The inclusion of operating rules in a daily reservoir simulation model to determine ecological reserve releases for river maintenance

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Abstract

A component of the proposed new water law for South Africa specifies that a proportion of the natural flow regime of a river should be reserved for environmental maintenance when major water resource development schemes are planned. The quantity of water that is required for this purpose is frequently determined by an instream flow assessment workshop and a previous paper described a technique (the IFR model) that could be used to translate the workshop results into a representative time series of required flows, using climatic cues and a set of release rules. This paper addresses the issue of conflicting demands for abstractions and environmental releases from reservoirs and presents a further model (DAMIFR) that simulates the conditions in a reservoir. The IFR model generates a time series of required (or design) releases, while design and reserve abstractions are defined as parameters in the DAMIFR model. The reservoir model then uses sets of operating rules to determine the actual distribution of available water. The paper describes the model and illustrates its operation for three rivers. The two models are demonstrated to be flexible in that they can simulate the effects of a variety of different abstraction/release priorities.

Abbreviations

BBM	Building block methodology
DAMIFR	Reservoir model incorporating IFR release rules
DWAF	Department of Water Affairs and Forestry
HYMAS	Hydrological modelling application system
IFA	Instream flow assessment
IFR	Instream flow requirement
MAR	Mean annual runoff
WRYM	Water resources yield model

Introduction

Legislation to reserve water for environmental purposes and to ensure that riverine resources do not deteriorate beyond a ‘desired future state’ (specified for each river) is being incorporated into the new South African water law. DWAF now requires that the quantity and patterns of flow that should be allowed to continue downstream of water resource developments are determined as part of the design of the scheme. The process of determining the nature of the environmental reserve is referred to as an IFA and is frequently carried out using what has become known as the ‘Building Block Methodology’ (King and Louw, 1998), which is applied during a workshop attended by a range of specialists. The application of the BBM results in a recommended flow regime (the IFR) which is expressed as a table of monthly flow values that are considered to be essential to sustain the river in a desired future condition. The tables (see Table 1, for example) define the low (or baseflow) and high (floods and freshes) flow requirements for maintenance (to facilitate the year-by-year maintenance of the river), as well as for drought situations (to provide for survival in drought years, and below which flows should never fall).

The values in the tables are a simple set of numbers that provide sufficient detail for planning purposes. However, the whole process assumes that the eventual pattern of releases will reintroduce some flow variability that reflects natural climatic occurrences within the catchment. To provide the workshop participants with the capability of visualising the consequences of their decisions, Hughes et al. (1997) developed the IFR model. This model combines the information from an IFR table, a reference flow time series to provide the climatic cues and a set of ‘operating rules’ to generate a representative daily time series of releases. The latter (after calibration of the model) should have all the characteristics of the modified flow regime specified by the group of specialists who carry out the IFA and should assist reservoir design engineers by providing more information about the nature of the desired releases.

Reservoir yield analyses, and the design of the storage capacity required to satisfy a specific demand, is frequently carried out in South Africa using stochastic simulation approaches (Basson et al., 1994). However, when the pattern of required releases are not independent of the inflow sequence, the situation becomes more complex. In most design situations, stochastically generated inflows could be used to trigger the releases, using algorithms similar to those contained within the IFR model. The current version of the WYRM model (BKS, 1998) contains facilities to account for the requirements of the ecological reserve, through rule curves linked to natural flow sequences. These rule curves could be determined in a relatively straightforward manner from the output of the IFR model. However, while an established stochastic systems model may not be available at every IFR workshop, it could still be important to have a preliminary understanding of the extent to which water demands are likely to conflict with the environmental reserve specified by the IFA.

This paper presents a relatively simple extension of the IFR model using a modification to an existing daily time-step, reservoir water balance model, that allows these conflicts to be addressed at the planning stage. The approach should not be

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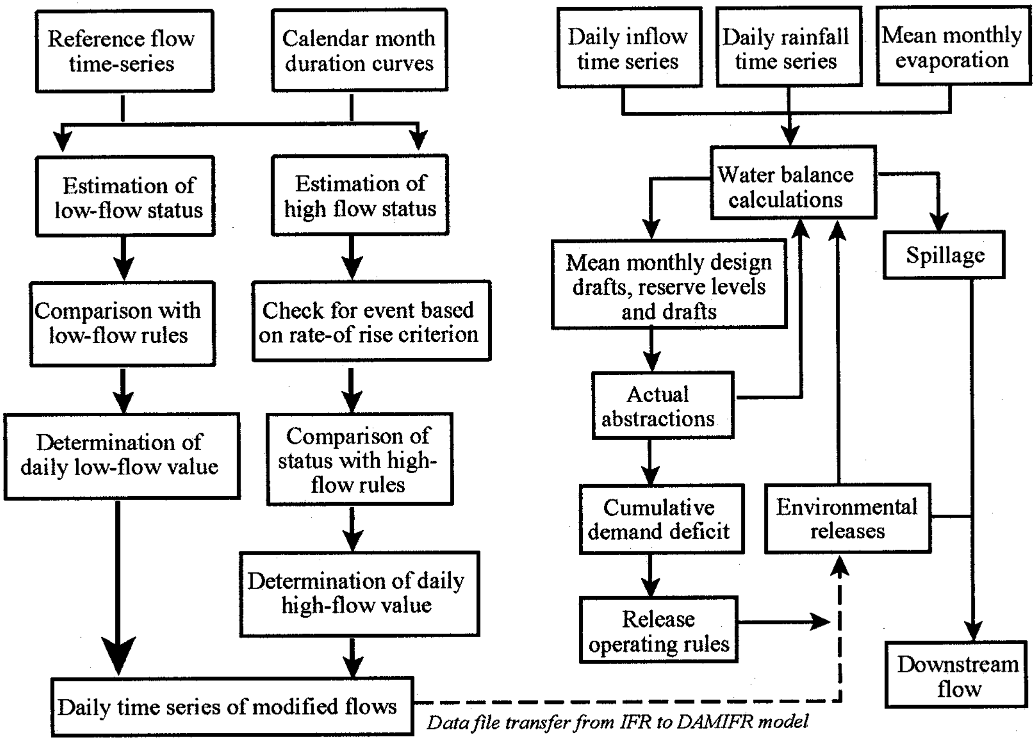


Figure 1
Flow diagram of the IFR (left side) and DAMIFR (right side) models indicating the main steps in the modelling processes

viewed as a replacement of the more traditional reservoir yield design techniques. It is a complimentary tool that could be combined with others to provide a more complete set of procedures contributing to sustainable reservoir design and operation.

The IFR model - A brief summary

Hughes et al. (1997) describe the IFR model in detail, but because it generates one of the inputs to the reservoir model discussed in this paper, a brief summary of its operation and use is provided here, as well as a flow diagram illustrating the main components (Fig. 1 - left hand side). The necessary inputs are as follows :

- A table of IFR values ($m^3 \cdot s^{-1}$) consisting of maintenance and drought low flows, peak values for high flow events and durations of events for each month of the year (Table 1, in Hughes et al., 1997, for example).

- A daily time series of reference flows that can represent the climatic cues experienced in the catchment above the IFR site. This may not necessarily be for the same river and can be observed or simulated data.

- A table of percentage points and flow values describing the one day flow duration curves for each calendar month of the year. These are generated from the reference flow time series.

- A set of operating rules for maintenance and drought low flows, which are duration curve, percentage-point interpretations of when to release flows at the maintenance (or above) rate, at a rate between maintenance and drought flows or at drought flow rates. These are the low-flow release parameters of the model and can be calibrated (by the workshop participants) to achieve the desired balance in the frequency of occurrence of different release rates.

- A similar set of operating rules for high-flow event releases, which include percentage-point interpretations and criteria to recognise the occurrence of an event in the reference flow time series used to trigger a high-flow release.

The model converts the flow values of the reference time series to duration curve percentage-point equivalents and calculates a low-flow status from the previous 30 d of these equivalents. The value of the low-flow status is compared on a daily basis with the low-flow operating rules to determine the required rate of release. The model also estimates a high flow status from the duration curve percentage-point equivalents for 10 d ahead in the time series and identifies whether an event is about to take place. This information is used to determine when a high flow release should be made and the rate of release is estimated by comparing the operating rules with the value of the high-flow status. Percentage point equivalents are used throughout the model because these values are generally more closely equivalent for two or more adjacent catchments than are flow values standardised either by catchment area or mean flow (Hughes et al., 1997; Hughes and Smakhtin, 1996) . This means that there are fewer constraints placed on the selection of the site to provide the climatic cues through the reference flow time series.

The details of the algorithms and an illustration of the model results are given in Hughes et al. (1997) and are not repeated here. The most important consideration, from the point of view of this paper, is that the output from the model is a time series of total release rates which depend upon climatic cues and the way in which the user has specified the operating rules. It is possible to achieve results which show very little variability and in which most of the daily releases are very close to those defined as maintenance requirements in the IFR table. It is also possible to calibrate the model to give a great deal more variability in both low and high flow releases. Inevitably, the final result will be a consequence of the interrelationship between the reference flow regime, the table of IFR values and the values of the calibrated operating rules (model parameters).

The reservoir model (DAMIFR)

DAMIFR was developed from an existing daily version of the monthly time-step reservoir water balance model described by Hughes (1992). The main water balance accounting procedures for a single reservoir are very simple and include inflows, rainfall, evaporation losses, abstractions, compensation flow and spillage. While the model is capable of simulating several linked reservoirs, it does not have the flexibility of a true water resource systems model. The water balance accounting procedures of the daily model are identical to the monthly model in all respects except that the full supply level can be exceeded in the daily version and spillage is calculated by a relatively simple hydraulic overflow equation. Thus:

$$\text{Spillage } (m^3) = \text{head}^{1.5} * \text{SPILLC} * \text{SPILLW} * 86400 \quad (1)$$

where:

head is the depth above full capacity, averaged over the start and end of the time interval and determined from the depth-volume relationship;

SPILLC and SPILLW are the spillway coefficient and width respectively and are model parameters; and

86400 represents the conversion factor from flow rate ($m^3 \cdot s^{-1}$) to volume (m^3) over 1 d.

The original model allowed for abstraction operating rules to be defined by five reserve (lower) drafts that apply when the reservoir volume drops below five reserve levels (expressed as a percentage of full supply volume). These simple abstraction rules have been retained in DAMIFR (Fig. 1 - right hand side) and the new model also calculates a demand deficit (DD) value on a daily basis.

$$\text{Demand deficit (DD\%)} = 100/30 * (\text{design draft} - \text{supplied draft}) / \text{design draft} \quad (2)$$

The cumulative demand deficit (CDD) is the sum of the daily DDs over a period of continuous deficit and is reset to zero when a DD of zero is encountered (i.e. when the stored volume returns to a value greater than the first reserve level and therefore abstractions are at the design value). The multiplier of 100 converts the deficit to a percentage value, while the divisor of 30 (assumed to be the average number of days in a month) converts the value to the relative difference between the design draft and the reserve draft after 1 month. For example, if the first reserve draft is 80% of the design draft in a particular month, and the reservoir remains between the 1st and 2nd reserve levels for a complete month, the resulting CDD will be 20%. The CDD is used to determine the balance between satisfying the environmental and abstraction requirements.

The original model allowed for compensation releases, defined by a fixed monthly distribution to be applied every year when water was available. These have been retained in DAMIFR, but are not viewed as the environmental release requirement. The required IFR releases are input as a time series using an output file from the IFR model. The final new component of the model is a set of operating rules designed to control what proportion of the daily IFR requirement to actually release from the reservoir, given that these could be competing with a draft requirement for other users during periods of low reservoir levels. There are several issues to consider when attempting to define such rules:

- From a pragmatic point of view, there may be water supply (rather than hydrological) drought situations where the requirement to satisfy the environmental releases has to be relaxed so that some level of water service provision to users can be sustained.

- The IFR releases specified for hydrological drought periods (King and Louw, 1998) are viewed as effectively having an assurance level of 100%. In the BBM approach these are considered to be the absolute minimum that the river needs for survival over drought periods (defined hydrologically and unrelated to water supply droughts).

- In some situations it may be desirable that the full volume of IFR releases, defined by the workshop and estimated using the IFR model, should be released. Such a situation may arise where the workshop participants have a high degree of confidence in their estimates and that they represent the minimum that an ecologically important river requires to continue functioning in a desired manner.

- The relative priorities of satisfying the abstraction demand versus the environmental demand may change over time as water requirements change or as more quantitative information about the environmental requirements of a river becomes available.

The implication is that the operating rules should be flexible and allow differential partitioning of the available water under different situations of water availability. The set of rule procedures that have been built into the model are based upon the cumulative demand deficit values calculated using Eq. (2). Up to 12 pairs of values are specified and comprise a cumulative deficit rule (CDR) as well as an equivalent release reduction rule (RRR). If the daily CDD value calculated by the model, exceeds one of the 12 CDR values, then the recommended IFR releases are reduced by the equivalent RRR, but never below the recommended drought releases.

Thus, given operating rules CDR_i and RRR_i (i = 1, 12 maximum), if CDD_j (where j is the day number) exceeds CDR_i, then ER_j (the environmental release for day j, calculated by the IFR model) is reduced by RRR_i %. These rules clearly interact with the draft operating rules (based on up to 5 reserve drafts and associated reservoir volumes), but in general terms, if the CDR rule values are high (several hundred %) and so are the RRR values (close to 100%), then the input environmental releases will rarely be reduced. Alternatively, if the operation of the dam is meant to favour the abstractions then the reserve drafts could be set quite high and the CDR and RRR values quite low. There is a wide spectrum of possibilities. For example, the environmental releases could be favoured up to a point at which the cumulative demand deficit has reached a critical level, after which the releases might be heavily curtailed to preserve as much water in the reservoir as possible.

Both models have been established as part of the HYMAS system (Hughes et al., 1994) which contains all the necessary utilities to prepare the data files, create and edit parameter data, run the models and analyse the results. HYMAS also contains several rainfall-runoff models and flow time series data generating methods (Hughes and Smakhtin, 1996). These can be used to create the reference flow time series required for the IFR model, as well as representative reservoir inflow data, in the absence of suitable observed records.

TABLE 1
SOME CHARACTERISTICS OF THE STREAMFLOW REGIMES AT THE THREE SITES

Characteristic/site	Luvuvhu	Sabie	Tugela
Available data period	10/1961 to 09/1990	10/1952 to 09/1993	10/1963 to 09/1993
Catchment area (km^2)	1598	1562	1920
CV of daily flows	2.49	1.45	1.54
CV of monthly flows - Feb.	1.48	0.84	0.77
CV of monthly flows - Aug.	0.52	0.26	0.47
CV of annual flows	1.02	0.52	0.44
Baseflow index (BFI)	0.53	0.60	0.39
Inflow MAR (10^6 m^3)	119	375	288
Assumed reservoir capacity (10^6·m^3)	156	375	288
Design draft A (10^6 m^3·y^1)	85	280	188
Design draft B (10^6 m^3·y^1)	65	225	158

Notes: CV = Coefficient of variation
Reservoir capacity for Luvuvhu taken as the planned size of Mutoti Dam, the others as 100% of MAR.
Design draft A values taken from the relevant storage-draft-frequency curves for a 50 year return period design given in Midgley et al. (1994).
Design draft B values taken as between 75% and 85% of draft A.

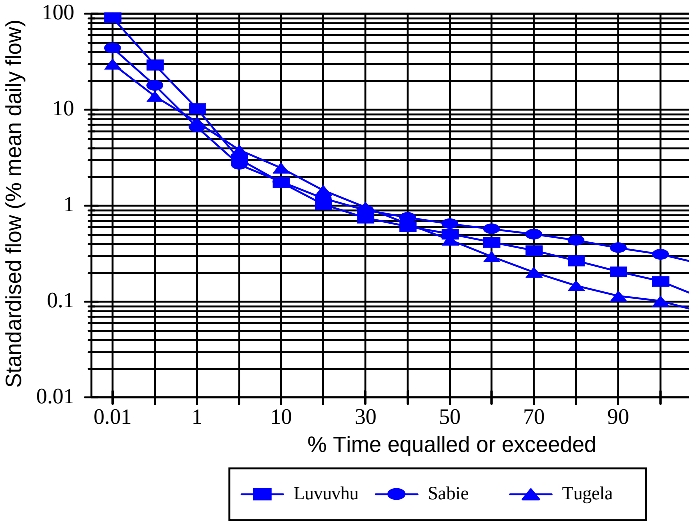


Figure 2
One day annual standardised flow duration curves for three sites. The flows are standardised by dividing by the mean daily flow over the total record period.

Application of the models

The models have been applied to three rivers where IFAs have been carried out in the recent past. To illustrate the operation of the models and the sensitivity of the results under different flow regimes, several sets of parameter values have been used in both the IFR and DAMIFR models. The IFR model results presented are the total release volumes and the length of time that the low flow releases fall within the different design categories (greater than or equal to maintenance flows, between maintenance and drought and at drought flow levels). DAMIFR results presented are the % time that the achieved drafts are at the design demand or at lower reserve levels, the volume of the achieved releases relative to those required and the % time that the required releases have been reduced.

In all three workshops more than one site was considered, but for the purposes of this paper a single site has been selected from each and the most recently refined IFR table of flows used. The three rivers are the Luvuvhu in the Northern Province (Site 1 referred to in LDC, 1995), the Sabie in Mpumalanga Province (Site 2 referred to in DWAF, 1996) and the Tugela in KwaZulu-Natal Province (Site 3B on the Bushmans River, referred to in DWAF, 1997). Some of the characteristics of the flow regimes are provided in Table 1 and Fig. 2, while Table 2 lists the most recently modified IFR values as determined by the specialists involved.

Luvuvhu: The Luvuvhu site has been described in detail in Hughes et al. (1997) and is situated downstream of Albisini Dam. The reference flow time series used for the IFR model was generated after calibration of the daily time step VTI model (Hughes and Sami, 1994) and a daily reservoir simulation model for a gauged site below Albisini Dam. The effects of the dam and other upstream developments were removed and the model re-run

TABLE 2
IFR TABLE VALUES FOR THE THREE SITES

Month	Luvuvhu				Sabie				Tugela			
	Maintenance		Drought		Maintenance		Drought		Maintenance		Drought	
	Low	High	Low	High	Low	High	Low	High	Low	High	Low	High
Oct	0.12	0.42	0.04	-	2.0	9.0	1.5	-	1.0	5.0	0.5	-
Nov	0.20	1.05	0.12	-	3.0	12.0	1.9	3.8	1.8	13.0	0.8	-
Dec	0.21	9.01	0.15	-	5.0	30.0	2.3	4.6	2.2	27.8	1.0	-
Jan	0.25	1.00	0.15	0.65	6.0	17.0	2.6	5.2	2.5	37.5	1.2	-
Feb	0.28	14.98	0.12	-	6.0	50.0	3.0	6.0	3.0	67.0	1.3	-
Mar	0.30	1.00	0.10	0.60	6.0	16.0	2.8	5.6	2.5	27.5	1.2	-
Apr	0.24	0.94	0.10	-	5.0	14.0	2.5	5.0	2.0	10.0	0.9	-
May	0.18	-	0.09	-	4.0	-	2.3	-	1.5	-	0.7	-
Jun	0.13	-	0.08	-	3.5	-	2.1	-	1.0	-	0.5	-
Jul	0.13	-	0.07	-	3.0	-	1.9	-	0.7	-	0.4	-
Aug	0.12	-	0.06	-	2.6	-	1.7	-	0.7	-	0.4	-
Sep	0.12	-	0.05	-	2.3	-	1.6	-	0.7	-	0.4	-

Notes: The values are all in $m^3 s^{-1}$, the low flows occur on every day of the month while the high flows are the peak values for limited duration events (the event durations are not provided in this table).
Where two or more peaks in the same month were specified in the workshops, these are added together as the model can only generate one per month at present.

TABLE 3
IFR MODEL PARAMETER COMBINATIONS (ALL VALUES WERE USED FOR THE LUVUVHU SITE, WHILE ONLY THE HIGHLIGHTED VALUES WERE USED FOR THE OTHER SITES)

Drought rule (equivalent % point)	98	**95**	**90**	**85**	**80**
Maintenance rule (equivalent % point)	95, 90	90, **85**, 80	**85**, **80**, **75**	80, **75**, 70	75, **70**
Low-flow upper limit (% point differential)	2, 5	**2**, 5	**2**, 5	**2**, 5	**2**, 5
Flood rule (equivalent % point)	**99**	**40**	**30**	**20**	**10**

to generate a representative natural flow record. The inflows to the planned dam (Mutoti), close to the IFR site, were generated using simulated present day conditions at the gauging site, which were then linearly extrapolated to the IFR site. The IFR table values (summarised in Table 2) used in this paper are modified ones and not the original workshop ones used in Hughes et al. (1997).

Sabie: The IFR site on the Sabie is situated just downstream of the confluence with the Marite River and the gauging station X3H006. The reference flow time series was generated as natural flows at the site using the VTI model, while the reservoir inflows were generated with the same model, but with all present day upstream developments (afforestation and irrigation abstractions) accounted for. While it is not the intention to construct a dam on the main Sabie River, it has been assumed for the purposes of testing DAMIFR that a 100% MAR dam is to be constructed close to the IFR site.

Tugela (Bushmans River): The IFR site is situated on the Bushmans River, close to its confluence with the Tugela. The reference flow and reservoir inflow time series have been assumed to be the same in this case and were generated using the patching model (Hughes and Smakhtin, 1996), based on observed data from several nearby gauged tributary sites where the flow regimes are reasonably natural. More details are provided in the hydrology chapter of DWAF (1997). The planned dam (Mieltuin) has been assumed to be close to the IFR site and to have a capacity of 100% MAR for the purposes of this paper. There are some developments (including Wagendrift Dam) upstream which have been ignored.

The IFR model was run for the Luvuvhu with a wide range of parameter scenarios, while for the other sites the range was reduced. The operating rules for each month of the year were kept constant. Table 3 summarises the parameter combinations that were used and indicates that a maximum of 26 model runs were carried out for the low flow sensitivity tests (13 combinations of drought and maintenance rules for each of two low-flow upper limit values), while 4 flood operating rule scenarios were tested.

A high value for the drought rule means that the low-flow status will rarely reach this value and that drought releases will occur infrequently. Similarly, a high value for the maintenance low-flow rule means that releases will be frequently in excess of the maintenance release specified in the IFR table. The low-flow upper limit affects the degree to which the specified maintenance release is exceeded but not the frequency of occurrence of

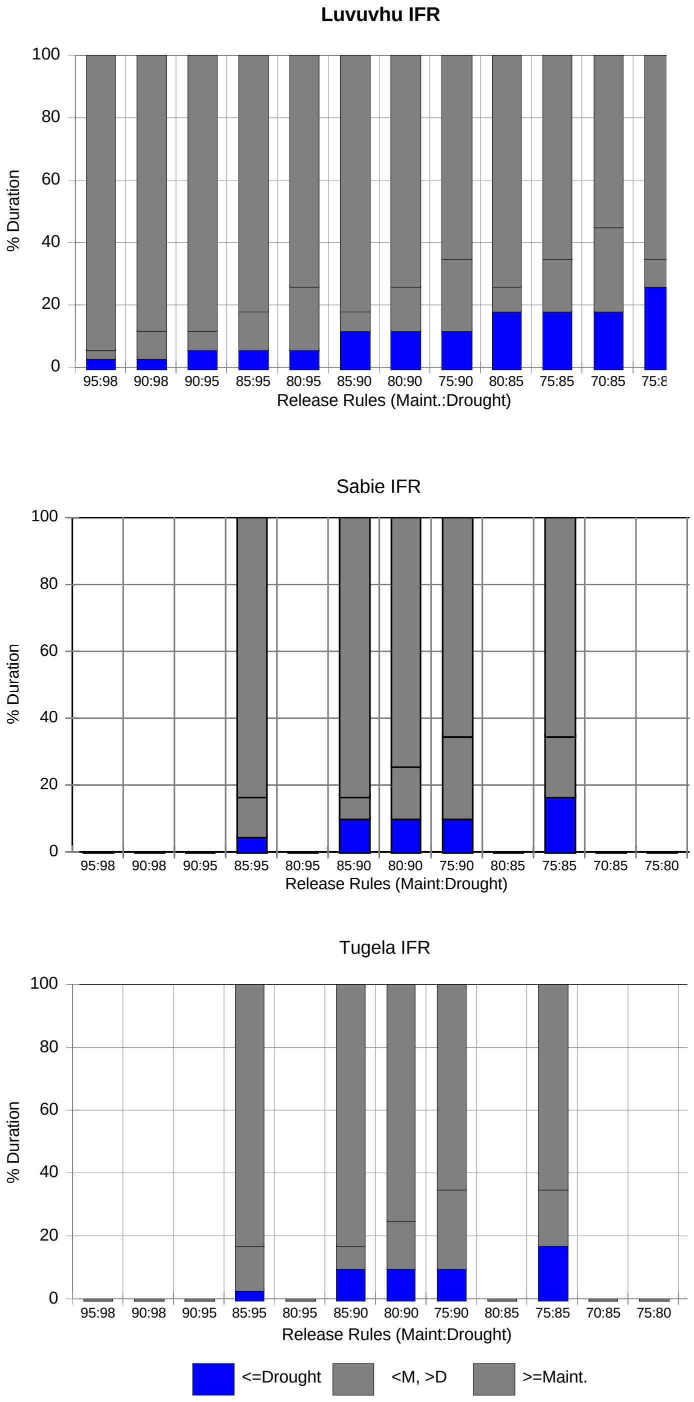


Figure 3

Histograms representing the percentage of time that the low-flow releases are at drought levels, between drought and maintenance and at, or above, maintenance for different combinations of maintenance and drought low-flow rules

different releases. A 5% rule will generate a higher release volume than a 2% rule. The relative increase will also be greater for smaller differences between the drought and maintenance rules because of the greater frequency of releases above the maintenance requirement.

The flood rule is compared to the flood status of the peaks in the reference flow time series which will have relatively low duration curve percentage exceedence values. A rule of 99% suggests that all events will be accepted as a full release, while a rule of 10% means that the flood release requirement will be reduced during smaller events in the reference flow time series. However, if an event rate-of-rise criterion (Hughes et al., 1997) is not satisfied, no high flow release will occur regardless of the flood rule value.

IFR model results

Figure 3 illustrates the effect of different combinations of drought and maintenance low-flow rules (with the low-flow upper limit set at 2%) for the three sites. It is clear that despite the differences in the flow regimes, the results are very similar. This is partly a consequence of the similar gradients in the low-flow parts of the duration curves (Fig. 2). The small differences that do occur can be broadly explained by the regime characteristics given in Table 1. The Luvuvhu, for example, always experiences a slightly higher frequency of drought releases, due largely to the higher coefficient of variation of flow in this river. Table 4 illustrates the effect of varying the low-flow upper limit rule for three different drought and maintenance rule combinations. As expected, the additional release volume consequent on an increase in the upper limit is greater for a lower difference between the other two rules and the effect is greater for the Tugela, which has the steepest low-flow portion of the duration curve.

Figure 4 illustrates the effect of varying the flood release rule between 40 and 10%, the release volumes being expressed as a percentage of the maximum possible release (i.e. a rule of 99%). The number of events that were recognised (based on the rate-of-rise criterion used) within the three reference flow time series were very similar. It is clear that the impact of different flood rules is far greater in the more variable flow regime of the Luvuvhu. This result demonstrates the value of the approach if one of the requirements is to maintain some degree of natural variability in the modified flow regime. It also suggests that the workshop flood requirements could be set at relatively high peak flow rates for a variable regime river, given that the simulated releases will be frequently reduced. The convergence of the Sabie and Tugela lines as the 10% rule is approached could be an indication that, while the Sabie has the more variable regime in general, at higher, less frequent flows they have similar degrees of variability.

DAMIFR model results

Four of the IFR model outputs were used to assess the effects of various DAMIFR operating rules. The low-flow upper limit rule was kept at 2% and the flood rule at 10%, while 4 combinations of maintenance and

TABLE 4
EFFECT OF VARYING THE LOW-FLOW UPPER LIMIT RULE. THE VALUES IN THE TABLE ARE THE MEAN ANNUAL LOW-FLOW RELEASE VOLUMES (m^3 x 10^6) AND THE FIGURES IN PARENTHESIS FOR THE 5% COLUMN ARE THE PERCENTAGE INCREASE IN VOLUME CONSEQUENT ON CHANGING THE RULE FROM 2 TO 5% (IN THE FIRST COLUMN M AND D ARE THE MAINTENANCE AND DROUGHT RELEASE RULES, RESPECTIVELY)

Low-flow release rules	Luvuvhu		Sabie		Tugela	
	2%	5%	2%	5%	2%	5%
M 85 : D 90	5.8	6.2 (7.1%)	122.8	127.4 (3.7%)	50.9	55.3 (8.6%)
M 80 : D 90	5.6	5.9 (5.1%)	119.9	123.6 (3.1%)	49.0	51.9 (6.0%)
M 75 : D 90	5.5	5.7 (4.0%)	116.9	119.8 (2.5%)	47.4	49.5 (4.4%)

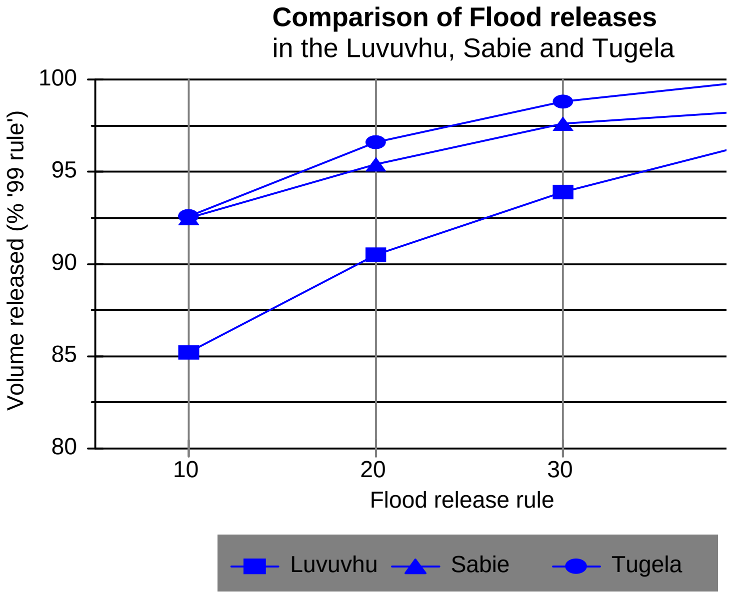


Figure 4
Illustration of the effect of different flood release rules (the flood release volumes are plotted as a percentage of the volume achieved with a rule of 99%).

drought low-flow rules were used (85 : 95, 80 : 90, 75 : 85 and 70 : 80). The reservoir capacities and two design annual drafts are given in Table 1, while two reserve drafts were set at 80 and 70% of the design draft and applied at 60 and 40% of the full supply capacity, respectively. The annual distribution of abstractions was assumed to be uniform. Two sets of seven reservoir release operating rules were used, one to favour the releases and one to favour abstractions (Table 5).

TABLE 5
DAMIFR RELEASE OPERATING RULES. THE RELEASE REDUCTION PERCENTAGE VALUES (RRR$_i$) ARE APPLIED TO REDUCE THE RELEASES SPECIFIED BY THE IFR MODEL AS THE CUMULATIVE DEMAND DEFICIT PASSES THE THRESHOLDS REPRESENTED BY THE EQUIVALENT CUMULATIVE DEFICIT RULE VALUES (CDR$_i$).

i	1	2	3	4	5	6	7
Release priority rules							
CDR$_i$ RRR$_i$	240 95	300 90	360 85	420 80	480 75	540 65	600 50
Abstraction priority rules							
CDR$_i$ RRR$_i$	60 80	120 60	180 50	240 40	300 30	360 20	480 10

Figures 5 and 6 illustrate the results of the eight different applications of the DAMIFR model (four release requirement time series for 2 sets of reservoir operating rules) for the three sites using the lower design draft (B in Table 1) in each case. Fig. 5 shows the percentage of the time that the achieved abstractions were at four levels, where level 0 represents the design demand, levels 1 and 2 the two reserve drafts and level 3 abstractions that were lower than the second reserve level due to insufficient water in the reservoir. The left hand histograms represent the release priority rules and the right hand histograms the abstraction priority rules (Table 5). Figure 6 illustrates the effects of the different rules on the final volume of release (excluding any natural spillage), expressed as a percentage of the required volume (as determined by the IFR model) and on the percentage of the time that the required release was reduced. The percentage time of reduction decreases as the IFR model rules change from 85:95 to 70:80. This is because the amount of time that the IFR model generates drought low-flow requests increases in the same direction (Fig. 3) and the DAMIFR model is forced to release at least drought low-flows.

Even the lower design demand that has been set (in this paper) for the Luvuvhu would appear to be too ambitious. This is related to the fact that it was established prior to the current study on the basis of an inflow MAR of 158 x 10^6 m^3 using data for 1975 to 1985, compared to the 119 x 10^6 m^3 estimated for the 1961 to 1990 period. The impact of the different rules on the abstractions is very small as the dam cannot easily satisfy such a high demand (54% MAR). Figure 6 illustrates that even under the release

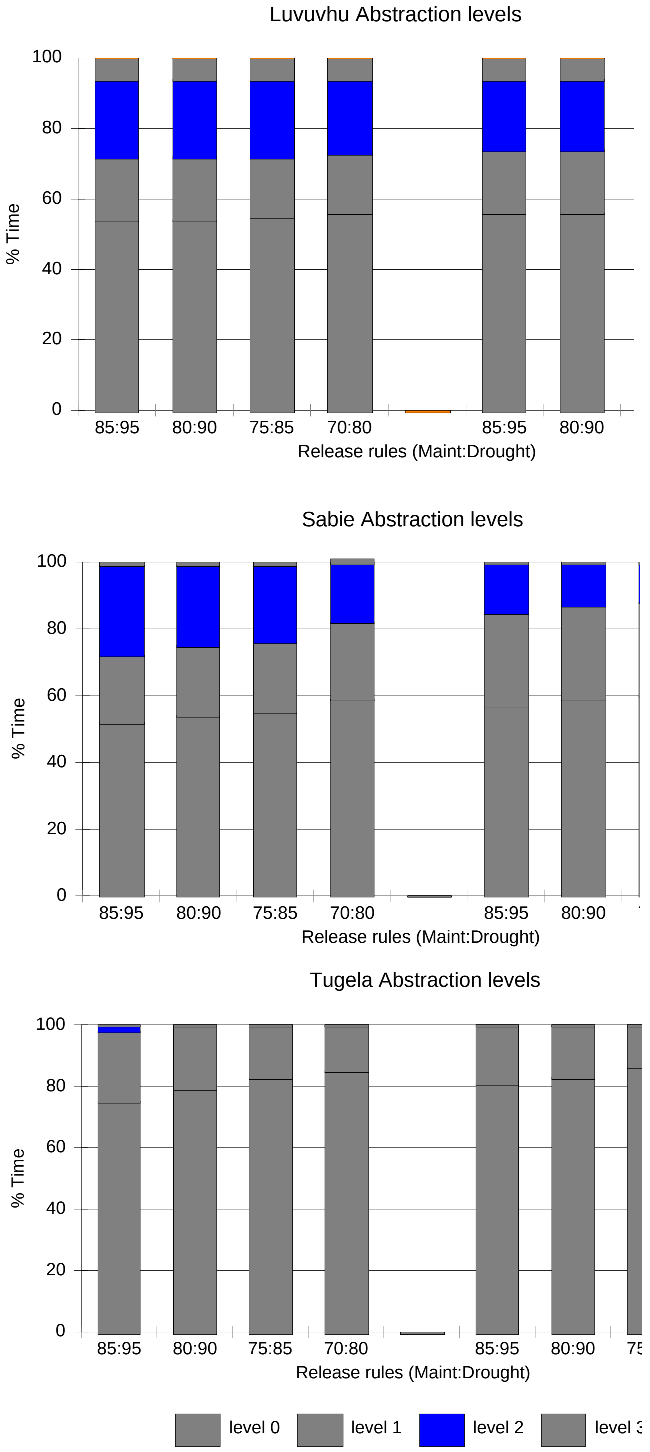


Figure 5
Illustration of the effects on achieved abstractions of release (left side) and abstraction (right side) priority rules for four patterns of release requests (level 0 refers to the design demand, level 1 to reserve demand 1, etc.)

priority rules, the releases can be reduced to below 90%, affecting some 20% of the days. The Sabie abstraction demand represents 60% of the MAR, while the release demand is approximately 32% (depending on the IFR model rules). It is hardly surprising that the biggest impact of different priority rules, on both achieved abstractions and releases, is seen for this river. The percentage of time that the abstractions are at the second reserve draft (level 2) is approximately double for the release priority than for the abstraction priority rules. The Tugela site has a somewhat less variable regime and the demands are lower (abstraction = 55% MAR and releases = 17% MAR). It is therefore inevitable that both demands can be satisfied more easily and that the effect of the different priority rules are relatively small. It should be noted that the design abstractions used in this paper are hypothetical, not necessarily realistic and are used to illustrate the model operation.

Climatic droughts can be identified as the times when the IFR model requests low flows at the drought requirement, while a water supply drought can be thought of as the time when the DAMIFR model reduces the release requests. Both are clearly dependent upon the operating rules and some comparisons are provided below using the 85:95 IFR model rule and the DAMIFR release priority rules.

Luvuvhu: Climatic drought occurs 6% of the time.
Water supply drought occurs an additional 27% of the time.

Sabie: Climatic drought occurs 5% of the time.
Water supply drought occurs an additional 29% of the time.

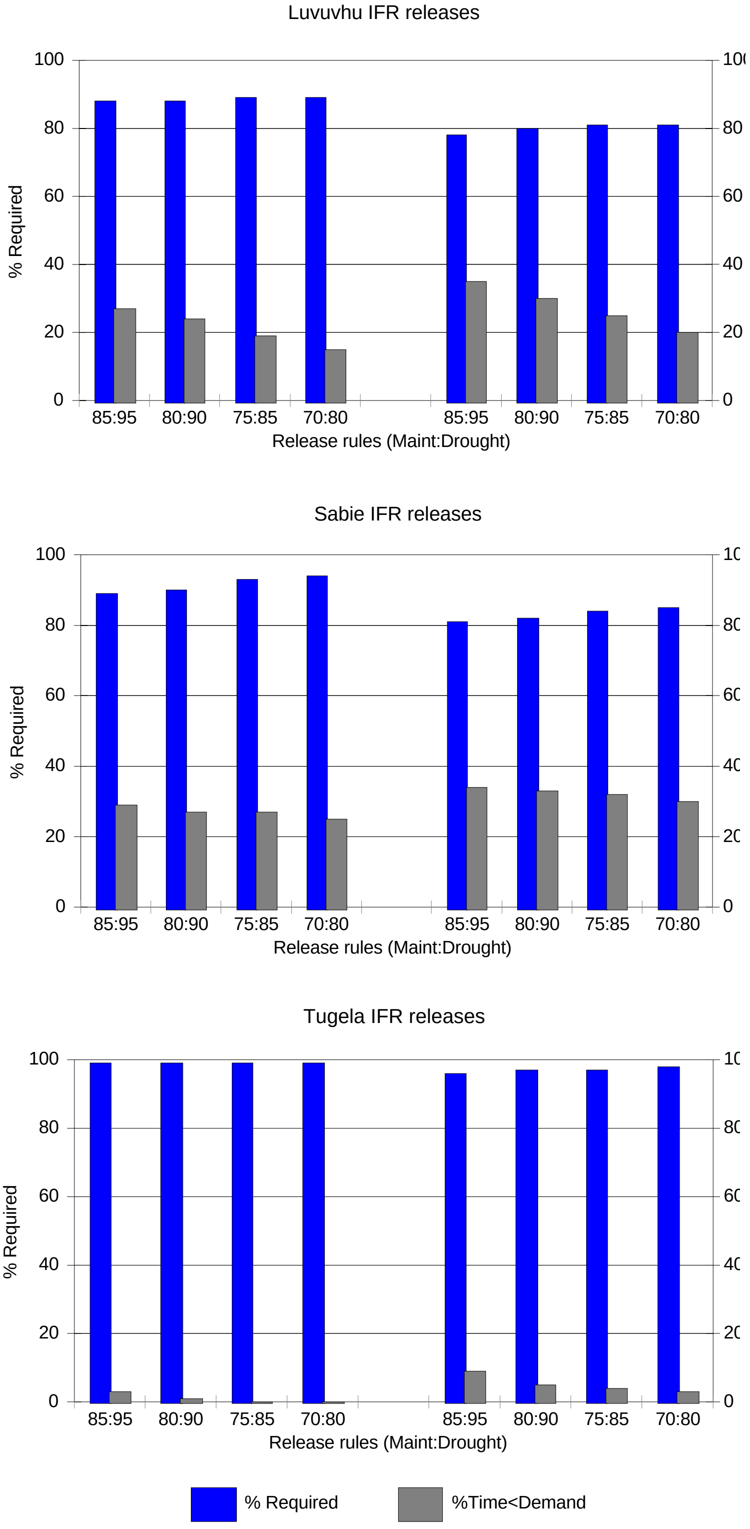
Tugela: Climatic drought occurs 3% of the time.
Water supply drought occurs an additional 3% of the time.

Discussion and conclusions

Both models are flexible in their ability to simulate a range of different situations depending upon the values that are assigned to relatively simple operating rules. This is particularly important given that the BBM approach and procedures followed during the IFA workshops are still evolving. Any model that is linked to these developments must therefore be flexible enough to account for potentially different perceptions of the workshop participants and their interpretations of the meaning of the various flow rates in the IFR tables. The paper has demonstrated that the IFR model is certainly flexible and that a wide variety of flow scenarios can be generated and assessed for suitability. The fact that there is relatively little difference in the low-flow results for the three rivers indicates that general calibration guidelines (illustrated by Fig. 3) can be provided to potential model users. It is difficult to predict whether these guidelines will still apply for rivers with totally different flow regimes to those represented by the three rivers. The effects of changing the flood rules are simple to understand and correlate well with what would be expected given the characteristics of the three flow regimes.

The operating rules used in DAMIFR are also relatively simple and the examples provided in this paper should provide initial guidelines for future calibration exercises. The use of the CDR and RRR rules, linked to the supply deficit, is considered by the authors to represent a simple, yet equitable, method of resolving water distribution conflicts. Given that the overall pattern of distribution can be controlled by up to 12 rules, it is difficult to imagine a desired situation that cannot be simulated, regardless of how the relative priorities between satisfying abstraction demand and environmental release demand are determined. The use of up to five reserve levels and drafts may not provide adequate abstraction operating rules in complex situations where more than a single supply source is involved. However, the original monthly reservoir simulation model can simulate several linked reservoirs and so can DAMIFR.

The models have been applied in a relatively simple way in this paper, where the dams are assumed to be more or less immediately upstream of the IFR sites. However, combining some of the models contained within HYMAS can allow complex situations to be modelled. Examples could include the simulation of multiple reservoir sites, tributary inflows between a dam and an IFR site, as well as several IFR sites linked together. While the issue of how to predict the future likely occurrence of a high-flow event (Hughes et al., 1997) has yet to be resolved, both models are theoretically capable of being applied operationally in real time situations. Their potential strength therefore lies in their ability to provide information for planning purposes (including the design of release patterns and of reservoir size and operation) as well as being applicable in a similar form for operational use. The author is aware of the procedures and models currently used by water resource engineers for the design of water supply systems and the determination of yield (Basson et al., 1994) within South Africa. It is not the intention of this paper to suggest that the approaches outlined here represent replacements for such stochastic systems models. The suggestion is that the IFR and DAMIFR models are better suited for use by the BBM specialists within an IFR workshop situation to generate the information that would then assist the systems modellers to establish satisfactory release rules for their models.


Luvuvhu IFR releases

Sabie IFR releases

Tugela IFR releases

Figure 6
Illustration of the effects on achieved releases of abstraction (right side) and release (left side) priority rules for four patterns of release requests

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