A monthly time step, multiple reservoir water balance simulation model

DA Hughes
Institute for Water Research, Rhodes University, PO Box 94, Grahamstown 6140, South Africa

Abstract

A monthly time step, multiple reservoir water balance model is described. The model is based upon the RESSIM model, but algorithms to control transfers between dams in the system have been added. The model has been formulated for use in conjunction with either observed inflow volumes or a monthly time step, catchment rainfall-runoff model. Two examples of how the model can be set up and used to assess water resource schemes are given. One of these relates to a small irrigation scheme, while the other looks at the dynamics of a municipal water supply operation.

Introduction

In water resource planning and management there is often a need for simulation models that allow long time series of available rainfall and evaporation data to be used to generate similar length series of catchment runoff data, groundwater levels or reservoir storage volumes. Once such models have been calibrated (if necessary) and validated they can be extremely useful to examine the effects of changes such as upstream land use, gross water requirements or the operating rules and management approach to water utilisation as well as examining such things as the frequency of drought conditions of different severities or storage-yield relationships.

There are a number of hydrological simulation models referred to in the literature (O'Connell, 1991) and they vary from very simple, single function empirical models to complex multi-function models whose parameters can be estimated from measurable physical characteristics of the system (catchment, aquifer or reservoir) being modelled. The degree of complexity is usually related to the time step used in the simulation procedure as well as the extent to which spatial variability is accounted for in the distribution approach used. Consequently, simple models tend to be spatially lumped and operate over coarse time intervals (one month) while more complex models tend to be spatially distributed and operate over much shorter time intervals (less than one day). The recent trend in the hydrological modelling literature has been to support the use of distributed models (O'Connell, 1991) which are made up of algorithms (model component equations) demonstrated to be realistic in terms of our current knowledge of physical hydrological processes.

In practice, the choice of which type of model to use is commonly constrained for several reasons. In the field of practical water resource planning, there may be insufficient available data to determine the parameter values of a complex model or insufficient time and funds to collect such data (Hughes, 1991). Similarly, the resolution, accuracy and reliability of the results obtained from the careful application of simpler models may be adequate for the purposes of long-term planning and the development of management strategies. It is extremely difficult to generalise, as the specific requirements and amount of available information will dictate the best choice of model. The extensive use and general acceptance of the "Pitman" model (Pitman, 1973) for water resource planning in South Africa is a testament to the principle that users will often prefer a relatively simple model with a proven track record to a more complex one whose abilities have not been thoroughly demonstrated. This may not be a very healthy situation from the point of view of future developments in hydrological science or modelling theory (James, 1991; O'Connell, 1991), but is nevertheless the inevitable result of the need to solve practical problems in the short term.

This paper discusses a reservoir simulation model based on a monthly time step and using the same basic water balance approach adopted by the developers of the RESSIM model (Middleton et al., 1981). The original model has been expanded to allow several closely linked reservoirs to be simulated together and incorporates a number of functions to describe the format of the linkages. In developing the model the author has attempted to avoid including unnecessarily complex algorithms and to use parameters whose values can be evaluated from generally available information. It therefore remains as relatively simple and easy to operate as the original RESSIM model, but contains additional functionality to allow more complex water resource schemes to be simulated.

The model and all the necessary programs to establish the time series and parameter data files and to summarise the results in numeric and graphic format are contained within a more generalised modelling system (HYMAS - Hydrological Modelling Application System) which is written in "C" specifically for DOS-based microcomputer systems. This system is being developed at Rhodes University as part of a Water Research Commission funded project to improve the general applicability of a range of hydrological models.

At present several models can be operated from within HYMAS, including a semi-distributed version of the monthly time step Pitman (1973) model, a variable time interval (1 d to 5 min) catchment simulation model, a simple design flood model, a phosphorus export model, a daily runoff and sediment yield model and the reservoir simulation model discussed in this paper. The advantages of HYMAS are that all the models share the same set of utilities that are used to prepare model input data, run the models and assess the model output. The selection of these utilities is driven by a set of user-friendly menus.

Basic water balance approach

The water balance of a single reservoir may be described by the

Received 14 January 1992; accepted in revised form 5 June 1992.

following equation :

$$dS/dt = Qin - Qout + P - E - Sp \qquad (1)$$

where:

dS/dt	represents the rate of change of storage in the reservoir;
Qin	represents the inflow volume to the reservoir and is made up of natural inflow from the upstream catchment area (Qcin) and regulated input from other sources (Qrin);
Qout	represents water released to other reservoirs (Qrout) and drafts to consumers (Qdout);
P	is the precipitation onto the reservoir surface;
E	is the evaporative loss from the surface; and
Sp	is the uncontrolled overflow or spillage from the reservoir.

The time series of natural inflow for each reservoir (Qcin) could be derived from observed data at gauging stations or may be simulated using a suitable modelling approach. Within Southern Africa, the so-called Pitman model (Pitman, 1973) or the more up to date version of the same model contained within the water resources systems model, WRSM90 (Pitman and Kakebeeke, 1991) are appropriate for this purpose. Other deterministic rainfall-runoff or stochastic streamflow models could also be used.

Time series of precipitation data (P) are available at a large number of sites using the Weather Bureau monthly rainfall data base accessible via the Computing Centre for Water Research (CCWR) at the University of Natal, Pietermaritzburg. Similar records of pan evaporation (E) are available from the same source but at far fewer sites and usually shorter record lengths. Alternatively, the model allows a mean monthly distribution of pan evaporation values (corrected to represent free water surface area evaporation depths) to be used. Information on regional values for Southern Africa are available in the *Surface Water Resources of South Africa* volumes (e.g. Middleton et al., 1981), while information at a more detailed spatial scale will soon become available from the work being undertaken at the Department of Agricultural Engineering, University of Natal, Pietermaritzburg (Schulze and Maharaj, 1991).

Draft information (Qdout) can also be supplied as a time series of monthly requirements or as a mean monthly distribution. If the latter approach is used, it is also possible to define up to five reserve levels (expressed as a % of reservoir capacity) and associated lower monthly distributions of lower drafts. If the reserve level is specified as greater than 100%, the parameter value will be reduced by 100% and the model will assume that the reserve level is to be based on the total water stored in all dams. Otherwise, the reserve level will be based only on the individual dam. There is therefore reasonable flexibility in the users ability to define the draft operating rules of the individual reservoirs in the system.

The remaining time series (Qrin, Qrout, Sp) are calculated within the model using algorithms defined by the values of some of the model parameters. A complete list of the parameter set (1 to 32) is given in the **Appendix**, while the details of the algorithms used to control the input, interchange and output of water in the reservoir system are discussed below.

Draft calculations

The required draft may be specified in two different ways. The first is by simply specifying the draft as a monthly volume (either as an input time series or as a mean monthly distribution). The second is to specify the area of land (Parameter 8, **Appendix**) that the reservoir is to be used to irrigate as well as information on the monthly required depth (mm) of irrigation water. A further parameter (9) specifies the proportion of monthly rainfall input (effective rainfall) that contributes toward satisfying irrigation requirements. The required draft from the reservoir is the remaining amount of irrigation water required.

Thus:

$$Qdout = IA \times (ID - (Par9 \times P)) \times 10{,}0 \qquad (2)$$

where:

Qdout = actual required draft in one month (m^3);
IA = defined irrigation area (Parameter 8, ha);
ID = required depth of irrigation water (mm); and
Par9xP = effective rainfall on the irrigation area (mm).

Clearly, if the effective rainfall is equal to or greater than the irrigation requirements a zero draft will result. Similarly, if more water is required than available, Qdout will be reduced to the amount available.

The storage volume at the end of the previous time step is temporarily updated to include natural inflows, regulated inflows from reservoirs higher in the system and the first estimate of the usable draft. This new volume is used to estimate the surface area using:

$$\text{Area } (km^2) = \text{Par } 5 \times \text{Volume } (10^6\ m3)^{Par6} \qquad (3)$$

where:

Par5 and Par6 = scale and power parameters, respectively, in the reservoir area - volume relationship.

The volume of evaporation is estimated from the product of the current reservoir surface area and the net evaporation depth (evaporation - rainfall). The new storage volume is then further adjusted to account for evaporative losses. If the calculated volume is less than dead storage (Parameter 3), the achieved (or usable) draft volume is adjusted downwards to compensate.

Spillage calculations

Spillage is assumed to occur if the above components of the water balance equation result in a stored volume exceeding the dam's defined capacity (Parameter 1 adjusted during the time series by Parameter 4). As this spillage could be utilised by other reservoirs lower (further downstream) in the system, it is necessary to specify the components in the correct order. Spillage can only contribute to reservoirs which have a higher number in the ordering system (i.e. Dam 1 can spill to Dams 2 and 3, but Dam 3 cannot spill to Dams 1 and 2). Regulated releases (see below) are treated in a different way. The calculated volume of spillage can be distributed through a maximum of three downstream dams on the basis of several parameters related to the spilling dam as well as the receiving dams.

Natural flows are known to be temporally variable and it is not straightforward to adequately account for variations in the actual

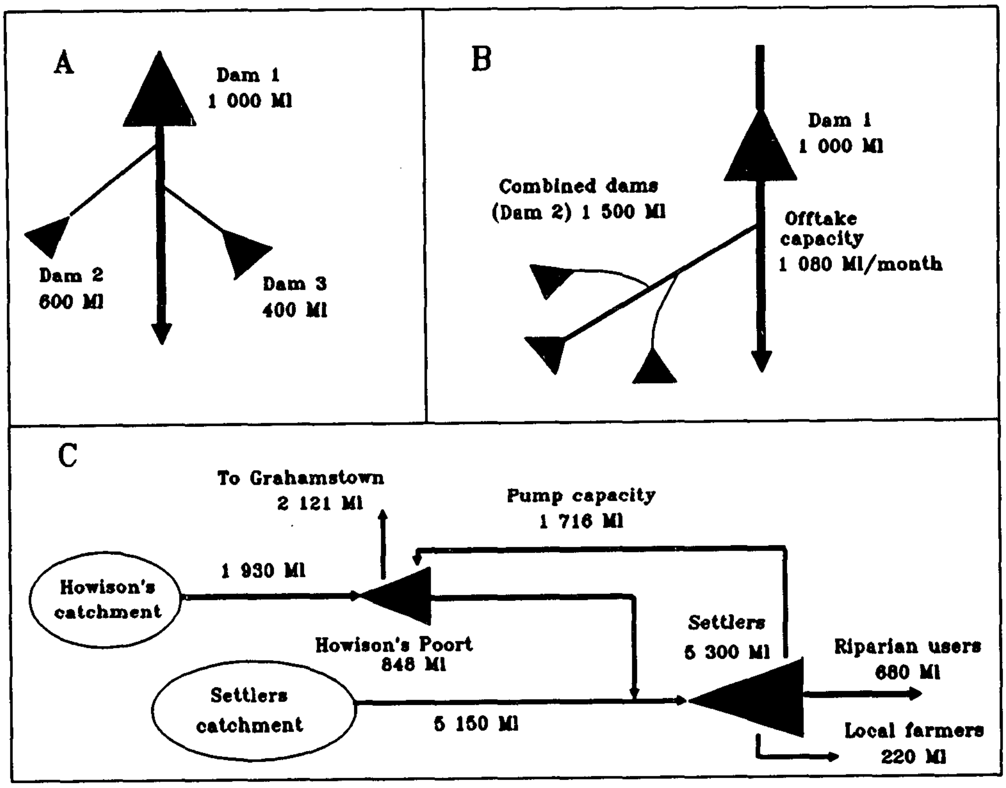

Figure 1

Systems diagrams to illustrate the layout of the dams for:
A) The example used to illustrate spillage and release calculations
B) Example 1, the Langkloof irrigation supply scheme
C) Example 2, the Grahamstown municipal supply scheme (figures are either dam capacities or annual means)

monthly time distribution of flows within a monthly time step model. A pragmatic approach has been adopted that uses a single parameter (19) referred to as the spill time distribution factor. This parameter can assume values between a maximum of 30 and a minimum that is only constrained to be greater than zero. A low value implies a very "flashy" regime where the total volume of spillage is assumed to occur over a much shorter time period than the model time interval of one month. A value of 30 assumes an even distribution of spillage druing the month. The use of this parameter to control redistribution is explained below.

Parameter 20 is used to specify the volume of compensation flow released from a dam each month. This flow is added to any spillages that occur before the downstream dam calculations are performed.

Each of the specified downstream dams has a priority level associated with it that controls the maximum proportion of the spillage that can be assigned to that dam. If the priority level for a downstream dam is specified as zero, it is assumed to have a direct channel link and spillages can be received in an unrestricted manner. If the sum of these priority levels is set to less than 100%, the remainder of the spillage will pass downstream (unless one or more of the downstream dams has been specified as directly connected). Each of the recieving dams also has two other parameters which potentially control the amount of spilled water and regulated releases that they can accept. The first of these represents the maximum storage capacity (18) to accept controlled spillage or regulated releases. The second parameter (16) represents the monthly capacity of the system (canals or pipelines for example) used to transfer water between the dams.

The distribution of spillage is therefore controlled by four factors:

- the capacity of the distribution system (if not a direct channel connection);
- the assumed monthly distribution of the spillage;
- the allowed maximum capacity of the receiving dam (if not a direct channel connection; and
- the priority level of shared distribution (0 for a direct channel connection).

The spill time distribution factor is used to correct the capacity of the distribution system to absorb natural overflows from an upstream reservoir. An example is the best way to explain the approach used.

Suppose there are three dams in a system, an upstream balancing dam supplying two others via weirs across the outflow channel and two canal systems (Fig. 1A). Table 1 lists some of the parameter values and variables at a specific step in the simulation. Using Parameter 18, Dams 2 and 3 can be increased by spillage from Dam 1 to maximums of 540 and 320 Mℓ, indicating that they may accept 340 and 10 Mℓ respectively. The spillage is corrected to 10 x 30/15 = 20 Mℓ (using the spill time distribution factor) for the purposes of comparison with the

TABLE 1
SOME PARAMETERS AND VARIABLES FOR A THREE-DAM SYSTEM EXAMPLE

Parameter or variable	Dam 1	Dam 2	Dam 3
Par 1 - Capacity (Mℓ)	1 000	600	400
Par 16 - Inflow capacity (Mℓ)	N/A	10	20
Par 18 - Limit for receiving dam input (% capacity)	N/A	90%	80%
Par 19 - Spill time distribution factor	15	15	15
Canal take-off priority level	N/A	70%	30%
Storage before spill and release (Mℓ)	1 000	200	310
Spillage (Mℓ)	10	N/A	N/A
Storage after spillage distribution (Mℓ)	10	205	313
Available for regulated release (Mℓ)	900	N/A	N/A
Regulated inflow (Mℓ)	N/A	5	7
Storage after regulated inflow (Mℓ)	988	210	320

TABLE 2
PARAMETERS FOR EXAMPLE 1:
EFFECT OF BALANCING DAM ON AN IRRIGATION SCHEME

Parameter No.	Description	Dam1 (no dam)	Dam1 (built)	Dam2
1	Capacity (Mℓ)	N/A	1 000	1 500
5	Scale parameter in area-vol. relationship	N/A	0,3	0,5
6	Power parameter in area-vol. relationship	N/A	0,8	0,62
8	Irrig. area (ha)	N/A	N/A	700
9	Effective rain (%)	N/A	N/A	50
16	Inflow capacity (Mℓ)	N/A	N/A	1 080
17	Max. release (% storage)	N/A	100	N/A
18	Limit for no release input (% capacity)	N/A	N/A	100
19	Spill time distribution factor	12,5	17,5	12,5/17,5
20	Compensation releases (Mℓ·month^{-1})	0	0	0
21	Downstream dam	2	2	N/A
22	Canal take-off priority (%)	100	100	N/A
27	Capital cost of dam (R·m^{-3})	N/A	2,5	N/A
28	Capital cost of supply works (R·ha^{-1})	N/A	N/A	N/A
29	Repayment interest rate (%)	N/A	18	N/A
30	Repayment period (years)	N/A	20	N/A
31	Profit for successful supply (R·ha^{-1})	N/A	N/A	5
32	Supply failure penalty (R·ha^{-1})	N/A	N/A	2

inflow capacity values.

The priority levels will allocate up to 14 Mℓ (70%) and 6 Mℓ (30%) of adjusted spillage to Dams 2 and 3 respectively. The former is greater than the capacity of the relevant canal and only 10 x 15/30 = 5 Mℓ is received by Dam 2. The latter is less than the capacity of the canal feeding Dam 3 and 6 x 15/30 = 3 Mℓ can be passed through to Dam 3. Both amounts will not raise the dam levels above their defined receiving limits and therefore no further restrictions are applied.

Of the available 10 Mℓ of spillage, 5 Mℓ will be used in Dam 2, 3 Mℓ for Dam 3 while 2 Mℓ will continue downstream. The remaining capacities of the two canal systems are:

supplying Dam 2, 5 Mℓ (10-5)
supplying Dam 3, 17 Mℓ (20 -3).

These capacities are available to accept regulated releases into the two dams which are now at storage volumes of 205 and 313 Mℓ respectively.

Had the priority levels of Dams 2 and 3 both been set to 100%, which implies a "first come first served" basis for allocation, the inflow to Dam 2 would be unaffected as it is limited by the capacity of its canal. The available inflow to Dam 3 would then be 5 Mℓ, which even after correction for the spill time distribution would still be below the capacity of 10 Mℓ and Dam 3 could have absorbed the complete amount, leaving no spillage to continue downstream.

Regulated release calculations

Much the same procedure used to estimate the distribution of spillages is used for regulated releases. An additional parameter (17) for the releasing dam is involved, which is the maximum amount of water that can be released, expressed as a % of the available volume.

The example used in the previous section can be continued with the additional assumption that the value of Parameter 17 for Dam 1 is 90%, suggesting that 0,9 x 1 000 = 900 Mℓ is available for release. The canal take-off priorities suggest that maximums of 630 and 270 Mℓ could be released to Dams 2 and 3 respectively. However, there is only 5 Mℓ of canal capacity remaining for Dam 2 and therefore its stored volume will increase to 210 Mℓ. The remaining inflow capacity to Dam 3 is 17 Mℓ, but Parameter 18 indicates that it can only be raised to 320 Mℓ such that only 7 Mℓ is released to this dam. It should be noted that other components of the water balance (drafts, rainfall and evaporation) are ignored in this example for the sake of simplicity.

The way in which the release calculations are described above demonstrates releases to downstream dams (higher values in the dam numbering system). However, the model also accommodates regulated releases (not spillages) to upstream dams. No additional parameters are required to achieve this, but it should be noted that the releases will only be included in the water balance of the upstream receiving dam in the time interval after the releases occur.

Other considerations

The parameters listed in the **Appendix** include those that allow a relatively simple economic analysis of the dam system to be carried out. The initial capital costs of the dam and water supply works (irrigation canals, for example) can be specified, as well as the repayment interest rate and the repayment period (or design life). Two further parameters specify the profit value of successful supply and the penalty cost for supply failure. These parameters are not used within the model itself but by a separate program that summarises the performance of the reservoir system over the period of time being simulated. The complete time series of input, state and output variables are stored in a file and HYMAS contains facilities for listing them, graphically displaying them or analysing them.

If it is required to simulate a system of upstream inflows and dams that is too complex for a single set-up of the model a "batch mode" operation is included as part of HYMAS. This allows several set-ups of either the same, or different, models to be linked together and includes a set of time series management routines as well. An example might be where two dams are far enough apart that natural inflows between the dams need to be simulated.

A separate implementation of the reservoir model carries out a storage-yield analysis for a single dam, or all dams in the system in a similar way to Professor Alexander's OPRULES program (Univ. of Pretoria, undated). This program uses the same time series data files as the normal model but simulates in reverse time sequence to calculate the required storage to satisfy drafts of 10 to 90% of the mean annual inflow.

Example 1

The problem in this example is to assess the impact of constructing a balancing dam directly on the stream channel of a catchment supplying 700 ha of irrigated orchards in the Langkloof area of the Southern Cape. The existing situation consists of several small dams, each supplied from canals fed from weirs built across the river channel. For the purposes of simplicity, all the existing dams and supply systems are combined as a single representative dam (Dam 2) of 1 500 Mℓ (Fig. 1B).

The area above the scheme is a 9 km^2 mountain catchment with a mean annual rainfall of about 1 000 mm and a relatively high runoff potential. A 55-year time series of monthly streamflows has been simulated using the version of the Pitman (1973) model contained within HYMAS and the resulting mean annual runoff volume is 3 310 Mℓ. A neighbouring gauged catchment indicates that this figure is acceptable and suggests that the monthly runoff regime is likely to be characterised by relatively frequent short duration storm events superimposed on a generally continuous baseflow. The spill time distribution factor for the streamflow reaching the canal off-take points has been set at 12,5 (Table 2) to account for the assumed flow regime. After the upstream balancing dam has been constructed, the flow regime of the spillage is assumed to be somewhat attenuated and the spill time distribution factor has been increased to 17,5. The inflow capacity of the canals serving the irrigation dams has been calculated assuming a combined flow capacity of 1 m^{3}·.s^{-1} operated for an average of 10 h a day.

The parameters of the reservoir model are given in Table 2 for Dam 1 in the undeveloped (no dam) and developed situation as well as for Dam 2 (combination of all the irrigation dams). Some of the unused parameters have been omitted. The economic parameters (27 to 32) have been set at somewhat arbitrary values and are used mainly to illustrate their use.

The initial simulation, given no balancing dam, indicates that of the 3 300 Mℓ mean annual river flow, 2 000 Mℓ is drawn off into the irrigation dams. This produces a usable draft of 1 870 Mℓ

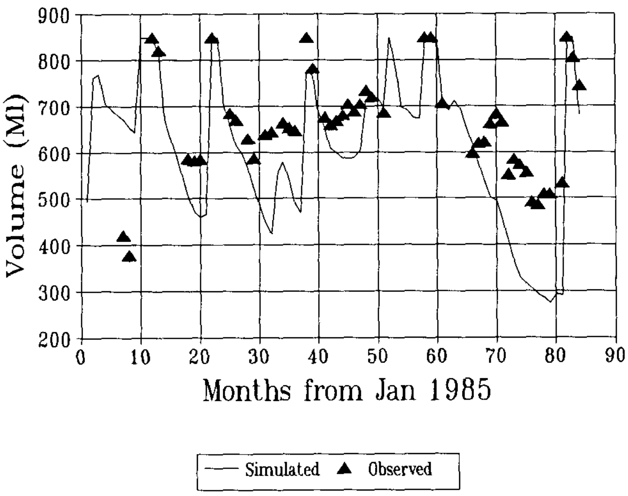

Figure 2
Simulated and observed volumes for Howison's Poort Dam

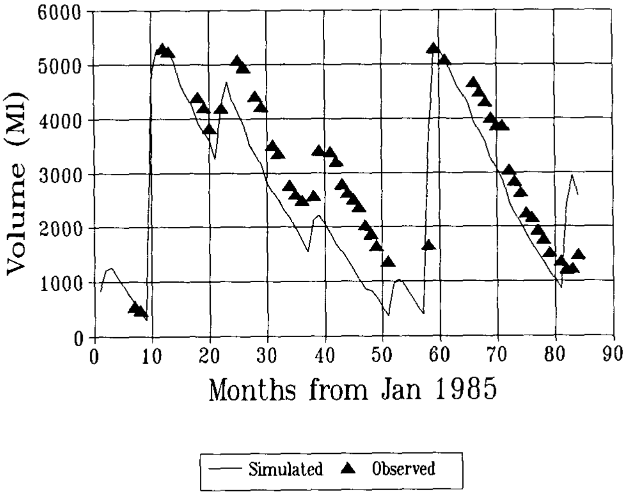

Figure 3
Simulated and observed volumes for Settlers Dam

out of the total required draft of 3 070 Mℓ. The economic parameters suggest a mean annual profit of R1,86m. The effect of the balancing dam is to increase the inflow to the irrigation dams to 2 600 Mℓ and the usable draft to 2 400 Mℓ. The mean annual profit (after allowance for capital repayments) increases to R2,11m.

Closer examination of the time series of drafts indicates that the critical period appears to be the first four months of the year. In the undeveloped situation, a draft of equal to or beter than 90% of that required is only met during 35% of these months over the 55-year period. After the balancing dam is included, the simulation suggests that this figure will increase to 58%.

This example could be extended to assess the effects of different size balancing dams, as well as the additional area of irrigation that could be economically supported if more realistic economic parameter values are used. It would also be possible to break the system down further and to model some of the irrigation dams separately. Although many of the parameters have only been roughly quantified in the example, it does serve to illustrate one of the type of problems that can be analysed by the model. In a situation such as this, where no observed data are available to calibrate the model, an experienced irrigation engineer should be capable of assessing and interpreting the results to assist in the final decision-making process.

Example 2

The second example is a simulation of seven years (1985 to 1991) of the dynamics of the two main reservoirs constituting Grahamstown's water supply (Fig. 1C). Settlers Dam is located at the outlet of a 176 km^2 catchment which includes the Howison's Poort Dam catchment as part of it. Howison's Poort Dam is built at the outlet of a 42 km^2 steeply sloping subcatchment of the total area. Within the other part of the catchment are two major private dams with a total capacity of some 1 000 Mℓ. Time series of inflow volumes to Howison's Poort and Settlers have been simulated using two separate runs of Pitman's model resulting in mean annual flow volumes of 1 930 and 5 150 Mℓ respectively. Observed dam volumes (Figs. 2 and 3) are available for most of the months during the period selected which contains a number of sequences of dry periods, during which water restrictions were implemented in Grahamstown, interspersed with occasional months of high flow.

The parameters of the reservoir model for the two dams in the system are listed in Table 3. The capacities and area-volume relationships have been obtained from the City Engineer's Department of Grahamstown Municipality, as has the information required to establish the other parameter values. The water required for Grahamstown is pumped from Howison's Poort Dam, which in turn receives water pumped from Settlers Dam. The available records indicate that the normal monthly water consumption is approximately 177 Mℓ with little systematic difference between individual months of the year. Restrictions are commonly enforced when the total volume stored in the two dams is below 40% of capacity. Parameter 11 has therefore been set at 140% (i.e. 40% of the combined storage in Settlers and Howison's Poort Dams). Reserve drafts of 85% of normal draft are used when the total storage falls below 40% of the combined capacity.

The annual direct draft (excluding water pumped to Howison's Poort Dam as regulated releases) of Settlers Dam (Par 8) is made up of 220 Mℓ.a^{-1} pumped out of the dam by local farmers and an obligation to release water four times a year to downstream riparian users (approximately 680 Mℓ.a^{-1}). This obligation falls away when it is necessary to place restrictions on Grahamstown users. The reserve draft is therefore set at 220 Mℓ.a^{-1} and is applicable when Settlers Dam is below 40% of capacity (Par 11). This reserve level has no effect on the amount of water transferred to Howison's Poort Dam.

The inflow capacity to Howison's Poort Dam (143 Mℓ) has been calculated from information about the capacity of the pump used and the length of time over which the pump normally operates. A spill time distribution factor is not relevant for either dam as Howison's Poort Dam only receives controlled releases from Settlers Dam which in turn has a direct channel connection to Howison's Poort Dam and can accept all spillages.

Given the fact that the simulated inflow time series cannot be checked for accuracy due to the lack of observed data, Figs. 2 and 3 indicate that the reservoir system performance has been reasonably successfully simulated. The model has generally under-estimated the total amount of water available in the dams and while this may be largely related to under-estimation of the

TABLE 3
PARAMETERS FOR EXAMPLE 2 :
SIMULATION OF GRAHAMSTOWN'S WATER SUPPLY RESERVOIRS

Parameter No.	Description	Daml Howison's	Dam2 Settlers
1	Capacity (Mℓ)	848	5 300
5	Scale parameter in area-vol. relationship	0,17	0,17
6	Power parameter in area-vol. relationship	0,7	0,7
8	Annual draft (Mℓ)	2 121	900
11	Reserve level 1 (% capacity)	140	40
16	Inflow capacity (Mℓ)	143	N/A
17	Max. release (% storage)	N/A	80
18	Limit for no release input (% capacity)	95	N/A
19	Spill time distribution factor	N/A	N/A
20	Compensation releases (Mℓ·month^{-1})	0	0
21	Downstream dam	2	1
22	Canal take-off priority (%)	0	100

inflow, it is also possible that the municipal records of water consumption are over-estimations. Without further detailed investigation of the available data, it would be difficult to draw any firmer conclusions.

Conclusions

The two examples demonstrate the possible uses of the multiple reservoir simulation model. They are not intended to demonstrate the model's ability to reproduce observed volume data. This would be extremely difficult as part of the success will depend upon the ability of the user to accurately define the inflow records. In both examples the inflows have been simulated using a monthly time step rainfall-runoff model, which will be prone to some inaccuracies.

Several limitations to the use of the reservoir simulation model have been highlighted by the two examples:

- The use of a monthly time step in any water resource simulation model is always problematic, particularly in a country such as South Africa that has a highly variable hydrological regime.
- In reality, the individual processes that make up the water balance equation operate continuously. However, without any internal iteration, the use of a monthly time step requires that a decision has to be taken to perform parts of the water balance equation before others. As the processes are not always independent of each other, the order in which the calculations are made can effect the results. However, to incorporate an iterative procedure would increase the amount of computer time taken to carry out a simulation.
- The spill time distribution parameter has been incorporated to allow the inter-month variability to be accounted for in one part of the model. However, this has been done at the expense of a parameter which may be difficult to quantify in some situations.
- It is inevitable that the definition of reservoir operating rules within a relatively simple model will have limitations. Draft volumes can be specified as a monthly distribution. Five lower draft distributions can be defined and are used depending on the current relative storage volume in either a single dam or all the dams in the system. It is possible that such a simple procedure will not cater for all the likely operating rule procedures.

Despite these limitations, the model is flexible enough to define a wide variety of multiple dam configurations. If a more complex system is to be simulated, the HYMAS "batch mode" procedures can be used to link several implementations of this model as well as a monthly rainfall-runoff model. The reliability of the simulations will be largely determined by the amount and quality of the available data that can be used to define the configuration of the system, the input time series as well the parameter values.

Acknowledgements

The research undertaken to develop the model was carried out under a project funded by the Water Research Commission of South Africa. Grahamstown Municipality are thanked for providing information on the operation of their water supply scheme. The author would like to acknowledge the contribution of Mr Andrew Murdoch, computer programming specialist in the Institute for Water Research at Rhodes University, to the development of the HYMAS package, of which this model forms a part. Thanks are also due to Dr John Herald for commenting on the initial drafts on this paper.

References

HUGHES, DA (1991) Catchment hydrolocial modelling: Where are we and where do we go from here? *Proc. of the 5th S. Afr. Natl. Hydrol. Symp.* Stellenbosch. Nov. 1991.

JAMES, LD (1991) Hydrology: Infusing science into a demand-driven art. In: Bowles, DS and O'Connell, PE (eds.) *Recent Adv. in the Modelling of Hydrol. Syst.* 31-43.

O'CONNELL, PE (1991) A historic perspective. In: Bowles, DS and O'Connell, PE (eds.) *Recent Adv. in the Modelling of Hydrol. Syst.* 3-30.

MIDDLETON, BJ, LORENTZ, SA, PITMAN, WV and MIDGLEY, DC (1981) Surface Water Resources of South Africa. Volume V, The Eastern Cape. Report No. 12/18. Hydrological Research Unit, Univ. of the Witwatersrand, Johannesburg.

PITMAN, WV (1973) A mathematical model for generating monthly river flows from meteorological data in South Africa. Report No. 2/73. Hydrological Research Unit, Univ. of the Witwatersrand, Johannesburg.

PITMAN, WV and KAKEBEEKE, JP (1991) The Pitman model - Into the 1990s. *Proc. of the 5th S. Afr. Natl. Hydrol. Symp.*, Stellenbosch. Nov. 1991.

SCHULZE, RE and MAHARAJ, M (1991) Mapping A-Pan equivalent potential evaporation over Southern Africa. *Proc. of the 5th S. Afr. Natl. Hydrol. Symp.*, Stellenbosch. Nov. 1991.

UNIVERSITY OF PRETORIA (undated) Water Resource Studies, *Analytical Methods for Equitable Water Resource Development*, Chapter 15, Case Studies, Dept. of Civil Engineering, Univ. of Pretoria.

APPENDIX: List of model parameters

No.	Description
1	Reservoir capacity (Mℓ)
2	Initial storage (Mℓ)
3	Dead storage (% capacity)
4	Annual decrease in capacity (Mℓ·a^{-1})
5	Scale parameter in area-vol. relationship
6	Power parameter in area-vol. relationship
7	Draft units (-1=Mℓ x 10^3 : 0=Mℓ : 1=mm·ha^{-1})
8	Annual draft (Mℓ x 10^3 or Mℓ) or Irrigation area (ha)
9	Effective rain on irrigation area (%)
10	Number of reserve levels (maximum of 5) for lower drafts
11-15	Reserve level 1-5 (% capacity)
16	Inflow capacity (Mℓ)
17	Max. release (% storage)
18	Limit for no release input (% capacity)
19	Spill time distribution factor
20	Compensation releases (Mℓ·month^{-1})
21	First downstream dam number
22	Canal take-off priority (% or 0 for direct connection)
23	Second downstream dam number
24	Canal take-off priority (% or 0 for direct connection)
25	Third downstream dam number
26	Canal take-off priority (% or 0 for direct connection)
27	Capital cost of reservoir works (R·m^{-3})
28	Capital cost of supply works (R·m^{-3} or R·ha^{-1})
29	Repayment interest rate (%)
30	Repayment period (years)
31	Profit for successful supply (R·m^{-3} or R·ha^{-1})
32	Supply failure penalty (R·m^{-3} or R·ha^{-1})