# An inter regional water resources planning model

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**ABSTRACT**

Increasing competition for the Republic of South Africa's (RSA) scarce and unevenly distributed water resources necessitates a planning strategy to cope with inter regional water scarcity. The RSA National Water Act (No. 36 of 1998) therefore requires the development of a national water resources strategy to ensure the sustainable and equitable use of resources. The RSA Department of Water Affairs and Forestry has responded with the development of a model to assist in preparing a suitable strategy.

The model is a water balance based decision support system for reconnaissance level planning. The model is GIS linked and supported by a comprehensive database of spatial water related information. State of the art technology was applied to ensure rapid processing capabilities, user friendliness and effective methods for dealing with scenario analysis. As a result the model is suitable for use in a boardroom or a workshop environment. Strategies for water supply and demand management can be rapidly tested for scenarios of land use, demographic and economic change.

This paper summarises the model and then focuses on novel methods used to overcome issues identified during development. These include variations in data quality and output needs, geographically incompatible administrative and catchment boundaries, large volumes of data and rapid run time requirements. The paper emphasises the sound generic nature of the model and data management system which could facilitate its use for other countries, international water sharing and in global water accounting.

## 1. Introduction

Water plays an essential role in the existence of human society and in sustaining the natural environment. South Africa is a water scarce country with an average annual runoff of 44 mm, compared to the average for Africa of 139 mm and the world average of 330 mm (McKenzie & Bhagwan [1]). Local projections by Basson, Van Niekerk and Van Rooyen [2] indicate that virtually all of the countries' available water resources could be exploited by 2030. Strategies for sustaining and distributing water resources require *inter alia* inter-basin transfers, demand management, changes in land use and improved water resources management. The development of these strategies requires support in terms of sufficient data and predictive tools for water resources planning. A new model described below (Department of Water Affairs and Forestry [3]) provides a means of simulating, at a reconnaissance level, options for inter regional water resources development and inter-state water sharing.

## 2. Background

South Africa recently promulgated the National Water Act No 36, 1998 which recognises the need for the development of strategies to overcome increasing scarcity and uneven spatial distribution of its water resources. There is strong emphasis on sustainable resource utilisation and ensuring that water is equitably distributed to the benefit of all users. This is to be facilitated by the development of a National Water Resource Strategy (NWRS), which will provide direction and constraints for regional management. The key requirements to be included in the NWRS are the provision of numerical information on the balance between water availability and water requirements and development of future water requirement scenarios. The Act also requires consultation with a wide range of stakeholders.

Existing models used for detailed planning and water resource management are not well suited for reconnaissance level evaluation in a consultative environment requiring rapid simulations, at workshops, of present and future options for water resource development, management, planning and conservation. One of the tools developed to assist with implementation of the NWRS is a user friendly model developed using “state of the art” software. It was designed as a decision making support tool to rapidly quantify surpluses and deficits at local, regional and national scales, as well as to undertake scenario analyses.

## 3. Model description

The model uses a data base representative of water related information for the whole country and any adjoining drainage areas in neighbouring countries. It is able to address questions related to scenarios of future conditions and strategies for water resources development, planning and management. Effective involvement of stakeholders is possible because the model is capable of providing rapid feedback to questions that could arise during a consultation process without the need to resort to further lengthy studies.

This section provides a brief description of the model and its development while subsequent section outlines some of the issues that were addressed in attempting to develop the model as a versatile planning tool.

### 3.1 Basic structure of the model

The model is structured to accommodate an interlinked flow system consisting of catchments and water transfer schemes. Outflows from upstream catchments form input to the next downstream catchment. This water together with runoff generated within the catchment itself, imports to the catchment and supplies from groundwater are combined to determine the total water resources of the catchment. Water demands, streamflow reduction activities, as well as exports from the catchment, are the main water requirements imposed upon the catchment’s resources. All dams in the catchment are modelled as one pseudo reservoir, positioned at the outlet of the catchment.

Once all the demands and available resources of the catchment have been quantified, a balance is done in terms of resource yield capability and the impact of demands on yield to determine whether a surplus or deficit situation exists. The overall yield balance of the model is undertaken using a standard level of supply assurance of 98%. It has been selected as the basis for comparing water demands and water resources in the model. The model could however also be modified to run at some other level of assurance. Surplus yield is cascaded from one unit catchment to the next, until the model has solved the water balance in all sub-catchments.

The incorporation of information from other studies for use in model development and application in the National Water Resource Strategy is summarised in Figure 1 below.

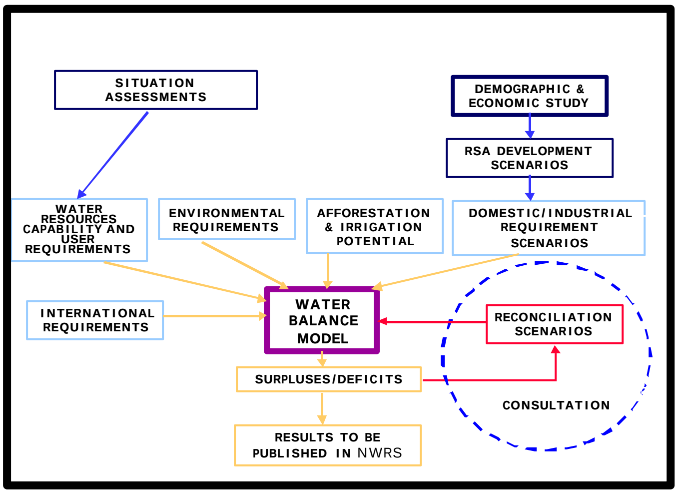


Figure 1: Model development (source: van Rooyen, DWAF, Pretoria, pers. comm. 1999)

The manner in which various sub-models and flows are linked within a single catchment in the model the model is described below and summarised in Figure 2.

### 3.2 Water use

Consumer water demands are supplied from rivers or dams, but can also be obtained directly from imported water. These demands include losses that are determined differently for each demand type. The following water demands are included in the model:

The **bulk** water-use sub-model represents large users outside of urban areas, such as thermal power stations, mines, etc. A primary objective of this sub-model is to enable the prioritised supply of water to strategic users but it also accommodates the effects of mine dewatering on supplies and water quality.

The **urban** water-use sub-model distinguishes two major components of urban water use: *direct urban water use*, which is mainly driven by population and levels of service and *indirect urban water use*, which is the total of urban industrial, commercial, institutional and municipal water uses.

**Irrigation** water use is driven by climatological factors that affect crop demand. Efficiency of irrigation determines total use and the quantity of return flows.

**Rural** water-use is driven primarily by population. It also includes components for water-use by livestock (including game) and subsistence irrigation.

Legislative requirements for maintaining minimum water supplies to meet basic human needs are determined according to population numbers and a minimum per capita water requirement. A check is undertaken to establish whether the resources available to a catchment are sufficient to meet this basic requirement.

Return flows from water demands are calculated individually for each sector. The amounts are adjusted in cases where water demands can not be supplied in full. Unless the return flows are re-used within the catchment of origin, they are allowed to flow to the downstream catchment.

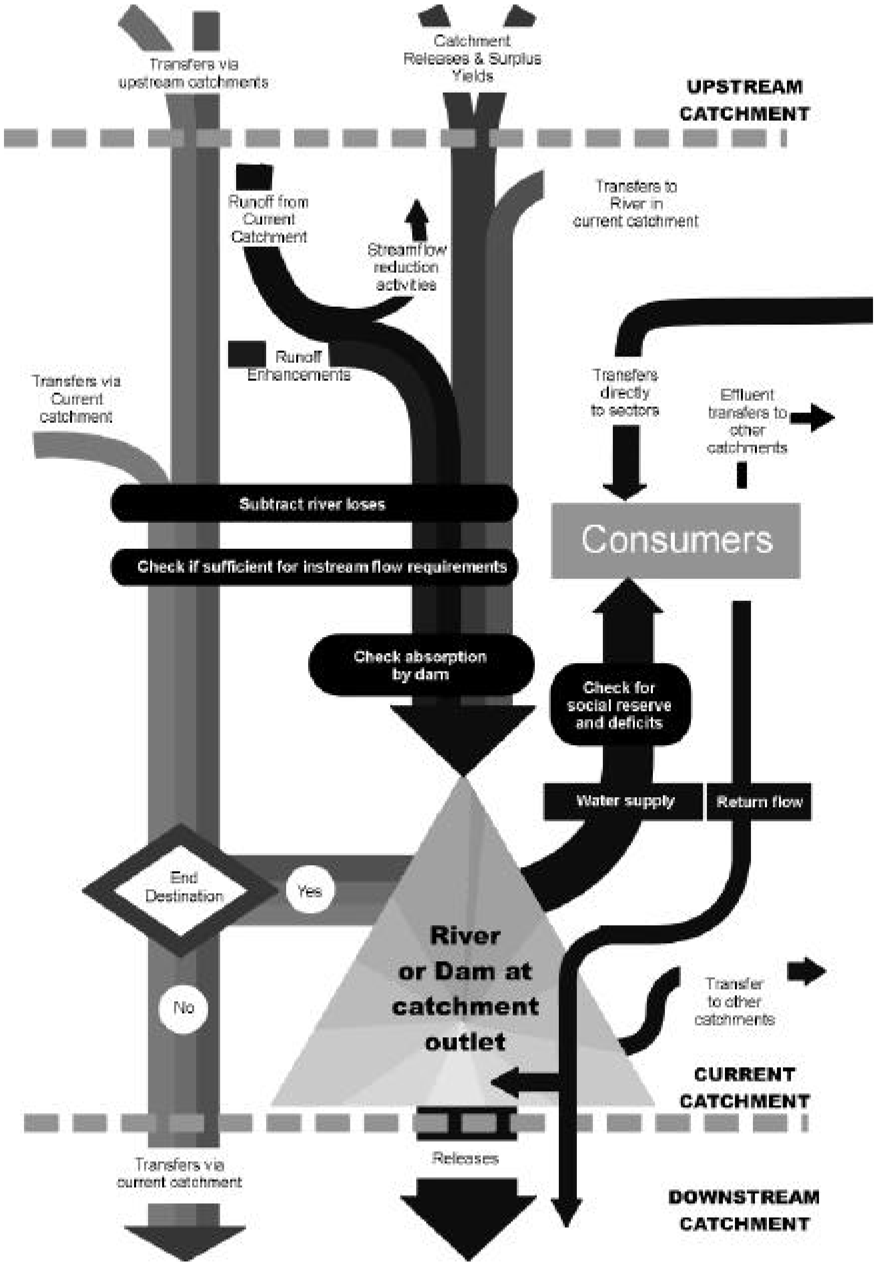


Figure 2: Model structure

### 3.3 Streamflow reduction activities and non- consumptive uses

Streamflow reduction activities are those land use and other activities that reduce runoff. Examples include forestry, dry-land sugar cane, alien vegetation, groundwater abstraction (which reduces base flow) and evaporation from farm dams.

A test is carried out for every catchment to ensure that specified ecological water requirements are being met. In addition, water releases from an upstream catchment can be specified to support ecological requirements in the catchments downstream of it. These requirements have been determined as part of a separate study to produce a classification system which is used to determine the instream flow requirements (IFR) of rivers.

A hydropower algorithm controls the amount of water released from storage for the purpose of generating hydropower. It also provides the user with the capability to specify what proportion of the release is utilisable in downstream catchments.

### 3.4 Water resources

Three components of water supply are included, namely surface water, groundwater and inter-basin transfers (see Section 4.3 for details on transfers).

The utilisable **surface water** in a catchment is dependant on the yield available from the total of all the flows running into the catchment from upstream, and the contribution of natural runoff generated within the catchment itself after adjustment for streamflow reduction activities, plus a re-usable portion of return flows. Unlike conventional water resource analysis software, the model does not use a time-series simulation (see details in section 4.1).
**Groundwater** sources are modelled to supply water directly to water demand centres (bulk, urban, etc). These resources are based on the exploitable groundwater potential, which takes into account the characteristics of aquifer as well as the influence of hydraulic conductivity.

Two water resource related losses are considered in the model, namely river losses and evaporation from reservoirs. The river losses consist of seepage and evaporation from rivers and wetlands. Other losses associated with water use are accounted for in the water supply algorithms.

## 4. Issues addressed

In developing the model several challenges were encountered, some of which are briefly described below.

### 4.1 Hydrological time series problem

The estimation of the available water resources of a particular area at a given level of assurance necessitates the use of long term time series data. In the case of South Africa this would have to be done for more that 2000 catchments using approximately 80 years of flow data. Simulations of this nature are simply not possible within the time frame of a few minutes in a boardroom and the data constraints of an average desktop computer.

The problem is overcome in the model by representing natural hydrological variability by a method of gross yield accounting. Gross yield is determined as a percentage of mean annual runoff using catchment specific storage-draft-frequency characteristics ( Schultz, Watson and Moore [5])

The impact of upstream dams on the yields of downstream catchments is accounted for by using the combined upstream yield to determine an equivalent volume of upstream storage. This is combined with the storage in the incremental catchment and the yield of the total upstream catchment is determined from the storage-draft-frequency curves specific to this combined catchment. Parameters to describe the relationships have been derived in a separate study, from simulated time series data of natural flows at the outlet of each catchment. Additional parameters are determined to describe changes in the characteristics of the relationships for different levels of assurance. Only the parameters describing the relevant relationships are stored in a model.

### 4.2 Multiple Users

It is recognised that a wide range of users with varying backgrounds, disciplines, levels of experience and competence are likely to use the model. The model is therefore designed to be user friendly. Transparency of model operation is provided by on-line displays of the model structure and of the equations used to calculate output parameters.

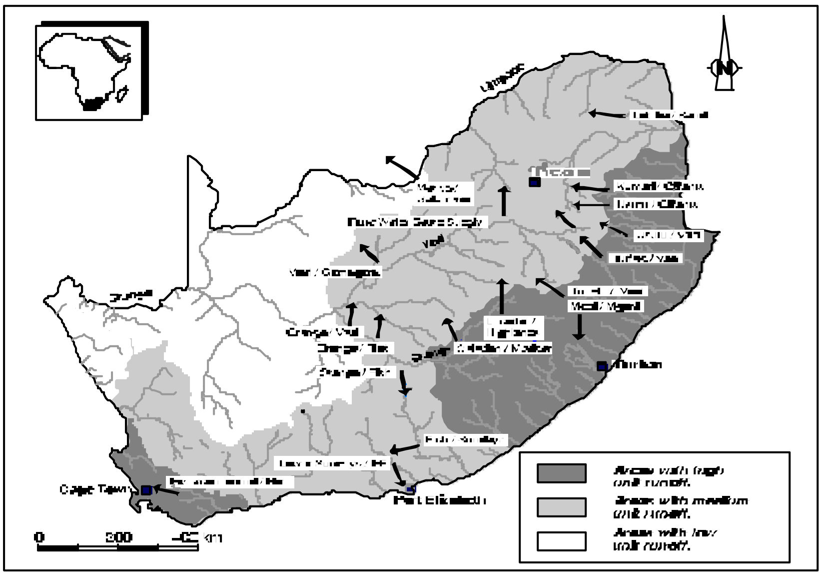


Figure 3: Inter-basin transfers in RSA (source: McKenzie & Bhagwan, [1])

Different users and user groups are likely to focus on different areas of interest and have different output requirements. The model is therefore structured to enable users to define, for output purposes, their own spatial areas of interest. They may also select parameter groups that are relevant to them and customise the appearance of their output tables and graphical results. Areas of interest and parameter groups can also be used in the definition of potential future conditions and development of scenarios.

Stability of base data in a multi-user environment is ensured by means of change lists. Change lists allow users to modify model input in order to correct errors, update parameters with improved estimates or perform sensitivity analyses by varying the input values and comparing run results. Multiple change lists may be included in a particular model run, and each list may be named and stored for later use. The change list facility enables independent studies to keep their work comparable. It allows flexibility in model runs while maintaining an unmodified base dataset.

### 4.3 Accounting for inter-basin water transfers

The downstream flow direction provides the logical basis for interlinking catchments and processing of results. The sequence is, however, complicated by interlinking water transfer schemes (see Figure 3) and the need to determine whether water is available at the source of the transfer prior to implementing the transfer.

In order to avoid an iterative approach in processing the flow system, the model assumes that all water transfers are met and then produces a list of errors at the end of the run to indicate where the transfers are not met. The user must then implement a scenario containing a new water scheme to ensure that sufficient water is available or alternatively the water requirement must be reduced.

### 4.3 Water Quality

The importance of water quality is recognised in the model development but has not yet been finalised. The model uses yield curves rather than a time series to represent the flow of water and therefore the resulting water quality will be output as an indicator rather than a measurable concentration. This indicator will be determined from average concentration values, which will be e processed in the mass balance of the flow system, and should realistically represent spatial and temporal trends in water quality. For example, increases in water demands will result in increasing return flows that cause a deterioration in downstream water quality. On the other hand, inter-basin transfers of high quality water will dilute polluted rivers. The indicator is intended to provide a comparative measure of water quality changes in the system.

### 4.5 Area type conversion

For each sub-catchment a water balance is conducted in a manner that accommodates all inflows, water transfers, losses and water use within the catchment as if they occurred at a single point, namely the catchment outlet. Results for sub-catchments can be combined to present information for larger catchments.

Users of water related information often, however, require outputs based on administrative boundaries rather than on catchment boundaries. Examples of such boundaries include international boundaries, provincial boundaries, water management areas and water boards.

The model accommodates such areas by apportioning parameter values between adjacent administrative areas when the administrative border cuts across a catchment. Simulations are conducted on a catchment basis and parameter values for an administrative area are derived according to the relative proportions of catchments occurring within the administrative area. These values are combined to produce a single value for the administrative area.

### 4.6 Data Management

Data management is complicated by the use of a large number of parameters (260), numerous sub-catchments (about 2000), and large variations in the quality of the data.

The number of parameters used in the model has been kept to the perceived minimum required to produce meaningful results for each modelled process. Considerable volumes of data are avoided by replacing time series data with parameters to describe relevant equations depicting the main characteristics of the data.

Data management is simplified by presenting a complete data set for all parameters for only one predefined base year. Changes in data values subsequent to that year are defined by parameters describing annual growth rates rather than storing separate values for each year. This approach also facilitates the definition of future scenarios. Model outputs are therefore provided at user selected points in time. The use of a base year of predefined data provides a stable set of data for comparative purposes from which all users can make their own future projections. The base data set can be updated by a co-ordinating body from time to time and redistributed to all users.

Access to information on meaningful parameter ranges and the significance of changes in these values in terms of the sensitivity of the model outputs, assists the user in evaluating the data. This is further enhanced by documented guidelines for data preparation as well as appropriate error checking and warning messages for unrealistic values.

Inconsistencies in the accuracy of available data are easily accommodated in the model and poor quality information can be updated as improved information becomes available. All data values are accompanied by meta-data that provides additional information on the source and accuracy of the information.

The metadata also makes it possible to report on the reliability of the parameter values together with the model results, and provides a structured way of improving the results. In particular, metadata may be used to identify which of the parameters have low reliability, and these parameters may be targeted for use in sensitivity analysis or for re-evaluation.

## 5. Scenario based analysis

Use of growth parameters and of libraries of planned schemes allow users to efficiently model scenarios of the influences of land and water use as well as the effects of water resources management and development options. Examples of the types of information that can be studied separately or jointly in combined scenarios are the in-stream flow requirements, streamflow reduction activities, water resources, water use, hydropower releases and water quality.

Scenario testing can be aimed at evaluating the following:

- Identification of water stressed areas and areas with surplus water.
- Strategies for water resource development (e.g. dams, water transfers, development of groundwater, utilisation of additional resources).
- Water demand management (efficiency, recycling and waste reduction).
- Effects of population changes on water demand.
- Effects of upgrading housing and levels of water services and sanitation.
- Changes in international demands and environmental requirements

## 6. Potential applications

The model has been developed for the South African situation as part of the support technology needed for the development of the NWRS. It enables reconnaissance level assessments of the future water situation by incorporating scenarios of growth, land use and water use developments, water resource planning, management and development. It can rapidly process large volumes of data and provide meaningful results from a wide range of data values of varying levels of accuracy. The parameters can be used to represent the majority of the land and water use developments that are likely to be encountered in evaluating the status of water resources relative to water requirements.

The model provides a facility which could easily be applied to other countries, groups of countries or even on continental scale. There is, for example, currently a proposal to use the model for a joint study of the Maputo River basin with Mozambique, Swaziland and South Africa. This will provide a basis for joint planning for this important river system which is common to all three countries.

## 7. Conclusions

It is anticipated that the model will be widely used in reconnaissance level studies in South Africa and has strong potential for use elsewhere and could possibly contribute towards continental scale studies of water resources. The model is suitable for producing indicative water resource and water balance estimates using unreliable and crude data with accuracy that can be improved substantially with time as more reliable data becomes available. It is well suited for rapid identification of present imbalances in supplies and requirements as well as possible future water resource and water quality problems. This can conveniently be addressed at regional and national scales. A sound basis is provided for rapidly eliminating unsuitable options for water resource development. The model does not replace the need for more complex time series or stochastic modelling in detailed design and finalisation of operating rules for water schemes.

The model database is an ideal source of basic information related to water resource availability and consumer requirements. The sound model structure and user friendly interface provide a basis for users of diverse backgrounds to become actively involved in interpreting and debating the implications of land and water use developments, particularly within the context of sharing scarce water resources and the need to sustain future water supplies.

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## REFERENCES

[1] McKenzie RS & Bhagwan JN, *Some recent development in water demand management in South Africa.* Ninth South African Hydrology Symposium: University of the Western Cape, Cape Town, 1999

[2] Basson, Van Nierkerk & Van Rooyen, J., *Overview of Water Resources Availability and Utilization in South Africa*, Department of Water Affairs & Forestry, Pretoria, 1997.

[3] Department of Water Affairs & Forestry. *Water Balance Model* User Manual, Pretoria, 1999.

[4] Watson MD, De Jager FCB, McKenzie RS & Schultz CB. *WBM: Overview & Last Developments.* 9th SA Hydrology Symposium. Cape Town, 1999.

[5] Schultz CB, Watson MD and Moore WR, *Water Balance Model: Revised Methodology for Yield Assessment.* Ninth South African Hydrology Symposium. University of the Western Cape, Cape Town, 1999.