Development of an operating rule model to simulate time series of reservoir releases for instream flow requirements

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Abstract

The output from many of the instream flow assessment workshops, currently being held in South Africa whenever a major water resource development is proposed, is a matrix of monthly flow rates that describe the recommended nature of a river's modified regime (IFR) that will maintain the river in a pre-determined ecological condition after the development has been implemented. This paper describes a technique that may be used to translate the IFR information into reservoir release operating rules for both low-flow and flood event releases and that can generate a time series of releases. The technique is based upon the use of a reference time series of daily flow data to represent the prevailing climate and trigger the various releases. To avoid the necessity of having a reference-flow time series available for the specific IFR site, the release trigger is based on duration curve percentage point data. These values are believed to be more closely equivalent across adjacent catchments than are weighted flows. Ultimately, the technique is expected to be used for planning purposes, to illustrate the effect of a given IFR on the likely day-to-day pattern of releases, as well as operationally, to control releases. This paper explains the technique and how it has been incorporated into a preliminary version of a model to simulate the pattern of releases that is expected to occur. The definition of the operating rules and the application of the model are illustrated using an example from the Luvuvhu River, Northern Province.

Abbreviations

BBM	Building block methodology
DWAF	Department of Water Affairs and Forestry
HYMAS	Hydrological modelling application system
IFA	Instream flow assessment
IFR	Instream flow requirement
MAR	Mean annual runoff
VTI	Variable time interval model

Introduction

It is becoming increasingly recognised that the large-scale abstraction of water from river systems cannot continue in an uncontrolled manner without having long-term repercussions with respect to the ecological status of the rivers and/or downstream users of water. To counteract the deteriorating condition of South Africa's rivers, DWAF now requires information on the quantity and patterns of flow that should be allowed to continue downstream of a proposed water resource development. The process of determining the nature of the required releases has been referred to as an IFA (King and Louw, 1995) and is commonly carried out during a workshop involving a multidisciplinary team of specialists. The purpose of the workshop is to define a modified flow regime that will maintain the river in a pre-determined condition. The modified flow regime is referred to as the IFR for the river and details the different flow conditions needed at different times of the year.

The IFR is commonly defined as a set of month-by-month low-flow and high-flow values for river maintenance and another set for drought years (Table 1 - LDC, 1995). In addition, some supporting information that describes the duration and other features of the required high-flow events, or the manner in which variations are expected to occur between wet, average and dry years is frequently included. It has become clear that the workshop participants prefer to use a description of the natural flow regime of the river, with a daily time resolution, as the starting point for the IFA. The described IFR can readily be translated into required monthly release volumes and used, in combination with design water abstractions, to assess the feasibility of various reservoir design options. However, before this information can be effectively used to determine the day-to-day releases that must be made from a reservoir to satisfy the IFR, it must be translated into a set of reservoir operating rules. Those developing the IFR process consider it of the utmost importance that such operating rules should somehow be linked to the prevailing climate. If such a technique was available and could be used to illustrate the suggested modified flow regime, the authors consider that it would enhance the whole IFA approach. Specifically, it would allow the scientists to look beyond the rigid numbers in the IFR table, which take that form because of the requirements of the planners, and see a more normal-looking daily time series that reflects the IFR and is linked to natural climatic variations. This paper discusses some approaches that could be used to translate the IFR into operating rules and introduces a model that is being developed to allow the impact of the operating rules to be assessed during the planning phase and eventually to be used to determine the actual reservoir releases after the dam has been constructed.

The IFR determination method

The approach that is currently being used to assess IFRs for South African rivers is known as the BBM (King and Louw, 1995), so named because it aims to identify different components, or blocks, of the natural flow regime of a river, which are ecologically most significant, and build these into a skeleton of the natural flow regime. The methodology is constantly being refined and developed as it is applied to rivers in different parts of the country, and has been accepted for use when developments are planned and time and data are limited. The application of the BBM results in a recommended flow regime which defines the

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TABLE 1
INSTREAM FLOW REQUIREMENTS IN THE LUVUVHU RIVER
(IFR SITE 1 - BEFORE MATCHING WITH THE OTHER IFR SITES)

Component/month	1	2	3	4	5	6	7	8	9	10	11	12
Maintenance												
Low flows ($m^3 \cdot s^{-1}$)	1.8	2.0	2.0	1.6	1.0	0.9	0.8	0.6	0.6	0.6	1.0	1.3
High flows ($m^3 \cdot s^{-1}$)	6.8	>10.0	7.0	6.6						5.6	6.0	6.3
High-flow period (d)	7	7	7	7						3	7	7
Drought periods												
Low flows ($m^3 \cdot s^{-1}$)	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.1	0.1	0.1	0.2	0.2
High flows ($m^3 \cdot s^{-1}$)	10		10									
High-flow period (h)	1		1									

volume of water that should remain in the river, incorporating the variability that is considered essential for the maintenance of the natural biota and ecological processes in a river. The following is a summary of the methodology, which is fully described in King and Louw (1995). Examples of the use of the BBM for assessing the IFRs of a number of rivers can be obtained from the Subdirectorate, Environment Studies, DWAF, Private Bag X313, Pretoria 0001.

At present, the essential components of flow are seen as the low or base flows, the small increases in flow, referred to as freshes, and the small and medium floods. Large floods, which can loosely be defined as those which are unlikely to be intercepted by a planned impoundment, are ignored because they cannot be managed. The base flows will obviously vary between naturally wet and dry seasons.

Prior to an IFR workshop, information is collected on the natural and present hydrology of the river, the present conservation status, geomorphological characteristics, aquatic biota and their habitat requirements, riparian vegetation, direct use of the river and its associated resources by the local people, water quality, and hydraulic characteristics of the river. At the workshop, experts in all these subjects combine their knowledge to identify, in a structured approach, the crucial water quantity and quality requirements for the river, in order to sustain it in a required future condition, or "desired state". These flow requirements may be in the form of a minimum depth at a rapid to maintain fish passage, or a yearly flood to inundate riparian vegetation, to name but two examples. Such information is converted to discharge requirements using rated hydraulic transects, and checked against the hydrological information to make sure that it is within the limits of flows that naturally occur in the river.

This procedure is followed at the workshop in order to define flows required for each month, that together will facilitate the year-by-year maintenance of the river. Drought-year flows are also defined and these are viewed as the minimum flows that are required during rare drought periods. Prior to the workshop, relatively homogeneous zones of the river are identified, and if possible one IFR site is selected for each zone. The result is a series of tables such as that presented in Table 1, each of which defines the month-by-month flows required at one IFR site for river maintenance (LDC, 1995). Each of the recommended flows is accompanied by a justification of its necessity and the whole is obviously generalised and not intended to prescribe the flows in the river for every year. The tables have three main purposes:

- To define the generalised minimum flow patterns and the temporal variability in flow that, given the best current knowledge, is essential to sustain the diversity of animals, plants and processes in the river.
- To define minimum flow requirements during drought years which would provide survival conditions for the riverine ecosystem. These are flows below which the riverine biota and local users will suffer severe deprivation, and which, if applied continuously, would result in irreversible damage to the river, including loss of much of its natural resources. For example, the extended drought in the Luvuvhu River during 1991/92, exacerbated by water abstractions, resulted in the downstream reaches of the river drying up, with the death of large numbers of mature riparian trees, as well as local hippo and crocodile populations.
- To provide planners with estimates of water volumes that will be required as a "block-booking" to sustain the riverine ecosystem in the desired state. For example, the recommended maintenance flows at IFR Site 1 on the Luvuvhu River (Table 1) translates to 44 $\times 10^6$ m^3 (21.4% of natural and 28.6% of present MAR). This is the environmental equivalent of the total requirements for irrigation, industrial use, or domestic use.

The results of the IFA process are therefore only aimed at providing general environmental recommendations. However, it is intended that the implementation of flow releases for river maintenance after an impoundment is built be governed by both a combination of climatic events in the catchment and the recommended IFR flows. For example, although a small flood of 6 $m^3 \cdot s^{-1}$ is recommended for the Luvuvhu River IFR Site 1 in November, there is no intention that this flood should be engineered unless sufficient rainfall occurred at that time to indicate it would have happened naturally. Similarly, during a particular year, the low-flow releases might be required to be higher than those recommended, depending on climatic cues in the catchment. However, because the workshop participants defined the minimum flow necessary for river maintenance, low-flow releases are only expected to be lower than the IFR if the climatic cues suggest the onset and persistence of a drought period. The basic philosophy of the BBM is that natural conditions are the best possible signal for maintaining natural biodiversity, and that floods and droughts are part of the natural environmental framework of a river.

Transforming the IFR into release-operating rules

The previous paragraph suggests that while the BBM represents a rapid and successful approach to defining the basic components of an IFR, additional methodology is required to define the actual daily patterns of release and how these are to be controlled. It is therefore necessary to transform the output from the BBM into release-operating rules and develop an approach whereby decisions on release flow rates can be made.

The reference-flow time series concept

Defining operating rules for abstractions from reservoirs is usually based on the storage volume state of the reservoir. This is clearly a logical approach as the storage state in relation to the patterns of demand defines the potential future supply. However, the storage state of the reservoir is largely irrelevant to the downstream requirements if one of the main principles of the BBM is accepted. This main principle is that the final modified flow regime should reflect, in some way, the virgin-flow regime. It is therefore necessary to define a time series that can be used to determine the conditions that would have existed in the river prior to developments and use these conditions, combined with the operating rules, to define the patterns of release that should occur. Several possible approaches could be suggested.

The first is to use a time series of rainfall over the catchment area coupled with some understanding of the relationship with patterns of runoff. This may be an attractive proposition because of its relative apparent simplicity. However, the relationship between catchment rainfall and runoff at the daily time scale is known to be complex and it is unlikely that a simple relationship could be defined that can be used to define both the low-flow status of a river as well as flood or high-flow conditions.

A second option is to use an observed flow record from a nearby gauged catchment. This could be on the same river, or on an adjacent river. The main criteria are that the time series of flow should reflect relatively natural conditions and that the nature of the runoff response should be similar to that of the catchment (under natural conditions) above the IFR site in question. This is an attractive option given that a suitable gauged site can be found. Hughes and Smakhtin (1996) have demonstrated that adjacent catchments can have similar flow time series characteristics and that scale problems can be circumvented by relating the flows at the two sites through the percentage points of duration curves. This concept formed the basis of a model that is being used to patch (missing values) or extend time series of flow.

A third option is to use a suitable daily rainfall-runoff model that has been calibrated for the IFR site and demonstrated to be able to simulate the virgin-flow conditions satisfactorily. Such an exercise formed part of an IFA for the Sabie River flowing through the Kruger National Park, to provide some of the hydrological information required for the workshop where there was a lack of appropriate observed data close to the IFR sites. It is beyond the scope of this paper to discuss the details of specific models for simulating catchment hydrology, suffice to say that there are several such models available for use in South Africa today that can be used for this purpose. The confidence that can be expressed in the simulation results varies greatly from situation to situation. It is very dependent upon the availability of adequate input rainfall time series data, descriptions of the catchment characteristics and observed flow data for validating the simulations. The potential value of this approach would have to be evaluated by an experienced hydrological modeller in each specific case.

The last two options are effectively the same, given that either a suitable reference gauged catchment can be found, or that reasonable confidence can be expressed in the model simulation results. They will also generate more realistic and reliable patterns of flow conditions than the first and are based on currently available information or techniques. The first option, on the other hand, would require a separate study for each catchment to determine the characteristics of rainfall events that generate flow and could result in more effort than applying an existing rainfall-runoff model which has a strong experience base. Consequently, the authors have chosen to base the technique on either of the last two options and the remainder of this section explains how a reference time series may be used, in conjunction with the normal output from an IFA workshop, to define what the modified flow regime is likely to look like over a number of years. The issue of how such a technique can be used to control releases from a reservoir in real time will be addressed later in the paper.

Definition of low- and high-flow status using duration curves

Simple linear scaling, to estimate the flow at a specific site from known flows at an adjacent site, is not always successful. This is largely due to the non-linearities that may be present in the relationship between flows of different magnitudes at the two sites, or between flows in different seasons at the two sites. For example, one catchment may have a "flashy" flood response coupled to a weak baseflow response compared to the other catchment, which may have a more subdued flood response and a more consistent baseflow response. Linear scaling from the former to the latter would tend to over-estimate peaks and under-estimate low flows. A better approach is to use a non-linear transformation function to scale the flows at the two sites and the percentage points on flow duration curves can form the basis of such a function. This is illustrated in Figs. 1A to 1C using daily flow data for 1969 from two gauging stations on the Black Umbuluzi in northern Swaziland. The Lower catchment area is 722 km^2, while the Upper is 166 km^2 (a ratio of 4.3). Figure 1A shows the actual mean daily flow values, while Fig. 1B shows the equivalent percentage points taken from duration curves derived for each calendar month of the year using approximately 25 years of data. Figure 1C illustrates the variation in the ratios of flows and percentage points (Lower/Upper) at the two sites. Apart from a few days when they are very different, the percentage point ratios demonstrate a high degree of consistency close to a value of 1.0. In contrast, the flow ratios vary from below the catchment area ratio of 4.3, during the wet and early dry seasons, to above during the late dry season.

The basis of the patching model described by Hughes and Smakhtin (1996) is that the flows occurring in relatively closely adjacent catchments (regardless of relative size) on the same day will be represented on their respective duration curves (for that month of the year) by approximately the same percentage exceedance value. The basic assumptions underlying the method are that similar meteorological events occur over the catchments and that there are no non-linear artificial influences affecting their flow regimes. If the flow time series were converted into time series of duration curve percentage points, they should be approximately similar in shape and scale, as illustrated in Fig. 1B. Hughes and Smakhtin (1996) provide a number of examples from Southern Africa to illustrate cases where the assumptions can and cannot be considered to be valid.

A similar principle can be used to link the patterns of flow variation in a reference time series to release operating rules, regardless of whether the reference time series represents flows at the IFR site or at a nearby site with a different catchment size. The procedure adopted for use in the model being developed to estimate the required releases, is to use the percentage point information to define a "baseflow" status and "flood" status for every day during the time series. To achieve a status value that will be higher for "wet" conditions and lower for "dry" conditions, the percentage point information is inverted (i.e. 100 minus % point).

The "baseflow" status is defined on the basis of the flows occurring over the previous 30 d. The algorithm finds the minimum inverted percentage point (i.e. lowest flow) within 16 overlapping 15 d periods and estimates the status as the median value of these minima. The algorithm is designed as a simple way of obtaining a relatively smooth variation in "baseflow" status and gives similar results to drawing a baseflow separation line beneath the total flow hydrograph and taking the mean of the percentage points of this line. The choice of 30 d is somewhat arbitrary but has been chosen on the basis of smoothing flow variations over a period of about a month. The result of applying the algorithm is illustrated in Fig. 2 for a two-year time series of flows (from October 1980) associated with the Luvuvhu River downstream of Albisini Dam (catchment area 915 km^2). The reference flows (Fig. 2A) are based on a simulation that excludes the effects of Albisini Dam and abstractions from the main river as well as other artificial influences in the main tributaries. The simulated flows are therefore considered to be a reasonable representation of virgin flow conditions. The effect of the drought in the second year on the "baseflow" status can be seen clearly. The 1979 hydrological year was also relatively dry and this is responsible for the relatively low values of the status at the start of the 1980 season.

While a period of days prior to the current day (i.e. the day of release) can be used to establish a "baseflow" or low-flow status, the same is not true for a "flood" status. This is mainly because one of the objectives of a high-flow release is to ensure that it matches, as far as possible, the timing of an event that would have occurred in the river naturally. This is particularly relevant if the releases are expected to combine with downstream tributary flood inflows to help satisfy a flow requirement at a site lower down the channel system. This means that the "flood" status should ideally be assessed from future flows. This is a relatively straightforward task during the planning phase when historical time series of flows are available, but is more difficult if the same procedure is to be used for the operational phase when the future is unknown.

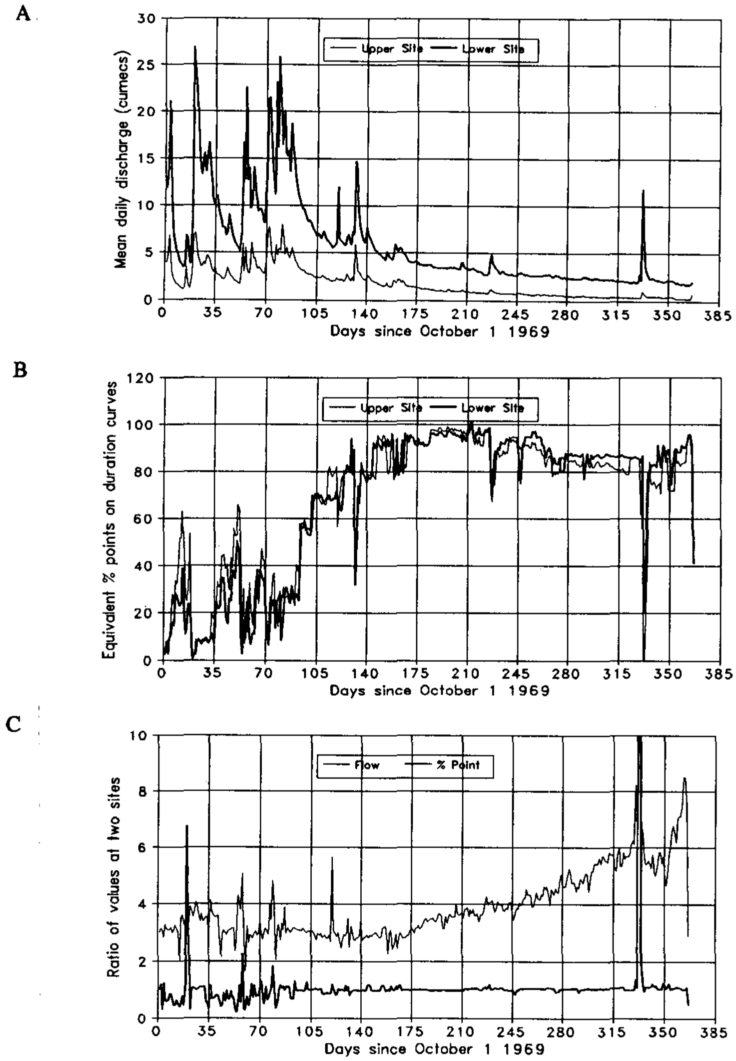


Figure 1 (top)
Illustration of flow (A), percentage point (B) and their ratios (C) for two gauged sites on the Black Umbuluzi, northern Swaziland

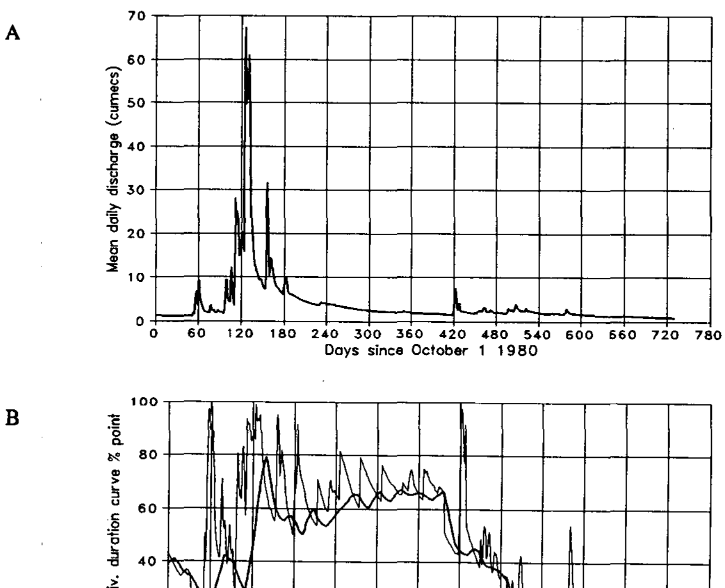


Figure 2 (bottom)
Illustration of a time series of flows (A) and equivalent inverted percentage points on the duration curves (B). The bold line on B represents the calculated baseflow status

The "flood" status algorithm consists of initially identifying the maximum flow within the next 10 d period and converting it to an inverted equivalent duration curve percentage point. The second part consists of deciding when the largest flow occurs during the 10 d future period and if it can be considered an "event" based on a decision criterion using two parameters; the time-to-peak (TP days) and a minimum rate of rise (dQ $m^3 \cdot s^{-1}$). The algorithm therefore identifies the highest peak during the next 10 d, that also falls within the same month as the current day and that satisfies a rate-of-rise criterion as follows :

$$\text{Flow}[i] - \text{Flow}[i\text{-TP}] \geq dQ \times TP \qquad (1)$$

where: Flow[i] is the flow rate on the day of the possible peak
Flow[i-TP] is the flow TP days previously.

The choice of a 10 d period is largely related to the future use of the procedure for operational control of releases after dam construction and represents the longest time over which a forecast of future flows is likely to be possible. This issue will be dealt with further in a later section.

Definition of the low- and high-flow release operating rules

In order to develop an initial model that decides when to allow releases to occur and at what flow rate, it is necessary to translate the output from an IFA into operating rules that can be related to the information on "baseflow" and "flood" status derived from the reference flow time series.

The low-flow component of an IFR specification is commonly expressed in the form of two sets of desired low flows; one for normal river maintenance (NLQ_i $m^3 \cdot s^{-1}$, where i=1,12) and one for drought years (DLQ_i $m^3 \cdot s^{-1}$). These are then interpreted into suitable values of equivalent reference-flow duration curve percentage points (NPP_i and DPP_i %). This would normally be carried out by studying the reference flow regime for typically average and drought low-flow conditions and quantifying the duration curve percentage points for these flows. As the IFR low flows for maintenance are viewed as the minimum releases, it is also necessary to specify an operating rule to define an upper limit to the low-flow releases. This is specified as a single percentage point differential for all months of the year (MPP %). The following flow values can then be defined for the reference-flow time series (the % points are taken from the calendar month duration curves derived from the reference-flow data) :

QRD_i = Reference flow at % point DPP_i (drought rule)
QRN_i = Reference flow at % point NPP_i (normal or maintenance rule)
QRX_i = Reference flow at % point NPP_i - MPP (upper limit rule)
QR = Reference flow at current day

The low-flow release operating rules are specified in the model as follows, using simple interpolation between the reference flows at the defined percentage points and the low-flow releases specified by the IFR :

If the "baseflow" status suggests drought flow conditions (i.e. $\leq 100 - DPP_i$) the release is equivalent to the low-flow IFR for drought years.

$$\text{Release} = DLQ_i \qquad (2)$$

If the "baseflow" status suggests conditions between drought and average flows (i.e. $> 100 - DPP_i$ and $\leq 100 - NPP_i$) the release is a linear interpolation between the drought and maintenance IFR low-flow values.

$$\text{Release} = DLQ_i + (NLQ_i - DLQ_i) \times (QR - QRD_i)/(QRN_i - QRD_i) \qquad (3)$$

If the "baseflow" status is above average flow conditions (i.e. $>100 - NPP_i$ but $\leq 100 - NPP_i + MPP$) the release is above the maintenance IFR low-flow value.

$$\text{Release} = NLQ_i \times QR / QRN_i \qquad (4)$$

If the "baseflow" status is above the defined upper limit of low-flow conditions (i.e. $> 100 - NPP_i + MPP$) the release is the maximum possible for that month.

$$\text{Release} = NLQ_i \times QRX_i / QRN_i \qquad (5)$$

The high-flow, or flood component of an IFR is commonly expressed in terms of a peak value (NHQ_i $m^3 \cdot s^{-1}$) and event duration (D_i days) for some months of the year (Table 1). In addition, a minimum event (DHQ_i $m^3 \cdot s^{-1}$) may be specified to ensure that potentially critical events do occur even during drought periods. The duration in this case is assumed to be 1 d because of the limitations of the modelling time step, although the IFR may specify a higher peak over a shorter duration. In a similar approach to that used for defining the low-flow operating rules, a critical duration curve percentage point value (HPP_i %) is defined for each month to be used to compare with the "flood" status to determine the size of the event to release in each month. It is also necessary to define hydrograph shapes for each duration and at present these are fixed within the model using non-dimensional values. The following approach is then used to determine the flood release. If an event has been identified as about to occur within the reference-flow time series (using the criterion given in Eq. (1)), the peak release is calculated as follows:

If the "flood" status is above the critical high-flow condition (i.e. $\geq 100 - HPP_i$) the high-flow release is equivalent to the maintenance IFR high flow.

$$\text{Peak} = NHQ_i \qquad (6)$$

If the "flood" status is between the critical high-flow condition and the upper low-flow condition (i.e. $< 100 - HPP_i$ but $\geq 100 - NPP_i + MPP$) then the high-flow release is reduced based on a linear interpolation as follows :

$$\text{Peak} = NHQ_i \times [(\text{status} - (100 - NPP_i) - MPP)/(NPP_i - MPP - HPP_i)] \qquad (7)$$

If the "flood" status is below the upper low-flow condition (i.e. $< 100 - NPP_i + MPP$) then no high-flow release event occurs in association with the reference-flow event.

The effect of the high-flow release operating rules given in Table 2 is illustrated in Fig. 3. The algorithm assumes that the peak value defined by the IFR only applies when the reference "flood" status is above a critical value ($100 - HPP_i$ %, e.g. Fig. 3, event A in December) and that if the "flood" status only reaches the percentage point limit for low flows ($100 - NPP_i + MPP$ %) then no high-flow release will be made. Between these limits the IFR peak value is proportionally reduced (Fig. 3, event B in January and event C in February). The peak value is then used to scale the non-dimensional hydrographs for the specified duration (D_i days). If a high-flow release spans the end of a month and a

TABLE 2 AN EXAMPLE SET OF FLOOD RELEASE OPERATING RULES												
Component/month	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
Normal flood release peak (NHQ_i $m^3 \cdot s^{-1}$)	5	10	5	5	0	0	0	0	0	5	0	5
Release duration (D_i d)	7	7	7	7	0	0	0	0	0	3	0	7
Critical flood status (HPP_i %)	15	20	20	20	0	0	0	0	0	20	0	20
Drought flood release peak (DHQ_i $m^3 \cdot s^{-1}$)	0.5	0	0.5	0.5	0	0	0	0	0	0	0	0

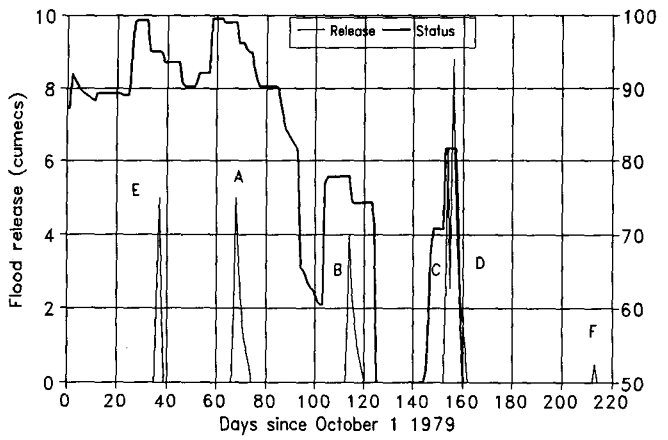


Figure 3
Illustration of the effect of the operating rules given in Table 1 on the releases generated during hydrological year 1978 for a site on the Luvuvhu River

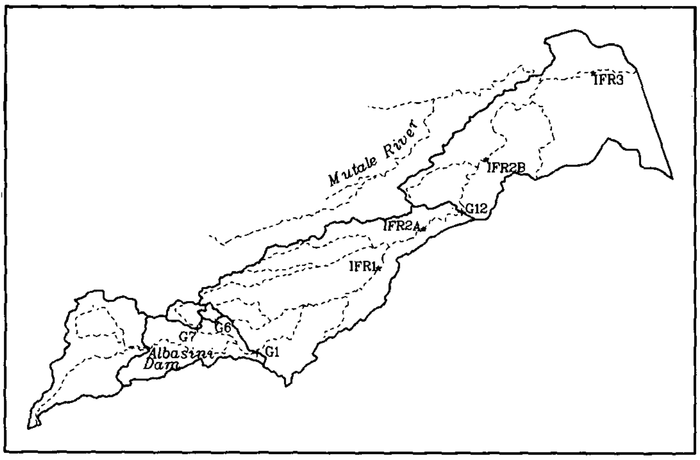


Figure 4
Luvuvhu River catchment, some streamflow gauging stations and the IFR sites

new release event is identified at the start of the next month, the current release discharge of the first event is added to the calculated peak of the second event (Fig. 3, events C and D in February and March). If no event was found within a month and the following month does not have a high-flow release specified in the IFR, then the release requirement is carried over into the second month (Fig. 3, event E in November). In addition, if no event has been identified and that month has a drought flood requirement, it is released on the last day of the month (Fig. 3, event F in April). It is interesting to note that although the "flood" status for October suggests quite high flows (a status of about 90% or higher), no high-flow release occurred. This is because no event satisfied the trigger criteria defined in Eq. (1) and may suggest that the requirements of a flood release for October are not realistic.

The high-flow release operating rules, in combination with the method used to identify the trigger event in the reference time series, are a pragmatic compromise using a limited length of future time and flow conditions. It is inevitable that some releases may be triggered by relatively small events, and generate lower than optimum peaks, when an event much later in the month is bigger and would have triggered a peak closer to the IFR specification. However, any flood-operating rule will always be faced with the same dilemma - should we wait for a bigger event that may never arrive?

Application of the model to the Luvuvhu River, Northern Province

Figure 4 shows the Luvuvhu River IFR sites in relation to the main flow-gauging sites (G1 = A9H001, G12 = A9H012, etc.) and the position of Albisini Dam. The development of the water resources of the Luvuvhu River in the Northern Province, up to about 1985, has been aimed at meeting specific requirements without an holistic consideration of the needs of all water users, or of the river itself. Increasing abstractions have significantly reduced streamflow which has impacted on riverine ecosystems and downstream users, one of which is the Kruger National Park. The Luvuvhu River Basin Study (HKS, 1990) was designed to quantify the availability and use of water within the basin to provide a database that could be used for planning, implementing and managing future water resource development projects. The report suggested that the water resources of the basin were under-utilised and that the construction of one or more large dams could satisfy the primary water needs of several large communities situated within the middle reaches of the river. The IFA workshop, held during July 1994, formed part of the pre-feasibility study designed to make recommendations about the most viable development options, taking a holistic view of all needs into account. Four representative sites were identified (Fig. 4, IFR sites 1, 2A, 2B and 3) and the workshop defined the flow requirements at each one (LDC, 1995). IFR Site 1 is used in this paper to illustrate the application of the technique for determining operating rules and the results of applying the release simulation model.

Selection of a reference-flow time series

There are several gauging stations within the Luvuvhu Basin, however, most of them have very short records (A9H012 - 1987 to present day) or are located on tributaries (A9H006 and A9H007, for example). The gauge of most value for determining the IFR at Site 1 is A9H001 (catchment area 915 km^2) which is located below Albisini Dam and for which daily flow records are available since 1931. This station is some 30 km in channel distance above the first IFR site (catchment area 1 598 km^2) and some major tributaries join the Luvuvhu River over this reach. The ratio of the natural MAR volumes at IFR Site 1 and A9H001 was estimated (based on Pitman model simulations) to be 1.53 (Pullen, 1994). The observed flow records are highly non-stationary, being seriously impacted by the construction of Albisini Dam during the early 1950s and subsequent irrigation abstractions. In addition, the recorded mean daily flows prior to 1963 were based on daily observations and only subsequent to this date extracted from digitised continuous flow records. Despite these limitations, the record at A9H001 for the period 1931 to 1961 was considered to be a satisfactory representation of the virgin-flow conditions at Site 1 and a suitable base for estimating the IFR (Pullen, 1994), given the understanding that the record would show the true peak flows as truncated in most flood events.

The authors accept that the reference-flow time series used during the IFA was acceptable for the purposes of the workshop. However, given the limitations of the gauging procedure in the past, the degree of abstraction impact in the present and the effect these will have on the duration curves, it is unlikely that it can be considered a suitable reference time series for the purposes of defining releases. The alternative that has been adopted for the Luvuvhu example is to use a simulation of the virgin-flow conditions at the same site (A9H001). The daily time step, semi-distributed, VTI model (Hughes and Sami, 1994), coupled with a daily reservoir simulation model, were set up and calibrated until an acceptable correspondence of observed and simulated flow regimes was obtained at A9H001, as well as at A9H005 (just below Albisini Dam) and the two gauged tributaries (A9H006 and 7). Most of the information about land use and water abstractions was obtained from the Luvuvhu River Basin Study (HKS, 1990). The calibration period used was 1975 to 1985 which covers a range of wet and dry years. The simulations were then repeated but with the impacts of Albasini Dam, all abstractions and some afforestation removed to generate an equivalent virgin-flow record. In terms of monthly flow volumes, the results are in close agreement with those given in the 1990 basin study derived through the use of the Pitman model (HKS, 1990).

IFR components and operating rules

Table 3 lists the operating rules that have been defined for IFR Site 1 (after matching with the other three IFR sites) on the Luvuvhu River (LDC, 1995). Columns 1, 3, 4, 7 an 9 have been extracted directly from the results of the IFA (LDC, 1995). The durations are assumed to be the length of time of the complete release hydrograph. The drought period flood peaks were specified as 10 $m^3 \cdot s^{-1}$ over 1 h. However, as the release estimation model under development is designed to operate at a fixed daily time step, the drought release has been interpreted as a mean daily flow of 0.42 $m^3 \cdot s^{-1}$ to ensure that the correct volume of release is preserved.

The other columns (2, 5, 6 and 8) in the upper part of Table 3 list the remaining rules based on interpretations of the output of the IFA in combination with a study of the reference time series. The maintenance and drought year equivalent percentage points for low flows have been derived from a visual inspection of low-flow sequences for a range of years in relation to the relevant months' duration curves. A similar approach has been followed to determine approximate high-flow equivalent percentage points. The time-to-peak, dimensionless hydrograph and event rate-of-rise parameters have been determined from an examination of a number of individual flood events. All of these analysis methods were carried out using the facilities provided within HYMAS (Hughes et al., 1994) which, apart from representing an integrated hydrological modelling environment for several different models, also allows observed or simulated time series to be examined, or analysed, in a wide variety of ways. The values given in Table 3, columns 2, 5 and 8, are essentially "first guesses" and would normally be revised once the results of applying them within the release simulation model have been examined and discussed with the workshop participants. The suggested procedure is therefore similar to calibrating a hydrological model, whereby the interpretations of the IFA results into the percentage point components of the final operating rules will be carried out through trial and error, but based on a previous examination of the available flow and duration curve information. It is even possible that this trial-and-error testing could be extended to the selection of the most appropriate reference-flow time series to be used, if more than one is available.

Discussion of results

The model being developed has been included as one of several available within the HYMAS package, all of which share common routines for time series handling and analysis. It is therefore a simple matter to prepare either observed or simulated flow time series for input to this model. The outputs from the model include time series of reference flow for up to three possible sites or sources (although only the first is used to determine the releases), design low-flow releases for average and drought years, actual low-flow, high-flow and total releases, equivalent percentage points for the first reference site flow values and finally, values for the "baseflow" and "flood" status. Time series graphs of these can all be compared so that the acceptability of the operating rules can be evaluated and the parameters changed where necessary. Figures 1A, 1B, 2A, 2B and 3 have all been compiled directly from the output files and represent examples of the types of graphic display that are possible.

Table 4 lists the volumes of the low-flow, high-flow and total releases that have been simulated. The volumes are presented as mean annual values for the period 1975 to 1985 (11 years) in million m^3, as well as percentages of estimated virgin and present day runoff volumes. The present day runoff volume (158 x 10^6 m^3) has been estimated from 1.53 x observed MAR (103 x 10^6 m^3) at A9H001 (scaling factor recommended by Pullen, 1994) and the virgin runoff (219 x 10^6 m^3) as 1.53 x simulated MAR (143 x 10^6 m^3) using the VTI model at A9H001. The release volumes are not substantially different to those estimated directly from the IFR tables by LDC (1995).

Flow duration curves for present day and virgin conditions at A9H001, as well as the release flow regime at IFR Site 1, are given in Fig. 5. It should be noted that the release line does not represent the complete modified flow regime that would be likely to occur at the IFR site as some of the larger flood events will inevitably pass over the proposed dam. While it would also be better to be able to compare the release-flow regime with the

TABLE 3
DEFINED RELEASE OPERATING RULES FOR SITE 1 ON THE LUVUVHU RIVER, NORTHERN PROVINCE (DERIVED FROM THE MATCHED IFR GIVEN IN LDC, 1995)

Month	Maintenance flows						Drought flows		
	Low flows ($m^3 \cdot s^{-1}$)	Equiv. % point ($m^3 \cdot s^{-1}$)	Flood peaks (d)	Flood duration	Equiv. % point ($m^3 \cdot s^{-1} \cdot d^{-1}$)	Event rate of rise ($m^3 \cdot s^{-1}$)	Low flows	Equiv. % point ($m^3 \cdot s^{-1}$)	Flood peaks
Column	1	2	3	4	5	6	7	8	9
Oct	0.6	75	3.0	3	20	0.5	0.12	90	
Nov	0.8	70	6.0	7	20	0.5	0.22	90	
Dec	1.0	70	12.0	7	20	0.5	0.22	90	
Jan	1.3	70	6.0	7	20	0.5	0.22	90	10.0
Feb	1.6	70	15.0	7	20	0.5	0.22	90	
Mar	1.8	75	6.0	7	20	0.5	0.22	90	10.0
Apr	1.4	80	5.0	7	20	0.5	0.22	95	
May	1.0	80	0.0	N/A	N/A	N/A	0.22	95	
June	0.9	80	0.0	N/A	N/A	N/A	0.22	95	
July	0.8	80	0.0	N/A	N/A	N/A	0.22	95	
Aug	0.6	80	0.0	N/A	N/A	N/A	0.12	95	
Sep	0.6	75	0.0	N/A	N/A	N/A	0.12	90	

Fixed (i.e. no monthly variation) parameters

Assumed time to peak = 2 d	Low-flow upper limit % point differential = 10 %

Dimensionless hydrographs

Duration	Day 1	Day 2	Day 3	Day 4	Day 5	Day 6	Day 7
3 d	0.4	1.0	0.4				
7 d	0.4	1.0	0.6	0.4	0.25	0.18	0.1

TABLE 4
SUMMARY OF SIMULATED RELEASES FOR IFR SITE 1 (THE PRESENT DAY AND VIRGIN MAR VALUES OF 158 AND 219 x 10^6 m^3 ARE BASED ON A FIXED SCALING FACTOR OF 1.53 x OBSERVED AND SIMULATED MAR VALUES FOR GAUGING STATION A9H001)

	This study based on simulations for 1975 to 1985	LDC (1995) estimates
Total low-flow releases (10^6 m^3)	32.8	32.5
% of simulated virgin MAR	15.0	15.8
% of observed present MAR	20.7	21.1
Total flood releases (10^6 m^3)	10.7	11.5
% of simulated virgin MAR	4.9	5.6
% of observed present MAR	6.8	7.5
Total releases (10^6 m^3)	43.5	44.0
% of simulated virgin MAR	19.9	21.4
% of observed present MAR	27.5	28.6

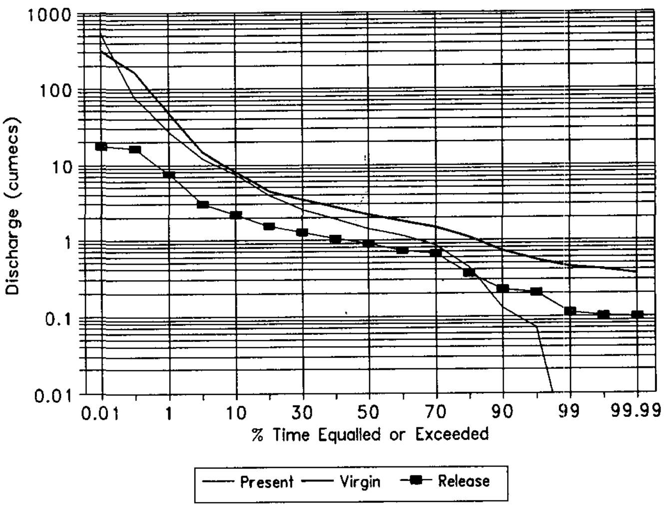


Figure 5
Annual 1 d flow duration curves for present day and virgin conditions at gauging station A9H001 and for the simulated IFR releases at Site 1

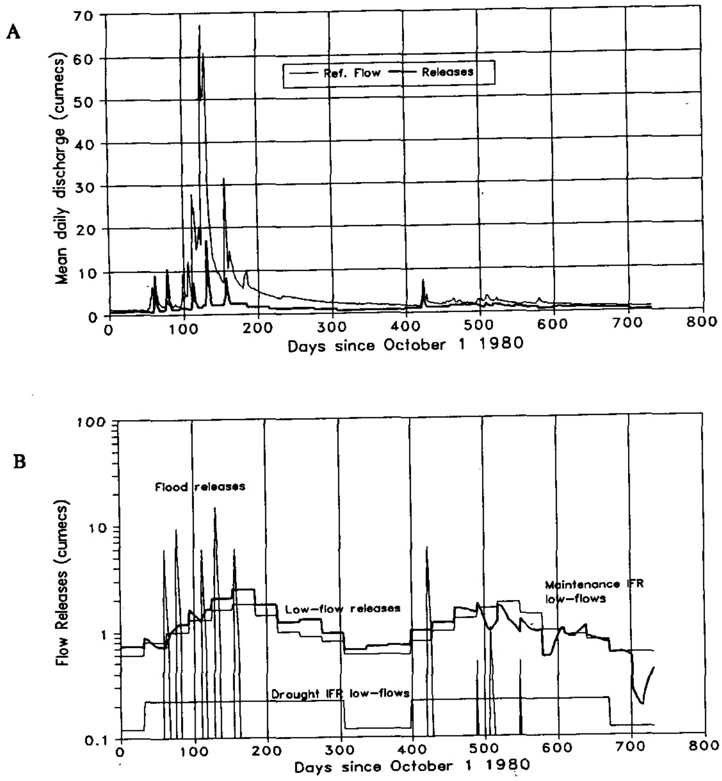
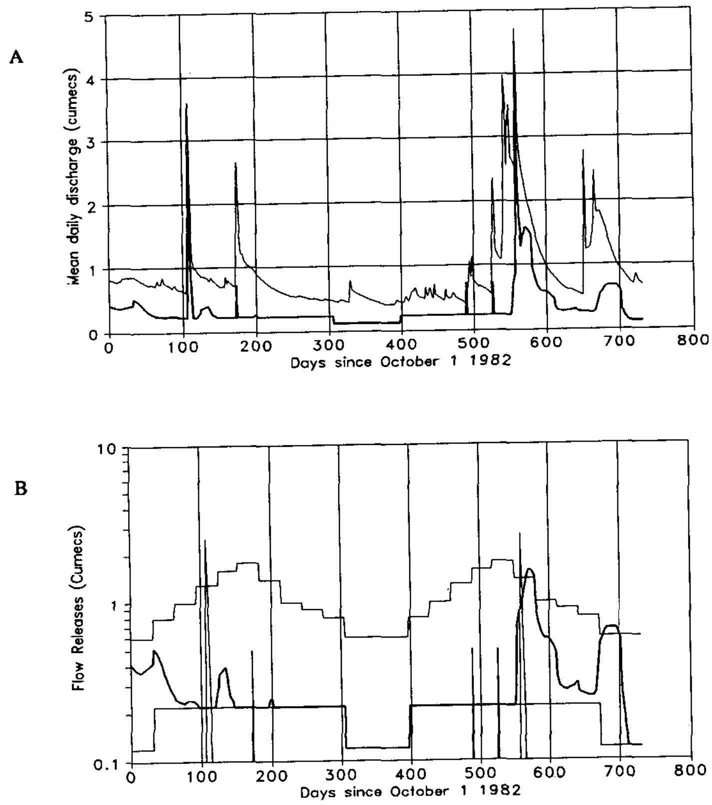


Figure 6

Luvuvhu IFR Site 1 1980 and 1981 hydrological years. (A) Reference flows and total releases. (B) Simulated low flow (continuous bold line) and flood releases compared to IFR definitions of maintenance and drought low-flow requirements (continuous normal lines).



present day and virgin regimes at the IFR site, these are not available on a daily basis.

Figure 6A shows a two-year time series of releases (from October 1980) for IFR Site 1 compared to the reference-flow time series. Figure 6B shows the two individual components of the releases (low flows as a bold continuous line, high-flow releases as the "spiked" line). Also plotted on Fig. 6B are the IFR low-flow requirements as maintenance (Table 3, column 1) and drought (Table 3, column 7) flows for each month of the year. During most of the 1980 season the low-flow releases are above the maintenance IFR flows and only during the middle part of the 1981 season do they drop to levels between the maintenance and drought IFR flows. The 1982 and 1983 seasons continued to be very dry and the low-flow releases dropped to the drought IFR flows during late 1982 and remained there until the drought was broken during September/October 1984 (Fig. 7). With respect to high flows, most of the IFR requirements were met during the 1980 season, but there are few natural events in the reference time series during the 1981 to 1983 seasons and consequently, any high-flow releases that have been predicted are below the IFR specified peaks (Table 3, column 3). Only during the 1984 season, after the prolonged drought, does the pattern of high-flow releases return to something close to the maintenance IFR high-flow specifications.

Future developments

The authors recognise that the current level of development of the model only addresses part of the problem and that there are at least two further considerations that must be included before it can become an effective planning and management tool. One is to incorporate the various release decision-making algorithms into a reservoir simulation model and the second is to account for any additional methodology required for operational purposes.

Incorporation of the model into a reservoir simulation model

The release operating rules included in the first version of the model are purely dependent upon the discharge values given by the IFR. In reality, the full operation of a proposed impoundment will also be somewhat dependent upon the stored volume and the patterns of required abstraction. During the planning phase it would also be useful, if not essential, to quantify the impacts of the IFR on the patterns of abstraction possible from the impoundment, relative to the design abstractions. A daily reservoir simulation model already forms part of the HYMAS package and the next stage of the release model development is to incorporate the IFR release algorithms into the existing reservoir model. At present, the reservoir model contains relatively simplistic facilities for defining abstraction operating rules and it is envisaged that these will have to be modified and combined

Figure 7 (left)

Luvuvhu IFR Site 1 1982 and 1983 hydrological years. A: Reference flows and total releases. B: Simulated low-flow (continuous bold line) and flood releases compared to IFR definitions of maintenance and drought low-flow requirements (upper and lower continuous normal lines).

with the IFR release rules. The final downstream outflow from the revised reservoir model will then be the controlled releases and the natural spillages and a more realistic impression of the modified flow regime will be possible.

The current version of the model only addresses the IFR of a single site, whereas most IFAs are concerned with flow requirements at several key sites in a river system. The existing facilities and models that are available within HYMAS should allow the releases to be routed downstream and coupled with tributary inflows (observed or simulated) in most circumstances. Natural transmission losses (bed, bank and evaporation) and abstractions between IFR sites can also be accounted for.

Requirements for operational purposes

As already referred to, the low-flow release operating rules are based upon an estimate of the antecedent flow conditions in the river, but the high-flow release rules are based upon the recognition that events would naturally have occurred in the future. This is relatively straightforward for the planning version of the model when an historical time series can be used to assess the likelihood of occurrence of a suitable future event. It is much more difficult to use the same approach for operational purposes in real-time and it would be necessary to rely upon the use of a flow forecasting tool to predict the likelihood of a future event.

It is beyond the scope of this paper to discuss the feasibility of establishing a flow-forecasting model that might be based upon real-time inputs of catchment rainfall and could operate in parallel with the reservoir/release model. The real question is whether the resources required to establish and run such a model at the site of interest are available and justified. Without such a forecasting model it is inevitable that the high-flow releases would have to be made in retrospect and that they would not be synchronised with events that would have naturally occurred during pre-development conditions. The extent to which high-flow releases would be out of phase will inevitably be dependent upon the response characteristics of the catchment and the availability of reliable information that could be used to recognise an impending event. The importance of the extent to which the releases would be out of phase may also be related to the relationships between natural flow patterns in the river at the dam site and those downstream which would be influenced by tributary inflows. The implications of not being able to use a flow forecast (for whatever reason) is that the high-flow release operating rules would have to be changed and based upon different information that would be more readily available to the operating staff of the dam.

Conclusions

A reference-flow time series can be used to estimate what the natural low- and high-flow status of a river affected by existing and/or planned water resource developments would have been. This approach provides the basis of a method that can supplement the IFA methodology, currently in use in South Africa, to determine the daily time series of releases that are required. The main consideration in the choice of a suitable reference time series is that it should have a pattern of flow variation that closely reflects that which would have occurred at the site of interest under natural conditions. The main assumption underlying the method described in the paper is that the natural flow at the site, and the flow at the same time in the reference time series, will be represented by similar percentage points on their respective daily flow duration curves for the relevant month of the year. The reference flow and associated duration curve characteristics are then used in a model to determine baseflow and flood status conditions which trigger the type of release required. The model parameters (release operating rules) are the required maintenance and drought year low- and high-flow release rates (obtained directly from the IFR) and the duration curve percentage point interpretations of the conditions when these different releases should apply. The latter may be quantified on the basis of experience, or through trial and error calibration until an acceptable pattern of releases is generated over a representative historical period.

While the preliminary version of the model already has potential value in its ability to illustrate the consequences of an IFR for a specific river, further work is required to develop a tool that can effectively be used by both ecologists and engineers during the planning and implementation phases of a water resource development. Specifically, the release determination algorithms need to be incorporated into a reservoir simulation model and additional features are required for the operational use of the developed model.

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