

A DECISION SUPPORT SYSTEM FOR BENEFICIAL USE OF NATIONAL DAM WATER RESOURCES IN SWAZILAND

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ABSTRACT

Globally water is unevenly distributed in time and space. In Swaziland the highveld region receives high rainfall ranging from 1200 to 1500mm annually while the lowveld region receives the lowest amount of rainfall ranging from 300 to 500mm annually. The Planning, development and management of water storage and transmission facilities is an attempt to change the spatial and temporal availability of water, to make it available where and when needed.

The Government of Swaziland has undertaken the development of water storage and distribution facilities as a process towards overcoming the unevenly distribution of the water resource. However, the current water storage facilities with a total capacity of $568.65 \times 10^6 \text{ m}^3$ can not meet the water demand which stands at $1795 \times 10^6 \text{ m}^3$ annually. The overall objective of this project was to develop an optimum and sustainable utilization decision support tool for water allocation and rationing options for national water reservoirs.

A Decision Support System (DSS) is defined as a user-oriented computer system which supports decision-makers in addressing unstructured problems. The rationing mode in the developed DSS was used to distribute the available stored water at the beginning of April in order to arrive at a priori predetermined reservoir storage level at the end of October. The DSS has three major components and that is the model input, modeling options and outputs screens. The model input component comprises of technical data (inflow, reservoir level, intended % volume at end of October and allowed lowest rationing %), and policy data (uniform rationing or differential rationing). The modeling options comprise of commands to determine optimum rationing %, provide % rationing and observed dam response and imposed rationing %. The output of the DSS comprises of the optimal rationing (%), monthly reservoir volume from April to end of October as well as a graphical representation of the reservoir response and the final recommendation. The DSS also provides the total crop hectarage and thus the net benefits for the different initial and end of season (October) for the corresponding optimal irrigation water rationing (%).

The results of the DSS with a starting reservoir level at 15m at the beginning of April and a 10% reservoir level at the end of October, is that there is no need for rationing (that is the water demand for all uses are met) and the reservoir level stands at around 29% at the end of October. The results of the DSS with a starting reservoir at 6m at the beginning of April is that the rationing is 46% for all uses in order to arrive at a 10% reservoir storage level at the end of October is not recommended. This is because, with 54% deficit, there is a danger of crops to wilt beyond recovery. The final DSS recommendation starting with a reservoir level at 6m at the beginning of April is irrigation rationing at 60% (i.e. 40% water deficit) combined with a reduction of 14% of the hectares of irrigated fields.

The Nyetane dam was used as a pilot reservoir in the development of the DSS. The developed DSS with all the relevant input data can be used to allocate water efficiently in other reservoirs in the country.

Keywords: Beneficial, Decision support system, Optimum, Rationing, Sustainable use

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BACKGROUND

The Kingdom of Swaziland, is situated in South Eastern Africa between latitude 25° and 28° South and between longitudes 31° and 32° East. It lies some 48 to 225 kilometers inland of the Indian Ocean littoral and hence physically land locked. The country has a total surface area of 17,360 km² and therefore, is the smallest country in the southern hemisphere.

It is bounded by the Republic of South Africa in the north, west and south, and by Mozambique on the east. Although small in size, Swaziland is characterized by a great variation in landscape, geology and climate. It also lies within the Maputoland Centre, an area reported to have the greatest biodiversity in Southern Africa.

There are four distinct physiographic regions within the country namely: highveld, middleveld, lowveld and lubombo, which are clearly distinguished by elevation and relief (Murdoch, 1970). Swaziland enjoys a climate which is generally subtropical, with hot and wet summers and cold and dry winters. Further variations in climatic conditions occur within the different physiographic regions giving rise to three clearly distinguishable climate types.

The highveld and upper middleveld are characterized by a Cwb climate. The lower middleveld and lubombo range have a Cwa climate whilst the western and eastern lowveld have a Bsh climate (Murdoch, 1970). Mean annual rainfall ranges from about 1500 millimetres in the highveld to less than 500 millimetres in the southern lowveld.

The highveld's temperate climate is characterized by wet summers and dry winters, and annual rainfall averaging 1500 millimetres. Temperatures vary between a maximum of about 33°C in mid-summer and 0°C at night in mid-winter. On the other extreme end is the lowveld which experiences a sub-tropical climate. This region receives the lowest annual rainfall of about 450 mm. There is also a large diurnal temperature range experienced here with maximum temperatures reaching the upper 30°C are not uncommon. Semi-arid pockets of areas are found in this region, which is also liable to desertification. The frequency of heavy downpours is more uniform across Swaziland than the total rainfall. Between 75% and 83% of precipitation (summed mean monthly amounts) comes in summer months (October – March).

The water sources in Swaziland are mainly surface waters (rivers, reservoirs), ground water and atmospheric moisture. Figure 1 shows the major drainage basins of Swaziland namely: Komati, Usutu, Mbuluzi, Ngwavuma, Lomati, Pongola and Lubombo. The Komati and Usutu rivers both

originate in South Africa while the rest of the basins originate within Swaziland. It should also be noted that all the rivers in Swaziland are international rivers and therefore, the development and management of the surface water resources must be undertaken in collaboration with the other riparian states namely: South Africa and Mozambique.

Water is unevenly distributed in time and space all over the world and Swaziland is no exception. The major objective of water resources planning and development is to alter the temporal and spatial availability of water. To make the water available where and when needed and this is possible through the construction of storage and distribution facilities.

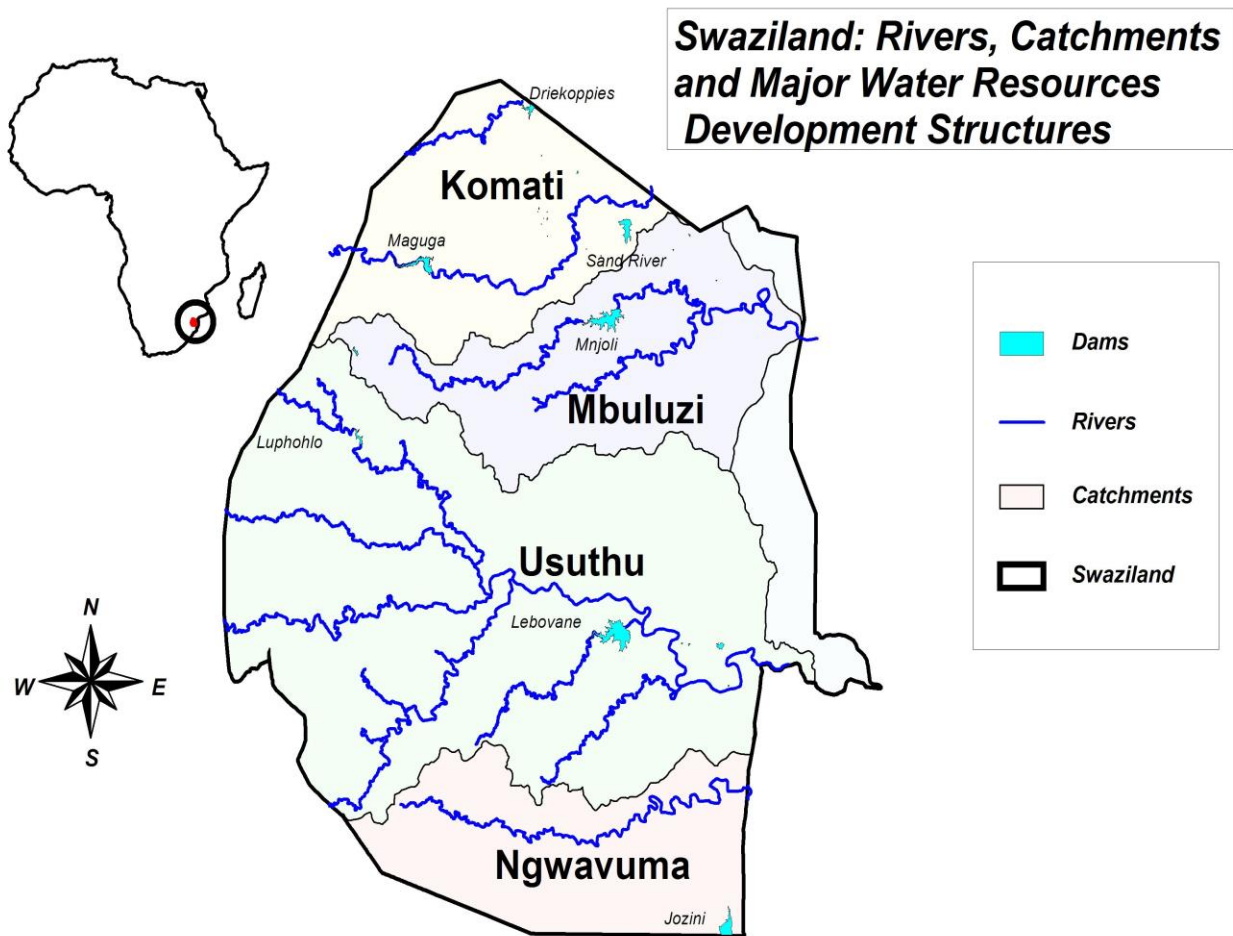


Figure 1. Map of Swaziland showing the major drainage basins and location of existing water storage facilities

There are ten big dams in Swaziland which are greater than 5 million cubic metres (MCM). The dams are located in the Komati, Usuthu and Mbuluzi catchments. Three of these reservoirs are

government owned located in each of the three catchments whilst the remaining six reservoirs are owned privately.

The existing infrastructure is not sufficient to cater for the whole country and currently the lowveld region continues to suffer from drought related problems. The challenge to the Government, remains that of constructing water storage and distribution facilities and transfer it to areas of acute water shortage. Water resources management is posing a complex challenge due to the increasing competing and conflicting water uses amongst different sectors and also due to population increase which puts pressure on the natural resources.

The overall objective of this project is to develop an optimum and sustainable utilization decision support tool for water allocation and rationing options for national water reservoirs. The specific objectives of this project were: (i) To determine dam water use relationship in the following water uses: Hydropower/Power generation; Agricultural water use; Domestic water use; Industrial water use; Recreation Industry; Environmental water use etc. (ii) To develop different scenarios for optimal utilization to meet conflicting and competing dam water needs. (iii) To develop a decision support tool for competing dam water requirements, to help in the prioritization of allocations and rationing in times of scarcity i.e. during droughty years.

LITERATURE REVIEW

The fragile components of the spaceship Earth are principally air, land and water. These three highly interactive resources must be properly managed in order to ensure adequate public health, food supplies and transportation. The quality of human life is directly dependent on how well these natural resources are managed. Water is the most important catalyst for human economic development. It is a major input in almost all sectors of the human endeavour. Ancient civilizations grew up in the river valleys of Tigris and Euphrates, the Nile, Indus, Hwang Ho etc. where there was plenty of water. When the management of the water resources collapsed, the civilizations also weathered away.

It has been established by scholars that water resources management problems are more complex world wide (Simonovic, 2000; Wurbs, 1998; Singh, 1995). Population growth, climate variability, regulatory requirements, temporal and spatial scales, socio- economic and environmental considerations, competing and conflicting water uses and transboundary considerations all of these contribute to the complexity of water resources management problems.

The literature on water resources management is rich with Integrated Water Resources Management models that have tended to focus either on understanding how water flows through a watershed in response to hydrologic events or on allocating the water that becomes available among competing and conflicting water uses. Examples of such models are: The US department of Agriculture's Soil Water Assessment Tool (SWART , Arnold and Allen, 1993); RiverWare™ DSS (Zagona et al., 2001); The USA Geological Survey's Modular Modelling System (Leavesley et al., 1996); The US Army Corp of Engineers, HEC-ResSim (USACE, 2003) etc. The SWAT model includes sophisticated physical hydrologic watershed modules that describe,

rainfall-runoff processes, irrigated agriculture process, and point and non-point watershed dynamics but with a relatively simple reservoir operation module. The RiverWare™ DSS is a hydrologic and hydraulics operations model, which can be used to develop multi-objectives simulations and optimizations of river and reservoir systems. The HEC-ResSim is a reservoir simulation model that can describe operating rules such as release requirements and constraints, hydropower requirements, multiple reservoir operations etc. All the above water management models require prescribed flows from other models.

Decision Support Systems (DSS) are a specific class of computerized information system that supports business and organizational decision-making activities. A properly designed DSS is an interactive software-based system intended to help decision makers compile useful information from raw data, documents, personal knowledge, and/or business models to identify and solve problems and make decisions. A Decision support system was used in California USA to handle conflict between two groups who have on-demand water management for irrigation, drinking water and hydropower generation (Rajasekaram and Nandalal (2005). Gu and Tang (2000) developed a Water Resources Management Decision Support System to unify the objective world, organization and human factors during intervention. Karamouz *et. al*, (2005) developed a multi-criterion decision making (MCDM) that utilized an analytical hierarchy process which enabled decision makers to incorporate the priority of different objectives in obtaining optimal reservoir operating policies. Both economic and MCDM utility functions are implemented and coupled with deterministic and stochastic optimization models. The DSS was applied to the largest surface water resources system in Iran (the Dez and Karoon river-reservoir system).

METHODOLOGY

Data collection

The information that was required for carrying out this project is: Dam characteristics, hydro meteorological data, water use data, irrigation water requirement, area under irrigation for each crop, and net financial income.

Dam characteristics:

The information that characterize, a dam is the reservoir water level, the corresponding surface area and volume. This information is available from the dam designs and was obtained from the Ministry of Agriculture and Cooperatives which constructed the Nyetane dam. This information was used to compute the evaporation and seepage water losses from the reservoir which are both a function of the reservoir water level. The reservoir level at the beginning of April was used in the Dam height surface area and volume relationship by interpolation to get the corresponding reservoir surface area and volume. The reservoir levels and corresponding surface area and volume were input to the DSS where all the computations are carried out. The dam level was also used to calculate the water seepage losses from the reservoir. The reservoir volume and the volume of seepage losses are used in the water balance equation.

Hydro meteorological data

The hydro-meteorological data needed in this project are: reservoir inflows, temperature, and evaporation values. There is no hydrometric station along Nyetane river and therefore, rainfall runoff modelling was used to establish the monthly inflows into the Nyetane dam. Air temperature and evaporation data was obtained from the department of meteorology. The air temperature and pan evaporation data was required for the computation of water losses from the reservoir through evaporation. The following relationship was used in the computation of evaporation loss from the reservoir:

$$E_t = e_t \cdot A \left(\frac{V_t + V_{t+1}}{2} \right)$$

Where E_t is the total reservoir evaporation for month t , e_t is the evaporation index for month t (which is obtained from the pan evaporation values), A is the reservoir surface area which is a function of the reservoir volume in month t and $t+1$ (this is usually the reservoir volume at the beginning of month t and the reservoir volume at the beginning of month $t+1$, which is equal to the reservoir volume at the end of month t).

Water use data

The water use data for domestic was obtained from the Rural Water Supply Board while the water use for livestock and irrigation was obtained from the Ministry of Agriculture and Cooperatives. Water use for industry was obtained from the Swaziland Water and Sewage Corporation while water use for hydropower was obtained from the Ministry of Natural Resources and Energy. It should be noted here that water use for hydro power generation is non-consumptive use. That is water can be used to generate hydro power and for other uses down stream. This information was input to the water balance computations in the DSS.

Irrigation water requirement per hectare.

The irrigation water requirement for sugar cane, maize, cotton, vegetables and fruits was obtained from the literature review material. The expression to estimate the crop water consumptive use is as follows:

$$ET_c = ET_r * K_c \text{ (mm/day)}$$

Where ET_c is the crop water consumptive use, ET_r is the potential evapotranspiration for a reference crop and K_c is the crop coefficient. Crop coefficient values have been established experimentally for different crops and in this study the crop was assumed to be at full canopy cover. Therefore, the crop water requirement as a volume per hectare was obtained when the ET_c was multiplied by the area and in this case the hectare. This information was input to the DSS for computing the water demand abstraction.

Area under irrigation.

The area under irrigation for the different crops was obtained from the stakeholders who are irrigating using the water from the Nyetane reservoir. This information is necessary in quantifying the water demand and therefore, the required water abstraction from the reservoir in each month. This information was input to the DSS.

Net financial income

The gross income, input costs and net income per hectare for each crop was obtained from SWADE. This information was required in the DSS for the determination of the returns (net benefits) for the acreage under irrigation for the corresponding optimum water rationing (%).

All the information required for running the Decision Support System (DSS) is presented in Appendix A. All the other calculations are carried out within the DSS (the rationing component).

Development of Scenarios for reservoir operation

The major objective of reservoir operation (post contract problem) is the maximization of net benefits due to water releases for the different uses. This problem is set as follows:

$$\text{Maximize } b_w \cdot Q_t + b_p \cdot P \quad (1)$$

Subject to

$$V_{i+1} = V_i + I_i + R_i - Q_i - E_i \frac{V_i + V_{i+1}}{2} \quad (2)$$

The water release Q_t is the sum of all the water demand for all the activities during month t . The above relationship was used in the DSS in the water rationing process which is carried out from month $t = 1, \dots, 7$ (which is from April to October). This is because the water rationing procedure is carried out during the winter months to ensure that the reservoir is used efficiently. Secondly the rain season has been observed to have shifted to the beginning of November that is there is a delay in the onset of the rain season instead of starting at the beginning of October it has currently been observed to start in early November.

The scenarios that were considered are those based on the occurrence of drought recurrence interval such as one in five years, one in ten years etc. The average and wet year conditions are also scenarios for consideration when operating the reservoir. However, it should be noted that the wet year scenario is not of a problem because the water demand is expected to be met and should give the maximum net benefits.

Reservoir starting and ending levels were considered as scenarios in the management of the dam waters and they are linked to the frequency of droughts. This is because if the reservoir is full at the beginning of the season and operated to meet the water demand for the whole season and end up with a low reservoir level (depending on the inflows during the season) then the reservoir is not well operated. Thus, starting the next season with such a low reservoir level gives a high risk

for the farmers, and that they might get severe losses. Therefore, the DSS was used to find optimal starting and ending reservoir levels for the different drought scenarios explained above.

Conceptualization of the DSS

Important characteristics of a Decision Support System (DSS) for sustainable water resources management include flexibility for tackling various 'what-if?' scenarios, the facilitation of problem identification and solving by analytical tools enabling the end-user to manage, analyse and present information, and interaction and ease of use to involve the stakeholders into the management process themselves [Simonovic and Bender 1996]. Integrated water resources management comprises numerous complex and unstructured management problems including a geographical component. Resolving ill-structured problems, however, can be achieved by disaggregating them into a series of structured components, each of which tackled with its unique set of tools [Reitsma 1996], and integrated into a comprehensive framework system.

According to Wurbs (1998), the concept of Decision Support Systems became popular during the 1980s in the water management community, as well as in business, engineering and other professional fields (Wurbs, 1998). Wurbs, 1998 defines decision support system as a user-oriented computer system which supports decision-makers in addressing unstructured problems. The general concept of a DSS emphasizes:

- (a) solving unstructured problems which require combining the judgement of manager-level decision-makers with quantitative information.
- (b) supporting capabilities to answer "what if" questions quickly and conveniently by making multiple runs of one or more models
- (c) using enhanced user-machine interfaces and
- (d) outputting graphically

Decision support systems include a collection of software packages and hardware. The decision support system might include data management software, watershed runoff, stream hydraulics, and reservoir system operation models, a computer platform with peripheral hardware devices and an automated real time stream flow and rainfall data collection system.

There are basically two distinct elements of the DSS, namely; *Rationing and Allocation* decision support tools.

(i) ***Rationing decision support tool***

This component of the DSS is long overdue in Swaziland and its absence's impact has been evident in a number of reservoirs especially the Nyetane reservoir which was empty during the development of the DSS and amount 400 hectares of sugar cane was wilting attracting huge debts from the financiers. This tool which was embedded in the DSS has provided intelligent information on:

- When to ration (giving various scenarios)
- Extent of rationing (giving various scenarios)
- Differential rationing (which category of use to be rationed first etc.)

This tool is quite comprehensive and the datasets required was acquired from the Ministries of Natural Resources and Energy, Agriculture and Cooperatives; Works and Transportation etc.

Ming-Yen Tu *et. al.*, (2003) developed a mixed integer linear programming (MILP) model that considers simultaneously both the traditional reservoir rule curves and the hedging rules to manage and operate a multireservoir system. During normal periods of operation when inflows are plentiful, this optimization model efficiently distributes the available stored water from different reservoirs to meet the planned demands imposed by the competing users. However, during periods of drought, and/or when anticipating a drought the planned demand can not be fully met and a water shortage occurs. To minimize the impact of drought, the hedging rule was used to effectively reduce the ongoing water supply to balance with the target storage requirement.

As explained earlier Swaziland receives rainfall during the summer months with very little rain during the winter months. In fact the Lowveld region where the Nyentane reservoir is located does not receive any rainfall during the winter months and has been experiencing drought related problems since 2001 to date. Therefore, the approach by Ming-Yen Tu *et. al* (2003) was used in the developed DSS. The rationing mode in the DSS was used to distribute the available stored water at the beginning of April in order to arrive at reservoir target levels at the end of October which were determined a priori.

(ii) *Water allocation between different uses decision support tool*

This is a more broad component of the DSS and is less dynamic than the one above due to the fact that water allocations are administered by the Water Act 2003 which gives long term permits. This component also need quite lot of data and other comprehensive spatial studies covering the whole country on crop-water requirement per crop. Without this spatial information on crop-water requirement this component may not function adequately.

The water resources from the Nyetane dam is used for agricultural activities (sugar cane, citrus fruits, vegetables, and livestock) and domestic. All crops get the required water demand when there is enough water. Rationing is done to all crops and other uses during years with water scarcity.

The current situation in the country under irrigated agriculture is that the growing of sugarcane is a continuous process. That is come the rain season a farmer will have sugarcane fields at different growth stages. Therefore, the problem of water allocation among different crops can not be carried out in the usual way using optimization techniques. Therefore, the approach in this study was to rank the crops according to their net income per hectare. All other crops except dry maize have a high net income per hectare than sugarcane. Therefore, under water scarcity situations the hectrage under sugarcane will be reduced in order to make the available resource enough for part of the sugarcane field and other crops.

Since only a single reservoir site was used to pilot the DSS, a good framework was developed that could be expanded to cover other reservoirs and other scenarios. Figure 2. below illustrates the developed Decision Support System.

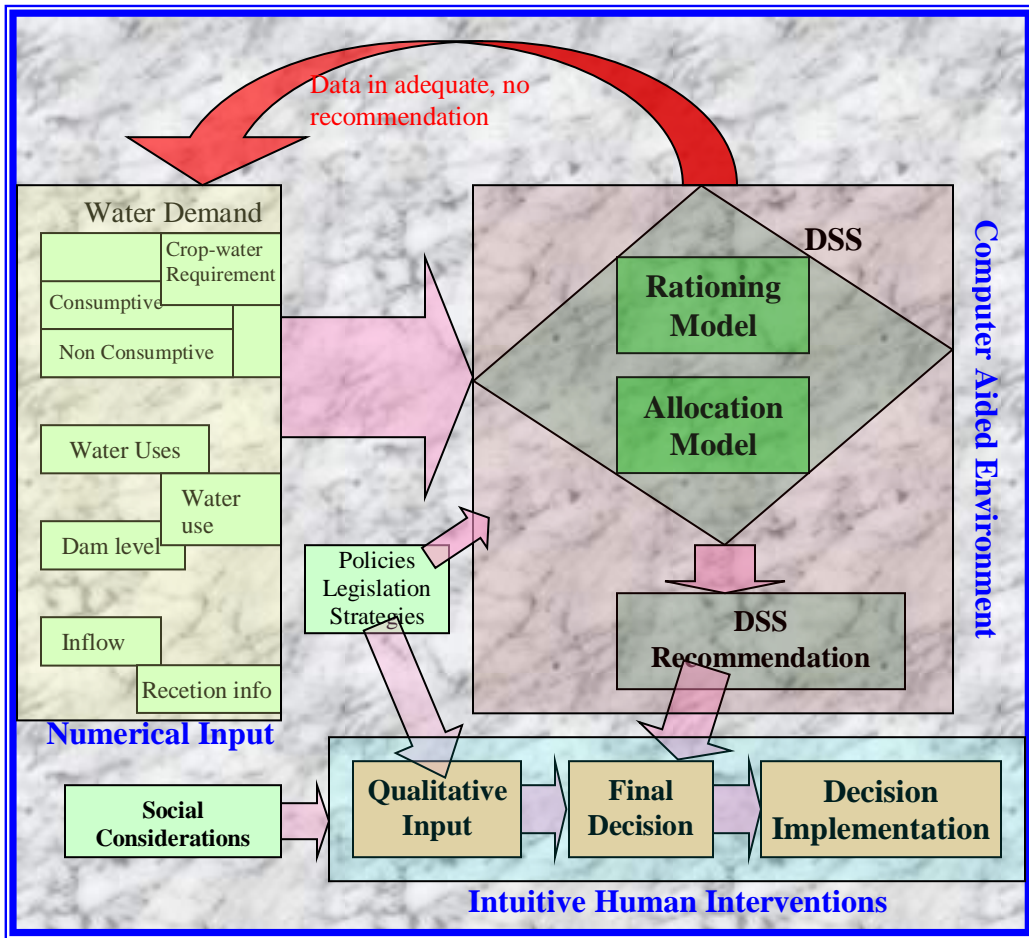


Figure 2: A diagram showing the DSS layout and components

Computational procedure in the DSS.

The water balance equation was used in the computational processes in the DSS and is presented below :

$$Q_{t+1} = V_t + I_t - Q_t - Q_l - e \left(\frac{V_t + V_{t+1}}{2} \right) \quad (3)$$

The reservoir level at the beginning of April was used to determine the corresponding reservoir volume using the Dam level, surface area and volume relationship through an interpolation procedure. The inflow for the months from April to October is computed using the following equation:

$$I_{t+1} = I_t \rho^{k(t+1)} \quad (4)$$

Where I_{t+1} is the inflow at time $t+1$ and k is the groundwater recession constant and ρ is the natural log.

This is because the inflow into the reservoir during the winter months is due to ground water contribution and is recession flow. Q_1 is the water loss in the reservoir through seepage and percolation which is computed as a function of the Dam level. Q_t is the total water abstraction for month t (irrigation, domestic, livestock, industrial etc.). The water abstraction is obtained from the water use tables. The water abstraction for each month is subjected to a water rationing iteration process in the DSS using the water balance equation from the beginning of April to the end of October.

Given the reservoir level at the beginning of April, the target reservoir level at the end of October, uniform rationing or differential rationing and the lowest allowed rationing (%), the DSS performs an iteration procedure from April to October to determine the optimal rationing (%). The rationing in this study is the % of the total water demand for that month. That is if the optimal rationing is 90% it means that a 10% water deficit is incurred for all the crops during that month.

RESULTS AND DISCUSSION

The developed DSS has three major components and that is the model input, modeling options and outputs. The model input component comprises of technical data (inflow, reservoir level, intended % volume at end of October and allowed lowest rationing %), and policy data (uniform rationing or differential rationing). The modeling options comprise of commands to determine optimum rationing %, provide % rationing and observed dam response and imposed rationing %. The output of the DSS comprises of the optimal rationing (%), monthly reservoir volume from April to end of October as well as a graphical representation of the reservoir response and the final recommendation.

The DSS is started by inputting the reservoir level at the beginning of April, the intended end of October reservoir volume (%) and the allowed lowest rationing (%). The policy data input is either uniform rationing or differential rationing. When differential rationing is selected two boxes become active at the bottom requesting to input the % of irrigation rationing and the % of rationing the other water uses and then click finish, modeling option and the compute buttons to activate the iterations in the DSS.

The starting reservoir level at the beginning of April is a function of climate and the previous history in the catchment (i.e the rainfall distribution during the previous rain season (October to march). That is during wet years, the reservoir level at the beginning of April is expected to be at maximum supply level and during dry years, the reservoir level at the beginning of April is expected to lie between minimum and maximum supply levels.

A sample output results for the developed DSS are presented in Figures 3 to 6. It can be seen from Figure 3 that with a starting reservoir level at 15m at the beginning of April, there is no

need for rationing and the reservoir level stands at around 29% at the end of October. Figure 4 shows the DSS results with a starting reservoir level at 8m at the beginning of April and with uniform rationing the DSS recommends a 63% rationing for all water uses (that is a 37% deficit is incurred by all uses) in order to end up with a reservoir level at 10% at the end of October. Figure 5 shows the results of the DSS with reservoir level in April at 8m but with uniform imposed rationing of 80%. The DSS recommendation is that the imposed rationing of 80% is not recommended (because the reservoir storage is 0 at the end of October) and that a more stringent rationing should be used or to choose the optimization option. Figure 6 presents the results of the DSS with a reservoir at 6m at the beginning of April with uniform rationing. The DSS recommendation is that of rationing at 46% for all uses in order to end up with 10% reservoir storage at the end of October is not recommended. This is because, with 54% deficit, there is a danger of crops to wilt beyond recovery. The final DSS recommendation is irrigation rationing at 60% combined with a reduction of 14% of the hectares of irrigated fields.

CONCLUSIONS AND RECOMMENDATIONS

A Decision Support System (DSS) tool has been developed with the use of input information from Nyetane Dam as a pilot reservoir. The Developed DSS can be used to give optimal rationing given the starting reservoir level at the beginning of April and a priori reservoir level at the end of October. The corresponding hectrage for the different crops that were irrigated in the season and net benefits can also be obtained. Input data from any other reservoir can be used in the developed DSS for optimal rationing of water resources for that dam.

It is recommended that the developed DSS be implemented in the rationing of the water resources of the Nyetane dam in order to establish the output results of the model in real time operation. This information can then be used to evaluate the sensitivity of the DSS and effects of the water deficits in relation to crop yield can also be analysed.

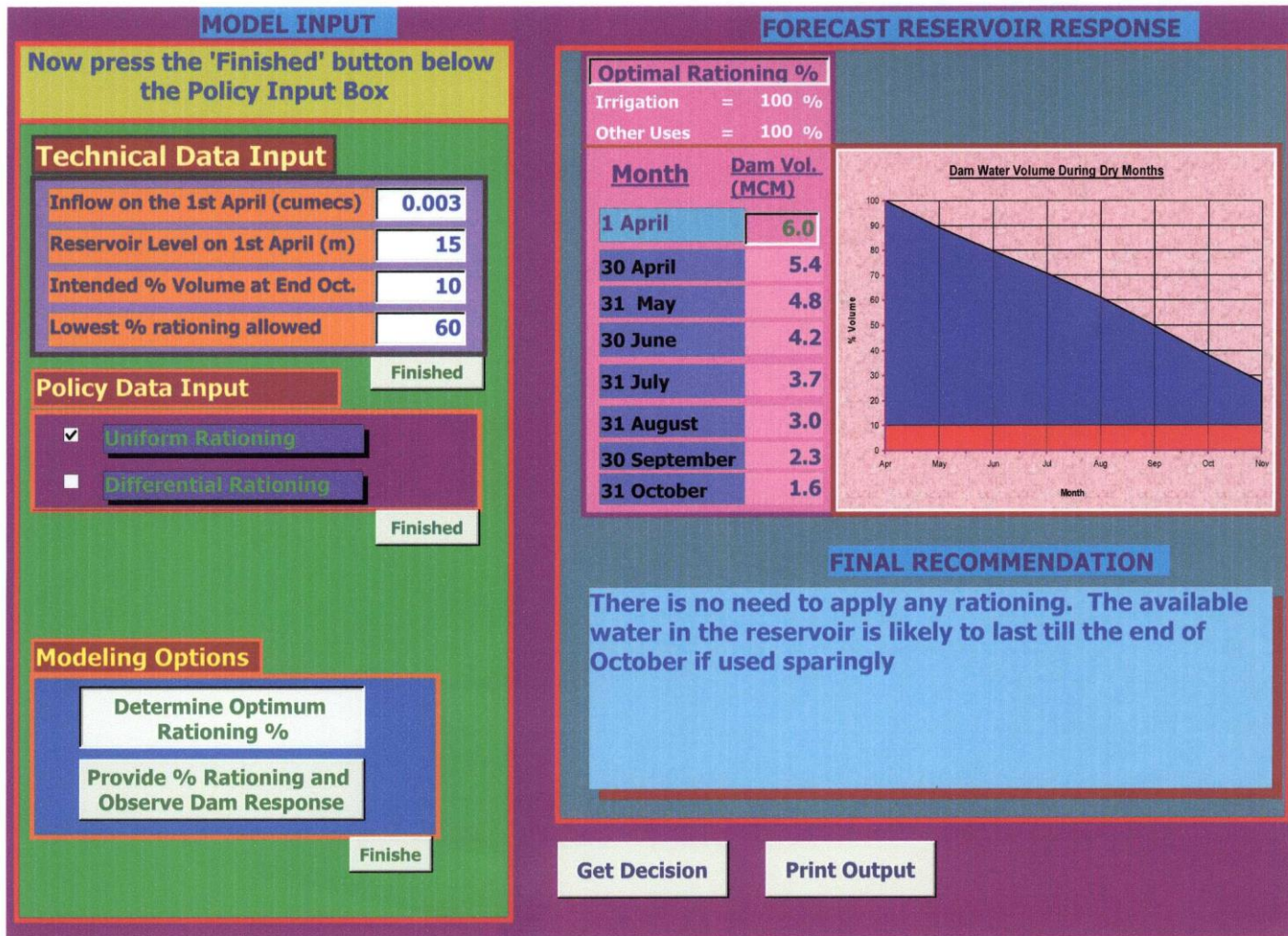


Figure 3: DSS results with starting reservoir level in April at 15m and 10% reservoir level at the end of October

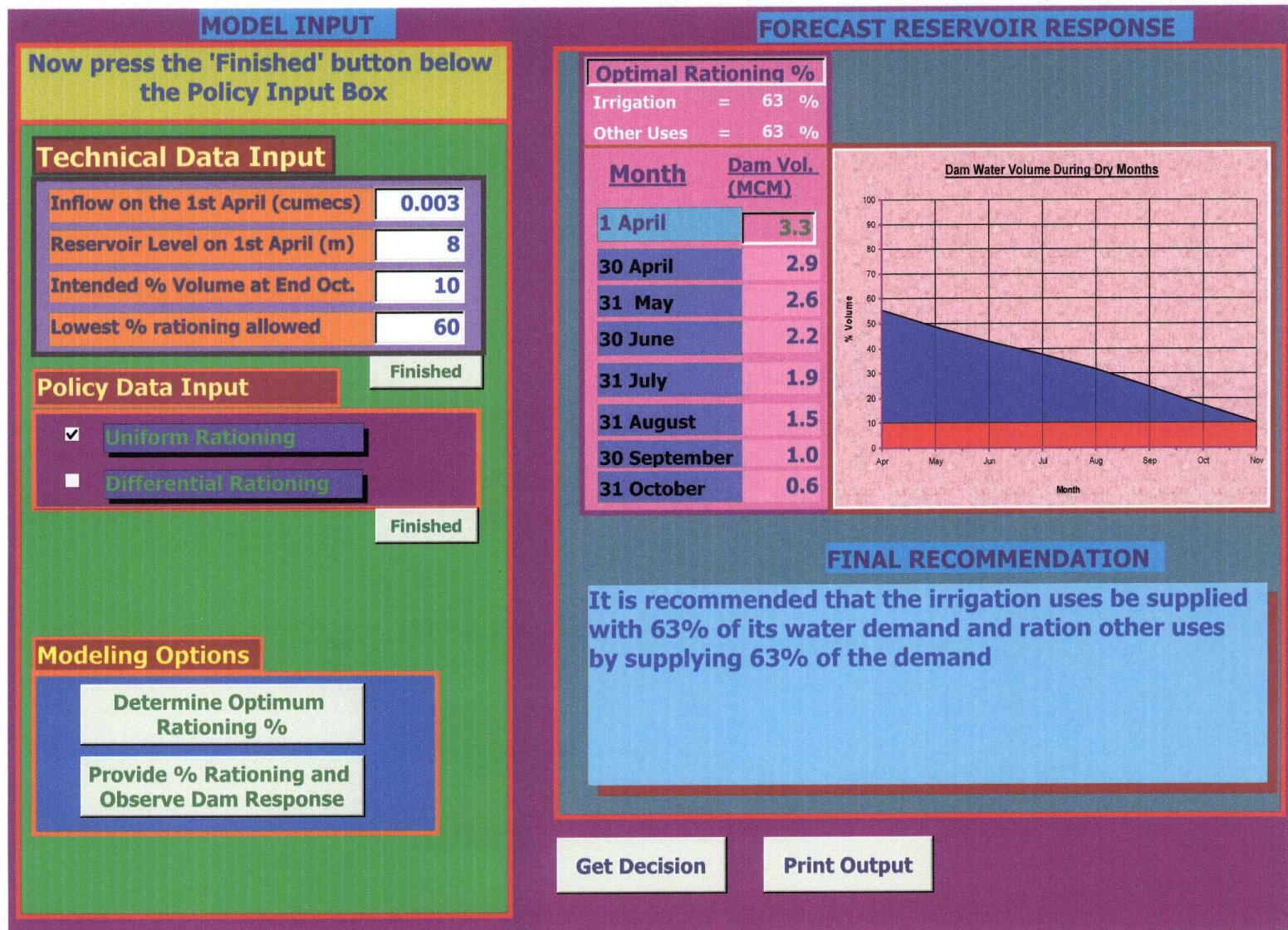


Figure 4: DSS results with starting reservoir level in April at 8m and 10% reservoir level at the end of October

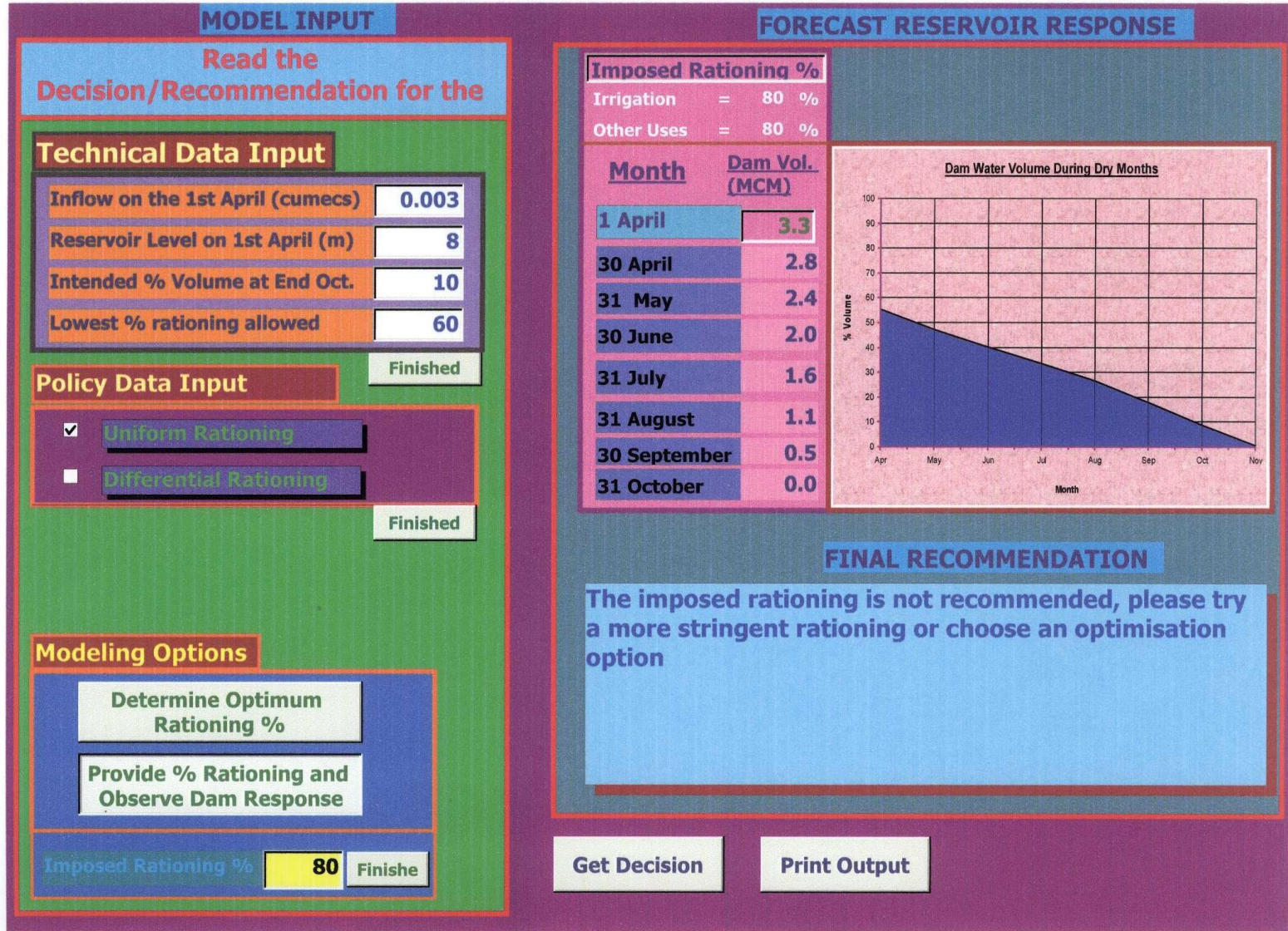


Figure 5: DSS results with starting reservoir level in April at 8m and 10% reservoir level at the end of October

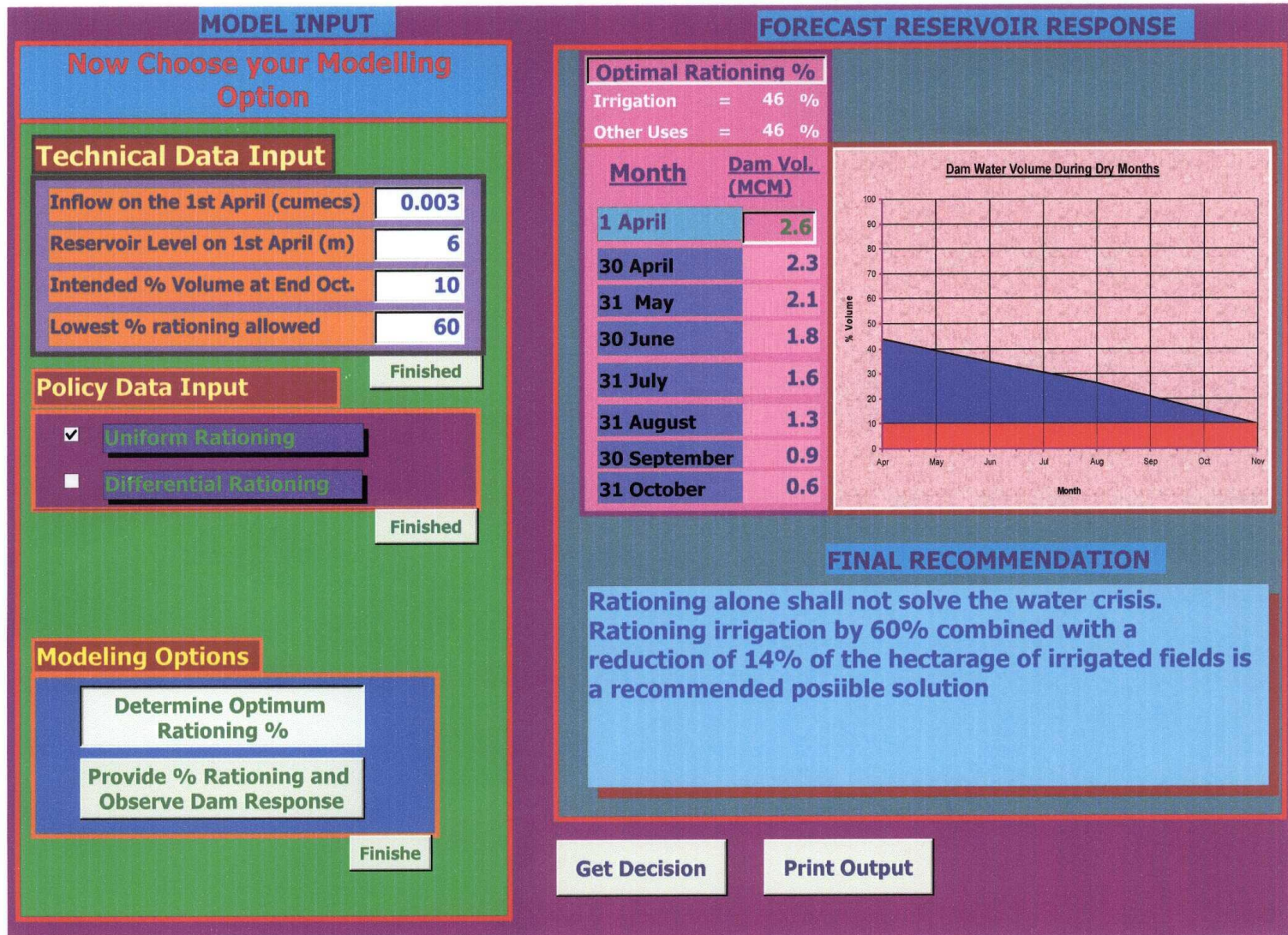


Figure 6: DSS results with starting reservoir level in April at 6m and 10% reservoir level at the end of October

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