1. INTRODUCTION AND OBJECTIVES

External environmental forces operating on the water resource sector are shaping the sector and the associated modelling industry. Substantial political, social and economic changes have taken place in South Africa in the past decade. These changes have been bought about by profound political change, the influence of globalisation and substantial advances in computer and communications technology (Dent, 1999). The National Water Act (NWA – Act 36 of 1998) was formed in response to these external forces and is in itself an external force driving the water resources modelling community. Albert Einstein observed 'The significant problems we face cannot be solved at the same level of thinking that we were at when we created them.'

The NWA calls for water to be used in the most *equitable*, *efficient* and *sustainable* manner. This requires a multi-disciplinary understanding and approach to water use. The Department of Water Affairs and Forestry (DWAF) has identified the need to strategically view the planning and allocation of water resources in terms of water availability, the social and economic cost and benefits, the environment and the opportunity cost in the light of international needs and priorities.

The Strategic Environmental Assessment (SEA) process was introduced by DWAF in 1997 as a method of looking at conflicts arising from permit applications for further afforestation of commercial tree species in South Africa (Steyl *et.al*., 2000). Within DWAF a SEA team was established in order to implement the SEA principles. However, shortly after the introduction of the SEA, the NWA was promulgated in 1998. The mandate of the DWAF SEA team was, therefore, broadened to strategically assess water use of the environment (sustainability criteria), society (equity requirement) and the economy (efficiency criteria) in a way which may assist water resource managers to meet the objective of managing water resources in the most equitable, efficient and sustainable manner. The main purpose of the DWAF SEA team is to develop and test a replicable, participatory and affordable methodology and to for incorporating SEA into decision-making regarding water use within Water Management Areas (WMAs) and individual catchments.

A number of challenges face the successful undertaking of a SEA, including:

- South Africa has been divided into 19 WMAs, which are each governed by a Catchment Management Agency (CMA). Each WMA will probably require an SEA, which needs to be undertaken as soon as possible. The DWAF SEA does not have the capacity to meet this challenge. It has been decided that the DWAF SEA team will document the SEA process to be undertaken and will develop tools and methodologies to assist the multi-disciplinary SEA approach, which will then be made available to the WMAs as guidelines. The CMAs will be responsible for undertaking the SEA process themselves in consultation with the DWAF SEA team using the tools and guidelines provided by the DWAF SEA.
- The challenge of the SEA is to not only provide information regarding individual disciplines (the economy, the environment and society), but rather to provide integrated information (e.g. hydro-economic, socio-economic, environmental economic information). Tools, such as models, may need to be developed to generate the required multi-disciplinary information.
- The multi-disciplinary data may be required from a number of disciplines, as well as from a number of state departments (e.g. DWAF, DOA, DEA). The systems in which the required data are stored often differ. Sometimes a number of departments have access to the same type of data; however, the quality of the

data differs. In other words, a large amount of time is spent obtaining and checking the data.

The objectives of this project include to
- identify the information and data requirements for the DSS;
- review the current hydrological modelling methodology used by DWAF which includes
  - identifying weaknesses in the current approach; and
  - formulating a new hydrological modelling methodology to realise a strategy whereby the SEA principles and practice are put in to place to support the implementation of the NWA;
- assess the development of a SEA database, in which data/information relevant to an SEA is
  - drawn from other state databases;
  - generated from SEA developed tools/models; and
  - generated from discussions with stakeholders, water resource managers and other government departments.

  The assessment includes a scrutiny of the databases currently used in DWAF, as well as the databases available internationally. The assessment of the database is undertaken giving consideration to the type of information required by the SEA;
- assess the development of a hydrologically focussed scenario generator, in which the database is seamlessly integrated with the ACRU hydrological model. The scenario generator is to be developed in ArcView (a GIS package) that allows the easy generation of selected water supply and water demand scenarios that are consistent with the NWA. The focus of the hydrological modelling is the generation of water quantity information; and
- assess the types of water quality related issues that may need to be included into the hydrological modelling application (either by further developing ACRU, or by linked another hydrological model/s to the database).

Therefore, the main objective of this project is to select a suitable database structure to be used by the SEA to store the multi-disciplinary information. The second objective is to develop an application for use with the database that automatically draws off the information from the database and writes the results back to the database.

The database linked to suitable applications is seen as the Decision Support system (DSS). Thus, the DSS consists of a number of applications feeding off, and writing to, a central database. No one tool or model is thus seen as the DSS, but rather the combination of all tools with the database.

The reason for developing the DSS is that it can be handed down to WMAs with the SEA guidelines. In this way, SEAs of a high quality may be undertaken throughout the country, with guidance by the DWAF SEA team. It also allows a consistent and transparent approach to be adopted in South Africa.

The success of a specific DSS is dependent on its ability to solve the problem it is trying to address, at the scale required and the extent to which it can support the decision making process. In the context of this review the DSS will be analysed in their ability to support the SEA in its objective of developing an overall framework approach to ensure South Africa's water resources are utilised optimally in the short and long term to the best benefit of the people and environment of South Africa.

The philosophy used in tackling this document in not how the current set of modelling tools and methodologies can service the needs of the NWA, but rather a more rounded perspective of what tools and methodologies need to be put into place in order to service the water resource use and management community in implementing the NWA.

2. WHAT IS MEANT BY DECISION SUPPORT SYSTEM?

There are a broad variety of frameworks, protocols, processes, methods, tools and models, that have been defined as Decision Support Systems (DSSs) for integrated water resource management in South Africa and around the world (Stewart *et al*., 2000).

Each DSS is specifically designed to provide the decision maker with a set of information that will enhance their decision-making capabilities. Most DSSs are therefore designed around the problem they are trying to solve, the concern they are attempting to address or the question they wish to answer and only represent a small subsection of the overall generic decision-making process.

The purpose of a DSS is, therefore, a function of

- the type of concern, problem or question being addressed; and
- the scale at which the solution needs to be met.

The success of a specific DSS is therefore dependent on its ability to solve the problem it is being used to address at the required scale and the extent to which it can support the decision making process. It is therefore crucial when designing any DSS to define the needs that the user is trying to fulfil at the scale at which the solution / solutions need to be addressed.

In the context of this review the DSS will be analysed in its ability to support the SEA in its objective of developing an overall framework approach to ensure South Africa's water resources are utilised optimally in the short and long term to the best benefit of the people and environment of South Africa.

The main objective of the DWAF SEA team is to develop and test a replicable, participatory and affordable methodology for incorporating strategic environmental assessment into decision-making regarding water use at a National scale, scale of WMA and a local area scale. In this project the definition of a decision support system will be formulated in terms of a system that will provide the information required to service water managers at the Catchment Management Agency (CMA) level in terms of the NWA established in 1998. The CMA scale was chosen because of the challenges faced at an operational level in Water Management Areas (WMAs) in order to meet the requirements of Section 27 of the NWA (1998). It is also possible to use the techniques developed at the lower scale to produce information that can be aggregated and summarised and used in decision making at a higher level within DWAF and other state institutions. The DSS proposed in this document attempts to address the criteria laid out in S27. The provisions in S27 have influenced the design of the proposed SEA DSS.

Stewart *et al.* (2000) have suggested that the following stages, processes and activities represent the generic decision-making process:

- Acquiring of information
- Problem structuring
    - Providing a framework
    - Identification of alternatives, criteria, stakeholders and constraints
    - Supporting the participation of stakeholders

    - Supporting the inclusion of societal values, tangible, intangible, qualitative and quantitative
    - Supporting the process of obtaining and including necessary data and information
- Evaluation of and choosing between alternatives
    - Visualisation
    - Ranking and scoring (aggregation, integration, discussion)
    - Supporting the trade off process
- Making provisional decisions

Jewitt and Görgens (2000) looked at DSSs from an ICM perspective where they defined DSSs as computer based information systems, where tools representing an extensive set of capabilities are integrated to provide decision support to managers and stakeholders. In order for such computer based tools / systems to provide realistic and useful information they need to combine several sources of information or databases, more than one problem representation or model and a multifaceted and problem orientated user interface, in a common framework. Jewitt and Görgens (2000) identified the large number of definitions of DSSs and, hence for the purpose of their project, DSSs are considered as software systems that facilitate management through the integration of three types of information, namely

- information on the state of the environmental system (data);
- modelling (simulations) of that system; and
- evaluation of different scenarios/plans.

Figure 1 is a representation of the combined definition of the decision making process outlined by Stewart *et al*. (2000) and the definition of a DSS according to that of Jewitt and Görgens (2000). In this document Figure 1 will be used to as the framework upon which the DSS to support the SEA in the implementation of the New NWA (1998) will be designed.

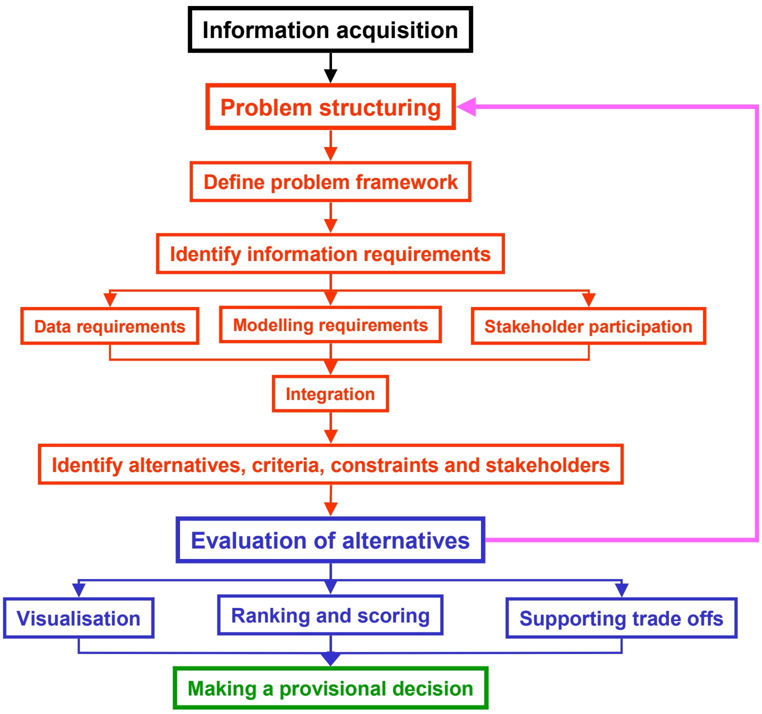

Figure 1 Schematic representation of the decision making process (adapted from Jewitt and Görgens, 2000 and Stewart *et al*., 2000)

3. DSS DESIGNED TO SUPPORT THE SEA IN IMPLEMENTING THE NATIONAL WATER ACT (1998)

As previously mentioned it is necessary to define the problem framework within which a DSS has to work to support the decision making process. In terms of the DSS design proposed in this document, an attempt will be made to support SEA in implementing the NWA (1998). For the purpose of this document a DSS will be defined as a system consisting of a set of tools that will enable Catchment Management Agencies (CMAs) to develop their Catchment Management Strategy (CMS) and accordingly assess individual licensing applications taking into account the equity, efficiency and sustainability criteria set out in the NWA (1998).

In undertaking an SEA in terms of the NWA (1998), consideration needs to be given to the impact and dependencies of water use by a number of water-using activities from various perspectives, including socio-economic and environmental considerations. It is from this perspective that the decision making process will be analysed in the development of a DSS.

In the following sections the processes of

- information acquisition (Section 4);
- problem structuring which includes the information, modelling, data and database requirements to establish a DSS for the DWAF SEA team (Sections 5 to 7);
- establishing a scenario generator to integrate the models used in the DSS with the database available (Section 8); and
- displaying and assessing information using the DSS (Section 9) are discussed.

4. INFORMATION ACQUISITION

There are two areas of information acquisition in the decision making process. The initial phase of information acquisition is structured around the problem identification and is essentially the information required to identify the problem that the DSS will need to support (cf. Figure 1). The second phase of information acquisition falls within the problem-structuring phase of decision-making process and is the information required to help the decision maker in formulating a decision.

The information required to define the problem in this study was obtained from the NWA (1998) and the SEA principals and practice. In this project it is necessary to identify the generic decisions supported by the DSS in order to create the computer software necessary to fulfil these needs. In terms of the SEA, the generic level has already been defined as a DSS needed to support the CMAs in developing their CMS and assessing individual licensing applications.

In the initial phase of information acquisition it is also necessary for the users of the DSS to identify specific problem areas in the catchment under investigation and include these in the scenarios that will need to be tested using the DSS. The information collected in this phase could be demographic data and developmental goals for the region as well as planned projects. Public surveys could also be carried out to identify pressing needs and concern within communities in the region. Environmental organisations could also be approached to identify some of the more critical environmental concerns that could exist in the catchment. These aspects could hence be structured in the decision making process which would be supported by the DSS.

Information acquisition in the initial phase is extremely broad and leads to development of scenarios that will need testing. As each catchment will have unique problems that need to be addressed it is not in the scope of this project to identify all the different possibilities that could exist in any catchment. In the design phase it is necessary to identify the majority of generic issues that will need to be addressed by CMAs and provide a framework to support the decisions that they will need to make.

5. PROBLEM STRUCTURING

In the problem structuring phase of the decision support framework, three main steps need to be followed (cf. red boxes in Figure 1 as shown in Figure 2), namely to

- define the problem framework;
- identify the information requirements; and
- identify alternatives, criteria, constraints and stakeholders.

The context in which the DSS has to perform has already been defined as providing a framework to support the CMA in setting up and implementing their CMS. The problem is thus structured around two different dimensions, which are

- the planning dimension; and
- the implementation dimension.

In providing the problem structure it is necessary to define the problem framework from these two different dimensions. The alternatives, criteria, constraints, stakeholders and information requirements can thus be deduced once the problem framework has been defined.

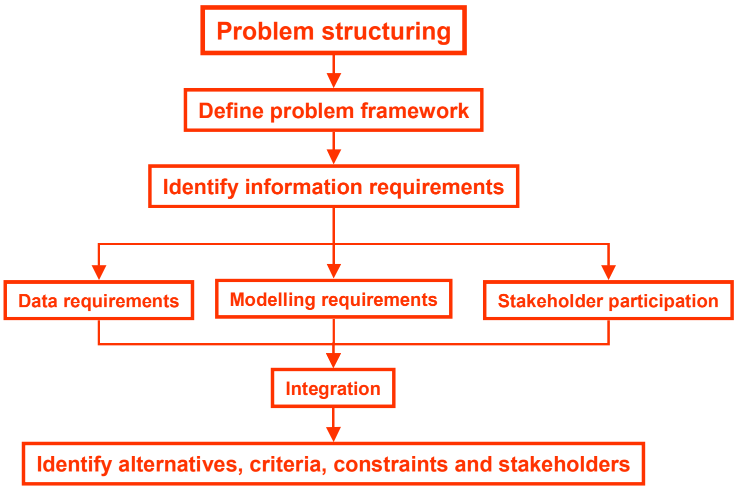

Figure 2 The problem structuring phase of the decision support framework

6. DEFINING THE PROBLEM

In defining the problem framework it is necessary to outline the responsibilities of the CMAs as the DSS is being designed to support the activities associated with CMAs. In terms of the 1998 NWA, CMAs are responsible for the development and implementation of the CMS as shown in Figure 3.

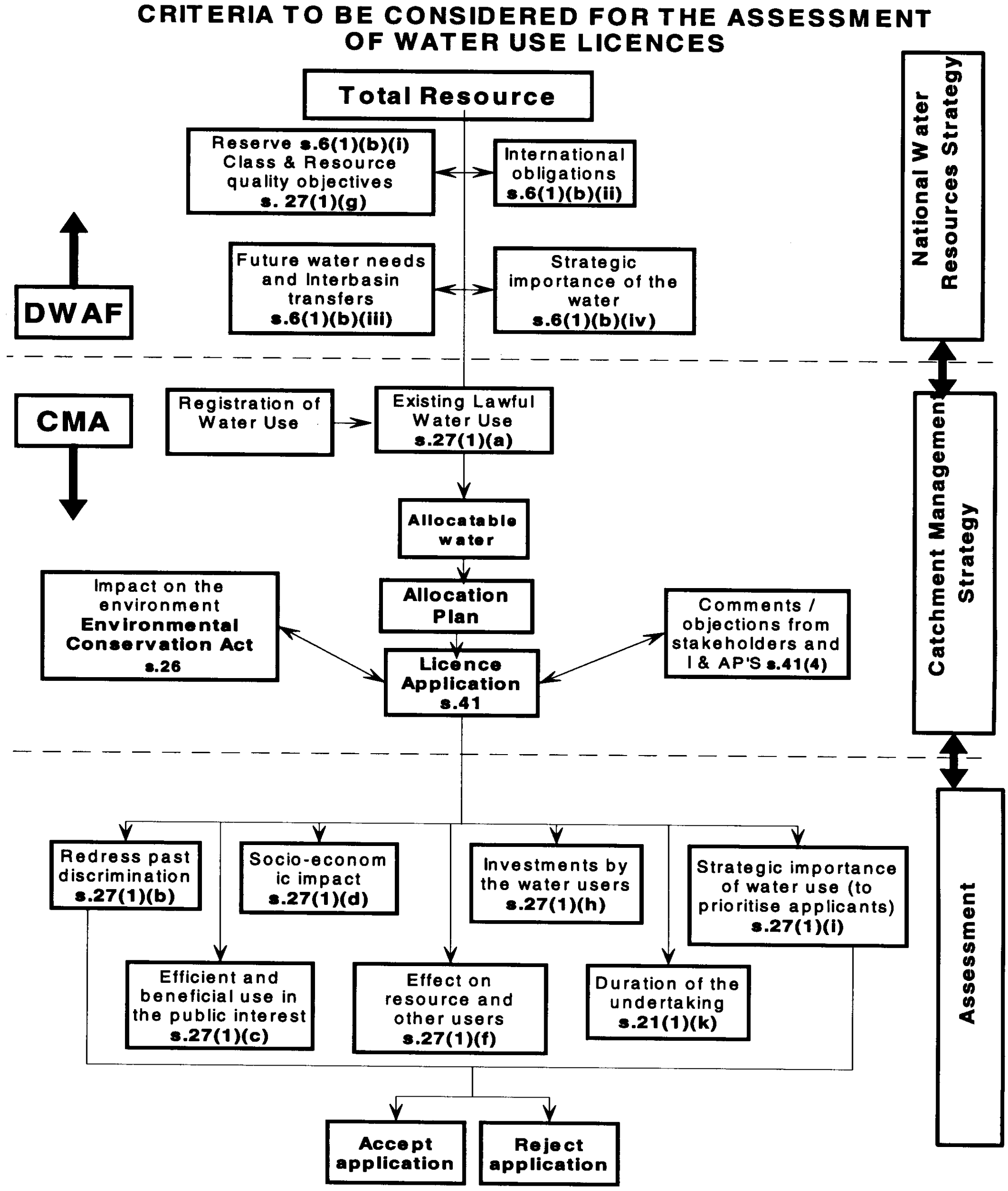

Figure 3 Criteria to be considered for the assessment of water use licenses

A CMS must set principles for allocating water to existing and prospective users, taking into account all matters relevant to the protection, use, development, conservation, management and control of water resources (NWA, 1998). The CMS must be in agreement with the National Water Resource Strategy (NWRS). In the process of developing this strategy the CMA must seek co-operation and agreement on water related matters from the various stakeholders and interested persons.

CMAs are responsible for the allocation, registration and licensing of water users. According to the NWA (1998) all water uses must be licensed "unless it is listed under schedule 1, is an existing water lawful use, is permissible under a general authorisation or if a responsible authority waves the need for a license". When allocating water and issuing water licenses the CMA needs to take into account the following factors (Section 27 of the NWA, 1998):

- Whether it is an existing lawful water use
- The need to redress the results of past racial and gender discrimination
- Efficient and beneficial use of water in the public interest
- The socio economic impact of
  - water use or uses if authorised; and
  - the failure to authorise the water use or users
- The likely effect of the water use to be authorised on the water resource and on other water users
- The class and the resource quality objectives of the water resource
- Strategic importance of the water use in question
- Water quality objectives and international obligations.

The CMAs are therefore responsible for both longer term planning for the WMAs and the short term processing of individual water licensing applications.

In developing the CMS, the CMA must formulate water allocation plans that contain strategies around water allocation, with the objectives and guidelines associated with such strategies. The CMA, then needs to formulate procedures required to implement the allocation plan set out in the CMS as set out in Figure 3.

The CMA must conform to the guidelines provided in the NWRS in terms of

- reserve class and resource quality objectives;
- international obligations;
- future water needs and inter basin transfers; and
- water use for strategic importance.

It is also necessary for the CMA to take into account any other plans from other institutions which may be directly or indirectly associated to the water sector. Hence, the CMA must, when developing and implementing its strategy, foster the development of cooperative governance.

The CMA is also responsible for the implementation of the CMS as well as the assessment of individual license applications. When assessing individual license applications it is necessary for the CMA to take into account all the aspects outlined in Section 27 of the NWA (1998), which has been outlined previously.

When making a decision on individual license applications the representatives of the CMA need to consider the following aspects before the issue of the license:

- Ensure that the license application is in line with the NWRS and the CMS in terms of; reserve classification, international obligations, strategic water use and future water needs and inter basin transfers.
- Ensure that the license takes into account all the aspects outlined in Section 27 of the NWA (1998).

In defining the problem framework, the information requirements of decision makers can be deduced in terms of both the relevant information needs and the scale at which the information is required. Information can hence be broken down into three different levels in terms of base data requirements, modelling requirements and stakeholder participation. In the next section the information requirements to set up the CMS and assess individual license applications are outlined.

7. INFORMATION REQUIREMENTS

In the assessment of information requirements two different levels will be considered, namely

- to set up the Catchment Management Strategy (CMS), and
- to assess individual license applications.

7.1 Information Required To Set Up a Catchment Management Strategy

The central focus of any CMS developed by a CMA is the water allocation plan. In order to develop a CMS, and consequently the water allocation plan, the CMA must first determine the allocatable quantity of water available in the WMA. The allocatable quantity of water could perhaps be defined as the amount of water available for use within a particular catchment or area at a certain level of risk. It is also necessary within the allocation plan to take into account the future water demand and constraints that may limit development. Therefore, when formulating the allocation plan, water managers need information on

- allocatable quantity of water;
- projected demands; and
- developmental constraints as shown in Figure 4.

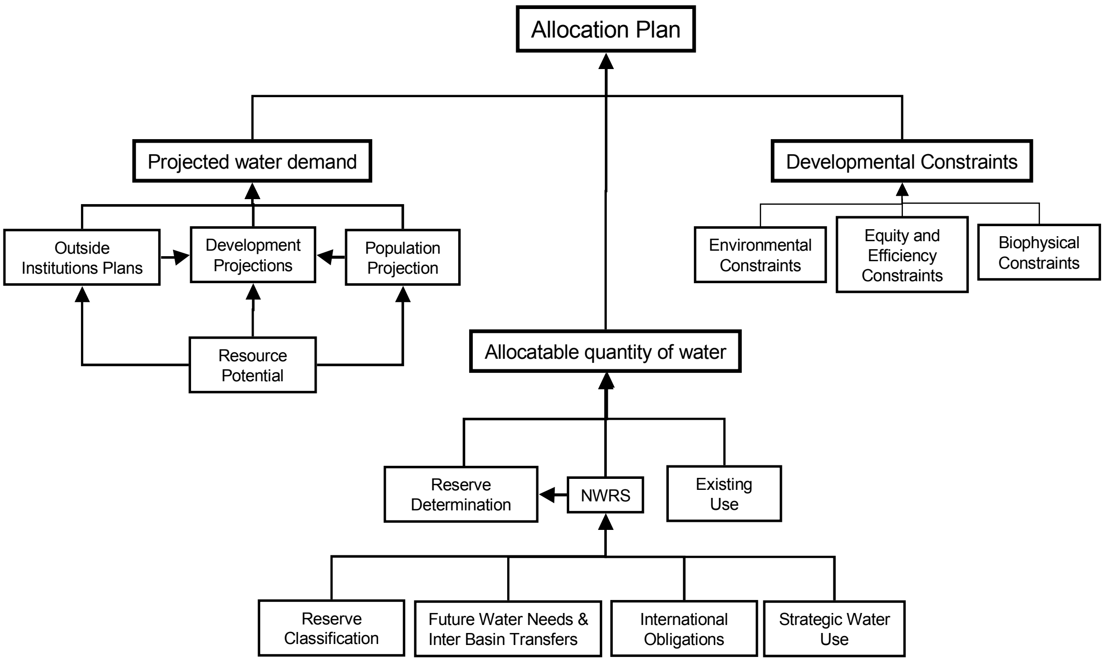

Figure 4 Considerations and information requirements needed for the development of a catchment allocation plan

➢ **Allocatable quantity of water**

To determine the allocatable quantity of water within a particular area, the CMA must first take into account criteria set out in the NWRS. Hence, before any water can be allocated to specific users the CMA must set aside specific quantities of water to fulfil the reserve quantity and quality requirements, international obligations, water users of strategic importance and future water needs and inter basin transfers set out in the NWRS. Once these have been taken into account, it is necessary to determine the actual level of water use in the catchment by different water users. In this regard an initiative is currently underway whereby all water users must register their water use.

For any CMA to institute a practical allocation plan it is necessary for the paper water to correspond to real water. This means that not only is accurate information on current water use required but that the modelling of such systems needs to reflect the reality in terms of both the temporal and spatial scale that water use is operated at and decisions are made.

The reserve is perhaps the most fundamental aspect of allocatable water determination. The reserve determination has implications for both the sustainability criteria and equity criteria in the NWA (1998) and, hence, deserves special mention in this analysis.

The reserve is defined as the quantity and quality of water required for basic human needs, as well as the quantity and quality of water required to sustain the aquatic ecosystem. The basic human needs reserve provides for the essential needs of individuals served by the water resource and includes water for drinking, for food preparation and for personal hygiene (NWA, 1998). The basic human needs reserve is essentially a function of the population and could be determined on an annual basis in the course estimate required for the implementation of the NWRS.

The ecological reserve is essentially the quantity and quality of water required to ensure that rivers, estuaries, wetlands and aquifers are sustained in a predetermined condition (Hughes, 1999). The predetermined condition is referred to as the Environmental Management Class (EMC) and is associated with the amount that the required condition varies from the natural or pristine condition. There are four main classes (A to D), where A refers to a condition that is mostly natural, while D refers to a condition that is highly modified where there is large loss of natural habitat, biota and ecosystem functioning (Hughes, 1999). It is essentially the responsibility of DWAF, with stakeholder participation, through the authority of the Minister of Water Affairs to determine EMC for a specific water body.

While it is the responsibility of DWAF to classify the resource according to its EMC the estimation of the reserve at a national level is an enormous task and, hence, a simplified version needs to be instituted for the NWRS. Owing to the coarse level of information required in the NWRS it would be acceptable to determine the water quality and quantity requirements (Environmental Flow Requirements) at an annual level. The onus would then fall on the CMAs as part of the CMS to perform a more detailed investigation of the environmental flow requirements, which conform, to the estimates and classification determined in the NWRS.

While the basic human need remains relatively constant, the environmental reserve fluctuates on a daily basis in some cases on a sub daily basis. In order to implement the reserve at a catchment and sub-catchment level the CMA will need water quantity and quality information on at least a daily basis from both its modelling and monitoring systems.

Allocatable quantity of water is often determined by means of systems yield, which is the amount of water that a catchment system is able to supply at a certain risk of failure. In terms of water availability in modelling the system the CMA may need more detailed information than just the systems yield as it may be critical to determine water availability at different points in the catchment. Hence, information is required for both individual and potential users as well as the system as a whole.

- **Projected Water Demands**

In order to develop a CMS and its associated allocation plan the CMA needs information on projected water demands in different sectors of the economy. Water demands are influenced by population and development trends, which are in turn influenced by socio-economic factors acting within and on the WMA. The demand projections are also influenced by the institutional arrangements in the WMA.

In assessing potential projected water demands it is important for the CMA to take into account outside institutional developments and it is hence necessary for the CMA to foster co-operative governance relationships with other government departments and parastatal organisations. Consultation with stakeholders is also essential in determining developmental plans.

Demographic information is needed to assess population trends. Population trends affect both the basic human needs reserve as well as developmental water demands within a WMA.

Socio-economic factors influence industrial, commercial and agricultural development in a WMA. These factors, combined with population dynamics, influence the quantity and distribution of water demand. Resource potential is on of the major overriding factors that will limit population growth and development in South Africa. Hence, information on the resource potential is critical in determining the water demand in a particular WMA.

- **Developmental constraints**

Developmental constraints are aspects that will restrict development in certain areas. These consist of environmental constraints that include conservation areas such as game parks as well as areas of high biodiversity. In such cases the loss of such areas could cause irreversible damage within the catchment area and significantly impact the sustainability.

The resource potential is another major constraint, where in the case of agriculture and forestry the biophysical potential of the area has a major impact on the types of crops that can be grown in particular areas. Resource potential is also limiting in other primary activities such as mining where the distribution of mineral deposits is a major limiting factor.

Other constraints that may inhibit development are infra-structural constraints such as access to efficient transport routes. Distance can also be a major constraint where distance from markets or mills can significantly increase transport costs and impacting on the economic viability of specific enterprises.

The equity, efficiency and sustainability criteria set out in the NWA (1998) can place major constraints on development. In terms of equity certain developments may only take place once the discrimination of the past has been redressed. The efficient, beneficial use of water is another factor that needs to be considered in undertaking a project or proposed development and can have a major impact on development if a water use is considered inefficient.

7.2 Information Required To Assess Individual License Applications

In terms of individual licenses the CMA needs to assess the following main criteria before it can issue a license:

- Is the application in compliance with the CMS and the NWRS?
- Does it fulfil the equity, efficiency and sustainability criteria set out in the NWA (1998)?
- Is the impact on other users, the water resource and the environment acceptable?

Each of these criteria is dealt with in more detail in the following sections.

- **Is the application in compliance with the CMS and the NWRS?**

The CMA water manager reviewing the various license applications needs to assess if the water license in question is in line with the both the NWRS and the CMS. Before issuing water use licenses the CMS and the NWRS should have been developed and the necessary information will be passed down to water resource managers assessing the licenses.

The CMS, which must be in compliance with the NWRS, should allow the manager to assess the license in terms of the following criteria set out in Section 27 of the NWA (1998), namely

- the class and resource quality objectives of the water resource;
- the strategic importance of the water use in question; and
- the water quality objectives and international obligations.

The information required to assess the licenses in terms of these criteria is therefore the same as those needed to develop the CMS, which has been discussed in Section 7.1 of this document.

- **Does it fulfil the equity, efficiency and sustainability criteria set out in the NWA (1998)?**

In addressing this question two aspects in Section 27 of the NWA (1998) are addressed which are

- the need to redress the results of past racial and gender discrimination; and
- the efficient and beneficial use of water in the public interest.

To assess the equity criteria, in terms of redressing the results of past racial and gender discrimination, information on the existing status quo in terms of catchment water use is needed. This aspect is already being addressed through the water registration process where all water users are being registered with the WARMS system. This aspect should also be provided for in the CMS to some extent, as certain developmental plans will already incorporate the redressing of past racial discrimination. The information requirements for this type of decision consist of socio-economic information as well as hydrological information in terms of actual and projected water use.

The efficient, beneficial use of water in the public interest incorporates both the efficiency and sustainability criteria. In order to determine efficient water use both hydrological and economic information are required. Efficiencies can then be determined in terms of the economic return per unit of water used. Feed forwards and feedbacks in the economy need to be taken into account when assessing the economic returns and also lead to a better assessment of the beneficial use of water.

Beneficial use of water has not only an economic implication, but social and environmental implications too. The water use needs to be sustainable so as not to reduce the water resource carrying capacity and reduce the resource potential thereby having a negative impact in the long term on society. Social impacts of water use also need to be considered in terms of jobs created and benefit to communities as a whole. Social, economic and environmental information are required to assess the efficient and beneficial use of water.

➢ **Is the impact on other users, the water resource and the environment acceptable?**

The impact information required by the water manager in a CMA is outlined in two different aspects of Section 27 of NWA, namely

- the socio-economic impact of
    - water use or uses in authorised; and
    - the failure to authorise the water use or users; and
- the likely effect of the water user to be authorised on the water resource and on other water users.

Modelling is thus required to provide social, economic, hydrological and environmental information to estimate the impact of a particular development might have. The modelling could consist of a suite of models that can take into consideration both hydrological impacts in terms of both quantity and quality, as well as social, economic and environmental impacts. The scale of information required would need to reflect the operations and decision framework of the development being considered and will need to be at least on a daily scale in terms of hydrology to get a accurate assessment of the water quantity and quality impacts. The next section addresses the modelling requirements for a DSS to support the CMS of a CMA.

7.3 Modelling Requirements

Our philosophy in tackling this document is not how the current set of modelling tools and methodologies can service the needs of the NWA (1998), but rather a more rounded perspective of what tools and methodologies need to be put into place in order to service the water resource use and management community in implementing the NWA.

Models are usually structured collections of physical laws and empirical observations written in mathematical terminology and combined in such a way as to produce a set of results based on a set of known and / or assumed conditions. In hydrology, such models are applied as real world decision tools in the planning, design and operation of hydrologically related systems and structures.

In the context of the DSS design being reviewed in this document the information requirements for both the development of the CMS and the actual assessment of license applications are the driving force behind the modelling requirements. Owing to the high level of stakeholder participation required by the NWA (1998) there are several generic model requirements needed to foster communication and understanding in the stakeholder community. These factors thus need to be discussed over and above the more technical modelling requirements needed to provide information for the CMS and licensing applications.

7.3.1 Generic modelling requirements needed to foster stakeholder interaction

Models are useful in generating information about the water resource systems so that options can be considered and decisions taken to manage the resource and resolve conflict. In the NWA (1998) there is a strong emphasis on stakeholder participation and indeed a CMA is comprised of members representing different stakeholder groups. The process of developing allocation plans and allocating water to different individuals has become not only a scientific but also a social process. This aspect places new demands on models and tools used in the decision making process. Information generated from models now needs to gain the trust of the stakeholder community in order to be accepted in decision making.

Information generated from the modelling process will need to be *credible, trusted*, and *promote shared understanding* (Dent, 1999). "This in turn could promote *transparency* in the modelling and decision making process leading to the *acceptance of decision* and a *shared understanding* of their consequences" *(*Dent, 1999).

The processes, which yield this type of information, need to be replicable and consistent, offering regular, affordable and meaningful communication among stakeholders and their representatives. The processes should be open and transparent enabling implicit assumptions and mental models to be made more explicit. Processes and models used need to overcome the barriers to communication between stakeholders, which arise from geographic, disciplinary and institutional / organisational separation. While these are the generic requirements that all modelling tools need to fulfil, the next section will concentrate on more specific modelling requirements of a DSS required to fulfil the objectives of the SEA in helping CMAs develop and implement a CMS.

7.3.2 Modelling requirements in the DSS designed to support the CMA

To set up an allocation plan several different levels of information are required. While the majority of the information required is in the form of raw data, such as landuse, water use, demographic information and biodiversity data (as described in Section 7.5), some information needs to be generated with the use of models, particularly in the case where planning projections are needed to expand beyond the catchments or WMAs current status.

While the discussion in this document is on a complete system concentrating on incorporating SEA principals and practice into CMAs the focus of this research is on the hydrological and economic components and while modelling requirements in terms of other aspects such as social and environmental will be mentioned the main focus will concentrate on hydrological and economic modelling.

7.3.3 Modelling requirements to assist in compiling the CMS and associated allocation plan

The initial focus on developing a CMS and associated allocation plans is to determine the allocatable quantity of water. In order to perform this function it is necessary to determine

- the reserve estimate in terms of quantity and quality; and
- current water use status in the catchment in the catchment.

A complete allocation plan, however, must include projections on water demands into the future and prediction on how these demands are influenced by physical, environmental and social constraints. In the following sections a description of the modelling requirements needed to determine the allocatable quantity of water will be presented followed by those requirements needed to provide for future water demand projections.

➢ **Reserve estimation**

The modelling requirements in terms of estimating the reserve are rather rigorous as the detail of the information required is high. While the information passed down from the NWRS in terms of reserve classification need not be rigorously defined, the information needed to implement the reserve needs to be far more detailed. For the purpose of implementing and determining the reserve water quality and quantity information is required on at least a daily basis and at a sub Quaternary Catchment scale. It is also necessary to estimate both the water quantity and quality from present conditions as well as those that would have occurred under relatively pristine conditions (Acocks' Veld Types or naturalised flows).

Models are also required to perform in a data poor environment where lack of streamflow data at gauging weirs is a major constraint in terms of model verification. This means that calibration modelling is not a viable alternative due to lack of gauging stations, while physically based process rainfall runoff modelling is able to provide both more reliable inputs at ungauged sites and for pristine conditions. Modelling needs to be able to incorporate operational hydrology to simulate the operating conditions in the catchment and will help in developing a strategy to implement and maintain the reserve.

The hydrological modelling requirements to assess the reserve can be summarised as follows:

- Process based physical conceptual modelling
    - o Impact of LUMPs
        - SFRAs (Agricultural and alien invasives)
        - Irrigation
        - Urbanisation
    - o Flow sequences (Historical, naturalised, denaturalised, stormflow and baseflow) on at least daily time steps
- Water quality modelling (cf. Section 7.4)
    - o Point and non point
        - ▪ Erosion and sediment
        - ▪ Chemical and salts
- Operational systems modelling
    - o Water availability (yield)
        - ▪ System
        - ▪ Individual
    - o Operating rules and curtailments
        - ▪ Water abstractions (Bulk and IBTs)
        - ▪ Dams
- Scale
    - o Daily

- o Sub Quaternary Catchment

Other modelling requirements that fall outside the hydrological estimates will include models on ecological variables.

7.3.4 Current status of water use in the catchment

The NWRS sets aside certain quantities of useable water for specific needs such international obligations, strategic water user, future water needs and interbasin transfers. The development of the NWRS requires broad level information, which is currently being provided by the WSAM. This model provides estimates on a yearly basis, which for the purposes of a CMA are too broad and need to be used as guidelines in developing and implementing the CMS.

Before allocation plans can begin it is necessary to model the catchment at current level of development and determine from this the actual quantity of water currently being used in the WMA. The current water use and the information provided from the NWRS will allow the CMA to determine the actual quantity of allocatable water left in the catchment. If, as has occurred in some catchments in South Africa, the allocatable quantity of water is less than the actual water use, the catchment is considered stressed and water supply needs to be augmented or the water demand need to be adjusted in order to bring it in line with the supply.

In modelling the actual quantity of water being used in the catchment cognisance needs to be taken of land and water use activities that impact the water resource. The model / models must also be able to account for the operational framework within the WMA, which incorporates all the water supply and demand systems within the catchment and how they are managed. In the past the estimates of actual quantity of water used were established using calibration models and statistical relationships derived from experimental results. The systems were modelled on monthly basis using system optimisation models, which could generate large sequences of stochastic results.

While these modelling techniques give a reasonable estimate of water use in a catchment or WMA, with the advent of the NWA (1998) and the requirements of the reserve to be operated at a daily scale as well as the more rigorous requirements on users to use water beneficially and efficiently, the information and associated modelling requirements have become more detailed.

Physical process based modelling systems are able to simulate current and past landuse, able to produce naturalised and denaturalised flows directly. In estimating the operational hydrology it is also necessary to simulate water use and management at the level of operational decisions, which is often less than a monthly time step where decisions are made on a daily to weekly basis. Physical process based modelling also has the advantage of representing the system more explicitly while the assumptions and results from empirical modelling are not explicit leading to lack of transparency and decreased bargaining power.

The modelling requirements to determine current land and water use can be summarised as follows:

- Physical process based water quantity and quality models operating at daily time steps, and
- Operational models operating at daily to weekly time steps are needed.

7.3.5 Modelling projected water demands and developmental constraints

As has already been mentioned, the modelling of projected water demands requires demographic information, outside institutional plans, and developmental projections, which are inhibited by resource potential or have a direct impact on the resource potential. Developmental constraints include environmental constraints such as biodiversity value and conservation areas, biophysical constraints such as carrying capacity and production potential and social constraints such as equity considerations.

Development projections and demographic information can be obtained with simple population growth rate projection models which are superimposed over demographic trends in terms of rural urban migration patterns. Certain indicators could be used in collating population variables with water demands and industrial developments. In assessing outside institutional plans it is possible to identify specific areas of development and model the hydrological consequences. Hence, information on projected water demands can be determined from actual known consequences such as planned developments as well as projections connected with population growth and associated developments. All these factors are, however, limited by certain constraints and the resource potential.

Resource potential is essentially the potential that a natural resource has in supporting a specific type of activity. Resource potential in terms of agriculture is essentially a combination of different factors such as climate, altitude, slope and soils. Simple crop modelling could be combined with geographical information systems (GIS) to give estimates of biophysical landuse potentials. Yields from certain potential crops and livestock carrying capacity could also be modelled, which when combined with economic information will provide estimates of economic returns. Resource potential in terms of mining is a directly dependant on mineral deposit distributions, while certain industries may be constrained by lack of raw material in the near vicinity. These can all be mapped and determined combining simple modelling with GIS capabilities.

Constraints on the system, such as conservation areas and local zoning in terms of town planning, can once again be mapped using a GIS. Constraints, which may influence the economic viability of certain operations, such as distance from markets, and infrastructure can again be estimated using simplified algorithms combined with GIS data. Biodiversity values can also be calculated using a combination of indicators with different algorithms and GIS to map out areas of high and low biodiversity potential.

The hydrological impacts associated with the different water demand projections and landuse changes can be modelled using physical conceptual process based modelling systems where the system is not represented as empirical relationships but is represented explicitly as a set of physically based processes. The physically based hydrological modelling approach allows more flexibility in terms of planned scenarios as it can account for the unique and novel situations that arise. It is also necessary to incorporate operational systems modelling into the planning framework as it allows the modeller to assess the potential impacts of new and proposed schemes. Using the above approach future scenarios can be identified and built up and the interrelated hydrological, economic, social and environmental consequences can be identified.

In summary the modelling requirements associated with determining water demand projections are

- Geographic Information Systems;
- simple mathematical algorithms that use indicators to assess future water demand projections;
- processed based hydrological models to assess the impacts of different scenarios; and
- operational system hydrological modelling.

7.3.6 Modelling required for the assessment of individual license applications

In terms of assessing any license application it is necessary to account for the factors outlined in Section 27 of the NWA (1998). In addition, the application is required to be in line with the CMS and the NWRS and, therefore, the modelling requirements need to be at least as rigorous as those required to develop the CMS and NWRS. In terms of individual license application it is necessary to estimate the hydrological, economic, social and environmental consequences of issuing or not issuing a specific license. It is only once all these factors have been taken into account that the license can be issued.

To estimate the environmental consequences of the issuing or refusing of a particular license it is necessary to estimate the associated impacts on the reserve in both terms of water quantity and quality. In such cases, depending on the type of development, whether it is a water use or a land use, which is being changed, it is necessary to model these impacts in terms of the operational framework on the system as whole. In the case of landuse change a physical process based model is needed, as calibration and empirical statistical modelling cannot account for novel situations that occur as the result of testing different scenarios. It is also necessary to include modelling that is able to handle operational hydrology. This could include system optimisation models and other modelling systems that can more explicitly account for the operation of a system by specifically determining operating rules.

Impacts on other users can also be estimated by combining physically processed based models with operational modelling. The socio-economic impacts are, however, a little more difficult to estimate and require resource potential estimates and viability constraints in terms of transport and environmental, to be combined with hydrological modelling. The hydrological modelling in terms of the operational hydrology which includes all the impacts of structures and associated operating rules, needs to provide not only the impact of different land and water use options on the system as a whole but also needs to represent the impact on other individual users within the system.

The modelling requirements in terms of hydrological modelling for the assessing individual license application could be summarised as follows:

- Process hydrology
    - Impact of LUMPs
        - SFRAs (Agricultural and alien invasives)
        - Irrigation
        - Urbanisation
    - Flow sequences (Historical, naturalised, denaturalised, stormflow and baseflow) on at least daily time steps
- Operational hydrology
    - Water availability (yield)

        - System
        - Individual
    - Operating rules and curtailments
        - Water abstractions (Bulk and IBTs)
        - Dams
- Water quality modelling
    - Point and non point
        - Erosion and sediment
        - Chemical and salts
- Scale
    - Daily scale
    - Sub Quaternary Catchment
    - Water availability on system as well as on individuals.

Modelling requirements in terms of social and economic modelling could be summarised as follows:

- Economic values of various land and water use activities
    - GIS modelling
    - Crop modelling
    - Estimates of return
- Social values of different economic activities
    - GIS modelling
    - Demographic trend modelling
    - Regression and correlation modelling.

In the sections to follow several different models (both local and international) are analysed in terms of their ability to satisfy the above criteria. A brief discussion of the present approach used in water resources management in South Africa and some of the perceived shortcomings in this approach is initially provided. This is followed by a description of different hydrological water quantity models and the identification of their suitability in terms of the factors mentioned in the initial parts of the Section 7.3 and perceived shortcomings in each case. A summary table describing model suitability in terms of certain criteria specifically mentioned for this project will conclude the modelling section.

The discussion will begin with a review the current modelling methodologies used in water resource assessment.

7.3.7 Assessment of modelling methodologies currently used by DWAF

In the past in South Africa a “horses for courses” approach has been adopted in water resource management and practice. The belief being that specific water management and implementation tasks require information at specific levels of complexity, such tasks should then be supported by methods and models of a level of complexity and with data requirements that are at the appropriate level of the information required (Gorgens, 1999).

This philosophy has led to the use a multiple model approach where each specific model is designed to accomplish a certain task. The result is that when performing a water situation assessment a large array of different models are used with each performing a specific task. These models are then fed into each other using a series linking approach. A series linking approach takes the output from one model once it has completed running and feeds it into another model to execute some other function. The modelling methodology described in stepwise sequence below is a generalisation of the methodology used by many water situation assessment studies and is similar to the methodology currently being adopted on the Breede River. The methodology usually incorporates the following sequence with a set of different models being used.

- Assess the river flow gauging calibration for accuracy, assess the reliability of the records, and carry out gauge re-calibrations where required.
- Select riverflow gauges for model calibration purposes and configure and calibrate the Pitman monthly catchment model at each gauge. In such cases the WRSM90 or SHELL models are used.
- Obtain rainfall data for all stations in the study area, classify and infill these records based on suitable groupings and generate long term catchment rainfall records for catchments upstream of calibration points and points of interest.
- Use the calibrated model parameters to generate runoff sequences at all points of interest. Again the WRSM90 or SHELL models are used to achieve this.
- Produce naturalised and denaturalised monthly flow sequences taking into account the developmental influences in the catchments. To produce these results routines within the WRSM90 and SHELL model are used. SFRA activities and the effects of alien vegetation are taken into account using statistically derived curves.
- Generate stochastic hydrology for the system model and test the sequences generated for integrity. WRYM and its routines derived from GENMAC model are usually used in this component.
- Model the operational hydrology using the WRYM or WRPM. Yield estimates can be derived using both historical and stochastically generated flows.
- Disaggregate the monthly flow data where necessary to produce the daily flow sequences required for the IFR studies (this component was not included in older methodologies as the IFRs did not exist in the previous NWA).
- Determine flood flows at proposed dam sites for spillway sizing purposes and at IFR sites for IFR determination. The SCS model is used in some areas with a depth duration frequency analysis being performed in areas of reliable streamflow gauging.
- Water quality modelling is performed with the WRYM or with other models such as the WQT or DISA models, which use outputs from other models such as the WRYM, WRPM and SHELL.

While the multileveled, multidisciplinary, multi-model modelling approach does offer many advantages in choosing the level of detail which modelling can follow there has been some concern levelled at this particular approach in the international community. Mesarovic *et al*. (2000) express concern with following an integrated modelling approach which consists of developing models in different disciplines and linking them together without due regard to how much is known about the linkages. It could be suggested that an integrated model is only as good as its sub models. However, the problem of such an integrated modelling approach described above is not only with the models used but also lies in the linkages between the different sub models and their integration into the main overall model. Mesarovic *et al*. (2000) suggest that the while phenomenon within disciplines can be models with a degree of confidence, linking disciplinary models is highly conjectural. The series modelling approach in many ways ignores the linkages and can compromise the validity of results.

Added to this concern is the detail required in the implementation of the NWA (1998). Monthly modelling approach adopted by the Pitman – WRYM combinations may not offer the solutions required. While finer scale modelling may be too complicated for many of the tasks required, the upward aggregation of variables from, say, daily to monthly, is a more accurate technique than that of disaggregating monthly to daily flows where many inaccuracies can be introduced.

Some concern has been levelled at the use of finer resolution models for exercises that require less information such as scoping or broad level assessments. Data limitations are often seen as constraints that inhibit model accuracies, and reduce the accuracy of upward aggregation. While, these concerns are extremely valid they ignore the recent advances in technology, which in the fields of remote sensing technology, geographic information systems and database development, are increasing the accuracy and validity of data, needed to feed many finer resolution process physical based models.

While, data needed for calibration models (in particular streamflow measurements) are inhibiting the use of coarse resolution calibration models, data needed to drive physical process based models such as landuse and soils information are becoming increasingly more accessible and accurate, making the use of physical process based methodologies increasing more attractive.

Calibration and statistical methods such as those described above are also becoming less attractive as they tend to be black box approaches, which do not make the assumptions explicit. The result is that, in general, such modelling efforts are less likely to have credibility in the stakeholder community who may not be able to understand the results produced. Whereas physically based process models have more complicated algorithms and are generally more time consuming to set up, the inputs and outputs are generally easier to understand as they represent real world quantities. Calibration models and statistical methods are, in general, situation specific and the results are non transferable to other areas or novel situations. This means that the testing of different scenarios and extending deriving estimates at ungauged sites can result in large inaccuracies with the use of calibration and statistical methods. In the next section of this chapter a more detailed perspective of different local and international models is provided.

7.3.8 Assessment of models used by DWAF in terms of the DSS design

This review of models is not intended to be exhaustive but concentrates on the main hydrological water quantity models currently available and in use in South Africa.

- **Water Situation Assessment Model (WSAM)**

The Water Situation Assessment Model (WSAM), initially known as the Water Balance Model (WBM), was commissioned for development by the Directorate of Water Resource Planning of the Department of Water Affairs and Forestry. The model development started towards the end of 1997, with the conceptual phase, which focused mainly on the development of model algorithms (Watson *et al*., 1999).

A direct implication of the NWA (1998) for overall resource planning, requires the establishment of a National Water Resource Strategy (NWRS), which must be taken into account by each CMA in their future formulation of catchment management plans (Wolff-Piggott *et al*., 1999). It is in this context that WSAM was developed to fulfil the need for a long term planning tool that is able to provide information on the balance between supply and demand for given user defined scenarios at different area based levels (Watson *et al*., 1999). WSAM is now almost complete and this tool should support decision-making behind the development of the NWRS by integrating available information on present and projected water requirements, as well as availability, to indicate surplus and deficits on a per-catchment basis across the country (Wolff-Piggott *et al*., 1999).

In the application of WSAM, the developers own words should be headed. WSAM was designed from the onset as a broad planning tool only. It was never the intention to compete with complex models of water resource systems. WSAM's main function will always be to identify areas of water deficit before they occur and to test various options with relative ease, so that more promising options can be identified for further analysis.

WSAM is a broad level strategic model, where the processes are described on an annual basis and the algorithms are empirically derived using various statistical and calibration techniques. The water quantity assessments made using the model are too coarse to be used for individual licensing assessment and allocations plans set up by a CMA. Added to the coarse nature of the assessments are some concerns that could be raised with the method of gross yield accounting, which assumes a static description of the gross yield curves derived for each Quaternary Catchment in the South Africa.

In the words of the authors "gross yield is determined as a percentage of MAR using catchment specific storage-draft-frequency characteristics" (Schultz *et al*., 1999). This definition is based on the fact that a yield from a reservoir (or system of reservoirs) depends primarily upon the magnitude and degree of variability of the inflow stream, the storage capacity of the reservoir and the desired level of assurance of supply" (Watson *et al*., 2000). Again this is reiterated in the statement "the gross yield is sensitive to the variability and amount of flow as well as the size of the dam" (Schultz *et al*., 1999). As the gross yield curves are dependant on the magnitude and degree of variability, the assumption that the curves will not change, when structures or land uses that influence the variability such as dams and forestry are introduced into the catchment area, is highly questionable.

Added to this is the empirical nature of the methods derived. Although the model assumptions are made reasonably explicit, it could still be considered black box. It may, therefore, lack the credibility needed for it to be used as a tool by both water resource managers and stakeholders alike. The model does, however, offer many advantages in terms of broad assessment and its speed in processing makes it a reasonable tool to be used in a workshop environment. It should not be used as a tool for more intricate assessments such as the development of allocation plans and the assessment of individual licenses.

- **WRSM90 and SHELL (Monthly)**

The WRSM90 model was developed to facilitate the completion of the surface water resources of South Africa 1990 study (Middelton *et al*., 1993). The WRSM90 monthly model is a PC based model, which uses the monthly Pitman model (Pitman, 1973, as cited in Jewitt and Görgens, 2000) as its main rainfall / runoff producing function. The WRSM90 model also incorporates a number of routines that enable, on a monthly basis, the simulation of

- natural rainfall runoff processes;
- reservoir and farm dam balances;
- irrigation and other abstractions;
- landuse and return flows; and
- streamflow reductions due to afforestation.

The model is supported by a range of GUIs and has been linked to a GIS database containing hydro-meteorological data and landuse information. The model does allow the user to configure multi-catchments multi-reservoir flow systems as well as the varying some of the landuse impacts over time.

The SHELL modelling package was developed by Ninham Shand and is essentially an extension of the WRSM90 model and allows for easier calibration of the model (Berg *et al*., 1991). SHELL also uses the Pitman monthly model as its main rainfall / runoff model and can also simulate the same set of impacts listed in the WRSM90 model via the incorporation of several other routines. The SHELL modelling system does, however, include more components that are able to simulate a larger range of time varying human and landuse impacts. Some of the more notable additional components include

- the calculation of monthly time series of streamflow reduction by alien vegetation, based on the CSIR's biomass/streamflow reduction curves;
- calculation of alluvial bed transmission losses;
- allowing for the modelling of time varying landuse area sizes (e.g. afforested areas in catchments upstream of farm dams); and
- calculation of time series of irrigation water demands, allowing for changes in irrigation techniques and crop types.

The SHELL and WRYM models use the Pitman monthly model as their base flow generator. The Pitman monthly model is a calibration model and the results are not transferable to novel situations such as those produced at ungauged sites and in scenario generation. The models also use statistically derived quantities for modelling the use by alien vegetation and SFRAs. The models which are calibration and statistical are highly dependant on the modellers input variables, making the assumptions non explicit and it is essentially a black box modelling approach. This may result in lack of credibility and buy in from stakeholders, as there is a lack of consistency and transparency in the modelling.

Both these tools are relatively easily set up by the various model users. The estimates derived could be used for the broader planning issues in a catchment, and to gain an overall idea of the water resource situation. They may, however, not be adequate for the development of water allocation plans and the assessment of individual license applications.

- **Network simulation models**

There are two main network simulation models, which are commonly used in water resource analysis in South Africa are

- the Water Resources Yield Model (WRYM); and
- the Water Resources Planning Model (WRPM).

There are other models available in the world that perform similar functions, however, not many have been used in South Africa. In this section the MIKE BASIN network simulation model will be included, as it has been used in the modelling of the Umgeni Catchment system.

- **Water Resources Yield Model**

WRYM was designed to assess the long-term yield capabilities of a system for a given operating policy. The WRYM is a general, multi-purpose, multi-reservoir simulation program, which can be used to analyse a system at a constant development level where the systems demands remain constant throughout the simulation period. The WRYM has been set up as a current state model to incorporate the following processes:

- Naturalised streamflow
- Precipitation and evaporation associated with reservoirs
- Diffuse irrigation and afforestation demands from the various catchments
- Storage and releases from reservoirs
- Physical discharge controls at the outlets from reservoirs
- Specified inflows from adjacent subsystems on a monthly basis
- Water flow in channels (e.g. natural streams, power generation channels, hydropower releases, irrigation diversion channels, normal diversion channels, minimum flow channels, pumping channels)
- Losses in channels
- Aquifers

The WRYM model is capable of simulating a wide range of operating policies governing the allocation of water in a multi-purpose, multi-reservoir system. The WRYM model allows the user to define operating policies governing the allocation of water by altering the penalty structure associated with channels and reservoirs in the data sets used to run the model. The WRYM is based on the assumption that a flow network can represent a water resource system. The network can be analysed for each time period and solved using an efficient network solver (subset of linear programming techniques) with the careful selection of penalty structures. The network solver will solve a particular network problem using a minimum cost approach, where appropriate costs (penalty structures) are allocated to channels and reservoirs in such a manner as to define the relative "value" of water in each storage zone. The penalty structure is also selected to dictate the most attractive route (i.e. minimum penalty) for transferring the water from the storage zones to the demand centres.

❖ **Water Resources Planning Model**

The WRPM is more complex than the WRYM and was designed to carry out more detailed operating runs. The model is capable of modelling dynamic demands (increase over time) as well as changing system configurations. It can be used as a planning tool to assess the likely implementation dates of new schemes or resources and also as an operating tool to assist in the month-to-month operation of a system. It is based on the same optimisation techniques as the WRYM and uses penalty structures to route water through the system.

In lieu of the relatively short streamflow records available and the long critical periods associated with many reservoirs in South Africa, it was considered necessary to incorporate the capability of generating monthly stochastic streamflow sequences into the network simulation models WRYM and WRPM used in South Africa. The algorithms used in the GENMAC monthly stochastic streamflow simulation have been incorporated into both the WRYM and WRPM models. The routines used in the stochastic modelling of streamflow where originally developed by Pegram (1986) and when incorporated into the models can generate monthly stochastic streamflow simultaneously at up to 50 different inflow sites. The basic statistical properties of the historical streamflow sequences are maintained and the statistical cross correlations are preserved in the stochastic streamflow generation process (McKenzie and van Rooyen, 1997).

Both the WRYM and WRPM use monthly input although the WRPM can handle and use weekly data. The modelling technique used in both models is based on the penalty structure concept where the user attributes certain penalties (streamflow quantities or dam levels with a derived, usually arbitrary, relative cost associated with them) to different water users and dams in the system. The water is then routed through the system in terms of a least penalty concept. As the models are highly dependent on user defined penalty structures, which need to be defined relative to each other to describe the system operation properly, the models are extremely dependant on the users interpretation of the system. This means that the structure defined in the system can vary depending on the user and means that two different modellers could obtain extremely different results. This system leads to lack of transparency, consistency and credibility with the stakeholders.

The monthly estimates may be too coarse for those required by the CMA to develop the CMS and assess individual license applications. As the model requires monthly denaturalised or naturalised flow to generate the stochastic flow sequences a large amount of pre processing needs to be performed. The model results also require a large amount of post processing and are not in an easily translatable format (usually in the form of yield reliability curves). This again leads to lack of transparency.

Some concern has been raised about methods of testing the total system yield for failure. It is possible in the current structure of testing the model to have a failure in terms of individual demand while the system or sub system does not fail. This is due to the fact that the WRYM model works of a single main yield channel. It is hence possible that under particular circumstances the subsystem yield is satisfied while and individual demand linked to the main channel can fail (De Smidt *et al.*, 1993). This can lead to problems in the equity criteria and requires large amounts of post processing analysis as individual water availability is not tested automatically.

The WRYM and WRPM models are DOS based systems, which are difficult to configure and set up. An attempt has been made to improve the setup with a more user friendly interface known as SAWRAM for the WRYM. The assumptions made in setting the model up are highly subjective in terms of the penalty structures. The high amount of pre and post processing also make the model tedious to run and results difficult for stakeholder to accept.

- **MIKE BASIN**

MIKE BASIN is a network model, which provides a mathematical representation of the river basin encompassing the configuration of the main rivers and their tributaries, the hydrology of the basin in space and time as well as existing and potential major schemes and their various demands of water. Rivers and their main tributaries are represented by a network of branches and nodes; the branches represent individual stream sections while the nodes represent confluences, diversions, locations where certain water activities may occur, or important locations where model results are required (MIKE-BASIN, 2001). The model operates on the basis of a digitised river network generated directly on the computer screen in ArcView GIS.

Time series data of catchment constitute the basic input to the model, while additional input files define reservoir characteristics and operation rules of each reservoir, meteorological time series, and data pertinent to each water supply or irrigation scheme such as diversion requirements and return flows.

Model output comprises information on the performance of each individual reservoir and associated hydropower units, as well as other schemes with water demands, such as irrigation. For the entire simulation period, the magnitude can thus be illustrated. Moreover, time series of river flow at all nodes are simulated enabling the user to determine the combined impact of selected schemes on river flows. All results can be visualized in various formats, including animation.

The MIKE BASIN model also needs generated pre process flows to run. The time step used can vary from daily to monthly depending on the type of simulation required. The operating rules are explicitly defined attaching certain operating conditions to reservoir levels or river levels and not through the penalty structure system of the WRYM and WRPM. Stochastic flow generation operations are available and have been derived for South African conditions (Kjeldsen, 2001, personal comm.). The model setup is relatively easy with the GIS linked system with GUI. User-friendly GUIs make pre and post processing far quicker and user friendly. The explicitly defined operating rules make the system more transparent the WRYM and WRPM. The speed of processing also makes this system an attractive alternative. However, the purchasing costs are extremely high and could prove prohibitively expensive.

- **ACRU**

The ACRU modelling system (Schulze, 1995), established at the University of Natal, is a deterministically based, physical-conceptual model revolving around a daily time step water budget. Internal state variables (e.g. soil moisture), model components (e.g. interception) as well as end-product model output (e.g. streamflow or sediment yield) have been widely verified under different hydrological regimes in Africa, Europe and the Americas.

This is an integrated multi-purpose modelling system which can be applied to design hydrology, crop yield modelling, reservoir yield simulation, irrigation water demand/supply, water resources assessment, planning optimum water resource utilisation and resolving conflict demands on water resources. At present the ACRU model has the ability to model sediment yield from a catchment with new developments, however, new routines should include options for phosphorus, nitrate and operational hydrology modelling (Network simulation).

Daily climate data is used in ACRU; however, more cyclic, less sensitive variables such as temperature or reference potential evaporation can be entered on a monthly level if daily values are not available. Fourier Analysis transforms these monthly inputs to daily inputs. The soil water and runoff regimes in the model are structured to be highly sensitive to land cover / use change. A database of inputs to ACRU at a Quaternary Catchment scale is already in place, which can be used to run the model. This structure that has been set up enables experienced users to run the model relatively quickly by changing input information in the database.

The model has been designed to be a multi-level model with a hierarchy of alternatives possible in many of its routines depending on the level of input data available. The ACRU model is physically processed base, with inputs being defined explicitly in terms of land and water use information. The information is hence transparent and allows for stakeholder understanding, interaction and query. The parameters are locally developed and are suited to South African conditions. The new water quality and systems operation components being introduced into the model allow for more flexibility. The system does not however include the stochastic runoff generation and many of the components still need to be developed.

- **Hydrological Simulation Program Fortran (HSPF)**

HSPF is a model which consists of a set of modules arranged in a hierarchical structure, which permit the continuous simulation of a comprehensive range of hydrological and water quality processes (Bicknell *et al*., 1997).

HSPF is a multifunctional model, which incorporates a set of modules designed around features of the following models (Bicknell *et al*., 1997):

- LANDS subprogram of the Stanford Watershed Model (Crawford and Linsley, 1996)
- HSP (Hydrocomp, 1976)
- Non point source (NPS) model (Donigan and Crawford, 1976)
- Agricultural research model (ARM) (Donigan and Crawford, 1976), and
- SERATRA amongst others.

HSPF is more than a mere translation of the above models, as many of the modules have had extensions and modifications made to the algorithms in the course of accommodating them into the HSPF design framework. The modules are arranged in a hierarchical structure that enables the user to select the required modules to perform the simulations required.

The HSPF model is designed around a time series data management system. The sound data management component is designed to extract input data from the data management system and write output to the data management system with a minimum of user input. This system is designed to free modellers from becoming entangled in data manipulation, which would result in more time been spent on simulation work.

One of the major strengths of the model is its ability to simulate both water quantity and water quality providing a more integrated perspective of the catchment as a whole. The water quantity simulations include the ability to simulate both catchment hydrology and operational hydrology within a system. The model also has the ability to simulate water quality components on the land surface, in the river channel and in reservoirs, which it treats as simple mixed reactors. This integrated approach along with the data management facilities make the HSPF modelling system an extremely powerful tool, which could be used in water resources management.

The HSPF model is a parameter optimisation or calibration model in that it requires the model to be run repetitively to find the optimum value of its model parameters (Jewitt and Görgens, 2000). The model is able produce systems yield and other operational hydrological information such as water availability through the use of conditional special actions, which control user and reservoir operating rules. The calibration approach, however, means that the model cannot be used for scenario generation.

The model is extremely flexible and can operate with different time intervals ranging from seconds to years. It could be used with other process based models such as the ACRU model to produce a system that could handle most of the requirements of the DSS that have already been described. The problem is that many of the parameters are not suited or derived for local conditions and a large amount of translation of South African data is required to transform it into parameters suitable for use in the model. The time requirement to perform this transformation could prove to be prohibitive and the South African users would be tied in with USA needs and priorities in terms of further development.

- **Variable Time Interval model (VTI)**

The VTI (Variable Time Interval Model) (Hughes and Sami, 1994, as cited in Jewitt and Görgens, 2000) is an extended version of the single flood event model (OSE2) (Hughes, 1984; Hughes, 1989, as cited in Jewitt and Görgens, 2000), which has been adapted into a continuous time series model.

The model uses a variety of parameters. Some of these parameters have physical meaning, others are estimated from physical indices and some are completely empirical. The complexity of the model algorithms has been limited to prevent the models information requirements becoming too limiting. This model allows for simulation at a variable time interval according to user selected rainfall thresholds. The model is operated from within the HYMAS software package, which offers several support facilities for results analysis.

VTI uses a semi-distributed approach as opposed to a grid square or slope element. The model components are thus based on simulating the integrated response over sub-area, rather than at a representative point. As a result many of the functions are of a distribution type, where probability distributions represent the internal sub-area variation in hydrological processes. Two basic runoff generation methods are available; the one is dependent on rainfall intensity and the infiltration characteristics of the catchment soils, while the other depends on the dynamic moisture status of the catchment or sub-areas. A third runoff generation function allows for the simulation of groundwater baseflow.

No water quality constituents are simulated by the model, nor are any river channel transport processes. Only basic hydrological routing capabilities are offered. The VTI model has been reported as difficult to apply in cases where there is insufficient information on catchment physical characteristics. It has also been described as very empirical and difficult to calibrate when the processes involved are not well understood.

- **PRMS**

The Precipitation-Runoff Modelling System (PRMS) is a modular-design, deterministic, distributed-parameter modelling system developed to evaluate the impacts of various combinations of precipitation, climate and land use on streamflow, sediment yields and general basin hydrology. Basin response to normal and extreme rainfall and snowmelt can be simulated to evaluate changes in water balance relationships, flow regimes, flood peaks and volumes, soil-water relationships, sediment yields and ground water recharge. There is also a provision for parameter optimisation and sensitivity analysis within selected model parameters where both individual and joint effects on model output are evaluated. PRMS offers a flexible framework for continued model-system enhancement and hydrologic modelling research and development (USGS, 2001)

This is a useful physical process based hydrological model. There is, however, extremely little local expertise in the running of the model. The parameters are of a USA standard and would need to be transformed and tested in South Africa.

- **SWAT**

The Soil and Water Assessment Tool (SWAT) is river basin, or watershed, scale model developed for application in large, complex rural basins. SWAT is a continuous daily time-step model, which simulates the impacts of alternative land use management practices on surface and ground water, sediment and agricultural chemical yields in ungauged watersheds, over long periods of time. The model is capable of simulating hydrology, pesticide transport by runoff, percolate, and soil evaporation. In addition, SWAT allows for the simulation of nutrient cycling, erosion and sediment transport. Large river basins are subdivided into homogenous parts and each part is then analysed individually as well as its interaction with the whole.

The SWAT interface extracts spatially distributed parameters of elevation, land use, soil types and ground water table. The interface creates a number of input files for the basin and subbasins, including the subbasin routing structure file. Input consists of files, information from databases and information from a GIS interface. More specific information can be entered singly, for each area of the watershed as a whole. The SWAT-GIS linkage incorporates advanced visualization tools capable of statistical analysis of output data (Soil and Water Assessment Tool, 2001).

SWAT requires specific information about weather, soil properties and topography, vegetation and land management practices occurring in the watershed. The physical processes associated with water movement, sediment movement, crop growth, nutrient cycling and the like are directly modelled by SWAT using this input data. The benefits of this approach are that the relative impact of alternative impact data on water quality or other areas of interest can be quantified even in watersheds with no monitoring data (Arnold *et al*. 1993)

SWAT uses readily available inputs, is computationally efficient and enables users to study long-term impacts. A number of output files are generated by SWAT. The type of data stored in the file can group these files. Other than the standard output file, the files produced during a model run are formatted as spreadsheets to facilitate importation of the data into spreadsheet software.

The SWAT model is ideal for assessing land and water use impacts. It is a processed based model and requires easily understood input. The model was developed in the USA and there is some question as to its applicability to South African conditions. The model has been used by the CSIR to perform landuse impacts in South Africa. The model does not include operational hydrology and would need to be linked to a network simulation model to obtain yield and water availability estimates. It could be linked with models such as HSPF and MIKE BASINS to perform these components.

- **SAPWAT**

SAPWAT is a planning and management tool, which relies heavily on an extensive South African climate and crop database (SA Waterbulletin, 2000). One of the primary objectives of the SAPWAT development programme was to provide for the specific circumstances and requirements of emerging irrigation farmers and community gardens. The impact of irrigation practices and strategies on water budgets was an additional force driving the development of this model.

This model is general in its applicability, while it is able to simulate a variety of different management practices and irrigation methods. In addition, the effect of soil water management options such as deficit irrigation can be evaluated. SAPWAT also facilitates consultation and interaction with farmers and advisors.

SAPWAT is easy to apply from an operational point of view and demands minimum computer expertise (SA Waterbulletin, 2000). Moreover, this tool can be used in a variety of applications. SAPWAT principles have been recognised by the DWAF and incorporated in the irrigation inputs into the national water balance model. This model has also been indicated by the DWAF as the method for determining the annual irrigation requirement. "SAPWAT in the absence of general metering, enables all water use for irrigation to be quantified equally thereby ensuring a cost recovery in a fair and systematic manner" (SA Waterbulletin, 2000). The strength of SAPWAT lies in an extensive database that saves the user an enormous amount of time and effort. Furthermore, this model is designed to accommodate updated historic weather data to the present should the user require it. Although SAPWAT is not a real-time scheduling model it can be a valuable complement to instrumented soil water content methods.

The SAPWAT model is used to determine irrigated areas required demands and hence specify the allocations required by different users. It is not an overall catchment model and the model cannot estimate the impacts of a water use on other users within the catchment. If used with individual licensing applications it should be used in combination with other models that are able to determine impacts on specific users and the catchment as a whole.

7.3.9 Selection of hydrological model to use in DSS

In reviewing the different water quantity models available (Table 1) it was concluded that the new ACRU model, which is currently under development, fulfils the majority of the criteria required by the DSS. These include that is a physically based, daily time step model. Because the model is physically based it can test scenarios and be transferred to ungauged situations will reasonable confidence. The model is particularly suitable for land use impact studies. The daily resolution allows for IFRs which are assessed on a daily basis. The model needs to reflect the management level within the system where water users and water supply operators make decisions on daily to weekly time steps. The daily time step allows for the assessment of water quality issues, which can fluctuate on a daily and even sub-daily time step.

The new operational hydrological components currently being developed in the model allow for the assessment of different water use and water supply impacts. The model should be able to test the water availability yielded from the system as a whole as well as the water availability for individual users. The model has been developed under South African conditions and a pre-populated database exists for use with the Quaternary Catchments.

There have some questions raised in terms of the approach of using ACRU as the base hydrological model in the DSS. These questions are given in italics and responses to the questions follow each question:

Table 1 Summary table of the attributes of models used by DWAF

Model	Calibration or physically based	Operational hydrology	Water quantity modelling	System yield	Individual water availability	Water quality modelling	Finest temporal scale	Spatial scale	Trans-parency and credibility	Applicable to SA conditions	User friendly	Model under develop-ment
WSAM	Calibration	Limited	Yes	No	No	No	Annual	Catchment	Low	Yes	Yes	Yes
WRSM90	Calibration	No	Yes	No	No	No	Monthly	Catchment	Low	Yes	Yes	No
WRYM	Calibration	Yes	Yes	Yes	No	Limited	Monthly	System	Low	Yes	No	No
WRPM	Calibration	Yes	Yes	Yes	No	Limited	Monthly	System	Low	Yes	No	No
MIKE-BASIN	Calibration	Yes	Yes	Yes	?	No	Daily	Catchment	Low	Some recent develop-ments	Yes	Yes
ACRU	Physically based	UD	Yes	UD	UD	Limited	Daily	Catchment	High	Yes	No	Yes
HSPF	Calibration	Yes	Yes	Yes	?	Yes	Sub-daily	Catchment	Medium	No	No	Yes
VTI	Calibration	No	Yes	No	No	No	Sub-daily		Low	Yes	No	
PRMS	Physically based	No	Yes	No	No	No	Monthly	Catchment		No		
SWAT	Physically based	No	Yes			Limited	Daily	Catchment	High	No	Yes	
SAPWAT	Calibration	No	Yes					Farm level		Yes	Yes	

UD = Under development

The ACRU model was developed using an algorithm that was developed using small catchments of less than 50 km^2 (SCS). Can it be applied to larger catchment areas the size of the Quaternary Catchments?

- To answer this question one first needs to ask 'do the dominant physical processes change when moving from smaller to larger scale?' The only way to test this is to perform verifications on larger catchments, say, the size of Quaternary Catchments, with the model identifying which variables the model is most sensitive to. The ACRU model has been tested on larger catchments such as the Mgeni and Mkomaas to name a few and the verifications are relatively good (see the Mgeni study report). The answer is, therefore, that the dominant physical processes do not seem to change as one moves from small to large scale catchments and that the model performs adequately at the larger catchment level.

The ACRU model is data intensive in terms of land use, soils, rainfall and other biophysical data. Does this not make the model extremely complex and hard to run requiring a large amount of set up time?

- There is already a database in place, which can be used to run the model relatively quickly. This facility is available at a Quaternary Catchment scale and is already automated in terms of most of the inputs that the model needs. This structure that has been set up enables experienced users to run the model relatively quickly by selecting various input information stored in the database. The current database would need to be updated with some additional biophysical data, in terms of actual land use and soils.

Is the data necessary to run the ACRU model available?

- Yes. Land use parameters derived from Landsat images and soils parameters are available which can readily input into the model. The rainfall data has recently been updated by Smithers (2001), of the University of Natal, Pietermaritzburg, using a newly developed patching technique. These data can be incorporated into the model relatively quickly.

Which variables is the ACRU model most sensitive to? How much will slightly inaccurate information affect the model simulation results in terms of land use and soils?

- The ACRU model is particularly sensitive to rainfall data inputs. It is also sensitive to irrigation data and other system altering abstractions such as inter-basin transfers. The current methodology is that the ACRU model will be used to simulate runoff from the natural basin in terms of natural, current and future possible land use scenarios. The irrigation and water transfers would be looked at, however, the accuracy of these estimates is dependent on data availability. While the ACRU model is able to simulate different land uses is not as sensitive to land use and soils data (shallow soils excluded), so slight inaccuracies in these values will not make a large difference.

How well does ACRU perform on first time estimates at a Quaternary Catchment scale?

- The ACRU performs extremely well when results have been verified and good quality data have been input. The question remains as to how well the will model perform at a Quaternary Catchment scale when all the data is not available to the degree of accuracy required to get optimal performance. The model has performed relatively well in the past on first time estimates where no significant hydrological altering schemes have been instituted (i.e. irrigation and basin transfers). The model used at a Quaternary Catchment scale should not produce results with more that a 20% inaccuracy (Schulze, 2001). These results can also be improved at a later stage as more biophysical data becomes available. Improvements in remote sensing technology should also be able to provide better and cheaper biophysical data in the future. Obtaining better observed streamflow data is a more time consuming and expensive task that will only deliver returns many years from present.

Can the results from ACRU be used to produce stochastic runoff sequences of monthly flows to increase the existing record lengths?

- This question is more concerned with the idea that using ACRU might introduce trends in the runoff that will produce skewed results in the stochastic sequences. The answer to this is simply that trends will not be introduced as the development levels will be held constant throughout the ACRU simulation period. The ACRU outputs can be linked into the stochastic streamflow simulation component of the WRYM to produce stochastic streamflow sequences to extend the streamflow records if the link to the WRYM is required.

- The ACRU model itself will not have a stochastic flow generator developed owing to the complexity in generating daily streamflow simulations. The daily stochastic generation process is complicated by the need to account for daily cross correlations between the different catchments that are being modelled. If a technique is developed that can account for the cross correlations on a daily basis then the stochastic generation of daily sequences is a possibility that could be explored.

Can this technique be replicated in other catchments and generic issues be addressed by incorporating this in with a database and a DSS?

- The entire project will focus around setting up a framework that can be easily and cost effectively set up in other WMAs. The specific aspect of the project will focus on getting a standard to input data into and extract data out of a specific database structure that is standardised and used by DWAF.

7.4 Water Quality Considerations

This DSS will primarily be applied to water quantity issues, however, there needs to be the potential in future to address water quality issues as well. Therefore, in this section some water quality considerations are addressed.

Management of resource quality requires management of water quantity, water quality and habitat. Although water quantity and quality are interlinked and interdependent the complexity of the environment as well as the necessity in many cases to manage the water quality and quantity aspects independently in a catchment usually require these aspects to be addressed separately

7.4.1 Background in terms of the National Water Act (1998)

The NWA (1998) under Section 1 defines resource quality as the quality of all the aspects of the water resource including

- the quantity, pattern, timing, water level and assurance of instream flow;
- the water quality, including the physical, chemical and biological characteristics of the water;
- the character and condition of the instream and riparian habitat; and
- the characteristics, condition and distribution of the aquatic biota.

Of particular concern in terms of water quality under Section 21 of the NWA are

- engaging in a controlled activity identified as such in Section 37(1) or declared under Section 38(1);
- discharging waste or water containing waste into a water resource through a pipe, canal, sewer, sea outfall or other conduit;
- disposing of waste in a manner which may detrimentally impact on a water resource;
- disposing in any manner of water which contains waste from, or which has been heated in, any industrial or power generation process; and
- 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.

In Section 137 of the NWA (1998) it is specified that monitoring systems must be established to assess, among other matters

- “the quantity of water in the various water resources;
- the quality of water resources;
- the use of water resources
- the rehabilitation of water resources;
- compliance with resource quality objectives;
- the health of aquatic ecosystems, and
- atmospheric conditions which may influence water resources."

Management of water quality issues occurs at a local scale and therefore water quality management plans, decisions and actions are generally at a sub-catchment scale. However, the decisions made have implications for downstream users (and upstream impactors). Therefore, alignment between sub-catchments within a WMA (and possibly between WMAs) is required.

➢ **Significance of changes in water quality**

Possible water quality problems include

- the presence of toxic substances such as aluminium, arsenic and mercury;
- changes in system variables such as salinity, temperature and dissolved oxygen;
- non-toxic inorganic substances such as total dissolved solids and total suspended solids; and
- the presence of nutrients such as nitrates, ammonium and inorganic phosphates

In terms of domestic water supply there are various short and long term health impacts of deteriorating water quality. Aesthetic impacts include changes in odour, taste and colour. Economic impacts include increased treatment costs, scaling, corrosion or deposition of sediments in distribution systems.

In industrial plants water quality concerns include damage to equipment, problems in the manufacturing process as well as impairment of product quality. Agricultural industries could experience decreased crop yield, impaired crop quality, impaired soil suitability and / or damage to irrigation equipment owing to decreased water quality. Livestock farmers also rely on a certain water quality for efficient operations.

The Constitution of South Africa regards a healthy environment as a basic human right. In order to provide a healthy aquatic environment water quality managers and politicians needs water quality data and information to base water management actions and decisions on. To secure the availability of such data and information the National Water Act requires that the Minister, as soon as practicable to do so, establish national water quality monitoring systems.

7.4.2 Data required for addressing water quality issues

To address these aspects of water quality information is required on

- Natural attributes of the catchment which include
  - soils;
  - vegetation;
  - geology; and
  - sediment production potential.
- River information such as
  - main stem rivers and tributaries – volumes of water and locations;
  - wetlands and estuaries;
  - catchment boundaries; and
  - instream flow requirements.
- Monitoring stations which could be
  - water sampling sites at both rivers and effluent sites;
  - flow gauging ; and / or
  - rainfall stations.
- Infrastrucutre which includes
  - storage dam dimensions;
  - irrigation components;
  - water transfer schemes; and
  - water and wastewater treatment works.
- Demographic distribution in catchment
- Land use such as
  - human settlements;
  - commercial and industrial areas;
  - irrigation activities;
  - mining details;
  - solid waste sites;
  - nature reserves; and
  - indigenous veld and forests.

Information on both point and non-point sources of pollution in a catchment is required. Point source pollution refers single source pollution, for example, from water works, industrial plants, sewage treatment sites or pipe outflows. Non-point source pollution refers to pollution that emanates from land use types, areas and activities that result in conveyance of pollutants is a manner other than through a discrete source. Non-point source pollution can result in diffuse and intermittent pollution over a widespread area. Alternatively it may be concentrated and associated with localized high activity areas such as mines, feedlots and landfills.

➢ **Sources of information**

For water quality assessment in a catchment, information is required both on the desired water quality levels as well as the present condition of the quality of water in a catchment.

Water quality information in a catchment is available from a number of sources. The Department of Water Affairs & Forestry (DWAF) operates the most comprehensive water quality monitoring programme in South Africa. DWAF is, in terms of the NWA, responsible for the coordination, organization, control and further development of national water resource quality monitoring programmes. Monitoring, recording, assessing and disseminating information on water resources is critically important for achieving the objectives of the NWA (Section 137).

A number of national water resource quality monitoring programmes are already in place. The national chemical water quality programme has been operational for many years. A national biomonitoring programme is currently being implemented.

Much of the responsibility for reporting on surface water quality in South Africa rests with the Institute for Water Quality Studies (IWQS) of DWAF. The water quality samples analysed at IWQS are obtained from about 1750 surface monitoring stations around South Africa, at gauging weirs (1200), lakes (450), springs (50), water purification works (35) and canals (15).

Many stations are monitored at two-weekly intervals, but some are only monitored intermittently and others are intensively monitored for short periods during specific investigations. The main chemical analysis is for major inorganic ions, while a few samples are tested for trace metals and organic compounds. Results are stored locally on a Laboratory Information Management System (LIMS) and at DWAF head office on part of its mainframe Hydrological Information System (HIS). About 40 000 borehole sample analyses are stored in a separate database.

The framework for monitoring and assessment of water resources at DWAF includes:

- Maintaining and co-ordinating national and regional data and monitoring networks. Key activities include:
  - o National Water Quality monitoring programmes
  - o Maintain and assess current trophic status monitoring
  - o Radioactivity monitoring
  - o National biomonitoring programme
- Assessing monitoring and data collection services
- Maintaining and updating water resource and related databases, digital cartographic data and geospatial data systems
- Distributing, publishing and providing water resource data and information.

Other potential sources of water quality information in South Africa include water service providers such as water boards e.g. Umgeni Water, local authorities, metropolitan councils as well as research institutions, however, the key sources of water quality data and information need to be established for the catchment under investigation (DWAF, 2000; DWAF, 2001b; DWAF, 2001c) .

7.4.3 Modelling water quality issues

Information on the soils and general rainfall intensity of a catchment would allow modelling of sediment loads for example. Information on agricultural, industrial and mining water use is required to establish the amount of phosphorus and nitrate loading to model nutrient contents, for example, which have regional impacts.

Assessment techniques range from complex water quality process models for non-conservative variables, to simple mass balance models for conservative substances. Simple heuristic models based on previous studies may also prove to be valuable tools. In general, these assessment techniques should not focus on processes that lead to pollution, but rather on the impacts of pollution loads on water quality.

Configured and calibrated water quality predictive tools/ models can serve to

- indicate whether point or non-point source pollution is dominant, or which sub-catchments in a basin are dominant water quality load contributors, etc; this would help to prioritise certain types of management actions
- estimate water quality constituent loadings from a range of land uses and water uses that result in non-point source pollution, and indicate which non-point sources are dominant
- indicate the likely effects of pollution load increases or decreases on downstream water quality, or receiving waters
- simulate water quality constituents at key points in river-reservoir systems in response to particular system operating rules
- simulate water quality variables at points of concern for different future scenarios of land use and water use
- support prioritisation and appropriate selection of competing management options
- extend, infill or simulate time series of water quality variables at points of concern.

The temporal and spatial scales of water quality modelling need to be addressed. Ideally water quality status should be modelled on a daily basis owing to daily changes in water temperature and therefore water quality. In terms of spatial scales, modelling is best carried out at a catchment or sub-catchment scale. Sub-catchment scale modelling is required where instream flow requirements (IFR) need to be met and therefore modelling streamflows and water quality up until these IFR points is needed.

Catchment wide point and non-point source assessment techniques are also important in the formulation of source management objectives, as they indicate which sources are contributing to current pollution loads. These models may be quantitative or qualitative, and contribute to assessing the feasibility of pollution load reductions.

Streamflow modification associated with land use change is also a type of non-point source pollution, which can adversely affect the physical and biological integrity of surface waters. The management of non-point sources is complicated by the dispersed and variable nature of the impacts, being primarily driven by rainfall events. The potential lag between polluting activity and effect also complicates non-point source management. These characteristics obscure the impacts from different sources and restrict the opportunities for their measurement. Therefore, non-point source contributions can generally not be monitored directly, but have to be inferred by experience-based interpretation, mass balances against measured point source loadings, or simulation modelling. However, the importance of non-point source management in South Africa is increasing as point sources are better controlled and catchments are developed.

Regulations exist to control the quality of discharge from point source pollution outlets. However, the cumulative effect of pollution from point sources has resulted in degradation of the water quality in many South African rivers to the point of decreased fitness-of-use for specific water users. Consequently, the assessment of contaminant load contributions to streamflow and other water bodies originating from point sources is a prerequisite for understanding of water quality patterns and problems in catchments.

Other modelling issues include the importation of salts through inter-basin transfers and the need to predict the implications of future developments in a catchment on catchment water quality.

There are conflicting demands on the water source of a catchment to both supply water users with a desired level of water quality as well as to use the water source as a method of disposing of waste. It is necessary for stakeholders to express their water quality requirements in terms of "the impact of water quality on their livelihoods". These requirements are then compared to the present water quality status.

7.4.4 Models presently used for water quality modelling

The models used in South Africa for water quality modelling can be divided into five types, viz. simple process models, detailed process models, system analysis models, daily reservoir hydrodynamics models and sub-daily river hydrodynamics models. Brief descriptions of some of the models that fall under these categories are provided.

- **Simple process models**

Hydrosalinity Model (WQT) – monthly
This is a *coarse-scaled* model for *salinity* production and transport in *large multi-use catchments*, specially designed to be driven by the same natural flows that drive the Water Resources Yield Model (WRYM) and Water Resources Planning Model (WRPM) system analysis models. WQT is used to determine salinity parameters, which are then input to the WRPM model for multiple stochastic optimisation runs in large river systems.

IMPAQ (Impoundment/river Management and Planning Assessment tool for water Quality simulations) – monthly
This is a medium-to-fine-scaled model for salinity, sediment and phosphate production and transport in large multi-use catchments, specially designed to be driven by the same natural flows that drive the WRYM and WRPM system analysis models outlined in (iii) below. It has a washoff routine that uses SCS Curve Numbers to allow any mix of land-uses to affect sediment and phosphate production, which are derived from a combination of loading functions, potency factors and the USLE approach. Non-conservative processes are allowed to play a role in a channel transport module and a simple mixed reactor reservoir module. IMPAQ is used in conjunction with WRYM to generate very long sequences of monthly loads/concentrations of selected constituents in large river systems.

ACRU – daily
This is a *fine-scaled* model for *sediment and phosphate* production from *individual small catchments* with a limited range of agricultural land-uses. It is driven by daily

rainfall and uses soil-moisture budgeting according to a discretisation based on soil texture classes and agricultural practices. It is recommended to investigate localised impacts of land-use and their related management options.

NACL – daily
This is a medium-scaled model for *salinity* production and transport in large multi-use catchments. It is built around the relatively black-box daily Pitman rainfall-runoff model, it allows urban washoff as well as operation of reservoirs, wetlands, and coarse irrigation activities. It is recommended as background support for WQT applications where certain parts of a multi-use catchment require more detailed treatment, or to assess salinity management options.

DISA - daily
This is a fine-scaled model for salinity production and transport through formalised irrigation schemes and allows operation of supply reservoirs, river channel transport, diversion devices, primary and secondary canals, balancing dams, artificial drainage, groundwater variability and a wide range of irrigation practices. It is driven by daily rainfall and uses soil-moisture budgeting according to a discretisation based on soil texture classes, location on the landscape, and agricultural practices. It is recommended as support for any of the other models to assess irrigation impacts of large or multi-offtake irrigation schemes, or to examine management options for salinity control.

HSPF (Hydrological Simulation Program Fortran) - Sub-hourly to daily
This is a medium-to-coarse-scaled model for production and transport of salinity, temperature, sediment and a range of non-conservative constituents in medium-to-large multi-use catchments. Its water quality chemical simulation components are comprehensive and it uses relatively black-box rainfall-runoff functions, different forms of hydrological channel routing and treats reservoirs as simple mixed reactors. It may be used to assess water quality outcomes of management and operational options in medium-to-large catchments.

- **Detailed process models**

Detailed process models incorporate sophisticated processes, such as adsorption-desorption, decay and plant uptake, into the simulation of contaminant movement and transformation in soil and water. These contaminant processes are integrated with relatively complex hydrological and sediment models.

- **System analysis models**

The following two models are used to optimise the allocation of water on a monthly basis throughout a large multi-use river system, according to a penalty structure, for a given time horizon of water demands and allowing stochastic variation.

WRYM
This model is used to calculate the long-term yield from a specific flow series, to examine operating rules or to develop yield-reliability curves.

WRPM
WRPM allows various sub-systems to support each other during deficit periods and is used as a planning tool to explore augmentation or restriction strategies.

- **Daily reservoir hydrodynamics models**

The following models have seen operational use in South Africa:

CE-QUAL-W2
A 2-D finite difference model that incorporates all primary hydrodynamic processes as well as a range of conservative and non-conservative water quality processes.

DYRESM
A 1-D finite difference model using LaGrangian principles to simulate all energy and kinetic exchanges as well as salinity processes.

- **Sub-daily river hydrodynamics models**

Three one dimensional models have seen operational use in South Africa: MIKE11, ISIS and DUFLOW. All three models are based on a finite difference application of the full St Venant's flow equations to a series of cross-sections of the river channel and flood-plain. A range of conservative and non-conservative water quality routines are incorporated in all three models.

- **Results of water quality modelling**

Following an analysis of water quality three cases could occur

- the water quality is significantly better than is required by the stakeholders (unstressed status);
- the water quality is close to that required by the stakeholders in which case it may be necessary to revise the water quality requirements or the need to discharge waste (threatened status); or
- the water quality is worse than what is required by the stakeholders in which case the implications to other stakeholders would require assessment (stressed status).

Results from water quality modelling can be displayed using a GIS thereby showing both the types of problems that occur in a certain area as well as the location of the water quality issues.

Alternatively a time series of results or exceedence diagram to illustrate the acceptability of the water quality can be displayed.

7.4.5 SWOT analysis of water quality modelling and monitoring in a WMA

- **Strengths**

- Some systems (models and monitoring networks) are in place, however, these are currently far from ideal.
- Models or mathematical tools do go some way to address the problem of data shortages.
- Using long rainfall records for catchment modelling provides a useful method of extending or infilling streamflow and hence water quality records synthetically.
- Another method of dealing with data shortages is the use of simple empirical predictive tools based on the sequences of long sequences of streamflow information to make statistical estimates of water quality. Using simulation models usually requires more intensive data input than the simpler, more qualitative approaches.

- Models of differing complexity are available allowing simpler, more qualitative methods to be applied in catchments that are considered less stressed and more complex models to be applied in threatened or stressed catchments

➢ **Weaknesses**

- The present water quality databases in South Africa are limited in duration or spatial representativeness and often represent only intermittent samples.
- To date in many instances, monitoring points have been positioned to provide information on man-made impacts with little consideration being given to background or un-impacted state of a river or stream.
- Only a few models are available for water quality modelling. This is especially true of daily time step models.
- Most models that are used for water quality simulation are data intensive and are complex to set up.
- In some models the configuration and calibration of water quality simulation models for use in water quality assessments and investigation of management options requires quantified point sources as essential inputs. The current day point source waste discharges and historical waste discharge records or trends are required for proper calibration of the models over a representatively long time period. This information is generally not available in many parts of South Africa.
- Information on both point and non-point source pollution is needed for modelling. This information is often not available and non-point pollution is particularly difficult to monitor.

➢ **Opportunities**

- Advances in technology may provide a means to monitor water quality more effectively than in the past (e.g. the use of telemetry and data loggers)
- Continual advances in research allow more advanced water quality models to be developed.
- WMAs and CMAs should be empowered to address their specific catchment problems at a local level.

➢ **Threats**

- Ideally monitoring points should be distributed over the catchment to provide a balanced view of water quality changes.
- Many catchments are stressed in terms of water quality and lack both water quality data and catchment information. There could be a delay in obtaining a good monitoring network and database of water quality monitoring information for these catchments for management and modelling purposes.

7.5 Data Requirements for the SEA-DSS

The data requirements to establish the CMS and for individual license applications include

- water quantity and quality data (water quality data requirements have been addressed in Section 7.3) ;
- invariant data;
- variant data;
- ecological and environmental data; and
- economic information including projections of demographic trends and economic development and consequent water demands (cf. Sections 3.2.4.1 to 3.2.4.4).

The data may take the form of

- regular or intermittent time series;

- spatial coverages; or
- dimensions of infrastructure.

This data may be linked to
- points (e.g. monitoring stations, dams or weirs);
- river reaches; or
- polygons (e.g. land uses).

This following list of data requirements is a non-exhaustive list of the types of data required to assist in planning, design or systems operations by the CMA.

7.5.1 Invariant data requirements

Invariant data implies data, which remains constant over time. Minimum invariant data requirements include
- Baseline land use information (e.g. Acocks' Veld Types)
- Precipitation data (preferably daily rainfall)
- Maximum and minimum temperature (either daily or monthly)
- Physical catchment attributes which include
  - Location
  - Area
  - Altitude
  - Catchment configuration
- Mean monthly reference potential evaporation
- Geology
- Topography
- Soils data which includes at a minimum
  - depth; and
  - texture class
- Cadastral boundaries such as
  - provincial boundaries
- Natural features such as
  - rivers

7.5.2 Variant data requirements

In addition to invariant data there is also the need for data, which does vary over time such as land use information. Therefore data is required on the location and nature of
- roads and transport routes;
- game parks and nature reserves;
- commercial forestry;
- dryland agriculture;
- irrigated agriculture;
- markets;
- dams;
- transfer schemes;
- rural and urban centres;
- biodiverse areas;
- population distributions and status;
- mining zones;
- wetlands;

- return flows from water treatment sites and irrigation schemes; and
- point and non-point source loadings

in the WMA concerned is required.

Land use and water use data is required for the CMS depending on the land use in the individual catchments being managed. If irrigation demand and supply routines are activated in a catchment then data is further required on

- mode of scheduling;
- source of the irrigation water;
- supply and abstraction losses;
- crop characteristics; and
- soil texture class.

If dams are present in the catchment then data is needed on

- dam capacity;
- surface area;
- dimensions;
- storage to discharge relationships; and
- evaporation amounts from the dam.

If water is abstracted from the dam information is required on

- the amount of water abstracted from the reservoir month-by-month for uses other than irrigation (i.e. urban or ecological).

If an inter or intra-catchment transfer is in place then additional data required would include

- the total volume of water to be pumped into the reservoir month-by-month from an outside catchment/subcatchment.

The amount of water that can potentially be pumped from the river, if off channel storage is available, depends on the

- river conditions;
- pumping capacity;
- number of pumps; and
- number of hours per day that can be used to pump water.

Data required on SFRAs would include

- the type of trees being planted.

Non-SFRAs would require month-by-month inputs on

- water use coefficients;
- interception loss by vegetation; and
- fraction of roots in the topsoil.

7.5.3 Ecological data requirements

Ecological data requirements include

- class of the reserve;
- biodiversity data;
- operating rules;
- instream Flow Requirements (IFRs) at selected sites or reaches;
- environmental flow and tidal exchange requirements of estuaries; and
- aquatic biotic responses to flow changes due to upstream developments.

7.5.4 Economic data requirements

To make economic decisions data is also required on

- crop selling prices;
- distance to markets and mills;
- labour costs;
- transport costs;
- capital equipments costs;
- conversions costs from one land use to another;
- gross margins;
- enterprise margins;
- number of employees per activity; and
- water use charges.

Data is required on historical, present and projected water demand distribution in the catchments.

7.5 Basis and Requirements for a Common Database

There have been a number of developments in southern Africa over the past few decades that have contributed to the need for a more collaborative approach to some aspects of hydrological and water resource data analysis.

The amount of observed data has reached a level where efficient information management is critical to realising the full effective value of the data. This also implies that efficient methods of summarising and analysing these data are required. Large quantities of data are housed in different state departments and other institutions in inconsistent data formats. Even in DWAF itself there is at present no consistent standardised data formats between the different sectors involved in data storage and management. Consistent data formats and suitable protocols and standards would go a long way to fostering cooperative governance and enhance the communications between different state departments.

There have been some developments in the availability of hydrological and water resource modelling tools. There is now a diverse set of applicable models in practical use and the application of models is no longer confined to the groups that developed them. However, while most have built-in results analysis procedures, there has been little standardisation of approach with respect to the methods used to display and analyse the simulation results.

The recent proliferation of models simulating a number of different processes is a mixed blessing as is not only means that the user has to spend a large amount of time choosing between different models but must expend considerable effort amassing and manipulating huge quantities of data the model may require. If the user wants to perform an analysis of more than one process two or more models need to be coupled together, while the underlying assumptions may be somewhat incompatible, more frequently the data structures are so different that coupling requires extensive data conversion work. Extensive modelling data requirements coupled with inconsistencies in data storage within and between different organisation and state departments means that a large amount of a modellers time is spent, when performing catchment studies, on data management, collection and processing.

- As a consequence of the previous point, there are also quite large volumes of simulated data available, but in a variety of different data storage formats.

- Perhaps the most important consideration is that a broader group of scientists and engineers now require the information contained within hydrological time series. Many of these scientists are non-hydrologists who are not always familiar with the full range of methods that can be used to present hydrological data. A more standardised approach could possibly alleviate the confusion often caused by being faced with different methods of analysis and display.
- There is a trend toward viewing hydrological data in a spatial context and developing software products that allow spatial and time series data to be better integrated. This is essential for effective integrated catchment management.
- Some groups have had less than satisfactory experiences with the purchase and / or use of imported software, which has not been designed for the local situation.
- The funding agencies are under pressure to avoid financing duplication of research effort.
- One of the results of these points is that many different data sets and analytical / simulation tools are being used and that the outputs are being presented in many different ways. Modern software development tools make it relatively easy to generate programs that can produce impressive graphics displays, etc. and there is the real danger that several groups will follow independent paths toward creating products that satisfy only a limited range of users, but are largely incompatible with parallel developments. It therefore seems to be sensible to pool the available resources within South Africa and develop time series analysis and display software products that can be flexible enough to satisfy the majority of potential users requirements in an integrated package.

Hughes (2000) stated that in a workshop he attended in 1997 a number of differing viewpoints on the database format to use emerged on the possibilities of cooperating in the development of data management software. Some attendees favoured formats that are used with existing software such as Watershed Data Management System (WDMS), for example, while others argued strongly for a true 'database' type format such as Oracle, Paradox, Informix or dBase (Hughes, 2000).

It was, however, agreed that certain attribute information, such as the source and type of the data should be linked to the data themselves and that the software developed should allow for a variety of different formats. In technical terms this means that a library of data access routines (attribute builders and display software) has to be written, all of which pass the required information back to the main analysis and display routines. A user may then specify the database source type (or types), after which the data storage method is transparent and the software takes care of the rest (Hughes 2000).

It was concluded that if some basic principles are agreed to and established early in the design process, the allowance for different database types will be reduced to the ability of a software engineer to write the necessary library routines (Hughes 2000). The nature of the database access will be largely controlled by what the analysis and display software requires to be able to operate efficiently and in a user friendly way.

Thus there is a definite need for a common database, which can be accessed by multiple models. Input for the models and output from the models should be written in a common format, which can be accessed by different models as shown in Figures 5 and 6.

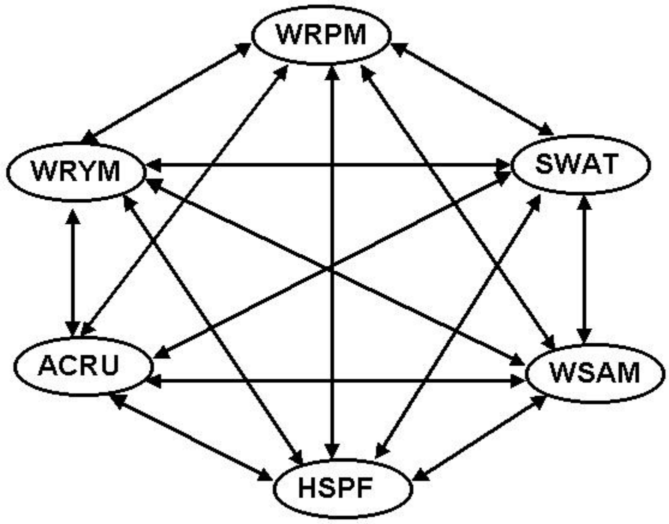

Figure 5 A complex approach to database management

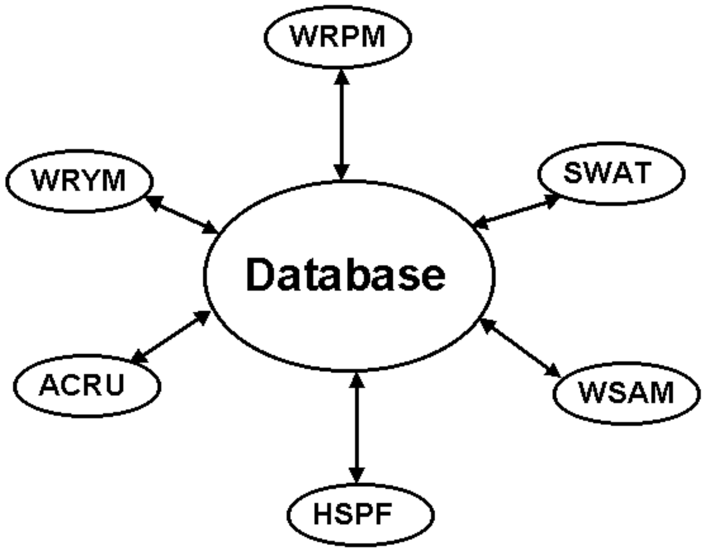

Figure 6 A simple approach to database management

Görgens (1999) identifies the need for an integrated catchment modelling and information system. A number of models are interfaced with a common database, which is in turn linked with time series and GIS viewing facilities. A system of this nature will, according to Görgens (1999), allow for varying levels of input depending on the complexity of the problem. Examples of some systems that have been developed along these lines include HYMAS, ICIS, IMPAQ, BASINS and NWBM. These systems appear to have strengths in the visualisation software however, often are restrictive owing to their resolution or preference for a single modelling system.

If the system in Figure 5 were used then methods would have to be devised to convert the output from one model to input to the next for each of the models used. However, if the system set out in Figure 6 is used then only one method of input and output extraction from a common database is required. As can be seen from the two diagrams the efficiency in data manipulation using a common database is much enhanced, as data manipulation only needs to take place between the database and the models, which reduces the amount of effort spent on data manipulation.

Linking models in series is the most common type of model linkage. It involves taking output from the one model and using it as input to another model. The implication of this is that all calculations by the one model need to be complete before commencing the next model's run. The usual requirement for linking models in series is the conversion of output from the first model from its unique format to the unique input format of the other model using a data transformation program. A time manager and a set of files that is accessible can facilitate communication by the models by all models.

Problems that can arise from this method of model linkages is that time resolution of the models may differ and therefore in some instances aggregated of information may be required. This type of link does not allow feedback between the models; however, communication through the input/ output files makes this type of loosely coupled models very flexible.

Linking models in parallel usually involves using output from one component as input to the next in the same time step and therefore has the facility to accommodate feedback between models. This generally involves restructuring the models to read the same database and compiling them in one executable program.

In both instances a common database is required to facilitate the use of multiple models.

7.6.1 Temporal and spatial scale considerations

Time is continuous, however, data is usually discrete in that it is recorded at distinct intervals in which intervening information of a specific type is disregarded or assumed to be unimportant. These intervals are not necessarily equidistant and discrete time can therefore be seen as an intermittent process.

The spatial scales of the data stored in the database may vary and may range from a fine scale such as a grid in a GIS system to a catchment scale. The gridded information may be aggregated to the spatial scale used in the database.

7.6.2 Database requirements for the DSS

The database required by the decision support system

- needs credible and trusted information in the database;
- needs to store both base or raw data and simulated model output;
- needs to store geo-referenced (spatial) data, attribute data and time series data;
- is required to link these data types together; and
- is required to operate at a daily time step and sub- Quaternary scale.

A present there is no system that is able to link spatial data with time series data and a viewing platform in GIS. The database behind ArcView for example is a dBase file format to store and link data. This requires the data storage in a flat file format that allows for a large amount of redundancy and is not easily queried. A relational database has the ability to reduce redundancy and allow for easier query options to be developed. The ARC/INFO and ArcView systems are being developed to incorporate relational database facilities, these are, however, not available at present. It was therefore decided to review several different existing database applications that have been developed locally and internationally to assess how they have dealt with the problem of linking time series, attribute and spatial data together. It was also believed that substantial time and effort might be saved if and existing database could be used.

When assessing the option of using an existing database system it is necessary to weigh up

- the time and expense that it will take to translate the data into formats compatible with the existing system; and
- the time it will take to develop the system with all the necessary requirements from scratch.

Several different systems were discussed with different organisations in the water sector ranging from the CCWR to DWAF. The CCWR recommended the use of the BASINS system for data management. The BASINS system fulfilled the criteria stated above. It stores both simulated and raw data and links both spatial, attribute and time series data together. It runs using the ArcView GIS, which is linked to the WDM Water Data Management system.

While using an existing BASINS system in this project seems like the ideal solution there are a several problems with the Water Data Management (WDM) system which may prove limiting (Pike, personal comm,. 2001).

- The WDM system stores binary data in a special specific data format in a direct access file and is extracted and manipulated via FORTRAN 77 subroutines.
- The relevant data in the WDM is inserted, extracted and manipulated using FORTRAN subroutines and the WDM comes with an entire Fortran library to enter, extract and manipulate various data sets from the WDM.
- If data is required to be extracted in a format that does not conform to the data in the data library new FORTRAN extraction code needs to be written.
- The WDM cannot be accessed through other programming languages (such as C++ and JAVA) without using a DLL. If the data is required to be used in programs that have been developed in other languages such as JAVA and visual basic then a DLL must be written. Various DLLs have been written between the WDM and other languages in order to get them to talk and extract the data in the formats necessary to run the different models. (This takes time and must be redone if the system changes requires different data)
- The added complexity of interfacing with different models etc. makes the system cumbersome and slow in terms of processing time.
- The WDM is not a relational database (such as Oracle, Access or Paradox) and could well be superseded by another database system in future versions of BASINS. It therefore does not afford the user the same powerful features available in true relational databases.

The problem basically comes down to a trade off between two different options.

- Conform to the standards of the USGS and use their systems to store data. South Africa's data requirements are different to those in the USA and current data formats are not consistent with those in America. Transforming our systems and data to conform with their system costs time and money and may not be 100% suitable.
- Produce our own data storage standards. These will then suit the South African data requirements and can build on existing standards that are in place. At present there is not much consensus on the data standards and many areas store data in different formats. Setting standards and agreed upon protocol will

take an enormous amount of effort and time. The setting up the system thus costs time and money and may not be 100% suitable.

Neither option is particularly suitable, as both would require prohibitively large investments in terms of both time and resources. It was therefore decided that the option of choosing a database structure that had been locally developed and was in general use would be the most appropriate option. In this regard DWAF was approached to gain an idea of the types of systems they are using and how these systems could be adapted to a working version of a database that could link to the models that were required in the DSS. It was believed that by “piggybacking” on the protocols and standards developed in DWAF the setup time for the database would be decreased and a functioning system would be in place in the least amount of time. It was also thought that by using a system that conformed with the standards of DWAF the system would be generally better accepted by DWAF and would be used more readily in actual applications especially in terms of the SEA process that the DSS supports. It was also believed that the most recent technology in terms of database systems should be used, as that would limit the possibility of the system becoming outdated and redundant.

In several meetings and discussions with different persons in different departments in DWAF it became clear that there is no real consensus on the database structure to be used in DWAF itself. There are several sections in DWAF involved with data manipulation and management however there is no standard method of storage or manipulation and most of the different sectors use their own data storage formats and database packages. In DWAF the integrator has been given the task of standardising all the different data formats and incorporating them into a common database and data storage format. It also became clear when speaking with various role players in DWAF that none had a system that stored both simulated and observed data and that DWAF was mainly concerned with the collection and storage of observed data.

Several of the current databases used in DWAF at the moment are named below. This is not an exhaustive list as other sectors in DWAF may have another systems.

- Informix system being used by the intergrator
- The Regis system used by the geohydrology section which combined an Oracle database with the ArcView GIS
- The WMS which is used by the Institute of Water Quality Studies
- The ArcView GIS which is used by Geomatics
- The HIS (Hydrological Information System) used by the hydrology section
- The hydrology section is looking at converting the HIS system and using another format such as the HYDSYS system developed in Australia

The integrator has set up a database architecture that needs to be conformed to in terms of database design and development. The data standards within the database architecture are not however explicitly defined. The Informix database system while being used by the integrator is not necessarily standard throughout DWAF. There also apparently seems to be some debate as to which is the best database package to use, in terms of Informix or Oracle.

It is clear from the discussions with DWAF and other organisations that the database issue needs to be given a lot more thought. It has been suggested that the consultants review some of the current databases used in DWAF at present and particularly the Regis system that is been used by the geohydrology section. It is, however, clear that the consultants must use the ArcView GIS for the spatial data storage component and link this to a relational database. At this stage several, options have been suggested in terms of which database to use and link to the ArcView system. The most promising link looks to be that which has been adopted by the Regis system which links an Oracle database to the ArcView GIS. It is hence this approach that is most likely to be suggested by the consultants in the design but is subject to further investigation.

8. DEVELOPMENT OF AN INTERACTIVE, GENERIC, HYDROLOGICALLY FOCUSSED SCENARIO GENERATOR

The objective of the Scenario Generator (SG) section is to introduce the potential benefits of developing a generic, hydrologically focussed SG for use by the DWAF SEA team in association with an experienced hydrologist (or someone with hydrological simulation expertise).

This section is laid out in the following format.

- The responsibilities and challenges faced by the DWAF SEA team are introduced;
- the generic hydrologically-focussed SG is introduced;
- the delineation of water use activities is discussed;
- considerations related to supply and demand scenarios are introduced; and
- the use of the SG and its potential limitations and opportunities are discussed.

8.1 Responsibilities and Challenges Faced by the DWAF SEA

The DWAF SEA team is tasked to strategically assess water use, giving consideration to the environment, the economy and to society. It is useful to carefully consider the words that constitute the SEA mandate:

- **Strategic**

The term strategic suggests the assessment to be done at a "high level", with information generated being used at a strategic level. However, the SEA process may be undertaken at various scales (Steyl *et.al*., 2000), including a National scale, the scale of a WMA, or local scale. The ability of the SEA to be undertaken strategically at the different scales appears to be paradoxical, in that one may question if information generated at local and WMA scale is in fact "strategic". It is however possible to relate WMA and local scale scenarios/assessments to strategic level *indicators and/or criteria*. For example, as part of a WMA scale SEA irrigation water use is curtailed by say 20%. The impact of this scenario may be expressed using indicators and/or criteria at the WMA scale, as well as the National scale respectively. An example of a WMA scale indicator could be the expected change in contribution by agriculture to the WMA product (this is currently not a recognised indicator), while a national scale indicator could be the change in the contribution of agriculture to gross national product (GNP). However, translating the impact of local or WMA scale SEA water use scenarios to national scale indicators and criteria (for the SEA to be considered of strategic importance) may be very complicated indeed, as vast sets of information at the national scale may be needed to undertake this translation.

Consequently, the term "strategic" in the context of this project has been interpreted as the nature of information related to water use that is deemed to be important (strategic) by the SEA at the respective scales. The identification of information deemed to be "strategic" at the various scales, and for different areas in the country, is the starting point of the SEA process, and will depend on whose interests the SEA is to serve. The SEA in effect, needs to answer the following questions at the scale that the SEA is undertaken at:

- Who will use the information generated by the SEA?

- What are the “strategic” economic, social and environmental water use related information requirements of the user/s?
- Where and how can this information be obtained?
- What water use related indicators and/or criteria need to be developed for economic, social and environmental considerations in order to provide a method of:
  - o Illustrating the water use conflicts and challenges associated with *current* water use, and to
  - o Comparing/assessing the outcome of potential *future* water use scenarios?

Notes:
- Although the client (i.e. the funder of the SEA process) usually is the user of information generated by the SEA process, this may not always necessarily be the case.
- There may be more than one user of the SEA generated information, which may complicate the SEA process, as the assessment may need to accommodate the requirements of multiple users.
- Strategic information in the context of an SEA would probably refer to information regarding both current and potential water use. In other words, the SEA is tasked to assess what water use scenarios (future water use) are potentially feasible.

➢ **Assessment**

The term “assessment” suggests that an appraisal (evaluation) is undertaken as part of the SEA process. The definition of assess reads as follows:

“Assess: to determine the importance, size or value of…” (Webster’s Ninth New Collegiate Dictionary).

In order for assessment to be possible, the SEA generated information should possess the ability to carry value, size or importance. One potential solution for the DWAF SEA team to meet this objective is to identify and/or develop suitable criteria and/or indicators of economic, environmental and societal use of water in a manner or format in which magnitude (or value) may be attributed to the indicators/criteria of water use. The importance (or value) of each selected and/or developed criteria and/or indicator will depend upon the importance of the indicator/criteria to the user/s of the information generated by the SEA.

➢ **Water use**

The term “water use” is central to the DWAF SEA mandate. The challenge is to define water use in a manner flexible enough to accommodate a multi-disciplinary use of water (i.e. the economic, societal and environmental use of water). A generic wording of water use, which is consistent with the NWA, is as follows: The SEA is responsible for quantifying the use of water by water using activities. These activities include economic activities and non-economic activities. Within the non-economic activities a differentiation may be made between the environmental use of water, and water used by people (society) for purposes other than commercial activities.

In effect, the SEA may need to undertake the following steps:
- Clearly identify the different categories of water using activities (i.e. categories of water using activities that relate to the economic, social or environmental use of water) (cf. Section 6.4).
- Quantify the water use of the *current and potential water* using activities, giving consideration to:

- o A suitable indicator of water use for the SEA decision making (e.g. mean annual streamflow reduction (MASR) by each activity, or the average streamflow reduction during dry periods, or the impact of each water use on catchment and/or systems yield)
  - o The spatial location of the activities, and
  - o The temporal variation of water use by the activities (e.g. water use during dry periods vs wet periods).
- Relate or link the water use of the categories of activities to indicators/criteria that reflect hydro-economic, hydro-socio and hydro-environmental considerations (and potentially combinations of these, e.g. hydro-socio-economic water use indicators).

Notes:

- The NWA may require categories of water use, such as SFRAs, to be further subdivided in order to provide the information at a level that decisions may be taken at. For example, the SFRAs may divided into a number of sub-categories, including, amongst others:
  - o The type of SFRA (e.g. forestry, vs say sugarcane if it is declared as an SFRA),
  - o The area of SFRA ownership (small growers may potentially not be subject to water use charges, hence must be discerned for scenario generation)
  - o The nature of SFRA ownership (e.g. previously disadvantaged persons may own the SFRAs)
- The quantification of water use by the various categories and sub-categories of water using activities is challenging for the following reasons:
  - o *Current and potential* water use must be quantified. A *hydrological model* will be required in order to simulate (estimate) the water use of current and future scenario water uses,
  - o The hydrological model selected should ideally be able to accommodate the different scales at which the SEA may operate, as well as for different areas in South Africa. A process based hydrological model, which operates at a fine time step (e.g. daily) is required to meet these objectives. We have selected the ACRU hydrological model for this purpose.
- There are two broad approaches to water conflict situations, including:
  - o Change the demand for water so that conflict is reduced, and/or
  - o Increase the supply of water so that conflict is reduced.

  These two broad categories need to be accommodated for in a generic hydrologically focussed scenario generator, which needs to be consistent with provisions made in the NWA (Act 36 of 1998) (cf. Section 6.5)
- Relating the water use of each activity to an indicator or criteria is challenging for the following reasons:
  - o Suitable indicators/criteria may need to be developed which requires a deep understanding of the requirements of the NWA, and
  - o The temporal variation of water use (e.g. water use during dry vs wet periods) may be difficult to accommodate in one criteria/indicator. Thus a number of criteria / indicators may be required, each of which may carry different values of importance.
- Relating the water use of each activity to indicators/criteria is outside the scope of this project. It is recommended that the undertaking that follows this project is to identify suitable indicators/criteria. It is recommended that these indicators/criteria be developed/selected in consultation with multiple-criteria decision analysis experts (MCDA), water resource managers, stakeholders, and economic, social and environmental experts.

The following concluding remarks can be made regarding the responsibilities and challenges faced by the DWAF SEA:

- The SEA may be required to provide information regarding water use at *various scales* (National, WMA or local scale),
- The nature of the water use *information* required by the SEA may vary for the different scales,

- Criteria and indicators of economic, social and environmental water use may need to be developed in order for a process of assessment to be undertaken,
- Assessing water use conflicts and challenges often requires a clear understanding of the conflicts and challenges from a number of varied perspectives that may be faced by various stakeholders and water resource managers. Thus the SEA is required to assess conflicts and challenges in a holistic, yet multi-faceted approach. This often requires a broad level of skill and strong participatory qualities by the SEA, which is a challenge in its own right.
- The nature of the information required from the SEA process largely depends on whom will use the information, and how the information is to be used,
- Water use conflicts and challenges may vary considerably from one *spatial* location to the next,
- Water use indicators and criteria may need to be *temporally* sensitive or specific (e.g. water use during dry vs wet periods),
- A *fine-time step physical processed based hydrological model* is ideally required to simulate (estimate) the water use by current and potential water using activities. This affords a generic method of estimating water use, both at different *spatial scales* (e.g. local vs WMA vs National), as well as for different *spatial locations*. The ACRU model has been selected as a suitable hydrological model to be used for the development of a scenario generator, and
- A number of indicators of water use are possible. It is important to select the appropriate water use indicator/s that address the needs of the SEA client (and/or information user/s), and
- There are two broad approaches to water conflict, which need to be included in the scenario generator, including
    - changes to the *demand* for water (i.e. change how, when or where water is used), and
    - changes to the *supply* of water.

8.2 A Generic, Hydrologically Focussed Scenario Generator

From the discussion above, the following important statements were made:

- The focus of the DWAF SEA relates to water use.
- There are two broad categories of water related scenarios that can be run, including
    - changes to the demand for water (i.e. changes to the use of water), and
    - changes to the supply of water.

The main objective of developing a hydrologically focussed scenario generator is to have a tool that can easily be used to generate water related scenarios, which broadly include scenarios influencing the demand for water and/or changes to the supply of water. The reason for developing this tool is relatively straightforward. The SEA is tasked to assess the water use of *current* and *potential* water use and supply conditions. The value of the scenario generator is to assist in the generation of accurate, meaningful water use and supply scenarios.

It is suggested that the scenario generator be GIS based, preferably in ArcView (as ArcView is easy to use, and has large functionality). Developing the scenario generator in ArcView has the potential to allow easy-to-understand, and realistic scenarios to be generated in a transparent manner. The technical challenge is to seamlessly integrate the ArcView SG with the ACRU hydrological model. Both ArcView and ACRU will also need to be seamlessly integrated to a carefully designed database. The seamless integration of the SG to ACRU may require that when certain water demand and supply scenarios are invoked, the user of the scenario generator is prompted for information that may be required by the ACRU hydrological model. For example, if a scenario to build a dam is invoked, the user may be prompted to supply information regarding, amongst other details, the capacity of the dam, the surface area of the dam and the release capacity of the dam.

A few of the requirements of the scenario generator are discussed in more detail.

- **Generic**

The term generic refers to the requirement that the SG should be able to accommodate water supply and demand scenarios at different scales.

- **Temporal considerations**

The ACRU model is a daily time step model. The outputs of the model (e.g. streamflow) may easily be aggregated to coarser time periods (e.g. monthly or annual streamflow).

- **Spatial considerations: size**

Although the ACRU model was developed with application to small-scale catchments (<30km^2), the model has been successfully applied to Quaternary Catchment scales (Schulze, 1995). The Quaternary Catchment is currently the smallest recognised hydrological response unit. The implication is that ACRU can in fact be configured to units smaller that Quaternary Catchment scale, which is useful as this level of functionality may be required in the future. The ACRU model hydrological simulations will be undertaken at Quaternary Catchment scale or finer, which can then be aggregated into Tertiary, Secondary or Primary Catchment scale.

- **Spatial considerations: location**

As the ACRU model is a physical process based hydrological model, the model can be applied generically throughout South Africa. The model has already been extensively used and verified in numerous locations in South Africa (Schulze, 1995).

Thus the scenario generator, seamlessly integrated with the ACRU model, may be regarded as being generically applicable with respect to both temporal and spatial considerations.

- **Water demand and supply scenarios**

A requirement of the scenario generator is to generate water demand and supply scenarios that are consistent with the NWA. Water supply and demand scenarios are discussed in more detail in Section 8.4.

- **The development of the scenario generator in a GIS**

The table below (Table 2) illustrates some of the information types required from a SEA as identified in the Mhlathuze SEA document (Steyl *et.al.*, 2000). In the same table comments have been made in the right hand column regarding the advantage of developing the scenario generator in ArcView.

Table 2 Types of information required by a potential SEA client. The column on the right comments on how a scenario-generator developed in ArcView may be used to meet these information requirements

	The decision maker should be able use the outputs of the SEA to see:	Comments on how the ArcView based scenario generator helps to meet these requirements
1	How this development is located in relation to similar and other uses of land	The GIS can be used to highlight this consideration.
2	Whether this site is suited to the development (climate, soils, infrastructure...)	The SEA GIS coverages, including amongst others, the biobase, landuse potentials, roads, towns, slopes, river, dams and current landuse, can be used to assist in this assessment.
3	Whether the availability of water is likely to be an issue	The GIS could be used to make a logical guess regarding this query. Conversely, this type of information could be captured into a database that can be queried within the GIS.
4	Position in relation to rivers and dams and likely impacts on the water resource	The GIS could be used to query this information, e.g. distance from a dam, altitude difference between a water source and the current location, etc.
5	Alternative landuse options	The GIS coverages can be used to assist in this consideration.
6	Assessment of the social and development circumstances of the area concerned	The GIS could be used to assess the biophysical conditions of a given location.
7	Information of ownership, neighbours, beneficiaries and other affected parties	This information may need to be pre-processed, and captured into the GIS. By clicking on a given area or water user, one can then query this information.

8.3 Delineating Water Use Activities

Water use activities can be delineated based on
- hydrological considerations;
- the location of the water use;
- environmental considerations;
- economic considerations; and
- social considerations.

More detail on each of these activities is provided in the following sections.

8.3.1 Delineating water-using activities: Hydrological considerations

The availability of water in a system is dependent on how and where water is used within the system. In other words the scenario generator should be sensitive to the location of water using activities, as well as the nature of the water using activity.

The manner in which water is allocated and used by water uses in a system varies, and the ability of water resource managers to control the use by these users also varies. The manner in which the water is used by the various activities may be divided into three broad categories, including:

- activities for which the source of water is predominantly from rainfall, generally in the form of the portion of rainfall that infiltrates and is stored into soil horizons which is accessible by roots of vegetation;
- activities for which the source of water is from rainfall (in the form of soil water) as well as from water applied by pumping or diverting stored or flowing water onto the lands; and
- activities for which the source of water is independent of rainfall, and is entirely dependent on the pumping or diverting of stored or flowing water to the activity.

The importance of these categories is that *human intervention* is required for the activities obtaining water from the pumping or diverting of stored or flowing water. With respect to the first category, it may be argued that humans are able to influence rainfall via cloud seeding. However, this is the exception and not the rule, and thus rainfall in this context refers to natural rainfall.

Table 3 below illustrates the 3 broad categories of water using activities, and a few examples of each category, as well as important considerations associated to each category.

Table 3 Examples of water using activities and some important considerations

Dependent on:	**Examples**	**Important considerations**
Rainfall	• Dryland agricultural crops • Dryland forestry crops (not in riparian zones) • Domestic water used for gardening purposes	• This category usually pertains to dryland agricultural landuses (including dryland forestry). • There is usually a high reliance on the rainfall for an agricultural crop to be successful • In areas with high rainfall variability, the risk of crop failure is high • Once a dryland crop has been planted, the water use is regulated by a combination of the water available in the soil, the atmospheric demand for water (e.g. a hot vs a cold day), and the biophysical characteristics of the landuse (e.g. root network and dept, leaf area, plant type etc). Of importance is that once planted, the water use is very difficult to regulate (i.e. out of human control). This is an important water management consideration.
Rainfall and human intervention	• Supplementary irrigated agricultural crops	• This category usually pertains to supplementary irrigated landuses. • Supplementary irrigated crops are irrigated when the soil moisture (due to low rainfall, or extreme heat) drops to low levels, and the farmer wishes to protect his crop yield. • The paradox with supplementary irrigated crops is that the irrigation water is required at times when stored or flowing water sources are least available (usually drought periods). • The timing and amount of water that is abstracted by a supplementary irrigator can be regulated by abstraction conditions. In other words, water resource managers can exercise a level of control over when and how water is

		abstracted for irrigation purposes. However, the paradox becomes more apparent in that water resource managers are most likely to want to restrict water use by supplementary irrigation during periods of water scarcity. In other words, the supplementary irrigation farmers will need the water most during periods of low water availability (stored or flowing water), yet it is during these periods that water resource managers will want to regulate the irrigation abstraction the most (in order to attempt to prevent the water availability dropping to dangerously low levels)
Human intervention	• Industrial and mining water use • Water for basic human needs • Irrigated crops	• There is generally no dependency of this category of water using activity on rainfall. For example, and industry may require Xm^3 of water per day (abstracted from a dam say), irrespective if it is raining or not. • Water resource managers can also control the timing and amount of water that can be abstracted by this category of water using activity. • This category of water using activity usually has a higher economic value of water than supplementary irrigated crops, and usually requires a higher assurance of water supply. In other words, although water resource manager may restrict the wateruse of this category of water using activity, the supplementary irrigators will usually faced more severe restrictions. • Water users of this category usually contribute to the development of water augmentation schemes in order to limit the financial loss that may be incurred during periods

Note:
The delineation of the categories above is based water quantity considerations. Further delineation may be required if water quality is considered.

8.3.2 Delineating water-using activities: The location of the water use activity

The scenario generator needs to be sensitive to the location of water using activities with respect to:
- Quaternary Catchment (QC) exits
- Basin exits
- IFR points
- EFR points
- Important engineering structures (Dams, weirs, IBTs, canals)
- Large abstraction points

The sensitivity of the scenario-generator to this level of spatial detail may allow very specific scenarios to be run. For example if it is found that a given QC is stressed, one may wish to assess reducing say SFRAs in the QC. The importance of the relation of a water use in relation to engineering structures is that these structures may have a significant impact on the availability of water in the system. An SFRA located above a dam may have a significantly different impact on the availability of water to the system that the same SFRA located below a dam.

8.3.3 Delineating water-using activities: Environmental considerations

The delineation required here is very similar to considerations related to the spatial location of a water use. The following delineations are important with respect to spatial location of water uses in relation to environmental considerations:

- IFR sites
- Important lakes and vleis
- EFR sites

8.3.4 Delineating water-using activities: Social considerations

The scenario generator must be sensitive to the *spatial location* of water uses in relation to

- international Flow Sites;
- important rural and urban abstraction points; and
- strategic water use abstraction points.

The scenario generator must be sensitive to the *nature of the water use*, giving consideration to the following categories of water use:

- Commercial water use by non-PDIs
- Commercial water use by PDIs
- Non-commercial water use by non-PDIs
- Non-commercial water use by PDIs

8.3.5 Delineating water-using activities: Economic considerations

The scenario generator must be sensitive to the spatial location of water uses in relation to

- irrigation schemes;
- industries; and
- rural and urban abstraction points.

The scenario generator must be sensitive to the *nature of the water use*, giving consideration to the following categories of water use:

- Commercial water use by non-PDIs
- Commercial water use by PDIs
- Non-commercial water use by non-PDIs
- Non-commercial water use by PDIs

Table 4 shows an example of the division of water use into categories necessary for the scenario generator to permit specific scenarios to be generated which are consistent with the NWA (1998).

Table 4 An example of the division of water use into categories necessary for the scenario generator to permit specific scenarios to be generated which are consistent with the objectives of the National Water Act (1998)

Sectors	**Hydrological Division 1**	**Hydrological Division 2**	**Economic Division**	**Social Division**	**Reason for division**
Agriculture/ forestry	Dryland	SFRAs	Comm.:	Non-PDI	• Equity: redress past discrimination • SFRAs: can be regulated, non-SFRAs can't. • Efficiency: how does one assess how efficient a subsistence farmer is?
Agriculture/ forestry	Dryland	SFRAs	Comm.:	PDI	
Agriculture/ forestry	Dryland	SFRAs	Non-Comm	PDI	
Agriculture	Dryland	Non-SFRAs	Comm. & Non-Comm	PDI & non-PDI	• Don't have instruments to influence these water users
Agriculture	Irrigated	Irrigated	Comm	Non-PDI	• Equity: redress past discrimination • SFRAs: can be regulated, non-SFRAs can't. • Efficiency: how does one assess how efficient a subsistence farmer is?
Agriculture	Irrigated	Irrigated	Comm	PDI	
Agriculture	Irrigated	Irrigated	Non-Comm	PDI	
Mining		-	Comm-	PDI & Non-PDI	• Sustainability (water quality)
Industrial	-	-	Comm	Non-PDI	• Equity
Industrial	-	-	Comm	PDI	
Domestic	Urban	-	Non-Comm	Non-PDI	• Efficiency (how does one assess the efficiency of domestic use) • Equity
	Urban	-	Non-Comm	PDI	
	Rural	-	Non-Comm	Non-PDI	
	Rural	-		PDI	
Non-traditional sectors					
	Environmental Division				
Environment	River	-	-	-	• Sustainability
Environment	Estuary	-	-	-	
Environment	Lakes	-	-	-	
International	-	-	-	International	• Equity

Notes:

- Consideration may need to be given to the location of the above-mentioned activities with respect to Quaternary Catchments, important dams, lakes, canals etc.
- More detailed delineation may be required for water quality considerations.

8.4 Water Demand and Supply Scenarios

The SG should be able to accommodate scenarios relating to changes to the demand and supply of water.

- **Changing the demand for water**

The demand for water may be influenced in the following broad ways:

- Direct control
  - Water use licenses and license conditions may be used to directly control how, where and sometime when water is used. This form of water demand management is to be included in the scenario generator, and is discussed in more detail below.

- Indirect control
  - Water use charges may be levied on registered or licensed water users (Perkins, 2000). The charges do not directly influence the use of water. This type of demand management will not be included in the development of a generic hydrologically focussed scenario generator, as it is very difficult to predict how water users will respond to water use charges, and water use trading.

- Suasion
  - Demand for water may be influenced by water resource managers making a plea for certain water users to change their demand for water. The effectiveness of suasion to influence demand is very dependent on the moral fibre of the water users. It is not possible to include suasion into the scenario generator, as there can be no guarantee that society will change demand in response to suasion.

- **Changing the availability (supply) of water in a system**

The water availability (supply) may be influenced by building water related engineering structures, as well as by optimising the operating rules that govern the operation of the engineering structures.

In the next section the direct control of water demand through the use of water use licenses is discussed in more detail.

8.4.1 Direct control of water demand via water use licenses and license conditions

Certain categories of water use require water use licenses to use water legally (e.g. SFRAs, irrigation, industrial water use). Water use licenses legally permit a given category of water use (e.g. irrigation) to be undertaken by the holder of the water use license. There are however generally conditions attached to water use licenses, which further stipulate when, how and how much water a given user may use, and the circumstances under which the water may be used. The scenario generator should therefore be able to accommodate scenarios, including amongst others:

- Issue a new water use license/s;
- Discontinue (remove) a water use license/s;

- Convert a water use license from one category to another (usually applicable to agricultural and forestry related activities); and
- Add, remove or alter conditions associated to a given water use license (e.g. curtailment structures faced by irrigators).

The scenario generator, seamlessly integrated with the ACRU hydrological model and a database, has the potential to assess the hydrological impact of numerous scenarios.

Notes:

- Hydrological impact in this context refers to the impact of water use scenarios on water quantity. However, should suitable water quality models be found, or should ACRU have water quality routines added to the model, the hydrological impact could refer to both water quantity, and aspects of water quality.
- The exact nature of the hydrological model output is not discussed in this document. It is however recommended that a REPORT GENERATOR be developed, which allows the user of the DSS to select hydrological output from a wide range of alternative hydrological output options.

8.5 Scenarios Relating to Engineering Structures and the Operating Rules Associated to the Engineering Structures

Water engineering structures are usually constructed in order to increase the water yield in the system. The scenario generator needs to accommodate:

- The addition and/or removal of water engineering structures, which include, amongst others:
    - o Dams (Reservoirs)
    - o Canals
    - o Weirs
    - o Inter-basin transfer schemes
    - o Changes to the specifications of existing water engineering structure/s. These changes will depend on the nature of the water engineering structure. In the case of a dam, examples of changes include, amongst others:
    - o Changes to the capacity of the dam (e.g. raise the dam wall)
    - o Changes to the spillway of the dam,
    - o Changes to the release capacity of the dam, and
    - o Changes to the dead storage in the dam.

Water engineering structures are usually financed by one or a number of water users. The amount of water a given water user has call to, is determined by the category of water use licenses held by water users having a call on the engineering structures, and the conditions of water use associated with a given water use license (as discussed above). However, there may be operating rules associated to a given water use structure, or combination of water use structures, which may be undertaken to achieve two broad conflicting goals, which include:

- The objective to maximise water yield, and
- The objective to minimise risk associated with flooding.

In order to meet these two conflicting objectives, system-operating rules may need to be developed, which may be triggered when certain criteria or conditions are met. For example, if a large dam is full at the beginning of the wet season, water may prudently be released from the dam to safeguard against flooding (i.e. due to dam over-topping). Information required for system operating rules will include:

- The criteria and/or conditions (at various locations in a catchment), which govern what types of operating rules are to be initiated, and

- The nature of the operating rules associated to the criteria/conditions.

The system operating rules thus govern how water is moved within or released from a system, over and above the water that is released to meet legal water demand.

8.6 Technical Challenges Faced by the Development of the SG: Stand-Alone and Linked Scenarios

The scenario generator should be developed with the following capabilities:

- Credible scenarios need to be scientifically translated into changes on the GIS map.
- The scenario generator must automatically translate the scenario into the correct model configuration.
- The scenario generator must either automatically provide the required model parameter information, or must query the user in the scenario generator for the appropriate information.
- The scenario/s may then be processed through the model/s (which are influenced by the scenarios).
- It is important that the model outcomes be systematically reviewed in the light of a deep understanding of the system (Görgens, 2001).

Notes:

- A distinction is made between a model parameter and a model variable,
- A model parameter refers to information related to the input of the model (e.g. dam size, landuse areas, etc), and
- Model variables refer to the output of the model, which are dependent on the configuration of the model, and the values of the input parameters.

The ability to automatically translate an ArcView generated scenario into the correct model configuration, with the required model parameter information (in this case the ACRU model), will require further detailed design, which is outside the scope of this project. A few technical considerations related to this challenge are however discussed below.

Within the two main subdivisions of scenario categories discussed above (i.e. scenarios related to water use licenses, and scenarios related to water engineering structures and system operating rules), a differentiation can be made between “stand-alone” and “linked” scenarios. These sub-categories of scenarios are discussed below in more detail.

- **Stand-alone scenarios**

Stand-alone scenarios refer to scenarios that have model parameters that do not influence other model parameters. This sub-category of scenarios is probably only representative of dryland crops, of which SFRAs are the most important to water resource managers. The term “independent scenario” may be explained by use of an example:

- If a scenario is run in which say a piece of land currently planted to a non-SFRA is planted to forestry (an SFRA the change to the ACRU parameters (in this case landuse areas) will not influence, or be influenced by other parameters (however will in most likelihood influence model output – or variables). In other words, should a dam be located downstream of the landuse swap, no changes to the dam will be induced by the change in landuse. The scenario is thus independent, in that only model parameters directly related to the scenario are influenced, with no impact on other model parameters.

Stand-alone scenarios should be relatively easy to accommodate, i.e. model configuration and parameterisation should be relatively straightforward.

- **Linked scenarios**

Linked scenarios refer to scenarios that may require further scenarios to be run (or for model parameters not directly associated to the scenario to be changed). For example, if a "build a dam" scenario is generated, a number of other scenarios will/may need to be considered, such as:

- Who has ownership to the water in the dam?
- When and how must the water be released from the dam (system operating rules)?
- Do the license conditions of the new proposed owners of the dam need to be updated to reflect the presence of the dam?
- Does the dam influence the operating rules of other engineering structures in the system?

Linked scenarios may be quite complicated, and thus setting up a linked scenario may require careful adjustments to water use license conditions and system operating rules respectively. The type of scenarios associated with a linked-scenario may be location specific. In other words, the type of scenarios that may be linked to "build a dam" in say catchment A may be vastly different to those in say catchment B. This will require the modelling system to be very flexible, and will also require that linked scenarios are set up and simulated by experienced personnel.

8.7 The Use, Potential Limitations and Opportunities of the Scenario Generator

Although the SG should be designed in a manner that is easy to use, it is recommended that the scenarios generated using the SG are either actively done by, or verified by an experienced hydrologist or simulation modeller. The purpose of the SG is not to replace a hydrologist with computer coding, but rather to allow the scenarios to be generated and run quickly and transparently.

Potential limitations with respect to the SG include:

- Seamlessly integrating the SG with ACRU is a challenge, as consideration will need to be given to both linked, and stand-alone scenarios,
- Linking both the SG and ACRU with a database will require a clear understanding of what information is required in the database, and the format in which the data needs to be stored,
- As the ACRU model is a daily time step model operating at a maximum size of a Quaternary Catchment, the time series data required as model input, as well as generated model output, may take up considerable computer storage space,
- The ACRU model will take quite some time (up to a few hours for a completed simulation) to perform simulations, the output of which may be stored in the database, and
- It is highly recommended that experienced hydrologists or simulation modellers set up, and assess scenarios.

Potential opportunities with respect to the SG include that

- the SG has the potential to facilitate the generation of feasible, transparent scenarios; and
- the SG may continue to be developed to include increased functionality, such as
    - real time systems could use a SG for risk evaluation;
    - the SG could be used with forecasting applications; and
    - the SG could be developed to include planning functionality.

9. EVALUATION OF ALTERNATIVES

The use of the DSS and Scenario Generator (SG) discussed in this document could lead to the generation of large amounts of information. However, more information does not necessarily lead to better decisions (Dent *et al.*, 2000). The belief that all managers need more information to make better decisions misses the critical aspect of information interpretation (Senge *et al.*, 1995). In many cases more information can complicate the decision making process, bombarding the decision maker or model user with large amounts of irrelevant and difficult to interpret information can lead to misinformation and can result in poor decisions. Stertman (1989) has shown that knowledgeable and experienced decision makers filter information through non-systematic mental models before making a decision. Large amounts of information make the filtering process more difficult for the decision maker to sift out the relevant information needed to make a decision.

It is hence critical to refine the information into quantities that can easily be used and interpreted by model users and decision makers. In terms of modelling and the development of a Decision Support System (DSS) the evaluation process requires certain specific sets of information that decision makers can interpret with relative ease. It is thus important to, in consultation with decision makers, identify the critical information requirements necessary for them to make certain sets of decisions.

The model developer and DSS system designer can then summarise the information requirements from the large amounts of information generated, filtering out all unnecessary and irrelevant information before it is shown to the decision maker. It is this summarised information that will be referred to as indicators and is a small set of the necessary information required to make certain decisions. The philosophy in this approach is to use complex accurate modelling and computer systems with highly sophisticated mathematical algorithms to produce simple and easily understandable outputs (indicators) that a model user can base decisions on with confidence.

Essentially this comes down to a problem of visualisation and it is necessary for model developers to identify critical indicators and an appropriate display method. Extensive consultation with stakeholders, water resource managers and other decision makers involved in the CMAs, is necessary to determine the types of indicators that will be needed to make water related decisions within a WMA. It is not in the mandate of this design to identify the different indicators, however, it is possible to hypothesise on the types of indicators that will be needed and the display format that will be most appropriate.

Visualisation can take three main forms namely

- graphical output at specific points of interest within the catchment,
- spatial output that shows descriptions of various critical indicators in a GIS format giving an idea of the spatial distribution in a particular area; and
- specific indicator output at critical points in the catchment.

The types of indicators that may be used for the SEA process could be divided into several different categories each with its own set of unique indicators which may aid in the decision making process. The list provided below is not exhaustive and is only the authors own thoughts on the matter which needs to be investigated in a lot more detail with the SEA team, stakeholders and water managers alike.

- Water use
    - Water use on an annual basis

    - Water use during critical low flow periods
    - Mean annual streamflow reduction
    - Streamflow reduction during critical low flow periods
- Water availability
    - Probability distributions of water availability for the catchment as a whole
    - Probability distribution of water availability for individual users in the catchment area
    - Minimum amount of available water to the system as a whole
    - Minimum amount of water available to specific water users
- Economic variables
    - Income produced by specific users per unit of water used (annual or low flow)
    - Income produced by a SFRA per unit of streamflow reduction (annual or low flow)
    - Income produced by specific landuse activities outlined above in terms of overall water availability of the system (System yield)
- Social variables
    - Jobs generated or lost by certain water and land use activities
    - Status of water use in poor communities
    - Water availability to poor communities and underdeveloped areas
    - Water availability to previously disadvantaged communities or individuals
- Environmental
    - Streamflow probability distributions at specific areas in the catchment produced from both pristine and developed conditions to establish and conform with environmental flow requirements
    - Biodiversity impacts as a result of different land and water use options
    - Downstream impacts on conservation areas

Once the different indicators have been identified or derived and the best method of visualisation chosen to display the different indicators is selected, it is necessary for the decision maker to use the information to make the decision. The problem the decision maker is now faced with is how to compare the information produced from the different scenarios being tested with one another. It is also necessary for the decision maker to make decision from indicators, which have come from vastly different disciplines. The decision maker must therefore attempt to weigh up the decision using different indicators from various disciplines on an equal footing. Added to this problem is the aspect that certain social and environmental data is ordinal and subjective while other aspects are derived through scientific means and represent real quantities such as water use.

It may hence be necessary to have an objective criterion of ranking and scoring the different indicators in order to transform them into a specific solution that can then be used to compare different scenarios. This can be achieved through several different methods such as Multi Criteria Decision Analysis (MCDA), Analytical Hierarchy Process (AHP) and Cost Benefit Analysis to name a few (Stewart *et al*., 1997). Each method attempts to assess the alternative by translating variables (indicators) into quantities that can be assessed on an equal footing. Once this type of scoring has been collated together it is possible for the decision maker to then analyse the different options that have been produced by the different scenarios being tested. In such a manner the decision maker can weigh up the different options available and understand the trade offs that result from the different options.

Working within a structured framework with proper indicators will result in the filtering out of irrelevant information and provide the decision maker with that information needed to produce a responsible decision. The assessment of alternatives is a difficult process to automate as it tends to include many subjective criteria. While it is the responsibility of the DSS tools and models to provide the necessary information (indicators) that will aid the assessment process it is not its responsibility to provide the ultimate output and decision. It would be better for the DSS to provide the framework that can automate the assessment of alternative criteria through extensive input required from the user in terms of weighting and scoring criteria. It may also be necessary to provide the outline on the methodology to follow in the assessment of different alternatives. This, however, falls outside the scope of this component of the project and will need to be pursued when the DSS is being developed.

Once the information on different alternatives has been generated and assessed this may lead to the identification of new problems and a feedback loop as shown in Figure 1 could occur where and iterative approach to problem solving is taken as more information becomes available and can be assessed.

10. ANALYSIS OF DECISION SUPPORT SYSTEMS

In the context of this review the DSSs will be analysed in their ability to support the SEA in its objective of developing an overall framework approach to ensure South Africa's water resources are utilised optimally in the short and long term to the best benefit of the people and environment of South Africa.

In this project the definition of a DSS will be formulated in terms of a system that will provide the information required to service water managers at the CMA level in terms of the NWA (1998). It must also be stated that in the course of reviewing the different DSSs currently developed or in place, that it is unlikely that they will fulfil the requirements of the SEA and CMAs as they will have been developed to address different problems and concerns.

10.1 Literature Review on the Different DSSs Used in South Africa

The review in this document is based on the review given in a WRC report by Görgens and Jewitt (2000) which was based on the review and testing of the different DSSs which were available in 1995 when the tests took place. Where possible new DSSs have been included in the review and updated information has been obtained on some of the systems. In this section common features pertaining to the various different DSSs are included and their application in terms of the requirements of CMAs will be assessed. Short reviews of all the different DSSs follows.

- **Catchment Management Support System (CMSS)**

Catchment Management Support System (CMSS) was developed in response to the needs of various organisations involved in catchment management in Australia (CSIRO, 1994, as cited in Jewitt and Görgens, 2000). It is a computer program, operating on a PC workstation in a graphical environment, used to assess likely changes in nutrient loads entering streams as a result of catchment landuse changes. Its design philosophy is based on the implementation of simple relationships between selected components. Input data are landuse, nutrient generation rates and management practice data. Output is a simple function of these inputs and is presented in the form of high quality colour graphs and maps, although the system does not place great emphasis on the GIS link.

The lack of linking to a GIS and the inability to incorporate other variables such as economic and social criteria are limiting factors for the use of this system.

- **GIS linked with Geographic Information Query, Analysis and Modelling (GIQAM)**

The aim of this system is the automation of information retrieval in support of complex GIS query, analysis and modelling. This system has the potential for the analysis of the spatial distribution of temporal trends in climate events, modelling spatio-temporal interactions in meteorological events and assessing the socio-economic impacts of extreme events in time and space depending on the information available (Yan, 2001).

This system is still in the developmental stages, although it does offer many of the advantages of linking GIS with modelling and could perhaps be an appropriate methodology to adopt in the design of the WMA DSS.

- **Catchment Centred Resource Assessment and Management System (CRAM)**

CRAM was developed as an integrated catchment management system by the CSIR using the Crocodile River as a prototype (Meyer and Scholes, 1994, as cited in Jewitt and Görgens, 2000). It is a hydrologically based system, which allows for the simulation of environmental, social, economic and hydrological impacts resulting from changes in the catchment.

The system is designed to be easy to use and navigate, with user input being guided by Graphical User Interfaces (GUIs). The system is linked to GIS and utilises an efficient database management system.

The major weakness of the model is the simplistic algorithms used to simulate the hydrology, in particular, but also in the other aspects that are been simulated (Jewitt and Görgens, 2000). CRAM could be used as a simple scenario generation or gaming tool, however, the model output cannot necessarily be accepted as accurate. The CRAM system is highly simplified and has become outdated.

- **G2-AEAM**

The G2 model is developed by utilisation of the adaptive environmental assessment and management process (Holling, 1976; Walters, 1986 as cited in Jewitt and Görgens, 2000). The AEAM process involves the development of simulation models in a multi-disciplinary workshop environment. Modelling algorithms are developed for predefined spatial and temporal scales by subgroups of the workshop. The algorithms that have been developed by the different subgroups are then returned to the workshop and entered into the G2 models basic shell. The model is then run to return simple graphics operating on real time, which represent the output of the model.

The obvious weakness is the limitation of the algorithms produced and the generalisation that may occur as the model is normally run at a regional scale with monthly time steps. The methodology does, however, produce some success through the workshop environment as consensus is achieved through the various expert groupings regarding the algorithms used in the model. The model is put together easily and results are available for discussion in a simple and usable form within the workshop. Once the model has been completed and run the discussion between the different participants is reported to be very useful.

The simplified nature of the modelling makes this system unusable for the decision making needs of a CMA.

- **HSPF – ANNIE**

This is more of a useful modelling system than a DSS, which manages and displays data stored in the WDM. ANNIE has a text based user interface. This system has, however, become outdated and has been superseded by the HSPF – BASINS link described next.

- **HSPF – BASINS**

The BASINS system was developed by the US EPA to help address water quality issues in the USA. The system uses ArcView as the framework to provide users with a fully comprehensive catchment management tool to particularly address water quality issues. BASINS was developed to take advantage of recent developments in software, data management technologies and computer capabilities. BASINS addresses three primary objectives which are

- to facilitiate examination of environmental information;
- to provide an integrated watershed and modelling framework ; and
- to support analysis of both point and non-point source pollution management alternatives.

BASINS consists of interrelated components required for catchment and water quality analysis such as local databases, assessment tools, models and post-processing output tools. The system has strong links to the HSPF model. The system is being constantly updated and new versions are released from time to time.

The BASINS-HSPF link offers many opportunities on the catchment management front. There are, however, limitations in terms of the database management (cf. Section 7.6). The system does not include socio-economic data and as it is not locally developed the incorporation of these variables could be both time and resource consuming.

- **HYMAS**

HYMAS (Hughes, 1994, as cited in Jewitt and Görgens, 2000) is a “DOS based shell used to operate several hydrological related models” which include the VTI and PITMAN models. HYMAS has a menu-driven user interface, which is both user friendly and easy to use, although at this stage it is only keyboard driven. This model uses a binary database, which has the ability to store data in a variety of a time steps, and allows the user to manipulate time series and edit input information for a variety of different models. HYMAS has a number of post-processing options, which allow for numerous different useful output options to be used.

HYMAS is restricted to the DOS platform and has no GIS link. It is, however, well written, easy to use and offers sensible options to the user. It does not at present incorporate social and economic data.

- **MIKE – 11**

MIKE-11 is a professional engineering software package, which incorporates modules for the simulation of flows, water quality and sediment transport in rivers, estuaries, irrigation systems, channels and other water bodies. MIKE-11 offers features such as a fast and robust numerical scheme; advanced cohesive and non-cohesive sediment transport modules as well as comprehensive water quality and eutrophication modules (MIKE-11, 2001). In addition, this model provides links to advanced hydrological, sewer and coastal modelling tools. A simple SCS based rainfall-runoff module is also included in the package. This system can be used under both DOS and Windows and is relatively user-friendly. Physical catchment and channel parameters are input into the model and the system allows the import and export of data in a number of commonly used ASCII formats. Graphical representation of simulated results is possible within this system.

Time series management is, however, not available and no land based water quality simulations are possible. A major disadvantage of MIKE-11 is its high cost.

- **The Modular Modelling System**

The Modular Modelling System (MMS) (Leavesley *et al*., 1994, as cited in Jewitt and Görgens, 2000) "has been developed as a common framework in which to focus multi-disciplinary work". MMS is operated through an X-windows based GUI on a UNIX based workstation. Data may be geographically represented and manipulated by means of the pre and post processing tools available. The system provides tools for linking process modules representing various catchment processes. A GIS link has also been developed. Other modules may be added provided they conform to the programming norms. Such modules may be written in FORTRN or C.

The model however offers little user-support and is somewhat complex requiring an extensive amount of time to become proficient in the system.

- **RAISON**

RAISON (Regional Analysis by Intelligent Systems ON microcomputers) is a Windows software package developed for ecosystem management on a catchment basis. It is a versatile environmental information system with built in expert system capabilities designed specially for decision support applications. RAISON offers a broad framework that allows for the integration of data, spreadsheets, text, maps, objects and knowledge input. In addition, there are also numerous user-friendly tools offered by the system thus enabling the user to produce output for interpretation, integration, advice, classification, analysis and recommendations. It is particularly suitable for applications which involve point (e.g. monitoring sites) and polygon (e.g. land use) data.

RAISON is able to import from, or export to, many commercially available databases, spreadsheets and GISs. RAISON includes an expert system for knowledge acquisition to provide a link between numeric and descriptive knowledge which is required for decision support and environmental information. It also offers a map-based GUI, which is customised for each application.

The RAISON software package is the most comprehensive DSS tool analysed in this document. It offers the integration of economic, environmental, social and hydrological data. This software is however relatively expensive and there is no local support available.

- **SWAMP – HYDRA**

The HYDRA system (Davies *et al*., 1994, as cited in Jewitt and Görgens, 2000) has been developed in order to connect pre-existing modules. The proto-type system SWAMP has been developed around the HSPF model. The HYDRA system builds upon advances, particularly in the in the field of databases, in the integration of GIS with other models. The system comprises a GUI developed on the basis that the water resources manager is the primary user and as a result options revolve around likely management questions. The central component of HYDRA is a system manager, which controls all model-model and model-user communications. The systems manager has its own local database which stores the data required by the various active model components. A library of existing models, each with its own driver, is also a component of HYDRA, each of which may be integrated by the system.

A disadvantage of this seemingly sensible system is the high level of computer science and information technology required.

- **WDM Guide**

The WDM Guide was developed as a prototype information system (Van Rensburg and Dent, 1997). The software runs under Windows or on a UNIX workstation and is based on ArcView Version 2 and its associated Avenue programming language. It provides flexibility to the user by utilising the multi-tasking facilities of the UNIX and Windows operating system. The system is user-friendly; it has a mouse and menu driven interaction with time series stored centrally in a WDM file on a workstation accessible through the Internet as well as image and ARC/INFO data sets, which reside locally on a PC.

Features of the WDM Guide include graphical query of selected variables at any point in the selected stream network. It is also able to query and plot a number of variables simultaneously. The system allows the query and display from available images per sub-catchment as well as the animation of monthly time-series of a selected variable. In addition data is accessible via remote networking.

The WDM Guide is based largely on easily available commercial software, to which simple functionality may be added by use of public domain software tools. This software has been outdated and superseded by the use of the BASINS-HSPF system.

10.2 Analysis of DSSs Available

Table 5 Summary table of attributes of the DSSs analysed in this document

DSS	Easy to use	GIS linked	High cost	Graphical output	Model/s used	UD / outdated / user support	Social / economic options
CMSS	Yes	Not really		High			No
GIQAM		Yes				UD	No
CRAM	Yes	Yes	No			Outdated	Yes
G2-AEAM							No
HSPF-ANNIE						Outdated	No
HSPF-BASINS		ArcView			HSPF	UD	No
HYMAS	Yes	No		Low	VTI and Pitman		No
MIKE-11	Yes	Yes	Yes	High	SCS based	UD	No
MODULAR	Yes	Yes		Medium		Little user	No

MODELLING SYSTEM						support	
RAISON	Yes	Yes	Yes	Yes		Little local user support	No
SWAMP-HYDRA	Yes	Yes		Yes	HSPF		No
WDM Guide	Yes	Yes		Yes		Outdated	No

UD = Under development

Out of all the systems analysed possibly the most promising options are provided by the RAISON modelling system and the Mike 11. Both systems are able to cope with data input and query and store data in a spatially referenced format. The Mike 11 model seems to concentrate more on the hydrological side of data capture and manipulation with a suite of models accessing the database. The RAISONs system looks like it would be able to cope with many different data formats and could possible be used to store and manipulate social and economic data. As it has been described as been able to store and manipulate both numeric and descriptive data. While no system would be ideal in solving the problems introduced by the NWA (1998) the RAISON system looks the most promising. The system is however extremely expensive which could make its use prohibitive and there is very little local support available. The best options in terms of the DSS is perhaps to develop the system from scratch making sure that it has the ability to cope with economic, hydrological, social and environmental data. The modelling tools associated to the system would then be local and designed to suit local conditions and data.

11. DESIGN IMPLEMENTATION PLAN

While the rest of this document has concentrated on the generic issues of concerning the design of a DSS to support the DWAF SEA in implementing SEA principals and practice at a WMA level, this section goes into the more specific needs of the DSS design being proposed.

The DSS has three major components that need to be implemented in the design and are shown in Figure 7.

- A database component which can be used to store data in a structured and easily accessible format
- A processing component which comprises of a set of modelling tools that can transform data into information
- A visualisation component which will enable users to view information in an understandable and visually pleasing format.

Each phase of the design will be discussed individually and the processing needs and requirements will be outlined. The actual design and implementation will need more thought than is shown in this document as a more accurate idea of the exact specifications should be known. This section, however, will give a breakdown of the processing requirements and the tools best suited to fulfil the purpose.

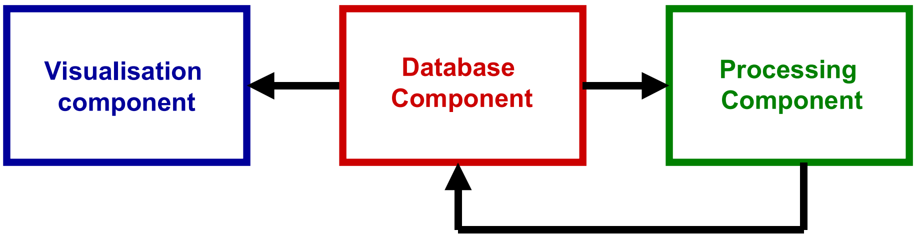

Figure 7 Major components of the DSS design

11.1 Database Structure

In this document the database used will be referred to as a generic structured database. It will perform two main functions, which are

- storing base or raw data such as streamflow and rainfall records; and
- storing simulated information generated from different models and tools, which draw from the database.

The most important attribute of the database is that it needs to be able to store:

- spatial data;
- attribute data; and
- time series data.

To achieve these goals it is necessary to look at the latest available technology that allows for flexibility in the data storage. Unfortunately, at present, there is no system that is able to link spatial data with time series data and a viewing platform in GIS. The database used by the ArcView GIS is dBase file format. This requires the data storage in a flat file format that can produce a large amount of redundancy, and is not easily queried. A relational database has the ability to reduce redundancy and allow for easier query options to be developed. The ARC/INFO and ArcView systems are being developed to incorporate relational database facilities, these are however not available at present.

In order to achieve this requirement of linking spatial, time series and attribute data together, it is necessary to link a GIS with a relational database. This methodology will allow the user to store attribute, time series (simulated and observed), and spatial data together in an accessible and functional format.

The BASINS system used in the USA has been designed to perform a similar operation to that described above, linking time series data with the ArcView GIS, using the WDM database. While it may appear the using an existing system such as the BASINS system which has been developed in the USA to perform the database functions is ideal there are several problems with using such as system which have been outlined in Section 10.1. When having a look at the option of using an existing system it is necessary to weigh up

- the time and expense that it will take to translate the data into formats compatible with the existing system; and
- the time it will take to develop the system with all the necessary requirements from scratch.

In the time frame of this project using a system such as BASINS will require an enormous amount of time to translate South African variables into those that are compatible with those used in the USA. It also brings with it all the concerns raised in Section 10.1 and ties the modeller down to one specific model. It was believed that for the purpose of this project it would be better to look at local efforts in terms of database development and use already constructed systems which can be conformed to and enhanced. This allows for less requirements in terms of translating the different variables into usable quantities and also allows more flexibility in post development support and modification as there is no dependence on development skills in other countries who's system you are tied in with.

The database design will therefore take on the form of a coupled system, which will link a relational database to the ArcView GIS. The databases that have been proposed for use consist of various relational databases include

- SQL;
- Oracle;
- Microsoft Access; and
- Informix.

The design of the database system is aimed at a PC platform. It appears the Oracle ArcView coupling looks like the most promising option in producing a spatial relational database link. The DWAF Geohydrology department is using the Regis, data storage system which already employs the ArcView Oracle link. There are some limitations especially in terms of the number of simultaneous access points that can be used by the access system and its inability to handle extremely large datasets. It is therefore clear that the other options such as SQL, Oracle and Informix offer the best opportunities in terms of database development.

The database design will follow the standards produced by the integrator, making sure that the database structure and architecture conform with the DWAF standards regardless of the database chosen to store the data. In such a case the system can be relatively easily translated if the data needs to be stored in another database at a later stage.

The database will house the data through a linked table format that associates a set of attribute or time series data to a spatial attribute code. The spatial attribute code, will then link to the GIS through a linked table which contains the spatial attribute code and the GIS attribute code which is associated to the data stored in the GIS. This format allows a “many to many relationship” to be used in the database and link the attribute and time series data to the GIS data. This feature should also allow the manipulation of spatial data and its associated attributes.

The construction of a spatial database that links GIS with a relational database is a time consuming process and needs much consideration on the specifics of how the data is going to be stored. This aspect is beyond the scope of this design as it requires more specific information. The database should conform with the standards proposed by DWAF as far as possible and should use the full range of capabilities afforded by linking a GIS to a relational database. The most likely storage facility to use would be the Arcview GIS linked with an Oracle database and most of the programming will probably done using Visual Basic coding as this is the new base language for ArcView 8. Regis and other systems presently used in DWAF will need further examination to prevent the duplication of effort.

The data stored in the database can further be classified into invariant and variant data (Figure 8). Invariant data is data, which comprises of mainly attribute data that will remain constant throughout a particular simulation or set of simulations such as soils and topographical data. Invariant data can include other data that can change over time, such as rainfall and temperature data, but remain constant for the simulation scenarios being tested.

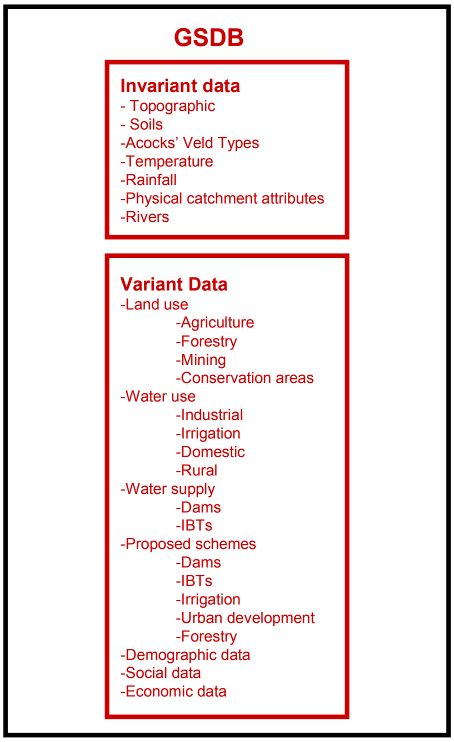

Figure 8 Some of the invariant and variant data requirements for the DSS

Variant data (cf. Figure 8) could be defined as data that can change dynamically over time or from scenario to scenario and is essentially land and water use data. Variant data also includes planning data such as the proposed constructions of new schemes. Simulated data is essentially variant data that also needs to be housed in the database. All the data should have a spatial component attached and be linked with the GIS.

Invariant data can be parameterised and placed into a model directly through the use of an attribute builder, which converts data from the database into parameters that can run the model. The variant data however might need to be manipulated and go through a transformation process before it is incorporated into the model. This could be done through the use of a Scenario Generator, which could be used to manipulate and change the initial primary data. An attribute builder could then be used to transform the data into parameters used by the model. The models once run also produce variant data, which will need to be stored in the database for query in the visualisation process. The processing required to perform these functions will be discussed in the next section.

11.2 Processing Component

There are several different processing requirements needed in the DSS. Initially there is the need to convert data from the database to the required format of different modelling tools being used in the DSS. This initial phase includes the attribute builder and Scenario Generator (SG).

The second level of processing occurs in the models themselves and manipulates the various inputs into the outputs required from the models. The third stage of processing is the transformation of model outputs back into a format suitable for the data storage.

The final level of processing required is the visualisation component and is the interpretation of both stored base data and stored generated (simulated) data into indicators that the decision maker can use. The first three phases will be addressed in this section and essentially deal with the primary processing components and not the visualisation.

Figure 9 is a systematic diagram showing the processing component and how it is linked to the database component of the design. The SG and attribute builder combine to manipulate the data into a format that is suitable for use in the different models. From the figure it can be seen that the invariant data feeds straight into the attribute builder, which feeds into the different models and tools. The variant data is transformed through a SG and is then fed into the attribute builder to be processed in the different models. The SG therefore allows the user to manipulate the invariant data changing it to suit the scenarios that need to be tested. The SG and the attribute builder are inextricably linked and are the basis of the processing component as they provide the input data for the different modelling tools.

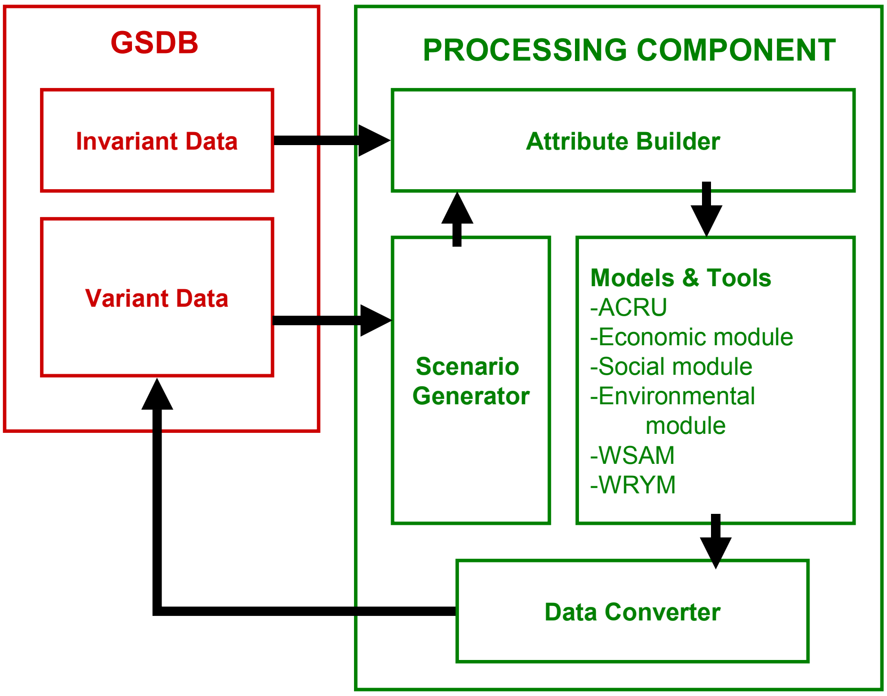

Figure 9 The processing component of the DSS

11.2.1 Scenario Generator and attribute builder implementation plan

The development of the SG will require the seamless integration of ArcView (or a similar suitable GIS package), the new ACRU model and other modelling tools being used in the DSS, and a relational database.

There are several large challenges that need to be addressed in the system integration:

- The SG must be easy to use. This will require well designed and complete graphical user interfaces (GUIs) and communication with the ArcView GIS.
- The scenario options must be relevant, and consistent with the NWA. Water use activities may need to be sub-divided in order to be consistent with the NWA.
- The generation of the scenarios must be understandable and transparent to stakeholders.
- The SG must be able to accommodate both linked and unlinked scenarios. This will require a very clear understanding of water resources management (demand and supply side management) and how this may be coded into a system.
- The SG needs to be linked with the relational database. Scenario simulation results may be stored in the database.

The SG could be used for the testing of individual licenses where it is already known what type of development is being instituted or addressed and also used to incorporate planning scenarios where the information may need to be processed before the chosen scenarios can be run. For example population projections may need to be modelled to determine future water use in some areas.

In this phase the DSS will be compiled in such a way that different scenarios can be quickly and effectively generated using Graphical User Interfaces (GUIs). This section requires the seamless integration of several models including the economic and hydrological systems, which, once the user has defined the inputs, will run in the background to produce the results. The outputs will then be generated using GUIs with different indicators showing the results of the scenarios. This is, however, addressed in the visualisation phase. Both the inputs and outputs could be spatially referenced with outputs given in GIS format. The seamless integration is a time consuming process and would need to be programmed using an object orientated programming language. This way future changes or additions could be made relatively easily. It has been suggested that Visual Basic be used as the programming language as it interfaces with most Microsoft office applications.

The attribute builder takes the output from the both the SG and the database directly in the case of invariant data as shown in Figure 9. The attribute builder allows for the quick setup of certain parameters that need to go into the model directly. These parameters can be obtained from the database in terms of invariant data but may need manipulation using a GIS before they can be placed in the model. The processing and manipulation of this data may be time consuming, it is therefore recommended that in the case of the invariant data that these manipulations could be reduced if the actual parameter data is stored in the database directly after manipulation and is only changed using the attribute builder if the data is updated or a change in the model configuration is needed.

The SG information will however still require the full manipulation. The attribute builder needs to perform both GIS manipulations as well as plain programming processing. It has been recommended that the new ArcView 8 system be used to perform the GIS manipulations and that the Visual Basic programming language could be used as the base programming language to process the data and develop the GUIs needed in both the inputs required for the SG and the attribute builder. It is recommended that the outputs from the attribute builder should be produced in XML format, which is highly versatile and is easily transformable into other types of data formats needed to feed the model as well as giving the option of automated error checking. It has also been suggested that the menu format that will be used for the new ACRU is the XML. There are however several different types of modelling required in the processing phase of the DSS, which will be discussed in the section to follow.

11.2.2 Modelling tools required in the processing phase of the implementation plan

Hydrological, economic, social and ecological modelling will be required to be performed using the DSS in the processing phase as detailed in the following sections.

- **Hydrological modelling component**

The hydrological modelling component will be performed mainly with the use of the new ACRU modelling system. This system is currently under development and at a later stage will be able to perform process based hydrological modelling that is able to address the operational hydrology in a system and water quality concerns.

The DSS, however, is not tied to one modelling system and more hydrological models could be used if necessary. It will, however, be necessary to write a transformation routine (attribute builder) for any new models that would be added on. The DSS structure, which is shown in Figure 9, is not model dependent. New models can be added to the system when and where appropriate. The database therefore could be used to provide data and house simulation results from a number of different models such as WRYM and WSAM.

➢ **Economic modelling component**

Developing an economic modelling component that combines feasibility criteria, yield potential and economic viability in a spatial framework is required. This will allow a decision maker to better understand the economic implications of particular land use management practice scenarios.

This task can be split into a two different main sub-tasks. The first sub-task is aimed at determining the feasibility of growing different crops under the various climate and topographic conditions. The second sub-task will aim at determining the economic viability of producing those particular crops in that specific area. Figure 10 is a schematic showing the different aspects of the economic modelling component of the project.

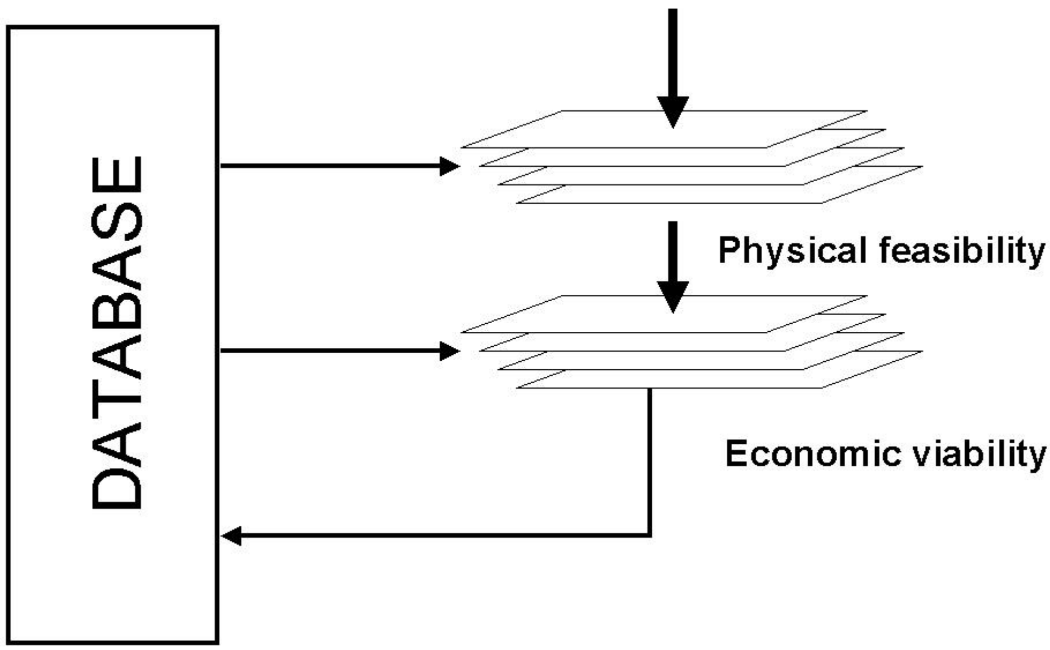

Figure 10 Economic modelling component of the DSS

The feasibility of growing a specific crop in a specific place is a combination of a number interacting climatic and geophysical factors. In order to determine the feasibility of growing crops in certain locations requires both climatic and topographic data along with the crops biophysical requirements.

A spatial representation of the yield potential could then be obtained by extracting both topographical and climatic data from the database in a GIS format. The different biophysical factors such as temperature, rainfall, soil depth and aspect, can then be weighted in a linear algorithm, which could then be used to determine the physical feasibility of growing a crop in a particular place. This is effectively equivalent to placing a number of different layers of spatially referenced information over one another manipulating each layer according to certain criteria to determining the potential crop yields in these areas (Figure 10).

In the initial feasibility study crop potential could be determined using the growing degree day concept, where yield potentials will be determined by the average temperature and rainfall conditions. They could be determined by the use of a crop growth model. The ACRU model is able to produce some estimates of crop yields but not the full range that may need to be looked at. It may be necessary to use a model that has been specifically designed to do crop modelling in this component of the study. Areas where crop growth is extremely unlikely will be excluded from the potential crop growth areas using a filtering process. While an area may potentially support a wide variety of crops other factors such as distance from markets and transport routes may restrict a specific crop's economic viability. Even if a crop can grow in a specific area it does not mean that it is economically sound to do so.

Once the physical feasibility of growing specific crops in certain areas has been determined, the economic viability of doing so must be investigated. Economic information thus also needs to be combined with the crop yield potential to determine the economic viability of growing a selected crop in the area. The database will hence also need to contain continuously updated data on crop sales prices both nationally and internationally, as well as value added information such as processed product costs, transport costs and number of people employed. This aspect of the economic component of the DSS will require both the manipulation of spatial referenced data and pure data. Spatial information will comprise of different aspects such as access to markets due to distance from transport routes, distance from the river in terms of irrigated agriculture amongst other spatial data. This section will take on a similar form to the physical viability as different layers of information will be given weightings that will help to determine the economic viability (Figure 10). Initially a filtering process will be used to eliminate areas that are totally unviable.

This will require a multidisciplinary team, including GIS, economic, hydrological and agronomic expertise. The initial system will be set up to account for a broad range of crops with only a few different genus included for the larger species. The database can be modified when more information is required.

- **Social modelling component**

This component will again consist of the use of both GIS technology and regression modelling. It will allow for a similar structure of that in the economic modelling component which has several different layers of information that are draped over each other with certain specific weights to produce social information that could be used to generate indicators that could aid the decision maker.

In this design the main concentration has been on the hydrological and economic modelling. Further studies are on the way to collect and determine specific social values that could be used to aid water managers and decision makers in assessing different water uses in terms of the equity, efficiency and sustainability criteria outlined in the NWA (1998). These could then be used in the SG to aid the development of different scenarios, which can be easily tested.

- **Ecological modelling component**

Ecological variables could be determined in much the same way as those in the economic and social modelling components. This component will require extensive GIS modelling where layers of information, such as biodiversity and conservation areas, could be draped together with different weights to determine certain ecological indices.

These indices could then be used to limit certain scenarios in the SG. Some ecological data will be generated in the hydrological modelling where impacts on the ecological reserve could be estimated. The ecological modelling is a subset that needs to be considered in the main structure of the DSS but is not the focus of the initial development, which is concentrating on economic and hydrological modelling.

11.3 Visualisation component

The visualisation component consists of two main aspects (Figure 11). The initial part is the translation of variables produced by simulation scenarios and base data into indicators that could be used by the decision maker and the second aspect is the display system used to display the different indicators in a suitable format that can be used by the decision maker.

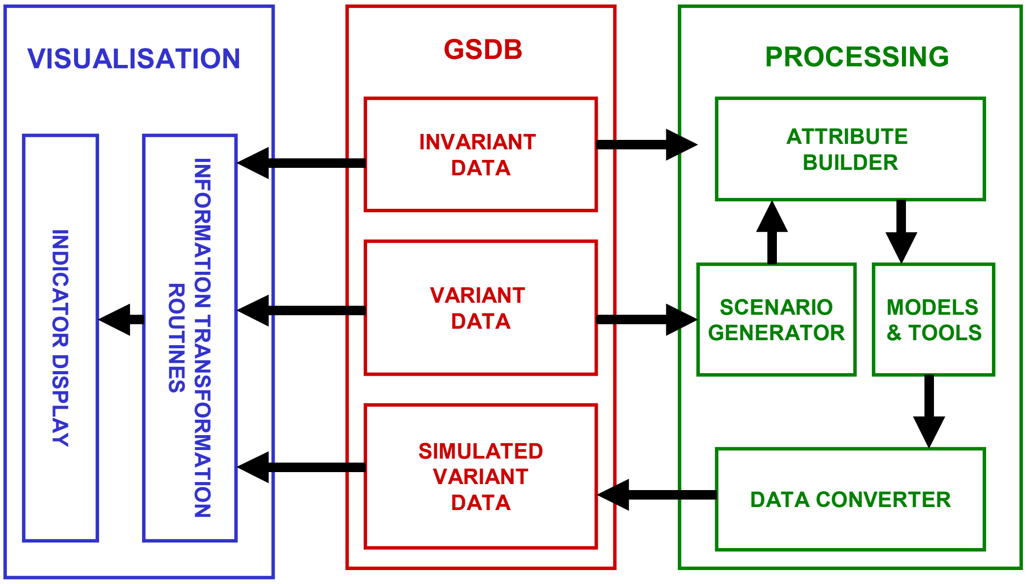

Figure 11 The visualisation component of the DSS and the linkages to the database and processing components

Before either of these phases can be embarked upon it is necessary to determine the types of indicators needed by the decision makers and stakeholders. This process will require a lot of consultation between the various parties involved in CMAs. Once a generic set of indicators has been defined the system could be put into place to generate the indicators from the database and visually display them.

The display format would need to combine GIS with other systems and be able to display results at certain points in the catchment of interest. It is recommended that the ArcView 8 system be used for display purposes. This could tie the use of the DSS to the ArcView format.

It was suggested that other display options such as Map Objects be considered for display purposes, however, the manipulation functions available in Map Objects are limited. The data manipulation needs to process both vector and rasta data this is not available in the Map Objects system.

The most likely programming language to be used for the visual display option is Visual Basic as it is designed specifically for display purposes and it is able to communicate via Visual Basic application programming to the ArcView 8 system as well as most Microsoft applications. The summarisation and translation of variables into indicators could be performed with any programming language, however, in the interests of consistency Visual Basic should perhaps again be used.

The visualisation component is exceptionally important (as it is the information provided by this component that the user will base a decision) in the system design and will need to be comprehensively thought through before embarking on any coding begins.

12. CONCLUSIONS AND RECOMMENDATIONS

The National Water Act (NWA) was revised in 1998 in response to political change in South Africa and a realisation for the need for sustainable, equitable and efficient use of water in a water scarce country. With the establishment of the new NWA (1998) came the delineation of South Africa into 19 Water Management Areas (WMAs) which are to be governed by Catchment Management Agencies (CMAs). The Strategic Environmental Assessment (SEA) is expected to provide both information and tools to support decision making of CMAs.

Development opportunities within the WMA need to be considered against other viable options for water use in that area. These different scenarios need to be modelled to simulate their potential impacts in the catchment thereby allowing a decision maker to review the implications of different scenarios. To allow comparative evaluation of alternatives requires a wide range of inputs for a range of scales to facilitate a selection of feasible scenarios to be assessed. These inputs will be required to be stored in a database, which is then linked to various models to ultimately form a Decision Support System (DSS).

The DSS in the context of this document is defined as a set of tools that will enable CMAs to develop their Catchment Management Strategies (CMSs) and assess individual license applications. The DSS is required to incorporate hydrological, ecological, biophysical, social and economic elements of information for processing by decision makers. To access this information requires the design of a Scenario Generator (SG), which will facilitate comparative analyses of the hydrological, economic and social implications of changes in land use or engineering structures.

The first step in the decision making process is the acquisition of information. There are two key components in the information acquisition phase, namely the problem identification and the problem structuring phase which is required to help the decision maker in formulating a decision.

To order to identify which problems will need to be addressed by a CMA information will need to be collected on demographics, issues of public concern and environmental issues in the area for example. This will assist in defining the problem framework. The CMA is required to establish the principles for allocating water to both existing and prospective water users within their respective WMA. To do this the CMA must take into account all matters relevant to the use, development, conservation, management and control of water resources. The CMSs developed by CMAs must be in line with the broader strategies established by the National Water Resource Strategy (NWRS). The CMAs are therefore responsible for both longer term planning for the WMAs and the short term processing of individual water licensing applications.

The information required for the DSS can be divided into three categories: data requirements, modelling requirements and stakeholder participation. Each of these information requirements was investigated. It was identified that the central focus of any CMA is the water allocation plan, which requires the identification of the allocatable quantity of water in the catchment, the projected water demands and the developmental constraints.

To establish the water allocation plan information is required on the current water use. The reserve is perhaps the most fundamental aspect of allocatable water determination. The reserve is defined as the quantity and quality of water required for basic human needs, as well as the quantity and quality of water required to sustain the aquatic ecosystem. While the basic human need reserve remains relatively constant, the environmental reserve fluctuates on a daily basis in some cases on a sub daily basis. In order to implement the reserve at a catchment and sub-catchment level the CMA will need water quantity and quality information on at least a daily basis from both its modelling and monitoring systems.

When assessing individual license applications the CMA needs to establish whether the application is in compliance with the CMS and the NWRS, whether it fulfils the equity, efficiency and sustainability criteria set out by the NWA (1998) and whether the impact of this activity is acceptable in terms of other users and the environment.

To address these and other issues modelling is required to provide social, economic, hydrological and environmental information to estimate what the potential impact of the activity under investigation or for which a license in being applied. In the NWA (1998) there is a strong emphasis on stakeholder participation which places new demands on the models and tools which are used in the decision making process. Information generated from models now needs to gain the trust of the stakeholder community in order to be accepted in decision making. To achieve this the information generated from the model or models must be credible, trusted and promote shared understanding. The processes which yield this type of information therefore need to be replicable and consistent, offering regular, affordable and meaningful communication among stakeholders and their representatives.

To set up an allocation plan several different levels of information are required. While the majority of the information required is in the form of raw data, such as landuse, water use, demographic information and biodiversity data, some information needs to be generated with the use of models, particularly in the case where planning projections are needed to expand beyond the catchments or WMAs current status.

To determine current land and water use requires physical process based water quantity and quality models operating at daily time steps, and operational models operating at daily to weekly time steps

The modelling requirements associated with determining water demand projections include Geographic Information Systems, simple mathematical algorithms that use indicators to assess future water demand projections, processed based hydrological models to assess the impacts of different scenarios and operational system hydrological modelling.

To date in DWAF a multi model approach has arisen to address the multitude of problems that arise in catchments with each model designed to accomplish a certain task. These models are then fed into each other using a series linking approach. While the multileveled, multidisciplinary, multi-model modelling approach does offer many advantages in choosing the level of detail which modelling can follow there has been some concern levelled at this particular approach in the international community. The concern is related to the linkage of different models without complete understanding of the linkages themselves. Added to this concern is the detail required in the implementation of the NWA (1998). Monthly modelling approach adopted by the Pitman – WRYM combinations may not offer the solutions required. While finer scale modelling may be too complicated for many of the tasks required, the upward aggregation of variables from, say, daily to monthly, is a more accurate technique than that of disaggregating monthly to daily flows where many inaccuracies can be introduced.

Calibration models are becoming less attractive for water resources assessment at the level of detail required by the NWA (1998) as they tend to follow a black box approach. The result is a loss of credibility with stakeholders. Calibration models and statistical methods are, in general, situation specific and the results are non transferable to other areas or novel situations. This means that the testing of different scenarios and extending derived estimates at ungauged sites can result in large inaccuracies with the use of calibration and statistical methods. Whereas physically based process models have more complicated algorithms and are generally more time consuming to set up, the inputs and outputs are generally easier to understand as they represent real world quantities.

From the review of available water quantity models that might be applicable for the requirements of the WMA DSS it was concluded that the new ACRU model complied with many of the criteria. It is a physically based, daily time-step model which is particularly suited to land use impact studies. The daily resolution allows for IFRs which are assessed on a daily basis and for the potential assessment of water quality issues, which can fluctuate on a daily and even sub-daily time step. The new operational hydrological components currently being developed in the model allow for the assessment of different water use and water supply impacts. The model should be able to test the water availability yielded from the system as a whole as well as the water availability for individual users.

The DSS will initially be used to address water quantity issues, however, in the future it should ideally be able to address both water quantity and water quality issues. From a review of water quality modelling and monitoring in South Africa it was found that although there is a lack of water quality data in many parts of the country this problem could be addressed by modelling. The complexity of the modelling method used can be altered depending on the status (i.e. stressed or unstressed) of the catchment concerned. Nevertheless, there are not many water quality models available and most are data intensive and complex to set up. Hopefully more monitoring sites will increase the water quality database in South Africa and advances in current research will allow more complex models to be established. The issue of water quality modelling clearly needs to be addressed.

Although there will be specific problems which require specialised data inputs to the DSS there is general information which will be required for all WMAs. This includes invariant (e.g. climate, catchment attributes), variant (e.g. land use), ecological, environmental and economic data. Data is also required on historical, present and projected water demand distribution in the catchments.

A system of housing the data applicable to a WMA is required and some consensus is needed on what form this will take. The database system will need to store geo-reference data, attribute data and time series data. It was also identified that there is a need to store both observed and simulated data in a consistent and easy to use format. Thus, the nature of the database access will be largely controlled by what the analysis and display software requires to be able to operate efficiently and in a user friendly way.

Examples of some database management systems that have been developed along these lines include HYMAS, ICIS, IMPAQ, BASINS and NWBM. From the analysis of various database management system it was concluded that there are two options, either to

- conform to the standards of the USGS – the disadvantage being that South Africa's data requirements are different to the USA which therefore means data transformation; or
- produce new data storage standards which will suit South African requirements and can build on existing standards – however, to set up such a system would take much time and money.

As neither of these options is considered particularly satisfactory the recommended method of addressing this issue is to choose a database structure which has been developed locally. A system which follows the standards and protocols of DWAF is necessary and one that uses the most recent technology to avoid the system becoming quickly outdated and therefore redundant.

It is clear from the discussions with DWAF and other organisations that the database issue needs to be given a lot more thought. It is, however, clear that ArcView should be used for the spatial data storage component and then be linked to a relational database. At this stage several, options have been suggested in terms of which database to use and link to the ArcView system. The most promising link looks to be that which has been adopted by the Regis system which links an Oracle database to the ArcView GIS. A relational database can reduce the redundancy found in flat format databases and allows for easier querying of data in the database.

The main objective of developing a hydrologically focussed Scenario Generator (SG) is to have a tool that can easily be used to generate water related scenarios, which broadly include scenarios influencing the demand for water and/or changes to the supply of water. The reason for developing this tool is relatively straightforward. The SEA is tasked to assess the water use of *current* and *potential* water use and supply conditions. The value of the scenario generator is to assist in the generation of accurate, meaningful water use and supply scenarios.

It is recommended that the SG should be ArcView based. ArcView has the potential to allow easy-to-understand and realistic scenarios to be generated in a transparent manner. The technical challenge is to seamlessly integrate the ArcView SG with the ACRU hydrological model and a carefully designed database. The seamless integration of the SG to ACRU may require that when certain water demand and supply scenarios are invoked, the user of the scenario generator is prompted for information that may be required by the ACRU hydrological model.

It is suggested that the SG be developed with the following capabilities:

- Credible scenarios need to be scientifically translated into changes on the GIS map.
- The SG must automatically translate the scenario into the correct model configuration.
- The SG must either automatically provide the required model parameter information, or must query the user through the SG for the appropriate information.
- The scenario/s may then be processed through the model/s.

Potential opportunities with respect to the SG include that the SG has the potential to facilitate the generation of feasible, transparent scenarios; and the SG may continue to be developed to include increased functionality, such as real time systems for risk evaluation; application with forecasting applications; and the SG could be developed to include planning functionality.

It is critical to refine the information generated using the DSS into quantities that can easily be used and interpreted by model users and decision makers. It is thus important to, in consultation with decision makers, identify the critical information requirements necessary for them to make certain sets of decisions. Visualisation of information can take the form of graphical output at specific points of interest within the catchment, spatial output that shows descriptions of various critical indicators in a GIS format giving an idea of the spatial distribution in a particular area; and specific indicator output at critical points in the catchment.

In order for the decision maker to make a decision it may be necessary to have an objective criterion of ranking and scoring the different indicators in order to transform them into a specific solution that can then be used to compare different scenarios analysed. Once this type of scoring has been collated it is possible for the decision maker to then analyse and weigh up the different options that have been produced and understand the trade offs that result from the different options.

The DSS has three main components which are a database component, a processing component (models) and a visualisation component. In terms of the database component it appears that ArcView is introducing a relational database component, however, these facilities are not available at present. The database design will therefore take on the form of a coupled system, which will link a relational database to the ArcView GIS. The database design will follow the standards set by the integrator, making sure that the database structure and architecture conform to the DWAF standards regardless of the database chosen to store the data. In such a case the system can be relatively easily translated if the data needs to be stored in another database at a later stage.

Hydrological, economic, social and ecological modelling will be required to be performed using the DSS in the processing phase. Hydrological modelling will be carried out using primarily the new ACRU model, however, the DSS will have the facility to introduce the options of other models through the addition of a relevant transformation routine. The economic modelling is necessary to facilitate decision makers to assess both the feasibility of growing crops in certain areas and the economic viability of these crops in the selected areas. To carry out economic modelling will require a multidisciplinary team, including GIS, economic, hydrological and agronomic expertise. The initial DSS will be set up to account for a broad range of crops with only a few different genus included for the larger species. The database can be modified when more information is required.

The social modelling will use layers of information which are given certain weightings in a similar way to the economic modelling component. Ecological variables could be determined in much the same way as those in the economic and social modelling components. This component will require extensive GIS modelling where layers of information, such as biodiversity and conservation areas, could be draped together with different weights to determine certain ecological indices.

The visualisation component of the DSS consists of two main aspects. The initial part is the translation of variables produced by simulation scenarios and base data into indicators that could be used by the decision maker and the second aspect is the display system used to display the different indicators in a suitable format that can be used by the decision maker. Once a generic set of indicators has been defined through consultation with the CMAs the system could be put into place to generate the indicators from the database and visually display them. It is recommended that the ArcView GIS package is used for visualisation purposes in conjunction with the Visual Basic programming language.

Summary of recommendations

- Develop a database that conforms with the DWAF standards that links spatial, attribute and time series data by coupling a GIS with a relational database. The ArcView/Oracle link is suggested as the most promising option at this stage. The Regis system used by the Geohydrology section of DWAF will be investigated to see if it can perform this task.
- The ACRU hydrological model that should be used to perform the hydrological modelling in the processing component of the DSS. The model is a physically based conceptual model that allows for the analysis of different scenarios and can be used with reasonable confidence in ungauged areas. The new developments currently being added to the model will allow it to analyse flow networks with realistic simulations of the operational hydrology. Water quality routines are also been added which will increase the flexibility of the model. The model is also locally developed and able to handle local conditions and data with the minimum of data manipulation needed.
- The system should not be restricted to the use of one particular model. Although the ACRU model has been suggested as the model of preference the system should be able accommodate the use of other models reasonably easily.
- The ArcView GIS should be used as it is the most widely used and accepted GIS available both locally and internationally. Its full range of manipulation abilities is required in the manipulation and display of information in the DSS.
- Economic, social and environmental modules will use both simplified weighting and regression techniques coupled with the ArcView GIS to manipulate and display the outputs.
- The system will need to be seamlessly integrated to simplify the user requirements, making the system more user friendly and hence easier to use. The visual basic programming language could be used for this purpose.
- The information produced by the model needs to be credible, and the assumptions made explicit to enhance stakeholder buy in and understanding.

13. REFERENCES

Arnold, J.G., P.M. Allen, and G.T. Bernhardt. (1993). Register of Ecological Models: SWAT. http://dino.wiz.uni-kassel.de/model_db/mdb/swat.html

Berg, R.R., Beuster, H. and Görgens, A.H.M. (1991) Innovative modelling strategies for flow generation in developed winter rainfall catchments. SANCIAHS 1991 Proceedings.

Bicknell, B.R., Imhoff, J.C., Kittle, J.L. (Jr), Donigian, A.S. (Jr), and Johanson, R.C., (1997). Hydrological Simulation Program – Fortran: Users manual version 11. U.S. Environmental Protection Agency, National Exposure Research Laboratory, Athens, Gs., EPA/600/R-97/080, 755p.

Dent, M.C. (1999). Installed water resource modelling systems for catchment management agencies. SANCIAHS 1999 Proceedings.

Dent, M., Howard, M. and DeVos, R. (2000). Hydrological and water quality modelling at catchment scale. Unpublished document.

De Smidt, K.O., Görgens, A.H.M., and Thompson, M.L. (1993). Application of the ARSP Water Yield and planning models in the Western Cape: Issues and Considerations. SANCIAHS 1993 Proceedings.

DWAF (Department of Water Affairs & Forestry) (2000). Water Quality Management Series, Sub-Series No. MS 8.3, Edition 1: A Guide to conduct Water Quality Catchment Assessment Studies: In support of the Water Quality Management Component of the Catchment Management Strategy. Pretoria.

DWAF. (2001) Guidelines for Water Resources Modelling Procedures to Support Water Management Institutions. Draft version 2.

DWAF (Department of Water Affairs and Forestry) (2001b). Water Quality Management Series, Sub-Series No. MS 8.1, Edition 1: A Conceptual Introduction to the Nature and Content of the Water Quality Management and Assessment Components of Catchment Management Strategies. Pretoria.

(DWAF) Department of Water Affairs and Forestry (2001c). Water Quality Management Series, Sub-Series No. MS 8.2, Edition 1: A Guideline to the Water Quality Management Component of a Catchment Management Strategy. Pretoria.

Görgens, A.H.M. (1999). A framework to assess modelling requirements of catchment management agencies. SANCIAHS 1999 Proceedings.

Görgens, A.H.M. (2001) Guidelines for water resources modelling procedures to support water management institutions. Unpublished document.

Hughes, D.A. (1999). Hydrological information requirements for the determination of the ecological reserve for southern African rivers. SANCIAHS 1999 Proceedings.

Hughes, D.A. (2000). Co-operative development of a hydrological time series analysis and display software package. Web published document

Jewitt, G.P.W. and Görgens, A.H.M. (2000). An integrated modelling system for predicting the impacts of changes in water quantity and quality brought about by upstream development. WRC Report No. 627/1/00, Water Research Commission.

Kjeldsen, T.R., (2001). Personal Communication. Department of Hydrodynamics and Water Resources, Technical University of Denmark.

Mesarovic, M.D., Sreenath, N., McGinnis, D. and Xercavins, J. (2000) *Methodology: Toward Integrated Assessments with Reasoning Support Tools.* Chapter 2

McKenzie, R.S., and Van Rooyen, P.G. (1993). GENMAC: User Guide: Supplement to System Analysis Course. BKS Incorporated.

McKenzie, R.S., and Van Rooyen, P.G. (1997). Short Course: Water Resource System Analysis. BKS, SAISI/SAICE and University of Pretoria

Middleton B.J., Pitman W.V. and Midgley D.C. (1993) An update of Surface Water Resources of South Africa. SANCIAHS 1993 Proceedings.

MIKE BASIN. http://www.dhisoftware.com/mikebasin/

MIKE 11. http://www.dhisoftware.com/mike11/

NWA (National Water Act). (1998). National Water Act, Act No. 36 of 1998. Government Printer, Pretoria, South Africa. pp 200.

Perkins, J. (2000). The assessment of water use authorisations and license applications in terms of Section 27(1) of the National Water Act, 1998. Department of Water Affairs and Forestry National Water Resource Strategy.

Pegram G.G.S. (1986) Stochastic Modelling of Streamflow. Report to the Department of Water Affairs and Forestry by BKS Inc. Report No. PC000/00/5186.

Pike, A. (2001). Personal Communication. School of Bioresources and Environmental Hydrology, University of Natal, Pietermaritzburg.

SA Water Bulletin (2000). SAPWAT- a powerful South African tool for planning and managing irrigation. Vol. 26. No 6 November/December 2000.

SAWRAM. (1999). Beta distribution documentation.

Schultz, C.B., Watson, M.D., and Moore, W.R. (1999). Water balance model: Revised methodology for yield assessment. SANCIAHS 1999 Proceedings.

Schulze, R.E. (1995). Hydrology and Agrohydrology: A text to accompany the ACRU 3.00 Agrohydrological Modelling System. WRC Report No. TT69/95 pp 503 Water Research Commission.

Schulze, R.E. (2001) Personal Communication. School of Bioresources and Environmental Hydrology, University of Natal, Pietermaritzburg.

Senge, P., Roberts, C., Ross, R.B., Smith, B.J. and Kleiner, A. (1995) The fifth discipline fieldbook:-Strategies and tools for building a learning organisation. Nicholas Brealey, London.

Smithers, J.C. (2001) Personal Communication. School of Bioresources and Environmental Hydrology, University of Natal, Pietermaritzburg.

Stertman, J. (1989) Misperception of feedback in dynamic decision making. Organisational Behaviour and Human Decision Procsses, Summer 1989, Vol 43, No 3 p 301.

Stewart, T.J., Joubert, A., Scott, L. and Low,T. (1997). Multiple Criteria Decision Analysis: Procedures for Consensus Seeking in Natural Resources Management. WRC Report No. 512/1/97, Water Research Commission.

Stewart, T.J., Joubert, A.R. and Liu, D. (2000) Group Decision Support Methods to Facilitate Participative Water Resource Management. WRC Report No. K5/863/0/1, Water Research Commission.

Steyl, I., Vesveld, D.B., and Nelson, P.J. (2000). Strategic Environmental Assessment for Water Use in the Mhlathuze Catchment. Department of Water Affairs and Forestry. Report No: SEA-01/2000.

Soil and Water Assessment Tool. (2000). http://www.brc.tamus.edu/swat/newmanual/intro.html

Taviv, I. (2001) Water Balance ModelConceptual Design. Unpublished document supplied by Irene Taviv.

USGS. (2000) Water Resources Applications Software: Summary of PRMS http://water.usgs.gov/cgi-bin/man_wrdapp?prms

Van Rensberg, J.D.J. and Dent, M.C. (1997) Development of a water quality and quantity modelling system which will provide a common currency for communication between researchers in the Kruger National Park Rivers Research Programme. WRC Report No. 654/1/97, Water Research Commission.

Water Resources Yield Model User Guide. (1999). Release 4.1.1. BKS (Pty) Ltd.

Watson, M.D., De Jager, F.G.B., McKenzie, R.S. and Schultz, C.B. (1999). Water balance model: Overview and latest developments. SANCIAHS 1999 Proceedings.

Webster's Ninth New Collegiate Dictionary. (1990) Merriam-Webster Inc. Springfield, Massachusetts, U.S.A

Wolff-Piggott, B.B, Watson, M.D., Strydom, C.J., and De Villiers, E. (1999) Water balance model: Software concepts, design and development. SANCIAHS 1999 Proceedings.

Yuan, M. (2001) Development of an Intelligent Geographic Information System to Support Spatiotemporal Queries, Analysis and Modeling in Hydrology. http://ouucgis.ou.edu/nima_abs.html

14. REVIEW OF THE PROPOSED SEA-DSS IN THE LIGHT OF GÖRGENS (2001) GUIDELINES FOR WATER RESOURCES MODELLING PROCEDURES TO SUPPORT WATER MANAGEMENT INSTITUTIONS

A draft document by Professor Görgens entitled “Guidelines for water resources modelling procedures to support water management institutions” has been used to assess how the proposed SEA-DSS will potential fare against the guidelines laid out in the DWAF commissioned document. The objectives of the guidelines contained in the report include:

- To guide the selection of appropriate water resources modelling approaches to support Water Management Institution (WMIs), such as DWAF, CMAs and Water User Association (WUAs).
- To guide appropriate application of water resources modelling approaches in terms of the nature of the management questions being addressed.
- To promote consistency of modelling procedures and data preparation procedures in support of water resources management.
- To assist understanding of the scientific and technical information requirements of water resources management.

In this paper, crucial *generic* activities, information and modelling requirements for IWRM are listed and described. The objective of this section is to review the proposed SEA-DSS output against the generically required information as identified by Görgens (2001). The guidelines presented in the draft Görgens document were used as the final document had not been completed at the time of completing this report.

The outcomes of the review are presented in Table 6. It should be noted that a few additions have been made to the requirements as listed in the draft Görgens report (2001). The symbols ✔ and ✖ in the SEA-DSS column indicate that the proposed SEA-DSS will or will not be able to meet the relevant requirements listed in the Görgens report, respectively. The words **UD** are used to represent activities currently “Under Development” in the New ACRU model.

Table 6 Review of the proposed SEA-DSS in comparison to the Gorgens (2001) report

Hydrology Discipline	**Generic Information Requirements & Model Capabilities**	**SEA-DSS (*ACRU*)**	**Comment**
Process Hydrology	Historical Flow Series	✔	
	Naturalized Flow Series	✔	
	Denaturalized Flow Series	✔	
	Stormflow (floods)	✔	
	Baseflow (low flows)	✔	
	Channel Transmission Losses	✖	This functionality currently does not exist in ACRU, however can be included into the model relatively easily
	Explicit Spatial Disaggregating	✔	Catchment can be subdivided into smaller units
	At Least Daily Time Step	✔	Monthly and Daily time steps

Stochastic Flow Generation	Stochastic Sequences	✖	As the ACRU model operates on a daily time-step, the generation of stochastic sequences distributed catchments is currently not feasible due to problems associated with the cross correlation of daily rainfall.
Operational Hydrology	System Yield	**UD**	
	Operating Rules & Curtailments	**UD**	
	Bulk Water Abstraction	✔	
	IBTs	✔	
	Return Flows	✔	
	IFRs	**UD**	
Quality Simulation	Average WQ Load & Chemical Constituents	<u>*UD*</u>	Water quality has not explicitly been included in the SEA-DSS. The potential DSS should be designed in such a way that water quality may be included into the operation of the DSS. This may require modifications to the ACRU model, or to the incorporation of other WQ models into the DSS
	WQ Time Series	**UD**	
	WQ Sources – Point	✖	
	WQ Sources – Non-Point	✔	
	Reservoir WQ Processes	✖	
Groundwater Simulation	Water Table Depth	✔	These routines may require further augmentation and verification
	Groundwater Recharge	✔	
	Aquifer Yield	✔	
	Baseflow Contribution	**?**	
	Deep Percolation Losses	**?**	
Land Use / Management Impacts Assessment	Irrigation	✔	
	SFRAs	✔	
	Urbanization	✔	
	Alien Vegetation	✔	This routine may require further modification
Ecological Modelling	Reserve Determination	✖	
	Aquatic Biotic Responses to Flow Changes	✖	
	Estuary Processes	✖	
Soil Erosion Simulation	Sediment Yield	✔	
	Sediment Transport	✔	
	Sediment Deposition (Channel & Reservoir)	✖	
Social & Economic Modelling	Economic Values of Various Water Use Activities	✔	The SEA DSS will include a simple economic analysis. Research may be required to further develop the DSSs ability to model socio-economic considerations
	Impacts of Changes in Water Using Activities on Incomes and Social Welfare	✔	
Potential Impacts of Climate Change	Streamflow Time Series	✔	Uses Downscaled GCM Output

The ACRU model is a core component of the proposed SEA DSS. The following review of the ACRU model has been made in the Görgens (2001) document:

ACRU is a multi-purpose and multi-level integrated physical-conceptual modelling system that can simulate streamflow, total evaporation, and land cover/management and abstraction impacts on water resources at a daily time step (Schulze, 1995). A “menubuilder” program controls input to the menu, where the user enters parameter or catchment related values, or uses defaults provided. The ACRU model uses multi-layer soil water budgeting. Streamflow is generated as stormflow and baseflow dependent upon the magnitude of daily rainfall in relation to dynamic soil water budgeting. Components of the soil water budget are integrated with modules in the ACRU system to simulate many other catchment components including irrigation requirements and sediment yield. Spatial variation of rainfall, soils and land cover is facilitated by operating the model in "distributed" mode, in which case the catchment to be modelled is sub-divided into sub-catchments. Within these sub-catchments, units of similar hydrological response, based largely on land use zones, are designated to facilitate simulation of land use changes. The model treats groundwater dynamics through a non-linear reservoir. The model allows riparian zones to be saturated from upland throughflow processes. The model requires a degree of calibration. ACRU is continually being upgraded and is currently being re-coded in object-oriented format with systems operating rule feed-back facilities

Görgens (2001) points out that the use of GIS and a relational database may be of great assistance to the users of such a system. As part of the SEA DSS, a scenario generator that operates in a GIS environment is being designed. The scenario generator will be used to draw information from a relational database. Results from completed simulations will be written back to the database. The seamless integration of the scenario generator in the GIS environment with the ACRU model and a relational database promises to add great value to the DSS, as scenarios can quickly, easily and transparently be generated, and displayed using this system.

The conclusion that may be made is that the proposed SEA DSS *is* consistent with most of the requirements laid down in the Görgens draft document. As mentioned in the review of the ACRU model above, the model is continually being updated. The guidelines that the model is currently not able to meet may be met in the future in as a result of further model developments.