

WATER RESOURCES MODELLING FOR THE NEW WATER ACT

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Abstract

The National Water Act (NWA) of 1998 puts a number of new and challenging requirements to water resources planners. Not only must the management of the water resources be sustainable, equitable and efficient, but public and stakeholder participation, which is entrenched in the NWA, implies that decisions made by the Department of Water Affairs and Forestry, the Catchment Management Agencies and their agents, must be transparent enough for stakeholders to understand. This puts water resource planners in a serious dilemma since increasing complexity of stressed systems on the one hand must be balanced on the other with tools which explain the situation and motivates the decisions made in simple enough terms for stakeholders to understand.

There is therefore an increasingly urgent need for water resources planning models which can carry out simulations rapidly enough for defensible decision making in a workshop environment.

This paper will describe a model, referred as the Rapid Simulation Model (RSM), which has been developed to address these pressing needs. The concept upon which this model is based is a cascading simulation using monthly time series in a system defined by nodes connected by channels. This in itself is not a new concept, but a tried and tested one which delivers reliable results. However, a number of innovative concepts have been incorporated into this model to address the challenges of the NWA:

- By considering the critical period of a dam, it is possible to accurately calculate the yield of a dam and the change of this yield for any change in upstream water use by means of a simple equation. This concept has been incorporated into a graphical user interface which can be used as a stakeholder participation tool by modelling scenarios rapidly enough for a workshop environment.
- While existing yield models determine the yield at a predefined user-selected node, RSM determines the yield available throughout the catchment, hence giving a catchment-wide perspective of the water resources situation, up to Catchment Management Area scale.
- New techniques have been developed for presenting this catchment-wide perspective which are based on the generation of a yield-reliability curve at each node which indicates the availability of water over a wide range of assurances. By indicating the water use, plotted at its assurance of supply (as determined by the model), a comprehensive picture of the water resource, water use and the availability of water emerges for the entire catchment under consideration.

It is suggested that tools such as these will be required for carrying out water use allocations in future.

1. INTRODUCTION

The National Water Act of 1998 puts a number of new and challenging requirements to water resources planners. Not only must the management of the water resources be sustainable, equitable and efficient, but public and stakeholder participation, which is entrenched in the water act, implies that decisions made by DWAF, the Catchment Management Agencies and their agents, must be transparent enough for stakeholders to understand. This puts water resource planners in a serious dilemma since increasing complexity of stressed systems on the one hand must be balanced with tools which explain the situation and motivates the decisions made in simple enough terms for stakeholders to understand.

There is therefore an increasingly urgent need for water resources planning models which can carry out simulations rapidly enough for defensible decision making in a workshop environment. The intention of this paper is not to compare models, but it would be an injustice not to mention the two models which have influenced the development of the model of which this paper is the subject, referred to in this paper as the Rapid Simulation Model (RSM). These are the Water Resources Yield Model (WRYM) (BKS, 1995) and the Water Resources Situation Assessment Model (WSAM) (DWAF, 2002). While both of these model have their strong points, neither of these models meet the objectives stated above and the perceived gap in the modelling capabilities available in RSA has led to the development of the modelling philosophies discussed in the paper.

The questions which need to be answered by a water resources yield and allocation model are:

- Is a catchment stressed?
- If so, which users in the catchment are experiencing water shortages?
- Are these shortages within acceptable limits?
- How would changes in water use in the catchment affect the availability of water to users in the catchment.
- If there is water available for allocation, how best should this be allocated given multiple users with various requirements in terms of assurance of supply?

The objective of the Rapid Simulation Model is to answer these questions in a workshop environment at levels of confidence which are comparable with benchmark models such as WRYM, and which can stand up to careful scrutiny and peer review. The question of allocating the available resources has not yet been fully developed but might be addressed in later versions of the model if the need for this is apparent.

2. METHODOLOGY

2.1 Basic conceptual approach

The Rapid Simulation Model (RSM) is a simulation model which uses naturalised monthly time series such as those prepared for the Water Resources 90 project (Midgley et al, 1994). The simulation methodology is essentially the same as that used in other simulation yield models such as WRYM. The essential difference between RSM and WRYM is that RSM carries out a cascading¹ solution while WRYM performs a simultaneous solution at each time step using a complex network solver. RSM is therefore much less complex than WRYM in this respect,

¹ Solving from upstream to downstream

but it is this simplicity which makes RSM fast enough for workshop type environments. The limitation is that operating rules which depend on decisions based on conditions downstream of the reservoir under consideration cannot be catered for. This is not usually a problem in non-complex or unregulated catchments.

The other major difference between RSM and WRYM is that while WRYM determines the yield at one particular point in the catchment (usually a reservoir), RSM determines the yield at every user defined node. It could be a major reservoir or a *Dummy Dam*, representing all the smaller dams in the catchment. If there is no dam, the *Run-of-River* yield is determined. For every hydrologist or water resource modeller there is a different interpretation of run-of-river yield, but the definition used here is simply the historic yield at zero storage. The advantage of this definition is consistency and continuity in the interpretation of the concept of yield.

2.2 The Concept Of Yield

There are a number of different ways of considering yield in the context of water resources modelling. RSM caters for several different ways of representing yield so that the model user can apply the method most suited to his particular needs. There are certain applications, such as the development of National or catchment strategies, when a combination of the approaches is required to present the full picture of the water resource availability and impact of uses on the available yield of a catchment. The different representations of yield are described below.

2.2.1 Cumulative yield

The terminology adopted here of a *cumulative yield* is that method or interpretation traditionally used by water resources planners and can be defined as the quantity water that can be abstracted from a reservoir, expressed in million m³/a, given the following constraints:

- Historic natural flow sequence
- Upstream development, including all inflows, abstractions, water related infrastructure such as dams, and streamflow reduction activities (SFRA).
- The monthly distribution of the yield.
- The level of assurance of the yield. The normal definition of yield is one failure in the historical sequence but RSM allows the user to specify the level of assurance of the yield.

The important point to note here is that the cumulative historical yield is the yield before abstractions from the reservoir or node under consideration. There may, however, be abstractions which are taken off before the yield is determined, such as releases for the ecological Reserve. The model has been structured in such a way as to give the user flexibility as how he interprets yield. It is crucial, however, that the user make his definition and assumptions clear when presenting results.

2.2.2 Incremental yield

It is often useful to know what contribution a particular sub-catchment makes to the yield of the catchment as a whole. To analyse this scenario, cumulative yields are determined as above at every node, but while the cumulative yield option determines what could be abstracted, an incremental yield analysis assumes that these yields are actually abstracted and lost to the system. The yield that is calculated using this method is therefore derived from incremental inflows to the sub-catchment in question and spills from upstream. This method determines the maximum yield that could theoretically be abstracted from a reservoir or from run-

of-river and is useful to determine the maximum potential yield of a catchment. This type of analysis is only applicable if there are no abstractions from the catchment but can be used to determine the impact of forestry and the ecological Reserve, using the natural condition as a base scenario.

2.2.3 *Yield Balance*

It is often useful to know how much yield is still available from a particular reservoir or from run-of-river at a particular point in the catchment. The water balance determined by RSM is therefore simply the cumulative historical yield as defined in 2.2.1, but *after* all abstractions from the dam or node have subtracted. The intention is that the Water Balance determined by RSM should be comparable with that determined by WSAM (DWAF, 2002).

2.2.4 *Incremental Yield Balance*

The Incremental Yield Balance is similar to the Yield Balance, except expressed incrementally and not cumulatively. This is useful since it allows the user to simply add up all the incremental balances in a catchment in order to determine the surplus yield available (if any) for the whole catchment. This is useful for developing National or catchment strategies where it is necessary to aggregate the resource into areas larger than quaternary scale.

2.2.5 *The 'Rapid Simulation'*

The original purpose of the *Rapid Simulation* concept was to provide a quick but accurate insight into how the various abstractions and *stream flow reduction activities* (SFRA) in a catchment impact on available yield at various points throughout the catchment. On first inspection, this may appear to be a trivial exercise. For example, if there is urban abstraction of 10 million m³/annum upstream of Midmar Dam, surely this will reduce the yield available from the dam by 10 million m³/annum? Correct in this simple case, but two important factors can make this apparently obvious assumption incorrect.

Firstly, the *seasonal distribution* of the abstraction can influence the impact the abstraction has on the available yield, especially the run-of-river yield. The two extreme cases are reduction in runoff by forestry (or sugarcane) and ecological requirement, which both follows a similar distribution to the natural runoff from the catchment. The impact of these water 'uses' vary considerably with the storage available at the point at which the yield is being determined and can only be determined accurately through simulation.

Secondly, the *assurance of supply* of the user also has a major influence on the impact the abstraction has on the yield available to downstream users. For example, an irrigator abstracting water from upstream of Midmar Dam may have a theoretical requirement of 10 million m³/annum, but due to upstream development only receives 5 million m³/annum on average. Of more relevance though, is that during the critical period of Midmar Dam the irrigator was only able to abstract 2,5 million m³/annum on average, and the impact of the irrigation on the yield of Midmar Dam is therefore only 2,5 million m³/annum and not 10 million m³/annum or even 5 million m³/annum as might have been assumed.

The *Rapid Simulation* method zooms in on the critical period of each dam, determined during the *cumulative yield* analysis, thus reducing the computational effort required to determine the impact of various abstractions and SFRA's on the yield. The basis for this method is given in Equation 1 below from which it is clear that if the critical period is known, the calculation of the historical yield is trivial. It is still necessary to consider the entire duration of the flow record in order to

determine the changes in inflow over the whole time series because the critical periods are not the same at every node. The calculation of the evaporation loss from the reservoir surface is also not trivial, but this is done through an iterative solution over the critical period of the dam. This *rapid* method is used in the graphical output to demonstrate how the yield of a dam changes with changes in upstream abstraction or SFRA's and could be a useful stakeholder participation tool.

$$\text{Historic yield} = \frac{[\text{Inflow}_c + \text{Live storage} - \text{Outflow}_c - \text{Evaporation}_c]}{\text{Critical period}} \times 12 \quad \dots \text{Eqn (1)}$$

Where:

Historic yield = Yield (cumulative) in million m³/annum

Inflow_c = Total inflow (in million m³) to the reservoir during the critical period

Live storage = Full supply capacity less dead storage (in million m³)

Outflow_c = Total outflow (in million m³) from the reservoir during the critical period

Critical Period = the time period in months from the reservoir being at its dead storage capacity back to when it was full

Evaporation_c = Net evaporation from the surface area of the reservoir during the critical period ie evaporation less rainfall (million m³)

3. MODEL CAPABILITIES AND LIMITATIONS

In the development of the Rapid Simulation Model, one of the objectives was to cater for a sufficiently wide range of possible development options to be useful in practice without becoming overly complex. This objective has been met and more complex features could be added for specific applications should the need arise. The capabilities or options catered for in the current Version 1 of RSM are as follows:

3.1 Water users

The Rapid Simulation Model caters for a wide range of different water users and SFRA's. These are as follows:

3.1.1 Direct Use

- Rural (can be used as an indication of the human Reserve)
- Strategic (water used consumptively for power generation)
- Industrial
- Urban
- Irrigation

In the case where there is more than one direct use or transfer (see 3.1.3) at a node, the user must specify the priority of use. Typically this would be in the order given above with the ecological requirements (see 3.1.3) receiving the highest priority of supply.

3.1.2 Diffuse or indirect use

Certain water uses, such as forestry, do not abstract water from available surface flow as such, but reduce the runoff through rainfall interception and increased evapo-transpiration. This is modelled by subtracting the use directly from the

natural runoff before other users get access to the water. Diffuse users such as irrigation and rural use can also be treated in the same way when there are a number of small abstractions, the exact locality of which is not known. RSM allows for four types of diffuse use:

- Afforestation
- Dryland sugarcane
- Irrigation, and
- Rural water use.

3.1.3 *Water transfers*

Within the RSM modelling context, water transfers are more than just the physical transfer of water from one catchment to another but refers to any water which is routed from one part of the catchment to another without being used consumptively. These are:

- The ecological Reserve
- Operational releases from a reservoir (usually for downstream users)
- Transfers to or from another catchment
- Return flows
- Mine water decant

In the case of the ecological requirements, operational releases, and transfers, these are defined as a time series and the user must specify the priority with which they are released or abstracted from the reservoir or river.

Return flows and mine water decant are also defined as time series but since these flows are added to the existing flow at a node, it is not necessary to prioritise these flows. Return flows are calculated as a percentage of the abstraction with which it is associated.

3.1.4 *Losses*

Losses can be modelled for any channel reach and is specified as a percentage of the flow in the channel.

3.1.5 *Groundwater use*

Groundwater use requires the simulation of the interaction between groundwater and surface water. This utility is one of the more complex in the RSM model and cannot be addressed fully in this paper. In brief, the method adopted was to incorporate simple groundwater/surface water relationships from the Pitman Model (Pitman, 1973) into RSM with which the reduction in surface flow can be determined for a given abstraction from groundwater. This simple technique seems to be technically sound but needs to be tested against more rigorous groundwater models to ascertain its level of accuracy and range of applicability.

3.2 **Scenarios**

RSM has been structured and coded specifically to model a wide range of scenarios. The main objectives strived for with scenario modelling are *simplicity* and *efficiency*, with the intention of producing results which are easily understood and can be produced rapidly enough for a workshop environment and accurately enough for decision making.

Scenarios are dealt with at two levels of resolution. Firstly on a catchment-wide resolution where any water user sector can be scaled up or down as required. Using this method it is easy to quickly determine how a particular user sector impacts on the availability of yield to others. The second level of resolution applies

to each channel and to each node in the case of diffuse use. It is therefore possible to scale any particular direct abstraction or diffuse use at any particular node up or down as required and hence determine the impact of this change on the yield availability throughout the system.

There is no facility as yet to compare the results of subsequent runs on a single screen but the output can be exported to a spreadsheet for comparison purposes.

3.3 Model limitations

The main limitation of the Rapid Simulation Model is that it does not carry out a simultaneous solution of the entire network at each time step and can therefore not deal with complex operating rules which relate an upstream action to a downstream condition.

The current version of RSM is limited in size to 300 channels and 200 nodes which is large enough to model any drainage basin in South Africa at a quaternary scale except the Orange/Vaal River Basin. However the programming language used (Delphi 7) sets no limitation on the size of data structures so it is possible to model larger systems. The limitation lies in the memory and disk space available on the computer but obviously very large systems could become too slow for workshop type environments.

RSM does not do stochastic modelling and all yields are based on the historical sequence. The user can however define the level of assurance at which the yield is determined and the option is available to generate yield-reliability curves based on the historical sequence. The historical firm yield obtained in RSM can also be related to the long -term yield if a long term yield curve is available.

4. MODEL SETUP

RSM has been structured and coded to be set up and used in two distinct modes - a *reconnaissance mode* and a *detailed analysis mode*, with the difference between these modes being simply the level of detail and the accuracy of the data used in the setup. For the purpose of *reconnaissance mode* analyses, a large number of utilities have been developed and/or incorporated into RSM to facilitate model setup. These include the following:

- Setup and capture incremental runoff data
- Setup and capture rainfall files
- Generate irrigation requirement time series
- Generate forestry requirement time series
- Generate time series for urban, industrial, mining or strategic water use
- Generate cumulative hydrology time series for input into the Desktop Reserve model (Hughes, 1999).

As far as possible the above utilities have make use of readily available data, such as:

- WR90 (rainfall, natural incremental flows, evaporation)
- WSAM pre-processor data: irrigation (crop area, types and crop factors), forestry (areas, tree type)
- WSAM exports (urban, industrial, mining, strategic, rural, groundwater abstractions)

The intention is to use the *reconnaissance mode* to get a broad perspective of the catchment and then, if more accuracy is required, to replace the datasets with more detailed data. This would probably be required in stressed catchments if decisions relating to water allocations are to be made. The first step in improving the accuracy of the model would be to replace the WR90 hydrology with more accurate hydrology. It is the experience of the RSM developers that WR90 hydrology tends to overestimate the yield available when compared with more detailed hydrology. Other datasets such as irrigation, afforestation, rainfall, and ecological requirements can then be replaced with more accurate data if available.

Model setup and editing is driven through drop-down menus and full on-screen editing using Paradox database tables as an interface between the raw data, which is stored in text files, and the user. All data changes are written back to the input file which can be stored for later use or for exchange with other users. Typically data such as hydrology, rainfall and abstraction would not be changed after the initial setup but altered only during run time in memory using scenarios.

5. MODEL UTILITIES

5.1 Graphics

A wide range of graphics tools are available which allow the user to plot any input or output time series, abstraction time series and reservoir trajectories. Scenario analysis options have been added to most of these graphics features to enable the user to see how a particular flow changes under changing land use conditions. Figure 1 is a plot of such a scenario analysis where the ecological requirement is plotted on the same axis as the modelled supply to ecology as well as the shortages. Using this tool the stakeholder, ecologist or modeller is able to get an understanding of the impact that any upstream use could have on a proposed ecological requirement. This tool could therefore be used in a workshop environment to set the ecological Reserve in consultation with representatives of all the major water user sectors in the catchment.

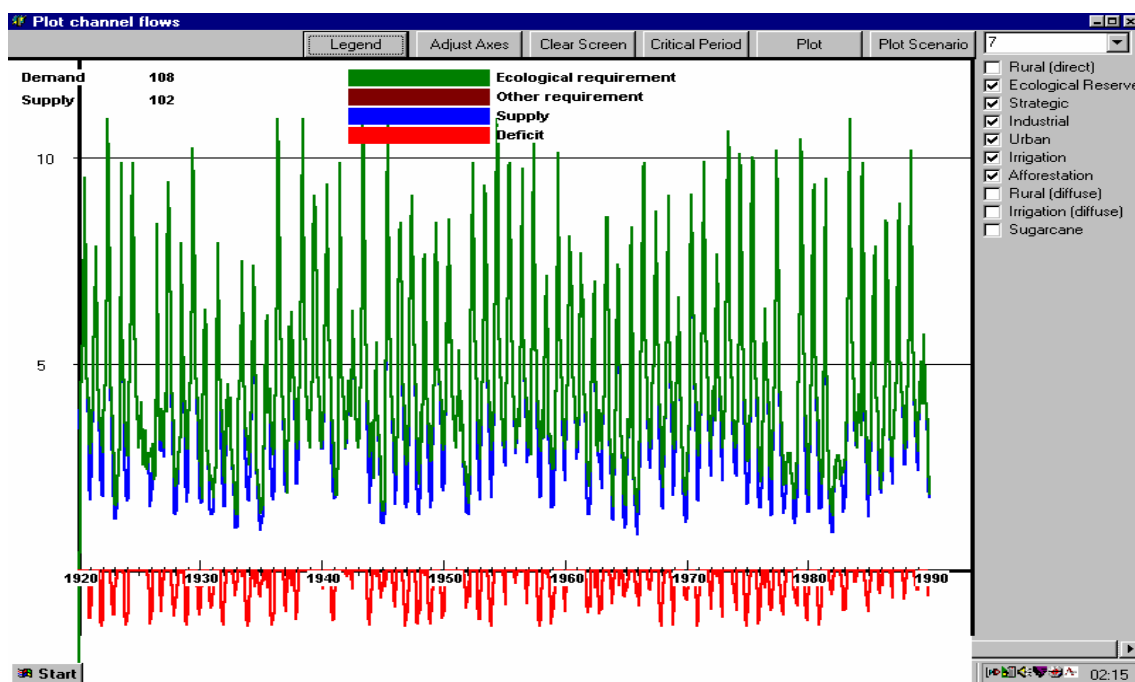


Figure 1: Graphics Features with scenario options

5.2 Stakeholder participation

Using the equation presented in 2.2.5, in combination with computer generated graphics, it is possible to impart an understanding of what the main drivers in determining the yield of a dam are and how the yield changes under changing operating conditions and changes in upstream development. A example of this presentation tool is shown if Figure 2.

A pre-requisite of this type of simplified analysis is a knowledge of the critical period of the dam under consideration. This is determined by first carrying out a simulation over the entire period of the historical flow sequence. Care must however be exercised with this type of analysis since large changes in the inflow hydrology or operating rules can lead to a change in the critical period of the dam. To overcome this problem, a full simulation is run for every new scenario selected and the 'Rapid' method is only used to give an indication to laymen as what is driving the yield in a catchment. Nevertheless, this method of analysis is proving to be remarkably robust and could be become a valuable for stakeholder participation in water allocation workshops.

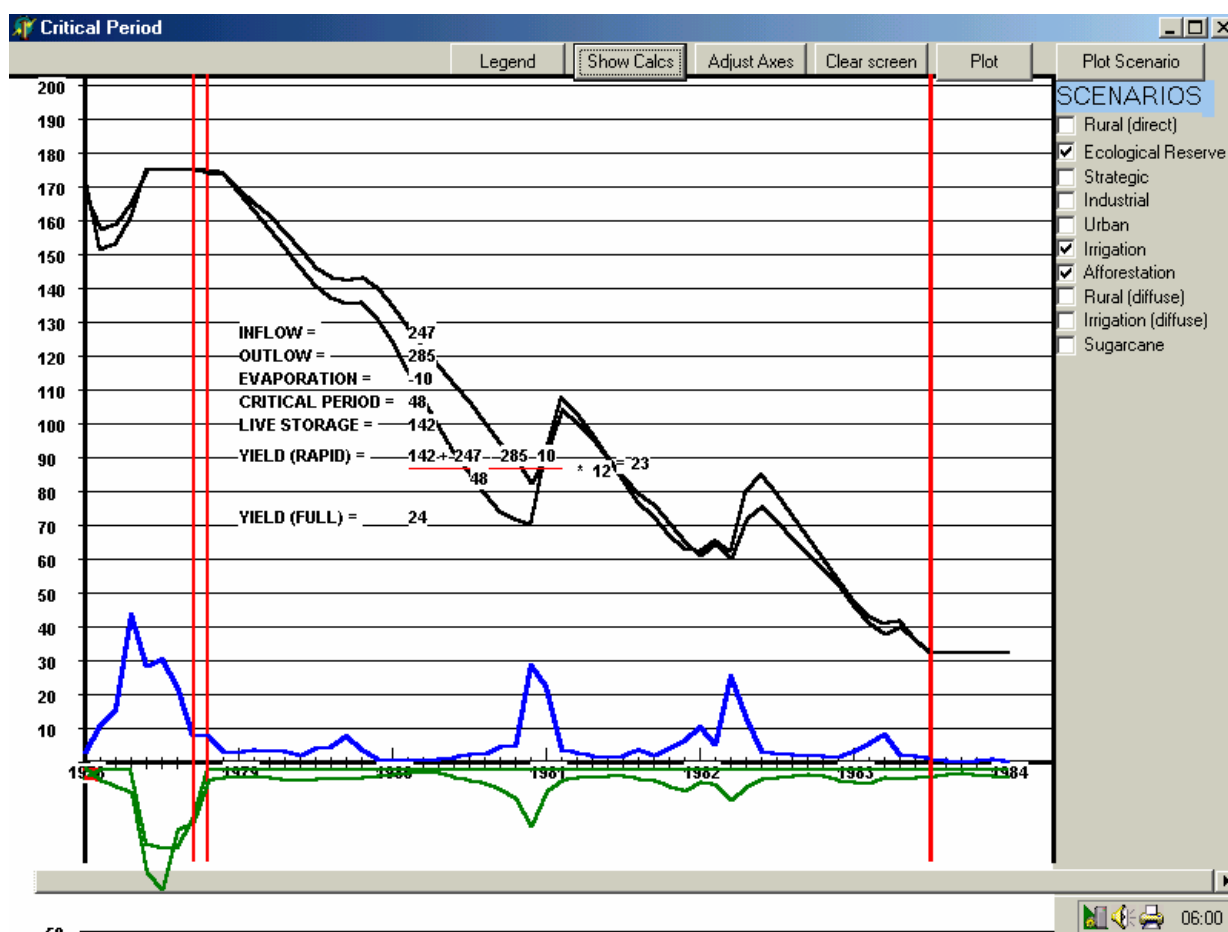


Figure 2: Yield Scenarios

5.3 Low assurance use and water use allocations

The so-called 'Water Balance' or 'Yield Balance' concept upon which WSAM (DWAF, 2002 and the National Water Resources Strategy is based is intuitive provided the water requirements are greater than the water resource and a positive 'Balance' is obtained. However, concerns have been raised as to what a negative balance actually implies and more attention needs to be given to this problem. As an example of this conundrum, consider a non-perennial river from which irrigators abstract water when available to irrigate their crops, with the knowledge that water is not available every year and that crop failures will occur periodically. In terms of the 'Water Balance' methodology, there is no 1 in 50 year yield available, and yet irrigation has developed and thrives despite this.

This negative balance or low assurance type of use can only be properly understood through a simulation type model. The approach developed and coded into RSM is to generate a yield-reliability curve using both the cumulative and balance type analyses described in section 2. The yield-reliability curve would typically be generated assuming SFRAs and the ecological Reserve to be in place so as to give an indication of the yield that is available before any surface water allocations are made, while the balance curve indicates the yield that is still available after all known users have abstracted their requirements from the river or reservoir under consideration. The supply to each user can be added to this graph with the position on the X-axis determined by the assurance of supply (determined during an accumulative analysis) and the Y-value determined by the requirement and/or the supply; by using both values the shortage in supply can also be indicated. An example of such a plot is shown in Figure 3.

Plots such as that shown in Figure 3 can be produced rapidly enough for a workshop environment for the same range of scenarios as other graphic features referred to in this paper. This gives a much clearer indication of how much allocable yield is still available and at what assurance. This could be used as a technical basis for workshoping water allocation scenarios.

6. TESTING AND APPLICATION OF THE MODEL TO REAL-WORLD PROBLEMS

The Rapid Simulation Model has been tested thoroughly against the Water Resources Yield Model and found to produce very similar results where the system operating rules are simple enough to make comparison valid. However, these tests have been carried out by the model developer and it acknowledged that testing by other users is required and is encouraged.

RSM has been used extensively over the last year on various projects for the Department of Water and Forestry, the most prominent of which were the Internal Strategic Perspectives for several Water Management Areas where it was used to provide estimates of the water resource and the impact of forestry and the ecological Reserve on the yield available to other users.

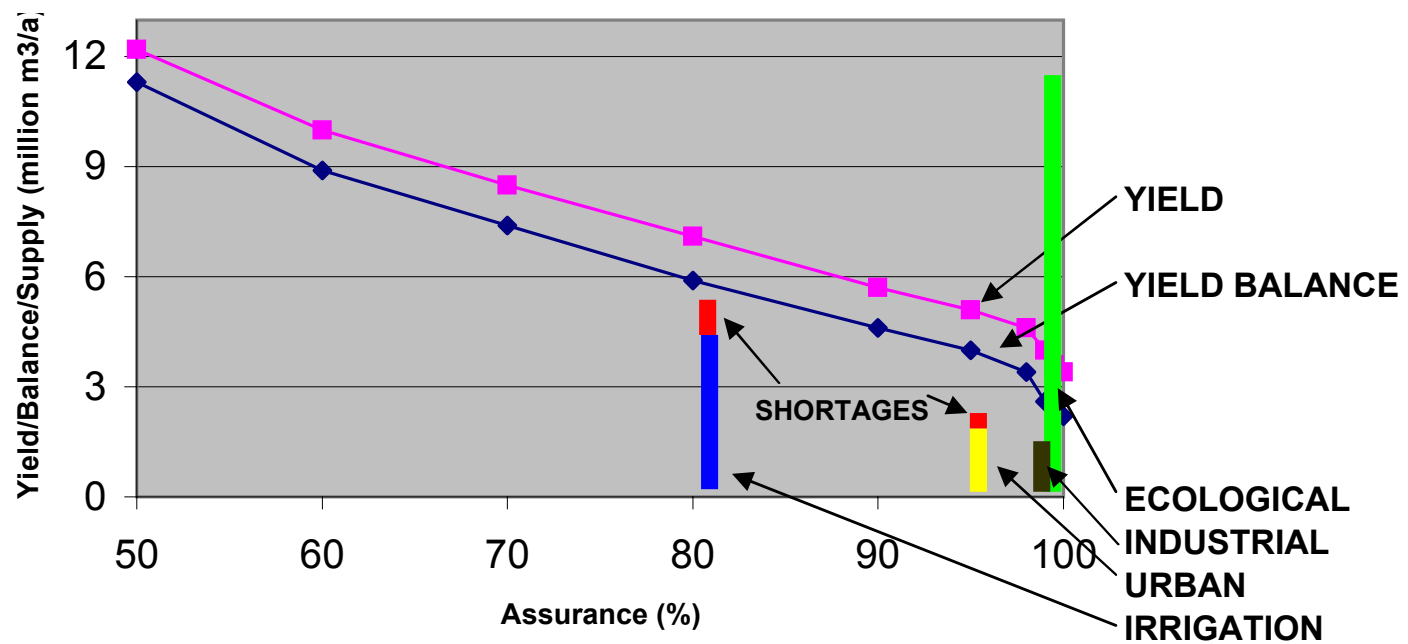


FIGURE 3: WATER RESOURCES SITUATION

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