research Institute
SCADA	Supervisory Control And Data Acquisition
WARMS	Water-use Authorisation Registration Management System
WCDM	Water Conservation and Demand Management
WCO	Water Control Officer
WMA	Water Management Area
WMP	Water Management Plan
WRC	Water Research Commission
WUA	Water User Association

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1 INTRODUCTION

BACKGROUND

South Africa is a water scarce country, in which a number of the Water Management Areas (WMAs) have either already reached a state of being fully allocated, or are approaching a state of being fully allocated. Although the first edition of the National Water Resource Strategy, NWRS, (First Edition, 2004) suggests that dams and other forms of water augmentation could be introduced to address the water scarcity, little mention is made regarding how the dams and water augmentation options will be financed. The NWRS (First Edition, 2004) does however make mention of the need to use water resources more efficiently.

This project relates to the assessment of an Institutional Arrangement (IA), referred to as the Fractional Water Allocation and Capacity Sharing institutional arrangement. The institutional arrangement allows for water use entitlements to be issued against individual water resources, such as dams.

OBJECTIVES OF THIS STUDY

The objective of this study was to improve efficiencies of water use from large dams by developing a water audit system to ensure that water users downstream of the dams did not over-use water, and to ensure that dam operating rules were complied with. The scope of the project was increased to develop the water audit system to cater for an entire catchment, and not just dams. The overall objective to improve the efficiency of water use within a catchment did not change, however the project did require more focus on the further development of the Mike Basin model in order to generate outputs required for water resources planning purposes.

A further objective of the study was to share with stakeholders and water resource managers in the Mhlathuze Catchment any insights gleaned from this project which could have an impact on the water allocation process, particularly in stressed catchments where the compulsory licensing process will be undertaken as part of the water allocation process.

CHAPTER OUTLINE

The document consists of seven chapters, with the first being the (this) introduction to the document.

CHAPTER 2: Is an introduction to the research area, i.e. the Mhlathuze Catchment. The catchment is located in KwaZulu Natal, and the main river, the Mhlathuze River, drains into the Richards Bay harbour, which is currently a hub for industrial activity resulting from the port. The Mhlathuze Catchment is currently deemed to be stressed on paper, resulting from the fact that a number of water users are currently not using their full water use entitlements. The catchment has recently started a process of compulsory licensing, as notwithstanding the fact that the catchment is stressed on paper, the demand for water in the catchment is expected to grow, and the water users who are currently not fully utilising their entitlements may well do so in the future, implying that the water stress will be very real.

CHAPTER 3: Is a discussion of Institutional Arrangements, including what they are and why they are important. The Fractional Water Allocation and Capacity Sharing (FWA-CS) and Priority-based River and Reservoir Operating Rules (PRROR) institutional arrangements are introduced and contrasted. The focus of the chapter is to highlight that many water use rules (arrangements) are possible, and that each rule option may carry with it certain advantages and disadvantages. The objectives of this project are to review rules which promote water use efficiency, and which lend themselves to being audited. The PRORR institutional arrangement is the set of water usage rules currently adopted (in general) in South Africa. The FWA-CS institutional arrangement promises to hold certain advantages of the PRORR system in that it promises to better promote water use efficiency by water users using water from large dams in particular.

CHAPTER 4: Is a discussion related to auditing in the water resources sector. The chapter outlines what is meant by an audit in the context of this document, and what some of the requirements and limitations of a water audit are. The chapter discusses the FWA-CS and PRORR institutional arrangements, and how computer models are required in order to calculate the water to which various water users are entitled for a given point in time, or time range.

CHAPTER 5: Is a discussion of computer modelling methods. The chapter differentiates between modelling required at a planning level, and modelling required at an operational level. There needs to be a high level of overlap between modelling at planning and operational level. The concept of a node and channel network model is introduced, and a differentiation is made between modelling to support the Priority-based River and Reservoir Operating Rules (PRROR) and Fractional Water Allocation and Capacity Sharing (FWA-CS) institutional arrangements. In the chapter the yield curves for both PRROR and FWA-CS scenarios are shown and discussed.

CHAPTER 6: Discusses the project, with relevant conclusions. In the chapter aspects of the monitoring and metering component of the project undertaken by the CSIR are reported on, as well as on the two similar yet different institutional arrangements, i.e. PRROR and FWA-CS.

CHAPTER 7: This chapter contains the recommendations of the report, which include monitoring related recommendations, as well as modelling and policy related recommendations.

A discussion of the monitoring related tasks undertaken in the Mhlathuze Catchment is included in Appendix C of the document. The monitoring tasks were undertaken by the Environmentek division of the CSIR. The monitoring tasks relate to both the monitoring of hydro-meteorological data for use in water balances (e.g. rainfall, evaporation, wind-speed, relative humidity etc), as well as the assessment of water abstraction metering. With respect to the latter, the CSIR worked closely with the University of Pretoria, who were working on a water-metering assessment project. The CSIR tested one metering option, an indirect metering option that makes use of pressure transducers to calculate abstraction.

2 THE RESEARCH AREA - THE MHLATHUZE CATCHMENT

2.1 Key issues in the Catchment

The Mhlathuze Catchment was chosen as a suitable research area for the following reasons:

- The Mhlathuze Catchment is believed to be currently over-allocated. However the over-allocation appears to be a "paper over-allocation" in that many of the existing lawful use entitlements are not being used to their full capacity. The implication is that there are a number of unused entitlements (sometimes referred to internationally as "sleeper" rights). If the entitlements are fully utilised however, the over-allocation will be evident.
- Irrespective of the fact that the catchment is stressed on paper, it is essential for authorities to address the over-allocation via the compulsory licensing process. The need for compulsory licensing is increased due to the fact that new demand for water is expected to grow in the future, as the Richards Bay harbour located in the catchment is growing rapidly as are industries in Richards Bay.
- The Mhlathuze Catchment has been selected as one of the first catchment in South Africa in which the compulsory licensing process is to be initiated. Lessons learnt in the Mhlathuze Catchment will guide compulsory licensing in other catchments throughout South Africa.
- The Mhlathuze Catchment is very dependent on water provided by a large government dam – the Goedertrouw Dam.
- Certain stakeholders in the Mhlathuze Catchment expressed interest at the concept of water banking. If fact, a form of water banking was successfully introduced in the catchment during a drought in the early 1990s. The DWAF personnel as well as the irrigators in the Mhlathuze Catchment attest to the water saving that was induced by the adoption of the water banking system.

For the reasons above it was decided that the Mhlathuze Catchment was a suitable research area for the project.

2.2 Location

The Mhlathuze Catchment is located in northern KwaZulu Natal, South Africa and forms part of the Usutu to Mhlathuze Water Management Area. The WMA is divided into sub-areas, one of which is the Mhlathuze sub-area. This sub-area is made up of tertiary catchmentsW11, W12, and W13. The Mhlathuze catchment itself is the W12 tertiary catchment and the descriptions in this chapter therefore concern the W12 tertiary catchment. This section includes a fairly detailed description of the most important components of the Mhlathuze Catchment where applicable to the Water Audit System. Figure 1 shows the locality of the catchment in South Africa.

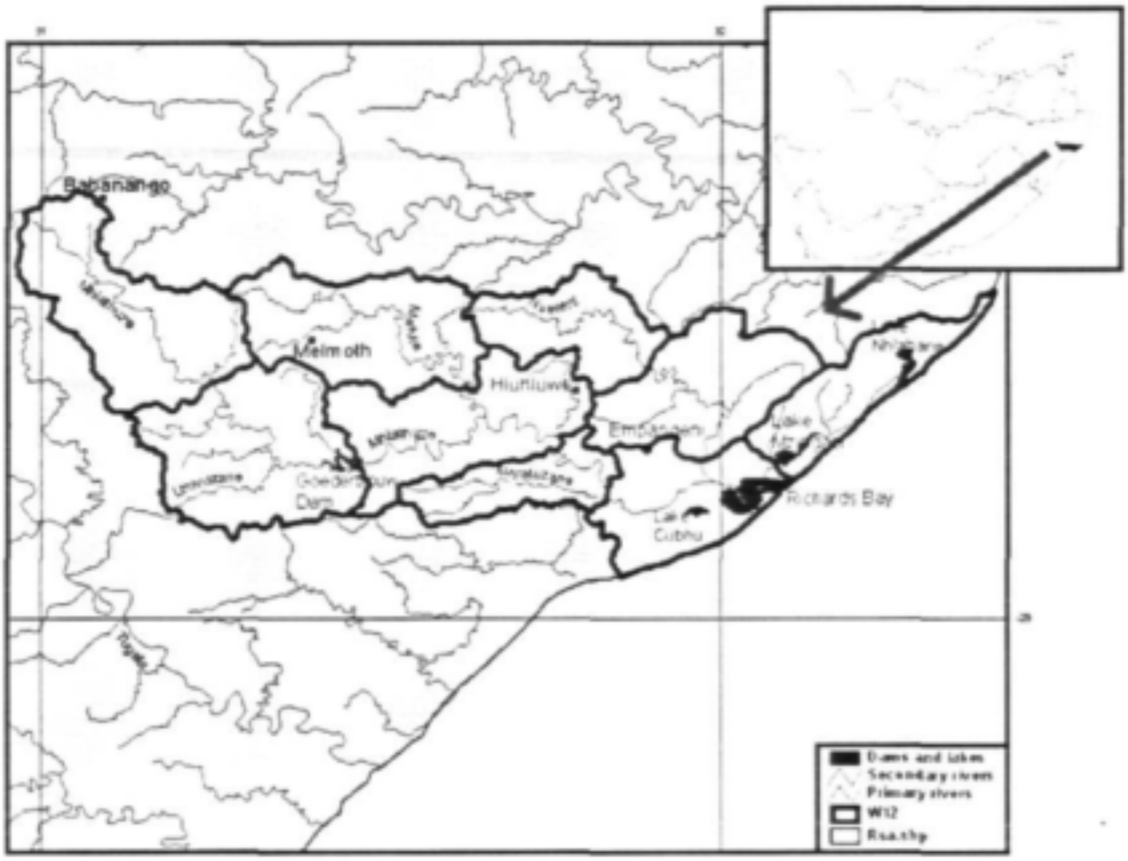

Figure 1 Main water resources in the Mhlathuze Catchment, including dams, lakes and rivers

2.3 Climate

2.3.1 Rainfall

The mean annual rainfall in the Mhlathuze Catchment ranges from 600mm.a^{-1} in the west to over 1200 mm.a^{-1} in the east. This is shown graphically in figure 2.

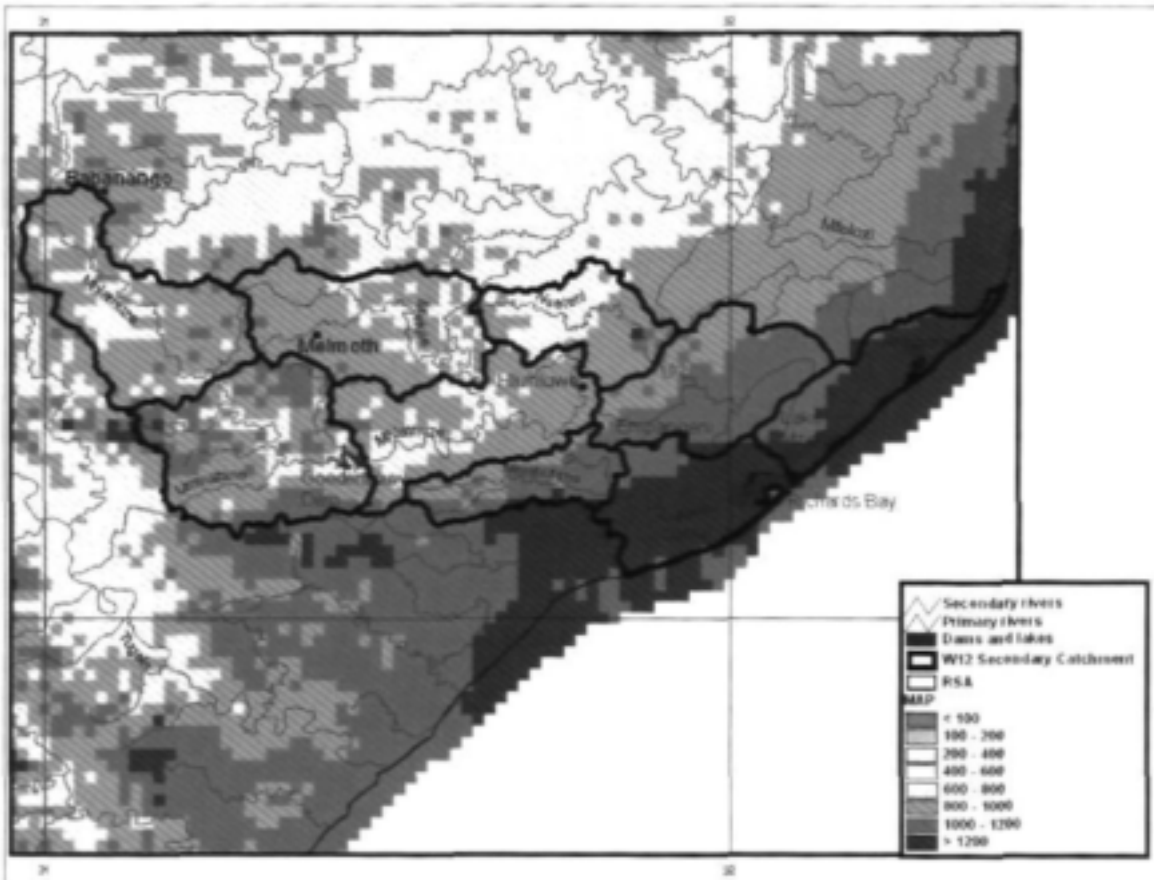

Figure 2 Mean annual precipitation values in the Mhlathuze Catchment and location of Mhlathuze weirs and irrigation boards (Schulze, 2001).

While the average rainfall is high over most of the catchment, it should be noted that there are many rain shadow areas. This may add complications to water allocations, particularly if curtailments are required to address over allocations.

The actual rainfall figures for the catchment above Goedertrouw dam are one of the big unknowns. Due to the quick response time of the catchments due to the terrain, rainfall information is critical. Sufficient warning of rainfall could potentially allow adjustment to releases and assist in flooding prevention and release efficiencies. This is discussed in Appendix C.

2.3.2 Evaporation

In order to be able to perform an audit on Goedertrouw Dam, the influence of evaporation should be quantified.

Although there is an A-pan and S-tank at Goedertrouw Dam, the importance of accurate evaporation determination was critical enough to warrant the installation of an Automatic Weather Station (AWS). This is discussed further in Chapter5. The A-pan and S-Tank readings are considered too coarse to give an accurate indication of evaporation from the dam.

The AWS installed at the dam (Chapter 5) allows for the computation of Reference Evaporation using the Penman Equation.

2.4 Water Resources

Water resources in the catchment consist of Goedertrouw Dam, coastal lakes and water from inter-basin transfers. Water is also used from the rivers in the catchment as well as being stored off the channel in farm dams.

2.4.1 Goedertrouw Dam

Goedertrouw Dam, a 3 MAR 300MCM dam, is a critical component of the Mhlathuze system and a large proportion of the river flow is generated in the currently ungauged catchment above Goedertrouw. It has been realised through interaction with stakeholders that although releases are not of great concern while there is abundant water in the system, which includes a few natural lakes fed from other water sources, it plays an important role in providing water for users downstream of the dam in times of drought and becomes the main water supply for the area. The dam provides water to a number of downstream irrigation schemes, industries and towns. Its location is shown in figure 3.

2.4.2 Lakes

There are a number of freshwater lakes in the catchment (see figure 1), including Lake Nsezi, Lake Nhlabane, Lake Cubhu and Lake Mzingazi. The lakes are fed by both surface water as well as groundwater flows. The lakes augment the yield in the catchment and are used by various water users in the catchment. The lakes do have ecological requirements attached to them, which translate into lake levels below which water users are not allowed to continue abstracting from these water sources.

2.4.3 Inter-basin transfers

The most significant transfer from outside the Water Management Area to the Mhlathuze Water system is from the Thukela Water Management Area and is for supplies to Richards Bay and Empangeni (NWRS, 2004). This amounts to 40 million

m^3 per year, which may be increased to a maximum of 94 m^3 per year – reserved in the Thukela water management area. However this facility is very expensive to use and is only used when needed, this is generally when dam drop to approximately 80%. A meeting is then held between stakeholders in order to discuss the need for the transfer, the cost of which is carried by those needing the water which is usually the industrial sector of the catchment users.

Provisional planning has also been done for the possible future increase of transfers from the Thukela River to the Mhlathuze sub-area to about 252 million m^3 per year, which would be dependent on the construction of additional storage in the Thukela River for that purpose – reserved in the Thukela water management area. (Usutu to Mhlathuze WMA; Overview of Water Resources Availability and Utilisation)

Main transfers within the Mhlathuze Catchment Study Area are from the Mfolozi River to Richards Bay Minerals in the Mhlathuze Catchment (NWRS, 2004). A substantial portion of the available water in the Mhlathuze catchment is therefore dependant on transfers (NWRS, 2004).

2.5 Land Use

There are several land uses in the Mhlathuze Catchment varying from cultivated lands (both irrigated and rain fed), to afforestation, sugarcane, residential, urban, rural and industrial use. An outline of the location of land uses is shown in figure 3.

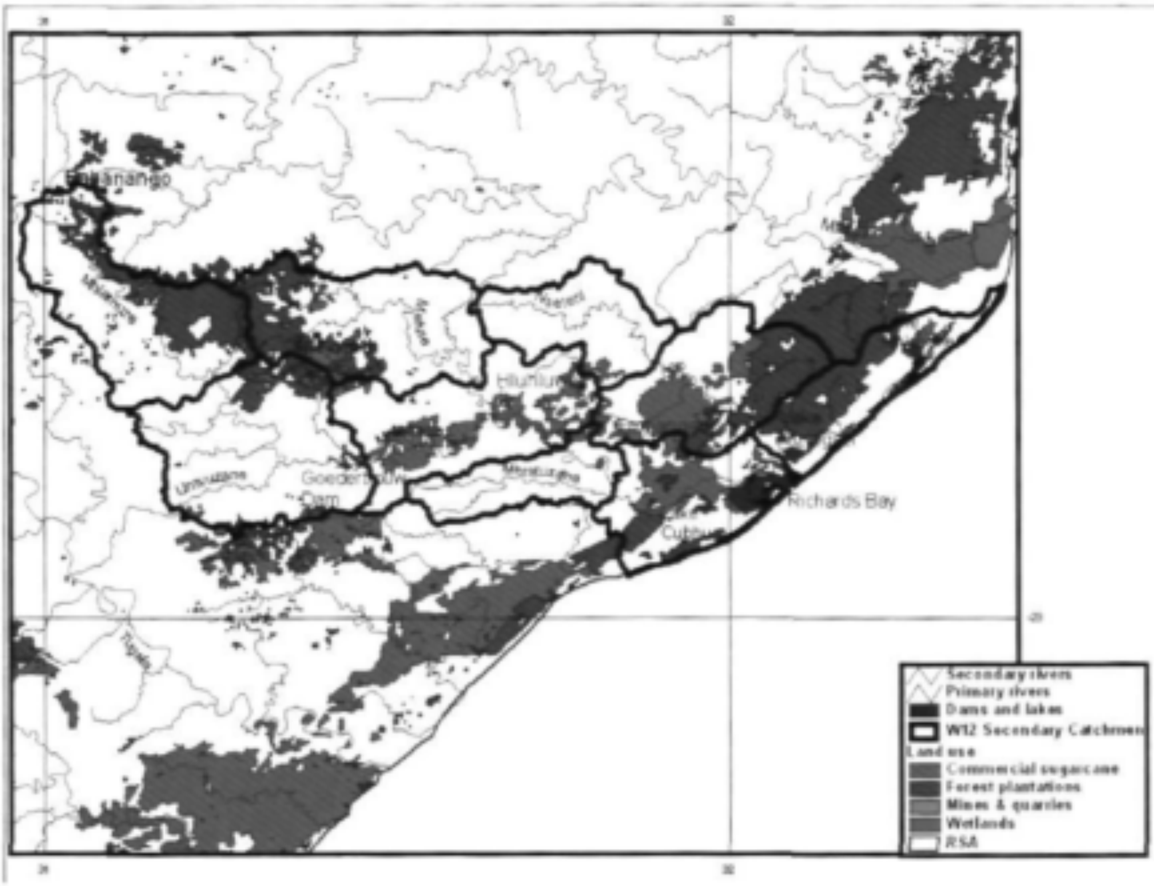

Figure 3 Landuse in the Mhlathuze Catchment

The water requirements of the different sectors for the Mhlathuze sub-area (W11, 12 and 13) as well as the Mhlathuze catchment are shown in table 1.

Table 1 Water requirements for the Mhlathuze sub-area of the Usutu to Mhlathuze WMA (source: Usutu to Mhlathuze WMA; Overview of Water Resources Availability and Utilisation)

Tertiary Catchment	Year	Irrigation	Urban (1)	Rural (1)	Mining and Bulk Industrial (2)	Power Generation (3)	Afforestation (4)	Total Local Requirements	Transfers out	Grand Total
W12	2000	84	25	4	84	0	18	215	3	218
W11, W12, W13	2000	94	28	8	86	0	19	235	0	235
W11, W12, W13	2025 (base)	94	34	8	86	0	19	241	0	241
W11, W12, W13	2025 (high)	94	105	8	86	0	19	312	0	312

1) Includes the basic human needs component of the Reserve at 25 ℓ/c/d.

2) Mining and bulk industrial water uses which are not part of urban systems.

3) Includes water for thermal power generation only. (Water for hydropower, which represents a small portion of power generation in South Africa, is generally available for other uses as well.)

4) Quantities given refer to impact on yield only.

While the table suggests that there will be no increase in industrial demand for water, the Richards Bay Harbour is not yet fully developed and when more development takes place, the demand for water is likely to increase.

2.6 Irrigation

Irrigation is not discussed in detail in this chapter, for details on the irrigation boards in the Mhlathuze Catchment please refer to Appendix B.

2.7 Potential application of the water audit system to other catchments

One of the objectives of the project is to see whether the water audit system could be applied to other catchments in South Africa. There are a number of attributes that are unique to the Mhlathuze catchment that will need to be assessed when applying lessons learnt from the Mhlathuze Catchment to other catchments in South Africa:

- The catchment is located on the eastern seaboard and the rainfall is high. The irrigators are therefore only dependent on irrigation systems in low rainfall periods, while in high rainfall periods, the crops are largely rain fed. In drier catchments in South Africa, the irrigators are highly dependent on abstraction for irrigation, and less dependent on rainfall.
- The Mhlathuze is a small catchment whereas other catchments to which an audit may be required could be significantly larger.
- It is a self contained catchment, meaning that the rivers flow from source to sea, and not into another catchment. This can be compared to the Upper Orange or Upper-Vaal catchments where the rivers flow from these catchments into another catchment.
- There are abundant groundwater and lake resources and much interaction occurs between these which is not entirely understood.
- Water Quality not an issue which may be the case in other areas.
- There is a fairly detailed monitoring network although there are still areas in the Mhlathuze catchment where more monitoring equipment could be installed.
- It is one of the only catchments in SA where water users pay for water on a volumetric (or per m^3) basis. This is done via Eskom electricity accounts where one can calculate a quantity of water used via the use of calibration coefficients and the KWH on electricity accounts. Calibration is done using a portable flow meter.
- During early 1990's drought James Perkins introduced a form of water banking and a number of users willingly used less water because of this, so they didn't adopt a 'use it or lose it' principle.

2.8 Chapter Overview

In this chapter details of the Mhlathuze Catchment were given, as well as key motivations for selecting the catchment as the project research area. The chapter also included a few notes on characteristics that may distinguish the Mhlathuze Catchment from other catchments in South Africa, which could influence the ability to use results from this research area in other catchments in South Africa.

The following chapter introduces the concept of institutional arrangements, which are in effect the rules which guide the apportionment of water amongst competing water users, particularly in times of water shortage. The water apportionment rules are of particular importance in that they are the foundations of a water audit system. If the water apportionment rules are not in place, or the rules are not clear, the ability to perform a water audit will be compromised. Relevant to this project is the fact that a new set of water apportionment rules is assessed, referred to as a Fractional Water Allocation and Capacity Sharing (FWA-CS) water apportionment system. This differs to the generally applied Priority-based River and Reservoir Operating Rule (PRORR) water apportionment set of rules.

3 INSTITUTIONAL ARRANGEMENTS

The overall objective of this project is to assess if efficiencies of water use can be improved via the (i) adoption of a new management system, which allows for the banking of water in large dams, and (ii) via the development of an auditing system to ensure that the system rules are adhered to. The management system, or set of working rules, is known as an Institutional Arrangement.

3.1 What are Institutional Arrangements?

An Institutional Arrangement (IA) can be defined as 'sets of working rules that are used to determine who is eligible to make decisions in some arena, and what actions are allowed or constrained. Further, the rules describe what procedures must be followed, what information must or must not be provided and what payoffs will be assigned to affected individuals' (Ostrom, 1990). This definition leads to the need to define "organisation", which is often confused with an institution.

According to Backeberg, (pers comm.), institutions are defined as the set of ordered relationships between people which determine their rights, exposure to the rights of others, privileges and obligations. This is distinctly different from organisations which are the cooperation between people which is conscious, deliberate and purposeful. Therefore the 1998 National Water Act is an institution and a Water User Association is an organisation. In theory and practice organisations cannot exist without the existence of institutions. Therefore to put it simply, organisations are the players and institutions are the rules of the game.

3.2 What are Guiding Principles?

The Oxford pocket dictionary defines a "principle" as "a fundamental source" or "fundamental truth as basis of reasoning" (The Pocket Oxford Dictionary, 1978). The relevance of principles is that they are often the foundations upon which the rules (institutional arrangements) are developed. The 1998 National Water Act (Act 36 of 1998) is founded on 28 principles. The principle that is most relevant to this research is:

Principle 13

As custodian of the nation's water resources, the National Government shall ensure that the development, **apportionment**, management and use of those resources is carried out using the criteria of public interest, sustainability, equity and efficiency of use in a manner which reflects its public trust obligations and the value of water to society while ensuring that basic domestic needs, the requirements of the environment and international obligations are met (NWRS, 2004).

The Fractional Water Allocation and Capacity Sharing (FWA-CS) institutional arrangement, which supports water banking, may influence how water is apportioned (but not to whom water will be apportioned, as this will be guided by the 1998 National Water Act, (First Edition, 2004) and CMS.

3.3 The Hierarchy of Institutional Arrangements

There is a hierarchy within which institutional arrangements can be set, which is clearly reflected in Principle 1 on which the 1998 National Water Act is founded, i.e.

Principle 1
The water law shall be subject to and consistent with the Constitution in all matters including the determination of the public interest and the rights and obligations of all parties, public and private, with regards to water. While taking cognisance of existing uses, the water law will actively promote the values enshrined in the Bill of Rights (NWRS, 2004).

3.4 The Interpretation of Institutional Arrangements

The 1998 National Water Act has been described as a framework Act (or enabling Act), in that it often does not spell out in meticulous detail how water resources are to be managed. Rather the emphasis appears to be on the desired outcome of the management, in that water resources are to be managed Equitably, Efficiently and Sustainably. The 1998 National Water Act leaves room for application as to how the outcomes can be achieved. This amount of leeway may be desired as circumstances will vary from catchment to catchment, thus possibly requiring different management approaches.

The National Water Resources Strategy, and the Catchment Management Strategies (which will be particular to the 19 Water Management Areas in South Africa), are in effect implementations of the 1998 National Water Act, outlining how the provisions in the 1998 National Water Act are to be achieved. The word "strategy" is derived from the Greek words "stratos" which is army, and "aegin" which means to lead. Strategy literally means a piece of generalship (as in leading an army). More generally, a strategy is an overall plan or campaign and course of action to achieve a specific objective, such as to win a battle or war.

A Catchment Management Strategy may therefore be viewed as an overall plan or campaign to handle the affairs of a WMA to achieve specific objectives. Since a campaign is an organised course of action, the word strategy could also be regarded as being a "process". Taken a step further, a strategy can be regarded as a process of using human, financial and water resources to achieve specific objectives in the most efficient and productive way (DWAF, Development of a Generic Framework for a Catchment Management Strategy – Final Draft).

3.5 The Importance of Institutional Arrangements

Institutional arrangements are important in that they are designed to influence behaviour of society (if the institutional arrangements are adhered to). Monitoring and enforcement of institutional arrangements may be required to ensure that behaviour in society is consistent with the intended behaviour of society, which is guided by institutional arrangements.

If institutional arrangements are to be upheld, they need to be meaningful, accepted by the public, and should be enforceable. This research document explores the concept of a water resources audit, which in effect is a process of ensuring that institutional arrangements are complied with. Where institutional arrangements are not clearly spelled out, and are open to various interpretations, it becomes difficult to undertake meaningful audits. A balance needs to be struck between the level of detail provided in an institutional arrangement (i.e. how clearly the institutional arrangement is defined), and the level at which audits are to be undertaken. This point is discussed throughout the document.

3.6 Factors Influencing the Evolution of Institutional Arrangements

Institutional arrangements, other than the Ten Commandments, are not cast in stone, and may vary from time to time. South Africa has recently witnessed significant changes to institutional arrangements. Relevant to this project, South Africa has a new Constitution (Act 108 of 1996), and a new National Water Act (Act 36 of 1998), as well as a number of new Acts which are not directly relevant to this research project.

institutional arrangements are shaped by the need to do things differently, and by the ability to implement new institutional arrangements. For example, there may be a need to do things differently, however human resource capabilities or technical capabilities may not be in place to give effect to the institutional arrangement. Furthermore, there may be legal constraints to the adoption of new institutional arrangements, as a change to an existing institutional arrangement may require a number of changes to other legislation.

Relevant to this research is the fact that South Africa has introduced a new Constitution of the Republic of South Africa, and a new (1998) National Water Act. The 1998 National Water Act is currently in the process of being "rolled out", and South Africa is thus in a transition period. This research project was based on the assessment of a new institutional arrangement, which may influence how water use entitlements are apportioned and subsequently audited.

3.7 Institutional Arrangements and South African Water Resources

The most senior institutional arrangements related to how water resources are to be managed include the Constitution and the National Water Act (both of which have been relatively recently established, i.e. 1996 and 1998 respectively). The old constitution was racially discriminatory, and required replacing. The 1956 Water Act on the other hand was not in itself discriminatory, but due to increasing demands for water since 1956 has become inappropriate for most catchments in South Africa. Important details in this regard are given below.

3.7.1 Provisions in the Constitution related to water resources

Key provisions in the constitution related to water include (DWAF: Guide to the 1998 National Water Act):

- Local government is in charge of municipal water services.
- Everyone has the right to have access to sufficient food and water,
- Everyone has the right to an environment that is not harmful to health or well being,
- The environment must be protected for the benefit of all people living now and who will live in the future,

3.7.2 A movement from a Riparian Rights system, to one of authorisations

The previous, now repealed, 1956 Water Act was based on a **Riparian Rights system**. In a Riparian Rights system, water rights are linked to land rights (in particular riparian lands). Although this system was not racially discriminatory, the Riparian Rights system did not allow for water to easily be made available for (i) re-allocation to previously discriminated persons, and (ii) for sustainable ecological processes (NWRS, 2004). Furthermore, this type of water rights system has been used primarily in regions where the supply of water exceeds demand (Simpson, 1997), which is not the case in South Africa.

The option to move an alternative water rights system, the **Prior-Rights system,** was not viable. The prior-rights system, also known as the "first-in-time first-in-law" would also not enable the government to deal with equity and sustainability considerations.

The most viable option was the adoption of water law **system based on authorisations to use water**. In effect, all water is held in trust by the government and water users have to apply for authorisation from a responsible authority to use water, unless exempt from this requirement. All water use must be authorised according to the 1998 National Water Act. South Africa is not the only country to adopt such a system, and there appears to be an international migration towards this type of system as it promises to be the most viable system to meet equity, sustainability and efficiency objectives in a representative manner (where water scarcity exists).

This research project involves the assessment of an institutional arrangement that relates to how water use entitlements are defined and apportioned.

3.7.3 Authorisations to use water

The Reserve, which consists of water for ecological flows (referred to as Ecological Flow Requirements (EFRs) and water required for basic human needs (referred to as Basic Human Needs), is the only form of water use that has a RIGHT to use water. Except for water required for the Reserve and Schedule 1 uses, all other water use must be authorised.

In the draft position paper for water allocation reform in South Africa (DWAF, 2005), four types of entitlements to use water are discerned, including:

- Schedule 1 water use, which is for small volumes of water for household use with little potential for negative impacts on the water resource, for which no application for authorisation needs to be made,
- General Authorisations, which are for larger volumes of water with some potential for negative impacts on the water resource which may be generally authorised in any catchment or for a specific type of water use anywhere in the country,
- Existing lawful water use, which is water use that lawfully took place in the period two years before the commencement of the 1998 National Water Act, and

- Licensed Water Use, which is for larger volumes of water or other water use authorised in terms of a license issued under the 1998 National Water Act, and upon approval of an application by a responsible authority.

3.7.3.1 Licensed Water Use

Eleven types of water use licenses have been discerned in the 1998 National Water Act, including:

1. Taking water from a water resource;
2. Storing water;
3. Impeding or diverting the flow of water in a watercourse;
4. Engaging in a stream flow reduction activity (afforestation being the only one);
5. Engaging in a controlled activity (cloud seeding, irrigating with waste, hydro power);
6. Discharging waste or water containing waste into a water resource;
7. Disposing of waste in a manner which may detrimentally impact on a water resource;
8. Disposing of water which has been heated, or which contains waste from any industrial or power generation process;
9. Altering the bed, banks, course or characteristics of a watercourse;
10. Removing, discharging or disposing of water found underground, if it is necessary for the efficient continuation of an activity or for the safety of people; and
11. Using water for recreational purposes

Notes:

- Not all the water uses listed above (1-11) are consumptive in nature.
- This research project relates to the development of a computerised model that can accommodate the first 4 water uses listed above.
- The 1998 National Water Act makes no direct mention of the "management system" or systems that should or could be adopted, within which the authorisations are issued. Section 28 and 29 of the 1998 National Water Act are pasted below to demonstrate that there are no provisions in the 1998 National Water Act that forbid the adoption of a managements system such as the FWA-CS system. Personal discussions with DWAF staff also revealed that the FWA-CS management system does not appear to contravene any clauses in the 1998 National Water Act.
- The efficiency with which water is used in a catchment could be influenced by the management system adopted.
- The management system adopted could influence the ability to audit water use in the catchment.

Section 28 of the 1998 National Water Act lists attributes that must be specified on the licenses, i.e.

(a) the water use or uses for which it is issued;

(b) the property or area in respect of which it is issued;

(c) the person to whom it is issued;

(d) the conditions subject to which it is issued;

(e) the licence period, which may not exceed forty years; and

(f) the review periods during which the licence may be reviewed at intervals of not more than five years.

Section 29 of the 1998 National Water Act lists the conditions for issue of general authorisations and licences

(1) A responsible authority may attach conditions to every general authorisation or licence -

(a) relating to the protection of -

(i) the water resource in question;

(ii) the stream flow regime; and

(iii) other existing and potential water users;

(b) relating to water management by -

(i) specifying management practices and general requirements for any water use, including water conservation measures;

(ii) requiring the monitoring and analysis of and reporting on every water use and imposing a duty to measure and record aspects of water use, specifying measuring and recording devices to be used;

(iii) requiring the preparation and approval of and adherence to, a water management plan;

(iv) requiring the payment of charges for water use as provided for in Chapter 5;

(v) requiring the licensee to provide or make water available to a person specified in the licence; and

(vi) in the case of a general authorisation, requiring the registration of the water use with the responsible authority and the payment of a registration fee as a pre-condition of that use;

(c) relating to return flow and discharge or disposal of waste, by -

(i) specifying a water resource to which it must be returned or other manner in which it must be disposed of;

(ii) specifying permissible levels for some or all of its chemical and physical components;

(iii) specifying treatment to which it must be subjected, before it is discharged; and

(iv) specifying the volume which may be returned;

(d) in the case of a controlled activity -

(i) specifying the waste treatment, pollution control and monitoring equipment to be installed, maintained and operated; and

(ii) specifying the management practices to be followed to prevent the pollution of any water resource;

(e) in the case of taking or storage of water -

(i) setting out the specific quantity of water or percentage of flow which may be taken;

(ii) setting out the rate of abstraction;

(iii) specifying the method of construction of a borehole and the method of abstraction from the borehole;

(iv) specifying the place from where water may be taken;

(v) specifying the times when water may be taken;

(vi) identifying or limiting the area of land on which any water taken from a resource may be used;

(vii) limiting the quantity of water which may be stored;

(viii) specifying locations where water may be stored; and

(ix) requiring the licensee to become a member of a water user association before water may be taken;

(f) in the case of a stream flow reduction activity -

(i) specifying practices to be followed to limit stream flow reduction and other detrimental impacts on the water resource; and

(ii) setting or prescribing a method for determining the extent of the stream flow reduction caused by the authorised activity;

(g) which are necessary or desirable to achieve the purpose for which the licence was issued;

(h) which are necessary or desirable to ensure compliance with the provisions of this Act (1998 National Water Act); and

(i) in the case of a licence -

(i) specifying times when water may or may not be used;

(ii) containing provisions for its termination if an authorised use of water is not implemented or not fully implemented;

(iii) designating water for future or contingent use; or

(iv) which have been agreed to by the licensee.

(2) If a licensee has agreed to pay compensation to another person in terms of any arrangement to use water, the responsible authority may make the obligation to pay compensation a condition of the licence.

3.8 The Transition from the 1956 Water Act to the 1998 National Water Act

Even though the 1998 National Water Act has been promulgated, South Africa can currently be considered to be in a transition period from the old (1956 Water Act) to the new 1998 National Water Act. The 1998 National Water Act requires a number of administrative organisations to be formed (e.g. CMA, WUAs). Furthermore, the 1998 National Water Act requires a process of compulsory licensing to be undertaken for catchments require such an undertaking (explained below).

In many respects one could say that the implementation from the 1956 Water Act to the 1998 National Water Act will be in its advanced stages once all required organisations have been formed, all necessary systems are in place (e.g. the Classification System), and the initial allocation of water use licenses has taken place (particularly in stressed catchments).

What is important to this project though is that although the compulsory licensing process has started in a few catchments, one of them being the Mhlathuze Catchment, the process has not been completed in any of the catchments as yet. The "system" being assessed, i.e. that of FWA-CS, appears to be consistent with all provisions in the Constitution, the 1998 National Water Act and interpretations provided in the NWRS (First Edition, 2004). The system appears to be an "interpretation" of the rules, which could/should be discussed as part of the water allocation process, of which the compulsory licensing process is a key component in stressed catchments.

3.9 The Compulsory Licensing Process

Upon promulgation of the 1998 National Water Act, water users were requested to register their water used between 1996 and 1998. The Department of Water Affairs and Forestry may verify that the registrations are accurate (i.e. that the water user was in fact using the water registered for) and may validate that the water use was legal at the time (DWAF, Guide to the 1998 National Water Act).

In catchments where water shortages exist, such as the Mhlathuze Catchment with is the research area for this project, a process of Compulsory Licensing will be undertaken, in which case all existing and potential water users (except for Schedule 1 users and users under General Authorisations), need to apply for licenses (DWAF, Guide to the 1998 National Water Act). The compulsory licensing process can be used to:

- Achieve a fair allocation of water in water scarce catchments
- Improve the efficient use of water in the public interest,
- Ensure efficient management of the water resource, and
- To protect water quality.

Table 2 The different steps in the compulsory licensing process (modified after the DWAF: Guide to the 1998 National Water Act).

No.	Task
1	Existing water use and its lawfulness is verified
2	Users that are not yet registered are identified (e.g. rural users)
3	All registered users and potential users are called to apply for licenses (through a notice)
4	Users and potential users apply for a license
5	License applications are evaluated according to factors outlined in the 1998 National Water Act.
6	A proposed Allocation Schedule is prepared and the public is invited to comment
7	A preliminary allocation schedule is published (which has considered all comments from the public)
8	The final allocation schedule is published in the Government Gazette (which takes into account successful Water Tribunal appeals).
9	Water licenses are issued to water users according to the allocation schedule

Figure 4 on the following page provides a more comprehensive outline of the compulsory licensing process. The "Water Balance" and "Proposed Allocation Schedule" components illustrated in the figure are of importance to this project, in that the institutional arrangement being assessed may influence how the water balance is undertaken, as well as the proposed allocation schedule.

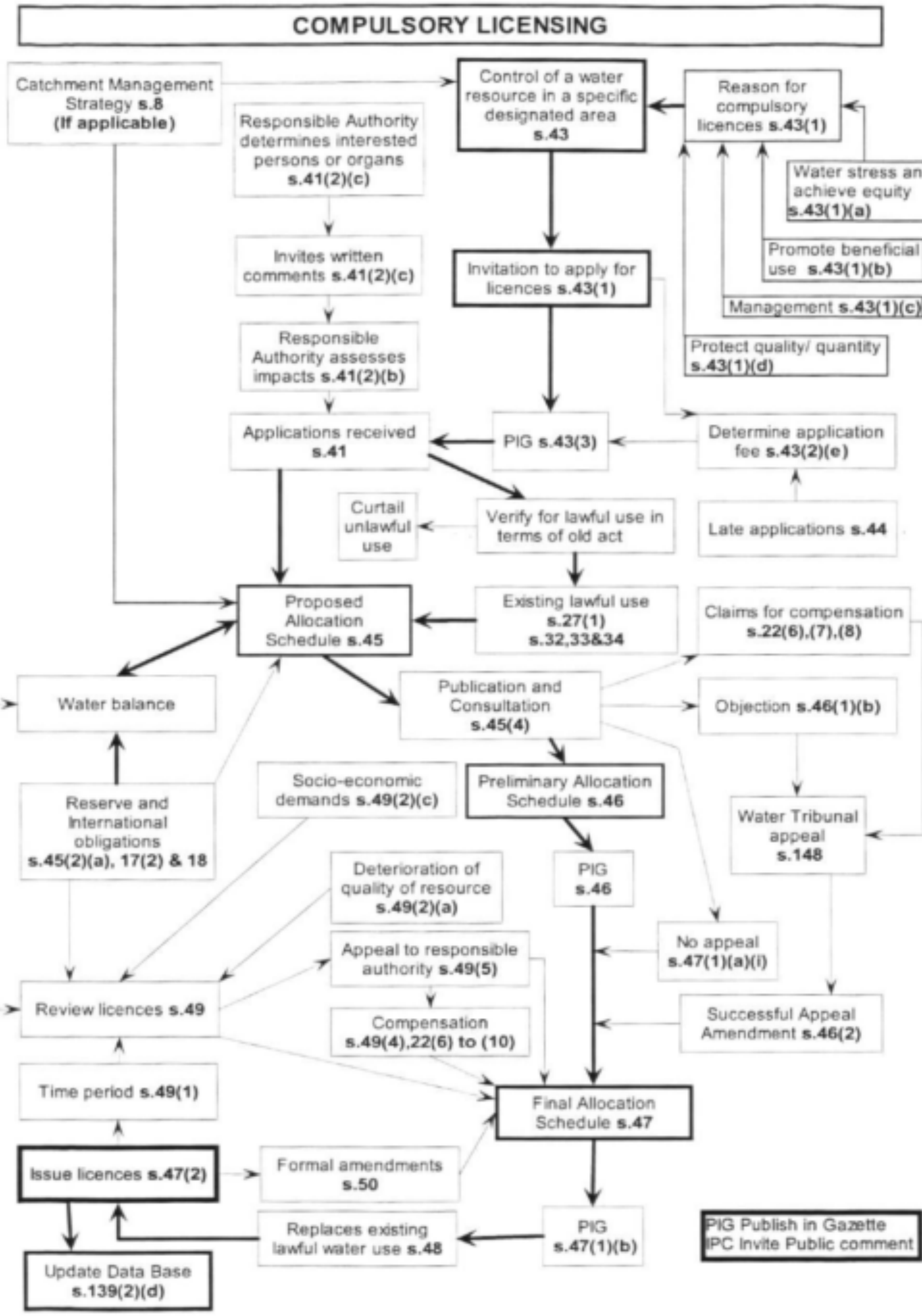

Figure 4 The compulsory licensing process (after Wessels, 2004)

3.10 Fractional Water Allocation and Capacity Sharing and Priority-based River and Reservoir Operating Rule Institutional Arrangements

Background

A catchment is generally comprised of a number of potential water resources, including rivers, dams, possibly lakes and groundwater reserves. Within the catchment there are a number of water uses (as defined by the 1998 National Water Act). South Africa has adopted an authorisation system (a form of institutional arrangement), with the objective to get the "right amount" of water to the "right users", with guidance given by the 1998 National Water Act, NWRS (First Edition, 2004) and CMS in this regard.

Water users require the appropriate authorisations to use water legally. However, the water management authority will need to keep track of the nature, number and location of authorisations in issue, giving consideration to the privileges and responsibilities attached to each license, in order to give effect to the authorisations.

The privileges attached to authorisations generally pertain to:

- The priority with which the water user is to receive water, and
- The level of water restriction that will be imposed on the water user during periods of water shortage.

FWA-CS and PRROR are in effect institutional arrangements that relate to how water authorisations are defined and catchments are operated. A very clear understanding of the rules governing authorisation to use water is essential for a water audit system. The water apportionment rules are used to work out who has entitlements to use water (and how much water) for a given point in time (or time range). An audit is a reconciliation of actual water use against the entitlement to use the water. The rules are required to calculate the entitlement to use water by the respective water users for a given point in time or time range. Bear in mind that the significance of the point in time or time range relates to the water availability in a catchment, which will influence who has entitlements to water, and the volume of water that may be abstracted. The rules are of particular importance in times of water shortage when certain water users may face water use restrictions. The rules clearly indicate who will be restricted in periods of scarcity, and the magnitude of the restrictions.

Internationally there are many possible options with which water allocation rules can be specified (Productivity Commission, 2003). Two options in particular are referred to in this document. The first is the Priority-based River and Reservoir Operating Rule (PRROR) water apportionment system, and the second is the Fractional Water Allocation and Capacity Sharing (FWA-CS) water apportionment system. The PRROR is discussed as it is the system which is most generally used in South Africa currently, while the FWA-CS is a newer system which may have certain advantages over the PRROR system related in particular to the positive incentives the FWA-CS system provides for more efficient water use from large dams, brought about by the water banking associated with the FWA-CS system.

3.10.1 Priority-based River and Reservoir Operating Rule (PRORR) system

In the PRROR system, the catchment is managed as a single system, and licenses are issued against the system. Water managers are tasked to apportion water within the catchment to the most appropriate users, using a Priority-based Reservoir and River Operating System. The operating rules refer to water restriction rules imposed on water uses. The entitlement is specified as a volume (usually per annum). With respect to irrigation related entitlements, it is possible for other conditions to be added to the entitlement which limit the area that can be planted to a given crop (DWAF, pers comm.) Use is made of the Water Resources Yield Model to capture the water resources, authorised water users and their linkages and priorities to the resources, as well as the restriction rules of the authorised water users.

PRROR system : representing the priority of water users

The Water Resources Yield Model (WRYM) is a node and channel network model which makes use of penalty structures to represent the priority of water use to the various water users.

PRROR system: restriction rule pertaining to stored water

Restriction rules are often based on water levels of storage facilities (e.g. dam water levels), and the nature of water users. The reason for this is that:

- The rule is simple to understand, and easy to enforce
- A high level of control can be exercised over dams (i.e. by the water control officer, who is in charge of releases from the dam), and
- Dams are generally a vital source of water during periods of water shortage.

Table 3 below illustrates how restriction levels of the PRROR system vary depending on (i) the nature of the water user, and (ii) the level of water in the dam. The table is just an illustration of restriction levels. The restriction levels may vary from one dam to another, however the general trend is for the irrigation sector to receive higher levels of water restriction that the other sectors. The restriction levels are an effective, but not necessarily and efficiency inducing operating rule that result in different levels of assurance to the various water use sectors.

Table 3 Varying restriction levels during periods of water shortage

DAM LEVEL	IRRIGATION	DOMESTIC USER	INDUSTRIAL USER
>= 75%	No restriction	No restriction	No restriction
>= 50% & < 75%	Less 25%	No restriction	No restriction
>= 25% & < 50%	Less 50%	Less 10%	No restriction
>= 15% & < 25%	Less 75%	Less 25%	No restriction
< 15%	Less 90%	Less 30%	Less 10%

Restrictions related to run-of-river flows

Just as restriction levels are imposed on dam level, so too can they be levelled on the availability of water in streams. Often, due to the inability of abstraction pumps to regulate the flow rate at which water is pumped at, rules are put in place to accommodate for this. Examples are given where certain abstractors on the left bank of the river are allowed to abstract on designated days of the week, while the right bank may irrigate on alternate days. Auditing (compliance monitoring) is also made easier given such a rule, as it will then be easy to identify users who are abstracting on the wrong day.

A few disadvantages of this system are:

- A use-it-or-lose-it principle is applied to dams. If water users do adopt more efficient water use technologies, or don't use their water (for whatever reason), the entitlement to this water is lost, and other user stands to use this water during periods of water shortage. The irrigation sector is currently the largest water user in South Africa, and has the lowest assurance of supply (inferring that it has the lowest priority level to use water, AND is faced with the highest level of restriction). The implication of this is that as water becomes scarcer, the irrigators have an incentive to use as much water as they can within their entitlements, otherwise they stand to lose it once restrictions set in.
- The PRROR is difficult to operationalise, and to audit in that information is required regarding:
    - Details of the respective water resources in a catchment, with an understanding of how the resources are linked with one another (if at all),
    - The volume of water available in the respective water resources of the catchment,
    - Details of all authorised water users and their location in the catchment, including their priority status, and details of restriction rules associated with the users, and
    - Details of the access the various authorised water users have to the respective water resources

All of this information is required to work out how to apportion the available water amongst the competing users (as per the "rules of the game"). Even though the WRYM is able to apportion water as required, the model operates on a monthly time step, which may be too coarse a time step for local requirements.

- The limited involvement of stakeholders in the management of the system may detract from the ability to and interest of stakeholders to "community police" water use in the catchment.

The different levels of assurance of supply between sectors, brought about by different levels of priority and restriction rules, complicate water trading between sectors.

3.10.2 Fractional Water Allocation and Capacity Sharing (FWA-CS)

In the FWA-CS system, water resources are divided into storage (dams in particular) and flow resources, and entitlements are issued against these respectively. The term FWA-CS is an acronym for Fractional Water Allocation (FWA - which is the allocation against the flow resources) and Capacity Sharing (CS – which is the allocation against the capacity of dam capacity).

Figure 5 below illustrates diagrammatically how the FWA-CS system operates. The diagram illustrates how the flow into the dam has been apportioned, with fractions (proportions) of the flow being allocated amongst water users. The capacity of the dam is also divided into proportions. The proportions of the dam capacity held by a user do not have to be the same as the flow proportions held by the same user. The user can vary these to tailor the assurance of supply that he desires.

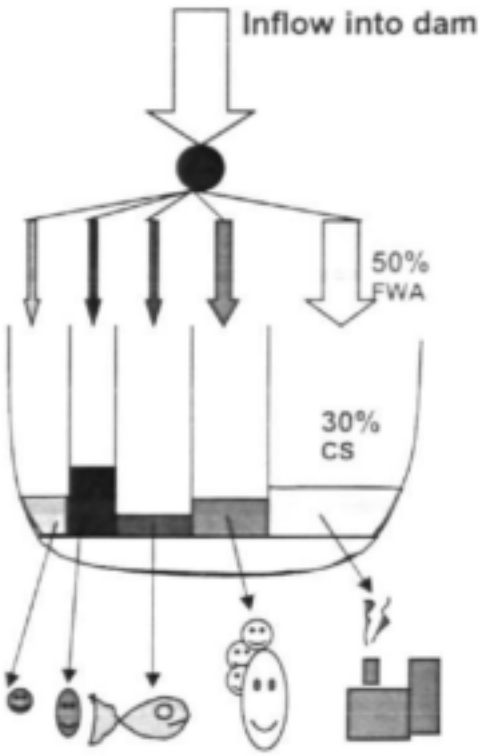

Figure 5 A graphical conceptual illustration of the Fractional Water Allocation and Capacity Sharing Institutional Arrangement

From an operational point of view, water users will operate their share of dam capacity like a bank account. Inflows will increase the account, whereas releases, pro-rata evaporation and pro-rata seepage losses will be deducted from the account. The account can be operated on a relevant time-step, e.g. weekly, fort-nightly, monthly etc.

The advantages of the FWA-CS system are:

- Water users are given an incentive to use water efficiently, particularly as the water level in dams starts dropping (and the economic scarcity value of the water starts rising). It is this incentive to stimulate more efficient water use (particularly from large dams) that is of particular interest to this project. A more detailed discussion of the mechanics of the incentive is given below.
- Previously disadvantaged communities can receive favourable lease options to shares of the dam which can then be sub-let to existing users. This can be done temporarily to help these communities build up capital reserves which may be required to use the water beneficially.
- DWAF or an appropriate Conservation Organisation can manage releases for the Reserve, while other water users can tailor their own assurances of supply independently (within their financial means). DWAF and/or consultants could provide the water users with planning and operational advice to ensure that water is used judiciously.

- Neighbouring countries can lease capacity shares of South African dams, and thereby cater for their own water releases. This may be a viable water related NEPAD (New Partnership for Africa's Development) initiative.
- The FWA-CS system promotes water trading, in that water use entitlements are very clearly specified, and the water user/s can quickly and easily establish who holds water rights, from where, and what the banked water levels are where dams exist.
- This option was the preferred option of stakeholders and was successfully adopted in the Mazowe catchment in Zimbabwe (Doertenbach, 1998), and is being applied in Australia (Ryan *et al*, 2000).
- A form of water banking was successfully (albeit temporarily) adopted in the Mhlathuze (Richards Bay) catchment in South Africa during the heat of a drought. Unfortunately this has not been formally documented.
- The water banking option is in harmony with the underlying principles of the 1998 National Water Act. In fact it could be argued that because it provides incentives to efficient water use, it is more in harmony with the 1998 National Water Act than the traditional volumetric and assurance of supply approach to water allocation.
- Software has been developed by the Danish Hydraulic Institute, in the form of Mike Basin, which can accommodate FWA-CS in an easy to understand format based on a GIS (arc-view) platform.
- With the FWA-CS framework it is possible to calculate and communicate entitlements to users at fine temporal scales (even as fine a time scale as daily), and audits can be performed at the time scale at which the entitlements are calculated at. The advantage of this is that while water is abundant calculations can be performed at relatively course time steps (e.g. monthly), however in times of water scarcity the scale can be increased to daily or weekly.

A few disadvantages of the FWA-CS system are:

- The initial configuration of catchments into allocation nodes against which Fractional Water Allocations are specified, as well as the process of initially allocating fractions (of dams and allocation nodes) to users will be a challenging undertaking. However, once done, the system should be simple to operate.
- Instrumentation and a relatively high level of management will be required to operate the FWA-CS system. However, the counter to this is that a higher level of management and monitoring instrumentation will be required irrespective of the system adopted.
- As FWA-CS is a new concept, and is largely untested in South Africa, there will be a resistance by many people, who may prefer to use established tried-and-tested methods.

- The FWA-CS institutional arrangement may not be suitable for all catchments in South Africa. In general, the larger the catchment, the more difficult it will be to apply this methodology.

3.10.3 The mechanics of incentives induced by water banking

The dam operating rules of the PRROR system reflect a "use-it-or-lose-it" approach to water management. The dam operating rules of the FWA-CS system reflects a "use-it-or-bank-it" approach to water management. Water users will have an incentive to find more efficient ways of using water, in that their saved water can be banked. The banked water can then, either be used for the same purpose as it originally was going to be used, just at a different time, or the banked water can be traded.

Water trading in the FWA-CS system should be relatively easy to administer (thus transaction costs will be kept low), and attractive to persons requiring extra water as the quantity and quality of stored water is known with a very high level of confidence. Consequently the price paid for trades may be higher than that of trades occurring in the PRROR system. The more water users can make out of trades, the more they will invest in finding ways to use water more efficiently. The funds generated from the trades may even be used to fund the tasks required to induce water use efficiency.

Given the fact that 10 of the 19 WMAs are considered to be stressed, implying that not everyone who applies for licenses will get the licenses they want, water trading may become a very important way for water users to get extra water use entitlements.

3.10.3.1 Possible impediments to the banking of water

The single most important impediment to the banking of water relates to high evaporative losses (with some losses attributed due to seepage). The extent of the evaporative losses will depend on a number of factors, including:

- The height, volume area relationship of the dam. The higher the water surface are relative to storage, the higher the evaporative losses will be,
- The time of year banking takes place

3.10.4 Water use metering and FWA-CS

If water users are able to bank unused water (resulting from more efficient water use practices), there will be a requirement to meter the water use by water users to verify actual water use. Assessing the irrigated crop area will not suffice to quantify the water saving, and water abstraction metering will be required.

If the FWA-CS institutional arrangement is found to be attractive to stakeholders, the stakeholders may be willing to invest in the installation of accredited water meters which are required for the FWA-CS institutional arrangement to work well. The installation of water meters may become even more attractive to stakeholders if water use charges are levied on actual water use, as opposed to a charge levied on the full water use entitlement. A water use charge levied on actual water use will on its own promote improved water use efficiency, and coupled with water banking and water trading, the incentive to use water more efficiently is enhanced.

RECOMMENDATION: The installation of accredited, high confidence water meters promises to be a significant management undertaking which could induce significant more efficient use of water by stakeholders.

Why is the FWA-CS institutional arrangement not more prevalent internationally?
There are a few possible reasons for this, including:

- The FWA-CS system is only really possible under an authorisation water management system. Thus the institutional arrangement is not suited to the Riparian Rights system, nor the Prior-Rights system. A number of catchments around the world are still operated under these legal systems.
- The FWA-CS institutional arrangement is a relatively new management option (even though it has been applied in Zimbabwe for a number of years now). The catchments appear to be relatively simple where the system has been applied, in that water users were located very near the dam to which the FWA-CS system was applied. In larger catchments, where there are a significant number of tributaries, it becomes more complicated to assign entitlements. However, the Mike Basin model (Danish Hydraulic Institute, 2005) has recently been updated to be able to accommodate both Capacity Shares, as well as Fractional Water Allocations, in a framework that allows water resources planning and operations to take place. The availability of this user friendly software, and increased public awareness of the FWA-CS institutional arrangement will probably see this type of institutional arrangement becoming more prevalent in the future, especially in water stressed areas with a high value of water.
- It is possible that the requirement to meter actual water use inhibited the up-take of this institutional arrangement. However, the advances in cell-phone technology, and reduction of costs related to metering systems, is resulting in this argument becoming less viable.

3.11 Computer Software to Support institutional arrangements

The FWA-CS and PRROR operating rules are relatively straight forward, however applying them to catchments is a complicated undertaking due to the complexity of catchments, the importance of spatial location of water users and water resources with respect to one another and water user abstraction preferences.

Computer models are required to assist water resource managers in the apportionment of water resources. A differentiation is made regarding the use of the models for planning purposes and for operational purposes.

3.11.1 Water resources planning

Give consideration to the Compulsory Licensing process for one moment. A number of license applications will be submitted by potential water users, and quantities of water will be set aside for the Reserve, International Flow Requirements (if relevant), Strategic Water Use requirements (if relevant), and water for future generations (if relevant). Water resource managers will need a method of reconciling the demands for water against the ability of the catchment to supply the water. Consideration needs to be given to the operating rules (reflecting the privileges and responsibilities) of the water users, as well as the nature of the water resources, and details of the water availability at the water resources over time.

Planning is in essence the process undertaken to work out "how big the water resources pie" is given all the details above. The process is undertaken by using long records of historical flow data, which is naturalised to remove the impacts of actual water use through the course of time. A series of water use scenarios are then run, with the scenarios mimicking how water will be used according to the operating rules. From these scenarios it is possible to assess how the catchment is able to supply the demands for various water users for the respective scenarios. Using this technique the water resources planning can ascertain roughly how many authorisations can be issued, and the nature and location of the authorisations, to ensure that acceptable levels of assurance are achieved by water users.

The initial allocation of licenses will based on the results of such planning exercises. The Water Resources Yield Model (and at times the Water Resources Planning Model), both of which are node and channel network models, are currently used by the DWAF for their planning purposes. The WRYM and WRPM are developed around the PRROR institutional arrangements, and operate at a monthly time step.

The WRYM and WRPM are not able (in their current form) to represent the FWACS institutional arrangement.

The Mike Basin model (developed by the Danish Hydraulic Institute) is also a node and channel network model, however the network solver operates differently to that of the WRYM. The Mike Basin model can represent both the FWA-CS institutional arrangement as well as the PRROR institutional arrangement. The model is developed within a GIS framework, which facilitates an understanding of the location of users and resources, and the relationship between them (i.e. the operating rules of the system).

3.11.2 Water resources operations

Water resources operations are the day to day operations of the catchment. Near real time data are required related to the water available within the respective water resources of the catchment. With this information, and details of the water users and the resources that the users can utilise water from, as well as the priority of water users, water resource managers can ascertain how to apportion the water as per the "rules" embodied in the PRROR or FWA-CS institutional arrangements.

For water resource planning purpose, the water use by users is calculated by the water resource planners. Remember that the planning model runs are often scenarios. With respect to water resources operations it is possible to measure (meter) actual water usage by the water users. The actual water usage, when compared to the water use entitlement is in effect a water audit.

A limitation of the WRYM is that it is a monthly time step model, and cannot as such be used to apportion water available in catchments at a relatively fine time step. This limits the temporal grain at which an audit could take place.

More details of the Mike Basin model and scenarios run with the model are discussed in chapter 5.

3.12 Chapter overview

An audit is generally a process of reconciling observed behaviour with expected or intended behaviour. In this chapter aspects relating to the rules which guide the expected or intended behaviour were discussed. The rules are generally referred to as institutional arrangements. Within this chapter it was pointed out that there are in fact a number of sets of institutional arrangements. For example, the Constitution of

South Africa can be seen to be the overarching institutional arrangement, with the various Acts (such as the 1998 National Water Act) supporting and being consistent with the Constitution. The point was also made that the 1998 National Water Act is a framework Act, which implies that it provides guidance as to how water resources are to be managed, but does not provide the specifics.

Currently, in general, South Africa adopts a Priority-based River and Reservoir Operating Rule (PRROR) set of rules which guide how water is to be apportioned amongst water users. A significant potential shortcoming of the PRROR system, identified in the course of this project, relates to the potential disincentive created by the use-it-or-lose it philosophy of water-use from dams. Given the fact that a key objective of the project was to find ways to improve water use efficiency, particularly from large dams, and given the fact that an alternative water apportionment set of rules exists, the Fractional Water Allocation and Capacity Sharing (FWA-CS) system, it was necessary to ascertain if a system such as the FWA-CS system would not be prohibited by the 1998 National Water Act, and any other higher level institutional arrangements. Relevant clauses in the 1998 National Water Act are included in the chapter above to illustrate that no clauses exist which prohibit the adoption the FWA-CS system.

In order to highlight some of the similarities and differences between the FWA-CS and PRORR system, both systems are discussed and contrasted in this chapter. The chapter also includes a discussion of water resource planning versus water resource operations. There relevance of the discussion relates to the fact that an audit is an operational undertaking, however, given the fact that the planning process will influence the nature and number of authorisations that will be issued, there needs to be a strong link between water resources operations and water resources planning processes. The set of water resource apportionment rules (the institutional arrangements) is common to both water resource planning and water resource operations.

It is important for the reader to appreciate that the original focus of the project was to develop a water audit system around the currently adopted institutional arrangement – i.e. the PRROR institutional arrangement. However, in the course of the project, it became apparent that the PRROR institutional arrangement could be replaced by a different institutional arrangement, that of the FWA-CS institutional arrangement, which due to the use-it-or-bank-it philosophy of water use from large dams, promises to promote improved water use efficiency. Improved water use efficiency was the key objective of the project. The research team was faced with a bit of a dilemma, as the FWA-CS institutional arrangement is still relatively new, and relatively little was known about it in South Africa. The implication is that in order to pursue the FWA-CS institutional arrangement, the research team had to ensure that the institutional arrangement was consistent with the 1998 National Water Act and NWRS (First Edition, 2004), which it appears to be. Furthermore, the research team had to adopt and modify software to support the FWA-CS institutional arrangement, as the PRROR system is supported by the Water Resources Yield Model (WRYM) in the DWAF, however the WRYM is unable to support the FWA-CS institutional arrangement.

The focus of the project thus shifted from developing a functional water audit system using an established model (such as the WRYM), to a more exploratory and proof-of-concept type of research related to the FWA-CS institutional arrangement.

The following chapter discusses what is meant by a water audit system. Although the functional water audit system was not developed in this project, it is an end-goal after a suitable institutional arrangement has been selected. Understanding what is involved in a water audit provides some guidance as to which institutional arrangement, i.e. a FWA-CS or a PRROR institutional arrangement, is more suitable for a given catchment area.

4 AUDITING IN THE WATER RESOURCES SECTOR

4.1 What is an Audit?

An audit in this context, which targets water users with abstraction licenses, is a process undertaken to ensure that the conditions of the licenses are adhered to. The following steps are required to perform an audit.

1. **The rules** attached to authorisations need to be clearly spelled out, and need to be meaningful, in that they must be translatable into a volume of water, that may be abstracted at a given geographical location, for a given period in time (or period range).
2. The rules need to be translated for a given point in time (or period range); from which volumes of water to which users have authorisations are **calculated**.
3. There needs to be **communication** from the water management authority to the water users as to the authorised volumes.
4. **Metering** (monitoring) is required.
5. The audit is a reconciliation of the metered use, at a given location, for a given point in time (or time range) against the volumetric entitlement, and courses of **action** to take in the event that license conditions are not being complied with.

The auditing procedure can be represented by the acronym RCCMA, which stands for **R**ules in place, **C**alculate volumetric entitlements, **C**ommunicate with stakeholders, **M**onitor actual usage, **A**ct according to the outcome of the audit.

It is only possible to perform an audit after the entitlement to use water at a given time, or time period has passed, as observed behaviour is a key component of the audit process. To clarify this point, it is in fact possible to calculate potential flows, and therefore apportion water use entitlements for the future. However, the final entitlement can only be calculated when actual water situations are observed (or calculated from observed rainfall). Therefore, audits cannot be performed for the future, and are thus always based on past activities. The ability to perform near-real time (or recent) audits is influenced by a number of logistics, most of which relate to the ability to access monitored information (e.g. rainfall, flows, and water usage), as well as the costs and benefits of performing audits at this level of "recency".

4.2 Constraints Facing Auditing Procedures

Aspects associated with any of the RCCMA components listed above will influence the ability to perform an audit, either in terms of:

- When it is physically possible to perform the audit,

- When it is economically viable to undertake an audit,
- The confidence associated with the audit.

The rules and the translation of the rules

FWA-CS and PRRORS are Institutional Arrangements (IAs) which translate into different rules. The rules in effect need to be spelled out in such as way that it is possible to work out how to apportion available water resources in various water resource components of a catchment, amongst the competing users of the water. Given the complexity of catchments, computerised systems are generally required to apportion available water amongst competing users. If the rules are poorly spelled out, and if various interpretations are possible for the rules, the ability to perform an audit will be compromised.

The translation of the rules requires that (i) the clearly spelled out rules are in place, and (ii) that computerised systems are able to accurately reflect these rules, and that all information required for the translation of the rules into volumes is available.

4.3 Giving Effect to Water Apportionment Rules

The rules associated with these institutional arrangements are clear, however representing the rules in complex catchments is a difficult undertaking, as the nature of the water resources is often not understood with high levels of confidence (e.g. what are the groundwater reserves and how large are they, what is the interaction of the various water resources with one another etc). These factors are important as they will influence aspects such as the time it takes (the lag) for water to move from one resource to another (referred to as routing considerations), losses associated with the movement from one resource to the next, impacts on water quality as water moves through a system.

4.3.1 Computer models

The objective of "getting the right amount of water" to the "right users" is a complex undertaking. Use is generally made of computer models to facilitate this management. It is often unrealistic to operate the models at very fine time scales, as near-real time data is not generally available in a usable format (i.e. it is possible that instruments are recording flows, and water usage daily, however, the data may only be downloaded monthly). The advances in telemetry, in particular cell-phone technology, is making the retrieval of recorded data more viable, however there the value of water has to be high to warrant data being retrieved at this fine time-step. With respect to the computerised models, the WRYM is constrained at the temporal grain at which it can operate in that it is a monthly model. It is also not an operational model, in that it was developed to run with long sets of historical data, which are often not that recent (e.g. the WRYM may be run with monthly data which ranges from 1925 to 2000).

The Mike Basin model can accommodate FWA-CS and PRROR institutional arrangements. The network solver of the Mike Basin differs from the WRYM solver. The Mike Basin solver is founded on a "rule-based" solver, whereas the WRYM solver is based on least-cost-routing principles and the use of penalty structures. The Mike Basin model is also a planning model, in that it makes use of historical data such as that used by the WRYM; however the Mike Basin model can interface with other DHI developed software that captures near-real-time data. In other words, the Mike Basin model can operate both as a planning, and an operational model. Further details are provided in the computer modelling section in Chapter 5. A comparison of the Mike Basin model and Water Resources Yield Model is shown in Appendix E of the document.

4.3.1.1 Operations

As mentioned above, neither the Mike Basin nor the WRYM have been designed for operational purposes (although Mike Basin can interface with another package, which provides it with operational functionality). In the absence of computer models (which reflect the various water resources in a catchment, the various water users in the catchment, and the rules of the game (i.e. the privileges – priority levels and restriction rules)), another method is required with which to calculate volumetric entitlements. This is achieved via stakeholder forum meetings, at which the water situation of the catchment is discussed, and entitlement decisions are taken.

Apportionment rules may translate into volumes that users may abstract in a period (such as a week). It is possible for the electricity meter readings to be taken weekly (however this will require a visit by a water control officer to each abstraction point to take the reading, unless telemetrically enabled meters are installed at the various abstraction points).

The potential danger of the consensus based approach relates to the possible "changing of the rules" compared to the rules used for planning purposes. Bear in mind that during the planning purposes, a number of scenarios are run reflecting certain operating rules. The output of the scenarios are used to guide "how large the water pie" is for apportionment, for given apportionment scenarios. In calculating how big the water pie is, consideration is given to assurance of supply levels required by the respective sectoral water users. If during operations, different operating rules are applied, it is plausible that the assurance of supply targets will not be met.

RECOMMENDATION: A recommendation given is that the computerised models be made to operate at relatively fine time steps, and/or that water resource managers adhere to the same rules of the game as employed in water resources planning exercises, if consensus based apportionment of water resources is undertaken.

Note:
It is in fact possible to perform an audit on institutional arrangement compliance… i.e. are systems being operated according the rules subscribed to and reflected in the water resources planning exercises.

4.3.1.2 Data

As mentioned above, the access to data (information) is a constraint to the ability to perform near real time audits. In the case of water abstraction metering, data is often not available in this regard. Most pumps do not have any form of water meters attached to them, although there is a growing recognition that this may be required. In the absence of direct water metering, indirect methods of water metering may be used (with implications on the confidence of the estimated water use). Indirect methods of metering include the use of monthly electricity bills, which with calibration coefficients can be used to calculate water usage (as is done in the Mhlathuze Catchment), or use can be made of satellite imagery (or other airborne imagery), from which the crop area can be calculated, and using scientifically developed crop water use models, one can estimate (generally with relatively low levels of confidence) what the extraction of water users was.

4.4 Auditing: Does it Matter?

To answer this question distinction needs to be made between the (i) process of auditing, and (ii) the ability to audit at relevant time and space scales.

Generally, South Africa experiences conditions of water surplus, in that flows exceed the demand for water. In such cases, an audit of water usage (unless there are water quality implications of the usage) may not be that pressing an issue. However, during dry periods, it is essential that an auditing system is in place, which can operate meaningfully at fine time and space scales.

RECOMMENDATION: The recommendation given in this regard is that (i) the rules of the game (the institutional arrangements) are clear and can be interpreted at fine time scales, and that (ii) high confidence water metering devices either installed permanently, or temporarily, from which high confidence estimates of water use can be attained.

A further recommendation is that digital loggers are used in conjunction with the water meters. The loggers can sample water use at specified time increments. This will allow the water resource manager to download the information captured in the logger, and details of the water use patterns of the water user will be well known. The loggers in effect help address the question, when was water used and how much water was used, as opposed to just knowing how much water was used since the previous water meter reading. The logistics and costs of metering and logging options are discussed below.

4.5 What Do the 1998 National Water Act and the NWRS (First Edition, 2004) say About Auditing?

The 1998 National Water Act refers to "monitoring, assessment and information" in Sections 137-143. Section 137 reads:

137. (1) The Minister must establish national monitoring systems on water resources as soon as reasonably practicable.

(2) The systems must provide for the collection of appropriate data and information necessary to assess, among other matters -

- *(a)* The quantity of water in the various water resources;
- *(b)* The quality of water resources;
- *(c)* The use of water resources;
- *(d)* The rehabilitation of water resources;
- *(e)* Compliance with resource quality objectives;
- *(f)* The health of aquatic ecosystems; and
- *(g)* Atmospheric conditions which may influence water resources.

The 1998 National Water Act does mention the term "audit" explicitly. Sections 53-55 deal with actions required to deal with the contravention of or failure of water users to comply with authorisations. Details are not provided as to how it is established if a water user is indeed contravening the authorisation.

4.6 Chapter Overview

In this chapter the full process of a water audit system was described, including the generation or selection of appropriate water apportionment rules (R), the use of the rules to calculate (C) water user entitlements to water for a point or time (or time range), the communication (C) of the entitlements to water users, the measurement

(M) of water used at the given point in time (or time range), and the action (A) that follows in response to the results of the audit.

If the apportionment rules are not clear, the ability to perform an audit will be compromised. Furthermore, if the rules do not promote water use efficiency, water resources will probably not be used as efficiently as they could be. The chapter introduced the need to use computer models to calculate water user entitlements to water for a given point in time, or time range. Computer models are needed for the reason being that although the water allocation rules may be quite straight forward, applying the rules to large catchments which are consisted of various water resources, is very complex.

It was highlighted in this chapter that water apportionment rules (institutional arrangements) are currently used for planning purposes, but not for operational audit purposes. As water becomes scarcer, the need to run the water apportionment models on a near-real time basis, for the purposes of a water audit, will increase. The access to near-real time information will be a vital component of the system, which will require adequate monitoring/metering infrastructure and will probably require the use of telemetry for the data to be accessed timeously.

5 COMPUTER MODELLING METHODS

5.1 Background

Institutional arrangements are "the rules of the game". The PRROR and FWACS institutional arrangements relate to the rules with which water is to be apportioned amongst authorised water users. At any given point in time there is a finite volume of water that can physically be apportioned amongst authorised users. However it is often prudent and necessary not to apportion all available water at once. Water apportionment rules generally relate to priority levels with which water users may use water, as well as the water restriction rules faced by the respective water users.

The factors influencing the volume of water apportioned (i.e. to which water users are entitled) at any given point in time include:

- The nature and number of authorised water uses,
- The apportionment rules (i.e. priority levels, and water restriction rules), and
- The status of water resources at the given point in time.

Computers have tremendous processing power. Although they themselves do not possess intelligence, they have the ability to follow prescribed commands (rules) with great speed and accuracy. Models can be created (configured) to represent the interaction between water resources and water users in a catchment, with details of the:

- Interactions between the water resources themselves (which are governed by physical laws (rules) such as the gravity movement of water from one sub-catchment to the next), and
- Water users and their demands for water (to which further rules may be attached, e.g. an irrigator may reduce his/her demand for water if it rains), and
- Operating rules which guide how water resources are to be apportioned amongst the competing water users.

What is required, at a relevant time step, is to input the water availability in the respective water resources in a catchment, and the model can very quickly and accurately apportion the water resources amongst the competing water users. This entitlement can then be reconciled against actual water use as part of the water auditing process.

However, models configured with details of water users and water resources (with operating rules) can also be used to assess the number of authorised water uses a catchment can sustain, with acceptable level of water supply reliability.

Thus computer models, configured with details of water resource, water users, and a given set of operating rules can be used to:

1. Calculate the number (and nature) of water uses that can be authorised with a catchment while meeting target water assurance of supply levels for the respective water users (this is a water resources planning undertaking), and
2. Calculate for the given nature and number of authorised water uses, the volumes of water to which the authorised uses are entitled for a given point in time, or time range (this is an operational undertaking).

The planning of water resources can be seen as a process, and the operational management of water resources another process. They are related, and both have a bearing on an audit in that planning guides the nature and number of licenses to be allocated for a given set of operating rules, while the operational process relates to the giving effect to the operating rules for the authorised water uses.

5.2 Modelling Techniques to Support Water Resources Planning

The Water Resources Yield Model and Water Resources Planning Models are the models currently used by the DWAF to support the PRROR institutional arrangement. The models are monthly time step models, and require long records of historical flow data for planning purposes. They are <u>not</u> operational models, i.e. they have not been designed to operate on a near-real-time basis for the purposes of calculating how water resources are to be apportioned amongst water users.

Water resources planning is particularly important to the Compulsory Licensing process. Bear in mind that the Compulsory Licensing process is being initiated in catchments that are currently deemed to be over-allocated. The implication of this statement is that if authorisations are issued for all water use applied for, the assurance of supply targets of water users will be compromised, inferring that the frequency and magnitude of water stress (demand deficit) will be beyond the acceptability levels of water users. Water resource planners need to have a thorough understanding of the allocable resource (i.e. how big is the water resources pie) for authorisation purposes.

For water resources planning the following tasks are undertaken:

- A model is configured to represent the water resources in a catchment.
- Long records of naturalised flow are obtained (from observed flows, or from synthetic generation based on statistical properties of observed flows).

Water resource planners then run various scenarios whereby changes can be made to:

- The nature and number of water users in a catchment, and/or
- Details of the water demand profiles of water users in a catchment, and/or
- Details of the operating rules of the catchment.

By running the model for a number of scenarios, the water resource planners can assess the impact of each of the scenarios on (i) the water resources, and (ii) the water users. With respect to the water resources key indicators may include dam levels (e.g. the frequency that a dam is above or below certain levels). With respect to water user, the key indicator is that of assurance of supply, i.e. the frequency with which respective water users receive their full entitlement (and the frequency with which their full entitlement is not met). Consideration can also be given to the recurrence interval of failures and magnitude of failures. These indicators guide the water resource planner as to the nature and number of authorisations that can be issued for a given set of operating rules.

Although not included in the terms of reference of this project, the research team spent considerable time tailoring computer routines required to generate model outputs that could be used by water resource planners. The motivations for this undertaking include:

- The WRYM, which supports the PRROR institutional arrangement is a monthly time step model, and has been developed for planning purposes. Thus the PRROR institutional arrangement is largely supported on planning level, and not on an operational level.
- The WRYM is not able to support the FWA-CS institutional arrangement.
- The FWA-CS institutional arrangement has the potential to induce water use efficiency from large dams.
- In order for the FWA-CS institutional arrangement to be considered for the Compulsory Licensing process, it would need to minimally (i) be supported by an appropriate model, and (ii) the modelling framework should be consistent with the water resources planning techniques currently adopted.
- Furthermore, in order to assess the potential costs and benefits of FWA-CS it would be necessary to run the model at a planning level.

5.3 Water Resources Planning versus Operations

The differences between water resources planning, and water resource operations include the following:

- For water resources planning a number of water authorisation and operating rules scenarios are run, whereas water resources operations will only require a model to be run for the authorised water users and operating rules in operation, and

- Water resources planning makes assumptions related to the use of water by water users. The model in effect mimics the water use by water users included in the model run for a given scenario. For the purposes of operations on the other hand, the model does not infer how water is used. Actual water use details are captured in other databases, and fed into the water audit system, but do not necessarily feed into the model used to apportion water at an operational level. Operational models do however require details of actual water availability in the various water resources of a catchment, in order to apportion the water amongst the water users.

The sections below:

- Describe the type of computer model generally used for the apportionment of water resources for purposes of both water resources planning and water resources operations (i.e. a node and channel hydrological network model), and
- Describe the Mike Basin model, and
- Describe the scenarios run with the Mike Basin model, which include scenarios in which both FWA-CS and PRROR are considered.

5.4 Node and Channel Hydrological Network Models

The use is generally made of node and channel network models in order to apportion water amongst water users. There are a number of different examples of node and channel network models (e.g. WRYM, WRPM, Mike Basin, Modsim, and Riverware), which are generally similar in nature; however often differ in how a solution of "entitlement" is attained, and how the node and channel network is constructed. The Mike Basin model uses a "rule-based" approach to calculate a solution (discussed below in greater detail), whereas the WRYM makes use of a least cost routing approach and the use of penalty structures. The Mike Basin rules accommodate priority levels, as well as water restriction rules. All the node and channel network models listed above are able to accommodate the priorities and restriction rules of the PRROR system. However, only the Mike Basin model is known to have functionality to explicitly accommodate the FWA-CS system, which resulted in the model being used for this project.

5.5 The Mike Basin Model

The Mike Basin model is a node and channel network model, developed by the Danish Hydraulic Institute (DHI). Information on the DHI is available from the following website http://www.dhisoftware.com. They are internationally known for their suite of 11 models of which Mike Basin is one. They employ approximately 30 programmers and are continually making improvements and developments to their models in line with contemporary thinking in hydrology. The Mike Basin model has been applied extensively globally, with the model being used to mimic different types of institutional arrangement (e.g. the Riparian Rights institutional arrangement, the Prior Rights institutional arrangement and the institutional arrangement that requires water use to be authorised).

In general terms Mike Basin is a mathematical representation of the river basin encompassing the configuration of the main rivers, tributaries, the hydrology of the basin in space and time, and current or future schemes and their various demands on water. It is structured as a network model where rivers are represented by a network of branches and nodes. The branches represent individual stream sections while the nodes represent confluences or places where activities occur (e.g. points of abstraction, diversion or discharge) for which the model finds a stationary solution to each time step.

Mike Basin is an extension of ArcView GIS and requires Spatial Analyst. It has all the functions available from ArcView 3.2 as well as the addition of specific tools and the network model. The cost of the model is approximately €6000 (which includes an Arc-View run-time license). Mike Basin is currently being updated to run on ArcView 8.

The screenshot shown in Figure 6 below is an illustration of a very simple catchment being configured. The creation of the network is done within the Arc-View environment. It is possible to overlay GIS layers, such as maps, onto the screen, which makes understanding the network relatively easy/straightforward. In the diagram the red pentagon represents an irrigator, while the green object represents a catchment (to which a runoff file will be attached). The nodes are the circular objects, which can be different colours which reflect different functionality associated with the nodes. Three types of nodes are discerned, including a normal flow node (blue), a diversion node (red) and an off-take node (green). The nodes are joined by lines which represent channels. Properties can be attached to these to reflect the lag associated with the movement of water from one node to the next.

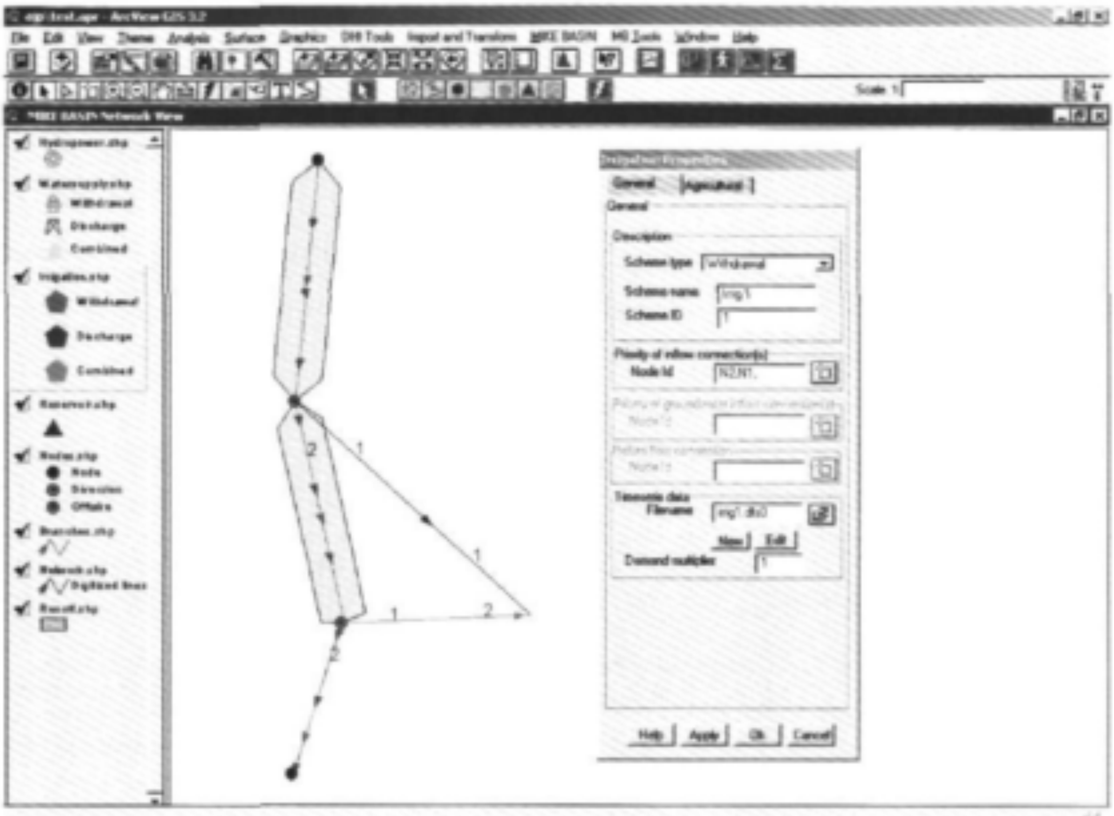

Figure 6 An illustration of a simple catchment being configured in the Mike Basin model.

In situations of water shortage it resolves the distribution of water through priorities and restriction rules. There are two options available, local priorities and global priorities as well as a number of different water management methodologies. The global priority rules do not support the FWA-CS institutional arrangement, and are not discussed further in this document.

5.5.1 Network solver: local priority rules

The local priority rule is the default rule structure used in Mike Basin. Under these rules, users are given a priority at the node from which they abstract. The network solver in local priority rules seeks to satisfy every user from the top of the system down to the bottom. With respect to the priorities consideration is given to both:

- The order of priority with which a water resource is to supply water to the respective water users who will use water from the resource (with restriction rules included), as well as
- The order of priority with which a water user will use water from the respective water resources that the user can access.

To illustrate this point, please refer to Figure 6 above, which represents a simple catchment configuration. There are three Quaternary Catchments in the figure (W12A-C), and a few water users.

5.5.2 Assigning priorities from the water resource to water users

When one takes a closer look at the off-take nodes (green), one notices that the off-take node is connected to various water users. The implication of this is that the off-take node can serve the water users linked to it. The order with which the off-take node is to serve the users attached to it must be specified for the network model to operate. Figure 7 below illustrates the orders of priority with which the different users are to be "served" is shown (with 1 indicating the highest priority water user, etc).

In this example, the highest priority user is the IFR, and the off-take node must first release the water required for the IFR before "serving" the water user with the next highest level of priority, which in this case is the Mondi Richards Bay mill, followed by the Nkwaleni Irrigation Board and then by the Heatonville Irrigation Board.

5.5.3 Assigning the order of preference with which users wish to receive water

When one takes a closer look at the Mondi Mill, it is apparent that the mill has entitlements to water from two water resources (i.e. from the first or second off-take node), but abstraction will take place at the second off-take node. The priority with which the water will be used from the respective resources suggests that water will first be used from the lower off-take node, and then the higher off-take node. The diagram may seem a bit senseless; however the diagram represents the basis for the scenarios undertaken below. A dam is placed at the upper off-take node for the other scenarios.

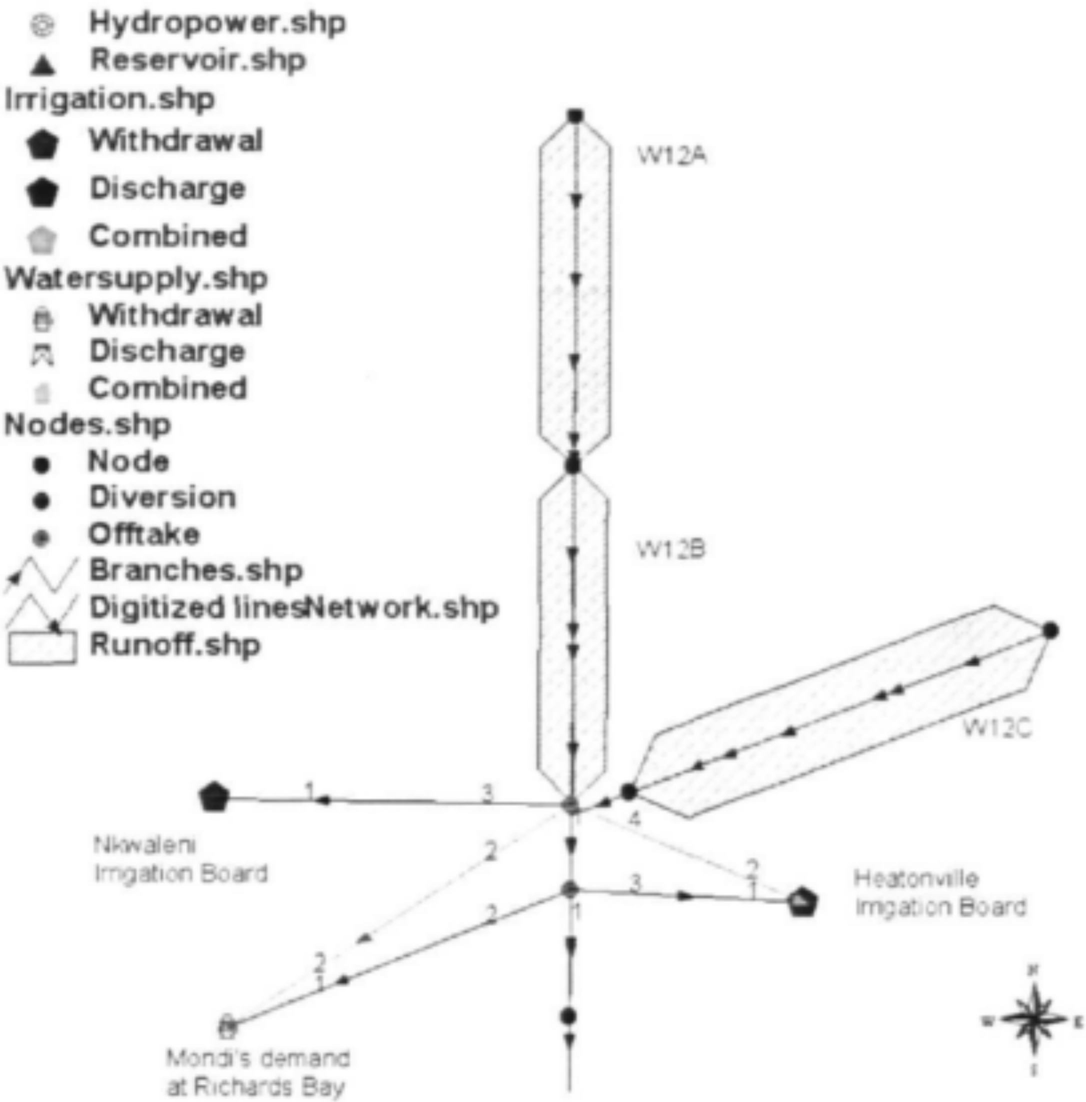

Figure 7 The Mike Basin configuration for the first scenario: 4 users with no dam

The diagram above indicates the order of priorities and preferences, but does not on its own indicate the volume of water the various water users are entitled to. There are two options that Mike Basin can accommodate with which to calculate the volume of water that the respective water users are entitled to.

5.5.4 Volume entitlements a function of user priority and user demand

In the first option, the rule is to satisfy the full demand of the water user/s with high priorities against the resources. Only if the full demand of the water users has been satisfied will the demands of lower priority users be considered. Consideration has to be given to the order of preference with which the various water users wish to use the water from the respective water resources. This is why a network model and solver is required, as the volume of water available at the location from which the water is abstracted will vary from time step to time step, depending on the water available at the respective water resources.

5.5.5 Volume entitlements as a function of fractional allocations and demand

In the second option, consideration is given to the flow. A water user can be assigned a percentage of the flow. If the volume of water associated with the percentage of flow at a given point in time exceeds the water demanded by the user at that point in time, the excess water is released into the system. Thus although priorities are used for the various water users, it is in fact the flow of water and the allocation of the flow that will determine who will get water and who won't.

The Figure 8 below illustrates the Mike Basin GUI used in the setting of the fraction of flow that a given water user is to receive from a given resource. Please note that DHI are currently revamping this GUI to be more effective to meet the requirements of fractional water allocation. These developments should be packaged in their new Mike Basin release version, which is due to be released in September 05. In this regard the Mike Basin model is continually being updated, with updates released annually.

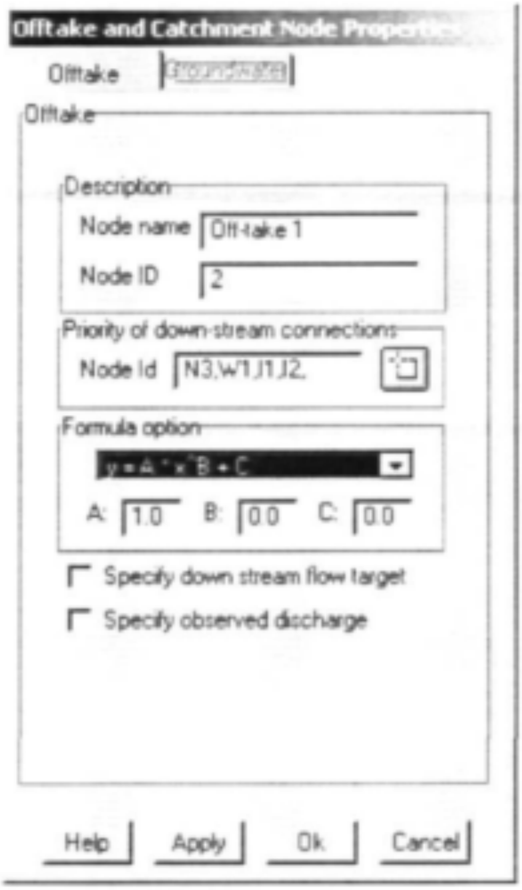

Figure 8 A Mike Basin GUI which allows the fractional allocation of water to be specified

5.5.6 Reservoir operating rules

Two types of reservoirs can be accommodated in Mike Basin, including:

- The standard reservoir (i.e. the type used to reflect PRROR rules), and
- The allocation pool reservoir (i.e. the type used to reflect FWA-CS rules).

The standard reservoir is based on the conceptual horizontal splitting of the dam into different water restriction levels (see figure 9). Water restriction rules are activated by the dam falling below certain levels (represented by the horizontal lines in figure 9). The level of water restrictions becomes more severe as the dam level drops.

The allocation pool reservoir is based on a conceptual vertical splitting of the dam where different users are assigned different portions of the dam storage capacity. Entitlements to the storage capacity of dams on its own are of relatively little value, as the only source of water into the dam will be the rainfall which falls into that share of the dam. It is necessary for the holder of dam storage entitlements to secure entitlements to the flow into the dam, which in effect fills the dam storage with water. Figure 9 shows the allocation pool reservoir. The allocation pool reservoir has been designed to include functionality that extends beyond the mere fractional allocation of the dam. The diagram shows a Flood Control Storage level. As dams may be used for both storage, and flood attenuation purposes, the Flood Control Storage option allows the modeller to state if the dam is to be used for flood control purposes. If the dam water level is above the flood control storage level, water is released from the dam at the maximum allowable rate in order to empty the dam to an acceptable level. The Flood Control Level can be by-passed by configuring the Flood Control Level to be the same height as the Full Reservoir Level.

The Common allocation storage is another feature of the Mike Basin allocation pool reservoir that can be used or by-passed (as above). The option allows water to be used by non-holders of dam storage, only if the dam level is above the Guide Curve and below the Flood Control Level.

The vertical separation of the dam into shares, represented by WS1, WS2, WSN and WQ Pool reflects the capacities of dam storage reserved by different water users, with user 1 being reflected by WS1, etc. The WQ Pool represents water that could be retained to manage water quality, in that this water may be reserved for releases required to ensure that downstream water quality targets are maintained. For South Africa's purposes water could be reserved for the IFR, which includes releases for water quality as well as water quantity.

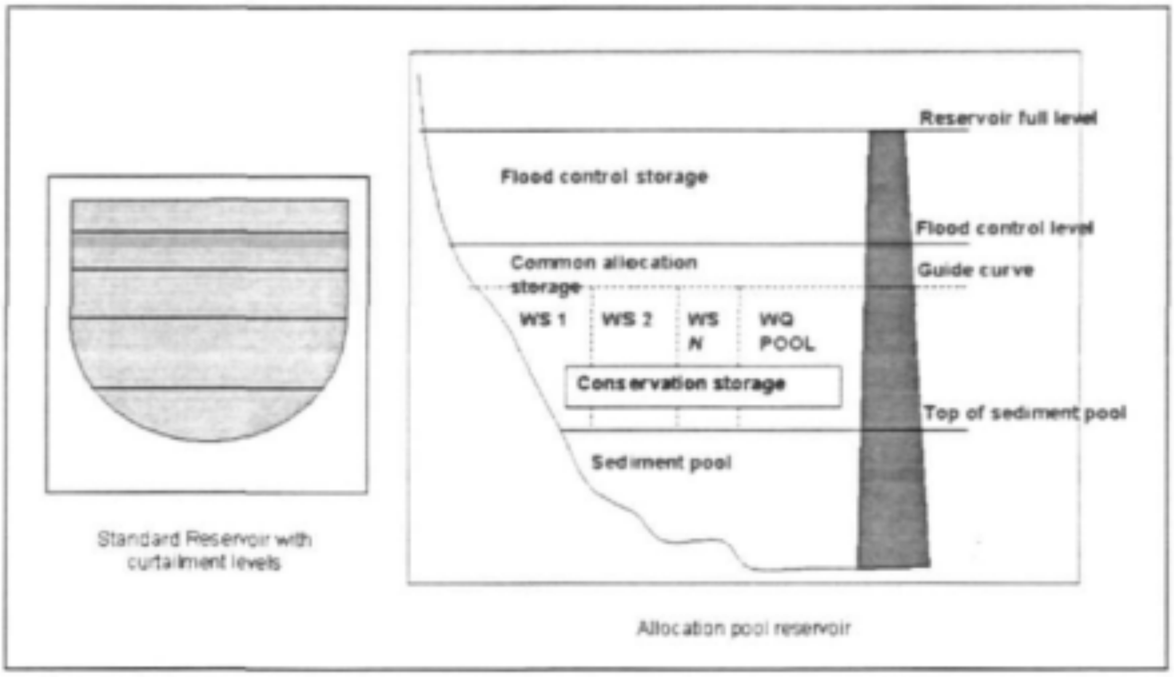

Figure 9 The two different types of reservoir operating rules available in Mike Basin, including a Standard Reservoir (PRROR institutional arrangement) shown on the left, and the Allocation Pool Reservoir (FWA-CS institutional arrangement) shown on the right.

5.5.7 Link to excel/optimisation

Although Mike Basin is not yet fully functional regarding fractional allocation, it has built in features that allow any form of input or output data to be easily accessible. Mike Basin follows the COM standard, so one can create a Mike Basin object in a Visual Basic macro. This makes it possible to automate the running of simulations as well as the adjustment of some input in order to optimise some result. The step-wise simulation offers essentially unlimited flexibility in implementing site-specific operation rules. One can see the previous time step's results and based on those update water demand in the current time step.

It is through the COM interface that it was possible to perform a yield analysis and programming of the Instream Flow Requirements (IFRs) as discussed below. It is thus a very flexible interface that allows a great deal of flexibility to input and output files and potentially further model development in the future. Of major importance is that it allows for development of the software without the need to work through the DHI.

5.6 Mike Basin Model Scenarios

The modelling scenarios were undertaken to assess the ability of Mike Basin to represent both a FWA-CS and a PRROR institutional arrangement for planning purposes. The modelling scenarios performed are relatively simplistic, as they are in effect exercises for "proof of concept".

It is important at this stage to point out that any model has three basic components, i.e. input, a computation component, and output. With respect to the different institutional arrangement, the input is very similar (e.g. the demand patterns of users, where they are and details of the water resources). There difference between the scenarios relates to differences in the definition of the rules.

The Mike Basin model was configured for the following scenarios:

- 3 Quaternary Catchment (QCs) assuming no dam was in the system
- 3 QCs with a "standard reservoir", with priorities but no restriction rules
- 3 QCs with a "standard reservoir", with priorities and with restriction rules
- 3 QCs with an "allocation pool reservoir" (FWA-CS institutional arrangement).

The model scenarios will show:

1. The importance of dams for the augmentation of the yield of a system (by comparing the scenario where no dam is included, with scenarios where the dam is included), and
2. The impact of water restriction rules on the yield of a system, as well as the assurance of supply of water users with different levels of water use priority, and
3. The conceptual difference between the FWA-CS and PRROR institutional arrangements.

5.6.1 Scenario1: 3 QCs assuming no dam

Figure 7 above illustrates the model configuration for this scenario. The priority rules (both from the water resources, as well as from the water users' points of view) are shown in the figure. The "Volume entitlements a function of user priority and user demand" rule described above was selected, as this probably best reflects the prevailing operating rule in the catchment.

Water supply

In the scenario water is supplied from three Quaternary Catchments, which happen to be the upper QCs in the Mhlathuze Catchment. Naturalised monthly flow records for the three QCs were used, with the data record including flows for 1920/01/01 to 1994/12/01. The Figure below graphically illustrates the time series of W12A in the

Time Series Editor of Mike Basin. The units for the flows are expressed as cubic meters per second (m3/s).

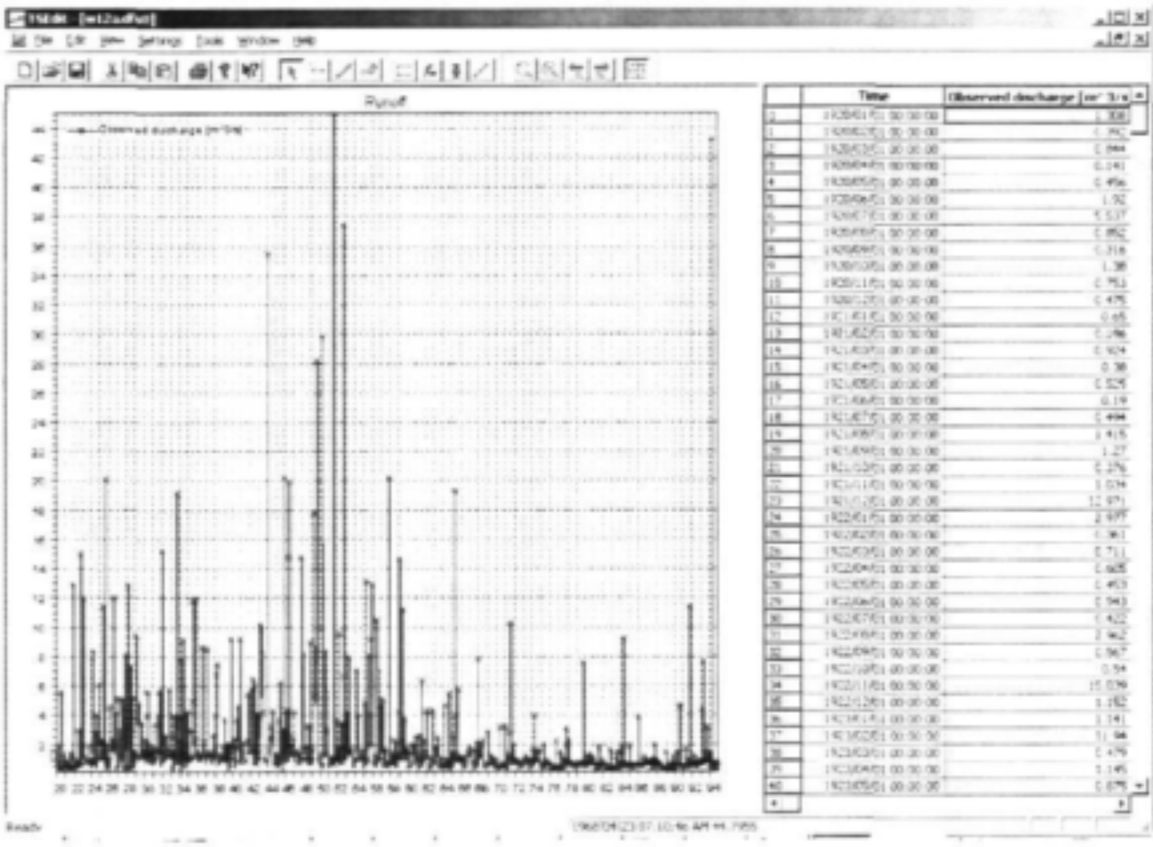

Figure 10 A screen shot from the Mike Basin Time Series Editor showing the naturalised flow sequence record from 1920 – 1994.

Water demand

For the exercise, the demand of 4 users was considered. Firstly, a simple IFR flow requirement was set (in order to simplify the modelling for demonstration purposes). The demand files for Mondi, Nkwaleni Irrigation Board and Heatonville Irrigation Board, used in a previous water resources study, were used. The demand files of the users (units are m3/s, varying monthly) are shown below.

Table 4 Water demand files

m3/s	Mondi_RichBay	Nkwaleni	Heatonville
Oct	0.93	2.02	1.57
Nov	0.93	2.09	1.62
Dec	0.93	2.65	2.07
Jan	0.93	2.59	2.01
Feb	0.93	2.28	1.79
Mar	0.93	2.15	1.66

Apr	0.93	1.53	1.19
May	0.93	1.32	1.04
Jun	0.93	0.95	0.73
Jul	0.93	1.10	0.86
Aug	0.93	1.48	1.15
Sep	0.93	1.89	1.44

Priorities and restrictions

The priorities are shown in Figure 7 above. There are no restriction rules. This is simply that the highest order water user can use as much water as he demands (as long as it is available). Only when this demand is satisfied will the demand of the next user be considered.

How the scenario is executed computationally

The model starts at the beginning of the flow time series and sequentially works through the time series at the relevant time step selected. As the input data used was in a monthly format, the time step selected was also monthly. For each time step the model apportions the available water amongst the competing water users, as per the operating rules specified in the model, reflected by priority levels, and restriction levels. The priority levels for the scenarios are shown in Figure 7 above. There are no restrictions, and the rule adopted is that water will be provided to the highest priority, until such time that the users demand for water is satisfied. Upon satisfying the demand of the highest priority user, the model will then determine the next most senior water user, and the same rule will be applied. The model will keep doing this until there is no more water to issue, or until all water users have been serviced. The model will then move on to the next time step. Any unused water from a given water source, will be passed down to the next node, following the path of the gravity flow of water.

Dams have different rules attached to them; however this scenario does not have dams.

Model Output

Assuming that a certain combination of water usage, sub-basin transfers and reservoirs has been defined, the model simulates the performance of the overall system by applying a basic water quantity mass balance approach in every branch and node. The simulation takes into account the user-defined priorities of river diversions and extraction of water from multiple reservoir systems as well as priorities for water allocation to multiple usages from individual extraction points. Model output also comprises information on the performance of each individual reservoir.

Node-related results can be viewed after a simulation has run. There are two types of results:

1. Time series
2. Monthly summary tables

Time series contain all results at a node, including those that can be chosen in a result group presentation. In addition, however, result time series include all flow to nodes connected to the node of interest. Time series are displayed in TSEdit.

Monthly summary tables summarizing all information in the above time series are produced if the corresponding option is checked in the Simulation dialog. These tables are in html format and can be viewed with any web browser (Mike Basin has a simple browser built-in). Each node's table has hyperlinks to tables of connected nodes. Thus, one can easily follow a river or along connections to/from water users. Monthly tables can be computed also when running a simulation with daily time step. In this case, the monthly values are averages of the daily results. The monthly tables also include low-flow statistics.

Summarising data to assist with water resource management

Due to the large amount of data produced with each scenario run, summaries are important to assist managers to meaningfully interpret the output of the scenarios. Factors that are important include the nature and degree of water demand deficit (i.e. when the demand for water exceeds water availability. Water resource managers will want to know which water users experience water shortages, and what the frequency and degree of the water shortages are. This is important as the water resource managers will want to ensure that assurance of supply targets for various water users are met.

Summarising single scenario runs.

A useful summary of a single scenario run is the frequency with which water user receive their full entitlements (or the frequency with which users do not receive their full entitlements, also known as demand deficit). The table below illustrates the frequency that the 4 water users, as part of this scenario, receive respective levels of demand. A 100% infers that water users receive their full water requirement. A breakdown can be given regarding the frequency that the respective water users receive their full entitlement.

Table 5 The frequency with which users meet their water demand.

Demand (%)	Frequency	Freq %
100	870	97%
90	11	1%

80	10	1%
70	5	1%
60	2	0%
50	1	0%
40	0	0%
30	0	0%
20	0	0%
10	0	0%
0	0	0%

Summarising multiple scenario runs

Water resource managers often need to run more than just one scenario. It is possible that the current level of water use is either beyond the sustainability level of the catchment (i.e. the catchment is over-allocated) or, alternatively, the system is not yet fully allocated, and a condition of surplus exists. Water resource mangers will want to know to what level water usage must be reduced, or what extent further usage can be permitted. This requires a number of scenarios to be run. The scenarios are generally run by reducing and increasing the current demands of water users, while keeping the operating rules the same for all scenarios, as well as all the flow files.

In order to enable the scenarios to be portrayed on one graph, the water demands for all water users of a given scenario are summed and then compared to a sum of the water supply to the same water users. The diagram below illustrates how the incremental increasing of demands results in increased demand deficits by water users. The dots in the diagram below represent scenarios of increasing water demand. The trend of the dots is to pull away from the 45 degree line, and eventually flattens off. The 45 degree line represents a situation where the demand for water is met in full.

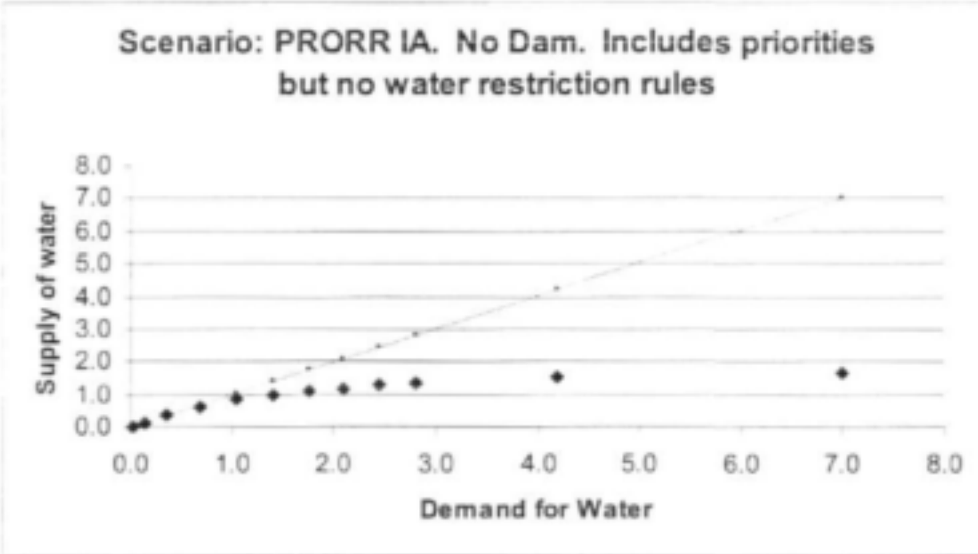

Figure 11 A yield curve derived for Scenario 1.

Figure 11 is used to calculate the firm yield of a system, with the firm yield being defined as the maximum level of abstraction before water demand deficit is incurred. The diagram does not itself give details of the water users who experience the demand deficit, nor details of the frequency of deficit. This is obtainable, as is shown by the diagram below. The respective assurance levels of supply for each user are shown for each respective scenario. The X – Axis in the diagram below represents the fraction that the current demands are multiplied with (e.g. a 25% scenario means that the demand is 25% of the current demand). Figure 12 illustrates that Mondi receives the highest level of assurance of supply, followed by Nkwaleni and Heatonville.

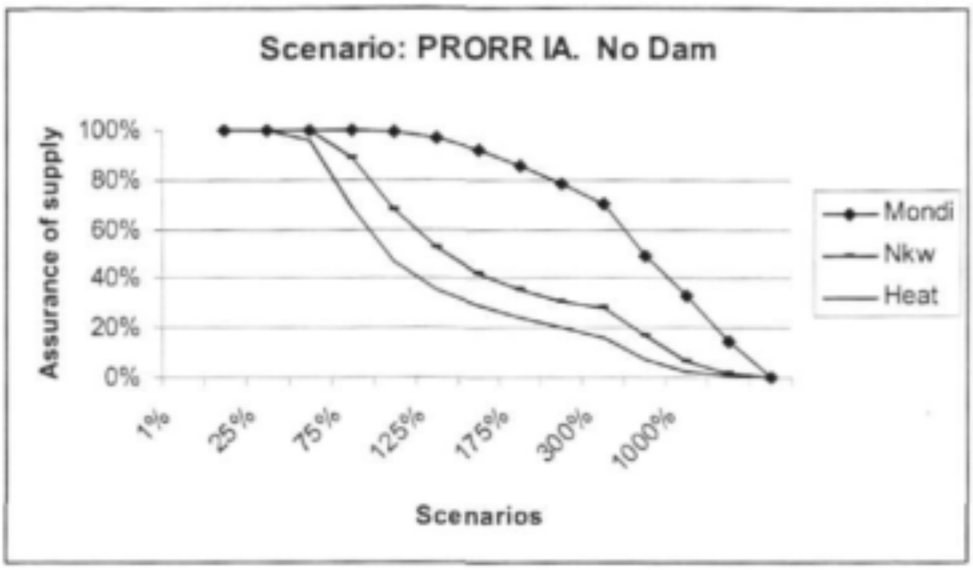

Figure 12 The assurances of supply received by 3 water users for different water demand scenarios.

5.6.2 Scenario 2: 3 QCs, a PRROR scenario with a dam but no water restriction rules

For the second scenario, a dam was included, as is illustrated by Figure 13. A "normal reservoir" was used, which reflects the PRROR institutional arrangement, however no restrictions were imposed on water users. This scenario was run in order to assess the potential impact on the yield of a catchment of not including restriction rules. As with Scenario 1 above, a number of scenarios were repeated in order to develop a yield curve. The results of the yield curve are shown in Figure 15 below, in which the yield curves of all the scenarios are compared. As with the scenario above, the same rules, which allow the highest priority uses to abstract to cater for their demands first before lower order priorities are served, are applied in this scenario for water received from W12C (i.e. the run-of-river flow).

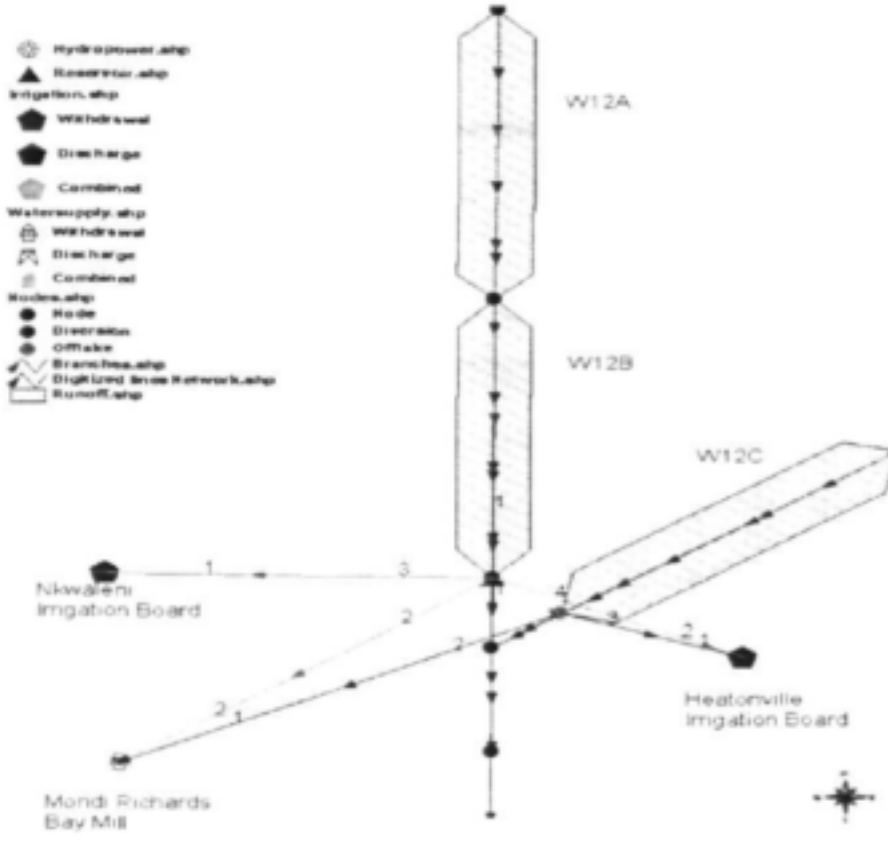

Figure 13 A diagrammatic representation of Scenario 2, 3 and 4 which all include dams

5.6.3 Scenario 3: 3 QCs, a PRROR scenario with a dam with water restriction rules

The third scenario is identical to that of scenario 2, except that water restriction rules are imposed on water use from the dam. The rule imposed on run-of-river flows is as above. The GUI below indicates where in Mike Basin the user reduction factors are set. Three reduction levels were set, when the dam level dropped below 75%, 50% and 25% respectively.

The values (1,1,0.9)(0.75,0.5,0.25)(0.75,0.5,0.25) refer to the reduction factors imposed on the water users, with the water user (Mondi) with the highest reduction factor being listed first. The values 1, 1 and 0.9 in the first bracket infer that if the dam drops below 75%, Mondi will receive 100% of its demand. Should the dam drop below 50%, Mondi will still receive 100% of its demand. Only when the dam drops below 25% will Mondi receive restrictions, in that it will receive 90% of its demand.

The restriction levels faced by the irrigators are more severe, in that a drop below 75% induces a restriction level, and the irrigators will only receive 75% of their demand. If the dam drops below 50% and 25%, the water irrigators will only receive 50% and 25% of their demand respectively. The differentiated rules result in different levels of assurance of supply for the different water users. Bear in mind that the industrialists (high assurance users) pay more for a unit of water than do the irrigators (low assurance users). There are however cases where the irrigators do pay high rates, and do receive higher assurance levels of water supply.

Figure 14 Mike Basin GUI in which details of dam user water restrictions are specified.

5.6.4 Scenario 4: 3 QCs, a FWACS scenario with a dam with no restriction rules

The fourth scenario relates to the configuration of the dam to enable the Capacity Sharing (CS) of the dam amongst the users, and the Fractional Water Allocation of the flow into the dam. The fractional allocations of dam storage capacity, as well as the inflow into the dams are shown in table 6 below.

Table 6 The fractional allocation of dam storage and flows amongst users

User	Fraction of dam capacity	Fraction of inflow into the dam	Initial storage level
IFR	0.1	0.1	0.5
Mondi	0.5	0.5	0.5
Nkwaleni	0.2	0.2	0.5
Heatonville	0.2	0.2	0.5

The table above indicates that for the scenario run, the fractions of dam capacity and fractions of inflow into the dam are identical for each respective water users. It is possible that the fractions differ from one another.

5.6.5 All scenarios compared

Figure 15 and Table 7 below show the comparisons of the 4 scenarios. The units for the Figure and Table are $m^3 s^{-1}$.

- *Scenario 1*: The scenario with no dam shows the lowest firm yield. This is expected as dams increase the yield of a system as flows are stored during times of plenty, which are then made available for use during periods of scarcity.
- *Scenario 2*: The presence of the dam increases the yield in the system. However it is evident that the yield curve of this scenario is higher than that of the same scenario however with restriction rules imposed. The reason for this that with no restrictions all water users are able to use what they want, unless water is physically not available. What the graph does not show is that the assurance of supply of the industrialist user is lowered, while the assurances of supply of the irrigators are raised beyond generally accepted target levels.
- *Scenario 3*: As discussed above, the firm yield is lower than that of a system with restriction rules imposed. The reason for this is that water users are faced with restriction levels when the dam drops below certain levels. The result is that certain users receive lower levels of assurance, as a result of the

imposition of the restriction levels, while other users receive higher levels of assurance as a result of the restriction levels imposed on others.

- *Scenario 4*: The graph and table show the yield curve for the fractional apportionment levels chosen. If the fractions were different, or if restriction levels were imposed on the users (which is possible), then the yield curves would differ from the one shown below.

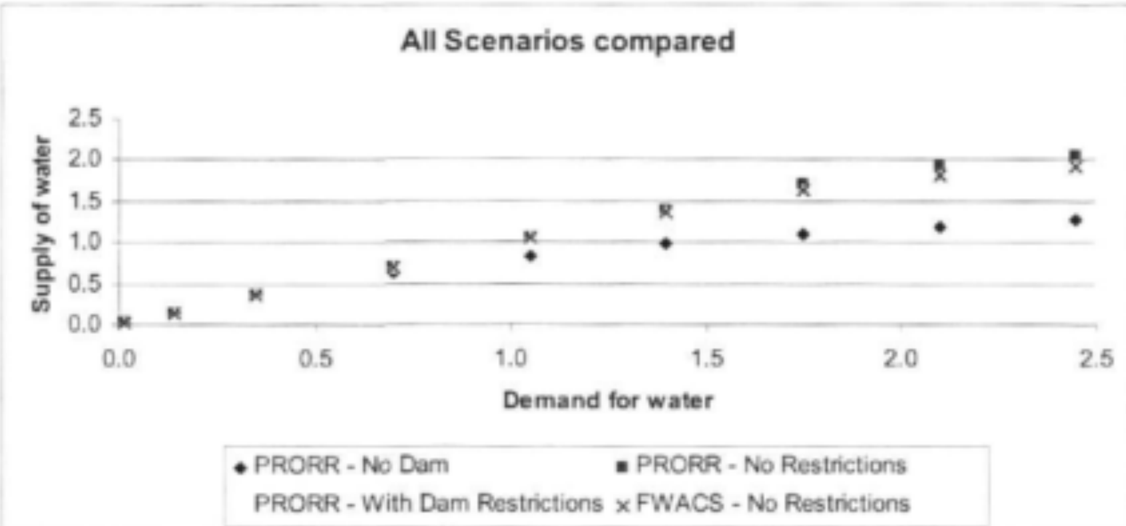

Figure 15 The yield curves of the four scenarios are compared

Table 7 The aggregated demand and supply for the respective scenarios

	Demand	PRROR - No Dam	PRROR - Dam with no restrictions	PRROR - Dam with restrictions	FWA-CS with no restrictions
1%	0.01	0.01	0.01	0.01	0.01
10%	0.14	0.14	0.14	0.14	0.14
25%	0.35	0.35	0.35	0.35	0.35
50%	0.70	0.63	0.70	0.70	0.70
75%	1.05	0.83	1.05	1.04	1.04
100%	1.40	0.97	1.39	1.36	1.36
125%	1.75	1.09	1.71	1.62	1.62
150%	2.10	1.19	1.92	1.81	1.81
175%	2.45	1.27	2.05	1.92	1.92
200%	2.80	1.33	2.08	1.98	1.98
300%	4.20	1.50	2.15	2.09	2.09
500%	6.99	1.64	2.20	2.18	2.18
1000%	13.99	1.72	2.27	2.26	2.26
10000%	139.90	1.74	2.35	2.33	2.33

5.7 Evaporative Losses and Water Banking

A concern expressed by a number of persons consulted in the course of the project was that any water banked would probably just evaporate. Evaporative losses will vary from one dam to another, with the evaporation being dependent on, amongst other things, the height-volume-area characteristics of the dam, and the climatic characteristics of the region in which the dam is located.

For the FWA-CS consideration, an assumption was made that the Nkwaleni Irrigation Board could reduce their demand by 15% without reducing levels of output (and quality of output) via the introduction of improved water use efficient management practices. The graph below indicates the ranked dam level for Nkwaleni's share of the dam for three scenarios, including (i) a base scenario (i.e. the current water demand pattern), (ii) a scenario that assumes a 15% reduction in demand for water, with evaporative losses on the dam, and (iii) a scenario that assumes a 15% reduction in demand for water, with no evaporative losses from the dam.

The curves indicate that approximately half the banked water will be lost due to evaporation. However, the curves also show that a significant of volume of water is not lost to evaporation, which could be applied at a later stage, or traded.

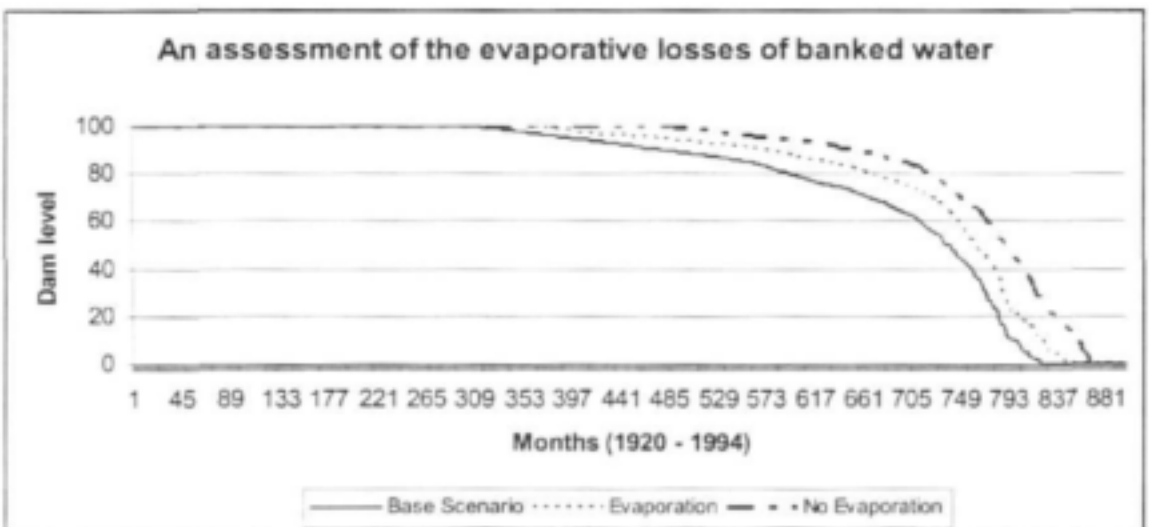

Figure 16 The individually ranked dam levels for three scenarios in order to demonstrate the potential water loss of banked water resulting from evaporation

5.8 The Use of Historical Data

The scenarios above made use of historical flow data. The demand files were static, however, the Mike Basin model can simulate crop water requirements, though in a simplistic fashion (as a function of growth stage of crops and rainfall). Throughout the document it has been mentioned that the use of historical data with the yield calculating models will be required for the initial allocation of licenses. The scenarios above indicate that Mike Basin can be used to generate the outputs required by water resource planners.

The link to a water audit system is simple. If the Mike Basin model is unable to perform the water planning functions required, it will not even stand a chance of being considered as a viable institutional arrangement. As such, time has been taken to explore the requirements of water resource planners. It is acknowledged that not all the tasks required by water resource planners have been undertaken (e.g. the inclusion of stochastic flows), however it is believed that these could be included.

5.9 The Use of Near-Real Time Data

Neither Mike Basin nor the WRYM were designed to operate at a near-real-time scale. It is however possible to do so in Mike Basin (even at fine temporal scales, as the model can run on a daily level or more aggregated if required). The problem is that it will be a manual process to get the data into Mike Basin. The DHI have developed other software that captures near-real-time data, which has been programmed to interface with Mike Basin. This however will have a cost implication on water users, as they will need to buy the additional software (called Mike Flood-Watch (DHI, 2005) which is also used for flood warning).

5.10 A Water Audit System

A fully integrated water audit system will need to include metered user data, which is to be compared against the entitlements calculated with the Mike Basin model (or similar model). Although this is possible to develop the audit system within Mike Basin, via the COM interface, this is not what Mike Basin has been developed for.

The development of a fully functional water audit system was not completed in the course of the project, for the following reasons:

- The existing planning models used in South Africa, i.e. the WRYM and WRPM can not in their current form support the FWA-CS institutional arrangement.
- As the FWA-CS institutional arrangement was believed to potentially hold certain water use efficiency inducing advantages over the PRROR system, it was necessary to adopt and tailor software that could support the institutional arrangement.

- Although it would have been possible to explore the development of an audit system based on the Mike Basin model, it is likely that without the Mike Basin having the outputs required for water resource managers (required for the water allocation process) that the FWA-CS institutional arrangement would not have been eligible for consideration for the first round of licensing.
- The research team thus invested time to code in an IFR and Yield analysis routine, which should allow the model to meet the requirements of water resource planners.

RECOMMENDATION: It is recommended that funding be provided for the completion of the water auditing system, with the water auditing system being developed for both the FWA-CS and the PRROR institutional arrangements. It is recommended that the Mike Basin model be used for this as the model can operate on fine time steps, and is easily customisable through the COM interface.

It is possible to use the Mike Basin model in an operational context with the support of a product known as Mike Flood Watch. The name flood watch is a not entirely accurate as the system has been designed for any type of real time operational application including drought analysis or just real time operational control of a water resources system.

DHI sells Mike Flood Watch as a decision support system for real-time forecasting that integrates data management, monitoring, forecast modelling tools and dissemination methodologies in a single user friendly environment. Mike Flood Watch is a GIS-based client server solution that facilitates efficient handling of all procedures required in the management of a real time forecasting and warning system. Operationally, it can be run automatically, manually or as a combination. The system is customised using built in visual basic scripting facilities.

Mike Flood Watch can be used to manage and examine data imported in real time from a range of external sources, including point observations and grid-based data from weather models, radar and satellite imagery. The user can specify quality control procedures for each data stream and the system supports common commercial database engines.

The Mike Flood Watch supports a number of modelling tools including Mike Basin and is becoming Open MI (Open Modelling Interface) compliant. The software comes with a scenario management tool which enables the user to carry out comparative analysis, which provides immediate answers which enable the user to respond accordingly. The user can identify and define key information for the system and decide how such information should be customised. User information can then be passed on to the user either manually or as part of a scheduled task or on an event driven basis.

These aspects make it possible to perform auditing on a system where information fed into the system is modelled and actual information compared. Discrepancies can thus easily be identified and people not complying with their usage rules or requirements can then be identified. Poor management action can thus also be identified early and adjustments made to increase and improve water resource system efficiency.

5.11 Chapter Overview

In this chapter details are given about the Mike Basin model, as well as the outputs of various scenarios run using the Mike Basin model. The scenarios developed for this document are simplistic in nature as they are intended to promote proof-of-concept. The scenarios include the model being run for both FWA-CS and PRORR institutional arrangements.

The purpose of the chapter is to provide the reader with more information about the Mike Basin model, as well as to demonstrate that the output of the model can be used to generate yield curves, which are used by water resource planners. What is shown is that although the FWA-CS institutional arrangement is a relatively new institutional arrangement, (i) it can be supported by an internationally tested model (such as the Mike Basin model), and (ii) the output of the model can be used to generate decision aiding outputs (such as yield curves), which water resource planners are familiar with in South Africa. This undertaking was considered to be important if this research is to potentially contribute to the potential adoption of the FWA-CS institutional arrangement as part of the water allocation process.

The model scenarios show that:

(i) dams increase the yield in a system

(ii) restriction rules may decrease the yield in a system, however certain users' assurances of supply will be increased by the implementation of restriction rules, while other users' assurances of supply will decrease (which leads to a reduction in the firm yield of the system)

(iii) It is possible to configure the Mike Basin model to accommodate both FWA-CS as well as PRROR institutional arrangements.

In the chapter it is also highlighted that although the scenarios were of a planning nature, it would be possible to combine Mike Basin with Mike Flood Watch to operate at a near-real-time basis. This combination would in fact be required for a water audit system which operates on a near-real time basis.

The FWA-CS institutional arrangement did not show the amount of water that could be saved as a result of adopting this system. In order to undertake a scenario of this nature more complex hydro-economic modelling will be required. What was shown however was that although there were significant evaporation losses associated with the storage of water, a large percentage of stored water was not lost, and this water could either be traded or applied by the water banker, which could yield financial returns in excess of those that would have been received if water banking had not been practiced.

6 DISCUSSION AND CONCLUSIONS

The original underlying objective of this project was to assess ways to improve the efficiency with which water is used in catchments. The original aim was to develop an auditing system targeted specifically at water use from dams. The rationale given was that auditing may prevent over-use (illegal use) by water users downstream of dams. Due to the importance of dams for the augmentation of the catchment yield, improved compliance by downstream water users, as well as improved adherence to reservoir operating rules was expected to result in improved water use efficiency.

The importance of access to high confidence and timeous water use and availability data for the purposes of a water audit was recognised. As part of the project the following instrument related tasks were undertaken:

- An Automatic Weather Station (AWS) was installed at the Goedertrouw Dam which is enabled with telemetry, which implies near-real-time weather data can be accessed remotely. This data is primarily used to calculate the dam water balance, in particular the surface water evaporation.
- A telemetry enabled automatic rain gauge was deployed in the upper reaches of the Mfule sub-catchment. Due to the relatively steep slopes in the Mfule sub-catchment, the rainfall-runoff response time is relatively quick. The Water Control Officer (WCO) currently has no method of knowing if it is raining, other than if someone informs him/her of a rainfall event. The purpose of the telemetry enabled rain gauge is to automate the sending of an SMS to the WCO, and other interested or affected parties. The SMS is initiated if a rainfall event of a pre-defined intensity is experienced.
- The logging of water metered data promises to be valuable to water resource managers, in that the water use by individuals can be logged at fine time steps (e.g. daily), even though the information is collected at longer time intervals (e.g. monthly). The logger can provide a detailed record of when water (e.g. per day), and how much was used. A record of this nature is important in that the timing of water use by water users, as it is possible for water users to over-use water on certain days (e.g. week days), and under-use water on other days (e.g. weekends). A cumulative record would suggest that a user has in fact complied with his/her entitlement, whereas the detailed record of the logger can indicate that on a number of days water use abstraction exceeded entitlements, while on others days this was not the case. Given the potential importance of loggers, and the fact that they are generally imported, and quite expensive (particularly when the Rand weakens), the CSIR researched a locally developed logger which was significantly cheaper than international loggers. However, faults were discovered with the logger, which were communicated to the local manufacturer.

- Loggers can only operate if an instrument is in place which is recording something. Working in collaboration with the University of Pretoria who were also involved in a metering related project, an indirect method of metering irrigation abstraction was tested in the Umlaas Catchment. The indirect measurement method made use of two pressure transducers, which are fitted to the inlet and outlet pipe of the pump respectively, from which a differential can be calculated. The volume of water abstracted is related to the magnitude of the pressure differential.

Planned tasks associated with the water entitlement component of a water audit system had to be changed, once it was realised that water use entitlements are not issued against components of a catchment (e.g. a dam), but rather against a system. The system with which water resources are currently apportioned is referred to as the Priority-based Reservoir and River Operating Rules (PRROR) system. It was agreed that there was a requirement to expand the development of the water audit system to operate for an entire catchment, and not just for dams. The PRROR institutional arrangement is supported by the Water Resources Yield Model (WRYM) and Water Resources Planning Model (WRPM), both of which have been locally developed in South Africa.

A review of literature revealed that an alternative water management approach to the PRROR system exists, termed the Fractional Water Allocation and Capacity Sharing - FWA-CS system (Dudley, 1988, 1990, 1992). The system has been applied in Australia (Ryan *et al.*, 2000) and Zimbabwe (Doertenbach, 1998, Natsa *et al.*, 2000). The system promises to hold an advantage over the PRROR system in that the FWA-CS system adopts a "use-it-bank-it" principle for water use associated with stored water (i.e. water in large dams).

The PRROR and FWA-CS management systems are examples of Institutional arrangements (institutional arrangements), in that they define the rules governing the apportionment of water amongst competing water users. As the WRYM and WRPM were unable to support the FWA-CS institutional arrangement, which promised to have water use efficiency inducing advantages over the PRROR system, the Mike Basin model developed by the Danish Hydraulic Institute was purchased. The Mike Basin model is also a node and channel hydrological network model, as are the WRYM and WRPM, however, the solver of the Mike Basin model differs from that of the WRYM and WRPM. The Mike Basin model makes use of a rule-based solver technique (the exact details of the solver are proprietary to the DHI), while the WRYM and WRPM make use of least cost routing via the use of penalty structures. The merits and demerits of the various solver options were not explored in this project; however, there does seem to be an international movement towards rule-based solver methods.

Although the Mike Basin model can support the FWA-CS institutional arrangement, certain developments were required in order to make the output of the model useable for water resource planning purposes, including the development of an IFR routine (with monthly IFR curves from which the IFR can be calculated), and the development of a module that performs a number of iterative runs in order to generate yield curves (and the firm yield quantity).

The Mike Basin model and the FWA-CS institutional arrangement have been demonstrated to DWAF:HO as well as DWAF:RO and to stakeholders in the Mhlathuze Catchment. Interactions with stakeholders indicated that stakeholders understand vaguely the details of how the water apportionment rules are to be used as part of the Compulsory Licensing process. The researchers of this document believe that it is important for stakeholders to fully understand all processes and assumptions undertaken in the translation of the PRROR or FWA-CS institutional arrangement into model algorithms, from which the allocable resource is determined which will influence the nature and number of authorisations issued in the catchment. Very little documentation was found in this regard by the researchers, and the recommendation is given that a document outlining how water resources are planned, and then subsequently managed, needs to be published.

Although the FWA-CS institutional arrangement is relatively new, a form of water banking was adopted in the Mhlathuze Catchment during the drought experienced in the 1990s. Although the water banking was discontinued once the drought broke, the water resource managers and stakeholders who participated in the banking initiative believe that there are merits in the approach. The banking was discontinued due to the absence of a formal water banking system, and possibly due to the absence of adequate monitoring in the catchment. The research team believe that it will be possible to introduce a FWA-CS system to the Mhlathuze Catchment, but there is a requirement for a weir (or alternative suitable monitoring structure or equipment) to be located on the Mfule River near the confluence with the Mhlathuze River. The weir network on the Mhlathuze River is believed to be adequate. Monitoring equipment will also be required for the lakes, as the lakes have ecological requirements attached to them that need to be audited.

It is difficult to predict what level of efficiency the FWA-CS system could induce. The FWA-CS system appears to be more attractive than the PRROR system with respect to the trading of water use entitlements, particularly from low assurance to high assurance users. The reason for this is that in the FWA-CS system water users tailor their own assurances of supply by leasing the appropriate capacity of the dam, fraction of inflow into the dam. The level of assurance is not attained through differences in priority levels and differences in water restriction rules.

The Mhlathuze Catchment is a relatively small catchment, however it is quite a complex system from an operational point of view in that there are a few Inter Basin Transfers into the system, and there are a number of freshwater lakes which certain water users have access to. There is also a strong groundwater – surface water interaction which is not yet fully explored and reflected in water apportionment models configured for the Mhlathuze Catchment. It would be more difficult to apply the FWA-CS institutional arrangement to larger catchments, in particular where there are a number of undeveloped tributaries that feed the catchments mainly due to the more extensive monitoring network that would be required in larger systems. In a catchment where water is released from dams for use long distances downstream of the dam, but there are few tributary flows along the way (i.e. in dryer parts of the country), the FWA-CS will relatively easy to implement.

It may be possible to introduce a combination of FWA-CS and PRROR system, as witnessed in the Mhlathuze Catchment in the drought of the 1990s. However, the implication of this is that the assurance of supply levels observed in a catchment may differ from the assurance of supply levels aimed for during the water resources planning exercise, as the introduction of the FWA-CS institutional arrangement will result in changes to the operating rules. If FWA-CS do indeed induce more efficient water use, the observed assurance of supply levels may be higher (i.e. more favourable) than if the system is not introduced. The challenge will be to identify when to introduce the FWA-CS institutional arrangement, as leaving this too late will reduce the potential for water users to bank water (as flows into the dam may already be very low).

The water use entitlements are in effect homogeneous in the FWA-CS institutional arrangement, in that the same operating rules will apply to any water user holding the same water use entitlement. In the PRROR system, a lower assurance water user faces different operating rules than higher assurance water users (as the operating rules are used to give effect to the various assurances of supply levels). The implication of FWA-CS being "homogeneous" is that the entitlements can easily be traded between various types of water users. Water users tailor their assurances of supply be securing larger fractional flow entitlements and/or larger fractional entitlements to dam capacities. Currently, in the PRROR system, water trading (particularly inter-sectoral water trading where the assurances of supply differ between the various water users) is significantly hindered due to the complications caused by converting water entitlements from one assurance level to another. The FWA-CS system promises to be an institutional arrangement that solves this shortcoming of the PRROR system.

7 RECOMMENDATIONS

- Weather data collected using the Automatic Weather Station installed at the Goedertrouw Dam as part of this project showed a very poor correlation with DWAF recorded data. Details for this poor correlation are not clear, and it may be appropriate for this to be further investigated.
- The 1998 National Water Act and NWRS (First Edition, 2004) make very little mention of the exact details in which water resources are managed, i.e. how the rules that govern the apportionment of water amongst competing water users are reflected in computer models, and how the results are used in the licensing process. Although this is a very technical discussion, it may be one which is required in order to build the capacity of stakeholders in catchments, so that they can better understand how their entitlements are influenced by upstream water users, and how their activities influence downstream water users.
- Accurate weather forecasts could improve the water use efficiency from large dams in that water users may require less water to be released from dams, if they know with a suitably high level of confidence that rainfall is expected in the near-future. Due to the travel time associated with water released from the Goedertrouw Dam, it can take up to 2.5 days for the released water to reach water users. In the Mhlathuze Catchment water users will thus require high confidence 3 day forecasts.
- The Mike Basin model makes use of a different solver to the WRYM. A recommendation is that further research be undertaken related to the solvers used for various node and channel hydrological models used locally and internationally, and that the advantages and disadvantages of the respective solvers be compared.
- It is recommended that the ACRU model be integrated via the COM (or Open MI) interface with the Mike Basin model. This link will enable ACRU to gain the functionality of a multi-user, multi-reservoir planning model (such as Mike Basin), which even be used on an operational level, as the Mike Basin model can operate at on a daily time-step, and can be hot-started.
- It is recommended that the full link between Mike Flood Watch and Mike Basin be explored in order to complete a fully functional water auditing system for catchments, for both PRROR and FWA-CS institutional arrangements.
- It is recommended that a technology transfer be undertaken, which includes the installation of the Mike Basin model in a few DWAF regional offices. As the model can accommodate both the FWA-CS institutional arrangement, the technology transfer could include the configuration of catchments for both institutional arrangements.

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APPENDICES

APPENDIX A CAPACITY BUILDING

Capacity building

Individuals

- Mr. S. Mbokazi, while studying on a part-time basis, worked on the project. Tasks performed by Mr. Mbokazi included (i) the generation and use of Excel Macros (to streamline the modelling of scenarios) and (ii) the configuration and execution of the Mike Basin model to run scenario's and (iii) the taking and preparation of minutes and (iv) the use if GIS while working with the Mike Basin model.
- Mr. A. Harris, as part of his requirement to do vacation work, assisted Mr Mbokazi with the configuration of the Mike Basin model.
- Mr. R. Fakeer was the water control officer at Goedertrouw Dam. The research team installed a modem on his computer and configured the computer to have web-access. Mr. Fakeer was shown how interrogate the SAWS website to see rainfall forecasts for the catchment area above and below the Goedertrouw Dam.
- Mr. S. Mtshali was exposed to the use of GIS, as well as the Mike Basin model.
- Mr. J. Hallowes learnt about COM interfaces in the course of the project, and coded an IFR and Yield application which operate with the Mike Basin model.
- Mrs. M. van Rooyen helped with the typesetting of this document.
- Mr. Y Tsehaye, assisted with the research of metering systems on a farm in Umlaas. Mr Tsehaye completed the research while studying towards a M.Sc(Applied Sciences) (Irrigation) degree in the Department of Civil and Biosystems Engineering at the University of Pretoria.
- Mr. A. Clulow exposure to monitoring equipment, and installation experience, has built his capacity in this regard. .
- Mr Pott had the opportunity of meeting with Dr. Bjornlund, a water trading expert from Australia. Dr. Bjornlund shared may valuable ideas with Mr. Pott (and others) while staying in KwaZulu Natal for a few days.

Communities

Not applicable

Organisations

- The Nkwaleni, Mfuli and Heatonville Irrigation Boards were visited on a number of occasions, and details of water banking options and water auditing procedures were shared with the irrigation boards.
- Visits were made to DWAF:HO to present details of the water audit project, and findings. Documentation was also sent to the Directorate Information Systems regarding the FWA-CS institutional arrangement. This documentation was distributed amongst the water resources modelling community.

- The Umzimkulwana IB near Kokstad in KwaZulu Natal was visited, and a simple water auditing system in Excel was developed for them. The Irrigation Board were experiencing significant water shortages, and they needed a way to calculate how much water each member could abstract daily (with releases of water being made from the dam), and how meter readings should be taken to ensure that the entitlements were complied with.
- The South African Sugarcane Research Institute (SASRI) was visited on a few occasions, and details were given of the (i) Mike Basin model, as well as (ii) the FWA-CS institutional arrangement.

APPENDIX B IRRIGATION IN THE MHLATHUZE CATCHMENT

Irrigation as a whole is a major abstractor of water in the Mhlathuze catchment. The Mhlathuze catchment is one of the only catchments in the country where irrigation water use is monitored by means of Eskom calibrated meters, and irrigators only pay for what they use. In the early 1990's there was a severe drought in the catchment and a form of water banking was introduced in order to save water. When the drought broke however, the water users reverted back to their previously existing methodology.

There are 3 major irrigation boards in the catchment: Nkwaleni, Mfuli and Heatonville. Heatonville is the largest user in the catchment followed by Nkwaleni. The Heatonville and Nkwaleni Irrigation Boards will therefore be discussed below.

Heatonville

Heatonville is positioned along the Mhlathuze River just below the Mfuli confluence. The scheme is made up of two parts. The main part is the Heatonville Scheme and comprises of 45 farms with a scheduled area of 3300 ha. Water is pumped into the scheme from the Mhlathuze River into firstly a main canal and then up into holding and balancing dams across the scheme. Water is thus provided by the scheme to the edge of the farm in general. Thereafter it is up to the farmers to organize their own water. Each farm is setup differently according to its specific needs but in general it has been organized that so that the water is gravity fed to the fields thus saving electricity costs. The scheme has a capacity to pump just over $3m^3/s$ when all the pumps are pumping. The entire volume of the holding and balancing dams on the scheme is approximately 525 000 L of water excluding private dams.

The other part is the Heatonville River Section Farmers who obtain their water individually by pumping from the river. These farmers' water management is undertaken by a Water Control Officer specifically for that river section. The area of the river section farmers is 1750 ha.

Registration details

The DWAF registration process leading up to the licensing needs to be improved before licensing can commence. Malcolm Easton, the irrigation board manager, has found the details to be poor with countless errors.

There have been extensive studies done on the scheme and water usage but they are currently going to use allocations based on previously scheduled areas.

The allocation figures for Heatonville Irrigation Scheme are 11800m^3/ha/annum.

Ordering of water

In order to be able to communicate water requirements to the dam for the scheme, the orders are collated and sent through to the dam on a Thursday evening. In this way the releases from the dam can be adjusted on a Friday, which due to the lags in the system will influence the system at the Heatonville Scheme for the following Monday morning; Lag times estimated by Malcolm Easton are:
Goedertrouw to Heatonville abstraction – 60hrs
Heatonville to W1H032 – 12 to 18 hrs

The farmers, along with Malcolm, meet on a Tuesday morning to place orders for the coming week. At this meeting water requirements are discussed and orders collated. Any stakeholders unable to attend will generally fax, email or phone their orders through to the manager before the Thursday.

Malcolm, from experience, generally orders approximately 70-80% of the demands submitted by the farmers. This has improved from 5 years ago when he was ordering 50% of their demands.

Malcolm has developed a spreadsheet which from the orders required as well as the levels in the holding and balancing dams he is able to estimate the orders required. The main holding dam has a dam level indicator on it which he reads off for his calculations. Other dam's levels are simply estimated by making a field visit. These demands he faxes to the dam on a Thursday evening. Part of the spread sheet program which Malcolm Easton has developed is a calculation indicating the number of hours he needs to pump with each pump from his demands.

In many cases orders are placed and rainfall becomes a significant causing a potential wastage in short-term water releases. Malcolm is frequently in communication with the dam and will at any point that he deems it necessary, ask for orders to be cancelled. Malcolm is not too concerned about farmers cancelling orders with him as he does any cancelling required for the scheme as a whole and has through experience got a feel for the influence of weather conditions on water needs.

Malcolm has also taken over the role of placing orders for the Heatonville River Section. Their demands are sent through to him from the Water Control Officer.

Details of pumps

There are 4 pumps that pump from the Mhlathuze River. Three are large pumps with a capacity to pump 1.25 m^3/s each. A fourth pump can pump at 0.2 m^3/s. This is an overall full pumping capacity of just over 3 m^3/s.

Due to the size of the pumps and the amount of water they can withdraw, it has been necessary to install orifice plates on the larger pumps to reduce their pumping rate. This is because there is not enough water in the river at low flows and the pumps switch off and can't pump small amounts of water. The monthly ESKOM electricity bill varied from R100 000 to R220 000 per month and the use of off peak electricity enables the scheme to make significant savings. Thus the pumping takes place predominantly at night.

Metering of abstractions

The main abstraction is metered near the pump house for the entire system.

There is a great deal of metering that takes place in the system and many measurements are performed on a daily basis. Supply to individual farms from balancing and storage dams are metered by a cumulative volume meters which are either read off by Heatonville staff or sent in by the farmers themselves.

The Heatonville River Users are not metered directly. Abstractions are calculated from a calibrated electricity consumption figure. In this way estimates are calculated on abstraction.

Heatonville Irrigation Scheme does have a SCADA system in place. It is not linked to flows or levels but is used for controlling pumps which can be operated remotely. The main pumps at the Mhlathuze River are however never operated remotely for safety reasons and the pumps are switched on manually in order to check that all is in order at the pump house before pumping commences.

Internal Scheme Audit

Although Malcolm has found that farmers in the scheme have on a whole improved their estimates of demands with experience, it has been necessary to perform and internal audit of the system. He makes a comparison of orders and usage for each farmer on a weekly, monthly and then seasonal level. This information is posted at the Country Club and has been shown to be an affective way of getting the farmers to encourage each other to be vigilant with their orders. In the early stages the farmers were known to use as little as 50 % of their order but today they have become much more efficient. If they show an efficiency of less 85% or greater than 115 % of their order then there water use efficiency statistics are posted for all other members of the scheme to see.

Surplus Condition Water

This can be simply defined as the water that would be in the system with the dam shut and not making any releases. This water is not considered to be part of the allocation and falls under the 'use it or lose it' principal.

It is of critical importance, in times of drought when farmers will be abstracting to the full allocation, to know what the Surplus Condition Water flow is as this can be abstracted over and above the allocation and it is preferable to extract this from the river before the allocated water.

Determining the Surplus Condition Water is currently a problem because a great deal of it comes into the Mhlathuze River from the Mfuli River. This river can provide a great deal of water to the system. It is known to be a quick responding catchment and responds very quickly to rainfall events followed by a quick drop in flows again after the event.

Malcolm does attempt to keep track of surplus condition water the scheme uses, which are presented on an annual basis, but has no idea how much is actually in the river. This is because of a number of influences on the river system such as:

- Water theft which is an ongoing occurrence but impossible to police
- Evaporation and seepage out of the river which can be severe on hot days.

Tugela Transfer

Heatonville Irrigation Scheme has never had to pay for any of these pumping costs.

Billing

Heatonville Irrigation Scheme sends in consumption figures on a monthly basis to DWAF for which they are billed on a 6 monthly level. Billing also includes a Water Resources Management charge of 0.32c per hectare on the registered area.

Summary

The major requirements identified at the scheme for assisting in better system management and improved efficiency are:

- Prediction and monitoring of flows in the Mfuli River

- Prediction or monitoring of flows in Mhlathuzana River
- Water bank for Heatonville Irrigation Scheme in Goedertrouw Dam.

Nkwaleni

Nkwaleni is the second biggest Irrigation Board in the Mhlathuze Catchment. It gets water from a canal at the Goedertrouw Dam as well as from the river. The canal has a capacity of approximately $1.1m^3/s$. There is also a supply to Nkwaleni from the river. For the month of June this was measured to be in the order of 1 700 $000m^3$/month. The request made to the dam was fairly close to this and as an Irrigation Board they are generally very good at matching request with usage (Fakeer, 2003).

APPENDIX C MONITORING RELATED TASKS

Metering (monitoring) is an essential component of an audit process. As part of the WRC project a few tasks related to monitoring were undertaken, including:

- The installation of equipment in the Mhlathuze Catchment to facilitate the testing of the "water audit system", and
- The assessment of metering technologies and process, including details of:
    - The types of metering instruments available,
    - The methods with which the metered data is stored,
    - The methods with which the data is validated, and
    - The methods with which the metered data is accessed.

There are numerous methods available for measurement and monitoring. A core component of the success of an auditing system is the reliable collection, storage and processing of data. The CSIR (Pietermaritzburg) was responsible for researching and implementing the most appropriate instrumentation for the Water Auditing System. Numerous factors influence this decision such as price, reliability, availability and compatibility. Unfortunately, due to the nature of the system there are no quick-fix solutions and thorough investigation was required.

Measurement Systems

In brief a measurement system is generally made of the following components:

1. Power supply
2. Logger
3. Sensor
4. Data output
5. Modem

Power supply is the most critical component of the system and failure thereof is the most common reason for data loss. At remote sites batteries are commonly used and depending on how long they last, are either swapped out when required or are augmented by a charging system using solar panels or wind-chargers. Power supplies are also unfortunately the most targeted item in the system by thieves as both batteries and charging devices are highly sought after items.

Eskom 220V power is the most favoured supply which is converted to a 12V DC supply with a standby battery for power failures.

The power consumption of the system is critical as this will determine how long batteries will last and what size charging devices are required. The lower the power consumption of the system, the more convenient and the less likely power related failures are.

The logger is essentially the device that converts a signal from the sensor to a meaningful value that can be recorded. Each sensor requires channels or connections on the logger. There are two main types of connections namely analogue and digital. Analogue channels measure a current range of 4-20mA. When the sensor sends a current of 4mA, it is measuring zero and when it is sending 20mA, it is measuring its maximum reading. Digital channels of a logger simply measure pulses for example the small electrical pulse that the tipping of a tipping bucket rain gauge would produce.

Sensors vary greatly in size, power requirements, quality and resolution and thus need to suit the particular application. There are sensors available to measure just about everything from temperature to vibration.

Data is most commonly downloaded with a storage device or may be downloaded directly to a PC in some cases. Most loggers have software that allows data to be displayed and analysed. If this is not available a spreadsheet can perform most of the requirements for data analysis.

A modem can be connected to a logger and instead of visiting a site to download data, remote telemetry or radio links can be used. Radio links are generally limited to line of site whereas landline modems and GSM modems allow the data to be downloaded across the world. GSM modems in particular are useful as they are dependant only on cell phone reception. Associated with this however is a relatively high power consumption which can be problematic in remote areas as typically no Eskom power supply is available. Also associated with modems, due to their sensitivity, is the threat of lightening damage or power surges. It is however very cost effective to be able to download data, verify battery voltages and that sensors are working by simply dialling into a station rather than expensive and time consuming field trips.

Water Extraction Measurement

The emphasis of this particular exercise was to verify whether extractions could be measured by monitoring differential pressures and whether a pump can be monitored through the GSM cellular network from a remote computer. The logger is therefore connected to a modem with a data SIM card and can be accessed from any dialup connection.

Initially a locally made logger from Vangard Digital was purchased for the project to measure 2 analogue and 1 digital input. The motivation for making use of this particular logger was to investigate the viability of a locally produced logger as the market is currently dominated by reliable and well tested but expensive imported loggers.

Due to the experimental nature of the use of this particular unit, it was decided to install the device at Umlaas Road near Pietermaritzburg rather than the Mhlathuze Catchment. This was logical due to the possibility of having to make regular field visits to monitor performance or deal with any problems which may have arisen. This particular site is suitable as there was other instrumentation in place for a WRC project (K5/1265) lead by Isobel van der Stoep. It was therefore mutually beneficial for both parties to share resources and reduce costs. Please see appendix C for further details.

Below, follows an explanation of the details of this measurement.

Vangard Logger

Differential pressures using pressure transducers

Two pressure transducers, connected to the analogue channels of the logger, measure the inlet and delivery pipe pressures which are converted to a flow rate or volume. Their details can be summarised as follows

1. Require 7-35V dc on Pin 1
2. They output 4-20mA output on Pin 2 referenced to the 12V dc+ on Pin 1.
3. Range of the inlet pressure transducer is 0-2 Bars and the outlet pressure transducer is 0-10 Bars.
4. Pin 3 is NC and Pin 4 an earth which were not connected.

It is necessary to perform scaling on the raw data from the pressure transducers. The output from the pressure transducers is in mA and needs to be converted to volts to be stored by the logger. This was performed internally by the Vangard Logger. The logger raw 12-bit full scale is 0-4095 which can represent 0-25mA. The pressure transducer output is 4-20mA which represents the pressure range of the pressure transducer. On the pump inlet the 0-2 bar pressure was represented by a raw reading in the following way:

0 bar is 4/25 x 4095 = 655
2 bar is 20/25 x 4095 = 3276

These values were set on the logger by Vangard Digital. It was however necessary to setup the output format which converts the raw data reading into engineering units. From the calculations above, the logger received a signal between 655-3276, representing a pressure of 0-2 bars. This needs to be setup for each pressure transducer according to its pressure range in the analogue scaling routine. Please refer to Appendix C for the Vangard Logger manual for the programming instructions.

In order to use the pressure measurements for quantitatively determining the water abstraction, the relationship between the flow rate and differential pressure needed to be established. This was done by simultaneously measuring the flow rate and pressures over a period of time to determine typical values on which to base the relationship.

The flow rate was measured with a portable ultrasonic flow meter (Panametrics AT868) which has an accuracy of ± 2% of actual reading over the flow velocity range within which measurements were being taken.

The specific pump station where the measurements were taken is used to pump water to a storage dam, via another booster pump along the pipeline. Since water is always taken from approximately the same suction head (the flow in the river is controlled up-stream by adjustments to the water released from the storage dam, resulting in a fairly constant flow depth in the river) and delivered against a constant head (the height of the pipe outlet at the dam which stays the same), the flow rate would always stay more or less constant. (There may be other cases where the pump is regularly operated at different duty points such as when it serves different sizes of irrigation blocks or different systems, and therefore a variety of flow rates may occur which has to be covered by the calibration procedure).

Calibration readings were therefore only recorded at one duty point. Statistical analysis showed that flow and pressure values occurred within the following minimum and maximum limits, with average values as shown in table 4.

Table 1 Calibration values for the Umlaas Road pumping station

	Minimum	Maximum	Average
Differential pressure, kPa	790	802	796
Flow rate, m^3/h	59	78	66

The data that was to be recorded at short time intervals, could then be evaluated through the following simple logical statement to determine the flow rate (Q, m^3/h) from the recorded pressure values (Δp, kPa):

IF $790 < \Delta p < 802$
THEN Q = 66
ELSE Q = 0

The abstracted volume of water per time interval (Δt, hours) could then be calculated by multiplying the flow rate by the length of the interval, or for a long period of time, t_i, calculated with:

$$V = \sum_{t_0}^{t_i} (Q \times \Delta t) \qquad (?)$$

To apply the statement, data has to be downloaded from the data logger and processed in a spreadsheet before the abstracted volume for a specific period is known.

Mechanical meter with reed switch

A reed switch in a mechanical meter was connected to the pump withdrawal pipe as a verification of the flow rates obtained from the pressure transducers. The digital signal from the reed switch was connected to the digital input channel of the Vangard logger. The reed switch was connected to the mechanical meter so as to output one pulse per $1m^3$. Referring to the Vangard manual, the digital input was set to 'counter' so that the signals were cumulative for ease of use.

Modem and SIM card

A modem and aerial were supplied by Vangard with the logger and were found to work well. There was moderate reception at the site but the connection was stable and trouble free. A data SIM card was purchased through Vodacom allowing an airtime of 2 years. This is an Incomer contract and for the purposes of this project, the most cost effective option. The data transfer speed for the SIM, modem and dialup from Windows Hyperterminal must be 9600 bits/s.

Conclusions relating to the use of the Vangard Logger

A large number of problems were experienced with the Vangard logger but on the positive side, through the development of a close working relationship between Vangard and the CSIR during the project, most of the bugs were sorted out. This unfortunately took most of the year and in order to actually collect data during the pumping season, a Campbell Scientific CR10X logger was supplied by the CSIR and installed at the site. This is discussed later.

A record of events related to the testing of the Vangard logger

Date	Action
June 2003	Logger collected from Vangard

July 2003	Logger modified locally for a problem with contact bounce on digital input from the reed switch
Aug 2003	Logger installed at Umlaas Road
Sept 2003	Logger can't be initialized by analogue input and count digital inputs and eventually stops working after 1 day– returned to Vangard for repair
Oct 2003	Logger returned to CSIR but feedback from modem freezes logger. Vangard notified of these problems
Nov 2003	Campbell Scientific CR10X logger installed at site for data collection purposes
Feb 2004	New Vangard logger returned with updated hardware and software – installed at site and currently undergoing testing but experiencing problems

Although a great number of improvements were made to the Vangard logger, it cannot be considered to be reliable and requires a great deal of further development. It took close to a year from date of purchase to get the logger working at the site and the same problems can be expected when applying the logger to other types of measurement. It would therefore not be recommended for any purpose other than development through research at this stage until the logger has been verified further. Its application compared to the Campbell Scientific logger is very limited and the following summarises the primary concerns the CSIR have with the logger:

- Storage space is limited to 6000 lines and 20 000 if extended memory is purchased. A standard CR10X can store 62280 data points expandable to 2Mb i.e. storage space is seldom limiting.
- There is no software available to analyse and manipulate the data other than Hyperterminal.
- There are software bugs.
- The hardware appears to be very sensitive and has no protection against lightening.
- The user manual is vague and incomplete.
- Backup support from Vangard Digital was very slow.

Campbell Scientific CR10X Logger

Due to the numerous problems and developments required by Vangard for their logger, a point was reached where it was necessary to start collecting data at the site before the pumping season was over. For this reason a Campbell Scientific CR10X logger, supplied by the CSIR, was installed at the site. The logger was installed in a few hours and ran reliably for 4 months until removed. Please see Appendix C for details of the CR10X program that was used.

Details below describe the methodology used to setup the CR10X logger.

The CR10X logger requires a voltage input. As with the Vangard logger, the mA output of the pressure transducers has to be converted to a voltage with a resistor and then scaled to a pressure. The following table describes the conversion.

CR10X logger conversions for 0-2 Bar Pressure Transducer

mA PT output	Conversion R=V/I (Ohms)	CR10X range mV	PT Range kPa	Regression
4	125	0	0	y=0.1x-50
To	125	To	To	y=0.1x-50
	125			y=0.1x-50
20	125	2500	200	y=0.1x-50

CR10X logger conversions for 0-10Bar Pressure Transducer

mA PT output	Conversion R=V/I (Ohms)	CR10X range mV	PT Range kPa	Regression
4	125	0	0	Y=0.5x-250
To	125	To	To	Y=0.5x-250
	125			Y=0.5x-250
20	125	2500	200	Y=0.5x-250

This formula is then placed into the program of the CR10X logger. The regression formula for the 10bar pressure transducer is input as a multiplier of 0.5 and an offset of -250.

The Pin 1 and 2 of the inlet pressure transducer were connected up to SE 1 and AG respectively. Pin 1 and 2 of the other pressure transducer was connected across SE2 and AG. Each of these connections had a 125 ohm resistor across them to convert the analogue mA into a voltage within the range of the CR10X which is 0-2500mV.

Campbell Scientific have become the industry standard in scientific loggers. They are made in Canada and are supplied locally by CSAfrica in Cape Town. They have been thoroughly tested and are reliable, have low power consumption, can have their memory extended, are compatible with telemetry/radio systems and are robust. Their most powerful feature however is that they are compatible with most sensors. Because they don't have special fittings that plug into them, any wire can be connected to the Campbell Scientific loggers. This compatibility is complimented by the programming language that allows manipulation, conversion or calculation to be performed in the logger. These features make the Campbell Scientific loggers some of the most flexible and respected loggers in the world. They supply a number of different loggers according to specific requirements. The middle of the range logger, the CR10X, with 12 analogue channels, costs approximately R9 700 depending on the exchange rate. For this particular application a CR510 logger could have been used with a cost of about R6000. Useful to this particular project is that the loggers are able to dialup and send SMS's. This can be based on any conditional statement. For example if a certain amount of water is pumped a warning is sent by SMS confirming this. Alarms indicating tampering/theft and power supply problems can also be sent via SMS to the relevant persons. Other factors such as pump/water temperature could be added to the monitoring.

These Campbell Scientific loggers are thus very flexible and capable and have undergone years of testing and development. This does however come at a high initial cost which does, however, frequently end up being the most cost effective solution when you take the low maintenance requirement, flexibility and reliability into account.

Other cheaper options are available such as the Hobo loggers. They are much simpler more basic loggers. They have either 2 or 4 input channels and low power consumption. They do not all have compatibility with telemetry which was one of the requirements identified for the system. They would thus require regular field visits in order to download the data manually. This is particularly limiting as problems are only realised on arrival and thus frequently require a second trip in order to make the repair. Each trip has a hijacking potential!

Verification of measurements

The pressure-based flow measurements were compared with the readings from a mechanical flow meter that was installed at the pump station for specifically for the purpose of verification.

The meter was a 150 mm Kent impeller type irrigation meter which was specified to measure the flow rate within ± 5 % of the actual flow rate. It was fitted with a reed switch to produce a pulse output which could be recorded by the same datalogger used for the pressure readings. The reed switch was installed to produce one pulse per 1 m^3 of water that flowed through the meter.

After the initial problems with the datalogger were solved, data was recorded for the period of 6 November 2003 to 23 February 2004. The data was processed as described in 1.1.1, and the results are displayed graphically in the Figure below.

The farmer experienced some problems with the pump in the time period between 21 November and 18 December 2003. Up to 21 November 2003, there was a good correlation between the data from the two measuring methods, but it seems that after repairs were done, the two graphs diverted further as time went by.

Due to the motor being repaired or rewound, the flow rate – pressure relationship that was established initially was not valid anymore, resulting in a difference of 2179 m^3 of pumped water between the two methods over the nearly four month period. If the mechanical meter output is used as reference measurement, this is equal to a measuring error of –4.09 %, which is acceptable since most irrigation meters are specified to be accurate within ±5 % of reading. Re-calibration could improve the accuracy – visual evaluation of the mechanical meter output showed that the average flow rate was closer to 70 m^3/h than the 66 m^3/h recorded during calibration.

The graph also shows the output from the Irrigation Board's current measuring method where hour meters are used. According to the hour meter fitted at the pump station, water was abstracted for a total of 1469 hours during the four month period, and since the pump is "calibrated" according to their system for 65 m^3/h, this translates into a volume of 95485 m^3 that was supposedly abstracted.

However, the other two measuring methods recorded only 767 hours of pumping over the four month period, or a total volume of 53253 m^3 according to the mechanical flow meter. Although a problem with the specific hour meter was reported and attended to in January 2004, this is a very large discrepancy (+79.30 % error) and may need to be investigated further to ensure that the problem has been resolved.

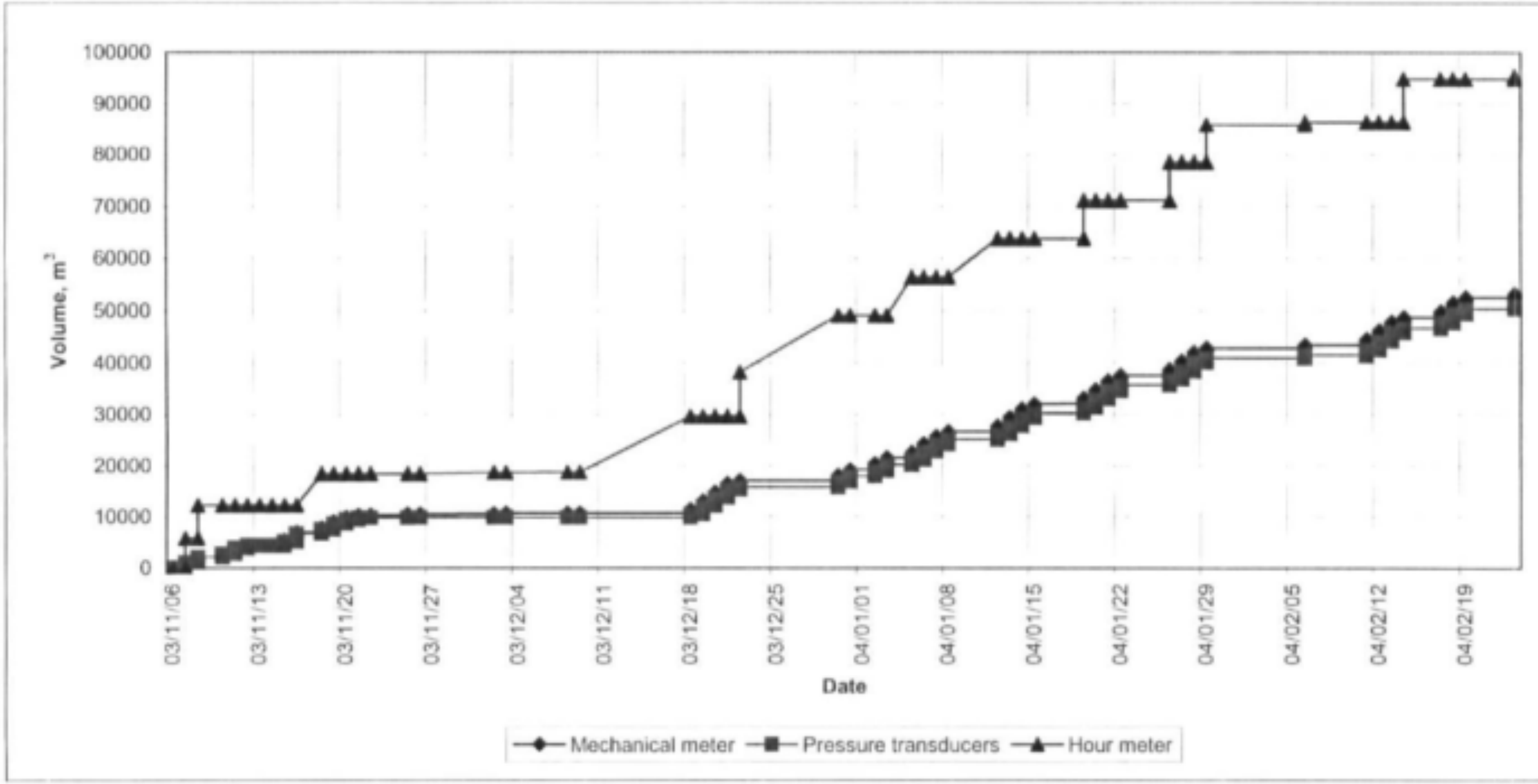

Figure 1 Abstraction of water at Umlaas pump station

Conclusion on Methodology Used

- Abstractions can be measured to an accuracy of 5% using differential pressures from pressure transducers.
- Remote communication can be setup so that the modem can be accessed from any dialup connection and downloaded over the GSM network. Alarms via SMS can also be sent from the loggers.
- The type of instrumentation used is critical. The locally developed Vangard logger is potentially a suitable logger and although certain bugs were ironed out through the project, more testing and development is required before it can be considered ready for application. The use of unreliable instruments is frequently more costly in the long run.

Automatic Weather Station at Goedertrouw

An Automatic Weather Station (AWS) was installed at Goedertrouw Dam in May 2003 by the CSIR. Although the Water Control Officer currently takes daily readings of rainfall and evaporation, these are not rigorous enough for the proposed audit system. The evaporation and rainfall influences on a body of water the size of Goedertrouw Dam are significant and need to be quantified as accurately as possible for the audit to take place. The methodology used was the Penman Open Water equation. The data collected from the AWS were used to calculate the Penman Reference and Open Water evaporation in real time in the data-logger (Everson 1999, Savage et al, 1997).

The details of the equipment purchased from Campbell Scientific for R54 878.83 (purchased in 2003) as follows:

- CR10X data-logger
- AWS tripod and housing
- Solar panel, regulator and 7Ah battery
- CS 500 temperature, RH and barometric pressure sensor
- Pyranometer
- Wind speed and wind direction
- Rainfall

The data-logger recorded hourly data weather variables, computed a daily average and also calculated the Penman open water evaporation. See Appendix C for details of the program. The data can be viewed in real-time while connected to the data-logger or it can be downloaded to a computer with a modem. Figure 2 is a plot of solar radiation and Penman open water evaporation over seven day periods for winter and summer 2003.

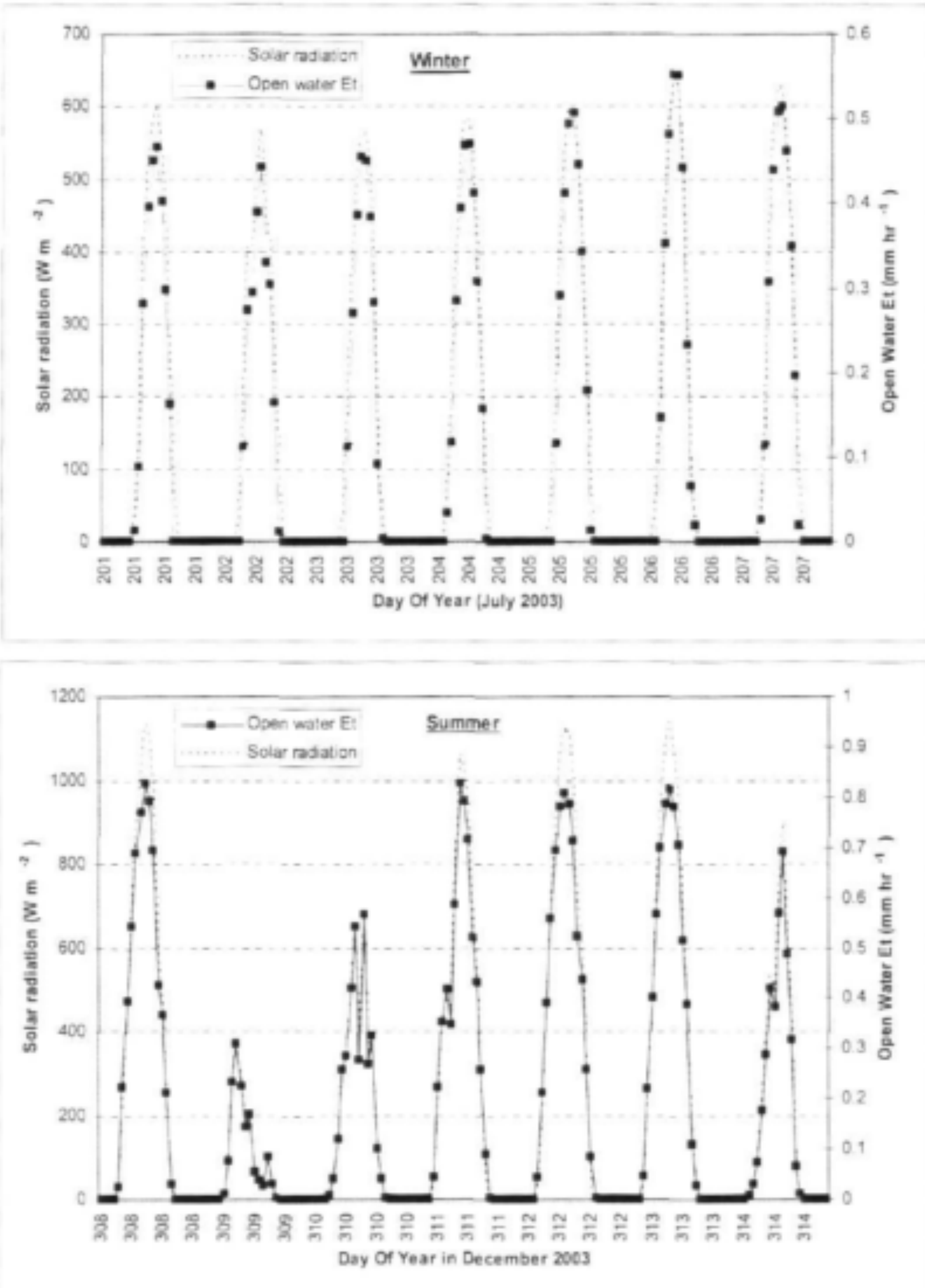

Figure 2 The diurnal course of solar radiation and open water evaporation for seven day periods in winter and summer. The left axis is the solar radiation (Wm^{-2}) and the right axis is open water evaporation ($mm.hr^{-1}$).

These data show that the radiation balance is clearly the principal driving variable in determining the evaporation from the Goedertrouw dam. Winter days are characterised by being cloudless and the diurnal trends follow typical bell shaped curves. Maximum daily winter rates (± 5 mm day^{-1} are about 40% less than peak summer rates (± 8 mm.day^{-1}), although summer values are reduced by cloudy and rainy conditions (DOY 309 & 310 of 2003).

The daily open water evaporation rates were strongly influenced by season, starting at about 2 mm day^{-1} in July (DOY 185) and peaking at 7.3 mm day^{-1} in mid January 2004. What is particularly relevant to this study is that this 636 day data set is 100% complete, demonstrating the reliability of the Campbell automatic weather station. Total evaporation losses for the 636 day period were 2 287 mm, rainfall inputs were 979 mm, resulting in a net loss of 1 308 mm from the system.

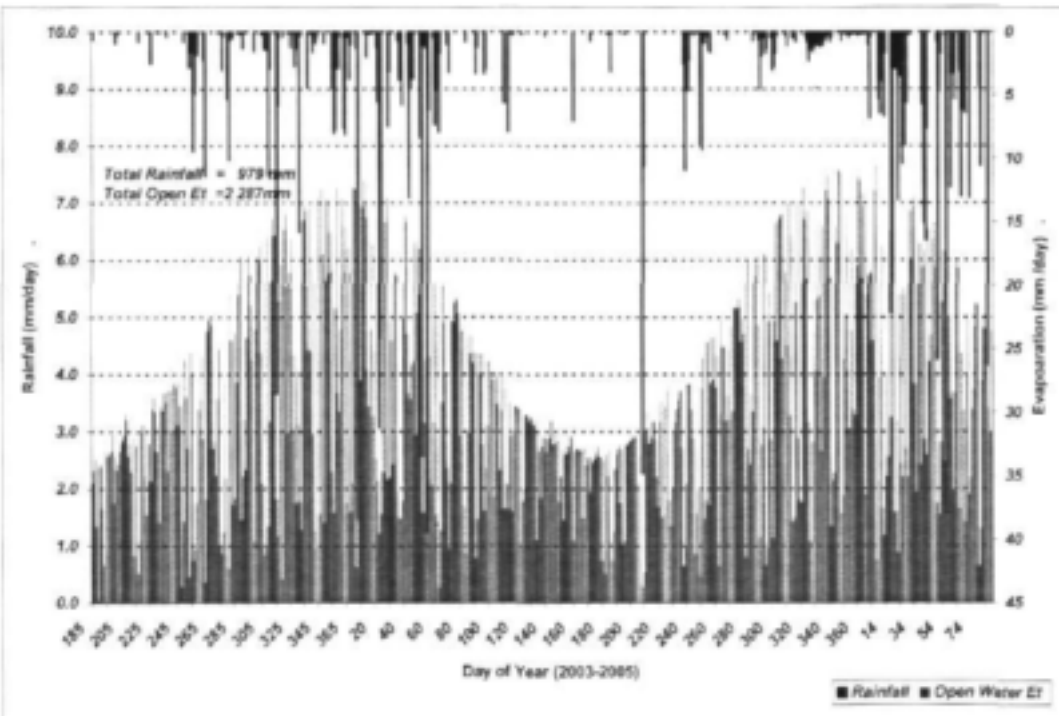

Figure 3 The daily totals of open water evaporation and rainfall for the Goedertrouw dam site

A comparison of the monthly data from the A-pan data collected by DWAF and the AWS showed that the A-pan was generally 5-15% lower than the Penman calculations (Figure 5). The A-Pan data was corrected by a monthly factor derived by DWAF to estimate open water evaporation from raw A-pan data. An X-Y scatter plot of the daily data for 2004 shows a fairly poor relationship between both methods (Multiple R=0.44). The slope of the regression line is 0.83 confirming the deviation between these techniques. Clearly this aspect requires further investigation to determine why the deviation is so large at a daily level.

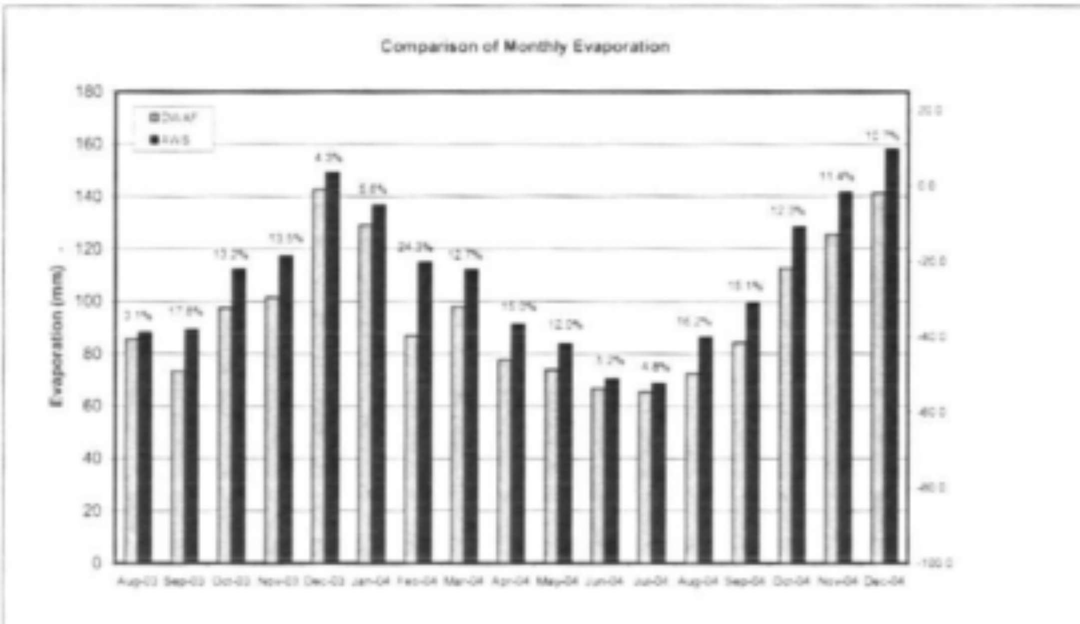

Figure 4 Comparison of monthly A-pan open water and Penman open water for the Goedertrouw dam site also showing the deviation of DWAF data to AWS data in percentage difference (August 2003 to December 2004).

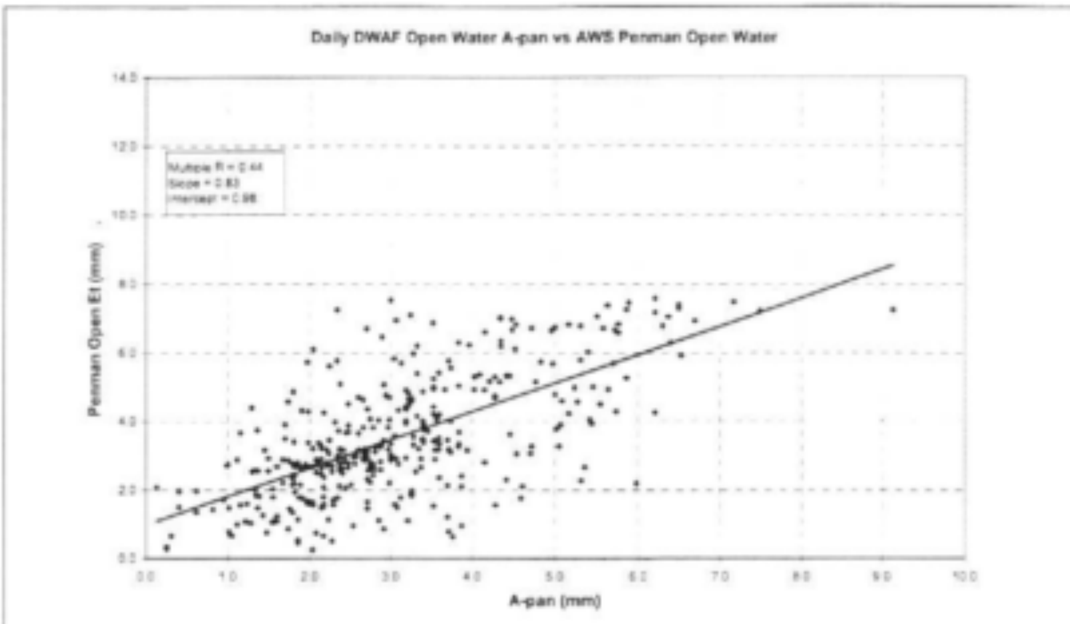

Figure 5 Scatter plot of the daily A-pan open water and Penman open water data for Goedertrouw dam (January 2004 to December 2004).

Rainfall Station on the Mfule River

A critical component of the Mhlathuze system that needs to be part of the Water Audit System is the contribution from the Mfule River. Malcolm Easton from Heatonville Water User Association has commented on the significance of the contribution from this tributary. Unfortunately this tributary is currently ungauged and the contribution thus unknown. The Water Control Officer is however releasing water for users below the confluence of the Mfule and Mhlathuze Rivers. He is ignorant of the extent to which the Mfule contribution will satisfy water orders and this has been identified as one of the major weak links in the system. Many of the other influences in the system can be quantified and audited. It is with this in mind that a rainfall station on in the catchment feeding the Mfule is required.

A significant characteristic of the Mfule River is that it responds very rapidly to rainfall events. The Water Control Officer should be able to adjust the releases from the dam according to potential flow in the Mfule River when rainfall starts. The transfer of this information to him needs to be rapid considering lags in the system. The rain gauge therefore not only records rainfall for post event calculations, but also has the ability to initiate SMS's when a critical intensity of rainfall is measured which will influence the Mfule River. This is particularly important due to the spatial variability of rainfall in the area. In some cases there may be heavy rainfall in the Mfule Catchment and very little rainfall at Goedertrouw Dam. The Water Control Officer may thus be unaware that the Mfule River has risen significantly. Should this course of events take place, the Water Control Officer would be informed of intense rainfall in the Mfule Catchment via the telemetry system of the rain gauge. He would receive an SMS on his cell phone informing him of the rainfall event and the intensity thereof.

A description of the equipment purchased from Campbell Scientific for R18 000 as well as the rain gauge supplied by DWAF is as follows:

- CR510 data logger
- Greenspan rain gauge 0.5mm/tip
- Solar panel, regulator and 7Ah battery
- GSM modem and Incomer data SIM
- Logger housing
- Data downloading equipment

This system is maintenance free but the rain gauge does need to be serviced at regular intervals to prevent clogging of the orifice by seeds etc.

For monitoring and observation of the system, it was installed at Heatonville near the Tongaat Hullett AWS. The data rainfall records were found to correspond well between the AWS and rain gauge system. One of the subjective decisions, which is dependant on local conditions, is intensity of the rainfall required to trigger the SMS alarm. For this site an intensity of 10mm/10minutes was programmed into the logger before the alarm SMS was sent to notify the Water Control Officer of the event. For the period in which the site was running, this was not triggered and may need to be reduced. There was however no significantly intense rainfall event during the logging period.

Weirs

There are a number of DWAF weirs on the Mhlathuze River System currently. Table 8 gives a summary of the weirs in the Mhlathuze catchment.

Table 2 Summary of the weirs in the Mhlathuze Catchment

	Analogue Logging			**Digital Logging**	
	Logging	Start	Gaps	Logging	Start
W1R001A01	Daily	1981		12 minutes	
W1H009A01	Daily	1962	2yrs 1992	12 minutes	
W1H028A01	Daily	1983		12 minutes	
W1H029A01	Daily	1983		12 minutes	
W1H030A01	Daily	1983		12 minutes	
W1H032A01	Daily	1983		12 minutes	
Stewards Farm			Under construction		

DWAF have recently installed digital loggers with modem connections to some of the monitoring points in the catchment. The logging takes place at a twelve minute interval and is stored on the loggers for a period of close to 3 months. The data is downloaded by SMS through the modem system at a daily level with a twelve minute interval. This data is however not guaranteed as there could be errors including missing data or calibration problems that are not picked up as the data has not been processed yet. The question remains whether this daily data could become accessible on the Hydstra system on a real-time level or at least daily. This would provide great value to any daily or even weekly audit which may take place.

At a monthly interval the data is downloaded in the field and readings are checked as calibration may be required. The data is taken to the DWAF, Midmar Office, where it is analysed and checked and any adjustments made. It is then input into Hydstra at the DWAF Durban and becomes available in the Hydstra system. This is emailed up to the main DWAF office in Pretoria where it is archived and stored.

There have currently been a number of different problems experienced with the data collection, which is associated mainly with power failures and format problems. Most of these are however of a short-term nature and are being sorted out. They do however result in periods within the data sequences that have no data or have incorrect data. This can result in fairly long sequences of data being unusable.

The logging of data is a fairly new operation and is getting through the teething phase. Because of this analogue recording of data is still taking place at most of the weirs in order to verify automatically logged data. Once confidence in the digital logging of data is established it is hoped that the data could be made available in Hydstra on a daily level rather then the 1-3 month lag which is currently experienced.

APPENDIX D SUMMARIES OF AN INDEPENDENT PROJECT FOCUSSING ON WATER METERING INSTRUMENTS

Summary of closed conduit devices

Method	Volumetric data output (standard)	Flow rate data output (standard)	Sensitivity to installation conditions (hydraulic)	Needs ext. electric power (standard)	Accuracy (relative)	Sensitivity to dirty water	Additional pressure loss in system	Continuous data recording possible	Typical cost of standard unit (including installation)
Turbine	Yes	No	High	No	Moderate	High	Low	Yes*	<R5000
Impeller	Yes	No	High	No	Moderate	Moderate	Low	Yes*	<R5000
Propeller	Yes	No	High	No	Moderate	High	Low	Yes*	<R5000
Bypass	Yes	No	High	No	Moderate/Low	High	Moderate	Yes*	<R5000
Electromagnetic (inline)	Yes	Yes	Moderate	Yes	High	Low	None/Low	Yes*	R10000 – R25000
Electromagnetic (insert)	Yes	Yes	High	Yes	Moderate	Moderate/Low	None/Low	Yes*	R6000 – R12000
Acoustic Doppler	Yes	Yes	High	Yes	High	Low	None	Yes**	R15000 – R40000
Acoustic Transit Time	Yes	Yes	High	Yes	High	Low	None	Yes**	R15000 – R90000
Electric power	Yes	Yes	Low	No	Moderate/High	Low	None	Yes*	<R8000
Pump differential pressure	Yes	Yes	Low	Yes	Moderate	Moderate/Low	None	Yes	<R8000
Elbow	No	Yes	Low	Yes	Moderate	Moderate/Low	None	Yes	<R8000
kiloWatt-hour	Yes	No	Low	No	Low	Low	None	No	<R1500
Hour meters	Yes	No	Low	No	Low	Low	None	No	<R500

* Additional hardware always required

** Additional hardware sometimes required

Summary of open channel devices

Method	Volumetric data output (standard)	Flow rate data output (standard)	Sensitivity to installation conditions (hydraulic)	Needs ext. electric power (standard)	Accuracy (relative)	Sensitivity to dirty water	Additional pressure loss in system	Continuous data recording possible	Relative cost of standard unit (including installation)***
Weir	No	Yes	High	No	Moderate/High	High	High	Yes*	Moderate/Low
Flume	No	Yes	High	No	Moderate/High	Moderate	Moderate/High	Yes*	Moderate/High
Mechanical velocity	No	Yes	Moderate	No	Moderate	High	Low	Yes*	Moderate
Doppler velocity	No	Yes	Moderate/High	Yes	Moderate/High	Moderate/High	Low	Yes*	Moderate/High
Floats	No	Yes	Moderate/Low	No	Low	Low	None/Low	No	Low
Orifices (Pressure controlled sluice gate)	No	Yes	High	No	Moderate	Moderate	Low	No	Moderate
Acoustic Doppler	No	Yes	High	Yes	High	Low	None	Yes**	Low-high****
Acoustic Transit Time	No	Yes	High	Yes	High	Moderate/Low	None	Yes**	Low-high****

* Additional hardware is always required

** Additional hardware is sometimes required

*** Prices vary widely with size and therefore are only relative.

**** Often "one size" device can be used to meter all flow rates. These instruments can be expensive for small canals but affordable for larger canals

APPENDIX E A COMPARISON OF THE MIKE BASIN MODEL TO THE WATER RESOURCES YIELD MODEL

CONSIDERATION	MIKE BASIN	WRYM	DISCUSSION
Development history	Developed by the Danish Hydraulic Institute.	Developed by BKS from the ACRES model	
Solver	Rule Based	Least cost routing using penalty structures	The Rule based solver promises to hold certain advantages over the least cost routing approach in that (i) the rule based system is easier to understand, which is important for stakeholder participation, and (ii) the rule based system is far quicker and easier (and therefore cheaper) to test different scenarios. The reason for this relates to the "relative" nature of least cost routing. For a scenario to be introduced, many penalties will need to be changed to ensure that the water moves correctly. The rule based system overcomes this requirement.
User interface	GIS	Schematic	The GIS interface promotes stakeholder understanding and participation, as the schematics tend to only be understood with persons familiar with the schematics.
Time step	Any	Monthly	The time step is significant for water auditing purposes, particularly if audits are required at intra-monthly time steps.
Planning versus Operations	Mike Basin can operate both as a planning and operational model. For operations use needs to be made of Mike Basin Interfacing with Mike Flood Watch	Only planning	Planning models make use of long sets of historical data. Operational models make use of rear-real time data. The WRYM and Mike Basin models have been designed as planning models. However, the Mike Basin model can be coupled with the Mike Flood Watch model (which is a system used to capture near-real-time data), and can be run on a near-real time basis.
Customisation	Easily customizable through the COM interface	Not easily customisable	The COM interface allows the user to easily access many of the Mike Basin state variables. Customisation is very easy. As part of this research project an IFR module, as well as a curve yield generating module were produced. Customisation of the WRYM is currently not possible.
Water apportionment rules supported	PRORR FWA-CS	PRORR	For the purposes of this research project it was essential to find software that could support the FWA-CS institutional arrangement. The Mike Basin model can support both the FWA-CS and PRROR institutional arrangements.
Requirements to run	Arc View and spatial analyst		Most organizations who would be involved in water resources planning

the model			or operations will already have access to Arc-View and Spatial analyst, so these are not seen as critical considerations.
Cost			The cost may be seen as a deterrent to the use of the model. However, the pay-back period is very quick in that
Development initiatives	Arc-hydro database		The Mike Basin model is updated annually. The model is kept in line with the latest developments in computer technology.
Cost/benefit considerations	• Easily understood by stakeholders • Changing scenarios is quick and easy • Software is updated continually. This is made affordable as DHI services an international community • Benefits are high relative to costs	• Not easily understood by stakeholders • Scenarios are timeous to set up due to the relative nature of penalties. • It will be expensive for the software to be updated	The Mike Basin model can support the FWA-CS institutional arrangement, which may induce more water use efficiency. This is a clear benefit over the WRYM which is only able to support the PRORR institutional arrangement. The GIS interface with the rule based system of the Mike Basin model allows scenarios to be configured quickly and clearly, and for new scenarios to be configured quickly and clearly. The cost saving of this quick turn-around time is significant.

Note: The table reflects the opinions of the authors.

APPENDIX F DATA STORAGE

All data collected for the project will be housed at the following address:
CPH Water
34 Bunny Anderson Rd
Worlds View
Pietermaritzburg

Other related WRC reports available:

Effective local management of water resources with reference to the middle Orange river.

Viljoen MF; Dudley NJ; Gakpo EFY; Mahlaha JM

A computer-based decision-support model based on the institutional arrangement of capacity sharing, is available for application in off-stream and instream water use management under conditions of uncertainty. This project evaluates the usefulness of this innovative approach under South African circumstances. This must be done within the context of the National Water Act, information requirements on the quantity and quality of water available, levying of water charges and tariffs in relation to water values for different uses and regulations for the performance of functions by the to-be-established WUAs. It is envisaged that the model will provide an appropriate tool for water management by irrigation farmers and other water users.

Report Number: 1134/1/04 **ISBN: 1 77005 279 8**

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