Towards the incorporation of magnitude-frequency concepts into the building block methodology used for quantifying ecological flow requirements of South African rivers

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Abstract

The current approach to setting the water quantity component of the ecological reserve for rivers in South Africa is based on the building block methodology (BBM) and carried out by a group of specialists in an IFR workshop. The BBM concentrates on setting flow magnitudes and there has been no formally defined approach to specify the frequency of exceedance relationships for these flows. This is a problem when attempts are made to implement the recommendations within the context of a water resource plan or management scheme for the river. In such situations information on how often flows of different magnitudes should occur is required. This paper offers a suggestion for improving the BBM by using a model to simulate a representative time series of modified flows and extract from the results assurance levels, or frequency of exceedance, for the different building block components. The implications of adopting such an approach, from both ecological and water resource development perspectives, are discussed.

Abbreviations

BBM	building block methodology
BFI	baseflow index
DWAF	Department of Water Affairs and Forestry
EMC	ecological management class
CV	coefficient of variation
IFR	instream flow requirement
MAR	mean annual runoff
WRYM	water resources yield model

Introduction

The BBM (King and Louw, 1998) has become one of the accepted approaches that is used in South Africa to establish the quantity of water needed to satisfy the ecological flow requirements of rivers. With the new South African Water Act (DWAF 1997a), a great deal of attention has been focused on the methods used to establish these requirements, which are now referred to as the 'environmental reserve'. Together with the use of water to satisfy basic human needs, the quantity component of the environmental reserve will become that proportion of a river's flow regime that has to be satisfied before allocations to other potential users can be considered.

The BBM is applied through a relatively complex process of interaction between various ecological, geomorphological, hydraulic and hydrological specialists whose task is to establish the components of a river's flow regime (instream flow requirement or IFR) that are required to maintain the river in a pre-determined sustainable condition (now referred to as the ecological management class or EMC). The EMC can vary from unmodified (category A) to largely modified (category D) and the responsibility for determining the specific state of any river will lie with the Minister of Water Affairs and Forestry. The IFR is defined as seasonal distributions of low and high flow values for river maintenance, applicable to 'normal' years, and a further set which are applicable during drought years. These four seasonal distributions are essentially the 'building blocks' and the concept is illustrated in Fig.1 using the results from the workshop held to determine the IFR for the Mkomazi River in KwaZulu-Natal (Louw, 1998).

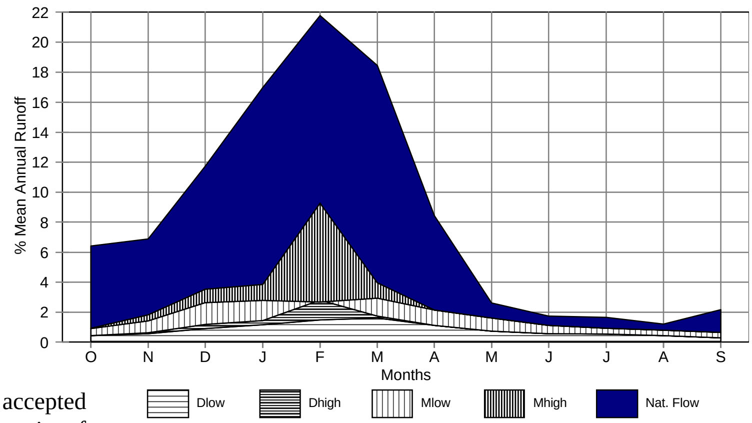

Figure 1
Monthly distributions of total natural flow (Nat. Flow), drought low- and high-flow (Dlow, Dhigh) and maintenance low- and high-flow (Mlow, Mhigh) requirements determined for Site 1 during the Mkomazi River IFR workshop held in 1998.

For the results of the BBM to be of use in the planning and management of water resource schemes, it is clearly necessary to define when the modified flows in the river should be at or close to the maintenance values and when (as well as how often) it is ecologically acceptable for the flows to drop to the drought requirements. It has always been understood by the developers and practitioners of the BBM that the rules for controlling these flow variations should be related in some way to the natural flow regime, which is in turn a reflection of the climate variations occurring over

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the catchment. Hughes et al. (1997) developed a model (referred to as the IFR model) that allows a daily time series of IFR modified flows to be generated using a reference flow time series. This provides the climatic cues and a set of 'rules' that can be calibrated with the assistance of the workshop participants. The model is flexible enough for the reference flow time series to be an observed flow record from the same, or nearby river, or it can be a simulated flow time series. The main constraint is that it should be representative, in terms of flow variability (short and long term), of the natural flow regime of the river at the IFR site under consideration. The model has been applied at several recent IFR workshops using historical time series of naturalised flows to help establish the 'rules', but also has the potential to be used operationally to determine the flow rates required for the modified flow regime in real time. Hughes et al. (1997) provide the details of the model and illustrations of its use.

The IFR model effectively allows the workshop participants to specify the amount of time within the modified flow regime when flows should be at, or above the specified maintenance requirements, between these and the drought requirements or at the drought requirements. The word 'effectively' is used because the model 'rules' have normally been established through visual interpretation of the model results (as a time series of modified flows). In the past the model has been applied as the final step of a workshop process. However, experience suggests that within the group of specialists, there are often diverse perceptions at the start of the workshop about how frequently maintenance flows should occur in the required modified regime. This is largely because the specialists have previously not had a common *a priori* perception of the frequency of exceedance relationships (or assurance) required for the flows defined as components of the IFR.

This paper examines the importance of defining the frequency of exceedance relationships, provides some illustrations based on previous IFR workshop results and discusses the implications with respect to future applications of the BBM approach.

The importance of defining frequency of exceedance

It is essential to address the issue of frequency from a water resource manager's point of view, particularly in terms of the planning of water supply schemes and the determination of yield. In most yield analyses, the potential users of water are defined by a combination of their volume requirements and levels of assurance of supply. For example, irrigation requirements may be divided up into high assurance supplies (failing rarely) and lower assurance supplies (not guaranteed in every year). While the environmental reserve is not viewed as a competing water user in the new Water Act, because a range of flows are specified by the BBM (maintenance to drought), it is essential to attach some level of assurance (or frequency of exceedence) to the specified flows to be able to determine the long-term average volume requirements. It is also clearly necessary to have a set of rules that can be followed in either a planning or operational framework so that the specific flow requirements at any point in time can be determined.

It has always been clear to BBM practitioners that the modified flow regime should retain the variability that is considered essential for the maintenance of riverine ecological processes at some defined level. It is also widely recognised internationally that hydrological variation is a primary driving force within riverine ecosystems (Richter et al., 1997). This is implicit in the definition of seasonal distributions (short-term variability) for the building blocks, rather than a single value, as well as in the definition of

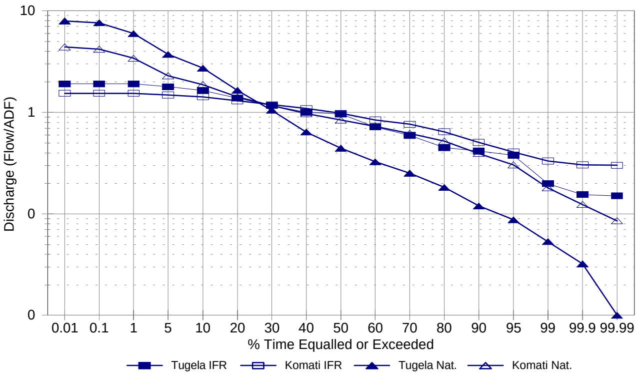

Figure 2
Comparison of annual 1-d flow duration curves for the Komati and Tugela rivers. All the curves are expressed as flow rates standardised by the average daily flow (ADF) for the specific time series. The IFR lines are based on the low flow output from the IFR model as calibrated at the workshop, while the other curves are natural baseflows.

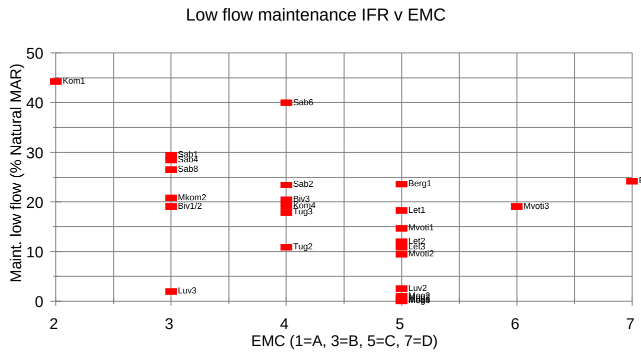

Figure 3
Annual maintenance low-flow requirements (expressed as % MAR) taken from a number of past IFR workshop results and grouped according to EMC (where 2=A/B, 3=B, 4=B/C, 5=C, 6=C/D and 7=D).

flows for both maintenance and drought conditions (longer term variability). However, there have never been any explicit statements about the level of variability that should be retained, largely because ecosystem responses to changes in flow regimes are complex, difficult to assess and therefore not always easy to quantify. Given the fact that South African rivers have flow regimes that are amongst the most variable in the world (Görgens and Hughes, 1982) it would seem to be of critical importance to attempt to address this possible shortcoming in the methodology of setting the quantity component of the environmental reserve for rivers.

Observations during past IFR workshops and additional discussions with experienced IFR practitioners drawn from several different disciplines, suggest that rivers with higher degrees of variability are expected to have lower reserve requirements set for them. This has been reflected in past IFR results by relatively lower maintenance flows being set for rivers which have greater flow variability. There has also been a relatively high degree of similarity in the position (with respect to percentage time exceeded) of the maintenance flows on the natural regime's one-day duration curves. Although the IFR model has only been used in a

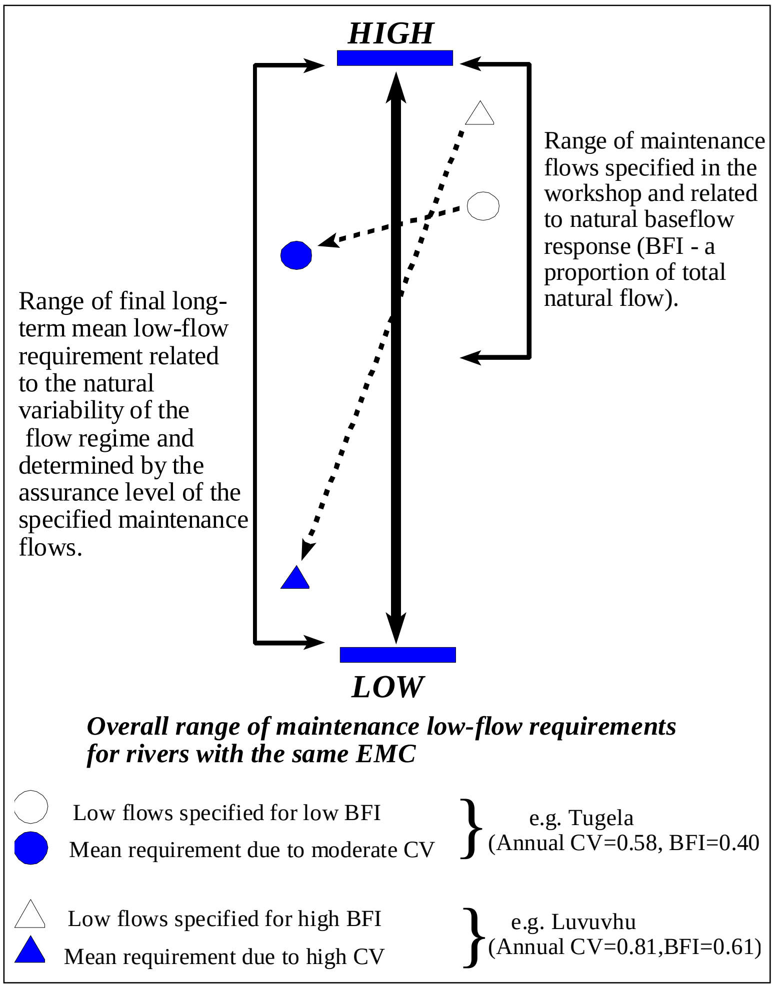

Figure 4

Conceptual illustration of the hydrological principles underlying the proposed modifications to the BBM to incorporate principles of assurance/risk. The CV values provided are based on annual totals.

limited number of workshops, a further observation is that the participants have often decided on rules that allow the modified flows to be at, or above, maintenance flows for most of the time and only drop down to drought flows on rare occasions (approximately 5% of the time).

The problem with such a standard result, is that rivers with different degrees of natural variability could end up having modified regimes with similar relative levels of variability. Figure 2 illustrates this point using the results from the Komati River (not published yet) and Tugela River (DWAF, 1997b) workshops. The Tugela has a coefficient of variation (CV) based on daily data for the winter months of 0.84, while the value for the Komati is 0.4. The natural baseflow duration curves confirm that the Tugela has a more variable baseflow regime than the Komati. The baseflow values have been based on a digital filtering technique, first introduced to hydrology by Nathan and McMahon (1990) and applied by Smakhtin et al. (1995) to a wide range of South African rivers. The approach separates 'high-amplitude' quickflow from the total streamflow hydrograph, leaving the balance as 'low-amplitude' baseflow. While the IFR flows for the Tugela are more variable than for the Komati, the differences are much less than for the natural regimes and are related mainly to the relatively low drought requirements that were set for the Tugela.

An assurance/risk based modification to the BBM approach

An alternative approach for rivers with naturally variable regimes would be to specify higher maintenance flows, but to accept that they are going to occur less frequently in the modified regime. The assumed ecological advantage of this approach is that a greater proportion of the natural variability will have been preserved in the modified regime for the same long-term volume requirement. Given that the variability in the modified regime will be controlled by real climatic cues (in some way), the advantage from a water resource manager's point of view is that high volume requirements should only occur at a time when overall water availability is higher and the supply system less stressed.

If such an approach were to be adopted, the implication is that the setting of maintenance flows and their approximate frequency of exceedance (assurance level) cannot be carried out independently as has been the practice in past IFR workshops. It would be necessary to set the two together, or alternatively, to reach a consensus at the start of the workshop process on the level of assurance that the design of the maintenance flows is to be based on. However, this adds a further complication to the process of determining the environmental flow requirements of rivers and it is difficult to judge whether the various specialists could provide the information with a reasonable degree of scientific confidence.

Figure 3 illustrates the maintenance low-flow volume requirements (expressed as % of natural mean annual runoff) that have been set at previous IFR workshops and shows that there is a great deal of variation in the requirements between rivers within each EMC. Figure 4 suggests a possible hydrological basis for setting the long-term low-flow requirements for a range of rivers given the same EMC. The approach illustrated is based on separating out the shorter-term variability effects (as represented by the BFI) from the longer-term variability effects (as represented by the annual CV).

The assumption is that rivers with a higher proportion of their flow regime occurring as baseflow would be expected to have relatively higher maintenance low-flow requirements. This is illustrated on the right-hand side of the diagram using the non-shaded symbols and suggests that the BFI differences would be reflected in the setting of maintenance flow values during the workshop.

Those rivers with more variable regimes, annually, would be expected (from a purely hydrological perspective) to have relatively lower drought low-flow requirements (100% assurance) and also lower assurance levels associated with the maintenance flows (illustrated by the left-hand side of the diagram and the shaded symbols). The consequence of these assumptions is that the long-term mean requirement would be substantially lower for rivers with more variable flow regimes. These differences would emerge during the calibration of the IFR model (Hughes et al., 1997) in that they would reflect the flow variations in the reference flow time series.

A 'Luvuvhu' type river (Fig. 4) may have a relatively high maintenance requirement due to the high BFI, but with a low

TABLE 1 LOW-FLOW IFR DETAILS FOR THE TUGELA REFINEMENT WORKSHOP - SITE 2						
Month	**Flow rate ($m^3 \cdot s^{-1}$)**		**Flow volume (m^3 x 10^6)**		**Maximum flow rate ($m^3 \cdot s^{-1}$)**	
	Maintenance	**Drought**	**Maintenance**	**Drought**	**Mlow1**	**Mlow2**
Oct	3.0	1.3	8.04	3.48	3.3	4.1
Nov	5.0	2.0	12.96	5.18	5.3	6.8
Dec	7.0	3.0	18.75	8.03	7.6	10.2
Jan	8.0	3.5	21.43	9.37	9.0	12.0
Feb	9.0	4.0	21.77	9.68	10.4	14.2
Mar	8.0	3.5	21.43	9.37	9.1	11.0
Apr	7.0	3.0	18.14	7.78	7.5	9.9
May	5.0	2.0	13.39	5.36	5.4	5.8
Jun	3.5	1.5	9.07	3.89	4.0	4.0
Jul	2.5	1.0	6.70	2.68	2.7	2.9
Aug	2.0	1.0	5.36	2.68	2.2	2.4
Sep	2.0	1.0	5.18	2.59	2.2	2.5
Total			162.00	70.00		

Notes: Columns 2 to 5 list the maintenance and drought flows specified during the workshop.
Column 6 (Mlow1) lists the maximum low-flow values simulated by the IFR model using the rules as calibrated during the workshop.
Column 7 (Mlow2) lists the maximum flow values simulated by the IFR model using the alternative calibration referred to in the text.

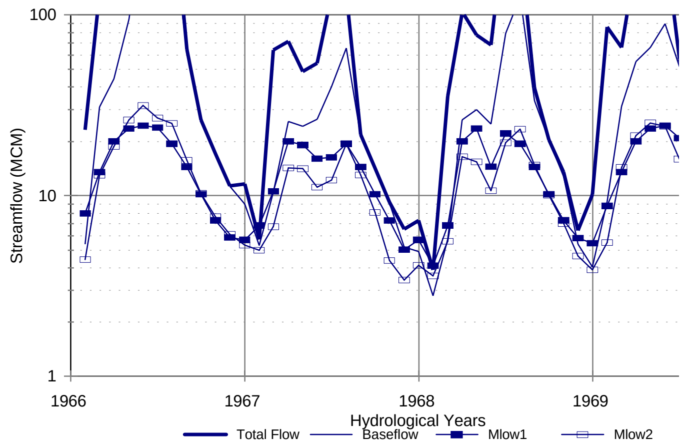

Figure 5
Four-year time series of monthly volumes for natural total flows and baseflows, as well as IFR model simulated low flows for the two calibration scenarios (Mlow1 - workshop calibration, Mlow2 - revised calibration).

assurance level and a low drought requirement. The result would be a relatively low long-term mean requirement. A 'Tugela' type river (Fig. 4) may have a lower relative maintenance requirement, but with a high assurance level and high drought requirement (associated with the lower CV) giving a relatively higher long-term mean requirement than for the 'Luvuvhu' type. While the high-flow components of the BBM have not been considered in detail at this stage of the development of the proposed method, they could be treated in a similar manner.

It must be remembered that Fig. 4 illustrates only the hydrological perspective and neglects any ecological considerations that might influence the relative values of the maintenance and drought flows or the required assurance level. While the ecological factors are clearly of dominant importance in the real IFR process, this paper proposes that they should be considered against a background understanding of the hydrological principles illustrated in Fig. 4.

The Tugela IFR refinement workshop results revisited

The original Tugela IFR workshop was held during 1995, but the requirements for some of the sites on the main river and the tributaries were refined during a further workshop held during 1997 (DWAF, 1997b). One of the sites is located on the main Tugela River just above the confluence with the Bushmans River. The catchment area at this point is some 6 818 km^2, the natural MAR has been estimated to be 1380 m^3 x 10^6 and the use of a digital filtering baseflow separation algorithm (Smakhtin et al., 1995) yielded a BFI of 0.4. The results of the refinement workshop in terms of the low-flow requirements are given in Table 1. The IFR model was applied at the end of the workshop to generate a representative 30-year time series (1950 to 1980) of flow requirements. Figure 5 shows four years of monthly volumes for natural total flows and baseflows, as well as the low-flow model results developed during the workshop (Mlow1). Figure 6 compares the annual volumes of the simulated low-flow requirements (Mlow1) with the natural baseflow regime for the whole period (using two vertical axes for clarity).

Column 6 in Table 1 lists the maximum flows that were simulated by the model for the workshop calibration (up to 15% greater than maintenance flows). Within the full 30-year time series, flows at maintenance rates or greater occur 89% of the time, while drought flow rates occur 5% of the time. The long-term mean annual volume requirement is 174 m^3 x10^6, some 7% higher than the maintenance volume. It is clear that the workshop participants based their calibration principles on maintenance flows occurring with a very high assurance level and the result is a modified low-flow regime which is considerably less variable than the natural baseflow regime (Fig. 6).

The model has been re-calibrated, for the purpose of illustrating some of the concepts proposed in this paper, to yield a more variable modified flow regime, but with the same values for monthly maintenance and drought requirements and constrained to result in the same long-term mean annual volume generated during the workshop. The results are given in Figs. 5 and 6 as Mlow2. Drought flows still occur 5% of the time, but flow rates at maintenance and above now only occur with an assurance of 62%. The constraint of ensuring that the long-term volume requirement remains the same, means that the model parameter controlling the maximum low-flow has to be substantially increased. Table 1 (column 7) suggests that the highest flow rates are now over 50% higher than the workshop specified flows in some months, but Fig. 6 indicates that the relative variability of the modified low-flow regime is much closer to the natural baseflows.

Figure 7 provides flow duration curves of simulated March low-flow volume requirements (for the two scenarios, Mlow1 and Mlow2), expressed relative to the maintenance requirement and based on daily aggregated volumes for each March of the 30-year series. The two lines on this graph can be thought of as March 'rule' curves for the two scenarios. Thus, in Scenario 2 (Mlow2), flows 25% greater than maintenance would have an assurance of about 20%, while maintenance flows have an assurance of about 72%. Neither scenario suggests that a full month of drought flows (44% of maintenance) is ever achieved.

A further model (Hughes and Ziervogel, 1998), developed recently, can use the simulated daily time series of the modified flow regime together with the water requirements of other users, to assess the impact of various operating procedures on the viability of a planned or existing water supply reservoir. 'Rule' curves of the type generated from the results of the daily IFR model (Fig. 7) can also be used in more complex monthly time step, stochastic water resource yield system models (Basson et al., 1994) for specifying the volume-assurance relationships for ecological reserve flows. The procedure would be to compare the percentage time of exceedance of naturalised monthly flow values, at a key point in the river system, with the relevant calendar month rule curve to determine the reserve requirement for that month. Although intra-month variability is lost (inevitable in a monthly time-step model), similar climatic cues are used to determine individual monthly reserve requirements as in the IFR model. WRYM is the model currently used by DWAF for yield determination in South African catchments and the links between output from the IFR model (Fig. 7) and the required input to WRYM have already been made. This represents an important step in that the links between the design of the ecological reserve (through the IFR process) and the engineering design of a water resource development scheme should now be possible. It should also be possible to quantify 'maximum assurance' levels in those cases where 'capping flows' are specified by the workshop to prevent excessively high flows occurring in the regime too frequently.

From a water resource use perspective it is useful to examine the consequences of the two simulated low-flow requirements with respect to the proportion of the total flow that would be available for other uses during drought periods. Table 2 lists the volumes (in $m^3 \times 10^6$ and %MAR) of the cumulative residual flow over the driest 6, 12, 18 and 24 months in the 30-year time series. The residual flow is calculated as total natural flow volume minus the ecological reserve low-flow requirement and ignores any high-flow requirements, which are likely to be minimal for most rivers during drought conditions. An important observation is that *the difference between the residual flows over the four periods for the two scenarios represents sufficient water to meet the basic human needs (assumed to be 25 ℓ·head^{-1}·d^{-1}) of between 2.3 and 3.4 m. people.* Therefore, the revised scenario has not only restored some of the natural variability, but also requires less water during critical periods for the same long-term volume requirement as the original workshop scenario.

TABLE 2
CUMULATIVE RESIDUAL FLOW VOLUMES (TOTAL NATURAL FLOW - IFR LOW-FLOW REQUIREMENT) FOR DROUGHT PERIODS DURING THE 30 YEARS

Drought duration (months)	Workshop simulations (Mflow1)		Revised simulations (Mflow2)	
	$m^3 \times 10^6$	%MAR	$m^3 \times 10^6$	%MAR
6	16.2	1.2	26.3	1.9
12	389.8	28.2	421.0	30.5
18	479.3	34.7	515.8	37.4
24	1 233.4	89.4	1 287.0	93.3

Notes: Although only low flows are considered in the calculation of the residual flow (i.e. that part available for other purposes other than the ecological reserve), high-flow requirements during extended drought periods are likely to be minimal.

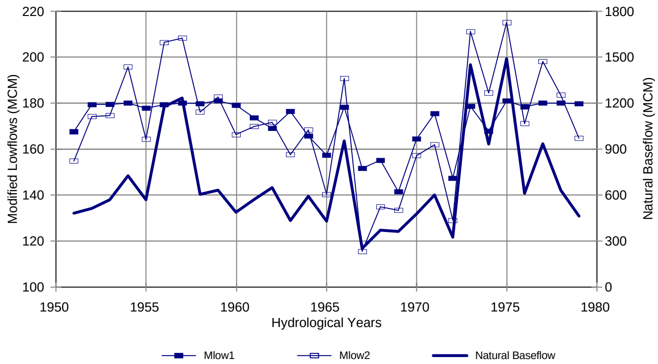

Figure 6
30-year time series of annual flow volumes for IFR model simulated low flows (left axis) for the two calibration scenarios compared with natural baseflows (right axis)

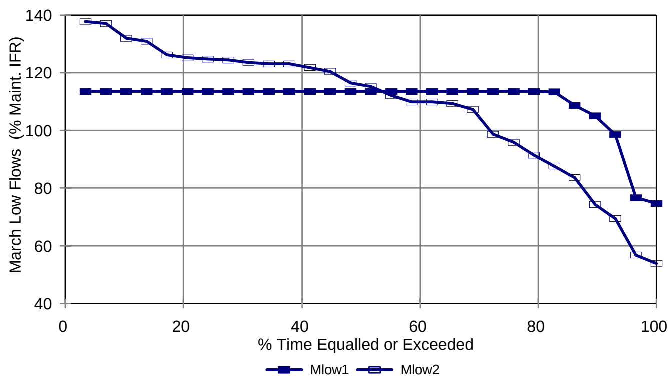

Figure 7
Flow duration curves for the simulated (30-year period) March low-flow volume requirements expressed relative to the maintenance flow requirement

Discussion

In presenting their 'range of variability approach' (RVA), Richter et al. (1997) refer to the need to identify the characteristics of ecologically relevant flow regime attributes and then transfer these into more simple flow-based management targets. The RVA method involves the use of 32 management targets, one for each of the ecologically relevant parameters. While this approach is well motivated by Richter et al. (1997), there is little doubt that it requires a great deal of both hydrological and ecological data (and understanding) to apply successfully. The BBM approach, if modified to incorporate frequency of exceedance (assurance) requirements as well as existing magnitude requirements, should be similar in concept but easier to apply both as a method for setting the reserve and for managing the system to satisfy the reserve requirements.

The issue of persistence of flows of a certain magnitude has not been considered elsewhere in this paper and yet could be quite critical to the ecological functioning of a river. However, as the modified flows are generated on the basis of climatic cues, it can be realistically expected that patterns of persistence in the natural regime will be reflected in the modified regime. It is, of course, possible for the workshop participants to check such patterns by viewing the time-series results of the IFR model and adjusting the rules where necessary.

While the combined use of the BBM and the IFR model may not constitute such a rigorous scientific and quantitative approach as the RVA, the author questions whether such rigour is appropriate given the current level of understanding of eco-hydrological relationships and processes in South African rivers. The more pragmatic approach that is proposed in this paper involves an initial qualitative assessment of the variability that is required, a quantitative evaluation of the building blocks during the workshop and a final qualitative check that the simulated time series of modified flows can be considered suitable. The qualitative assessments and checking can be carried out through visual, graphical interpretation of simulated time series (from the IFR model) by the non-hydrological specialists, which are then converted to quantitative interpretations of frequency values by the hydrological specialist. The quantitative magnitude-frequency relationships would then be used by the water resource engineers to design and implement a development scheme.

The concepts represented in Fig. 4 could form the hydrological basis of the qualitative assessment of assurance levels and are currently being considered as part of a developing method to set preliminary planning (low confidence) estimates of the reserve. The planning estimates need to be based on an approach which is quicker and cheaper to apply than the full BBM, but which can still be considered scientifically justified.

Conclusions

Very little consideration has been given in the past to specifying assurance levels for the various flows quantified during the application of the BBM. The problem is that without such information, the results of a workshop are difficult to incorporate into water resource planning or yield models. The development of the IFR model (Hughes et al., 1997) has partially addressed this issue, in that workshop participants can make use of the model to generate a representative time series of ecological flow requirements. The participants can visually (through graphical data displays) assess various alternatives and decide on the patterns of flow variation that best meet their perceptions of what the modified regime should look like. However, the use of the model at the end of the workshop, when the building blocks have already been established, does not prevent participants having different perceptions of the frequency of exceedance relationships for the components of the IFR. It is suggested by the author that any differences in these perceptions should be discussed and resolved before the flow magnitudes are quantified.

The revised simulation scenario presented for the Tugela site is not meant as a realistic ecological reserve alternative to the one concluded during the workshop, merely as an example of what could be achieved if the various ecological specialists had decided to retain a greater proportion of the natural variability of the low flows in this river. The whole analysis carried out for this paper has been based on a purely hydrological perspective and it must be emphasised that without the input of the ecological specialists the results of the second scenario cannot be considered as a viable practical alternative. However, the water resource planning and use implications, as illustrated using the approximate quantification of the drought period volumes, are such that due consideration should be given to more accurately and explicitly specifying the assurance levels for maintenance requirements. It is recognised that such a task is difficult, given the complexity of natural freshwater ecological processes. However, it is the author's considered opinion that unless attempts are made to address this issue, it will be difficult for the BBM approach to develop much further and find its true place in the toolbox of applied scientific procedures that are used to effectively plan and manage the water resources of South Africa.

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