THE DEVELOPMENT AND EVALUATION OF AN OPERATING RULE FRAMEWORK FOR THE *ACRU* AGROHYDROLOGICAL MODELLING SYSTEM

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DISSERTATION

Submitted in partial fulfilment of the requirements
for the degree of MSc in Engineering

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Pietermaritzburg

December 2001

ABSTRACT

Dams hold numerous benefits for society through their ability to store water on a long-term basis. However, it is well-known that there is a detrimental effect of dams on the rivers that they impound, and this has been taken into account by the South African National Water Act (1998). The Act specifies a two component Reserve to provide a basic water supply to humans and to provide protection to downstream rivers and their associated ecosystems. From an ecological perspective, emphasis is now placed on ensuring that flow in rivers is maintained in a state that closely mimics the natural flow regime in order to sustain the water resource and its associated aquatic ecosystems. The resulting challenge for water resources modelling is to develop operating rule frameworks that can account for water supply to multiple users, including the "environment" which represents downstream aquatic ecosystems. These frameworks need to consider both water stored in dams, as well as water in the river which has been allocated to different water users.

Such an operating rule framework has been implemented in the daily time-step *ACRU* agrohydrological model in order to:

(a) satisfy the requirements of water users in general,

(b) include the environment as a user of water, and thus

(c) attempt to satisfy the water requirements of rivers and their associated ecosystems by making artificial releases from dams using both a simple and a complicated approach for determining the environmental requirements.

The framework identifies four types of water users, each of which are capable of requesting water from a water source. These users are: a domestic user, representing the basic human needs component of the Reserve, an environmental user, representing the ecological component of the Reserve, an industrial user and an irrigator. The environmental user can generate water requests using either a simple or a complex environmental request method. The simple approach has proved to be oversimplified while the complex approach is capable of producing a flow regime downstream of a dam that closely mimics the natural flow regime.

Two operating rules are employed to supply water to the four users, a generic dam operating rule, which considers water requested from a dam, and a channel operating rule, which considers water

requested from a river. The two operating rules determine the amounts of water that each user can receive through the use of a curtailment structure, where abstractions made by users are limited, based on the storage level in the dam.

Extensive validation of the framework has taken place and a case study was undertaken on the Pongola-Bivane river system which includes the Paris Dam in order to run various real-life scenarios. The results obtained show not only that the operating rule framework is functioning correctly, but that the use of a curtailment structure holds advantages for increasing assurance levels of the water users. There is also evidence to suggest that future possibilities exist for practical application of the operating rule framework to "everyday" dam operations.

DISCLAIMER

I wish to certify that this dissertation is my own unaided work except where specific acknowledgement is made. In addition I wish to declare that this dissertation has not been submitted for a degree in any other university.

Signed: ......A. Buffler......................

ACKNOWLEDGEMENTS

The author wishes to record his sincere appreciation for the assistance given by the following:

Prof. J.C. Smithers, School of Bioresources Engineering and Environmental Hydrology, University of Natal, for supervising this project and providing invaluable guidance, support and encouragement throughout.

Dr G.P.W. Jewitt, School of Bioresources Engineering and Environmental Hydrology, for co-supervising this project and for his advice and guidance.

Mr D.J. Clark, School of Bioresources Engineering and Environmental Hydrology, for his invaluable assistance with object-oriented programming and the project in general.

Prof. D.A. Hughes, Institute for Water Research, Rhodes University, for his assistance with the development of operating rules for the ecological reserve.

Mr J. S. Hallowes, CPHwater, for providing technical advice on climatic forecasting and guidance with respect to developing and evaluating the operating rule framework.

Mr F. Cronje, Impala Irrigation Board, for providing explanations on the current operation of the Paris Dam and the Pongola Irrigation scheme.

The Water Research Commission, University of Natal and the National Research Foundation for providing financial support.

Mr E. Belshaw, for assisting with proof-reading the document.

My parents, friends and family for their support, encouragement, understanding and assistance.

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LIST OF ABBREVIATIONS

BBM	Building Block Methodology
DDP	Deterministic dynamic programming
DP	Dynamic programming
DWAF	Department of Water Affairs and Forestry
IFIM	Instream Flow Incremental Methodology
IFR	Instream Flow Requirement
IHA	Indicators of Hydrologic Alteration
PHABSIM II	Physical Habitat Simulation
RVA	Range of Variability Approach
SDP	Stochastic dynamic programming
UML	Unified Modelling Language
WRYM	Water Resources Yield Model
XML	Extensible Markup Language

1. INTRODUCTION

The construction of large dams is a much debated topic throughout the world. Dams are seen by many as essential for the well-being of society, primarily due to their long-term storage of water, as numerous water users rely on storage in a dam to satisfy their needs. Water from dams and rivers is used by humans for drinking and personal hygiene, for agriculture and for industry. In addition to these uses, sufficient water is required to remain in river systems to ensure the survival of aquatic ecosystems. Given this wide scope of users reliant on dams as a water source, it is not difficult to recognise that water in a dam needs to be distributed very carefully to avoid wastage. In order to achieve this, it is necessary to have an operational procedure associated with the dam that is able to ensure that the water users' requirements are met while also ensuring that the water is used efficiently.

Operation of dams is especially important in a country such as South Africa due to numerous physical, social and environmental issues. South Africa is a semi-arid country and with the increasing population, there is an ever increasing demand on the country's water resources. McCartney *et al.* (1999) note that dams provide benefits for society such as flow regulation and flood peak attenuation but state further, that the impacts of dams can have far reaching consequences for aquatic ecosystems, both upstream and downstream of the dam site, as well as having significant economic and social implications.

The most serious impact of a dam on a river is the interruption of flow. Rivers are extremely important in an ecological sense because of the wide variety of fauna and flora they support. McCartney *et al.* (1999) maintain that the ecological integrity of river ecosystems depends upon the variation in flow regime to which they are adapted. Dams typically tend to regulate the flow regime of a river, thus decreasing the variability in flow. It is suggested by McCartney *et al.* (1999) that the geographical location of a dam and the natural flow regime associated with the river are indicators of the potential impacts the dam will have on downstream ecosystems. This view holds serious implications for rivers in South Africa, which are adapted to unregulated and highly variable flow, sediment and chemical regimes (Davies *et al.*, 1994). The problem in South Africa is exacerbated due to the high number of impounded rivers in the country. Of the 65 000 km of river channels in South Africa, approximately 40 % (26000 km) are subject to interruptions of flow (O'Keeffe *et al.*, 1992; Davies *et al.*, 1993, cited by Davies *et al.*, 1994).

The numerous forms of biota existing in riverine ecosystems are affected in various ways by impoundments and it is therefore vital to explore techniques to alleviate these effects. The recent implementation of a new South African National Water Act (1998), referred to as the National Water Act throughout the remainder of this document, has provided the impetus necessary to better conserve rivers. Implementation of the National Water Act requires the determination of a Reserve, consisting of a basic human needs reserve and an ecological reserve, for all South African rivers, with those on which development is likely to take place receiving the highest priority (Jordonova *et al.*, 1998). The Department of Water Affairs and Forestry (DWAF) now requires that the necessary quantities and patterns of flow downstream of any water resource development are determined as part of the design of the scheme (Hughes and Ziervogel, 1998). A tool that can determine and then model the implementation of these quantities and patterns of flows is therefore required. Instream Flow Requirements (IFRs) are commonly used as a method of determination of the necessary flow quantities. In the National Water Act (1998), IFRs refer specifically to the flows required to ensure the preservation of the water resource, which includes the aquatic ecosystem. However, IFRs alone cannot aid in preventing the degradation of aquatic ecosystems downstream of impoundments as they have no means of implementation. In order to provide guidelines and to promote an effective synergistic approach in order to satisfy IFRs, a dam operating rule framework needs to be derived. Although the National Water Act recognises the ecosystem as the water resource base, in order to consider the IFRs from a modelling perspective, it is necessary to regard the "environment" as a separate user of water.

The main focus of this project is to provide a tool, in the form of an operating rule framework, which can assist in the planning and operation of flow releases from dams to better satisfy the requirements of all water users. The *ACRU* agrohydrological modelling system (Schulze, 1995) was chosen as the model into which this framework would be placed. The framework needed to be able to account not only for the usual water users, but in accordance with the National Water Act, needed to recognise the environment as a separate water user. The main objectives for the project were as follows.

(a) The development, validation and verification of an operating rule framework for the *ACRU* agrohydrological modelling system which can:

(i) simulate the operation of a dam using a generic set of operating rules,

(ii) simulate the operation of a river to account for situations where abstractions are made directly from the river,

(iii) supply water to various water users in an equitable manner,

(iv) include the environment as a water user and provide an artificial flow regime downstream of a dam, and

(v) be used operationally to assist in the real-time operation of dams.

(b) Illustrate the operation of the operating rule framework.

(c) Illustrate and assess how operating rules employing different curtailment structures can improve assurance levels of water users, through the use of a case study.

In this dissertation, the development and implementation of the operating rule framework within the *ACRU* agrohydrological modelling system is discussed. A review of the most recent literature available on IFR determination techniques as well as on operating rule techniques is included before providing detailed methodology as to how the implementation was achieved. Results are presented in the form of a case study to aid in:

(a) validation of the framework,

(b) providing a form of optimisation of the procedures included within the framework, and

(c) evaluating the possibility of using the framework for real-time dam operations.

The case study site used is the Pongola-Bivane river system which includes the Paris Dam. The results obtained are analysed and discussed and conclusions are drawn as to the effectiveness of the framework as a whole. Recommendations of possible future improvements that can be made to the framework are also provided.

2. REVIEW OF INSTREAM FLOW REQUIREMENTS AND OPERATING RULE TECHNIQUES

The promulgation of the National Water Act (1998) has resulted in more emphasis being placed on environmental requirements in rivers through the determination of IFRs and the role that dam operation needs to play in ensuring these requirements are met. This section reviews the basic principles behind both IFR determination techniques and dam operating rules in order to conceptualise ideas for their combination.

2.1 Background to Instream Flow Requirements

Following the development of many large reservoirs in the mid-20th century, concern about the loss of riverine fish and wildlife resources in the USA, resulted in certain states implementing IFRs to protect existing stream fishery resources (Stalnaker, 1994). Numerous methods for IFR determination have subsequently been developed.

Acreman *et al.* (1999) considers an approach of mimicking the natural hydrological regime as the most promising principle on which to base IFRs. The development of IFRs in South Africa has followed this approach. An IFR in a South African context refers specifically to the quantity and timing of flows required to sustain the water resource and support the ecosystems which form the basis thereof. The main impediment to IFR development is the lack of knowledge on exactly how much water is required to support the aquatic ecosystems (Acreman *et al.*, 1999). IFRs generally assume that a certain amount of water can be removed from the river without significantly affecting the functioning of the ecosystem (O'Keeffe and Hughes, 2000), although quantifying the exact amount of water that can be removed is complicated.

The implementation of the National Water Act (1998) has increased the need for sound techniques of IFR determination in South Africa. In the following section, the requirements of the National Water Act (1998) with respect to IFRs are discussed.

2.2 Instream Flow Requirements and the Application of the National Water Act

The National Water Act (1998) emphasises the need for sustainable and equitable water usage. In order to fulfill this requirement there is a need to establish a Reserve (Chap.3, Part 3, Sect.16(1)). The Reserve is defined as the quantity and quality of water required to satisfy basic human needs by providing a basic water supply to people reliant upon the relevant water source and to protect aquatic ecosystems in order to secure ecologically sustainable development and use of the relevant water resource. It seeks to ensure that adequate water exists in a particular catchment to support the *in situ* human population and the riverine ecosystems and is separated into the basic human needs reserve and the ecological reserve. The basic human needs reserve ensures that the water needs of an individual are met and incorporates water for drinking, food preparation and personal hygiene. The ecological reserve is the amount of water required to sustain the aquatic ecosystems within a water resource. Hughes (1999a) defines the ecological reserve as the proportion of a river's flow regime that has to be met after the basic human needs reserve has been satisfied, and before the needs of other users can be considered.

It is the responsibility of the Minister of Water Affairs and Forestry to determine the Reserve for any significant water resource (Chap.3, Part 3, Sect.16(1)). According to O'Keeffe and Hughes (2000), the definition of "significant" has yet to be determined. Reserve determination is to be accomplished by first providing a procedure for classifying water resources. However, until a system for classifying water resources has been prescribed, the Minister may make a preliminary determination of the Reserve (Chap.3, Part 3, Sect.17). This classification is of the utmost importance, for without quantifying the amount of water the Reserve requires, allocations to other prospective applicants or users cannot be made. The Reserve requirement will also not distinguish between existing and proposed water resource developments, and this may result in a reduced yield for existing water supply schemes (Manson, 1998). IFRs will be involved in determining the ecological reserve which means that they will play a vital role in this process of water allocation. In order to comply with the Act, the quantity and quality of water being released from dams will have to be carefully monitored to ensure that the Reserve is being met.

2.3 Methods Used for the Determination of Instream Flow Requirements

The National Water Act (1998) stipulates that the IFR must form an integral part of the release schedule from a dam. In order to comply with the Act and thus ensure adequate protection of the water resource, it is important that the technique used for IFR determination be as representative of the natural flow regime as possible.

A large number of IFR determination techniques are currently employed worldwide and a general classification of these would prove useful. Tharme (1996) and Tharme (1997, cited by Tharme and King, 1998) provide such a classification of IFR determination methods by placing them into four different categories. The first and most simple technique (Type 1) uses hydrological data (historical flow records) for IFR determination. Owing to the simplicity of these techniques, they are only applicable for streams of low flow variability (McMahon, 1993). The second and third categories can be classified as hydraulic rating (Type 2) and habitat simulation (Type 3) methods, and utilise an incremental relationship between instream habitat and discharge. A limitation of both is that they assume that a single hydraulic variable can adequately represent the IFRs for a target species, an assumption that is questioned by Tharme and King (1998). The fourth category, termed holistic methods (Type 4), have only been recently established (Tharme, 1996). These methods do not concentrate on a specific target species, but address the requirements of the entire water resource. Their main limitation in IFR determination, according to Tharme and King (1998), is that they rely heavily on the experience of the specialists involved. Nevertheless, the holistic methodologies appear to be the only techniques that will be able to ensure that the IFRs produced are in compliance with the requirements of the National Water Act.

A survey conducted by Dunbar *et al.* (1998) on IFR determination methods throughout the world, found that no country had developed a definitive all-encompassing method. In the following sections, three specific techniques are identified and their applicability to South African conditions is reviewed.

2.3.1 Instream Flow Incremental Methodology

The Instream Flow Incremental Methodology (IFIM) has been used regularly in countries such as the USA for IFR determination. The IFIM is a combination of Types 2 and 3 i.e. hydraulic rating and habitat simulation methods. The basic IFIM method uses transect-based hydraulic analyses to evaluate the habitat conditions associated with differing flow levels in rivers (Richter *et al.*, 1997).

The Physical Habitat Simulation system (PHABSIM II) forms a major component of the IFIM. McMahon (1993) defines PHABSIM II as a number of computer programs used to relate changes occurring to instream variables (such as depth or velocity), to changes in the availability of the physical habitat for a particular target species. According to Petts and Maddock (1994), PHABSIM II presents biological information in such a way as to make it suitable for immediate entry into the water resource planning process. This information is presented as changes that occur in the physical properties of the aquatic habitat.

King and Tharme (1993) conducted a comprehensive evaluation of the applicability of IFIM to South Africa. The main strength of the IFIM was considered to be its value as a training tool. However, despite the fact that the IFIM has been used regularly in many parts of the world, it has a number of limitations when applied under South African conditions. King and Tharme (1993) found that the IFIM appears to be "somewhat narrowminded", focusing on the management of individual species, rather than on the entire river ecosystem. PHABSIM II was found to be extremely complicated and often very poorly explained, with the result that only a specialist in hydraulics would be able to obtain hydraulic simulations. King and Tharme (1993) concluded that the large-scale use of the IFIM in South Africa would be inappropriate due to its high requirements of time, expertise, biological data and finances.

2.3.2 Range of Variability Approach

The Range of Variability Approach (RVA) was developed by Richter *et al.* (1997), and is described as a method for developing IFRs, incorporating hydrologic variability to maintain the river ecosystem integrity. It could be classified as a holistic method of IFR determination (Type

4) as its basis is the so-called "natural flow paradigm" adopting the assumption that the maintenance of the natural variability of the flow regime within certain limits will support the natural functioning of the resource. Application of the RVA is most appropriate when its main aim is the protection of the diversity of riverine biota and natural ecosystem functions (Richter *et al.*, 1997).

The methodology is described by Richter *et al.* (1997) and can be summarised as follows. Thirty two ecologically-relevant attributes of the flow regime are determined for the river under consideration. These include indicators such as the number of high pulses or flood events per year, and the mean duration in days of these events within a year. These are then translated into thirty two flow-based management targets which in turn are built into a management system containing management rules which are continually revised and updated. Determination of the thirty two ecologically-relevant flow attributes is achieved by using a method derived by Richter *et al.* (1996), named Indicators of Hydrologic Alteration (IHA). Jewitt *et al.* (1999) applied IHA in several catchments in South Africa and found it a useful tool for establishing whether impacts on the hydrological variability of the system had occurred, as well as for comparing hydrological variability before and after some form of development.

The RVA approach appears to offer a promising solution to the determination of IFRs in South Africa because the entire ecosystem is accounted for. However, Hughes (1999a) questions whether such a rigorous approach is required given the relatively low level of understanding of eco-hydrological relationships in South African rivers. Jewitt *et al.* (1999) also identify that certain parameters in the IHA method are not particularly well suited to semi-arid regions and that the development of other parameters more applicable to South African conditions is necessary.

2.3.3 Building Block Methodology

The IFR determination technique used predominantly in South Africa is the Building Block Methodology (BBM), which also employs a holistic approach to IFR determination. The methodology is so named because it identifies the most ecologically significant components (blocks) of a rivers natural flow regime, and then builds these into a representation of the natural flow regime (Hughes *et al.*, 1997). The final modified flow regime, is made up of low-flows interspersed with higher flows, with each adhering to the natural limits of magnitude, duration and timing (King and Tharme, 1993). The low-flows represent the baseflows in the flow regime. According to King and Tharme (1993), the function of low-flows is to maintain the perennial nature of the river, while also creating seasonal variations in conditions by altering their magnitudes depending on the month. The high-flows can be divided into freshes and floods. Freshes are small increases in flow and their ecosystem function is largely to stimulate spawning in certain fish species (King and Tharme, 1993). The floods are larger events than the freshes and occur less frequently. Their main function is to provide a scouring effect and maintain the basic channel shape (King and Tharme, 1993).

Hughes *et al.* (1997) describe the basic procedure of the BBM. Initially, information is collected on the hydrological and hydraulic characteristics of the river, geomorphological characteristics of the area and biological information on the aquatic and riparian fauna and flora. Once all the required information has been obtained, a workshop involving various specialists in the above fields is held to determine the water quantity and quality requirements of the river. The information from the workshop is converted into discharges using rated hydraulic transects and then tabulated into an IFR table, an example of which is illustrated by Table 1. The table specifies monthly flow requirements and is divided into maintenance and drought flows. The maintenance flows are those that occur under 'normal' everyday conditions while the drought flows are applied during dry years, when water restrictions may be necessary. Both the maintenance and drought flows are divided into low-flows and high-flows (freshes and floods). Included in the table are the magnitudes of these respective flows as well as the duration of each recommended high-flow. In order to ensure that the IFR produced by the BBM is useful for operational purposes, additional methodologies are required to transform the information in the IFR table into daily patterns of release (Hughes *et al.*, 1997). These methodologies are explained further in Section 2.6.

Table 2.1 An example of a basic IFR table (after Hughes *et al.*, 1997)

	Month											
Maintenance	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Low flows ($m^3.s^{-1}$)	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 ($m^3.s^{-1}$)	6.8	>10	7.0	6.6						5.6	6.0	6.3
High-flow period (d)	7.0	7.0	7.0	7.0						3.0	7.0	7.0
Drought periods												
Low flows ($m^3.s^{-1}$)	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 ($m^3.s^{-1}$)	10.0		10.0	1.0								
High-flow period (h)	1.0		1.0									

As with all IFR determination methods, the BBM has certain limitations. The incorporation of water quality into the methodology is not well developed and finding representative sites for the IFRs can be difficult (Tharme and King, 1998). Owing to the small time frame over which the BBM is concluded, it also often tends to rely on inadequate scientific knowledge (King and Tharme, 1993). However, Tharme and King (1998) describe the BBM as being simple in concept and easily understood by the layperson. Hughes *et al.* (1997) consider the BBM's main strength to be that it can be used when time and data are limited and conclude that the BBM fulfills the requirements of the National Water Act (1998) and consequently has been recognised by the Department of Water Affairs and Forestry (DWAF) as being capable of playing a major role in determining the ecological reserve.

2.4 Basic Principles of Operating Rules

A dam operating rule usually relies on a generalised water balance equation including the following variables:

(a) the storage in the reservoir;

(b) the inputs of water into the dam, which consist of inflow into the dam from the river, runoff, precipitation and groundwater;

(c) losses from the dam, which include all output of water from the dam such as evaporation and seepage, but exclude the controlled flow releases; and

(d) the controlled flow releases, which would be the direct abstractions out of the dam or the downstream releases made from the dam in order to satisfy water users.

Dam operating rules are usually based on a number of flow constraints with penalties being applied if the constraints are not met. These constraints and penalties provide a basis for optimising the operating policy of a dam. Optimal operation of a dam requires that the "best" releases are determined in order to satisfy the long-term purposes of the system as well as the short-term restrictions on the operations due to physical constraints (Can and Houck, 1984). According to Can and Houck (1984), most operating rule models attempt to maximise benefits and minimise penalties.

The various water users supplied by dams often have conflicting flow requirements (Johnson, 1990; Fontane *et al.*, 1997). Thus operating rules have to be adaptable to the objectives of a particular system as well as to the changing objectives of the individual users (Oliveira and Loucks, 1997). A relationship, known as an allocation function, may be derived based on the relationship between the amount of water released from a dam and the amount of water allocated to each different use, and provides a method of differentiating between the various users (Oliveira and Loucks, 1997). Mawdsley (1994) suggests that assigning priorities to different users is a further method of overcoming these conflicting objectives.

In the following sections, methods of deriving operating rules are discussed. These are separated into a section on generic dam operating rules and a section that focuses specifically on operating rules for IFRs.

2.5 Generic Dam Operating Rules

Generic dam operating rules for various water uses such as irrigation, hydropower, domestic or recreational use are often based on the fluctuating level of the dam under consideration. These rules are governed by a downstream requirement, which in turn will be a function of the number of water users reliant on the river as a water source. Releases must therefore be made from the dam in order to satisfy the needs of all the users, but it is extremely unlikely that the dam will be able to supply each user's requirement in full throughout the year. As a result, generic operating rules often employ a curtailment structure, in an attempt to use water efficiently and ensure that the dam does not run dry. A typical curtailment structure imposes constraints on the water allocation for each user, as the level of the dam fluctuates.

A simple curtailment structure provided by Langhout (2000) considers a single irrigator. The irrigator requests a specific "demand" which is then limited as the level of the dam decreases. The operating rules applied in this example are:

(a) if the current storage of the dam is between 75 and 100 % of full capacity, then the irrigator will receive 100 % of his demand (0 % curtailment) or,

(b) if the current storage of the dam is between 50 and 75 % of full capacity, the irrigator will receive 75 % of his demand (25 % curtailment) or,

(c) if the current storage of the dam is below 50 % of full capacity and above the dead storage level, the irrigator will receive 50 % of his demand (50 % curtailment),

provided sufficient water is present above "dead storage" in the dam, to supply whatever amount the algorithm specifies. Dead storage is a certain amount of water in the dam that cannot be released or abstracted due to physical constraints. For the purposes of hydrological modelling, it is often assumed to be 10 % of full capacity (Schulze, 1995).

A theoretical example of a table of curtailment values for a situation where multiple water users exist, is shown in Table 2.2. Each water user has its own requirement and the values in the columns represent the percentage of this requirement that each user is likely to receive, given the dam capacity. The dam capacity values represent the storage as a percentage of full capacity.

Table 2.2 A possible curtailment structure for multiple users relative to the dam capacity (after Langhout, 2000)

Dam capacity (%)	**100 - 80**	**80 - 70**	**70 - 60**	**60 - 40**	**40 - 10**
ESKOM	100	100	100	100	95
Industry	100	100	100	95	90
Domestic	100	100	100	100	100
Irrig. Level 1	100	100	90	80	50
Irrig. Level 2	100	90	75	75	50

The reliability of a given yield from a dam is extremely important as it provides an indication of the level of assurance associated with supplying that particular yield (McKenzie and van Rooyen, 1998). In Table 2.2, the levels of curtailment for each user provide an indication of the assurance level that each user requires. Consequently, in this example the assurance level required by ESKOM, a company responsible for electrical power supply in South Africa, is far higher than that for either irrigation level because ESKOM's "demand" is only curtailed by 5 % when the dam is relatively empty (40-10 %) as opposed to a 50 % curtailment for both irrigation levels.

In this regard, the Water Resources Yield Model (WRYM) is used extensively in South Africa to manage the country's water resources through conducting planning and operating analyses (McKenzie and van Rooyen, 1997). It is thus pertinent to review the basic principles on which this model operates. The WRYM simulates the allocation of water in multi-purpose, multiple dam systems on a monthly time-step and can model a wide range of operating policies for flood control, irrigation, hydropower and domestic use (McKenzie and van Rooyen, 1997). Links have also been made between the WRYM and the IFR model (discussed in Section 2.6) by DWAF, in order to include IFRs in dam operating policies (Hughes, 1999a). The WRYM is used to analyse systems at constant development levels i.e. the system and its associated demands remain constant throughout the simulation period (McKenzie and van Rooyen, 1998).

The WRYM represents a water resource system as a flow network which contains a set of nodes, channels and hydrological inflows (McKenzie and van Rooyen, 1997). Nodes can be either dams or junctions where one or more flows combine while channels connect nodes and can either represent a river reach, pipelines or canals (McKenzie and van Rooyen, 1997). The basic information that the network relies upon is the incremental inflow at a node, as well as that between two nodes (Langhout, 2000).

Although the WRYM cannot be called a true "optimisation model" as it has no mechanism for determining the optimal system performance for more than one period (McKenzie and van Rooyen, 1998), it does employ a form of optimisation which deserves mention. The rules in the WRYM are optimised using a penalty structure that is associated with the storage level of the dam, in a similar way to the curtailment structure discussed in the previous section. Figure 2.1 shows a schematic diagram of how a reservoir can be divided by the WRYM into different zones with each zone's associated penalty value shown in italics. The penalties are imposed on any water that is abstracted or released from the dam. The values of the penalties differ depending on the zone that the reservoir storage lies in on the day when the abstraction takes place. Penalties for allowing the dam level to exceed that of the full supply level (FSL) are high in an attempt to prevent wastage of water, while allowing the dam level to reach the dead storage level (DSL) results in extremely high penalties being imposed. Thus, the penalties attempt to restrict water use to the working storage of the dam only, where the penalties associated with abstracting water are much lower. A possible weakness with the use of this penalty structure is that the values have no real meaning and would probably be more useful if they were given for example, a monetary value.

Figure 2.1 Diagram of a reservoir as represented by the WRYM showing different zones (after McKenzie and van Rooyen, 1998)

2.6 Operating Rules to Account for Instream Flow Requirements

All IFR requirements derived using the BBM are based on the flows produced in the catchment without any anthropogenic influences. In order for operating rules to properly account for IFRs specified by the BBM, they must produce a flow regime which reflects the natural flow regime of a river. It is not sufficient to base these rules solely on the storage level of a dam as the correct volumes and timing of flows required by the IFRs, will not be achieved. The BBM methodology alone cannot function as an operating rule, because it is based on a monthly time-step, whereas an operating rule requires a daily time frame; and according to Hughes (1999a), no assurance levels are associated with an IFR.

The IFR model, developed by Hughes *et al.* (1997), attempts to overcome the problems mentioned above and develops a set of operating rules directly from an IFR table produced using the BBM, as described in Section 2.3.3 and illustrated by Table 2.1. The model converts the information in the IFR table into daily operating rules and produces a final modified flow regime that mimics the natural flow regime of the river. The final flow regime relies on a hydrological time series which can be derived either by using an observed streamflow record, or by using a daily rainfall-runoff model that has been calibrated for the IFR site (Hughes *et al.*, 1997).

A range of flows is usually specified by the BBM, and it is necessary to attach a level of exceedance (assurance level) to the flows, in order to determine the long-term average volume requirements (Hughes, 1999a). For example, in order to determine the required low-flow value for a day, a set of monthly rules for maintenance and drought requirements are established and compared to a smoothed time series of percentage points (Hughes, 1999b) using a value termed "baseflow status". If a flow lower than the drought rule is suggested by the baseflow status value, the monthly drought flow specified by the BBM is used, while if a flow between the drought and maintenance rules is proposed, linear interpolation is used to calculate the required flow between the two rules. These concepts are further explained below and for a comprehensive description on the algorithms used, the reader may refer to Hughes *et al.* (1997).

Table 2.3 shows a section of the IFR rule page in the model, which is used to edit the basic IFR data and assurance rules (Hughes and Munster, 2000). The values in the first two numerical columns are the monthly IFR low-flow values determined at an IFR workshop. The following two columns are the percentage exceedance (assurance) on which the maintenance and drought rules are based. The final column is a percentage point value that must be subtracted from the maintenance monthly rule value and is used to determine to what extent flows above the monthly maintenance flow value are required (Hughes and Munster, 2000).

Table 2.3 Examples of the rules used in the IFR model (after Hughes and Munster, 2000)

Month	Monthly flow values		Monthly rules given as assurance levels		
	Maintenance IFR ($m^3.s^{-1}$)	Drought IFR ($m^3.s^{-1}$)	Maintenance (%)	Drought (%)	Maintenance maximum (%)
January	4.4	1.33	85	95	4.0
February	6.3	1.81	85	95	4.0

The IFR model derives two sets of operating rules, one for low-flows and another for high-flows. The underlying principle of the IFR model is that a release can only be made if the particular flow would have occurred had no dam been present. To adhere to this, the model uses climatic cues to determine whether a release should be made or not. Cues for the low-flows are most often provided by a flow gauge on the river upstream from the IFR site which enables a good representation of the natural river conditions to be obtained (Hughes, 2000).

The derivation of rules for high-flows is more complicated. Initially, the high-flow rules were developed by using the reference time series to find the likelihood of a high-flow event occurring within the next 10 day period (Hughes *et al.*, 1997). However, in order for this approach to be used for operational purposes, a forecasting tool would be required to predict the likelihood of a future event (Hughes *et al.*, 1997). Recently, Hughes (2000) has developed a multi-level criterion in an attempt to make the method more useful for real-time operation. A separation of peak flows is conducted on a reference time series of naturalised flows, using a flood separation parameter. The aim of this separation of peak flows is to achieve a separation of individual flood events in the flow regime, in order to establish whether these flood events should be cued. Figure 2.2 shows a hypothetical example of a separation of peak flows and indicates the effect of changing the value of the flood separation parameter on the flows produced. The higher the value of the flood separation parameter, the less the reference time series is followed and fewer high-flow events will be cued.

In order to determine whether an individual event should act as a cue for a flood release, the rate of rise of the event is found and compared to a predetermined minimum value, which, according to Hughes (2000), is site specific and must ensure that a sufficient number of events are identified in a month. Events with a rate of rise lower than this minimum value do not act as a cue for a flood release. The event's position in the month is also taken into account; the further into the month, the more likely an event will act as a cue.

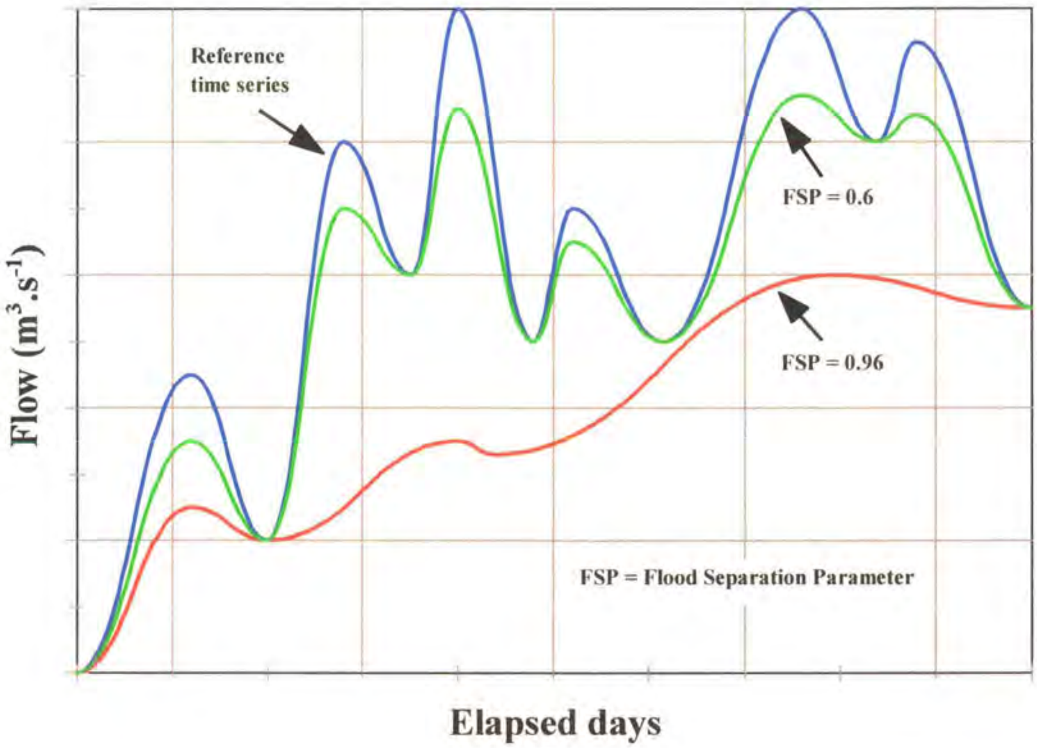

Figure 2.2 A hypothetical example of a peak separation of flows (Hughes, 2000)

One possible problem that exists with the release of high-flows is that of flood attenuation. It is necessary to estimate how much water should be released from an upstream reservoir so as to have the required discharge arriving at the IFR site (Hughes, 1999b). Hughes (2000) suggested that channel transmission losses may be of major concern in this regard, but that the issue could be resolved by using a suitable hydraulic model.

A model known as DAMIFR, has been developed by Hughes and Ziervogel (1998) from the monthly time-step reservoir water balance model of Hughes (1992), to account for environmental releases from dams. DAMIFR is used in conjunction with the IFR model and combines IFR releases with releases for other water users. The timing and volume of IFR releases required is input to DAMIFR from the output file generated by the IFR model (Hughes and Ziervogel, 1998). DAMIFR uses cumulative demand deficit rules for abstractions made by all water users and these rules impact on the IFR releases (Hughes, 2000). For example, if the cumulative demand deficit increases, IFR releases are reduced. However, since no differentiation is made between abstractors, DAMIFR is too simplistic to allow for its direct application to the operating rule determination process (Hughes, 2000).

2.7 Methods of Optimising Dam Operating Rules

Numerous optimisation techniques exist for dam operating rules with the choice of which particular method to use depending on the characteristics of the reservoir system, data availability and the objectives associated with the system (Yeh, 1985). In the following sections, selected optimisation techniques are reviewed.

2.7.1 Dynamic programming

Dynamic programming (DP) is an optimisation technique that has been used a great deal in reservoir operation and is especially appropriate for solving operating rule problems where multiple uses are involved (Karamouz and Vasiliadis, 1992). Numerous variations of DP exist with deterministic dynamic programming (DDP) and stochastic dynamic programming (SDP) being two of the main types. DDP relies on a sequence of historical streamflows while SDP is based on a statistical representation of the streamflow process (Karamouz and Houck, 1987).

DP techniques consist of an objective function and a number of constraints describing either the physical or economic limitations of a system (Karamouz and Vasiliadis, 1992). All techniques optimise a system over a number of stages (usually periods of time) and for each stage, variables are used to describe the system's state, which often varies from stage to stage (Manson, 1998). The aim of DP is to maximise (or minimise) the total return over all the stages of the problem at hand (Manson, 1998). The objective function specifies the required target releases and storage levels with a high level of probability and it is then up to the user to determine whether the objectives of the individual uses are met within acceptable levels of reliability (Alaouze, 1989).

According to Yeh (1985), a major advantage of DP is that it can decompose complex problems with many variables into a series of subproblems which can then be solved recursively. Loucks *et al.* (1989) defines recursion as "the successive solution of a series of equations, each one dependent on a knowledge of the values derived from the previous equations". Forward recursion can be used when a deterministic problem has to be solved more than once with varying planning horizons, whereas backward recursion is necessary for any SDP (Yeh, 1985). Yeh (1985) also noted that the two techniques can be used in combination for problems involving time.

An important requirement of DP is the specification of variables for the objective function and constraints. For reservoir operation problems, storage is generally regarded as the state variable and release as the decision variable (Yeh, 1985). It is paramount that the chosen variables be as representative of the problem as possible. Consequently, the better the hydrological state variables employed, the more effective the DP model (Stedinger *et al.*, 1984). A limitation of DP in this regard, is that only a limited number of variables can be used. The reason for this is that as the number of variables increases the computation time increases drastically (Tejada-Guibert *et al.*, 1993). This increased computation time is as a result of the exponential increase in the number of states that occur as the number of variables increases and is referred to as the "curse of dimensionality" (Loucks *et al.*, 1989). Liang *et al.* (1996) eliminate this problem in a multiple reservoir system, by aggregating all the reservoirs into one.

DP models have proven very useful in determining optimal operating rules for many situations with differing primary objectives. The technique is popular because of its ability to break down complex problems into smaller parts as well as being able to include both the non-linear and stochastic properties of problems (Manson, 1998). However, Manson (1998) states that DP cannot calculate a policy for the day-to-day operation of a reservoir.

2.7.2 Simulation models

Most reservoir operation studies are based on simulation modelling of the inputs, outputs and storage of the reservoir (Lund and Guzman, 1999). Simulation models have been used to develop operating policies by trial and error (Manson, 1998). A policy is proposed, the model is run and results are obtained. The results are analysed and the policy can then be revised and improved. The whole process is repeated until a policy that is satisfactory to the user is obtained. It is noted by Yeh (1985) that an advantage simulation has over mathematical procedures such as DP is that it can model the existing system exactly, although Manson (1998) states that simulation cannot represent the real system with 100% accuracy owing to the necessity of making assumptions about the system's response. A further disadvantage given by Manson (1998) is that simulation models require historical flow data as an input.

Simulation has also been used successfully by Nalbantis and Koutsoyiannis (1997) to aid in evaluating the objective function when parametric rules were used to determine a flow release policy. However, simulation is not a true optimisation technique and can only be used to evaluate the performance of a system (Loucks *et al.*, 1989). Nevertheless, simulation models can provide useful information on how well a system is performing.

2.7.3 Neural networks

A neural network is a mathematical model built on how the human brain operates with the typical network consisting of interconnecting "neurons", each containing an input layer, a hidden layer and usually a single output layer (Danh *et al.*, 1999). The input layer is made up of numerous inputs, each with its own weighting factor (Manson, 1998). According to Danh *et al.* (1999), the hidden layer is a function representing the non-linearity of the system. The output is found by applying the function in the hidden layer to the weighted sum of the inputs (Manson, 1998).

Back-propagation is a method of calibration (learning) that is used for multilayer neural networks, and uses a known set of pairs of input and output values (Danh *et al.*, 1999). The weighting factors in each neuron are adjusted until the output for a given input set matches the known output (Manson, 1998). Once the network has "learnt" sufficiently, it can produce the correct output by classifying input sets that are not included in the training set.

Neural networks have not been used extensively for water resource problems. However, some useful applications have been performed by Danh *et al.* (1999) and by Shaw (1993, cited by Manson, (1998)). Danh *et al.* (1999) showed the capability of a neural network in forecasting river flows. Shaw (1993), cited by Manson (1998), compared a back-propagation network, a mathematical model and an experienced human operator in the control of a balancing dam. The neural network was found to produce the most constant outputs with no water shortages or overflow of the dam occurring. The major problem noted by Danh *et al.* (1999) with neural networks is that no specific method exists on how to arrive at the best structure of the network.

2.7.4 Combinations of optimisation techniques

Combinations of different optimisation techniques, for determining optimal dam operating policies, have been reported frequently in the literature and with reasonable degrees of success. For example, Karamouz and Houck (1982) derived an algorithm that uses a combination of a DDP, a regression analysis and a simulation model. According to Karamouz and Houck (1982), the DDP converged in a finite number of steps defined by the user while, for each iteration, the algorithm became more constrained and the general operating rules produced were more refined. Karamouz and Houck (1982) noted two main advantages from using this particular combination of optimisation techniques. It was found to be easy to use, owing to all three components of the algorithm being relatively simple, and although the algorithm was tested only for single reservoir systems, it could easily be extended to incorporate more complex systems.

Fuzzy sets are defined by Fontane *et al.* (1997) as a mathematical construct that can be used to address imprecise concepts by allowing a gradual transition from a situation that completely fulfills a concept, to a situation that does not. Fontane *et al.* (1997) employed an adaptation of the DP technique in conjunction with fuzzy sets to help address the problem of noncommensurable objectives. Although the results obtained were inconclusive, it is believed that this was mainly due to inaccurate surveys by the water users and managers in order to develop functions associated with the operational objectives.

2.8 The Need for the Inclusion of Forecasting in Dam Operations

Barta and Rowse (1998) state that the main problem affecting the development of water supply systems is that of forecasting demands of the users ahead of time. Hourly, daily, weekly or monthly forecasts are necessary for this purpose. These short-term forecasts rely on historical demand data and need to be able to account for a deterministic and a stochastic demand component (Barta and Rowse, 1998). The deterministic demand component represents regular repetitive trends while the stochastic demand components are random events and are very difficult to predict. These short-term forecasts can play a major role in helping to minimise the costs of pumping operations for water supply from dams (Barta and Rowse, 1998).

Climatic forecasting is also of importance in a country such as South Africa, where rainfall is highly variable (Klopper, 1999). The application of rainfall forecasts to operational decisions involving water resource management could result in considerable annual financial savings for affected industries, as well as help in preventing hardship and loss of life (Hallowes *et al.*, 1999). The variability of rainfall will also greatly affect the efficiency of IFR operating rules. An IFR table produced by the BBM, usually requires that a certain number of freshes and floods be released in a particular month. In order to adhere to the natural flow regime, a flood can only be released when it has been cued, as described in Section 2.6. Assuming that one major flood was required in a month, if a heavy rainfall event occurred and the flood was cued, a release of this major flood would result. However, if an even greater rainfall event were to occur a few days later, this would have been a more appropriate event to use as a cue for the major flood. In order to properly mimic the natural flow regime, another large flood should then be released. This would then conflict with the IFRs specified by the BBM and highlights a weakness with this particular methodology. The use of climatic forecasting could help to eliminate this problem by providing a better estimate of whether an event should act as a cue or not (Hughes, 2000).

Climatic forecasting has already been incorporated into a number of reservoir operating rules with varying degrees of success. Karamouz and Vasiliadis (1992) used forecasting to predict inflows and inserted these into a Bayesian DP. An option of forecast uncertainty was included by Karamouz and Vasiliadis (1992) and by combining the forecast for the next period with its uncertainty, more realistic results were produced. Hsu *et al.* (1995) also describe a technique for forecasting streamflow and the results obtained were acceptable.

2.9 Applicability of the Available Techniques to South African Conditions

Dams are necessary in order to satisfy the water requirements of a rapidly increasing world population. This is particularly evident in arid countries with high population growth rates, such as South Africa. It is also clear that dams have negative impacts on downstream water resources and their associated ecosystems, and that in order for the provision of sufficient high quality water to continue well into the future, the protection of these resources is paramount. Although the need for dams is evident, a major challenge presented by the implementation of the National Water Act (1998) is to ensure that operating policies are efficient, especially from the point of view of the environment. The only way to achieve more efficient operation of dams with less impact on the ecosystems downstream is to employ operating policies that account not only for downstream users, but for the environment as well.

This need for the implementation of "environmentally-friendly" dam operating rules has been recognised by the National Water Act (1998). The Act requires the determination of a Reserve, for basic human needs and for environmental requirements. In order to establish an ecological reserve, as laid out in the Act, IFR determination techniques will need to be applied to all "significant" impounded rivers in the country. Although not without its limitations, the BBM seems to be the technique most likely to prove effective for this purpose. The method holds numerous advantages over other methods used internationally, in that it has been specifically developed for South African conditions, while also requiring less biological data, resulting in reduced time and expense.

However, defining the ecological reserve by determining the environmental requirements is only part of the problem. The flows for the Reserve need to be included in the operational procedures of the dam and this can only be achieved by including the IFRs into a dam operating rule framework. It is envisaged that the IFR model (Hughes *et al.*, 1997), or a system similar to it, will be used in order to determine the operating rules for dams in order to meet the requirements of the National Water Act (1998), and that it will rely mainly on the information generated by the BBM in the form of an IFR table. IFRs are determined specifically for the river reach in which they are to be applied, with the result that the IFR model holds a large advantage in that it has been developed for South African conditions. The model has also been improved through the introduction of the multi-criterion method of determining the cues for high-flow events. With this new adaptation the operational capabilities of the model with respect to dams has increased. One area of concern, albeit minor, is that of the transfer of high-flow events from one month to the next if they are not cued. Problems could arise when an event is not cued in a particular wet season and is then transferred forward until the following wet season. When this release is cued, it may not coincide with the current climatic conditions, resulting in a very much higher or lower release being made than is actually required. To eliminate this problem, a limit on the number of months that an event can be transferred forward should be set and if it is not cued in that time, then the event should be discarded.

In order to satisfy all water users, the generic operating rules required by the National Water Act (1998) are likely to be in the form of curtailment structures linked mainly to the storage level of the dam. The curtailment structures will also need to be configured so as to account for the prioritisation of the various users. Generally, the basic human needs reserve should have first priority, followed by the ecological reserve, industry and irrigation. Although the Act recognises the Reserve as being of the highest priority, in real-life situations this may not always occur and lower priority users may be ranked above the Reserve. A possible example would be ESKOM, who would require certain peak flows to satisfy the supply of electricity during peak demand hours. It is believed that this technique of basing the rules on the storage level of the dam is flexible enough to account for these possible changes in priority.

It is inevitable that a generic dam operating rule framework will not be able to satisfy all users reliant on a dam, all of the time. Thus, it is necessary to find a set of trade-offs for the respective users that results in the most benefit to all concerned. Optimisation techniques can be employed, in addition to a curtailment structure, to ensure that this is the case. Numerous dam operating rule optimisation techniques have been investigated, some of which have been presented in this dissertation. DP appears to offer a promising solution to most water resource problems, predominantly because it has had such widespread use in dam operation throughout the world. A disadvantage of DP commonly mentioned in the literature is that of excessive computing time, although with the rapid expansion in the capabilities and speed of computers, this problem is likely to become far less evident in the future. Due to the varied DP techniques available it could definitely play a major role in aiding optimisation in any project employing generic dam operating rules. It must be noted that, although it is thought that DP could hold possibilities for aiding in optimisation of a rule framework including IFRs, no literature could be found on any application where DP had been used for such a purpose. Thus, it is also possible that DP alone would not be able to meet all the requirements of the National Water Act (1998), and the combination of two or more optimisation techniques would be necessary.

The use of neural networks offers an interesting alternative to optimising operating rules. Neural networks are a fairly new concept in the context of water resource allocations, with the result that they have not been well researched with regard to this particular problem. They are very adept at recognising patterns and, as suggested in Section 2.7.3, could probably cope very well with optimising operating rules for general dam operation, where releases are often quite cyclical. It is postulated though that when the operation of the dam is based largely on climatic conditions, as in the case of IFR operating rules, the network may well experience problems when an uncharacteristic flow event takes place. It is unlikely that the network will be able to correctly classify this event, unless an event of similar timing and magnitude had been included in the training set. For this reason, it is believed that neural networks may not be able to fulfill the optimisation requirements of an operating rule framework needed to aid in the implementation of the National Water Act (1998).

The use of simulation holds numerous possibilities in the context of implementing operating rules in order to satisfy the National Water Act (1998). Hydrological models operating on a daily time-step, such as the *ACRU* model (Schulze, 1995), could be used to set up the water balance required by the generic operating rule framework, as well as to generate streamflow records if accurate observed records do not exist.

The major objective when determining a set of operating rules including IFRs is that of adhering to the natural flow regime. The use of a hydrological time series in conjunction with the IFR model seems to be the best current available methodology. The use of accurate short-term forecasts would be invaluable, and although not totally reliable, may well aid in eliminating wasteful releases. The ability to forecast the requirements of downstream users would also be useful. The inclusion of climatic forecasts into any operating rule framework to be used to satisfy the National Water Act (1998) would be extremely helpful. Nevertheless, no forecasting approach is likely to be foolproof (Hughes, 2001) and thus climatic forecasting should be used with caution.

3. THE *ACRU* AGROHYDROLOGICAL MODELLING SYSTEM

Schulze (1995) states that the need for streamflow estimates by engineers involved in the design of water supply systems resulted in the development of hydrological simulation models that could generate streamflow synthetically. Hydrological modelling has since advanced well beyond this original function. In the following section the *ACRU* agrohydrological modelling system, a well used South African simulation model, is discussed.

3.1 Description of the *ACRU* Model

ACRU is an agrohydrological modelling system which, according to Schulze (1995), integrates scientific hydrology, applied engineering and water resources-related hydrology with agrohydrology. *ACRU* is an acronym for the Agricultural Catchments Research Unit, previously part of the Department of Agricultural Engineering at the University of Natal and was developed using the FORTRAN 77 programming language. A comprehensive description of the model is provided by Schulze (1995) and by Smithers and Schulze (1995), and a brief summary from these two references highlights the more important aspects of the model.

ACRU is conceptually and physically based. The model is conceptual in that processes in the system are idealised and is physically based because it attempts to represent physical processes explicitly. The model operates at a daily time-step, largely because the driving input is rainfall, which is most often available as daily data. More cyclic or less sensitive variables can be input on a monthly basis and are then transformed internally into daily values by Fourier Analysis. Certain variables input on a daily basis (e.g. daily rainfall) may be transformed into sub-daily values if required. The model also employs multiple-layer soil water budgeting. The water budget employed is highly sensitive to climate, as well as to land cover and land use changes and their resulting effect on the soil water and runoff regimes.

Although the model has functioned effectively over the years and has been expanded greatly, it does suffer from certain limitations related to its structure. As a result, it was decided to upgrade the model to the new *ACRU*2000 version, details of which are introduced in the next section.

3.2 The *ACRU*2000 Model

The recent upgrading of the *ACRU* model to the *ACRU*2000 version involved a complete alteration of the programming techniques used. According to Clark *et al.* (2001), the two main reasons for restructuring the model were to make it more extensible and to better represent the individual spatial elements of the model and the order of processing, to aid in the modelling of water flow. The *ACRU*2000 model has been coded using an object-oriented programming approach and implemented in the Java programming language. It is not within the scope of this dissertation to discuss the methodology followed during the upgrade. However, a brief outline of object-oriented programming as well as the basic structure of *ACRU*2000 is required in order to fully explain the methodology followed during this project as detailed in Chapter 4. In the following section, object-oriented programming principles and the Unified Modelling Language (UML) are briefly described.

3.2.1 Object-oriented programming and the Unified Modelling Language

Recent programming paradigms have been developed to deal with the problem that software systems are delivered late, over budget and below the user's requirements (Hunt, 1998). A number of these paradigms exist and each embodies a particular philosophy, the most recently developed being object-oriented programming. The basic principle of object orientation is that the system being represented is based on a set of interacting objects organised into classes. Clark *et al.* (2001) describe objects as having two basic characteristics, these being attributes and behaviour. Attributes describe the object's physical characteristics while behaviour describes how the object interacts with other objects (Booch, 1991; Clark *et al.*, 2001). Classes are groups of objects all having similar attributes and behaviour (Clark *et al.*, 2001). Objects and classes are linked through three main relationships i.e. inheritance or "type of" relationships, aggregation or "part of" relationships and association or "basic interaction" relationships.

The UML is a standard method used to specify, visualise and document the artifacts of an object-oriented system under development (Object Management Group, 2001) and was used extensively in developing the *ACRU*2000 model. UML distinguishes between classes by representing them as rectangular boxes containing the class name, and also illustrates the three main relationships existing between the classes. Figure 3.1 shows an example of a UML class diagram depicting these relationships between classes and their associated notation.

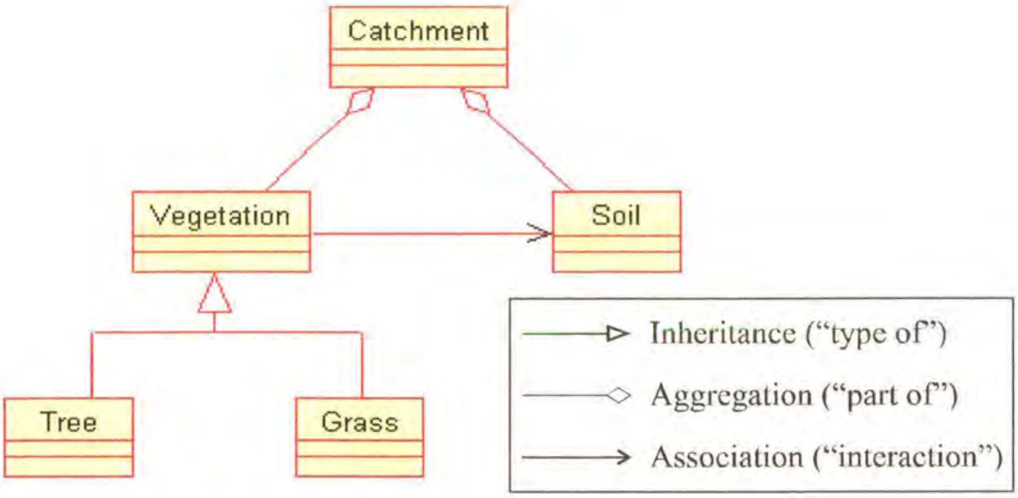

Figure 3.1 Example of a class diagram showing the three main relationships using UML notation

In Figure 3.1, Catchment is the primary class. Vegetation and Soil both form "parts of" the Catchment class and are linked to it by aggregation. Vegetation interacts with Soil because the Soil class will play a role in what type of Vegetation is most likely to grow in an area. Since Vegetation is neither "part of" nor a "type of" Soil, it is linked to Soil by association. Tree and Grass are both types of Vegetation and are related to the Vegetation class by inheritance.

3.2.2 Description of the basic structure of *ACRU*2000

*ACRU*2000 consists of seven different groups of classes as shown in Table 3.1. Four of the groups of classes employed by *ACRU*2000 (i.e. Model, Control, Exception and Interface) operate largely out of sight to the programmer and developers (Campbell *et al.*, 2001). The Model classes create the starting point for all the other classes used in the simulation while the main function of the Control classes is to govern the input and output of data (Clark *et al.*, 2001). The Exception classes handle errors occurring during a simulation while the Interface interfaces can be described most simply as a means of grouping classes of similar behaviour (Clark *et al.*, 2001).

Table 3.1 The seven object classes employed in *ACRU*2000

Class name	Examples of classes in *ACRU*2000
Model	*MAcru2000Standard*
Control	*AAcru2000StandardProcesses*
Interface	*IWaterFlow*
Exception	*EFileNotFoundException*
Components	*CLandSegment, CVegetation, CIFRSite*
Processes	*PSurfaceFlow, PGenericOperatingRule*
Data	*DPrecipitation, DDroughtFloodDuration*

Components, Data and Processes are the three most important classes for the purposes of this dissertation. The convention of using a letter before the class name that indicates the class type has been adopted for all the types of classes to aid in their identification. Thus all Components class names start with C, all Data class names start with D and all Processes class names with P. A further convention adopted for the purposes of this dissertation is that all names of classes found in *ACRU*2000 are written in italics as in Table 3.1. Components classes represent the physical components of the hydrological system (Clark *et al.*, 2001). Each Components class may have various Data classes associated with it that store attributes of the Components class using data types such as strings, boolean values, integers, double values or arrays of the types mentioned. The Processes classes represent the various hydrological processes employed within the model. A Processes class acts on one or more Components classes and specifies the required Data classes associated with each Components class. Examples of each of these three types of classes are shown in Figure 3.2.

Figure 3.2 is a schematic diagram containing a few examples of classes utilised by the model. The upper portion shows an example catchment where it can be seen that the catchment is divided up into a number of land segments or *CLandSegment* classes, as well as the flow configuration of the catchment. The detailed portion is an example of a single *CLandSegment* class. In Figure 3.2, the *CLandSegment* class contains a number of Components classes that are all related to it by aggregation i.e. *CVegetation*, *CClimate* and *CReach*. These Components classes in turn contain Data classes that describe them. For example, *DPrecipitation* stores the amount of rain that falls on *CLandSegment* over the period of one day, while *DReachFlow* stores the amount of flow that flows out of the *CReach* class for the day. From a UML perspective, Data classes can often be considered as attributes of the Components class and in this case will be linked to it by an Aggregation or "part of" relationship. Certain Data classes are not attributes of a Components class, and are merely used by the particular Components class. These Data classes would then be related to the Components class by Association. The Processes classes *PSurfaceFlow*, *PSubsurfaceFlow* and *PGroundWaterFlow* describe the flow of water along the ground surface, through and along the various soil layers and in and from the groundwater zone respectively. The relationship between Processes and Components classes commonly used in UML is that of Association where the Processes class makes use of the Components class.

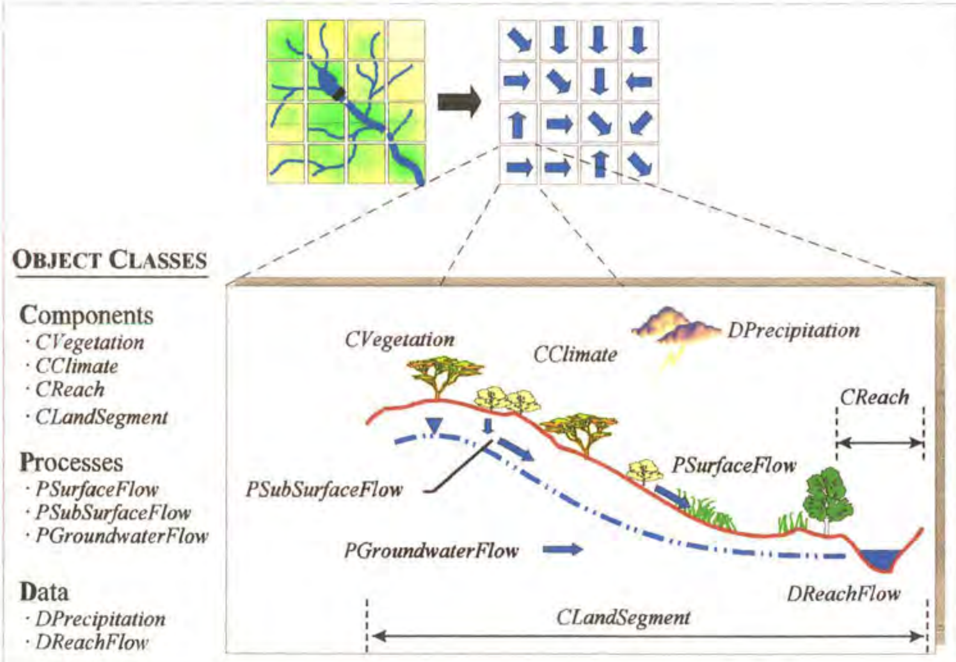

Figure 3.2 Examples of object classes in *ACRU*2000 (after Clark *et al.*, 2001)

The operating rule framework described in Chapter 4 was incorporated into the *ACRU*2000 model. Table A1 in Appendix A provides a brief description of certain classes already existing in the model that are utilised by the operating rule framework.

4. DEVELOPMENT OF THE OPERATING RULE FRAMEWORK

The primary objective of the operating rule framework is to supply water in as equitable and sustainable a manner as possible, to any water users relying upon a water resource. Four major components are required in order to achieve this: the water user, the water request, the operating rule and the water transfer. The four components are linked as illustrated in Figure 4.1 and a brief outline of each is given below.

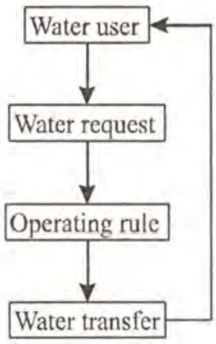

Figure 4.1 Flow diagram of the operating rule framework components

Four types of water users are considered by the operating rule framework:

(a) Domestic user - the domestic user represents the basic human needs reserve as specified by the National Water Act (1998) and is represented in *ACRU*2000 by the Components class *CSettlement*.

(b) Environment - the environment represents the ecological reserve as specified by the National Water Act (1998) and is represented in *ACRU*2000 by the Components class *CIFRSite*.

(c) Industrial user - the industrial user represents any industry that requires water in order to operate. The Components class *CIndustry* represents this user in *ACRU*2000.

(d) Irrigator - the irrigator represents any water user who requires water for agricultural production and is represented in *ACRU*2000 by the Components class *CIrrigatedArea*.

Any of the four types of water user may make a water request for a quantity of water from the relevant water source (either a dam or a river). Detailed descriptions of how water requests function and the procedures followed for determining the quantity requested by each water user are provided in Sections 4.2 to 4.6.

Two types of operating rules are employed by the operating rule framework in an attempt to ensure an equitable supply of water to the various water users. The type of rule used depends on the water source. The generic dam operating rule is responsible for supplying water from a dam while the channel operating rule supplies water from a river. The two rules are described in detail in Sections 4.7 and 4.8 respectively.

Finally, the quantity determined by the operating rule to be supplied to the water user is then transferred to the user either via direct abstraction or by making a downstream release if a dam is the water source. The water transfer thus provides the final link between the operating rule/ water source and the water user. Having provided a brief outline of the operating rule framework, the following section deals more specifically with how the framework accounts for the ownership of water.

4.1 Water Ownership in the Operating Rule Framework

Although the National Water Act (1998) no longer recognises "ownership of" and "rights to" water, except in the case of the Reserve, the concept of water ownership has been included in the operating rule framework in order to aid the long-term allocation of water to the various water users. The framework identifies two types of water present in a water source i.e. unallocated and allocated water. Unallocated water has no owner and is available for use by any user abstracting from the relevant water source. Allocated water has been assigned an owner and may only be abstracted by the particular water user that owns this volume of allocated water. The current operating rule framework requires that floods released to satisfy the IFR are allocated for that purpose. For the purposes of this dissertation, no other water users employed in any simulation were reliant on abstracting allocated water from the dam. Consequently, through the remainder of this document, if water is requested from allocated storage, it is assumed to be solely for the purposes of satisfying the environmental flood requirements. An approach where each user has its own allocation and can then request water from this allocation as desired could be adopted in the future. This would enable water users to bank water in times when they do not require their full allocation. The remaining allocated volume of water would then be used by the owner at any time in the future, such as during a drought, provided that sufficient storage was available in the dam. This concept of water ownership is important for the purposes of making a water request correctly. In the following section, a general description of a water request is provided.

4.2 General Description of a Water Request

As mentioned previously, any water user may generate a water request. Although the methods for determining the quantity requested differ for each user, the water requests themselves all have a common structure. Therefore, it is pertinent to first consider the basic structure of a water request and the information that it holds.

Each water request contains seven attributes. These are:

(a) the current owner of the water; which only exists if a request is being made from allocated storage and provides a means of differentiating between requests made from unallocated and allocated storage. In the case of allocated requests, it will be the water user making the request for the high-flow component of the ecological reserve i.e. *CIFRSite*,

(b) the new water owner; which corresponds to the water user being supplied and hence could be any of the Components classes *CSettlement*, *CIFRSite*, *CIndustry* or *CIrrigatedArea*,

(c) the water source; which is an instance of the Components class *CReach* and identifies the dam or river from which the water user is requesting the water,

(d) the water destination; which is any of the Component classes mentioned under (b) and is the user that is making the water request,

(e) the priority associated with the water user making the request; these priorities were introduced to aid in allocating water equitably and are discussed in more detail in Section 4.7.1,

(f) the quantity requested; which is the volume requested by the water user for the day, and

(g) the water supply path; which is a list of the Components classes involved in moving the water from the water source to the water destination. The former and latter will be the first and last entries in the list with those in between either being *CReach* classes along which the water flows or *CWaterTransfer* classes responsible for moving the water out of the relevant river or dam.

All the above information is held together in the Data class *DWaterRequest* which plays a vital role in ensuring the supply of water to any water user. Having given a generalised description of *DWaterRequest*, the following sections focus more specifically on each water user and detail the objects required to generate water requests and the methods used for determining the request quantities. The commercial visual modelling tool Rational Rose (Rational Software Corporation, 1998) was used to illustrate the various classes required in order to generate the requests for each user, as well as the relationships existing between these classes.

4.3 Generation of Requests for the Basic Human Needs Reserve

In order to consider the requirements of the National Water Act (1998), it was necessary to include the basic human needs reserve as a separate user of water with highest priority. It is assumed that water requested by any domestic user in the model consists only of this component of the Reserve and does not consider additional human demands or other water users supplying a human population, such as bulk or strategic users.

The component *CSettlement* is used to represent the basic human needs request user in *ACRU*2000. Figure 4.2 shows the relationships between *CSettlement* and its associated Processes and Data classes with definitions of all these classes given in Appendix B (Table B1). For more detail on the basic relationships existing between the *ACRU*2000 classes, refer to Sections 3.2.1 and 3.2.2.

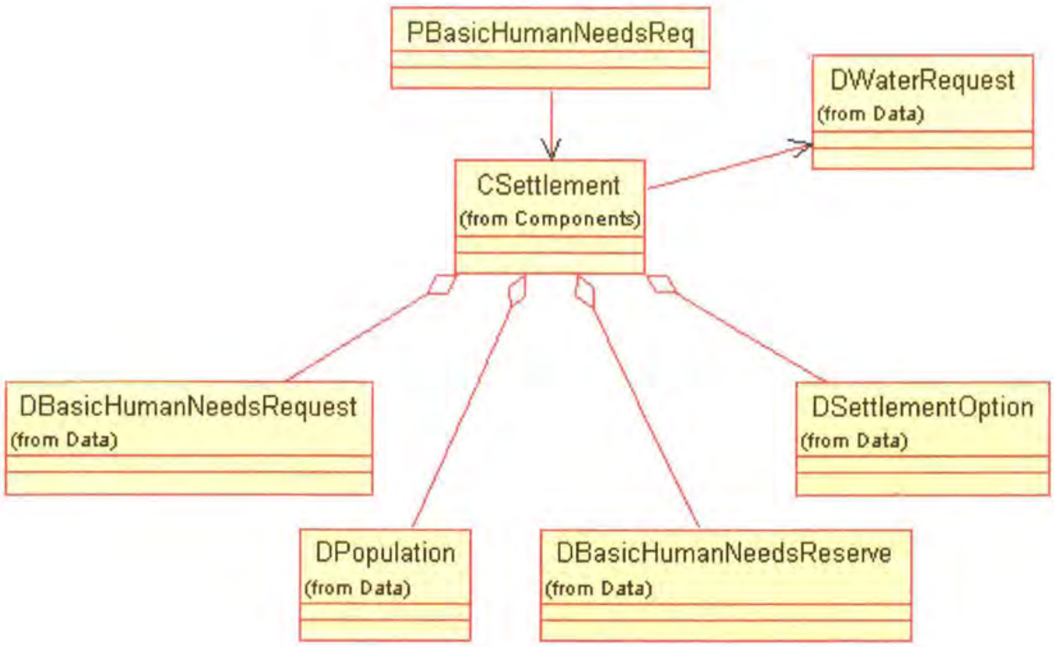

Figure 4.2 Class diagram of the *CSettlement* component and associated classes

The *PBasicHumanNeedsReq* process is responsible for calculating the actual value of the basic human needs reserve request quantity and generating the water request for the domestic user. The flow diagram in Figure 4.3 provides a summary of this procedure while the full definitions of all the variables used are included in Appendix B (Table B1).

The process provides two options for determining the request quantity, depending on the value that the variable *SettlementOption* is given (either 1 or 2). If *SettlementOption* equals 0, no settlement exists and thus no basic human needs reserve request will be generated. If *SettlementOption* has been set by the model user to 1, the request quantity (*DomesticReq* measured in m^3) is calculated using Equation 4.1.

$$DomesticReq = \frac{(DailyReq * PopulationSize)}{1000} \tag{4.1}$$

If *SettlementOption* has been set to 2, a value for the domestic user's request (*DomesticReq*) is input by the model user. The value for *DomesticReq* is then held by the

DBasicHumanNeedsRequest class and is read from the input data file. Once the value for *DomesticReq* has been obtained, the water request is sent to the relevant operating rule.

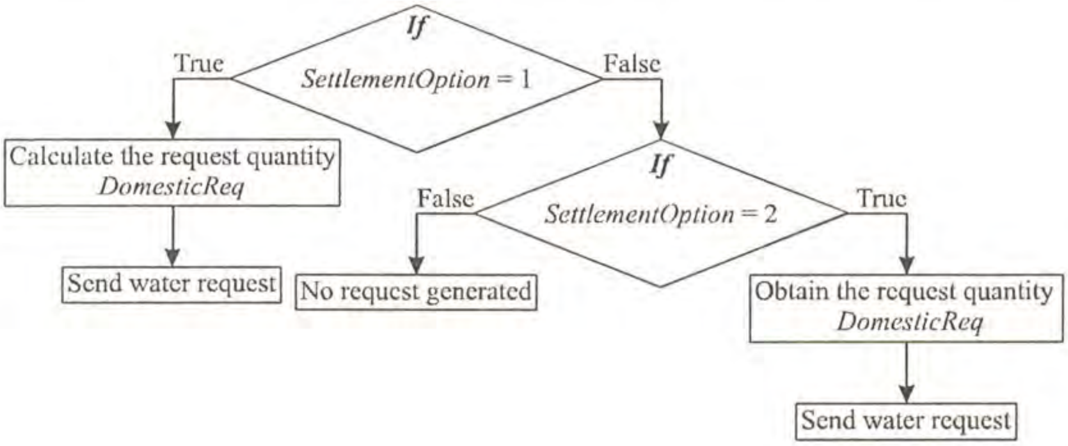

Figure 4.3 Flow diagram of the basic human needs reserve request (*PBasicHumanNeedsReq*)

4.4 Generation of Requests for the Ecological Reserve

The National Water Act (1998) is the main driving force requiring the operation of dams to satisfy downstream environmental flow needs. The recognition of the environment as a user of water has emphasised the need for effective IFR determination techniques that are compatible with an operating rule framework for dams and rivers. In *ACRU*2000, the environmental releases from the dams will replace the releases previously referred to as "normal flow". According to Schulze (1995), there is no actual definition for normal flow, but it has commonly been described as a constant amount of streamflow that would have been exceeded on 70% of occasions in the month of typically lowest flows. Flow variability is essential for the sustainable functioning of the water resource and its associated ecosystems. It is therefore necessary to provide an artificial flow regime downstream of the dam and the environmental request in *ACRU*2000 attempts to provide this. As a consequence of the complexity involved with developing such an environmental request, two methods (a simple and a more complex approach) have been developed. The simple environmental request method was implemented initially to assess how the ecological reserve functioned in conjunction with the other water user's requests before focusing on providing a comprehensive artificial flow regime that mimicked the natural flow regime above the dam. These two methods are discussed in detail in Sections 4.4.1 and 4.4.2.

4.4.1 Development of the simple environmental water request

The simple environmental water request attempts to simplify what is an extremely complicated process by basing all water requests on information from an IFR table (explained in Section 2.3.3) which is a product of the application of the BBM at an IFR workshop. In keeping with the format of the IFR table, the request is split into low-flow and high-flow requests accounting for both drought and maintenance conditions.

Although the simple environmental request involved making numerous simplifying assumptions, numerous classes were added to the model. The component *CIFRSite* represents the ecological reserve as a water user. *CIFRSite* represents a cross-section through a river where an IFR has been determined and is treated as a very short river reach (see description of *CReach* in Table A1 of Appendix A). Figures 4.4 and 4.5 show the basic relationships between *CIFRSite* and its associated Processes and Data classes for the generation of the low-flow and high-flow requests respectively. For further detail on the class definitions, refer to Appendix B (Table B2).

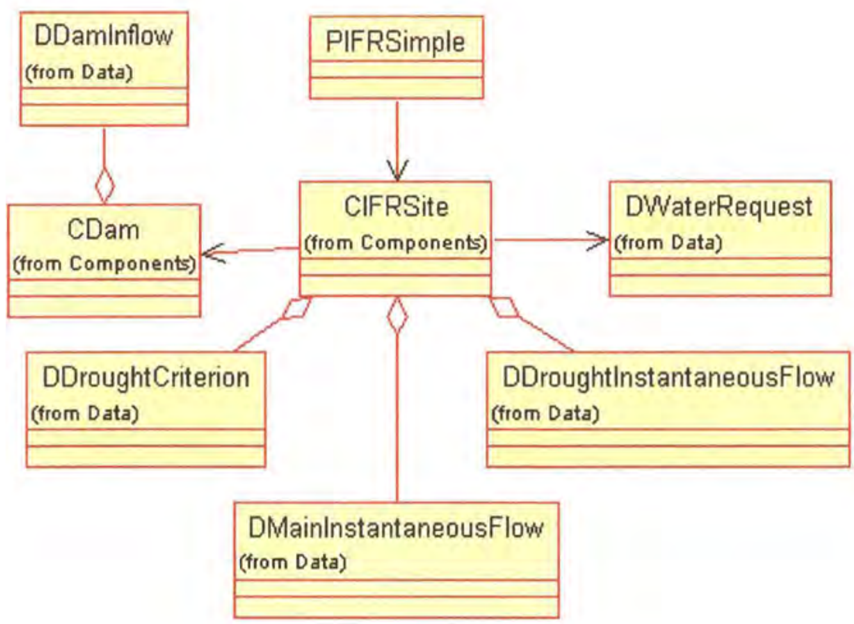

Figure 4.4 Class diagram of the *CIFRSite* component and associated classes for the simple low-flow request method

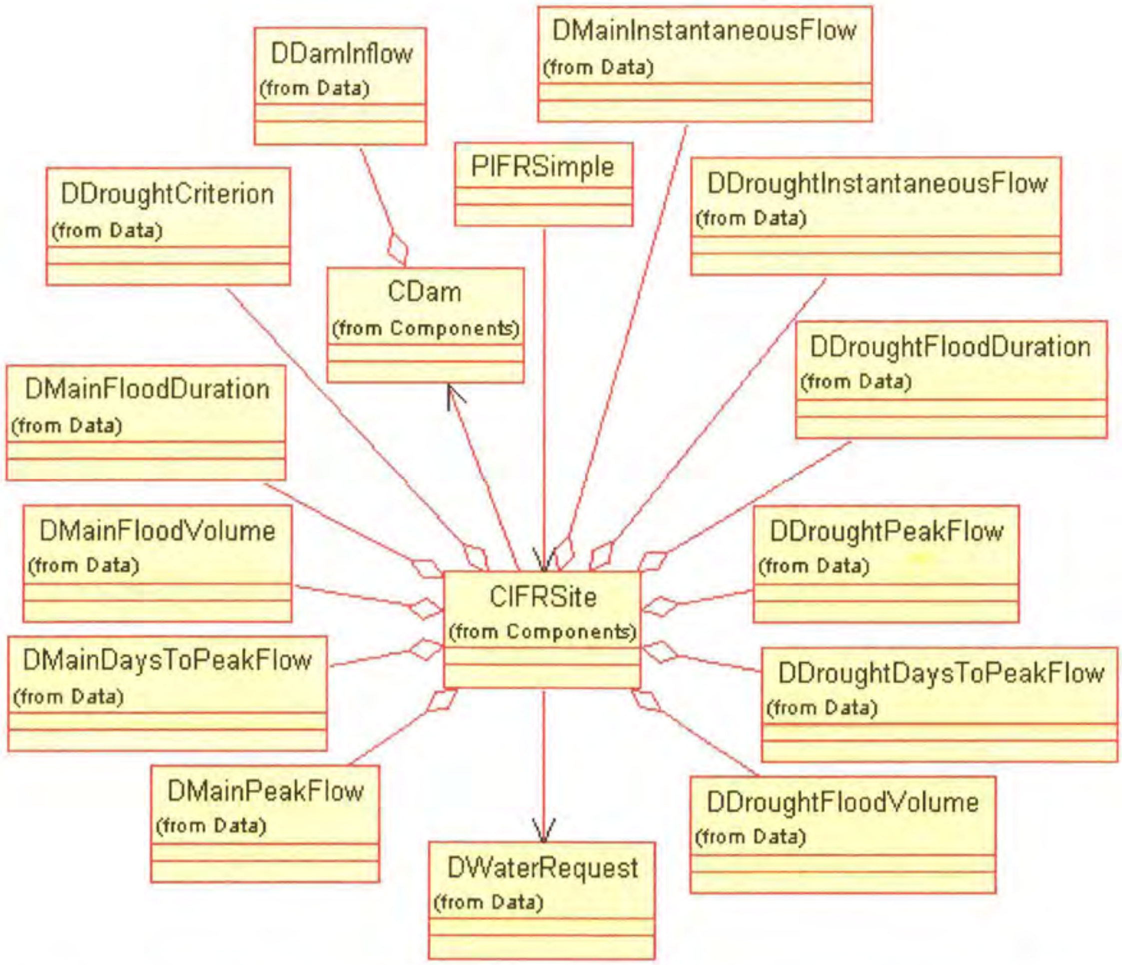

Figure 4.5 Class diagram of the *CIFRSite* component and associated classes for the simple high-flow request method

4.4.1.1 Determination of the low-flow request quantity using the *PIFRSimple* process

The simple environmental request for low-flows has few data requirements and operates according to the monthly flows specified by the IFR table. The request occurs daily and is controlled by the *PIFRSimple* process. A flow diagram of the low-flow request part of the process is given in Figure 4.6 and Table B2 in Appendix B holds definitions of all the variables used.

The process begins by determining whether to release the drought or maintenance low-flow for the day. This is achieved using three variables : *CurrentDayInflow*, *MainInstantaneousFlow* and *DroughtCriterion*. The variable *CurrentDayInflow* is calculated by summing all the volumes flowing into the dam from upstream reaches for the day and then converting this value to an average flow rate ($m^3.s^{-1}$). Thus *CurrentDayInflow* is the average flow entering the dam for the day. It should be noted that the use of *CurrentDayInflow* as a climatic trigger for the releases is probably not very suitable as these flows could be highly modified from those of the naturalised flows on which the BBM flows are based. The *MainInstantaneousFlow* is the maintenance low-flow value specified in the IFR table for the relevant month ($m^3.s^{-1}$). The *DroughtCriterion* variable is a percentage value which is used to lower the *MainInstantaneousFlow* to a level that represents a transition between drought and maintenance flow conditions. For the purposes of this dissertation, the value is found by dividing the *DroughtInstantaneousFlow* value by the *MainInstantaneousFlow* value. To determine whether a drought or maintenance flow release is required on the given day, the *MainInstantaneousFlow* is multiplied by *DroughtCriterion* and then compared to the value of *CurrentDayInflow*. The use of *DroughtCriterion* is therefore unnecessary in this case as the resulting product of *MainInstantaneousFlow* and *DroughtCriterion* is the *DroughtInstantaneousFlow*. However, *DroughtCriterion* has been included in *ACRU*2000 as a model input which thus allows the model user to alter it's value if required. If the product of the two variables is greater than or equal to *CurrentDayInflow*, the *DroughtInstantaneousFlow* value from the IFR table is used while if the converse is true, the *MainInstantaneousFlow* value is used. If drought conditions exist on the day, the low-flow volume requested (*ReqRelease* measured in m^3) is found using Equation 4.2.

$$ReqRelease = DroughtInstantaneousFlow * 24 * 3600 \qquad (4.2)$$

When maintenance conditions exist, *ReqRelease* is found using Equation 4.3.

$$ReqRelease = MainInstantaneousFlow * 24 * 3600 \qquad (4.3)$$

This *ReqRelease* value is the request quantity in the water request, which is then sent to the generic dam operating rule.

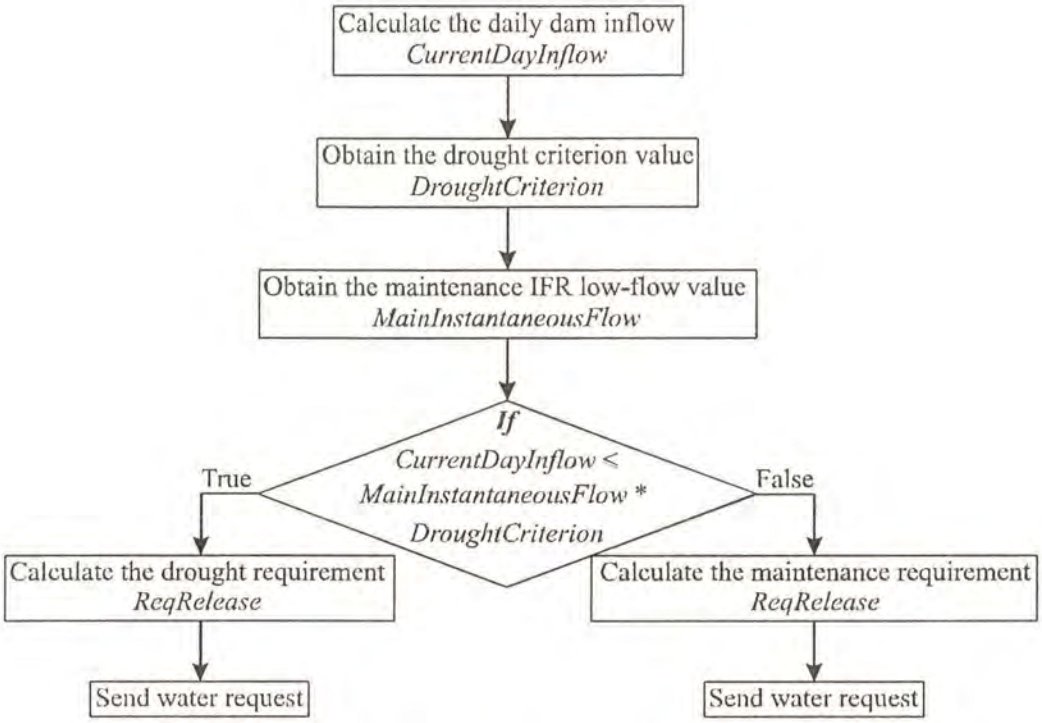

Figure 4.6 Flow diagram of the simple low-flow environmental water request (*PIFRSimple*)

4.4.1.2 Determination of the high-flow request quantity using the *PIFRSimple* process

The simple high-flow environmental request is controlled by the *PIFRSimple* process and is only considered in the months when a flood release is specified by the IFR table used. The procedure is governed by a number of flood allocation and release variables which are all reset on the first day of the month in which a flood is specified by the IFR table. These variables are not included in the following flow diagrams for the sake of brevity, but their main objectives are to ensure that while a flood is being released, no other floods can be allocated and that once a flood has been released for a month, no other floods can be released until the following month when a flood is specified. The high-flow request occurs in two parts: the allocation of the flood, and the determination of the daily quantity required for release. The allocation of the flood involves setting the entire flood volume as allocated storage in the dam acting as the water source. This is in order to avoid the situation where, during the release of a flood, the dam is drawn down to the dead storage level and consequently, no more water is available for abstraction resulting in the cessation of the flood. The daily quantity required for release of the flood is then found and draws from this water allocated to the IFR site. Once the flood has been released, the amount of water in the dam that is allocated to the IFR site should be 0. Definitions of all variables employed by the *PIFRSimple* process are given in Table B2 of Appendix B and flow diagrams for the two parts of the process are shown in Figures 4.7 and 4.8.

Figure 4.7 represents the flood allocation component of the *PIFRSimple* process. The first step is to determine whether drought or maintenance conditions prevail and thus which flood should be released, and is achieved in the same way as for the low-flow request. Figure 4.7 shows an example of allocating the drought flood and determines the drought flood volume (*DroughtFloodVolume*) and the volume of unallocated storage present in the dam that is available to satisfy the request (*AvailableWater*). If the *AvailableWater* volume is greater than the *DroughtFloodVolume*, the *DroughtFloodVolume* will be set as allocated storage in the dam with the IFR site as the owner of the water. However, if insufficient storage exists in the dam to supply the *DroughtFloodVolume*, the flood will not be initiated.

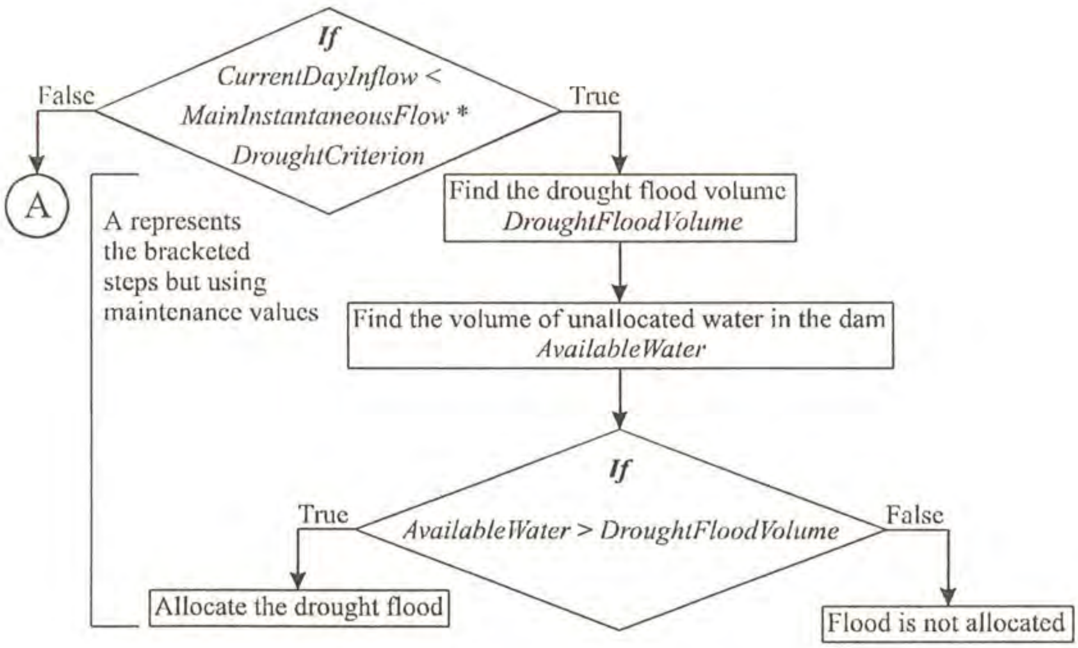

Figure 4.7 Flow diagram of flood allocation in the simple environmental request

Figure 4.8 shows how the daily request for the allocated flood is achieved. This part of the procedure is identical for both the drought and the maintenance flood and Figure 4.8 represents the steps followed for releasing the maintenance flood. The algorithm employed ensures the continued generation of daily water requests until the flood duration is completed. This is achieved through the use of the variable *ElapsedFloodDays*, which monitors the number of days that have passed since the flood began. If *ElapsedFloodDays* is less than the *MainFloodDuration* and it is the first day of the flood release (*ElapsedFloodDays* = 0), the variable *StartOfDayFlow* is set to equal the *MainInstantaneousFlow* value. This is necessary in order to release the flood over and above the low-flow requirements. *StartOfDayFlow* holds the value of the desired previous day's flow at the IFR site and *EndOfDayFlow* holds the desired value of the flow at the IFR site for the current day once the flood release for the day has been made. The flood hydrograph produced by an IFR table is considered to be triangular in shape and has a rising and a falling limb with different slopes. Therefore the algorithm can determine, based on the number of days required to reach the peak flow of the flood (*MainDaysToPeakFlow*) and the *ElapsedFloodDays*, whether the flood is currently on the rising or falling limb of the hydrograph.

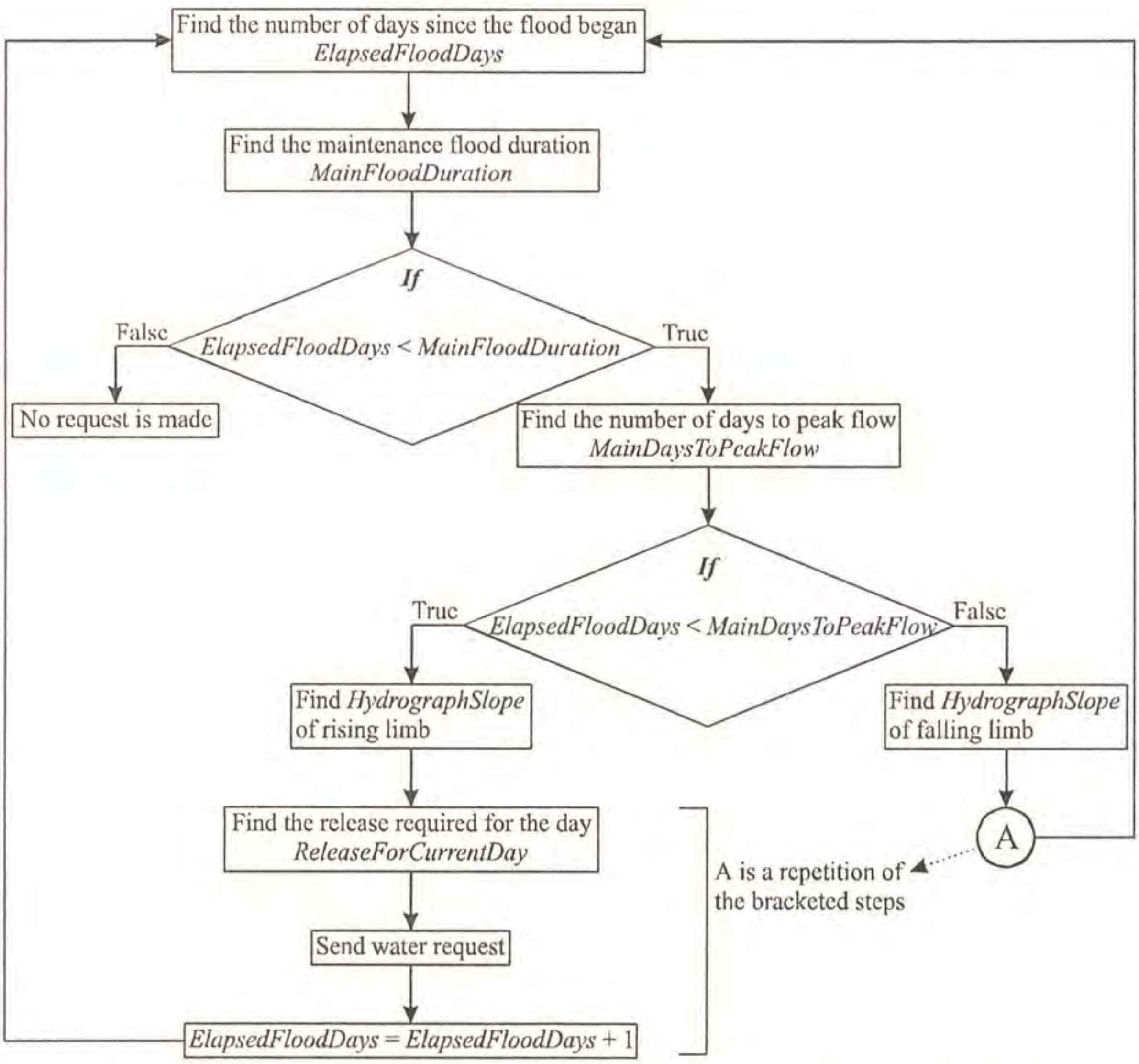

Figure 4.8 Flow diagram of daily flood request in the simple environmental request

Figure 4.9 provides a schematic diagram of a triangular hydrograph released by the procedure and includes all the required variables. In order to illustrate the procedure whereby the daily request quantity for the flood is calculated, the various equations employed by the procedure are given.

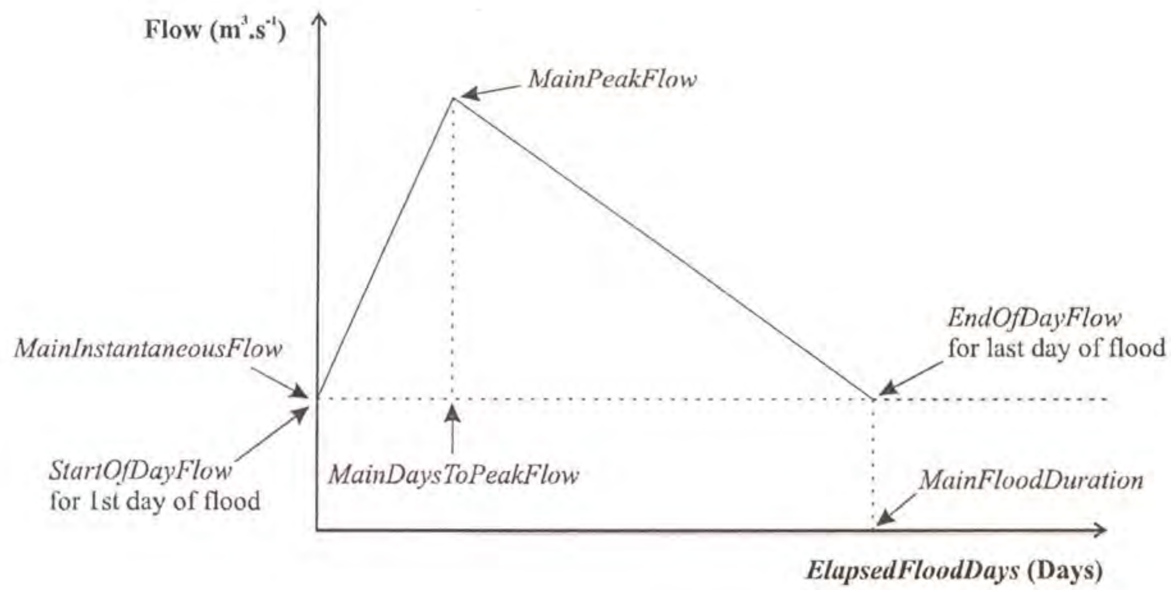

Figure 4.9 Schematic diagram of the triangular hydrograph requested by the algorithm

For the rising limb of the hydrograph, the procedure for calculating the daily flood request is as follows. Firstly, the hydrograph slope is found using Equation 4.4.

$$HydrographSlope = \frac{(MainPeakFlow - MainInstantaneousFlow)}{MainDaysToPeakFlow} \tag{4.4}$$

Secondly, the flow from the previous day and the hydrograph slope are used to calculate the flow required for the current day using Equation 4.5.

$$EndOfDayFlow = StartOfDayFlow + (HydrographSlope * 1) \tag{4.5}$$

Finally, the required release for the day (*ReleaseForCurrentDay* measured in m^3) is found using Equation 4.6.

$$\begin{aligned} ReleaseForCurrentDay = \{&0.5 * (StartOfDayFlow + EndOfDayFlow) \\ &- MainInstantaneousFlow\} * 24 * 3600 \end{aligned} \tag{4.6}$$

For the falling limb of the hydrograph the procedure for calculating the daily flood request is as follows. Firstly, the slope of the hydrograph is found using Equation 4.7.

$$HydrographSlope = \frac{(MainPeakFlow - MainInstantaneousFlow)}{(MainFloodDuration - MainDaysToPeakFlow)} \tag{4.7}$$

Secondly, the flow from the previous day and the hydrograph slope are used to calculate the flow for the current day using Equation 4.8.

$$EndOfDayFlow = StartOfDayFlow - (HydrographSlope * 1) \tag{4.8}$$

Finally, *ReleaseForCurrentDay* is found using Equation 4.6.

Once the value of *ReleaseForCurrentDay* has been calculated, *StartOfDayFlow* is set equal to *EndOfDayFlow* to be used on the following day, the water request is sent to the generic dam operating rule and *ElapsedFloodDays* is increased by one, in order to allow the following days request to be calculated when the process is entered again. When *ElapsedFloodDays* equals the *MainFloodDuration* in Figure 4.8, all the relevant flood release variables are reset until the next month is reached where a high-flow release is required.

4.4.2 Development of the complex environmental water request

The complex environmental water request is based on:

(a) information from the BBM,

(b) a natural flow time series, and

(c) the preceding hydrological conditions existing in the catchment;

and is an adaptation of the method derived by Hughes *et al.* (1997) described in Section 2.6.

Figures 4.10 and 4.11 show the basic relationships in UML notation between *CIFRSite*, *PIFRComplex* and relevant Data classes for the generation of the low-flow and the high-flow requests respectively, using the complex environmental request method. Table B3 of Appendix B holds additional details on all the Data classes contained in the diagrams.

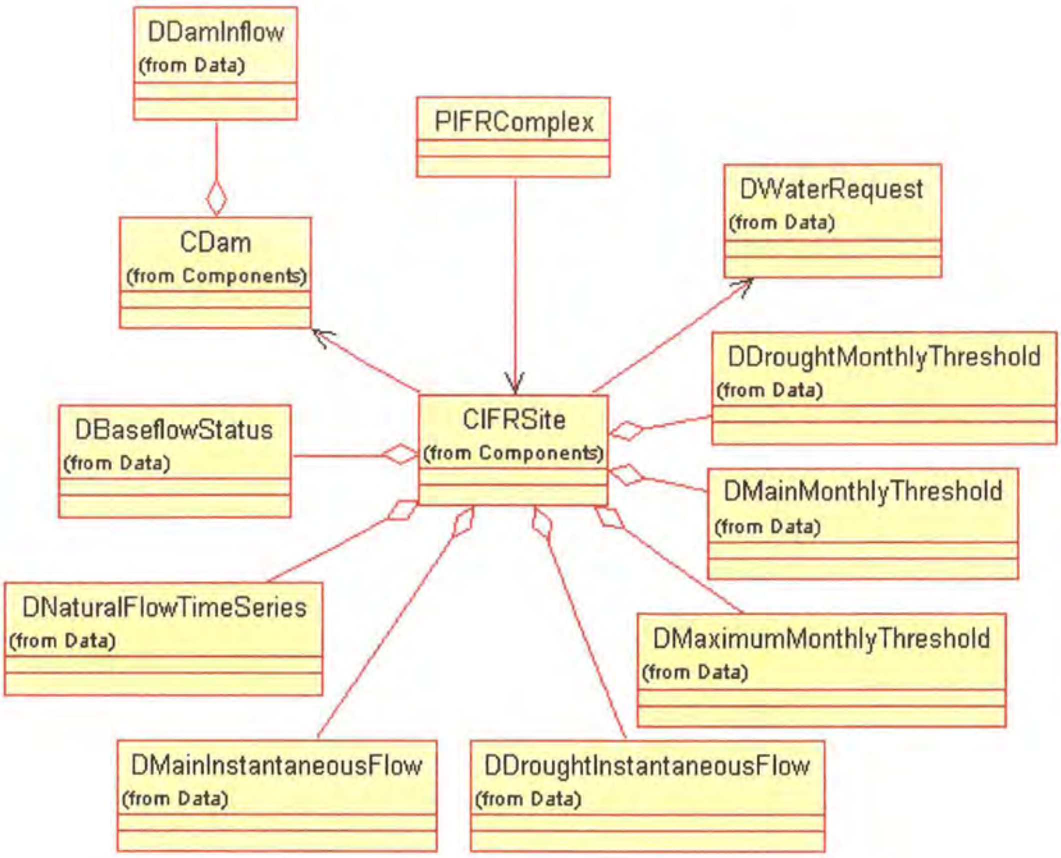

Figure 4.10 Class diagram of the *CIFRSite* component and associated classes for the complex low-flow request method

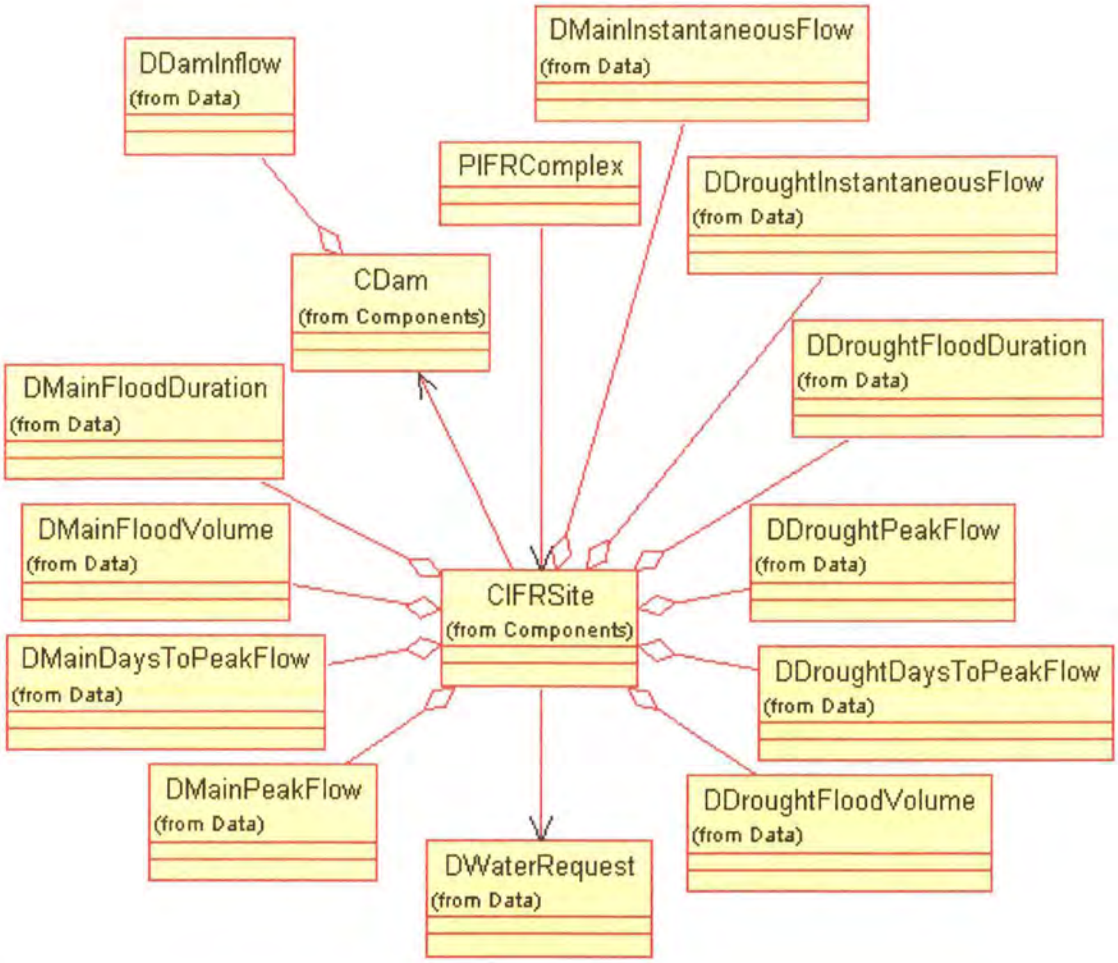

Figure 4.11 Class diagram of the *CIFRSite* component and associated classes for the complex high-flow request method

4.4.2.1 Determination of the low-flow request quantity using the *PIFRComplex* process

The *PIFRComplex* process is responsible for determining the flow requirements for the ecological reserve. The low-flow requests are based on monthly thresholds that are linked to the natural flow time series. The requests are made on a daily basis and attempt to link the volume requested to the current hydrological conditions existing within the catchment. A generalised view of the *PIFRComplex* process for generating the low-flow request quantity is given in Figure 4.12.

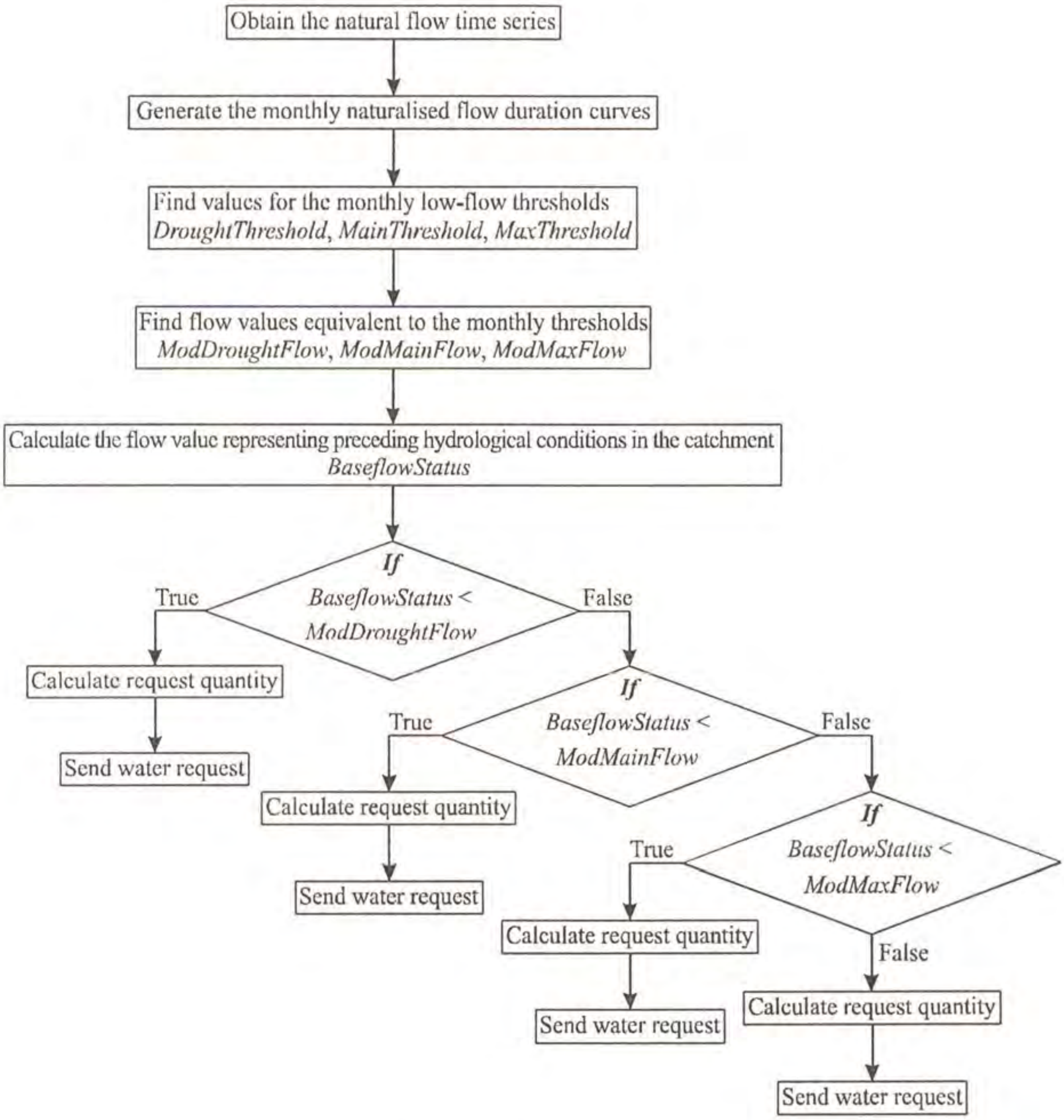

Figure 4.12 Flow diagram of the complex low-flow environmental request (*PIFRComplex*)

Before the procedure can begin, a time series of naturalised flows is required. This naturalised flow time series represents the flows resulting from the use of natural vegetation based on Acocks' (1998) vegetation classification i.e. the flows occurring under pristine conditions, and was generated via simulation. A naturalised flow time series is used because the IFRs account for the flows that would have occurred naturally without any anthropogenic influences. The daily flows at the site where the IFR is located are stored and this forms the basis of the natural flow time series. Once the time series has been obtained, monthly naturalised flow duration curves are computed for the target site. This is achieved by finding the flows throughout the time series corresponding to each month and arranging these flows in ascending order. For chosen values of percentage points (*PercentagePointValue*), equivalent flow values are calculated via interpolation between the naturalised flow values, using the method detailed by McPherson (1990), as outlined briefly below.

The position held by the *PercentagePointValue* for which the equivalent flow is being calculated is found first using Equation 4.9.

$$Position = SampleSize * PercentagePointValue \tag{4.9}$$

where:

SampleSize = the total number of *PercentagePointValues*.

The value of *Position* is then rounded down to the nearest whole number and substituted into Equation 4.10 to find the value of the variable *a*.

$$a = (SampleSize * PercentagePointValue) - Position \tag{4.10}$$

The flow values above and below the position associated with *PercentagePointValue* (*FlowAbove* and *FlowBelow*) are found before the equivalent flow (*EquivalentFlowValue*, measured in m^3) can be calculated using Equation 4.11.

$$EquivalentFlowValue = \{(1 - a) * FlowBelow\} + (a * FlowAbove) \tag{4.11}$$

The monthly flow duration curves for the natural flow time series are presently plotted externally to *ACRU*2000. The model employs three monthly threshold values for the low-flow determination: the drought, maintenance and maximum low-flow thresholds. These values are site specific and are found by calibration. The procedure employed in order to optimise these three values for the purposes of this project is described in Section 5.3.2.1. The drought threshold (*DroughtThreshold* in Figure 4.12) specifies the percentage exceedance for the drought flow in the month while the maintenance threshold (*MainThreshold*) specifies the percentage exceedance for the maintenance flow for the month. The maximum low-flow threshold (*MaxThreshold*) allows the maintenance flow to be exceeded by a certain amount. These three monthly values can then be plotted on the monthly duration curves and their equivalent flow values read off the curves. The equivalent flows for the three threshold values (*ModDroughtFlow*, *ModMainFlow* and *ModMaxFlow* in Figure 4.12) are calculated via interpolation. Figure 4.13 shows an example of a monthly duration curve with the relevant threshold and flow values included.

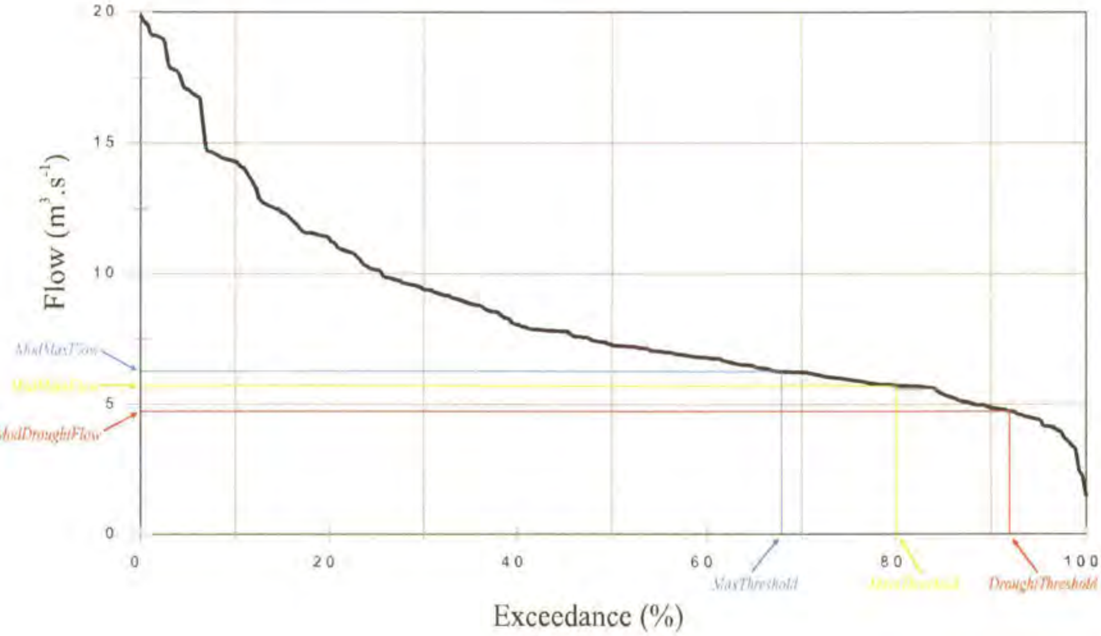

Figure 4.13 Example of a monthly flow duration curve including the threshold values

Referring again to Figure 4.12, the baseflow status (*BaseflowStatus*) algorithm is activated as the first part of the low-flow request quantity determination and is based on the procedure used by Hughes *et al.* (1997). *BaseflowStatus* is a flow value that represents hydrological conditions existing in the catchment and is reliant on present day flows. It is computed using flows for a period of 30 days preceding the current day. The algorithm sorts through the 30 flow values in sixteen 15 day periods and calculates the minimum flow for each of these periods. The 16 minimum values are arranged into ascending order and the *BaseflowStatus* value is taken as the median value of these minima.

Having determined the *BaseflowStatus* value, it is compared to the flow values equivalent to the three monthly threshold values, namely *ModDroughtFlow*, *ModMainFlow* and *ModMaxFlow*, in order to determine whether drought or maintenance conditions prevail. The daily amount requested is found using one of four equations.

If *BaseflowStatus* is less than the *ModDroughtFlow* value, the request quantity (*ReqRelease*, measured in m^3) is found using Equation 4.2.

If the *BaseflowStatus* is greater than the *ModDroughtFlow* value but less than the *ModMainFlow* value, the request quantity is found using Equation 4.12 :

$$ReqRelease = \left\{ DIF + \frac{(MIF - DIF) * (CDF - MDF)}{(MMF - MDF)} \right\} * 24 * 3600 \tag{4.12}$$

where:

DIF and *MIF* = *DroughtInstantaneousFlow* and *MainInstantaneousFlow* respectively,
MDF and *MMF* = *ModDroughtFlow* and *ModMainFlow* respectively, and
CDF = *CurrentDayFlow*, which is the flow present in the river on the current day.

If the *BaseflowStatus* is greater than the *ModMainFlow* value, but less than the *ModMaxFlow* value, the request quantity is found using Equation 4.13 :

$$ReqRelease = \frac{(MainInstantaneousFlow * CurrentDayFlow * 24 * 3600)}{ModMainFlow} \tag{4.13}$$

The *CurrentDayFlow* value has been included in Equations 4.12 and 4.13, in an attempt to provide as much variability as possible in the downstream flow regime. An alternative would be to use the *BaseflowStatus* value in place of *CurrentDayFlow*.

If the *BaseflowStatus* is greater than the *ModMaxFlow* value, *ReqRelease* is limited using Equation 4.14 :

$$ReqRelease = \frac{(MainInstantaneousFlow * ModMaxFlow * 24 * 3600)}{ModMainFlow} \tag{4.14}$$

The daily water request is then sent to the generic dam operating rule with *ReqRelease* being set as the request quantity.

4.4.2.2 Determination of the high-flow request quantity using the *PIFRComplex* process

The main objective of the complex high-flow environmental request is to improve on the actual triggering of the flood event during a month by linking it to the hydrological conditions in the catchment, and not purely to the storage in the dam as in the case of the simple approach. A flood release is triggered using two criteria:

(a) the rate of rise of the flow in the river from day to day, and

(b) the available storage present in the dam.

The actual characteristics of the flood events are the same as for the simple method and are obtained directly from the IFR table.

The high-flow procedure is similar to that of the simple environmental request because it also employs a set of flood allocation and release variables. Slight differences exist with an additional flood release variable being used which allows a flood to continue if it is only allocated near the end of the month and thus is released across two months. If this were to occur using the simple environmental request method, the flood release would cease on the first day of the new month. Since the flood in that case is allocated based on the storage in the dam, this almost always results in it being released on the first day of the month and so this situation is seldom encountered. The major difference between the two methods is in the way the flood is timed where the complex approach uses the rate of rise in the river to trigger the release of the flood event.

Figure 4.14 shows the method by which the flood is allocated in the *PIFRComplex* process and all variables mentioned are defined in Table B3 of Appendix B. The trigger for the flood is provided by the rate of rise of flow occurring in the river from day to day (*RateOfRise*, measured in $m^3.s^{-1}.day^{-1}$) using Equation 4.15.

$$RateOfRise = CurrentDayFlow - PreviousDayFlow \qquad (4.15)$$

This *RateOfRise* value is compared to a *MinRateOfRise* criterion found by multiplying the rate of rise of the maintenance flood specified in the IFR table (*MainRateOfRise*) by a percentage. The *MainRateOfRise* value is calculated using Equation 4.16.

$$MainRateOfRise = \frac{(MainPeakFlow - MainInstantaneousFlow)}{MainDaysToPeakFlow} \quad (4.16)$$

The *MainRateOfRise* value is lowered to obtain the *MinRateOfRise* criterion in order to make the criterion for releasing the flood less stringent. A set value of 50 % was chosen by which to lower the *MainRateOfRise* for the purposes of simplification. The effectiveness of this simplification is investigated in Chapter 5.

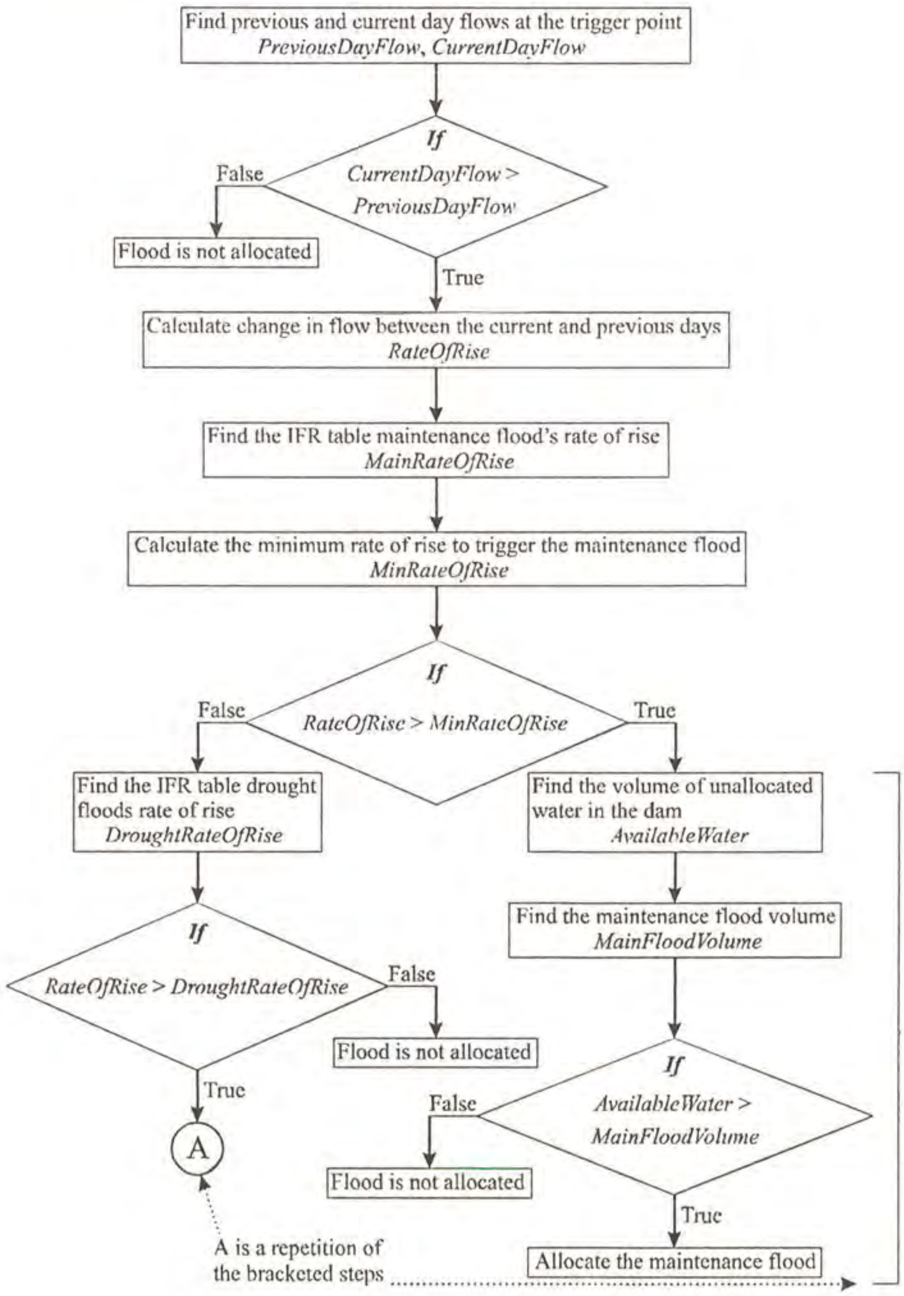

Figure 4.14 Flow diagram of the complex high-flow environmental request (*PIFRComplex*)

As indicated in Figure 4.14, if a positive *RateOfRise* has occurred on a particular day its value is compared to the value of *MinRateOfRise*. Should the value of *RateOfRise* exceed the *MinRateOfRise* criterion the algorithm calculates the volume of the entire flood (*MainFloodVolume*) and checks if sufficient water is available in the dam to satisfy the entire flood volume. If so, the flood volume is set as allocated storage in the dam and the generation of the daily requests can commence. These occur in the same way as for the simple environmental request method (See Section 4.4.1.2).

If the *RateOfRise* value is not greater than the *MinRateOfRise* criterion, the algorithm attempts to allocate the drought flood by calculating the rate of rise of the drought flood specified by the IFR table (*DroughtRateOfRise*) and again comparing it to the *RateOfRise* value. The value of *DroughtRateOfRise* is calculated using Equation 4.17.

$$DroughtRateOfRise = \frac{(DroughtPeakFlow * DroughtInstantaneousFlow)}{DroughtDaysToPeakFlow} \tag{4.17}$$

Should the *RateOfRise* value exceed the *DroughtRateOfRise* value, the drought flood will be allocated and released, provided that sufficient storage is present in the dam. No *MinRateOfRise* criterion is required in this case as the *DroughtRateOfRise* specified by the BBM is the minimum rate of rise that should trigger a drought flood (Hughes, 2000).

4.4.3 Description of the *PSimpleIFRFlow* process

The *PSimpleChannelFlow* process is responsible for taking all water arriving at the end of a river reach and transferring it to the next reach downstream. *CIFRSite* is considered as a type of channel and so was originally subjected to the same process. However, when the water allocated to *CIFRSite* passed through the IFR site itself, a problem arose downstream when users were abstracting directly from the river. To overcome this problem it was necessary to reallocate the water allocated to the IFR site to unallocated storage once it had passed through the IFR site, although it is recognised that this is not strictly correct as the ecological reserve should account for an entire river reach. Therefore, it was necessary to include a separate flow procedure (*PSimpleIFRFlow*) for IFR sites which is shown in Figure 4.15.

The procedure begins by finding the volume of unallocated water arriving at the IFR site (*SourceIFRSite*) on the day and transferring this volume to the downstream reach. If any allocated water arrives at *SourceIFRSite* the users to which this water is allocated are found (*WaterOwner*). If a *WaterOwner* is the *SourceIFRSite*, the volume allocated to *SourceIFRSite* is then set as unallocated storage before being transferred downstream, whereas for other *WaterOwners*, the allocated storage is transferred downstream unaltered.

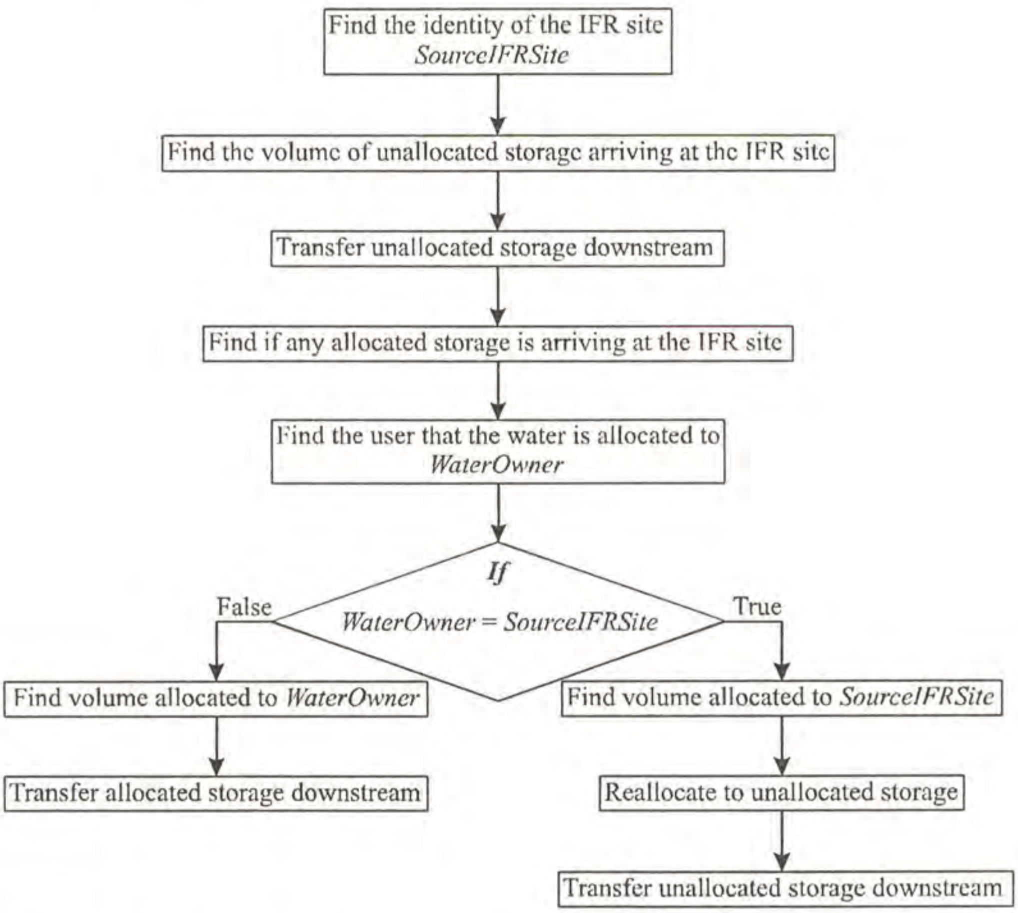

Figure 4.15 Flow diagram of the water transfer from the IFR site to the downstream channel

4.5 Generation of Requests for Industries

The *CIndustry* class represents any user that requires water for industrial processes. The relationships, in UML notation, between *CIndustry* and its associated Data and Processes classes are shown in Figure 4.16. The *PIndustryReq* process is responsible for determining the industrial request quantity by reading the daily value from *DIndustryReq*. This value is set as the request quantity and sent to the operating rule along with other information required for a water request.

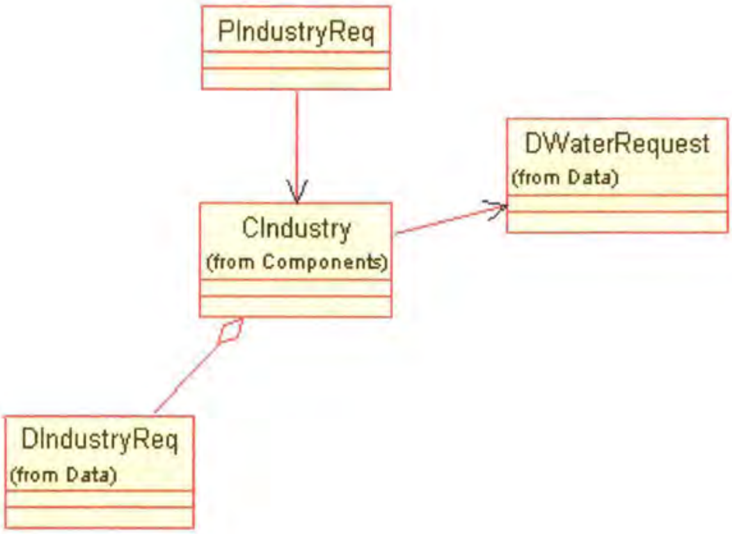

Figure 4.16 Class diagram of the relationships between the industrial user classes

4.6 Generation of Requests for Irrigation

The water requests for irrigation are made by the component *CIrrigatedArea*, which was included in *ACRU*2000 prior to the operating rule framework being developed. Water requests made by this class are dependent on a water budget, the major components of which are:

(a) evaporation of water from the soil surface, and
(b) transpiration in relation to atmospheric demand, available soil water and rooting characteristics (Schulze, 1995).

The frequency with which these requests are made depends on the mode of scheduling employed. Schulze (1995) states that modes of irrigation scheduling depend on system limitations, the level of management, water availability, climatic conditions, the type of crop and the crop's stage of growth. Five modes of scheduling exist in *ACRU*2000. These are:

(a) demand mode scheduling according to soil water depletion levels,
(b) irrigation with a fixed cycle and in fixed amounts of water application,
(c) irrigation with a fixed cycle and in varying amounts of water application,
(d) irrigating according to a predetermined schedule, and
(e) deficit irrigation.

4.7 Development of the Generic Dam Operating Rule

The generic dam operating rule was included in the *ACRU*2000 model to provide an efficient and equitable distribution of water to all water users relying upon a dam. Prior to the implementation of this operating rule, irrigators were the only water users recognised individually in the model, all other users being lumped together with the only existing method of supplying water to these other users being a dam draft option which operated according to monthly demands. The inclusion of the environment as a water user, required that a daily time-step be used, which meant that modifications were necessary in order to consider the requirements of the National Water Act (1998). The operating rule can be split into two major components of water allocations and water transfers, which are discussed separately in the following sections.

The process *PGenericOperatingRule* is responsible for performing the operational functions for any *CDam* component. Figure 4.17 shows the relationships in UML notation, between *PGenericOperatingRule* and associated Components and Data classes. Definitions of the classes shown in the diagram can be found in Table A1 of Appendix A and Table B4 of Appendix B.

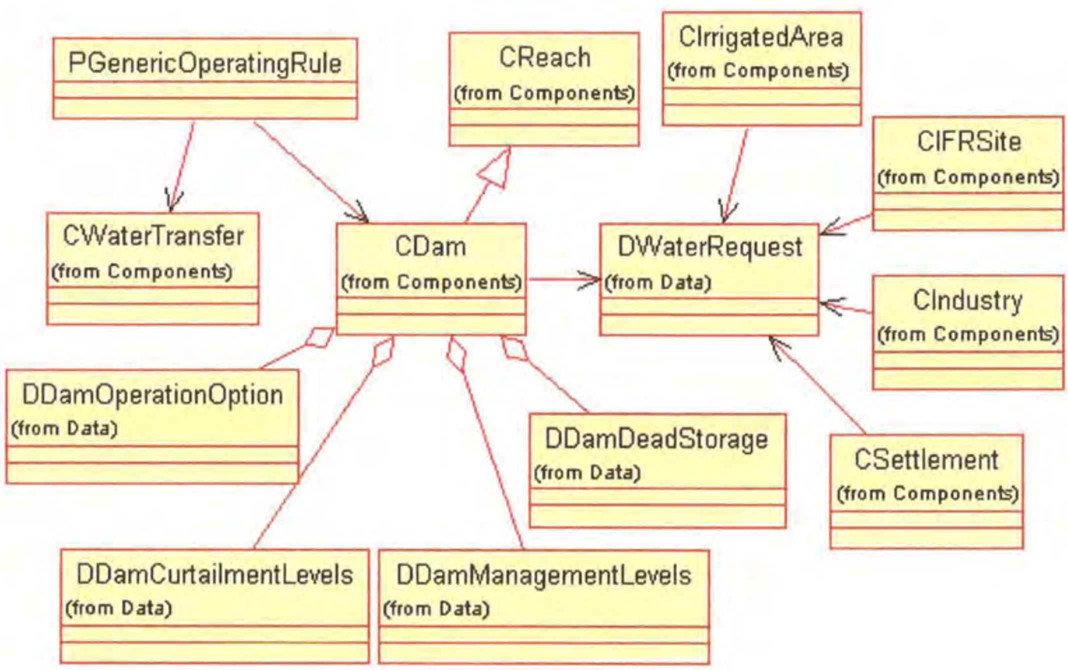

Figure 4.17 Class diagram of *PGenericOperatingRule* and other associated classes

The Data classes *DDamManagementLevels* and *DDamCurtailmentLevels* form the basis of the curtailment structure used to limit the quantities that water users may abstract from a dam. The following section outlines the basic principles of this curtailment structure.

4.7.1 Curtailment structure employed by the generic dam operating rule

The generic dam operating rule relies on a curtailment structure to determine how much water is released or transferred from a dam. Table 4.1 shows an example of a curtailment structure that would be used by the rule.

Table 4.1 Example of a user-defined curtailment structure

Management level (%)	**100 - 80**	**80 - 70**	**70 - 60**	**60 - 40**	**40 - 10**	**Priority**
Domestic	100	100	100	100	100	1
Environment	100	100	100	95	85	2
Industry	100	100	100	90	80	3
Irrigation type 1	100	100	90	80	50	4
Irrigation type 2	100	90	75	75	50	4

In Table 4.1, the percentage values in bold print are termed management levels and are stored by the Data class *DDamManagementLevels*. The values represent the dam's current storage as a percentage of full capacity. Thus 100 % represents full capacity and 10 % in Table 4.1 represents dead storage. Management levels are user input, firstly as to the number of levels, and secondly as to what values should correspond to each level. The values in fine print represent the corresponding curtailment levels existing within a given management level and are stored by the Data class *DDamCurtailmentLevels*. The curtailment level is the percentage of the user's request quantity that is likely to be supplied. Supply of the curtailed request quantity is dependent on both the current level of storage in the dam and the priority of the user. The curtailment structure is only applied to requests from unallocated storage. Any water that has been allocated to a water user is not subjected to the curtailment structure and the full amount can be supplied to the user if requested, provided that sufficient storage is available in the dam.

User priorities were introduced largely to account for the influence of the Reserve. Since the importance of the Reserve is legalised in the National Water Act, it becomes necessary to distinguish between water for the Reserve and water for other users. With the Reserve being split into two, the basic human needs reserve is generally assigned priority 1 and the ecological reserve priority 2. Following this, industry was assigned priority 3 and irrigation priority 4. However, the model user may alter the priorities of the various users to suit particular situations and this could also be extended, for example, to assigning different industries separate priorities.

4.7.2 Water allocations in the generic dam operating rule

The water allocation procedure forms a major part of the generic dam operating rule. This procedure takes the various water requests made to the dam and determines the quantities with which each water user will be supplied. The flow diagram in Figure 4.18 gives a generalised representation of the steps employed by the water allocation part of the generic dam operating rule. The definitions of all the variables used are given in Table B4 of Appendix B.

The process begins by calculating the current storage in the dam for the day (*CurrentStorage*) and comparing it to the dead storage volume (*DeadStorage*). If *CurrentStorage* is less than *DeadStorage*, no abstractions may take place. If *CurrentStorage* is greater than *DeadStorage*, the algorithm then considers all the water requests made to the dam, including the priority associated with each request and whether the request is being made from allocated or unallocated water. The requests of equal highest priority are then found (*ThisWaterRequest*) and the allocation to these users is completed before the next set of equal highest priority users is considered.

The process differentiates between the requests made from allocated or unallocated storage. For requests made from unallocated storage the volume of unallocated water present in the dam (*AvailableWater*) is computed, as well as whether operation of the dam is required (*DamOperationOption*). This is a user input and has been included to accommodate, for example, small farm dams which have no outlet works. If *DamOperationOption* equals 1 the dam will be operated according to the curtailment structure, whereas if this variable has been set to 2, no curtailment of requests will take place. If the former is true the quantity requested by each of the users is found (*RequestQuantity*). The management level (*ManagementLevel*) for each user is found based on converting the *CurrentStorage* to a percentage of the dam's full capacity and the corresponding curtailment level (*CurtailmentLevel*) can then be obtained. For each of the users the curtailed quantity that is likely to be received (*CurtRequestQuantity*) is calculated using Equation 4.18.

$$CurtRequestQuantity = RequestQuantity * \left(\frac{CurtailmentLevel}{100}\right) \tag{4.18}$$

The *CurtRequestQuantities* for all the users of equal highest priority are summed to obtain a *CurtRequestTotal* and compared to the volume of *AvailableWater*. If the value of *AvailableWater* equals 0, no water will be allocated to any water users. If the value of *AvailableWater* is greater than the *CurtRequestTotal* each *CurtRequestQuantity* is allocated to its respective user. However, if insufficient storage exists in the dam to supply the *CurtRequestQuantity* to each of the users i.e. *AvailableWater* < *CurtRequestTotal*, each user is then allocated a proportional amount of the available water remaining in the dam (*ReallocationQuantity*). Each user's *ReallocationQuantity* is found using Equation 4.19.

$$ReallocationQuantity = \frac{(AvailableWater * CurtRequestQuantity)}{CurtRequestTotal} \tag{4.19}$$

This equation has been used to ensure that each user of the same priority will receive the same proportion of its *CurtRequestQuantity*.

If a user is requesting water from allocated storage or if the *DamOperationOption* has been set equal to 2, the curtailment structure is not used to determine the water allocations and the method of allocation is described by Procedure A in Figure 4.19. For users of equal priority, the *AvailableWater* and each user's *RequestQuantity* are found with an *EqualPriorityRequestTotal* being calculated by summing the *RequestQuantities*. For requests occurring from allocated storage, *AvailableWater* is the quantity of water present in the dam that has already been allocated to the particular user. The value of *EqualPriorityRequestTotal* is then compared to the value of *AvailableWater*. If *EqualPriorityRequestTotal* is greater than *AvailableWater* the users of equal priority will receive their respective *RequestQuantities*. If there is insufficient *AvailableWater* to supply the *EqualPriorityRequestTotal*, the remaining storage in the dam is distributed proportionally among the users. Each user will thus receive a *ReallocationQuantity* calculated using Equation 4.19, with *RequestQuantity* and *EqualPriorityRequestTotal* replacing *CurtRequestQuantity* and *CurtRequestTotal* respectively.

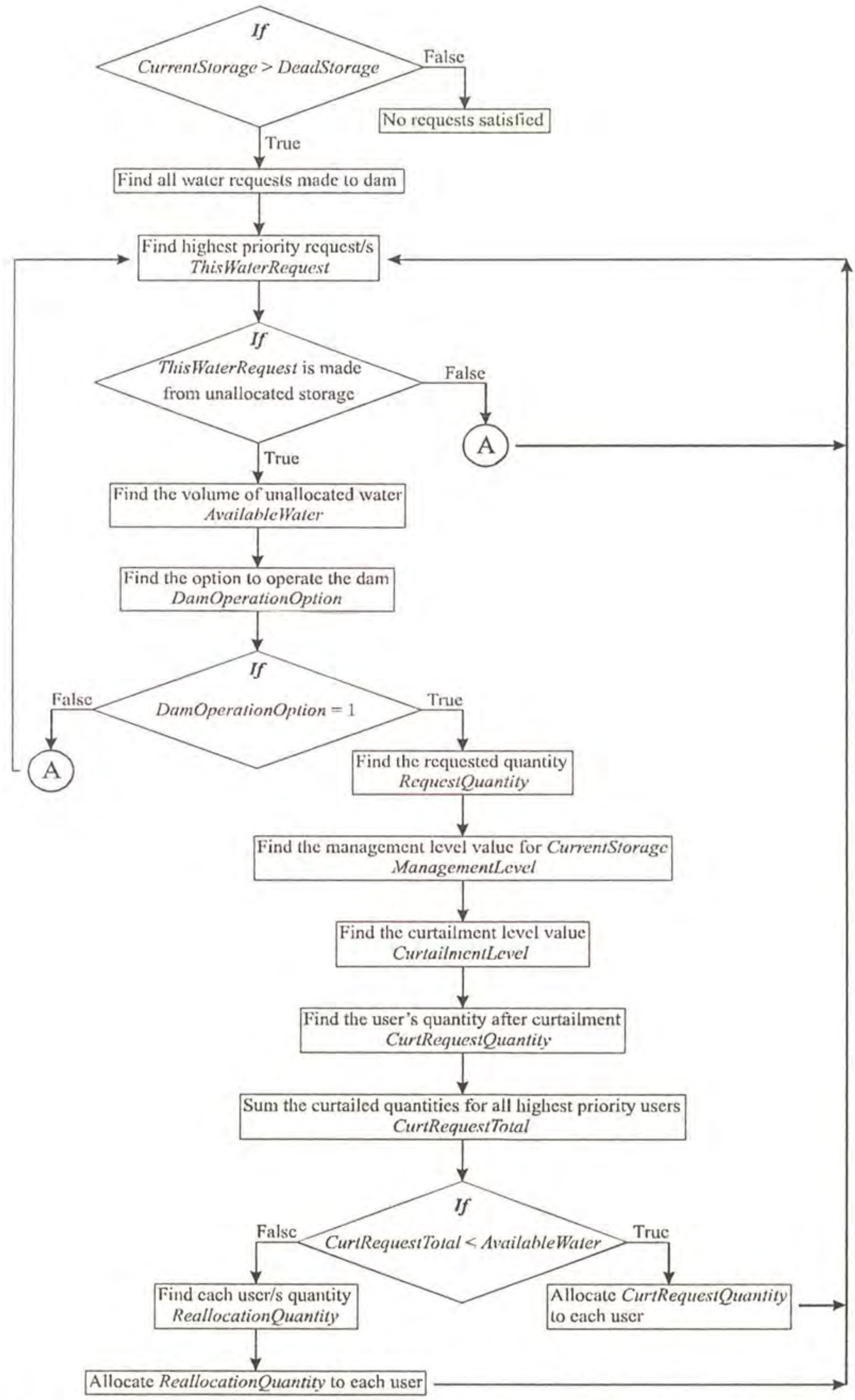

Figure 4.18 Flow diagram of water allocations in the generic dam operating rule (Part A is included in Figure 4.19)

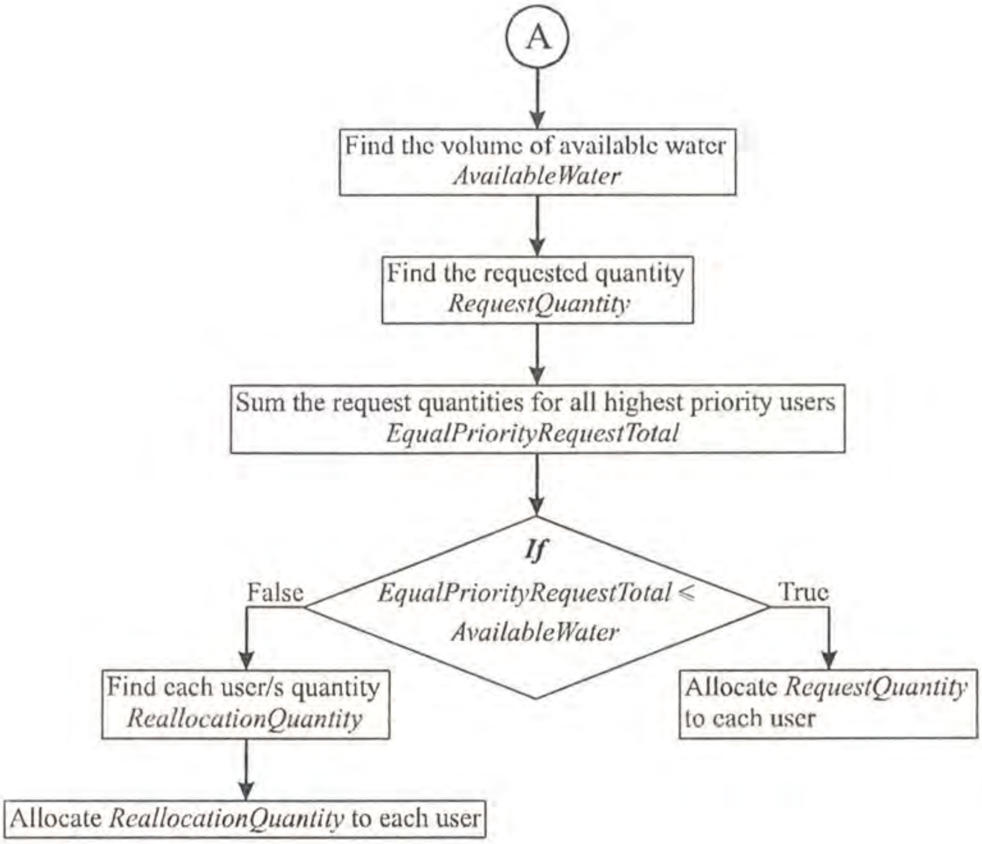

Figure 4.19 Flow diagram of water allocations to requests made from allocated water

The operating rule is illustrated by the following example in Table 4.2 and using the curtailment structure in Table 4.1.

Table 4.2 Generic dam operating rule example

Information	Units	Quantity	
Full capacity	m^3		50000
Dead storage	m^3		5000
Current storage	m^3		25000
Water users		Requested	Transferred
Domestic	m^3	5000	5000
Environment	m^3	10000	9500
Irrigation type 1	m^3	5000	4000

Table 4.2 shows the quantities requested by three water users and the quantities transferred from the dam to these users as well as information on the dams full capacity, dead storage and current storage for the day. By way of example, the irrigation type 1 user's request is only satisfied after

the other two requests due to this user's lower priority. The management level of the dam is set at the beginning of the day, so even if large amounts of water are abstracted from the dam, the user will still be curtailed on the original management level value, which is 50 % in this example. The corresponding curtailment level for the irrigation type 1 user is 80 % and the curtailed request quantity is $0.8 \times 5000 = 4000\ m^3$. The available storage in the dam is the amount of water present in the dam above dead storage and can be found using Equation 4.20

$$\text{Available storage} = \text{Current storage} - \text{Dead storage} - \text{Abstractions} \qquad (4.20)$$

where:

Abstractions = the transfers made to users of higher priority

From Equation 4.20, the available storage was found to be 5500 m^3, an amount greater than the irrigator's curtailed request quantity of 4000 m^3. Hence the quantity transferred to the irrigator is 4000 m^3. If however, the available storage had only been 3000 m^3, this amount would have been transferred to the irrigator.

4.7.3 Water transfers in the generic dam operating rule

Water transfers are the fourth component of the operating rule framework and have been included within the operating rules. Water can be transferred either as a direct abstraction from the dam or by making downstream releases. This distinction is provided in order to account for the influence of spillway flow on the downstream releases. Any water present in the dam above full capacity is transferred out of the dam at the end of the day, leaving the dam's *PercentCurrentStorage* at a level of 100 %. Consequently, the volume of spillway flow has to be compared to the total volume of the required downstream releases for the day. If the spillway flow volume exceeds this total downstream release volume, no downstream releases are made from the dam. However, if the spillway flow volume is less than the sum of the required downstream releases, the difference between the two volumes is released over and above the spillway flow volume. It is assumed that if a dam is not operated i.e. *DamOperationOption* = 2, it is incapable of making downstream releases. As mentioned previously, this is to accommodate small dams which have no outlet works.

4.8 Development of the Channel Operating Rule

Much focus has been given to the protection of impounded river ecosystems, while less attention has been paid to rivers from which direct abstractions occur. Water users relying upon dams for their water supply are curtailed depending on the current storage of the dam at the time. Despite existing legislation, water users abstracting directly from a river at times draw the river down to excessively low levels without consideration being given to the aquatic ecosystems and other downstream water users. In an attempt to prevent this from occurring, the channel operating rule takes the ecological reserve into account when allocating water to users abstracting from the river.

The *PChannelOperatingRule* process is responsible for determining how the requirements of water users abstracting directly from a river are met. Figure 4.20 shows the relationships between *PChannelOperatingRule* and other associated Components and Data classes. Definitions of these classes are given in Table B5 of Appendix B.

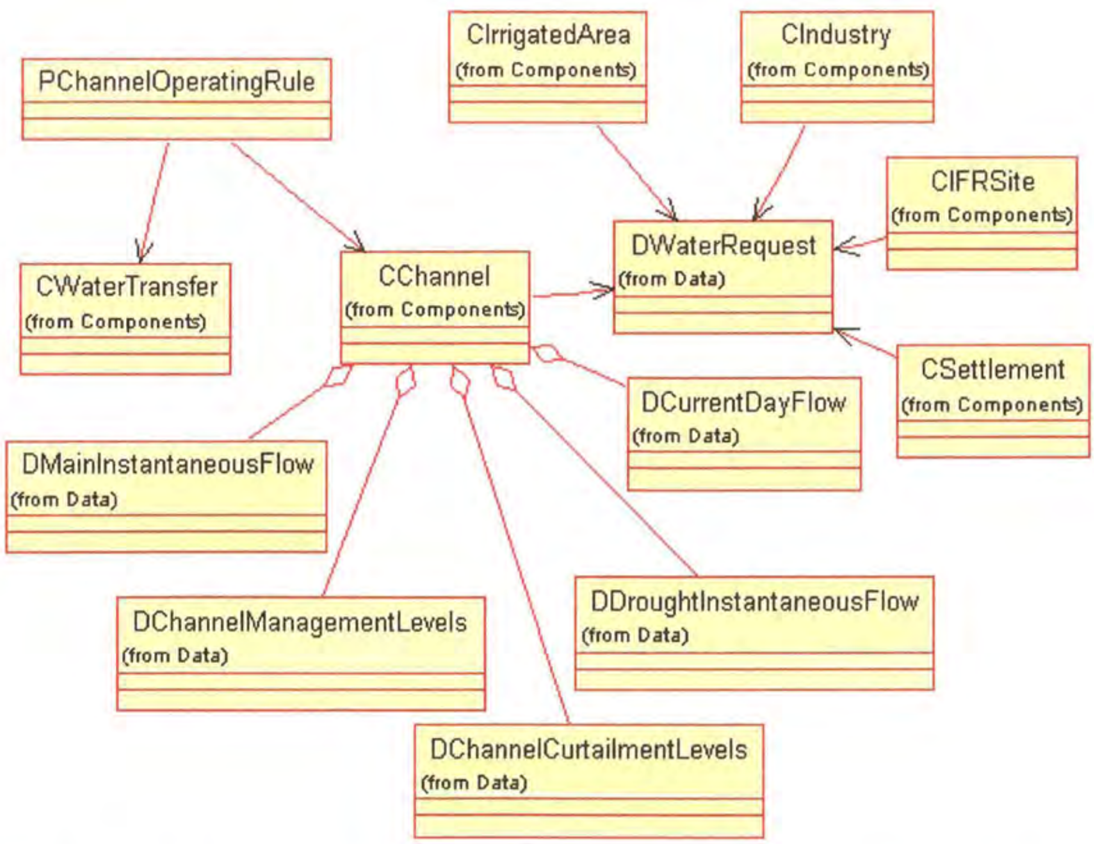

Figure 4.20 Class diagram of the *PChannelOperatingRule* process and associated classes

The following section discusses the water hierarchy employed by the channel operating rule as well as the curtailment structure employed which is largely made up of the classes *DChannelManagementLevels* and *DChannelCurtailmentLevels*.

4.8.1 Curtailment structure employed by the channel operating rule

In addition to the two types of water recognised by the generic dam operating rule i.e. unallocated and allocated water, the channel operating rule makes use of a water classification in the channel, based on the monthly IFR low-flow levels. The governing water levels are the monthly maintenance and drought IFR flow levels specified in the IFR table, and two types of water are classified, "excess" water and "curtailed" water as can be seen in Figure 4.21.

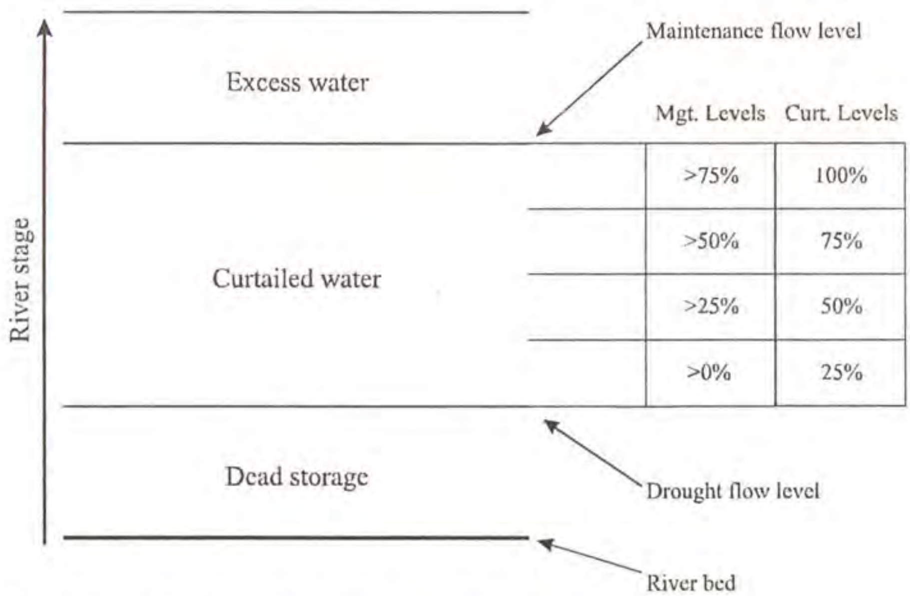

Figure 4.21 Water classification in the channel operating rule

"Excess" water represents any water that is present in the river above the maintenance IFR flow level on a particular day. It is considered free with water being drawn out of this region receiving no curtailment. During the water allocation procedure this water is allocated first and will usually go to the highest priority users. "Curtailed" water is present in the river between the maintenance IFR and the drought IFR flow levels. This water is not considered "free" and a curtailment structure based on the same principles as the generic dam operating rule's curtailment structure is applied to it. During the water allocation procedure "curtailed" water will only be allocated once no more "excess" water exists and once the "curtailed" water has been used, no further water may be abstracted from the channel. Thus the water below the drought IFR flow level is treated in the same way as dead storage in a dam. A detailed technical description of how the channel operating rule operates follows in Section 4.8.2.

4.8.2 Water supply to users via the *PChannelOperatingRule* process

As with the generic dam operating rule, the water allocation procedure forms the major part of the channel operating rule. This procedure takes the various water requests made to the river and determines the quantities that each water user will be supplied. The flow diagram in Figure 4.22 provides a generalised view of the procedures employed and is accompanied by Figure 4.23. The definitions of the variables described are provided by Table B5 of Appendix B.

The channel operating rule regards the channel as a form of reservoir with any flow below the drought flow specified by the IFR table (*DroughtInstantaneousFlow*) being treated as dead storage. Thus if the flow in the river on the current day (*CurrentDayFlow*) is less than the *DroughtInstantaneousFlow* value, no abstractions may take place. The rule functions in a similar way to the generic dam operating rule by finding all the requests made to the channel and then allocating water to these in order of priority.

Once the highest priority users have been found, the current day flow in the river is compared to the monthly maintenance low-flow value according to the BBM (*MainInstantaneousFlow*). If *CurrentDayFlow* is less than the *MainInstantaneousFlow*, only curtailed water exists and the users' requests are curtailed using the same form of curtailment structure employed by the generic dam operating rule. In this case the management levels are based on the maintenance and drought low-flows with a flow equal to the *MainInstantaneousFlow* level equivalent to a management level of 100 % and a flow at the *DroughtInstantaneousFlow* level to a management level of 0 % (See Figure 4.21). The relevant curtailment levels for the users can be found, and the *CurtRequestQuantities* calculated using Equation 4.18. These quantities are then allocated to the users, provided sufficient storage is present in the river above the *DroughtInstantaneousFlow* level i.e. *CurtRequestTotal* < *AvailableWater*. If insufficient storage exists the *ReallocationQuantity* for each user is found from Equation 4.19 and allocated to the user, while if *AvailableWater* equals 0, no water will be allocated to any water users.

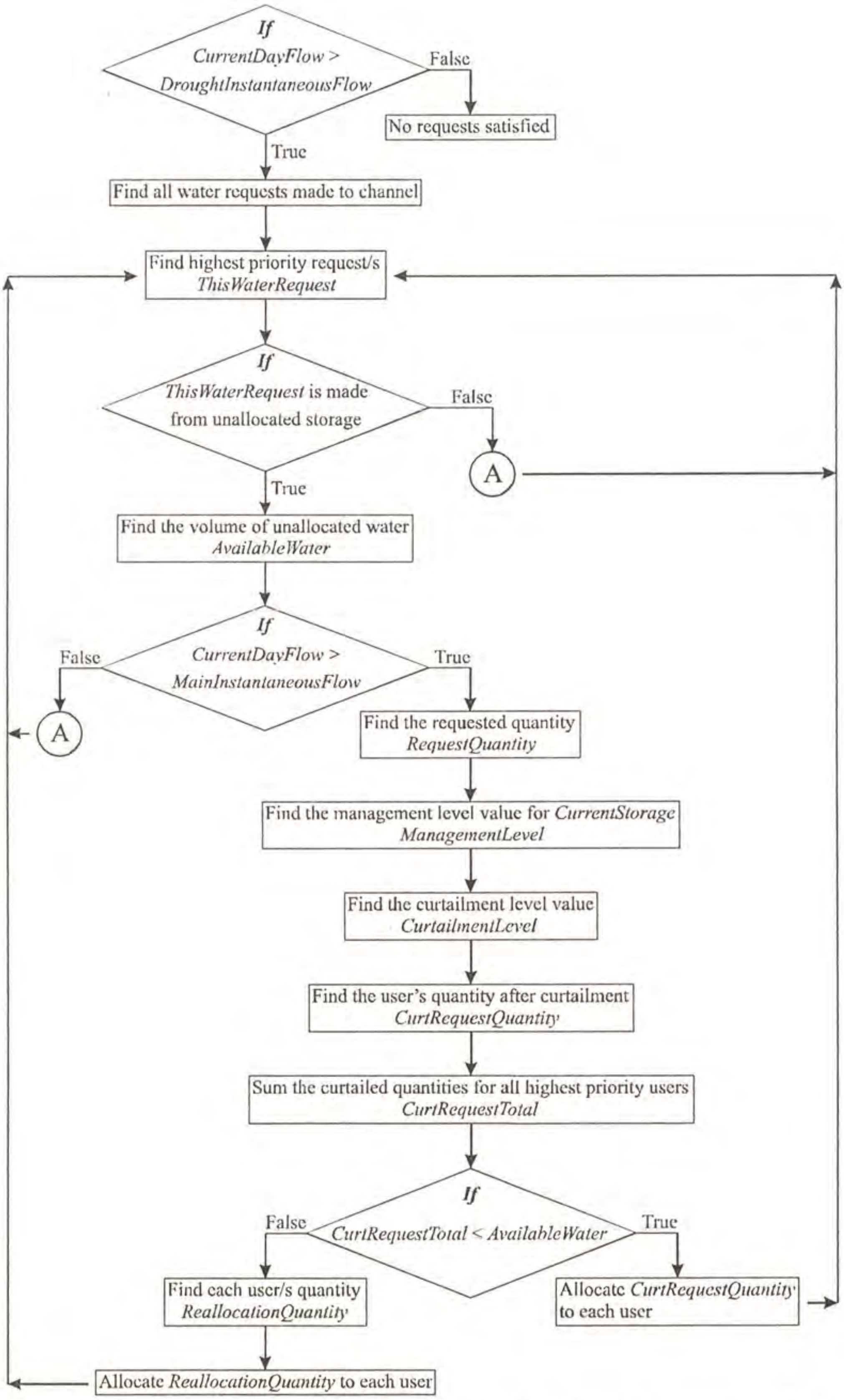

Figure 4.22 Flow diagram of water allocations in the channel operating rule (Part A is contained in Figure 4.23)

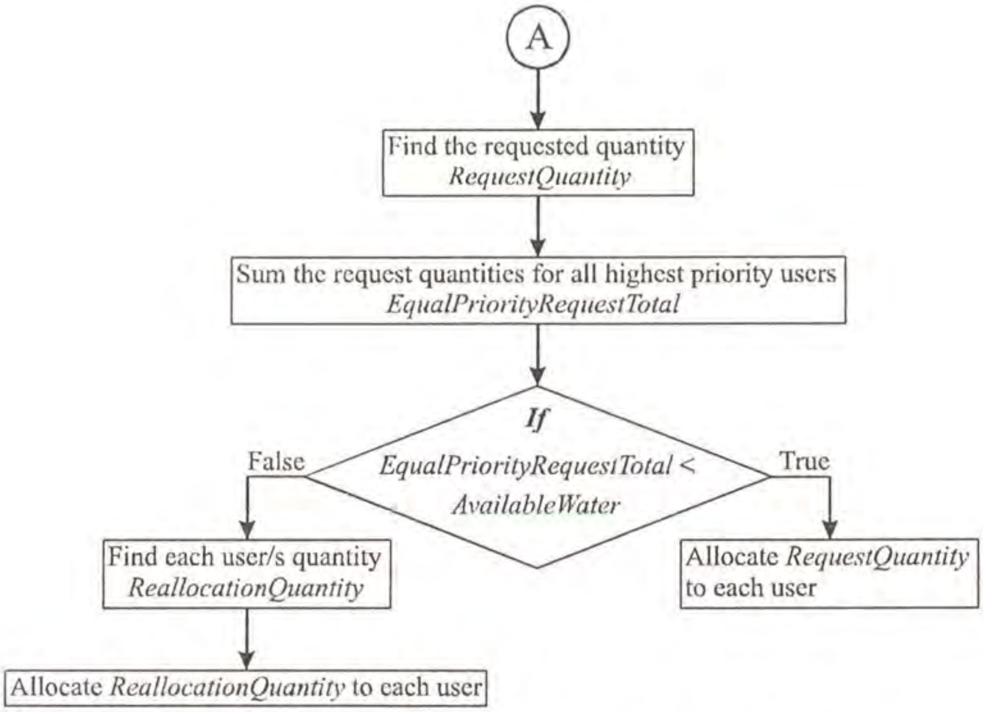

Figure 4.23 Additional flow diagram of water allocations in the channel operating rule

If the *CurrentDayFlow* value is greater than the *MainInstantaneousFlow* the allocation for users is virtually the same as for requests from allocated storage and is shown as A in Figure 4.23. In both cases, no curtailment structure is employed for the water allocations, the only difference being that requests made from allocated storage will occur while the *CurrentDayFlow* is above the *DroughtInstantaneousFlow* and not the *MainInstantaneousFlow* level. The *RequestQuantity* for each user and the *EqualPriorityRequestTotal* are found. The *EqualPriorityRequestTotal* is then compared to the volume of water available for use (*AvailableWater*). For requests from unallocated water *AvailableWater* will be the unallocated storage in the river above the *DroughtInstantaneousFlow* level, while for requests from allocated water it will be the quantity already allocated to the user. The *RequestQuantities* are finally allocated to the user or used to calculate *ReallocationQuantities* if insufficient storage exists, which are in turn allocated to the user. Finally, before proceeding to the next set of equal highest priority users, the flow in the river is recalculated with the amounts already allocated to users removed from it.

All transfers from the channel occur as direct abstractions and, as a result, the procedure is far simpler than that for dams. All water is abstracted from the channel via the *CWaterTransfer* component and conveyed to the user.

5. VALIDATION, CASE STUDY AND RESULTS

In order to evaluate the operating rule framework it was necessary to apply it to an operational situation. The testing of the model involved two procedures, initial code validation to determine whether the framework was producing the correct results and the running of real-life scenarios. The upper Pongola River catchment was found to be appropriate for this purpose, partly because it contains the Paris Dam, a large dam in accordance with the world classification of dams (LeCornu, 1998, cited by McCartney *et al.*, 1999) and partly because the ACRU model had already been configured for the catchment by Schulze *et al.* (1998). The following section gives a brief description of the Pongola River catchment.

5.1 Description of the Pongola River Catchment

The Pongola River catchment is situated in the northern part of the Kwazulu-Natal Province and stretches latitudinally from 27°05' to 27°45'S and longitudinally from 30°15' to 31°40'E, as shown in Figure 5.1. The catchment contains the Paris Dam situated on the Bivane River, a major tributary of the Pongola River. Effective operation of the dam is essential in order to comply with the requirements of the National Water Act (1998). Paris Dam was built largely to provide a source of assured water supply for the Pongola Irrigation scheme on the Pongola River near the town of Pongola (Schulze *et al.*, 1998). Figure 5.1 shows a map of the portion of the Pongola River catchment that was used for all simulations, and includes Paris Dam as well as the delimitation of the subcatchments.

5.2 The Basic Setup of *ACRU*2000 for the Pongola River Catchment

*ACRU*2000 represents a catchment as a set of subcatchments that are in turn divided into land segments. The simulated area of the Pongola River catchment, shown in Figure 5.1, covers 19 quaternary catchments as designated by the Department of Water Affairs and Forestry. The setup used by Schulze *et al.* (1998) recognised the site of Paris Dam as a designated, separate catchment outlet and thus a total of 20 subcatchments were used.

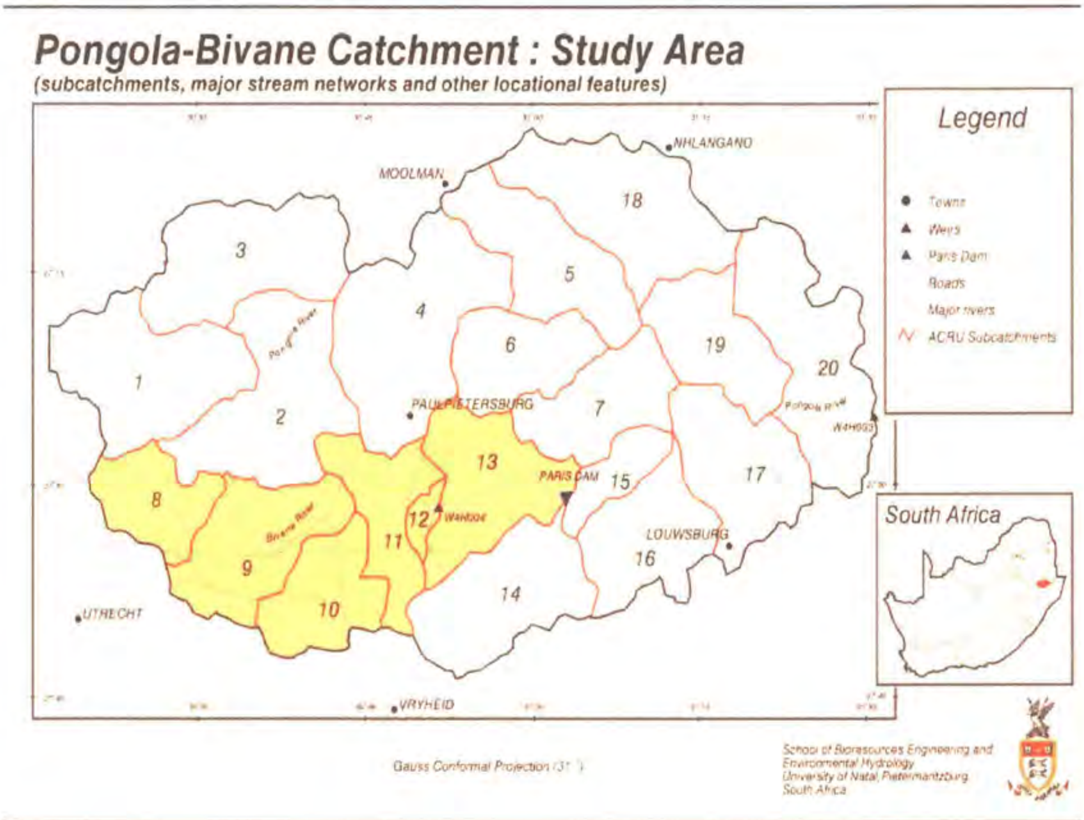

Figure 5.1 Location of the Pongola River catchment and subcatchment delineation (after Schulze *et al.*, 1998)

Figure 5.2 illustrates the flow configurations from one subcatchment to the next, used for the simulations. For the purposes of simplification, each subcatchment is regarded as having a single main channel or reach running through it and these are represented by the small blocks numbered R1 to R20. These blocks are all displayed in a light blue colour. The location of certain water users that are referred to in more detail in Section 5.8, and the necessary water transfers that take place to supply these users are indicated in Figure 5.2 along with the location of three IFR sites (shown in red). IFR site 1 lies directly below Paris Dam, IFR site 2 lies on the Bivane River directly above the confluence with the Pongola River and IFR site 3 lies on the Pongola River directly below the confluence with the Bivane River. IFR site 2 was chosen to act as the environmental user for all simulations over the other two sites because it was considered that the required flow regime at IFR site 1 would be impossible to meet due to the irrigation releases being made from Paris Dam for the Pongola Irrigation scheme. The requirements of IFR site 3 were not considered because it is situated on the Pongola River and thus should be satisfied largely by the flow in the Pongola

River. The Upper Pongola weir, shown in Figure 5.2, is used by the Pongola Irrigation scheme as a basis to determine how much water is required from Paris Dam on a day. This is discussed further in Section 5.6.

Figure 5.2 Diagram of the subcatchment configurations (after Schulze *et al.*, 1998)

Table 5.1 shows an IFR table determined for both IFR sites 1 and 2. It is not within the scope of this dissertation to discuss the exact reasons behind the flows determined in this table and more information on this is given by Impala Irrigation Board (1997). It is important to note that the drought flows represent a minimum amount of water required to ensure the survival of the aquatic ecosystems for brief periods when all users relying upon the resource are subject to water restrictions (Impala Irrigation Board, 1997). Many of the drought baseflows recommended are also lower than any flows ever recorded or simulated in the Bivane River. The values present in this table are used throughout this dissertation for simulations involving environmental releases from Paris Dam.

Table 5.1 IFR table for IFR sites 1 and 2 situated on the Bivane River (after Impala Irrigation Board, 1997)

		Month											
Maintenance flows	**Units**	**Oct**	**Nov**	**Dec**	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**
Baseflows	$m^3.s^{-1}$	1.1	2.4	3.2	4	3.5	3	1.8	1	0.8	0.65	0.5	0.8
Monthly volumes	$m^3 \times 10^6$	2.95	6.22	8.57	10.71	8.47	8.04	4.67	2.68	2.07	1.74	1.34	2.07
Flood	$m^3.s^{-1}$	5	10	6	30		10						
Duration	days	4	4	4	5		4						
Time to peak flow	days	1	1	1	1		1						
Flood volumes	$m^3 \times 10^6$	0.67	1.31	0.48	2.81		1.21						
Drought flows													
Baseflows	$m^3.s^{-1}$	0.35	0.4	0.5	0.75	0.6	0.5	0.45	0.4	0.3	0.3	0.3	0.3
Monthly volumes	$m^3 \times 10^6$	0.94	1.04	1.34	2.01	1.45	1.34	1.17	1.07	0.78	0.8	0.8	0.78
Flood	$m^3.s^{-1}$	1		2.5	6		2.5						
Duration	days	4		4	4		4						
Time to peak flow	days	1		1	1		1						
Flood volumes	$m^3 \times 10^6$	0.11		0.35	0.91		0.35						

5.3 Code Validation

Before attempting to apply and if necessary adapt the operating rule framework to a practical situation, it was imperative to validate the code in order to check if the algorithms described in Chapter 4 were producing the desired results. The following sections describe the validations and focus specifically on the simple and complex environmental request methods and the two operating rules, while also exploring the optimisation of certain parameters used in the framework.

5.3.1 Validation of the simple environmental request method

Validation of the simple environmental request method was required in order to determine whether the timing and quantities of the volumes requested every day for the purposes of satisfying the ecological reserve were generated correctly. This involved determining whether the transition between drought and maintenance flows for both low and high-flows was implemented correctly and that the quantities requested were correct. The following section describes the steps taken for validation of the low-flow requests.

5.3.1.1 Validation of the low-flow requests

As described in Section 4.4.1.1, the determination of whether to release a maintenance or drought flow on a day is achieved using the three variables *CurrentDayInflow*, *MainInstantaneousFlow* and *DroughtCriterion*, as described in Table B2 of Appendix B. For initial simulations, the *DroughtCriterion* value was chosen to have the same value throughout the year. However, in order to make the low-flow releases as realistic as possible, optimisation of the *DroughtCriterion* value was required for each month of the year. The assumption was made that the *DroughtCriterion* should be linked to the low-flow values specified by the BBM. In order to determine the *DroughtCriterion* value for a month, the *DroughtInstantaneousFlow* value was divided by the *MainInstantaneousFlow* value. The final monthly *DroughtCriterion* values used for all simulations using the simple environmental request method are shown in Table 5.2.

Having found more representative values of the *DroughtCriterion* for use in determining when drought or maintenance flow conditions exist, it was imperative to establish whether this parameter was producing the desired results. A simulation was run for four years (1946 to 1949) and the output produced was used to validate the correct functioning of the three variables. The simulation was run with IFR site 2 as the only water user included in the model configuration. Table 5.3 contains a sample portion of this output produced by the simulation.

Table 5.2 Drought criterion values used for code validation

Month	*MainInstantaneousFlow* $m^3.s^{-1}$	*DroughtInstantaneousFlow* $m^3.s^{-1}$	*DroughtCriterion* %
January	4.00	0.75	19
February	3.50	0.60	17
March	3.00	0.50	17
April	1.80	0.45	25
May	1.00	0.40	40
June	0.80	0.30	38
July	0.65	0.30	46
August	0.50	0.30	60
September	0.80	0.30	38
October	1.10	0.35	32
November	2.40	0.40	17
December	3.20	0.50	16

Table 5.3 Sample output used to validate the simple low-flow environmental request method

Date	*ReqRelease* m^3	*TransferQuantity* m^3	*CurrentDayInflow* $m^3.s^{-1}$	*DroughtCriterion* x *MainInstantaneousFlow* $m^3.s^{-1}$
08-Jan-46	64800.00	64800.00	0.55	0.76
09-Jan-46	345600.00	64800.00	5.36	0.76
10-Jan-46	345600.00	345600.00	55.81	0.76
11-Jan-46	345600.00	345600.00	47.01	0.76
12-Jan-46	345600.00	345600.00	30.66	0.76
13-Jan-46	345600.00	345600.00	21.15	0.76
14-Jan-46	345600.00	345600.00	16.76	0.76
15-Jan-46	345600.00	345600.00	17.70	0.76

In Table 5.3, the *MainInstantaneousFlow* value for January was set at 4 $m^3.s^{-1}$ and the *DroughtCriterion* value was set at 19 %, with the product of these two values equal to 0.76. In the algorithm employed, which is described in Section 4.4.1.1, this value was then compared to the value of *CurrentDayInflow* entering Paris Dam. If it exceeded *CurrentDayInflow* as occurred on the 8 January 1946, the drought flow should be released. The main reason that the *CurrentDayInflow* value was so low for the month of January was because these results were taken from the first few days of the simulation. Since this simulation was used purely for validation, no "warm up" period was employed and consequently, no major rainfall event occurred until 9 and 10 of January which resulted in the inflows entering the dam before this time remaining very low. It is important to note that a one day lag exists between the generation of any environmental request and the transfer of that request out of the dam. This is caused by the IFR site being situated downstream of the dam with the result that the *PGenericOperatingRule* process has already ended on the current day of the simulation before any environmental request is generated. Methods to avoid this problem were considered too time consuming for this project.

Referring again to the output on the 8 January the *DroughtInstantaneousFlow* for the month, as specified in Table 5.2 was set at 0.75 $m^3.s^{-1}$ and when converted to a daily volume, a value of 0.75 x 24 x 3600 = 64800 m^3 was obtained. This volume was then transferred out of the dam on the 9 January. On all the other days shown in Table 5.3 the *CurrentDayInflow* value exceeded the product of the *DroughtCriterion* and the *MainInstantaneousFlow*. The daily release required under maintenance conditions was 4 x 24 x 3600 = 345600 m^3 which is in agreement with the values in Table 5.3.

5.3.1.2 Validation of the high-flow requests

The main criterion for allowing the release of the high-flow request is that sufficient storage exists in the dam acting as the water source to supply the entire flood volume. Since no demands other than the ecological reserve requirements were placed on the system the dam never dropped below 94% of full capacity during the simulation, with the result that the flood was automatically released on the first day of the month for which it was specified. The more important consideration for validation was whether the correct flood (i.e. drought or maintenance) was being released. The determination of this is provided in the same way as for the transition between the maintenance and drought low-flows. From the same simulation used for the validation in Section 5.3.1.1, sample output produced is shown in Table 5.4.

Table 5.4 Sample output used to validate the simple high-flow environmental request method

Date	*ReqRelease* m^3	*TransferQuantity* m^3	*CurrentDayInflow* $m^3.s^{-1}$	*DroughtCriterion* x *MainInstantaneousFlow* $m^3.s^{-1}$
01-Oct-46	168480.00	0.00	6.53	0.352
02-Oct-46	280800.00	168480.00	7.06	0.352
03-Oct-46	168480.00	280800.00	2.96	0.352
04-Oct-46	56160.00	168480.00	2.14	0.352
05-Oct-46	0.00	56160.00	1.70	0.352
06-Oct-46	0.00	0.00	1.38	0.352

Table 5.4 shows output from the simulation during the month of October 1946. The values for *DroughtCriterion* and *MainInstantaneousFlow* (from Table 5.2) are 32 % and 1.1 $m^3.s^{-1}$ respectively. On 1 October 1946 when the flood is requested, the product of these two values is 0.352 $m^3.s^{-1}$ while the *CurrentDayInflow* value is 6.53 $m^3.s^{-1}$. Since the *CurrentDayInflow* value is greater than the product value, the maintenance flood for the month is released, again with a one day lag between the request and the transfer.

It was also considered important to check whether the daily flood volumes were released according to the triangular hydrograph shape described in Section 4.4.1.2. On the first day the flood is supposed to reach the *MainPeakFlow* value of 5 $m^3.s^{-1}$. The volume required for release is thus 168480 m^3 from Equation 4.6, which agrees with the value transferred on the following day in Table 5.4. Using a similar approach in conjunction with Equations 4.6 to 4.8, the following days were also checked and found to agree with the values transferred out of the dam. The total volume of the flood released was found by summing the releases occurring over the four days of the flood release and a total of 673920 m^3 was obtained. This agreed with the total volume of the flood as specified in Table 5.1 for the month of October.

5.3.2 Validation of the complex environmental request method

Validation of the complex environmental request method was also required to ensure that the timing and quantities requested for the purposes of satisfying the ecological reserve were correct. Initial simulations were run with the monthly threshold values (*DroughtThreshold*, *MainThreshold* and *MaxThreshold*) set as constant values throughout the year. This proved to be inadequate and optimisation of these was required before proper validations could be carried out. The procedure followed for optimisation of these monthly threshold values is discussed in Section 5.3.2.1.

5.3.2.1 Optimisation of the monthly threshold values to improve the low-flow releases

In initial simulations using the complex environmental request method, the values used for the monthly threshold values described in Section 4.4.2.1 were assumed to be constant for all months of the year with the *DroughtThreshold* set at 95 %, the *MainThreshold* set at 80 % and the *MaxThreshold* set at 75 %. However, the flows equivalent to these values from the duration curves were too high for most months of the year with the result that the drought flow was released the majority of the time. Consequently, optimisation was required with the assumption being made that the flow values equivalent to these three thresholds (*ModDroughtFlow*, *ModMainFlow* and *ModMaxFlow*, defined in Table B3 of Appendix B) should be as close as possible to the low-flows specified in the IFR table shown in Table 5.1.

In order to adjust the threshold values, a manual optimisation approach was adopted with each month being treated separately. A simulation of a few days in length was run using the same setup used in Section 5.3.1 and the variables, *DroughtThreshold*, *MainThreshold*, *MaxThreshold*, *ModDroughtFlow*, *ModMainFlow* and *ModMaxFlow* were noted. The three threshold values were then raised if the flow values produced were too high or lowered if the flow values were too low. This process was repeated until the *ModDroughtFlow* and *ModMainFlow* values were as close as possible to the *DroughtInstantaneousFlow* and *MainInstantaneousFlow* values for the month.

The *ModMaxFlow* value was obtained slightly differently. The Desktop IFR methodology, described by Hughes and Munster (2000), is a basic method used for determining the ecological reserve and utilises a set of regionalised values to determine maximum low-flow values. South Africa has been divided into various subregions with each region having its own set of maximum low-flow parameters, a set of monthly percentages by which the *MainInstantaneousFlow* value can be exceeded. The Pongola catchment is situated in the subregion designated as northern Natal, which has a constant maximum low-flow parameter throughout the year of 120 %. Therefore, all *MainInstantaneousFlow* values in the IFR table were increased by 20 % for all months of the year and the *ModMaxFlow* values were compared to these values during the optimisation procedure.

During this optimisation process it was assumed that the minimum increment used for the threshold values was 0.5 %. In addition, the *DroughtThreshold* value was assumed to have a maximum value of 99.5 %. When two values were very close to the value in the IFR table i.e. 88.5 % was equivalent to 4.08 $m^3.s^{-1}$ and 89 % was equivalent to 3.94 $m^3.s^{-1}$, where the desired flow was 4 $m^3.s^{-1}$, the higher flow value of 4.08 $m^3.s^{-1}$ was chosen.

Table 5.5 contains the results of the approach used for optimisation of the threshold values for the month of January. The values in bold print represent the values chosen as the threshold and equivalent flow values for the month. Table 5.6 contains the final values chosen for each of the three threshold values for each month of the year.

Table 5.5 Optimisation of the threshold values for the month of January

DroughtThreshold %	*ModDroughtFlow* $m^3.s^{-1}$	*MainThreshold* %	*ModMainFlow* $m^3.s^{-1}$	*MaxThreshold* %	*ModMaxFlow* $m^3.s^{-1}$
95	2.28	80	5.48	75	5.93
99	1.37	90	3.65	80	5.48
99.5	**0.89**	85	4.76	85.5	4.69
		88	4.15	**84.5**	**4.83**
		88.5	**4.08**		
		89	3.94		

Table 5.6 Threshold values used for all Paris Dam simulations

		Month											
	Units	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
DroughtThreshold	%	99.5	99.5	99.5	99.5	99	99.5	99.5	99	99.5	99.5	98.5	99.5
ModDroughtFlow	$m^3.s^{-1}$	0.89	0.73	0.73	0.86	0.45	0.59	0.45	0.38	0.31	0.4	0.47	0.56
Target IFR value	$m^3.s^{-1}$	0.75	0.6	0.5	0.45	0.4	0.3	0.3	0.3	0.3	0.35	0.4	0.5
MainThreshold	%	88.5	94	94.5	98	98.5	98.5	97.5	98.5	85.5	77	75	83
ModMainFlow	$m^3.s^{-1}$	4.08	3.68	3.07	1.87	1.05	0.87	0.71	0.5	0.8	1.1	2.41	3.27
Target IFR value	$m^3.s^{-1}$	4	3.5	3	1.8	1	0.8	0.65	0.5	0.8	1.1	2.4	3.2
MaxThreshold	%	84.5	91	90.5	96	98	97.5	96.5	97	78	69.5	68.5	79.5
ModMaxFlow	$m^3.s^{-1}$	4.83	4.24	3.7	2.17	1.23	0.97	0.8	0.53	0.97	1.33	2.91	3.9
Target IFR value	$m^3.s^{-1}$	4.8	4.2	3.6	2.16	1.2	0.96	0.78	0.6	0.96	1.32	2.88	3.84

5.3.2.2 Validation of the low-flow requests

The validation of the quantities and timings of the low-flow requests was achieved by evaluating the four scenarios which may exist when determining the low-flow request quantity, as specified in Table 5.7. Each scenario has an equation for calculating the daily request quantity and depends on the value of the *BaseflowStatus*. A five year simulation was run with IFR site 2 as the only water user employed, in order to properly check that these equations were all working correctly. Table 5.7 contains output from the simulation for each of the four cases. The equations used for computing the request quantity can be found in Section 4.4.2.1 and the number of the equation used for each scenario is given in Table 5.7. Validation of the *ReqRelease* values was undertaken using each of these equations, and the results produced by the model were found to be acceptable.

Table 5.7 Validation of the low-flow request quantities for the four different scenarios

Scenario 1 : *BaseflowStatus* ≤ *ModDroughtFlow*				
Date	**Units**	**07-Nov-47**	**08-Nov-47**	**09-Nov-47**
BaseflowStatus	$m^3.s^{-1}$	0.44	0.43	0.43
ModDroughtFlow	$m^3.s^{-1}$	0.47	0.47	0.47
ModMainFlow	$m^3.s^{-1}$	2.41	2.41	2.41
ModMaxFlow	$m^3.s^{-1}$	2.91	2.91	2.91
CurrentDayFlow	$m^3.s^{-1}$	2.07	3.85	18.59
MainInstantaneousFlow	$m^3.s^{-1}$	2.4	2.4	2.4
DroughtInstantaneousFlow	$m^3.s^{-1}$	0.4	0.4	0.4
ReqRelease (Equation 4.2)	m^3	34560.00	34560.00	34560.00
TransferQuantity	m^3	34560.00	34560.00	34560.00
Scenario 2 : *BaseflowStatus* > *ModDroughtFlow* and ≤ *ModMainFlow*				
Date	**Units**	**10-Oct-46**	**11-Oct-46**	**12-Oct-46**
BaseflowStatus	$m^3.s^{-1}$	0.98	0.98	0.98
ModDroughtFlow	$m^3.s^{-1}$	0.40	0.40	0.40
ModMainFlow	$m^3.s^{-1}$	1.10	1.10	1.10
ModMaxFlow	$m^3.s^{-1}$	1.33	1.33	1.33
CurrentDayFlow	$m^3.s^{-1}$	1.19	1.97	1.29
MainInstantaneousFlow	$m^3.s^{-1}$	1.1	1.1	1.1
DroughtInstantaneousFlow	$m^3.s^{-1}$	0.35	0.35	0.35
ReqRelease (Equation 4.12)	m^3	103035.75	175785.58	112628.58
TransferQuantity	m^3	89664.72	103035.75	175785.58
Scenario 3 : *BaseflowStatus* > *ModMainFlow* and ≤ *ModMaxFlow*				
Date	**Units**	**11-Jan-47**	**12-Jan-47**	**13-Jan-47**
BaseflowStatus	$m^3.s^{-1}$	4.34	4.47	4.47
ModDroughtFlow	$m^3.s^{-1}$	0.89	0.89	0.89
ModMainFlow	$m^3.s^{-1}$	4.08	4.08	4.08
ModMaxFlow	$m^3.s^{-1}$	4.83	4.83	4.83
CurrentDayFlow	$m^3.s^{-1}$	4.25	4.79	8.09
MainInstantaneousFlow	$m^3.s^{-1}$	4	4	4
DroughtInstantaneousFlow	$m^3.s^{-1}$	0.75	0.75	0.75
ReqRelease (Equation 4.13)	m^3	359684.26	405602.33	685165.46
TransferQuantity	m^3	403940.69	359684.26	405602.33
Scenario 4 : *BaseflowStatus* ≥ *ModMaxFlow*				
Date	**Units**	**21-Feb-49**	**22-Feb-49**	**23-Feb-49**
BaseflowStatus	$m^3.s^{-1}$	6.38	7.85	7.85
ModDroughtFlow	$m^3.s^{-1}$	0.73	0.73	0.73
ModMainFlow	$m^3.s^{-1}$	3.68	3.68	3.68
ModMaxFlow	$m^3.s^{-1}$	4.24	4.24	4.24
CurrentDayFlow	$m^3.s^{-1}$	16.53	14.54	11.64
MainInstantaneousFlow	$m^3.s^{-1}$	3.5	3.5	3.5
DroughtInstantaneousFlow	$m^3.s^{-1}$	0.6	0.6	0.6
ReqRelease (Equation 4.14)	m^3	348596.98	348596.98	348596.98
TransferQuantity	m^3	348596.98	348596.98	348596.98

5.3.2.3 Validation of the high-flow requests

With regard to the high-flow releases for the complex environmental request method, the most important criterion required for validation was whether the floods were being released by an appropriate climatic cue. As described in Section 4.4.2.2, the floods are released when the rate of rise in the river from one day to the next is sufficient to act as a trigger to cause either the release of the maintenance or the drought flood. Validation was achieved by analysing the high-flow requests and transfers produced from the simulation, a sample of which is shown in Table 5.8.

Table 5.8 Validation of the triggering of the flood release

Date	*ReqRelease* m^3	*TransferQuantity* m^3	*CurrentDayFlow* $m^3.s^{-1}$	*RateOfRise* $m^3.s^{-1}.day^{-1}$	*MinRateOfRise* $m^3.s^{-1}.day^{-1}$	*DroughtRateOfRise* $m^3.s^{-1}.day^{-1}$
09-Jan-46	0.00	0.00	5.36	4.81	13.00	5.25
10-Jan-46	1123200.00	0.00	55.81	50.45	13.00	5.25
11-Jan-46	1965600.00	1123200.00	47.01	-8.80	13.00	5.25
12-Jan-46	1404000.00	1965600.00	30.66	-16.35	13.00	5.25
13-Jan-46	842400.00	1404000.00	21.15	-9.51	13.00	5.25
14-Jan-46	280800.00	842400.00	16.76	-4.39	13.00	5.25
15-Jan-46	0.00	280800.00	17.70	0.94	13.00	5.25

In the example shown in Table 5.8, the *CurrentDayFlow* at the trigger point in the river on 10 January 1946 was 55.81 $m^3.s^{-1}$ and the *PreviousDayFlow* value was 5.36 $m^3.s^{-1}$, resulting in a *RateOfRise* of 50.45 $m^3.s^{-1}.day^{-1}$. The *MinRateOfRise* value for the month of January was set at 13 $m^3.s^{-1}.day^{-1}$. Hence, the *RateOfRise* value exceeded the *MinRateOfRise* value and the maintenance flood was released. The release of the correct flood volumes for each day was checked in the same way as in Section 5.3.1.2 and found to be in agreement with the values shown in Table 5.8. A similar validation of the release of a drought flood was undertaken and the results obtained suggested that the drought flood was also being correctly triggered and released.

5.3.3 Validation of the generic dam operating rule

In order to validate the generic dam operating rule, a simplified system was required. All dams were removed, with the exception of Paris Dam, and the only water requests used in the simulation were thus made to the Paris Dam and consisted of a domestic user, an IFR site, two industries and an irrigator. The domestic and industrial water users, as well as their daily request quantities used for this simulation, are fictitious and have been included solely for the purposes of the validation. The request quantities for these two users have been set very high in an attempt to draw the dam down into the lower levels of the curtailment structure and make it easier to assess the functioning of the curtailment structure algorithms.

A simulation was run for five years and the output produced was validated by checking if the curtailment structure was functioning correctly for the five users involved. The curtailment structure relies on the storage existing in the dam to determine the fraction of the demand that is likely to be met. In order to validate that the user's demands were being curtailed correctly, it was necessary to output the daily storage of the dam expressed as a percentage of full capacity, as well as the requests and water transfers for each water user. Table 5.9 contains the curtailment structure used for this simulation while Table 5.10 holds a sample of the output obtained.

Table 5.9 Curtailment structure employed by the generic dam operating rule

Management level (%)	100 - 80	80 - 60	60 - 40	40 - 20	20 - 0	Priority
Domestic	100	100	100	100	100	1
Environment	100	100	100	95	85	2
Industry (User 1)	100	100	100	90	80	3
Industry (User 2)	100	100	95	85	75	3
Irrigator	100	95	90	80	50	4

Table 5.10 Output used to verify the correct functioning of the curtailment structure

Date	Units	14-Oct-46	15-Oct-46	16-Oct-46	17-Oct-46	18-Oct-46	19-Oct-46
Dam storage	%	37.66	37.24	36.83	36.40	35.92	35.50
Domestic request	m^3	400000.00	400000.00	400000.00	400000.00	400000.00	400000.00
Domestic transfer	m^3	400000.00	400000.00	400000.00	400000.00	400000.00	400000.00
Env. Low-flow request	m^3	95040.00	95040.00	95040.00	95040.00	95040.00	95040.00
Env. Low-flow transfer	m^3	90288.00	90288.00	90288.00	90288.00	90288.00	90288.00
Env. High-flow request	m^3	0.00	0.00	0.00	0.00	0.00	0.00
Env. High-flow transfer	m^3	0.00	0.00	0.00	0.00	0.00	0.00
Industry1 request	m^3	100000.00	100000.00	100000.00	100000.00	100000.00	100000.00
Industry1 transfer	m^3	90000.00	90000.00	90000.00	90000.00	90000.00	90000.00
Industry2 request	m^3	10000.00	10000.00	10000.00	10000.00	10000.00	10000.00
Industry2 transfer	m^3	8500.00	8500.00	8500.00	8500.00	8500.00	8500.00
Irrigation request	m^3	0.00	0.00	0.00	63111.11	0.00	0.00
Irrigation transfer	m^3	0.00	0.00	0.00	50488.89	0.00	0.00

The 17 October 1946 is used for the purposes of an example. The current storage of the dam before operation began was 36.4 % and fell into the management level, from Table 5.9, of between 20 and 40 %. The domestic user requested a quantity of 400000 m^3 for the day and this amount was transferred to the domestic user as the relevant curtailment value was 100 %. The environment required an amount of 95040 m^3 for the day, but only 90288 m^3 was transferred due to the curtailment value being 95 %. Industry 1 requested 100000 m^3 on the day and the curtailment value for the given dam storage was 90 %, while Industry 2 requested 10000 m^3 with a curtailment value for the day of 85 %. Thus, the two industries' transfer quantities equalled 90000 m^3 and 8500 m^3 respectively. Finally, the irrigator made a request for 63111.11 m^3 of water. The curtailment value used was 80 % and the transfer out of the dam equalled 50488.89 m^3.

The curtailment structure was therefore functioning correctly when sufficient storage was available to meet the curtailed demands. It was also necessary to check if this was the case when the user's demands could not all be met and the dam could not satisfy all the requests on a day. The operating rule is driven by the principle that it must satisfy the highest priority users before considering the water requests of any users of lower priority. In the case of two users having the same priority but where insufficient water exists in the dam to satisfy their requests after curtailment, the remaining available storage in the dam should be distributed proportionally among the two users. Table 5.11 shows an example of where this occurred in the simulation.

Table 5.11 Output used to validate the reallocation quantities

Date	**Units**	**08-Nov-47**	**09-Nov-47**	**10-Nov-47**	**11-Nov-47**	**12-Nov-47**	**13-Nov-47**
Dam storage	%	10.38	11.49	11.67	11.60	11.44	10.73
Domestic request	m^3	400000.00	400000.00	400000.00	400000.00	400000.00	400000.00
Domestic transfer	m^3	400000.00	400000.00	400000.00	400000.00	400000.00	400000.00
Env. Low-flow request	m^3	207360.00	207360.00	207360.00	207360.00	207360.00	207360.00
Env. Low-flow transfer	m^3	43407.71	176256.00	176256.00	176256.00	176256.00	176256.00
Env. High-flow request	m^3	0.00	0.00	328320.00	547200.00	328320.00	109440.00
Env.High-flow transfer	m^3	0.00	0.00	0.00	328320.00	547200.00	286560.72
Industry1 request	m^3	100000.00	100000.00	100000.00	100000.00	100000.00	100000.00
Industry1 transfer	m^3	0.00	80000.00	80000.00	4147.97	80000.00	0.00
Industry2 request	m^3	10000.00	10000.00	10000.00	10000.00	10000.00	10000.00
Industry2 transfer	m^3	0.00	7500.00	7500.00	388.87	7500.00	0.00
Irrigation request	m^3	63111.11	0.00	0.00	0.00	0.00	0.00
Irrigation transfer	m^3	0.00	0.00	0.00	0.00	0.00	0.00

On the 8 November 1947 the storage of the dam was 10.38 % before operation began. The domestic user's request was considered first and satisfied fully. The environmental request was processed next, being of priority 2, with a quantity of 207360 m^3 requested. Dead storage in the dam is regarded as 10 % of full capacity and thus only an amount of 43407.71 m^3 existed above dead storage after the domestic user's request had been satisfied. The environment received this amount and all other users of a lower priority did not receive an allocation of water.

The simulation for 11 November 1947 provided an interesting situation with the dam storage initially at 11.60 %. The dam was able to supply curtailed amounts to the domestic and environmental users which corresponded to the curtailment values used. According to the curtailment structure, Industry 1 should have received 80000 m^3 and Industry 2 should have received 7500 m^3. However, insufficient available water was then present above dead storage to supply these amounts to the industries, which are of equal priority. Consequently, the remaining storage was distributed between the two industries as an equal portion of each industries curtailed request quantity. Equation 4.19 in Section 4.7.2 was used for this calculation.

5.3.4 Validation of the channel operating rule

A similar validation to that of the generic dam operating rule was undertaken for the channel operating rule and the results produced were correct. Having validated the various processes added to *ACRU*2000, it was now possible to begin making comparisons between selected methods. The following section focuses specifically on the environmental requests and compares the effectiveness of the simple and complex methods.

5.4 Comparison of the Simple and Complex Environmental Request Methods

The simple environmental request method was implemented purely as a starting point in order to account for the ecological reserve and it was hypothesised that this method would prove inadequate with regard to producing a simulated flow regime that adequately mimicked the natural flow conditions. It was further envisaged that the complex environmental request would account for some of the problems associated with the simple request. Before the operating rule framework could be properly applied to any real-life scenario, it was necessary to compare the two environmental requests in order to determine if either was capable of producing an artificial flow regime that was representative of natural flow conditions. It was also necessary to check if the equations used to determine the daily low-flow request quantities would prove adequate through the use of the *CurrentDayFlow* in the river as opposed to the *BaseflowStatus*. Selected output from the simulations run for validation of the two request methods at IFR site 2 is illustrated in Figure 5.3.

The three curves shown in Figure 5.3 represent the average daily flow entering Paris Dam from the Bivane River (*CurrentDayInflow* - blue line) and the average daily flows at IFR site 2 produced using the complex environmental request method (*PIFRComplex* - red line) and the simple environmental request method (*PIFRSimple* - green line). *CurrentDayInflow* has been included for the purposes of comparing the natural and artificial flow regimes, and also forms part of the triggering mechanism used by the complex environmental water request.

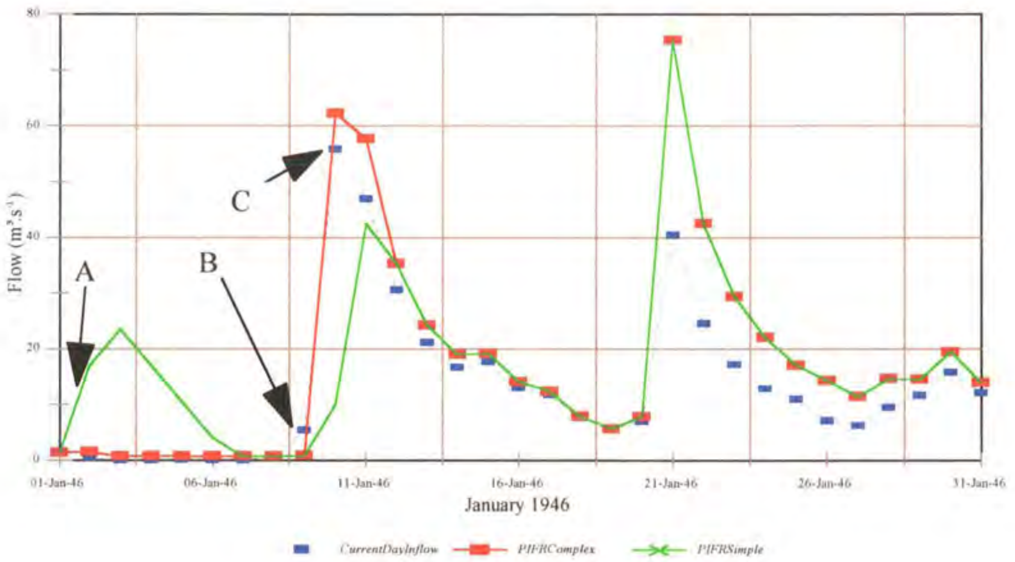

Figure 5.3 Simulated flows entering Paris Dam and at IFR site 2 for January 1946

From Figure 5.3, the low-flows for most of the month are similar for both the simple and complex environmental request methods. Although the flow regimes produced at IFR site 2 appear to follow the pattern of the flows above the dam reasonably well, the large difference in magnitudes could be a problem as the maintenance flow is being exceeded by large amounts during most of the month. These elevated flows at IFR site 2 can partly be attributed to a tributary of the Bivane

River situated between Paris Dam and IFR site 2. This tributary's influence is especially noticeable on 21 January 1946 where a large flood event occurring in the tributary has caused the flow at IFR site 2 to reach a level of 75 $m^3.s^{-1}$. To account for the effect of this tributary on the flow at IFR site 2, it would be necessary to find the average flow in it for each month of the year and then reduce the IFR low-flow requests by these amounts. A further reason for the flows at IFR site 2 being maintained at such high levels from 10 January 1946, is the large amount of spillway flow leaving the dam.

The simple and complex methods show marked differences concerning the release of the flood events for the month. The inflow entering the dam is relatively low at the beginning of the month and the letter A in Figure 5.3 indicates the first day of the release of the maintenance flood using the simple environmental water request. It should be noted that the desired peak flow of 30 $m^3.s^{-1}$ is not reached due to the daily flood release being averaged over the day. The flood releases continue until the five day duration of the flood is completed although no correspondence exists between this release of the maintenance flood and the flows at the upstream point. This discrepancy is caused by basing the criterion for the simple method's release of the flood purely on the storage in the dam. The complex environmental request method is partly able to overcome this problem through its use of the rate of rise in the river. The increase in flow at the upstream point of 50.45 $m^3.s^{-1}.day^{-1}$ (See B and C in Figure 5.3) is sufficient to cue the release of the maintenance flood using the complex environmental request and provides a link between the flood release and the natural conditions occurring in the river. The peak flow reached on the first day of the flood release is well above the 30 $m^3.s^{-1}$ specified by the BBM due to the large amount of spillway flow occurring as well as the contribution of the downstream tributary. Figure 5.4 shows another example of flows produced at the IFR site, for the month of October.

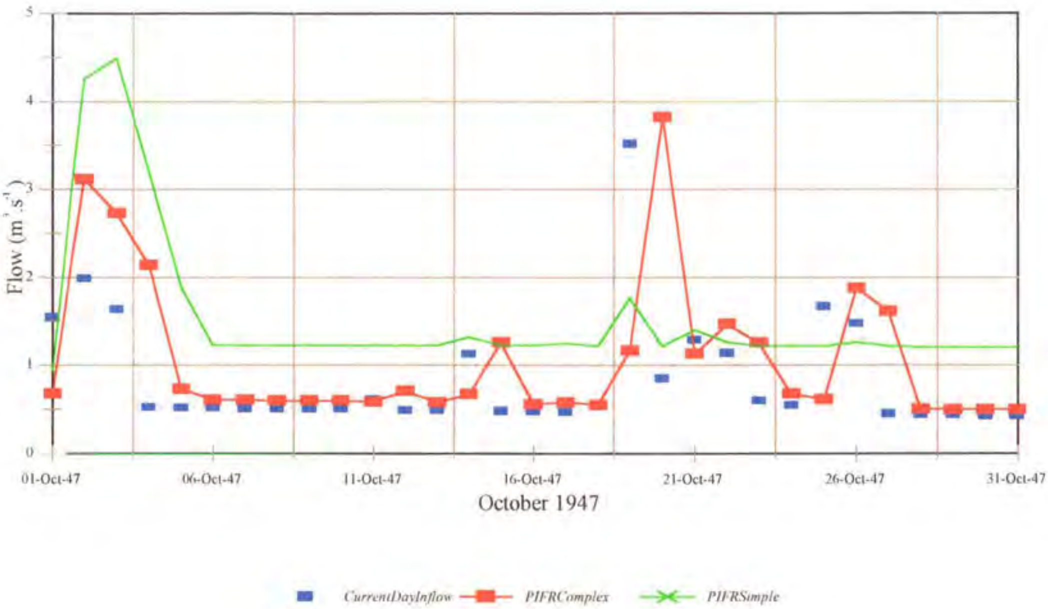

Figure 5.4 Simulated flows entering Paris Dam and at IFR site 2 for October 1947

This graph highlights a further weakness in the simple environmental request method with regard to the release of the low-flows. It can be seen that the simple method is providing the maintenance flow for most of the month, whereas the complex approach is providing a flow between the drought and maintenance levels. The flows produced by the complex method follow the pattern of the flow upstream of the dam more closely which can be attributed to the use of the *CurrentDayInflow* value. A flood is also specified in this month and is released on the first day of the month by both methods. The simple method releases the maintenance flood while the complex method only releases the drought flood as the rate of rise from the previous day (not shown in Figure 5.4) is 1.01 $m^3.s^{-1}.day^{-1}$, which is less than the *MinRateOfRise* criterion. It should be noted that the peak flows obtained by both the drought and maintenance floods exceed the values specified by the BBM, which can again be attributed to the influence of the downstream tributary. Given that a number of major weaknesses inherent within the simple environmental request method exist, any simulations presented in the remainder of this dissertation will utilise the complex environmental request method only.

The release of the drought flood by the complex method highlights a weakness with this particular methodology. This is indicated by the flows entering the dam on 19 October 1947, where there is a more significant rate of rise of 2.98 $m^3.s^{-1}.day^{-1}$. This rate of rise would have been sufficient to trigger the release of the maintenance flood for the month. However, this flood was not released due to the drought flood having already been released earlier in the month. The fact that a release is made on 20 October 1947 that mimics the flows entering the dam on 19 October 1947 indicates a further problem inherent within the complex method. The principle on which the low-flow releases are based is that the flows are limited to between the drought flow specified by the BBM (*DroughtInstantaneousFlow*) and a flow slightly above the value of the maintenance flow i.e. *ModMaxFlow* described and optimised for each month of the year in Sections 4.4.2.1 and 5.3.2.1 respectively. This flow on 20 October 1947 has been produced by a low-flow release which is too high and thus indicates a problem with Equation 4.12, which was used to determine the low-flow quantity. In Section 4.4.2.1, it was mentioned that the use of *CurrentDayFlow* in Equations 4.12 and 4.13 was in an attempt to provide a flow regime that mimicked flow conditions at the trigger point as closely as possible. However, this parameter appears to be inadequate as these equations result in flows less than *DroughtInstantaneousFlow* and greater than *ModMaxFlow*, depending on the value of *CurrentDayFlow*. It was therefore considered necessary to substitute the value of *BaseflowStatus* in place of *CurrentDayFlow* and compare the results obtained. Figure 5.5 shows the same month of flows i.e. October 1947 but with flows produced at IFR site 2 using the *BaseflowStatus* value (*BaseflowStatus* - red line) in Equations 4.12 and 4.13.

From Figure 5.5, it is evident that the sudden rise in flow above the dam on 19 October 1947 is no longer mimicked by the flow at IFR site 2. The use of *BaseflowStatus* in the two low-flow equations ensures that the low-flows are maintained within the two limits of the *DroughtInstantaneousFlow* and the *ModMaxFlow* for the month of October. Consequently, any further simulations presented in the remainder of this dissertation have been performed with *BaseflowStatus* in place of *CurrentDayFlow* in Equations 4.12 and 4.13. The small peaks occurring at IFR site 2 in Figure 5.5 can again largely be attributed to the influence of the downstream tributary. In the following section, further improvement of the complex environmental request method with regard to the releases for high-flows is investigated.

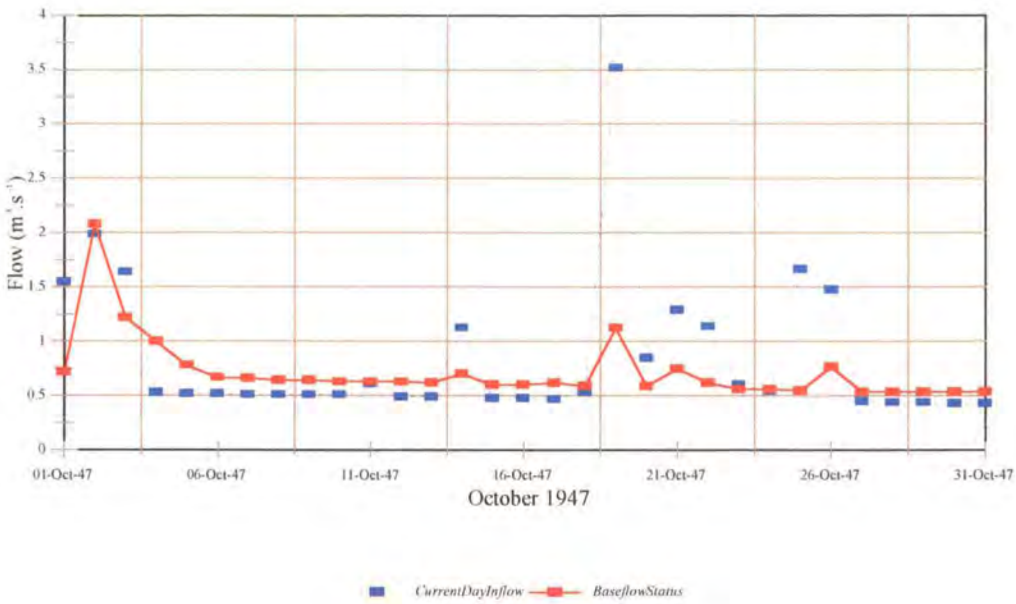

Figure 5.5 Simulated flows at IFR site 2 using the *BaseflowStatus* value

5.5 An Alternative Approach to Triggering the High-flows Using the *PIFRComplex* Process

As a result of the inadequacies of the trigger for high-flows used by the complex environmental request method discussed in the previous section, an alternative approach was developed, based partly in principle on methods employed in the IFR model (Hughes, 2000), in an attempt to make the flood releases more representative of the natural flow conditions. In this section, the alterations are discussed and comparisons drawn between this method and the previous method of triggering flood releases.

5.5.1 Methodology followed

As shown in Section 5.4, a major problem with the existing method of cueing floods using the *PIFRComplex* process, described in Section 4.4.2.2 and Table B3 of Appendix B, is that the drought flood was occasionally triggered early in a month, whereas the maintenance flood could have been triggered later on in the same month. This occurred because the *RateOfRise* for the day was less than the *MinRateOfRise* criterion but greater than the *DroughtRateOfRise*. This resulted in the drought flood being released whereas later in the month an event with a *RateOfRise* sufficient to cue the release of the maintenance flood occurred. In an attempt to overcome this problem an *AttenuationParameter* was applied to the *MinRateOfRise* criterion as the simulation proceeded further into the month. The value for *AttenuationParameter* is found using Equation 5.1.

$$AttenuationParameter = \frac{(MainRateOfRise - DroughtRateOfRise)}{DaysInMonth} \tag{5.1}$$

where:

DaysInMonth = the total number of days in the relevant month.

On the first day of a month the *MinRateOfRise* criterion is automatically set equal to the *MainRateOfRise* value specified by the BBM. For the remaining days in the month Equation 5.2 is used to calculate the *MinRateOfRise* value.

$$MinRateOfRise = MainRateOfRise - (AttenuationParameter * CurrentDay) \tag{5.2}$$

where:

CurrentDay = the current day in the month and will thus have a value of 1 on the first day of the month

On the final day of the month, i.e. when *CurrentDay* = *DaysInMonth*, the *MinRateOfRise* criterion equals the *DroughtRateOfRise*. The relationship between *MinRateOfRise* and *CurrentDay* is shown graphically in Figure 5.6. The *AttenuationParameter* could be considered as the slope of the graph.

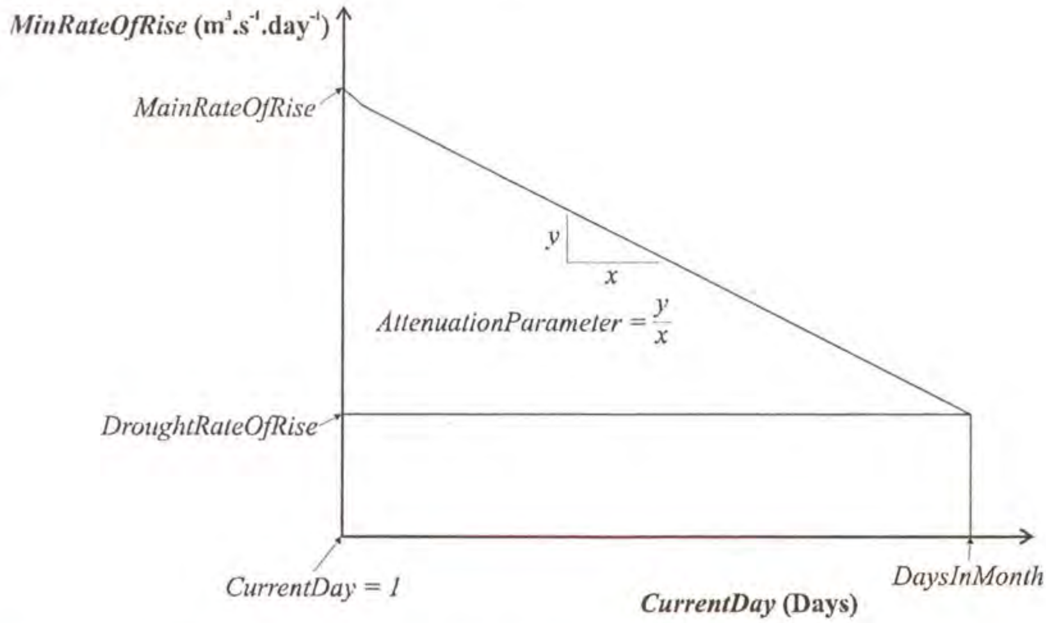

Figure 5.6 Graph showing the relationship between *MinRateOfRise* and *CurrentDay*

It was still difficult to determine whether a drought or maintenance flood should be released on the day using this technique. Hence, a further criterion (*BaseflowStatus*) was added to the algorithm to give some indication of whether drought or maintenance conditions prevail and is used in conjunction with a value termed the *FloodThreshold*. This *FloodThreshold* value is calculated using Equation 5.3.

$$\begin{aligned} FloodThreshold &= ModDroughtFlow + \{(ModMainFlow - ModDroughtFlow) \\ &\quad * ThresholdValue\} \end{aligned} \quad (5.3)$$

where:

ModDroughtFlow and *ModMainFlow* = the flows ($m^3.s^{-1}$) equivalent to the drought and maintenance low-flow thresholds (See Section 4.4.2.1 and Table B3 of Appendix B)

ThresholdValue = a percentage value used to raise the *FloodThreshold* value above the *ModDroughtFlow* value. The *ThresholdValue* was initially chosen to be a constant value of 25 % for all months of the year. In order to determine whether this was a valid assumption, the parameter was optimised and the procedure followed is explained in Section 5.5.2.

Figure 5.7 describes the new method of triggering the floods using the *PIFRComplex* method.

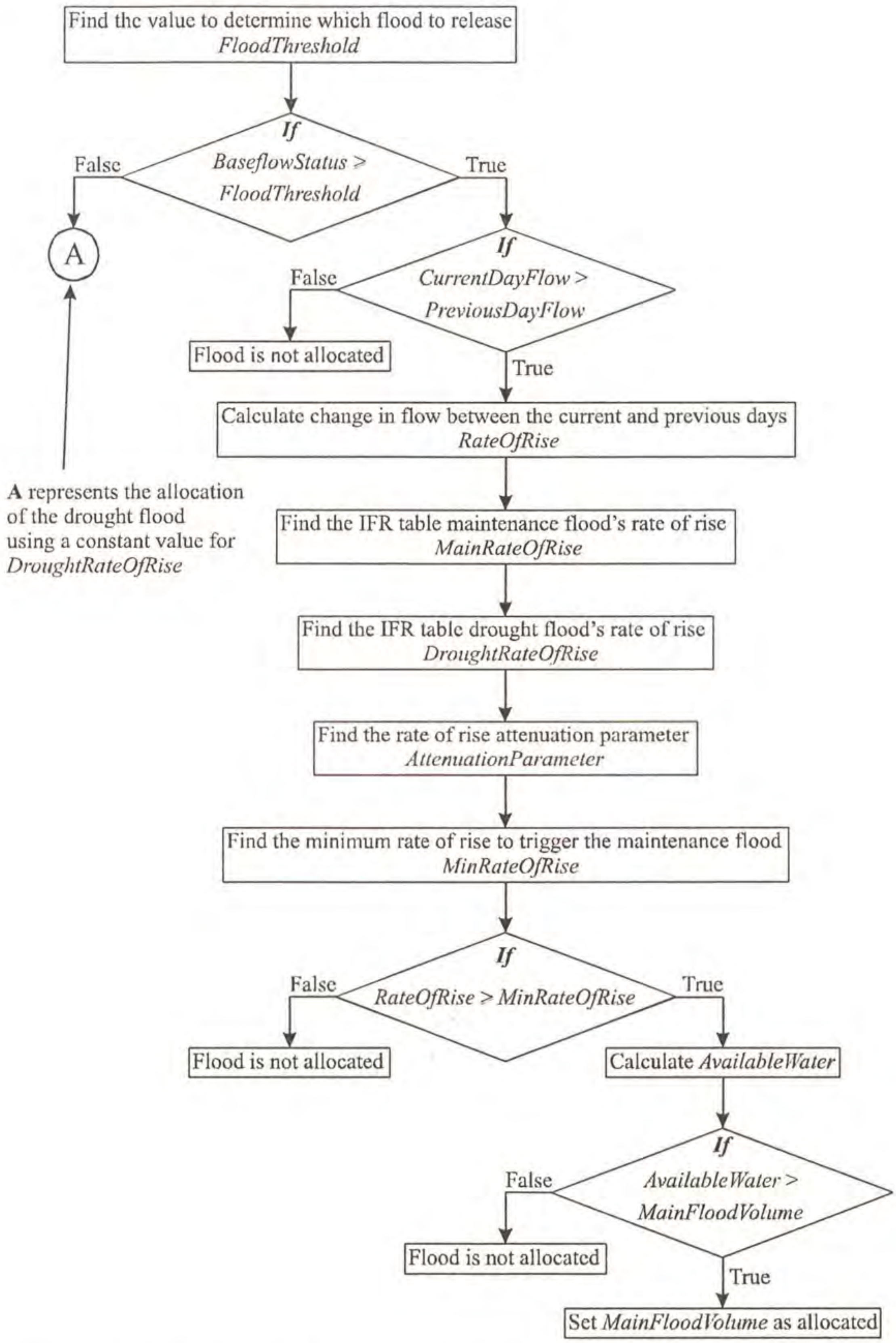

Figure 5.7 Flow diagram of the alternative flood triggering method employed by the *PIFRComplex* process

The *FloodThreshold* value is first calculated and compared to the *BaseflowStatus*. If the *BaseflowStatus* exceeds the *FloodThreshold* it is assumed that maintenance conditions exist. The procedure followed from there on is similar to the original method described in Section 4.4.2.2. However, instead of using a constant value for the *MinRateOfRise* criterion, its value is decreased until it equals the *DroughtRateOfRise* value on the last day of the month. If the *FloodThreshold* value exceeds the *BaseflowStatus* value, drought conditions prevail and procedure A, which is used to trigger the release of a drought flood, is entered. Procedure A also involves checking whether a positive *RateOfRise* value is obtained but instead of comparing this value to the *MinRateOfRise* value, it is automatically compared to the *DroughtRateOfRise* value which remains constant throughout the month.

5.5.2 Results and subsequent optimisation of the *ThresholdValue*

To evaluate the effectiveness of the new trigger method compared to the previous method described in Section 4.4.2.2, a graph of flows simulated at IFR site 2 for both methods during October 1947 is shown in Figure 5.8.

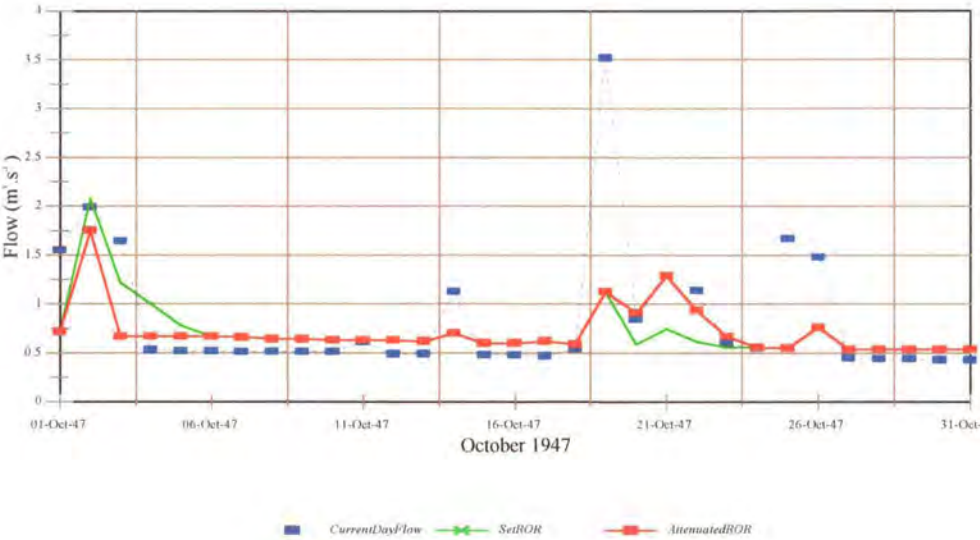

Figure 5.8 Comparison of the two alternative flood triggering methods

The flows produced using the two methods are exactly the same when low-flow releases are made. However, major differences were found throughout the simulation during periods of high-flow release. In Figure 5.8, the blue line (*CurrentDayInflow*) represents the inflow entering Paris Dam from the Bivane River, while the green (*Set ROR*) and red lines (*Attenuated ROR*) represent the two methods for triggering the flood using the fixed *MinRateOfRise* or the attenuated *MinRateOfRise* and *FloodThreshold* values respectively. Using the fixed *MinRateOfRise* value results in the maintenance flood being triggered by a small rate of rise occurring on 1 October 1947 (not shown in Figure 5.8). This rate of rise is insufficient to result in a flood release when the attenuated *MinRateOfRise* parameter is used. The *Attenuated ROR* method releases a drought flood from 19 October 1947 following a significant rate of rise of flow entering the dam on 18 October 1947. Although the *MinRateOfRise* criterion value used by the *Attenuated ROR* method would have been met by the rate of rise occurring on 18 October, a drought flood was released due to the *BaseflowStatus* at the time not being high enough to trigger a maintenance flood. Thus a drought flood was more suited to the climatic conditions existing in the catchment. This same scenario occurs regularly throughout the simulation and it can therefore be stated with confidence that the new method provides a trigger for the flood events that is more representative of the climatic conditions in the catchment.

The above simulations were produced for a 30 year duration. The *ThresholdValue* was set at 25 % for all months of the year and it was envisaged that this value would need to be altered for certain months and would require optimisation. It was assumed during this project that a maintenance flood should be released at least 80 % of the time with the drought flood being released on the remaining years. The number of times the maintenance flood was triggered in the period of simulation for each month in which a flood occurs was recorded. If the maintenance flood was triggered fewer than 24 out of the 30 years for a given month, the *ThresholdValue* was lowered, in accordance with the *BaseflowStatus* occurring in those months when no flood was triggered. If the maintenance flood occurred more frequently than 24 times in the simulation, the threshold value was left at 0.25. The results obtained showed that the threshold value of 0.25 (25 %) was acceptable for the months of January, March, October and December, with the maintenance flood being released at least 25 times for each of these months. The November maintenance flood was only released 22 times during the simulation and consequently the flood threshold was lowered to a value of 0.2 (20 %) which was found to be acceptable.

Having validated and optimised the various processes associated with the operating rule framework, it was decided to apply the framework to the actual operation of the Paris Dam as currently occurs in practice. Before this could be achieved it was necessary to investigate how the Paris Dam is currently operated and this is described briefly in the following section.

5.6 Description of the Current Operation of Paris Dam and the Pongola Irrigation Scheme

In order to simulate the operation of the Paris Dam it was necessary to investigate how the releases from the dam are currently made. This section describes briefly what releases are made, how the amounts to be released are determined and, more specifically, how the water is transferred from Paris Dam to the individual irrigation users making up the Pongola Irrigation scheme. Figure 5.9 below shows a view of Paris Dam while Figure 5.10 shows a view of the Bivane River directly below Paris Dam.

Figure 5.9 A view of a portion of Paris Dam

The main water user supplied by Paris Dam is the Pongola Irrigation scheme, while the dam is now also expected to account for the environmental requirements in the Bivane River. It supplies the town of Pongola and a few rural development water supply schemes with water for basic human needs as well as supplying an industrial requirement to the Illovo sugar mill and irrigation water to a community of small-scale farmers situated outside the town of Pongola. The releases for the Pongola Irrigation scheme are based on a telemetry system while those for the environmental releases are based solely on an IFR table. It is assumed by the dam operators that when a release for the irrigation scheme is made from the dam, this release contributes towards the requirements of the ecological reserve. High-flow releases are also made from the dam in accordance with the IFR table.

Figure 5.10 A view of the Bivane River from the wall of Paris Dam

The required amount of water to be released for irrigation on a day is determined using the daily flow in the Pongola River, measured at the Upper Pongola weir shown in Figure 5.2 and situated above the confluence of the Bivane and Pongola Rivers. The weir is linked via telemetry to the Impala Irrigation Board headquarters in Pongola. Total monthly demands for the irrigation scheme are converted to daily flow values and the daily release for irrigation is calculated by comparing the flow at the Upper Pongola weir to the daily flow required by the scheme. If flow at the weir exceeds the flow required by the irrigation scheme for a day, no water is released. If the flow at the weir is less than the required irrigation scheme flow, a release is made from the Paris Dam in order to increase the flow in the Pongola River to the desired value. To ensure that the sluices are releasing the correct amount a weir is situated about a hundred metres downstream of the dam and is shown in Figure 5.11. The dam wall can be seen in the background of this photograph.

Figure 5.11 Photograph of the measuring weir below the Paris Dam wall

The flow required for the irrigation scheme is then extracted at Grootdraai weir (Figure 5.12) on the Pongola River and flows into a settling dam. From there the desired flow is directed into an open canal system to supply the irrigation scheme, with a small amount being diverted back into the Pongola River. Figure 5.12 shows the main canal in the foreground with Grootdraai weir in the background.

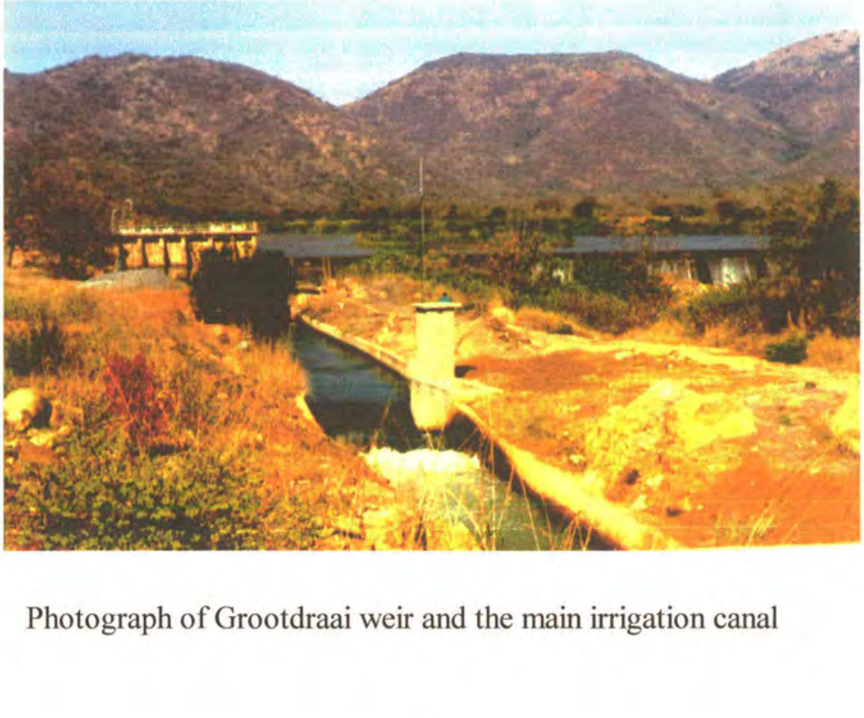

Figure 5.12 Photograph of Grootdraai weir and the main irrigation canal

The main canal has a capacity of 10 $m^3.s^{-1}$ and splits into two canals which can hold 2.5 $m^3.s^{-1}$ and 7.5 $m^3.s^{-1}$ respectively. Both canals split into a myriad of smaller canals and each farmer has his own individual off-takes. Most of these off-takes are sluice controlled while a few are pump controlled. Figure 5.13 shows a sluice controlled off-take.

Figure 5.13 Photograph of a sluice off-take system from a canal

In order for a farmer to extract water from the canal on which he is situated, he must request the water control manager at Impala Irrigation Board to open his/her sluice the desired amount. Each farmer has an allocation for each month and if the entire allocation is used and the farmer requires more water, he may purchase additional water from the Impala Irrigation Board, if it is available. The details of the irrigation canal system are not included in the model configuration and the whole scheme is regarded as a single water user. It may be possible in future to model even a very complex canal network such as this, given the current structure of *ACRU*2000.

5.7 Alterations Required to the Operating Rule Framework

In order to simulate the operation of Paris Dam as described in Section 5.6, a few minor modifications to the operating rule framework were required. Firstly, an alternative irrigation request process was required to represent the irrigation scheme. Secondly, changes to the generic dam operating rule were necessary to allow for combining the environmental and irrigation scheme releases. Finally, it was discovered that a slightly modified channel flow process would also be required. These three modified processes are briefly discussed in the following sections.

5.7.1 Inclusion of an alternative irrigation request process

As described in Section 5.6, the dam is operated according to the monthly flows required by the irrigation scheme and the flows present from day to day within the Pongola River. Figure 5.14 shows a flow diagram of the *PPongolaIrrigationSchemeReq* process used to generate the water request for the Pongola Irrigation scheme. Equations 5.4 and 5.5 show how the values for *FlowDeficit* ($m^3.s^{-1}$) and *ReqRelease* (m^3) are calculated and details of the other variables used are provided in Table B6 of Appendix B.

$$FlowDeficit = ReqIrrigationFlow - UpperPongolaWeirFlow \quad (5.4)$$

$$ReqRelease = FlowDeficit * 24 * 3600 \quad (5.5)$$

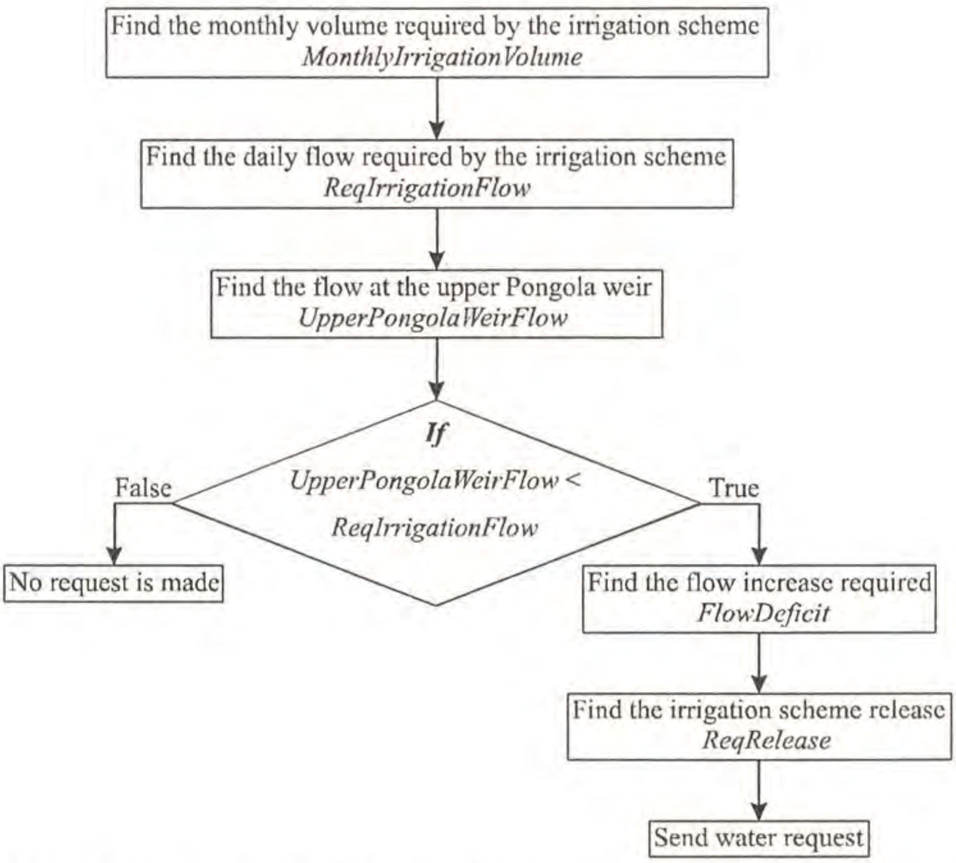

Figure 5.14 Flow diagram of the irrigation request process for the Pongola Irrigation scheme

5.7.2 Modification of the generic dam operating rule

The overall structure of the generic dam operating rule remained the same for the purposes of simulating the operation of Paris Dam. It was necessary to alter the actual methods of allocating water to both the irrigation scheme and the IFR site in order to allow the two releases to be combined. Rather than modifying the generic dam operating rule, this process was duplicated and altered to include the appropriate requirements and an alternative operating rule process was derived (*PParisDamOperatingRule*). Keeping this process separate from *PGenericOperatingRule* would enable operation of the dam using either of the operating rule processes. The additions occur after the water allocation procedure has been completed and before the water transfer process is entered as shown in Figure 5.15. For further information on the procedures followed during the water allocations in the *PGenericOperatingRule* process, refer to Section 4.7.2. The additional variables employed by the *PParisDamOperatingRule* process are described further in Table B4 of Appendix B and a brief explanation of the procedure is given below.

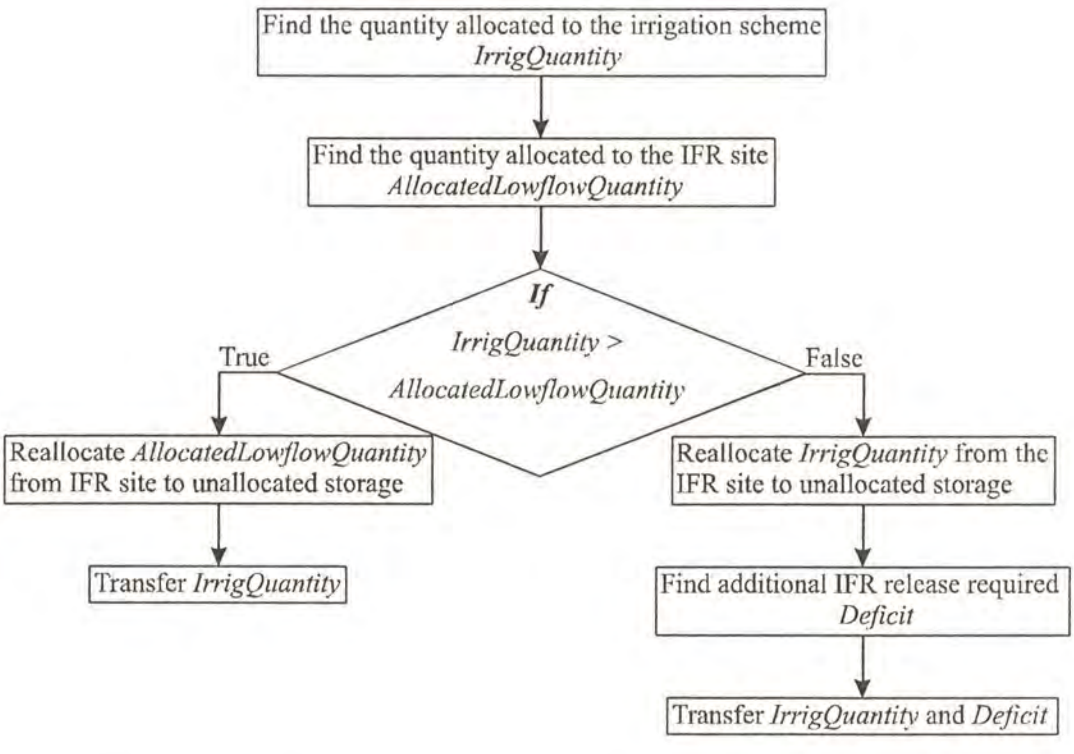

Figure 5.15 Additions to *PGenericOperatingRule* to form the *PParisDamOperatingRule* process

The variables *IrrigQuantity* and *AllocatedLowflowQuantity* are the quantities allocated to the Pongola Irrigation scheme and IFR site 2 after the water allocation part of the generic dam operating rule has been completed for the day. These two quantities are compared and if the *IrrigQuantity* is greater than the *AllocatedLowflowQuantity*, the irrigation release is capable of satisfying the environmental requirements. The *AllocatedLowflowQuantity* allocated to IFR site 2 is set as unallocated storage in the dam and only the *IrrigQuantity* is transferred downstream. If *IrrigQuantity* is less than *AllocatedLowflowQuantity*, the irrigation release can only satisfy part of the environmental requirement for the day and a quantity equal to *IrrigQuantity* is reallocated from IFR site 2 to unallocated storage in the dam. The additional quantity required to meet the environmental requirement (*Deficit*) is then calculated and released in addition to the *IrrigQuantity*.

5.7.3 Inclusion of an alternative channel flow method

The *PSimpleChannelFlow* process is responsible for transferring water from one channel to the next. When using this process for simulations involving the Pongola Irrigation scheme, the irrigation request was generated one day late as the flow in the Pongola was only calculated after all water requests had been sent to the operating rule. Since the flow in the Pongola on the day is required to generate the irrigation request, the request was only reaching the operating rule on the following day. To eliminate this one day lag the *PSimpleChannelFlow* process was modified to create the *PParisDamSimpleChannelFlow* process which allowed the irrigation request to be generated on the same day.

5.7.4 Validation of the modified processes

Before any proper scenarios could be run using the modified processes for Paris Dam, validation of these processes was required. It was necessary to test firstly whether the request for the irrigation scheme was generated correctly, and secondly, whether the transfers out of the dam were correctly combining the environmental and irrigation releases. In order to achieve these two objectives, a simulation was run for five years using the modified processes, with all users removed from the system except for the Pongola Irrigation scheme and IFR site 2, situated on the Bivane River.

As described in Section 5.6, the irrigation request for the day is determined by monitoring the flow in the Pongola River. The first part of the validation involved checking if the irrigation releases were generated on the correct day and that the quantities requested were correct. Table 5.12 shows the monthly demands of the Pongola Irrigation scheme, as well as the equivalent daily flows and Table 5.13 contains a section of output from the simulation that was used for the purposes of the validation.

Table 5.12 Monthly and daily demands required by the Pongola Irrigation scheme (after Institute of Natural Resources, 2001)

Month	Monthly demand $m^3 \times 10^6$	Daily flow $m^3.s^{-1}$
January	20.8	7.77
February	17.8	7.36
March	19.6	7.32
April	18.7	7.21
May	15.0	5.60
June	13.4	5.17
July	13.8	5.15
August	15.4	5.75
September	19.6	7.56
October	14.3	5.34
November	12.9	4.98
December	17.3	6.46

Table 5.13 Output used for the validation of the modified processes

Date	Units	03-Sep-46	04-Sep-46	05-Sep-46	06-Sep-46	07-Sep-46	08-Sep-46
Flow in Pongola	$m^3.s^{-1}$	3.38	13.12	18.19	10.07	8.03	6.62
Irrigation request	m^3	361270.15	0.00	0.00	0.00	0.00	81695.04
Irrigation transfer	m^3	361270.15	0.00	0.00	0.00	0.00	81695.04
Env. Low-flow request	m^3	83859.57	83859.57	83859.57	83859.57	83859.57	83859.57
Env. Low-flow transfer	m^3	0.00	83859.57	83859.57	83859.57	83859.57	2164.53

In order to check whether the irrigation releases were occurring at the correct times, the flow at the Upper Pongola weir was included in Table 5.13. From Table 5.12, the daily flow required in the Pongola River for the month of September in order to satisfy the irrigation scheme requirements is 7.56 $m^3.s^{-1}$. For any day in Table 5.13 on which the flow in the Pongola River was below this value, an irrigation release should have been made that was equivalent to the deficit between the two flow values. For the purposes of finding whether the irrigation releases were being combined correctly with those for the environment, the environmental requests and transfers were also included in Table 5.13. Three possible scenarios exist here, all of which are illustrated in the table. Firstly, if no irrigation transfer occurs, the environmental request quantity should be released as normal. This can be seen from the 4 - 7 September in Table 5.13 where the flow in the Pongola river was greater than that required by the irrigation scheme. Secondly, if no environmental low-flow transfer occurs, the irrigation transfer quantity should be greater than the quantity requested by the environment. This occurs on 3 September where the flow in the Pongola River is only 3.38 $m^3.s^{-1}$ and the transfer for the irrigation scheme of 361270.15 m^3 is greater than the environmental request made on the previous day of 83859.57 m^3, which is not shown in Table 5.13. Thirdly, when both an irrigation release and an environmental release occur on the same day, the sum of the two values should equal the environmental request quantity. This occurs on 8 September in Table 5.13 where the flow in the Pongola River is 6.62 $m^3.s^{-1}$. Consequently, the irrigation release required is quite small and does not meet the environmental requirement. As a result, a small release of 2164.53 m^3 is made purely for the purposes of satisfying the environmental requirements of the Bivane River.

The results obtained from this particular simulation provide sufficient evidence to indicate that the modifications made to the operating rule framework are functioning correctly. In the following sections, various scenarios are run in order to investigate certain aspects of the operating rule framework and to provide information on its effectiveness as a tool for determining appropriate operating rules and for aiding in real-time dam operations.

5.8 Scenario Testing of the Operating Rule Framework

The purpose of the scenario testing section was to assess the effect of the curtailment structure on both the individual user's performance and the overall performance of the system. In order to investigate this, a number of scenarios were chosen and the results obtained were plotted on graphs. The main objective of the section was to attempt to find the scenario that produced the optimal method of dam operation for all users and to show that the operating rule framework is capable of finding the most appropriate set of operating rules, in accordance with the objectives stated in Chapter 1.

5.8.1 Model configuration and the water users employed

The model was setup as described in Section 5.2 and five water users were simulated. The positions of these users within the simulated area is shown in Figure 5.2. The first was a domestic user that included the lumping together of several towns and rural water supply schemes including the Pongola town and Ncotshane township, the Simdlangentsha community water supply scheme, the Mthethwa / Dlamini regional water scheme, and losses from the water works responsible for these schemes. With all these demands summed together, the domestic user generates a constant daily request of 12137 m^3 and is represented by the user Settlement_120 in the simulations. The second user, an IFR site (IFR site 2) was dependent on the flows given in Table 5.1. The third user was the Illovo sugar mill (Industry_120 in the simulations) which has a daily demand of 8200 m^3. The fourth user was a community of small-scale irrigators (represented by IrrigArea_119) with a daily requirement of 50000 m^3 while the fifth user was the Pongola Irrigation scheme (IrrigArea_120), the demand of which is found as described in Section 5.7.1.

5.8.2 Description of the scenarios used

Three scenarios were run for a duration of 49 years (1946 to 1994) with each user's curtailment levels differing for each scenario. The first scenario, referred to as the 'No Curt' simulation, involved running a simulation with no users being curtailed, whereas the second and third scenarios were run with different sets of curtailment levels and are referred to as 'Curt 1' and 'Curt 2' respectively. The Curt 1 simulation used the curtailment structure given in Table 5.14. In order to identify the effects of the curtailment structure on each user's assurance of supply, the Curt 2 simulation was run using far heavier curtailment values than in Table 5.14. Table 5.15 shows the curtailment structure employed for Curt 2.

Table 5.14 Curtailment structure employed during the Curt 1 simulation

Management level (%)	100 - 80	80 - 60	60 - 40	40 - 20	20 - 0	Priority
Settlement_120	100	100	100	100	100	1
IFR site 2	100	100	100	95	85	2
Industry_120	100	100	100	90	80	3
IrrigArea_119	100	95	80	60	40	4
IrrigArea_120	100	95	90	80	50	4

Table 5.15 Curtailment structure employed during the Curt 2 simulation

Management level (%)	100 - 80	80 - 60	60 - 40	40 - 20	20 - 0	Priority
Settlement_120	100	100	100	100	80	1
IFR site 2	100	100	100	80	50	2
Industry_120	100	100	90	70	40	3
IrrigArea_119	100	85	60	35	10	4
IrrigArea_120	100	90	70	50	20	4

5.8.3 Results and discussion

The results obtained from the simulations were analysed by plotting various graphs. A first set of graphs was used to show the user's supply as a percentage of demand, for selected levels of assurance of supply. In order to plot these graphs, the daily supply as a percentage of demand was computed for each user. On a day where a user is not curtailed, the percentage supply equals 100. These calculations were performed for each scenario and three curves were obtained at each assurance level. Figures 5.16 to 5.19 show the percentage supply curves obtained for four of the users at the 99th percentile, which approximates a 1/100 year return period. Figure 5.16 also includes the dam storage as a percentage of full capacity associated with the 99th percentile for the three scenarios. It should be noted that the percentage supply value on the IFR site curves includes only the low-flow transfers. The percentage supply values for the given percentile value were found by performing a frequency analysis on the values throughout the simulation corresponding to each month. The blue line on each graph represents the percentage supply obtained from month to month for the No Curt simulation. The green and red lines show the percentage supply obtained for the Curt 1 and Curt 2 simulations respectively.

From the graphs presented, the percentage supply obtained from the No Curt simulation is noticeably more variable than the other two scenarios. For Settlement_120, the percentage supply is high for most of the year and does not show much significant difference between the three simulations. However, the month of September shows that the No Curt simulation has a far lower percentage of supply. This is caused by the demand of the Pongola Irrigation scheme for the month of September being high. The dam percentages shown in Figure 5.16 show marked differences between the three scenarios with the Curt 2 simulation resulting in the dam being maintained at higher levels than that of the No Curt or Curt 1 scenarios. This would appear to show that Curt 2 is better than the other two scenarios but this may not necessarily be the case and could indicate that the curtailments imposed by Curt 2 are too stringent and consequently some of the available storage in the dam is not being used.

The differences between the percentage supply values for the three simulations becomes more marked, the lower the priority of the user. For example, when using no curtailment IrrigArea_119 (Figure 5.19) receives zero at this assurance level for the months of May, August and September. The use of the curtailment structures appears to have an effect on keeping the percentage supply values higher for these months. The Curt 2 scenario enables the IrrigArea_119 user to receive between 35 and 60 % of its demand for most months of the year. This value of 35 % is governed by the curtailment level of 35 % that is used when the dam storage sits between 40 and 20 % while 60 % corresponds to a management level of 40 to 60 %. It is interesting to note that the Curt 1 simulation also provides between 40 and 60 % of the user's request for nine months of the year but that these values correspond to management levels of between 40 and 20 % and between 20 % and the dead storage level. This is caused by the saving of water resulting from the use of the Curt 2 scenario with the result that higher management levels are used to satisfy the requests of IrrigArea_119.

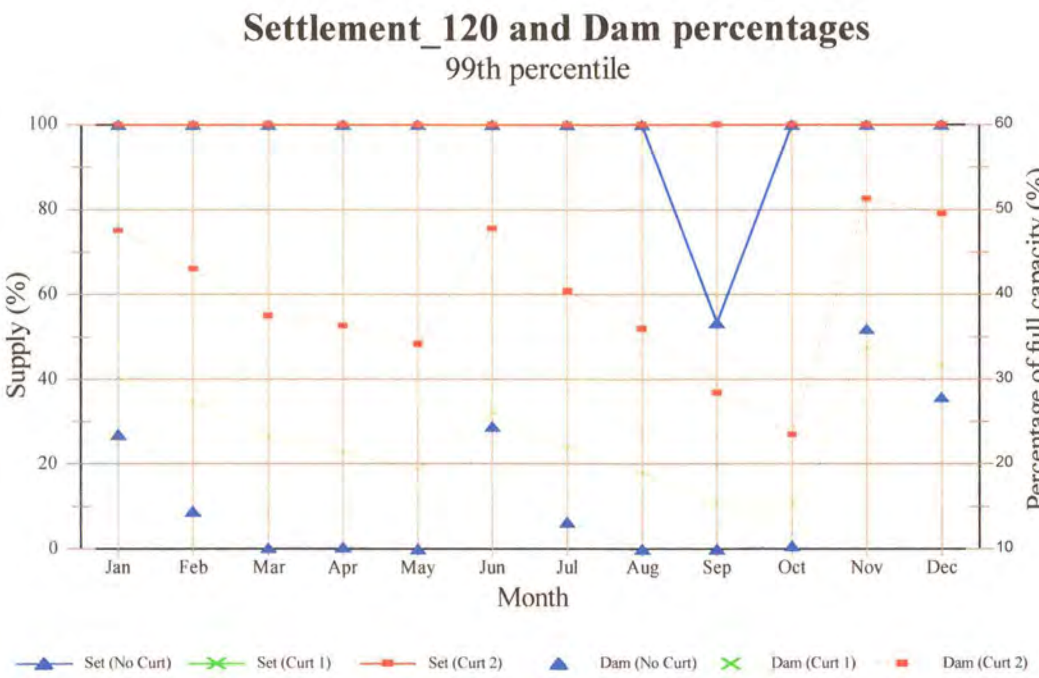

Figure 5.16 Supply to the domestic user, expressed as a percentage of demand, and dam storage for a 99 % level of assurance

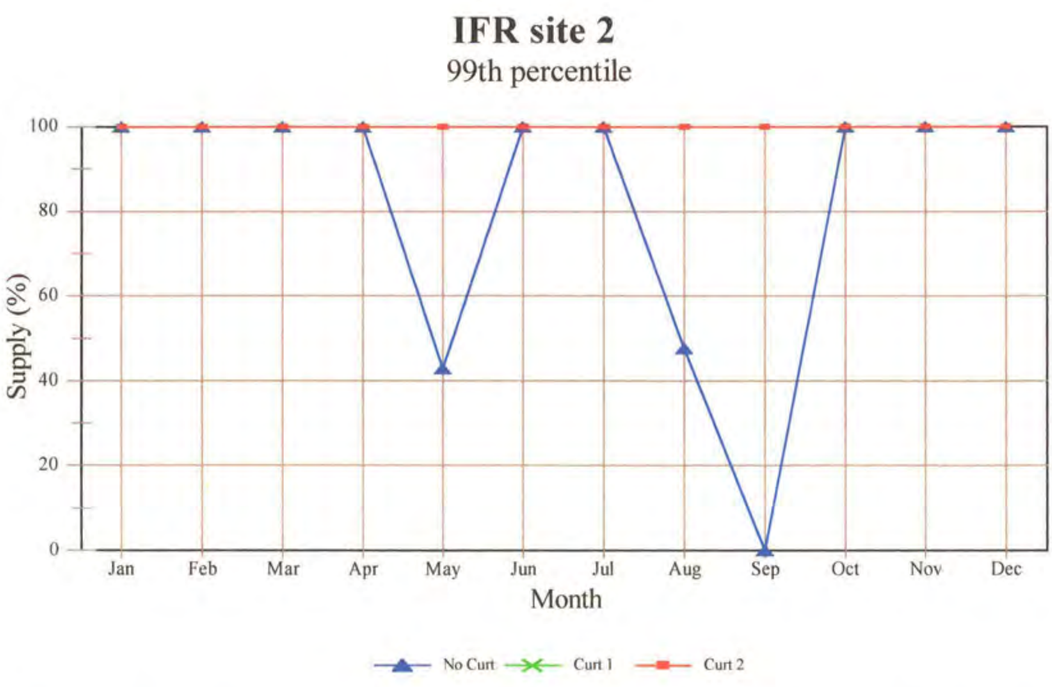

Figure 5.17 Supply to the environmental user, expressed as a percentage of demand, for a 99 % level of assurance

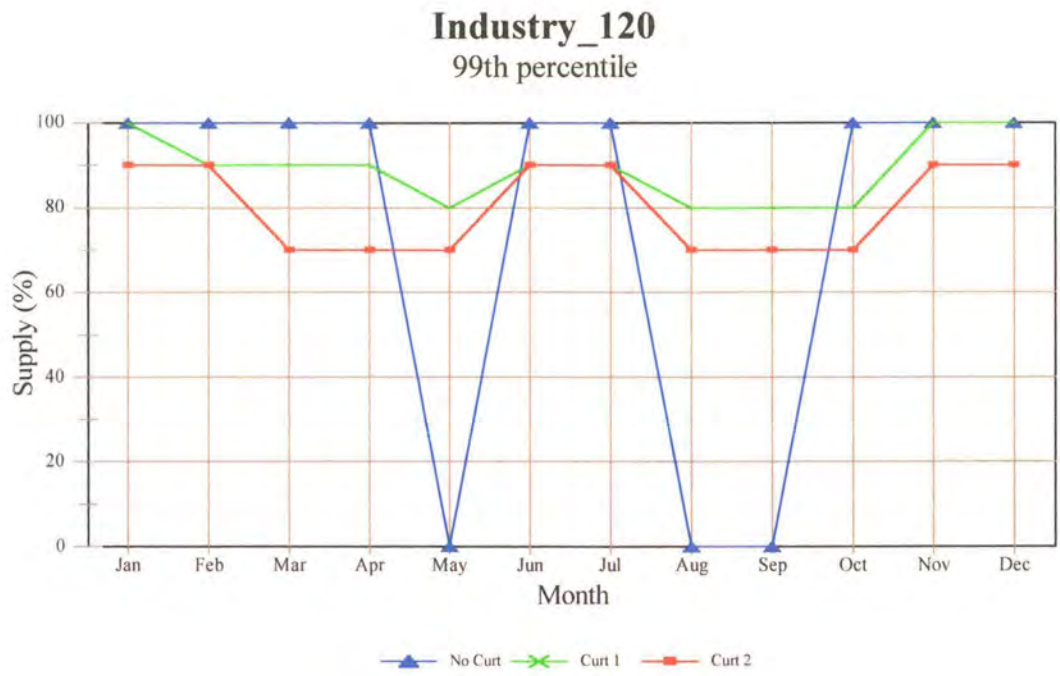

Figure 5.18 Supply to the industrial user, expressed as a percentage of demand, for a 99 % level of assurance

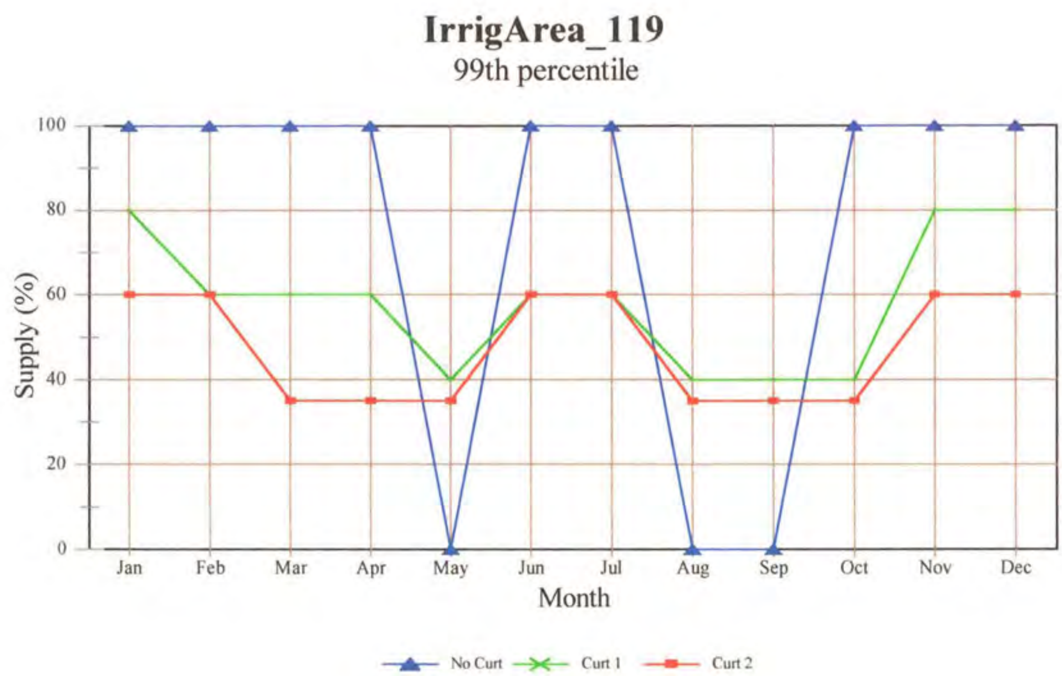

Figure 5.19 Supply to the small-scale irrigators, expressed as a percentage of demand, for a 99 % level of assurance

The second set of graphs used to evaluate the effectiveness of the dam operations employed in the three simulations show the number of "failures" experienced on a month-by-month basis throughout the entire simulation. For the purposes of this evaluation, a failure was defined as any day on which a user's curtailed request quantity could not be met and the dam, at some stage during the day, reached the dead storage level. For the users Settlement_120, Industry_120 and IrrigArea_119, the number of failures was found by comparing the percentage supply to the required curtailment level for the day, given the dam's current storage. If the percentage supply value was lower than the curtailment level, the curtailed request quantity was not supplied and a failure was deemed to have occurred. However, the Pongola Irrigation scheme (IrrigArea_120) only makes requests when required and a failure could not be determined in this way. Thus, for any day on which the IrrigArea_120 user did not request water from the dam, the Pongola River had sufficient storage in it to fully satisfy the requirements of the scheme and no failure was deemed to have occurred. Failures for IFR site 2 were also more complicated because, although the IFR site generates a daily request for low-flows, it is not always transferred due to the fact that the IFR releases are combined with those for the irrigation scheme. On days where the irrigation release was greater than the IFR requirement and no IFR release resulted, no failure was deemed to have occurred. Figures 5.20 and 5.21 illustrate the failures that each user experienced during the No Curt and Curt 1 simulations and Table 5.16 provides a summary of the results.

Table 5.16 Table summarising the number of failures experienced by the five users

User	Scenario	Month												Total
		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	
Settlement_120	NoCurt	0	0	0	0	10	0	0	8	29	4	0	0	51
	Curt 1	0	0	0	0	0	0	0	0	12	4	0	0	16
	Curt 2	0	0	0	0	0	0	0	0	0	0	0	0	0
IFR site 2	NoCurt	0	0	0	0	21	0	3	22	30	7	0	0	83
	Curt 1	0	0	0	0	0	0	0	0	13	6	0	0	19
	Curt 2	0	0	0	0	0	0	0	0	0	0	0	0	0
Industry_120	NoCurt	0	0	0	0	22	0	4	23	30	7	0	0	86
	Curt 1	0	0	0	0	0	0	0	0	13	7	0	0	20
	Curt 2	0	0	0	0	0	0	0	0	0	0	0	0	0
IrrigArea_120	NoCurt	0	0	0	5	25	0	5	27	30	14	0	0	105
	Curt 1	0	0	0	0	0	0	0	0	14	12	0	0	26
	Curt 2	0	0	0	0	0	0	0	0	0	0	0	0	0
IrrigArea_119	NoCurt	0	0	0	5	25	0	5	28	30	14	0	0	106
	Curt 1	0	0	0	0	0	0	0	0	14	12	0	0	26
	Curt 2	0	0	0	0	0	0	0	0	0	0	0	0	0

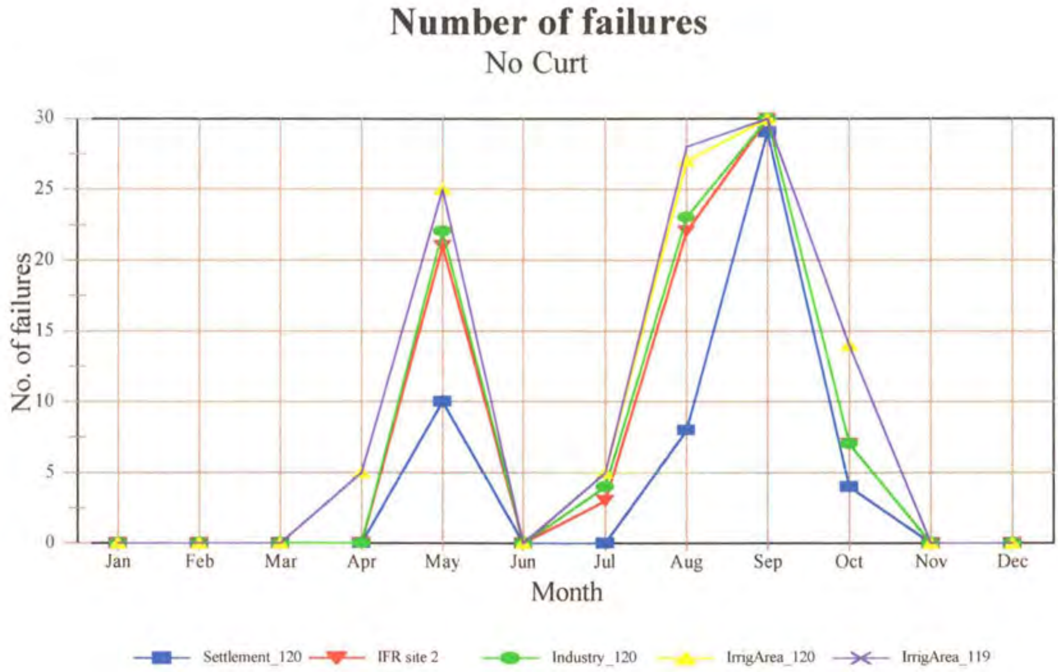

Figure 5.20 The number of failures experienced by the users during the No Curt simulation

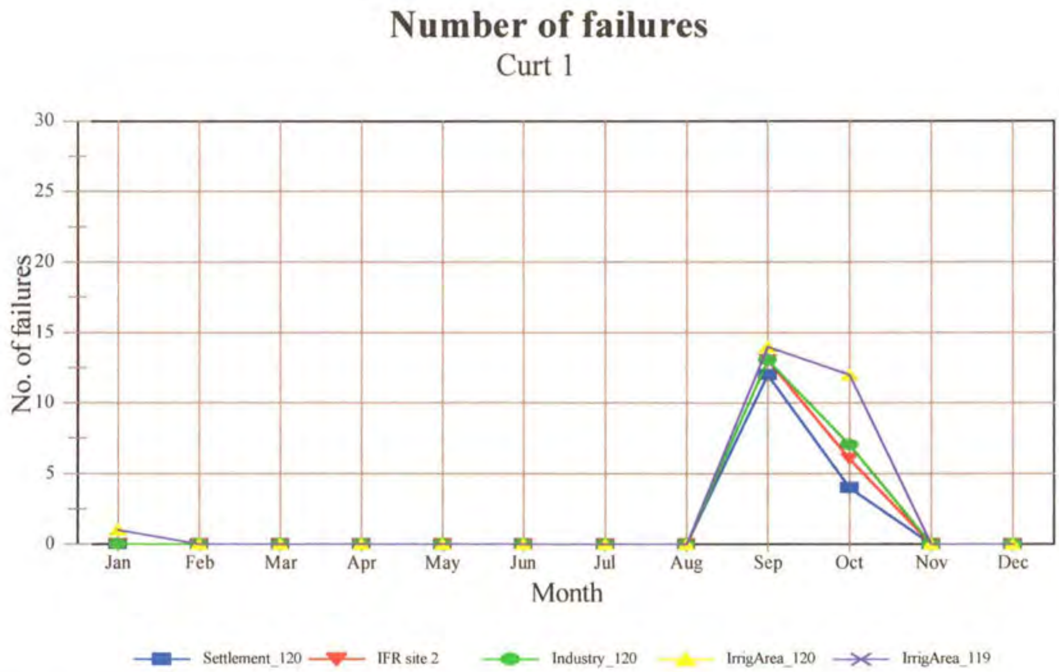

Figure 5.21 The number of failures experienced by the users during the Curt 1 simulation

Table 5.16 clearly shows that the number of times the dead storage level is reached in the dam during the No Curt simulation is far higher than for either of the scenarios employing curtailment.

Again, the effect of the user's priority is evident because of the high number of failures experienced by the low priority users; 106 for IrrigArea_119 as opposed to 51 for Settlement_120. Table 5.16 also shows the major strength of the heavier curtailment structure employed by Curt 2, where no failures were experienced for the entire simulation.

Although the curtailment structures had shown promising results in terms of supplying the water and maintaining the dam level above dead storage it was still difficult to say if one was better than the other. To further analyse the effectiveness of the three scenarios it was decided to analyse the three methods during a particularly dry period. After searching through the rainfall records and simulated streamflows it was decided to use the hydrological year from October 1982 to September 1983. A further motivation was provided by the number of failures that occurred during this time period. The results are summarised below in Table 5.17 which contains the total number of failures for the 1 year period for each scenario, as well as these failures expressed as a percentage of the total number of failures experienced throughout the entire simulation from Table 5.16. As can be seen, the percentage of failures experienced by each user during the No Curt simulation is very high with most around 90 %.

Table 5.17 Number of failures for the three simulations (October 1982 to September 1983)

User	Scenario	Number of Failures	% of Total for Entire Simulation
Settlement_120	NoCurt	47	92
	Curt 1	12	75
	Curt 2	0	0
IFR site 2	NoCurt	76	92
	Curt 1	13	68
	Curt 2	0	0
Industry_120	NoCurt	79	92
	Curt 1	13	65
	Curt 2	0	0
IrrigArea_120	NoCurt	92	88
	Curt 1	14	54
	Curt 2	0	0
IrrigArea_119	NoCurt	93	88
	Curt 1	14	54
	Curt 2	0	0

In order to provide a meaningful comparison of the three methods for this one year period, it was decided to plot what has been termed the 'Total daily demand deficit'. This value can be defined as the difference between the sum of the five user's requests for a day and the sum of the transfers made to each user for the day. Figure 5.22 shows the associated dam storage for each of the three scenarios, while Figure 5.23 shows the graph produced for this total daily demand deficit when plotted as a cumulative function.

From Figure 5.22, it can be seen that owing to the saving of water that has taken place prior to this period with the higher curtailment values employed, the dam storage for Curt 2 is higher than that for both the No Curt and Curt 1 scenarios and remains as such throughout the period. The high number of failures during this period is highlighted by the dam storage curve of the No Curt scenario where the dam level is frequently at the dead storage level of 10%. This extreme case highlights a major advantage of Curt 1 over the No Curt simulation as the dam level during this simulation only reaches the dead storage level for a few days at the end of the one year period.

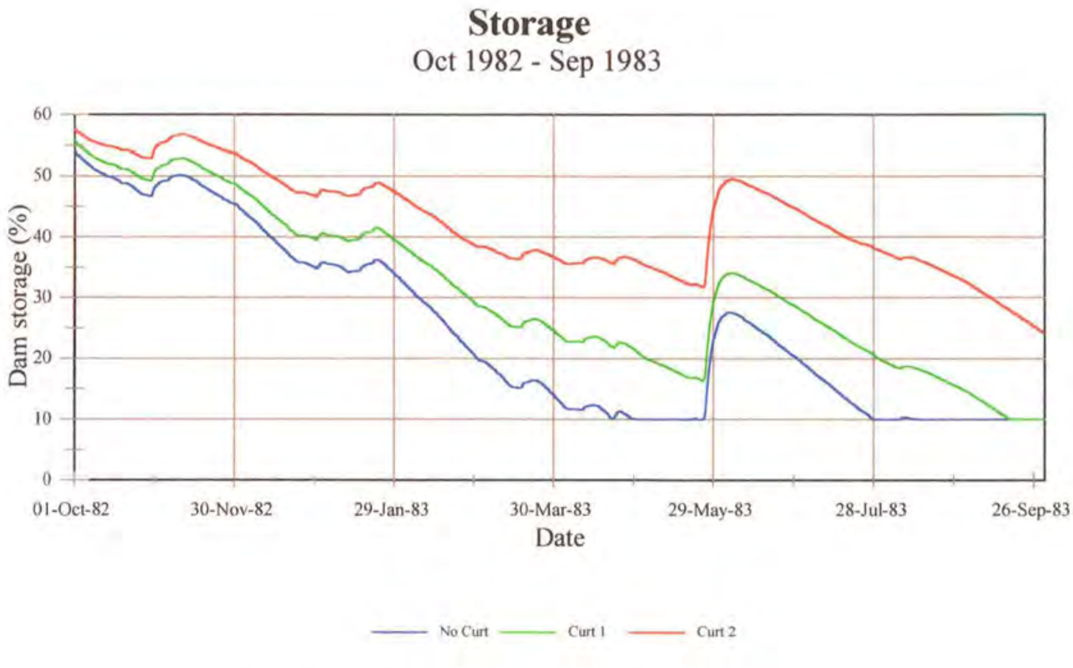

Figure 5.22 Graph showing the dam storage level for the period from October 1982 to September 1983

Figure 5.23 Cumulative total daily demand deficit experienced for the period from October 1982 to September 1983

Curt 2 would appear to be the best scenario based on Figure 5.22 as the dead storage level is not reached. However, Figure 5.23 shows that for the entire period the total supply deficit is much higher using Curt 2 than either of the other two scenarios with the result that the requirements of the five users as a whole are met far better by the No Curt and Curt 1 scenarios. This indicates that the curtailments imposed on the water users during the Curt 2 simulation are unnecessarily high. From Figure 5.23 it can be seen that over the one year period, the Curt 1 scenario best meets the requirements of the water users as the cumulative demand deficit at the end of this period is the smallest of the three scenarios.

The final part of the scenario testing was to focus specifically on an individual user and see how this user's demands were being met. The Pongola Irrigation scheme, IrrigArea_120, was selected and three graphs (Figures 5.24, 5.25 and 5.26) were plotted illustrating the percentage supply for assurance levels of 90, 95 and 99 %. Figure 5.24, in which the 90^{th} percentile is shown, indicates that the No Curt simulation has a more favourable percentage supply on certain months than either of the other two scenarios where the curtailment values cause the percentage supply to be lowered. As the percentile value increases from 90 through to 99 %, the No Curt scenario becomes increasingly less desirable in certain months with total failure to supply any water occurring in the months of May, August and September.

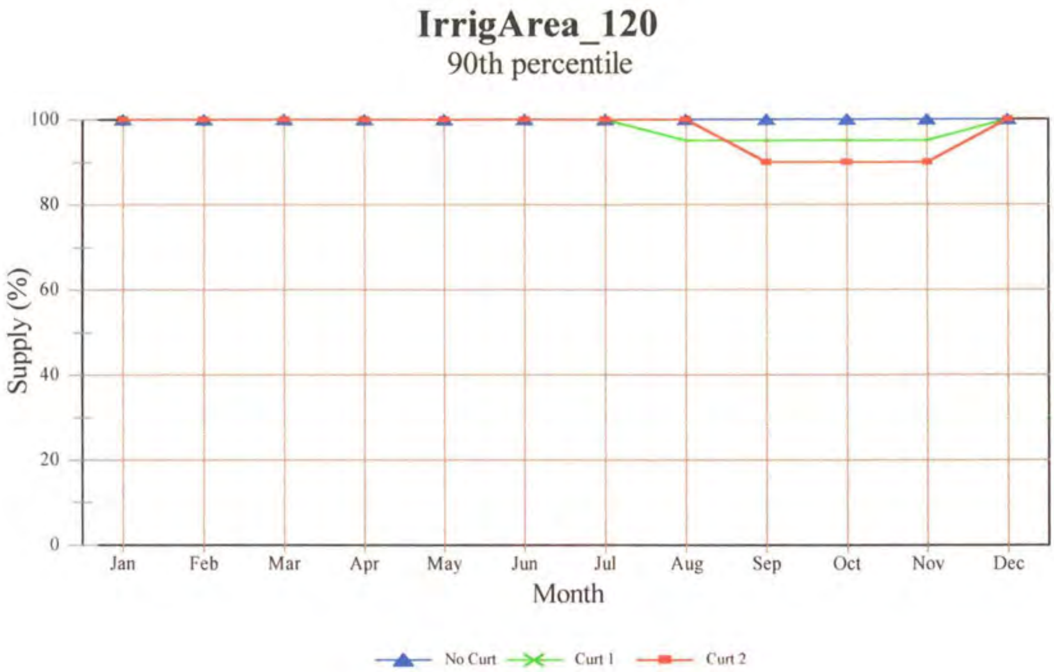

Figure 5.24 The Pongola Irrigation scheme's percentage supply at a 90 % assurance

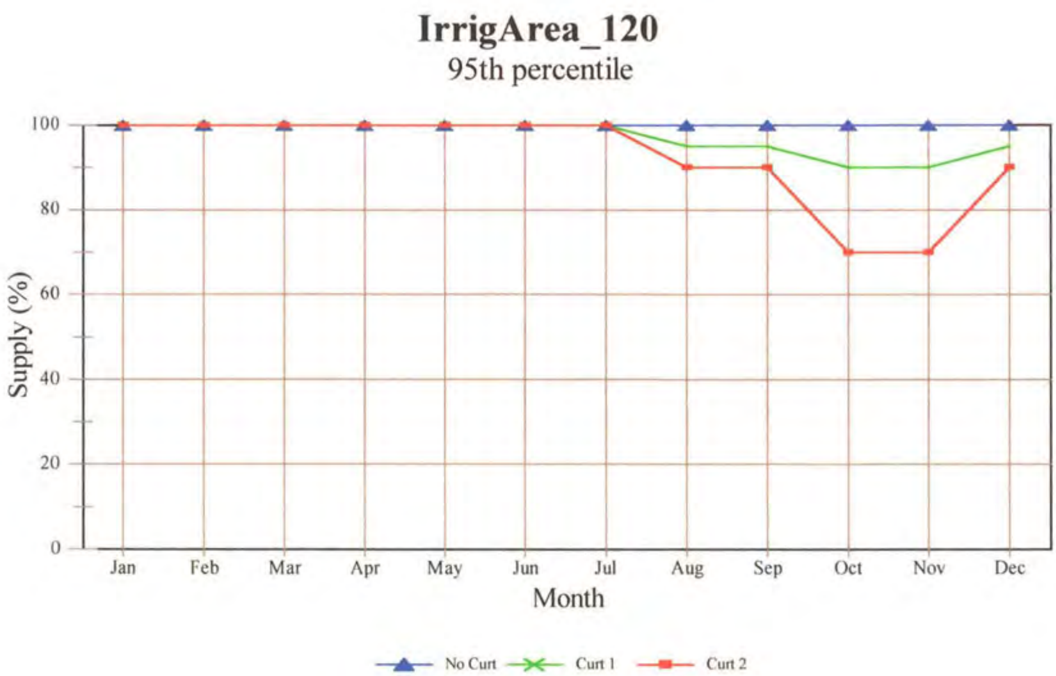

Figure 5.25 The Pongola Irrigation scheme's percentage supply at a 95 % assurance

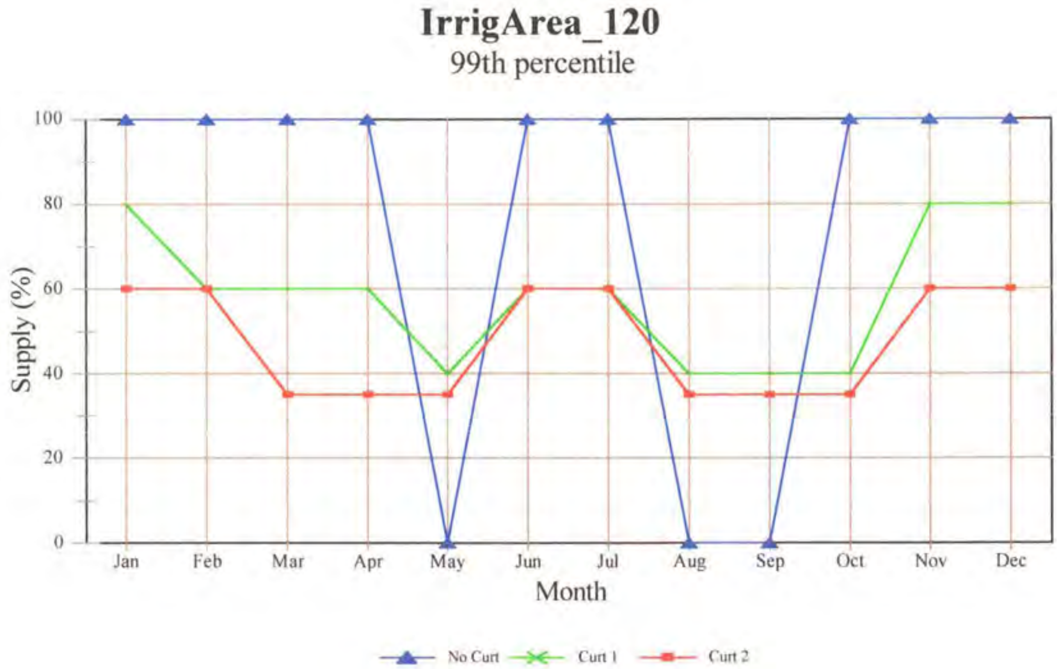

Figure 5.26 The Pongola Irrigation scheme's percentage supply at a 99 % assurance

A further point that is noticeable on all three figures is that the months of August, September, October and November have some of the lowest percentage supply values. This can be attributed to the large deficit between the irrigation requirement of the Pongola Irrigation scheme for these months and the flow occurring in the Pongola River under natural conditions. As a result, two further graphs were plotted of the IrrigArea_120 user's assurance levels versus the percentage supply for the months of January and September (See Figures 5.27 and 5.28 respectively). Figure 5.27 shows little difference between the three methods except at high assurance levels of above 98.5 %. Figure 5.28 shows that using no curtailment, an assurance level of 98 % would result in total failure to supply the irrigation scheme with any water during the month of September. Curt 1 reaches this same point at an assurance level of approximately 99 %, while for a 99% assurance using Curt 2, 50 % of the irrigation scheme's request can still be released. This value is significant in that it may make the difference between the irrigators' crops surviving or dying off completely.

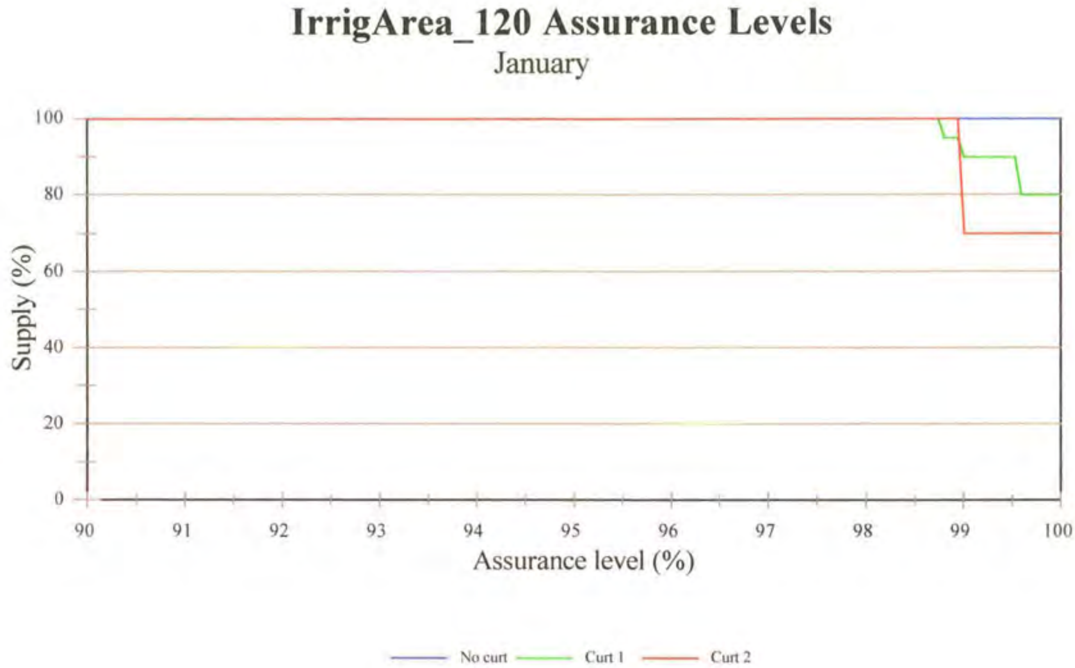

Figure 5.27 The Pongola Irrigation scheme's percentage supply in January for given assurance levels

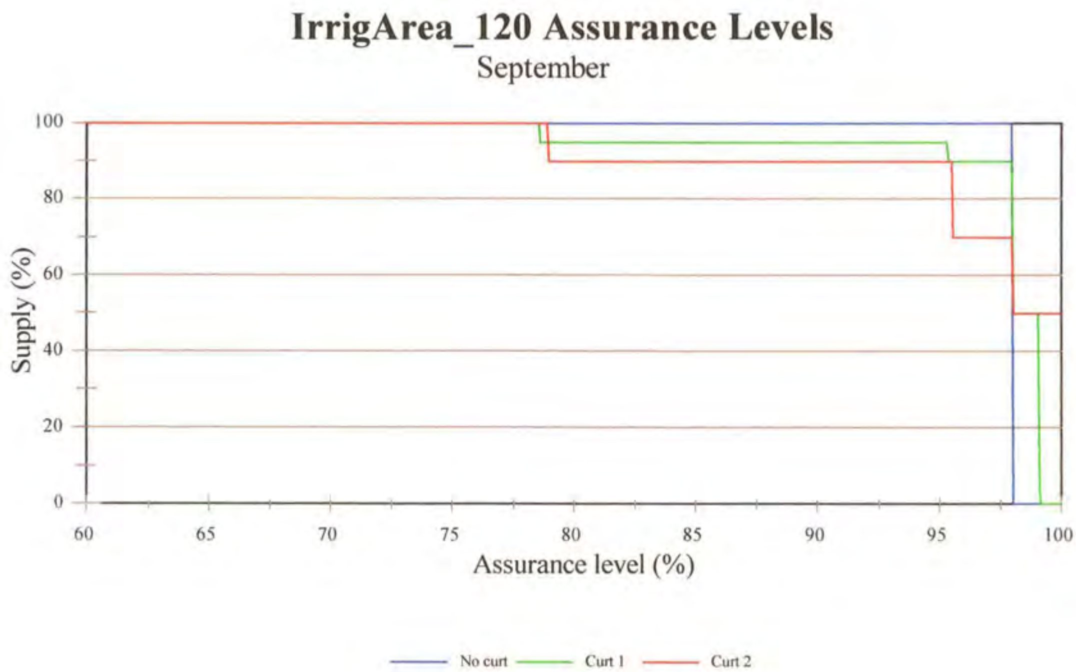

Figure 5.28 The Pongola Irrigation scheme's percentage supply in September for given assurance levels

5.8.4 Considerations with regard to choosing the final curtailment structure for use

The final choice of which method of dam operation to use depends on the principles on which the operation of the dam is based. These could either be that failure should be avoided at all times and operation would be governed by ensuring that water could be supplied to the users in drought years, or that a few failures are satisfactory because of the resulting higher percentage supply at certain assurance levels. If the former is the case, Curt 2 would be the best operation method since no failures occurred throughout the entire simulation period. If the latter is considered more important, then it may be better to operate the dam using Curt 1 with the risk of failures occurring in severe drought years. Although the Pongola Irrigation scheme has been given a low priority in the model simulations, Paris Dam was commissioned for construction by the Impala Irrigation Board and so was built largely to aid the irrigation scheme. Consequently, other higher priority water users demands could well be sacrificed in times of water shortages in order to ensure the survival of the irrigators' crops. The fact that Curt 2 allows the irrigation scheme to receive 50% of its total requirement at high assurances of 99 % and above in one of the worst months i.e. September, could prove significant. The ideal situation in the case of the Paris Dam using the three scenarios shown would possibly be to use more than one curtailment structure. This would entail using Curt 1 under average rainfall conditions and only employing Curt 2 for extreme drought events. This may not be practical though, as a certain degree of forecasting would be required. This dual use of curtailment structures may also not have the desired effect as Curt 2 manages to supply small amounts to users during the worst drought on record because the dam storage is maintained at a higher level. If Curt 1 was used and then Curt 2 was employed in times of drought, the dam level may already be too low for the use of Curt 2 to have any real benefit. A further alternative would be to use a curtailment structure that was not as stringent as that employed by Curt 2, but that imposed heavier curtailment on the users than that employed by Curt 1.

5.8.5 Evaluation of the environmental flows at IFR site 2

One of the objectives of this project stated in Chapter 1, was to be able to provide an artificial flow regime below a dam that mimics the natural flow regime. This would involve not only ensuring that the variability of the natural flow regime was followed, but that the flows required at the IFR site could be supplied at the desired levels of assurance. In order to test whether this objective had been achieved, a separate analysis was conducted on the flows at IFR site 2 produced during the three simulations described in Section 5.8.2. Figures 5.29, 5.30 and 5.31 show the results produced for percentile values of 90, 95 and 99 %. The flow values were obtained by performing a separate frequency analysis on the values for each month. The royal blue line (No Curt) represents the flows obtained at the IFR site when no curtailment of users' demands occurred, while the green (Curt 1) and red (Curt 2) lines are the flows obtained when a light and a heavy curtailment structure are employed, respectively.

Figures 5.29 and 5.30 also contain a curve of the monthly flow values required by the BBM for maintenance conditions, shown in dark blue and represented in the legend as "Maintenance flows". The first observation that can be made from these two figures is that the flows experienced at IFR site 2 for all 3 simulations are often above the level of flow required by the BBM. This can be attributed largely to the contribution of downstream releases for the purposes of the Pongola Irrigation scheme. The requirements of the irrigation scheme shown in Table 5.12 remain high in the drier months of the year which conflicts with the IFR that requires lower flows in these months. The implications of these raised flows from an ecological perspective has not been considered, but it is postulated that they may not have a major effect on the ecosystems, provided that the basic pattern of higher flows in wet months and lower flows in dry months is followed.

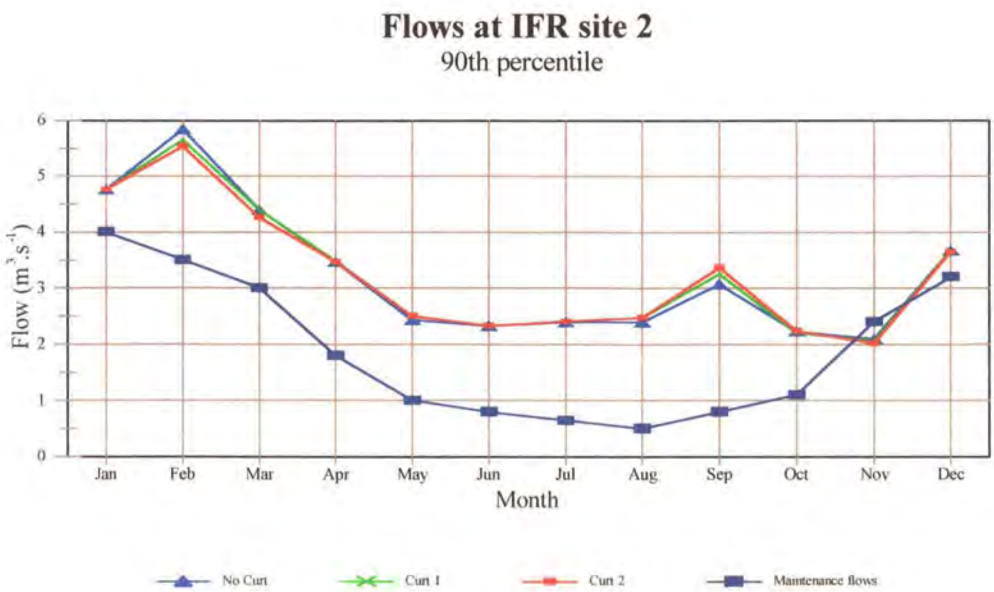

Figure 5.29 Flows produced at IFR site 2 for a 90 % assurance level

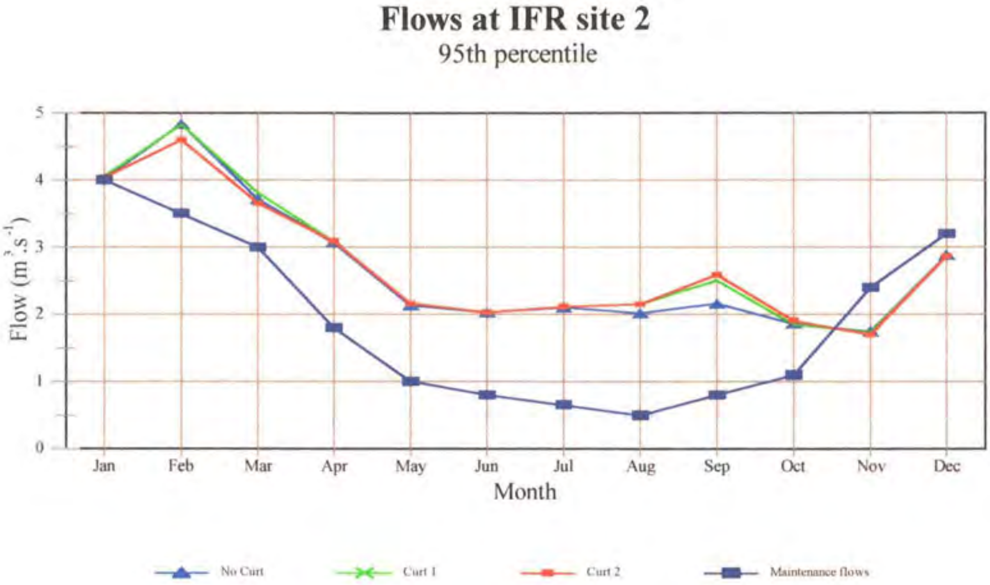

Figure 5.30 Flows produced at IFR site 2 for a 95 % assurance level

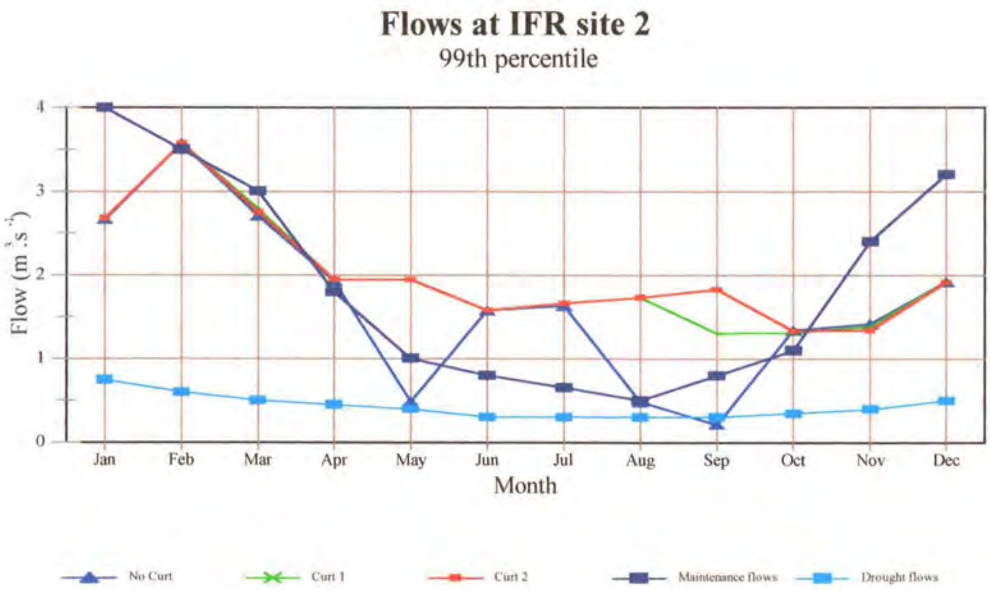

Figure 5.31 Flows produced at IFR site 2 for a 99 % assurance level

Referring to Figure 5.31, a comparison between the flows produced at IFR site 2 and the maintenance flows specified by the BBM, indicates that the No Curt simulation fails to supply the maintenance flow at an assurance of 99 % for eight months of the year whereas Curt 2 only fails to supply the maintenance flow in four months of the year (January, March, November and December). Again, the fact that the maintenance flows are being supplied at such a high level of assurance conflicts with the requirements of the BBM. Thus, the No Curt simulation meets the requirements of the IFR site better than the Curt 2 simulation. The flow values obtained at the 99 % assurance level are again being elevated greatly by the downstream releases that are being made for the Pongola Irrigation scheme.

In an attempt to show that the IFR releases are indeed capable of meeting the requirements of the BBM, further simulations were run with all downstream users, other than the environment, supplied with water from Paris Dam via direct abstraction. Figure 5.32 shows the flows produced at IFR site 2 for these simulations at a 90 % assurance level. The flows in the months of February, March, April and May are still too high and this can be attributed to the effects of spillway flow occurring from the dam as well as the influence of the downstream tributary entering the Bivane River between Paris Dam and IFR site 2. However, it is evident that the flows at IFR site 2 are far lower than those for the same percentile shown in Figure 5.29 which provides conclusive evidence that the flows at the IFR site in the previous simulations were being dominated largely by the downstream releases made for other downstream users.

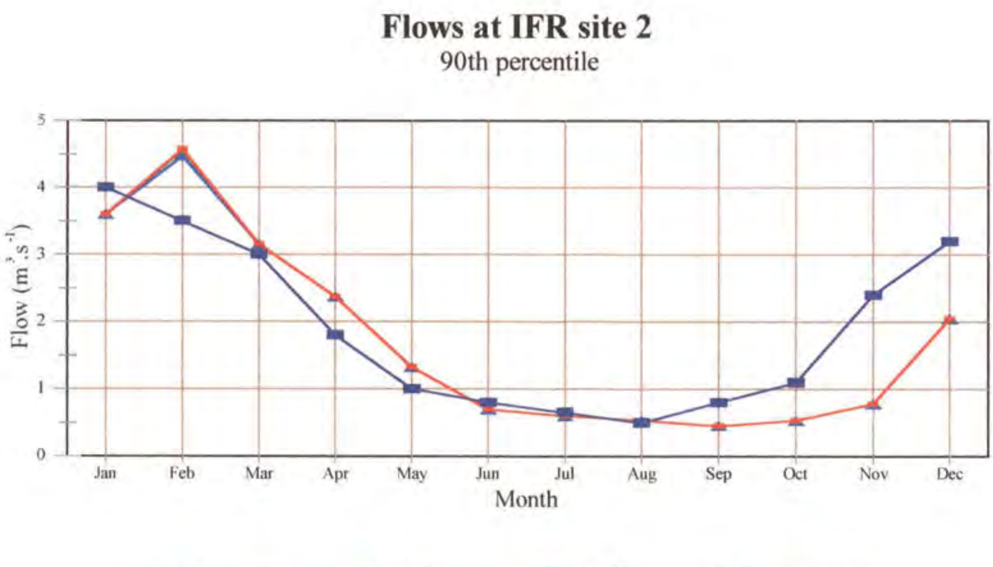

Figure 5.32 Flows produced at IFR site 2 with other downstream users excluded

To provide further information on how well the BBM flows were being met at IFR site 2 without the effects of the other downstream users included, two additional graphs were plotted for two months of the year. The months selected were January and July, in order to represent a wet and a dry month respectively. Figures 5.33 and 5.34 show the flows at the IFR site plotted against assurance levels and also include the maintenance and drought flows specified by the BBM. Figure 5.33 indicates that almost no difference exists between using any of the three scenarios during a wet month as the maintenance flow is supplied at an assurance of approximately 87 % for each. This assurance level corresponds well to the threshold value (*MainThreshold*) for the month of January determined in Section 5.3.2.1.

Figure 5.34 shows that during the dry month of July, little difference exists between the three scenarios with the maintenance flow being supplied at an assurance of approximately 88.5 %. The flows produced using the No Curt simulation fall below the drought flow value for very high assurances whereas this value is not reached during both the simulations involving curtailment of the users. The fact that the drought flow is not reached during the Curt 1 or Curt 2 scenarios is probably not a major problem as many of the drought flows have been specified to be lower than any flows ever recorded in the Bivane River for the month. From these results, it appears that the operation of the dam is capable of meeting the flow requirements of the IFR site with reasonable degrees of assurance, provided that no other downstream releases are made from the dam.

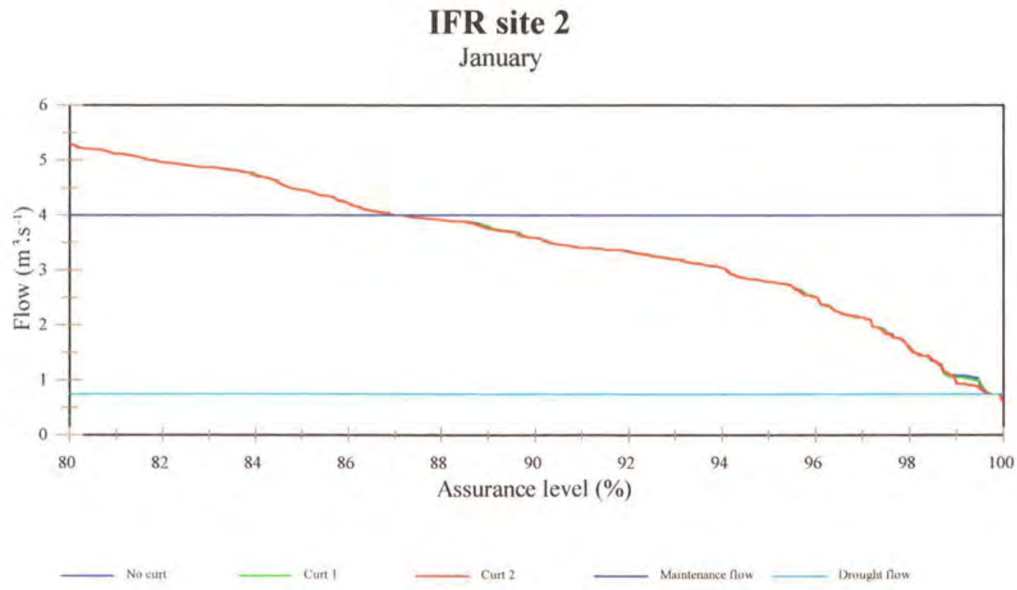

Figure 5.33 Flows at IFR site 2 in January for given assurance levels

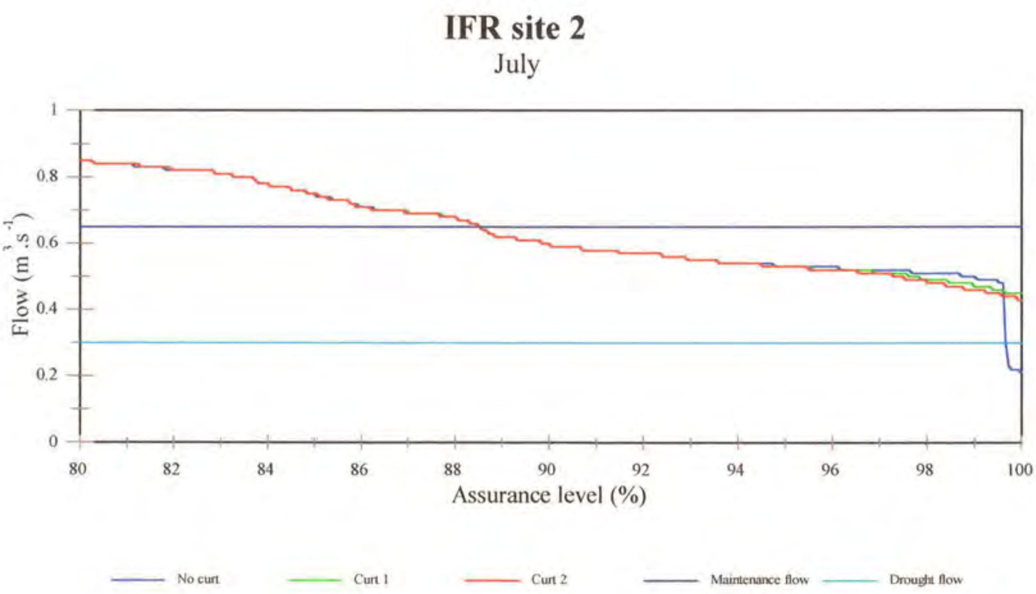

Figure 5.34 Flows at IFR site 2 in July for given assurance levels

6. DISCUSSION AND CONCLUSIONS

The operation of dams will form a vital component in ensuring that the requirements of the National Water Act (1998) are met in the future. Owing to the large number of dams present in South Africa and the associated negative impacts that dams have on the impounded river, the importance of developing effective operating policies that can eliminate these negative impacts to some degree is paramount. It is largely for this reason that the inclusion of the operating rule framework into the *ACRU*2000 modelling system has taken place, while at the same time adding to the capabilities of the model. The following sections discuss aspects of the project in accordance with the objectives stated in Chapter 1, derive conclusions and present various recommendations for further development and future research opportunities.

6.1 Evaluation of Object-oriented Programming and the *ACRU*2000 Modelling System

The process of converting the *ACRU* agrohydrological modelling system into an object-oriented structure and computing language is nearing completion. The concept of object-orientation was found initially to be difficult to grasp, although, once a certain level of understanding had been achieved and programming began, the approach was found to be very easy to work with. The Unified Modelling Language was used to some extent for determination of the various relationships existing between classes, but a simple pen and paper approach of drawing flow diagrams was found to be more useful, especially with regards to developing the algorithms required for the various processes.

Additions are currently being made to the *ACRU*2000 model and in certain instances it has already exceeded the capabilities of the previous versions of *ACRU*. A major objective of the restructuring process of the *ACRU*2000 model was to make the model more extensible. In this project, the ease with which new procedures were added to the model shows that this objective has been achieved as the algorithms were written and inserted virtually straight into the model with very little modification required to existing code. Currently, limitations do exist in the form of input constraints, some of which will be related in subsequent sections. One aspect that is likely to cause problems in the future is the limitation of not being able to place more than one water user of a certain type in a land segment. The model is constantly being developed and the future introduction of the Extensible Markup Language (XML) into *ACRU*2000 will eliminate this problem. Precision tolerance was also found to be a problem, although for the purposes of the operating rule framework where the quantities involved are normally large, the effects of this are minor.

6.2 General Evaluation of the Operating Rule Framework

The operating rule framework has been divided into the four main components which consist of water users, water requests, operating rules and water transfers. The four water users were chosen in an attempt to broadly represent all water users and can be altered with relative ease. The *CSettlement* object at this stage represents only the requirement of the basic human needs reserve. Other water uses associated with domestic use, such as watering gardens may need to be accounted for in the future. Another form of domestic user that will be required is the bulk or strategic water supplier, i.e. a company responsible for water supply to an urban area. This will also entail accounting for factors other than the basic human needs reserve. The constant daily request value of *CSettlement*, which is currently used could also be modified to incorporate a net population growth rate. This would enable the model user to predict the future requirements of a settlement which could have an impact on water supply if the population growth is significant.

The daily request of the industrial user (*CIndustry*) is very simplified in the current version and could also be modified in future to allow for the request to be altered over sub-daily periods. This could be useful for hydropower schemes that need to supply different rates at peak demand times. A further user that needs to be represented in the model is that of International Water Obligations where a dam is required to release a certain amount of water to sustain the river once it leaves the country in which the dam is situated. This was not implemented in this project because the rivers on which the case study was based do not flow into any of South Africa's neighbouring countries. However, it is an important consideration that will be required in the future.

The inclusion of the ecological reserve into the framework has been by far the most challenging part of the project. Two methods of producing an artificial flow regime downstream of the dam were employed, a simple and a complex approach. The simple approach was implemented purely as a starting point and was found to be oversimplified. The low-flows produced at times did not correspond to the flows entering the dam as the transition between the release of drought and maintenance flows was not well linked to the climatic conditions. The flood releases were always released on the first day of a month and consequently bore no resemblance to the current hydrological conditions in the catchment. The more complex approach was able to overcome these problems by using the parameter *BaseflowStatus* to give an indication of the conditions in the catchment over the preceding 30 days. The inclusion of the *BaseflowStatus* value in place of the *CurrentDayFlow* value in the low-flow equations resulted in the low-flows comparing very favourably with the natural flow conditions as well as complying with the requirements of the BBM. Releasing the flood events in accordance with the flows above the dam was greatly aided by the inclusion of a *RateOfRise* parameter that monitored the flow in the river from day-to-day. The final method of triggering the floods involved comparing the *RateOfRise* to a minimum criterion and lowering this criterion as the month progressed. This technique proved successful in providing a cue for each flood release that was made from the dam.

Limitations still exist within the complex approach. It is essential that the high flow peaks required at an IFR site are achieved as these have often been chosen to trigger, for example, fish spawning or invertebrate breeding by inundating certain parts of the river channel. The high flow releases occur as daily slugs of flow at a required flow rate to release the desired volume over the 24 hour period and it is assumed that the required peak flows are achieved. This will not be the case however, and in order to achieve these desired peaks, the flow rate of the flood release would need to be altered over sub-daily periods. This is not currently possible in *ACRU*2000 as the flood routing routines that would be required for this to occur are not in operation. Furthermore, attenuation of the released flood has not been taken into account and will be a major factor where the IFR site is situated many kilometres downstream of the dam. In order to consider this issue, a flood would have to be routed from the dam to the IFR site using, for example, the Muskingum technique and then the flow optimised until the desired peak was achieved at the IFR site. A further limitation of the flood releases is that only two possible flood sizes can be released i.e. maintenance or drought floods. This is not strictly in line with the BBM, where a range of flood sizes are expected and consequently, this problem needs to be addressed in the future. The combined use of climatic forecasting with the methods developed in the complex approach could also aid in providing an even more effective method of triggering the high-flow events. The influence of the forecasting technique would aid in avoiding the situation where an event with a rate of rise that meets the criterion for releasing a maintenance flood occurs early on in the month and consequently, a maintenance flood is released, while later in the month an event with an even larger rate of rise occurs. This event would have proved to be a more effective trigger for the maintenance flood. Forecasting would therefore allow the dam operator to find the most appropriate event in the month for cueing the flood.

Two operating rules were employed within the operating rule framework to ensure the sustainable and equitable supply of water to users abstracting from both dams and channels. The generic dam operating rule is governed by a curtailment structure based on the storage of the dam, the use of which was tested using the Pongola-Bivane river system, including the Paris Dam. After extensive validations were completed, scenarios were run in an attempt to assess if the curtailment structure could aid in ensuring the sustainability of the water resource whilst still achieving an equitable distribution of water between users. The results produced were extremely encouraging with the curtailment structure resulting in considerably less instances of system failure, where the dam was drawn down to the dead storage level, with resulting assurances of supply remaining reasonably high for all users, including those under severe drought conditions.

The generic dam operating rule does have certain weaknesses inherent within its water allocation procedures with regard to allocated water. Although this study has only regarded the ecological reserve as being able to store water, in future studies it may be necessary to allow other users to also store water. The problem is caused by the fact that allocated water is not curtailed by the generic dam operating rule. This could result in the situation where a low priority user has allocated water stored in the dam and the dam level is very low with the result that, for example, the basic human needs reserve cannot receive its request quantity. Water should possibly not be allocated to a user in this way, but rather the user should be allocated an amount annually which could then be divided between the months. This would enable the user to request water from its allocation as desired over the months of the year. Alternatively, if a user has allocated water present in a dam, this volume could fluctuate as the dam level fluctuates and the user's allocation would remain a proportion of the dam's available storage.

A further limitation of the current version of the generic dam operating rule is that it can only supply water to users from a single water source. It is vital that this problem is resolved in *ACRU*2000 as in practice many users rely on more than one dam to satisfy their requirements. The use of more than one dam as a water source would enable a water user to choose which dam to abstract from and, if the request could not be met by this dam, the user could request additional water from other dams. Currently, this is not possible in *ACRU*2000 because of the limitations associated with the input structure but the introduction of XML into the model could provide a solution.

The channel operating rule is responsible for supplying water to users abstracting directly from a river. It therefore needs to take into account the user's requirements while at the same time ensuring that the river is not drawn down to excessively low levels that are likely to be detrimental to the aquatic ecosystems. The rule is capable of supplying water to users but has been applied with an extremely simplified approach. The major problem associated with these simplifications is that the monthly maintenance IFR flow is used to determine whether a user should be curtailed or not. A more realistic value to use would be the daily request quantity determined by the complex environmental request method. This value could then vary from day to day with its lower limit being the drought monthly IFR flow level. This approach was conceptualised during this project but was not implemented due to time constraints and the complexities of implementation involved. The actual daily value should also fluctuate depending on where the user was situated in the catchment in relation to the IFR site. The value used to alter the daily environmental request quantity could be based on the percentage of the catchment contributing runoff to where the user is, relative to the percentage of the catchment contributing runoff to the IFR site. If the user was situated at the top of the catchment and the IFR site at the bottom, the daily request quantity would have to be considerably reduced for the stretch of river from which the user was abstracting. This approach would ensure that all parts of a catchment contribute to the IFR for the catchment, and would thus affect the quantity of water available to water users in each part of the catchment.

6.3 Evaluation of the Operating Rule Framework for Use in Real-time Dam Operations

One of the final objectives of this project was that the operating rule framework produced should in some way assist in the real-time operation of dams. Before testing the framework on Paris Dam, it became apparent that it is unlikely a generic dam operating rule framework could be developed so as to be applied without modification, to any dam in the country. Certain changes were necessary as a result of situations specific to the water users relying on Paris Dam. However, given the current structure of *ACRU*2000, these changes were made with ease.

The current operation of Paris Dam was investigated and then simulated using various curtailment structures. It was found that the curtailment structures helped to improve the users' assurances of supply in certain months. The operating rule framework was also found to be capable of producing a flow regime downstream of the Paris Dam that not only mimicked the natural flow regime, but once all other downstream users had been removed, supplied flows at the IFR site which met the flow requirements specified by the BBM with reasonable levels of assurance. The combined release of the environmental and the Pongola Irrigation scheme requirements is an interesting point for investigation where the question remains as to whether the environmental requirements should be regarded as being met when a single IFR site is satisfied or when the entire river downstream of the dam is taken into account. It is possible that the flow in the Pongola River downstream of the abstraction point of the Pongola Irrigation scheme could be significantly affected and this would in turn impact on the aquatic ecosystems existing in the river. An impact is also likely to be felt upstream where, especially on the Bivane River, the irrigation releases result in high flow levels in the drier months of the year which could prove detrimental to the aquatic ecosystems.

It has been demonstrated through the use of the case study on Paris Dam that the model could definitely help in determining the optimal operating policy. This process could possibly be further improved if one of the optimisation techniques discussed in Chapter 2 were linked to the operating rule framework. Real-time day-to-day use of the model for determining the IFR releases required may not be practical at this stage as a simulation would have to be run every day for all the years of available data. In time, it is possible that the model will be able to store information from a previous simulation. In order to determine, for example, the IFR requirements for a day, the model would then only need to be run for a single day. If this can be achieved, it is believed that the operating rule framework in *ACRU*2000 may have a large role to play in aiding in real-time operation of dams.

6.4 Conclusions and Recommendations for Future Research

The operating rule framework has been developed according to the objectives stated in Chapter 1. On completion of the project it is believed that these objectives have been fully satisfied. The framework has been extensively validated and evaluated and has been found to be capable of simulating the operation of both a dam and a river with the use of a reasonably generic set of operating rules. The environment has been included in the framework to account for the ecological reserve and the framework has been found to be capable of producing an artificial flow regime downstream of the dam that successfully mimics the natural flow regime. From the scenario testing employed, the results obtained suggest that if certain limitations can be accounted for, the operating rule framework in *ACRU*2000 could be used for finding the optimal dam operating policy, as well as aiding in the real-time operation of dams in the future.

Numerous research possibilities still exist for extending the capabilities of the framework with those considered as most important, as follows:

(a) The dam operating rule must be able to supply water to users from more than one dam at a time.

(b) The concept of allocated water needs to be altered.

(c) The channel operating rule needs to be improved by making use of the daily IFR requirement and converting it to a value representative of where the user is situated in the catchment.

(d) A method to account for flood attenuation of high-flows released to satisfy the ecological reserve should be introduced.

(e) The inclusion of climatic forecasting could aid in the triggering of flood events.

(f) The operating rule framework needs to account for International Water Obligations.

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8. APPENDICES

Appendix A.

Table A1 Table of classes utilised by the operating rule framework

Class name	Definition
CChannel	A Components class representing any channel along which water flows naturally.
CDam	A Components class representing a man-made structure built for the purposes of impounding water.
CIrrigatedArea	A Components class representing an irrigator as a water user.
CLandSegment	A Components class representing a part of a subcatchment with similar soil types or land uses.
CReach	A Components class representing any water body. This class includes both *CChannel* and *CDam*.
CWaterTransfer	A Components class that provides an artificial link between two components for the purposes of moving water from the one component to the other i.e. an irrigation canal that transfers water from a *CChannel* class to a *CIrrigatedArea* class.
DWaterFluxRecord	A Data class that stores the values of water entering and leaving a component. For example, this class would store the flows entering a *CDam* class from all the various *CChannel* classes flowing into the dam, as well as the quantity released from the dam into the downstream *CChannel* class.
DWaterRequest	A Data class used to request the transfer of a quantity of water from a particular water source to a particular component. This class is described in more detail in Section 4.2

Appendix B.

Appendix B contains tables of variables/classes employed by each of the processes added to *ACRU*2000 in order to implement the operating rule framework. The tables include the variable names used in flow diagrams in the text as well as the names of the associated classes. Certain variables are not linked to classes as they may only be used by a single process or their values may not be stored. These variables are given the name of "Local variable" in the tables. The tables also include definitions of each variable, some of which have been expanded on from those given in the text to provide further explanation.

Table B1 Table of the variables employed by the *PBasicHumanNeedsReq* process

Variable name	Class name	Definition
	CSettlement	This class represents a settlement as a water user and forms part of a land segment.
DailyReq	*DBasicHumanNeedsReserve*	The value of the minimum daily water requirement for a single person to satisfy basic drinking water and sanitation needs, as specified in the National Water Act (1998) i.e. 25 litres.
DomesticReq	*DBasicHumanNeedsRequest*	The value of the daily basic human needs request input by the user (m^3).
DomesticReq	*DRequestQuantity*	The value of the quantity requested by a settlement for the day (m^3).
PopulationSize	*DPopulation*	The population of the particular settlement.
SettlementOption	*DSettlementOption*	The option to specify whether a settlement is present in the given land segment or not: 0 = no settlement present 1 = settlement present, with request quantity calculated using *PopulationSize* and *DailyReq*, 2 = settlement present, with request quantity input by user.

Table B2 Definitions of the variables employed by the *PIFRSimple* process

Variable name	Class name	Definition
	CIFRSite	This class represents an IFR site as a cross-section of a channel. *CIFRSite* is considered as a type of *CChannel* class (See Appendix A, Table A1).
AvailableWater	Local variable	The storage volume in a dam that is available for use by water users, i.e. dead storage excluded (m^3).
CurrentDayInflow	*DDamInflow*	The flow entering the dam from the main upstream river channel. For the purposes of this study, this flow value can be assumed to be supplied fully by the Bivane River ($m^3.s^{-1}$).
DroughtCriterion	*DDroughtCriterion*	A percentage value that when combined with *MainInstantaneousFlow* is used to determine whether a drought or maintenance low-flow IFR release should be made (%).
DroughtDaysToPeakFlow	*DDroughtDaysToPeakFlow*	The days required before peak flow is reached for the drought flood specified in the IFR table (days).
DroughtFloodDuration	*DDroughtFloodDuration*	The duration of the drought flood specified in the IFR table (days).
DroughtFloodVolume	*DDroughtFloodVolume*	The volume of the drought flood specified in the IFR table (m^3).
DroughtInstantaneousFlow	*DDroughtInstantaneousFlow*	The monthly drought low-flow value specified in the IFR table ($m^3.s^{-1}$).
DroughtPeakFlow	*DDroughtPeakFlow*	The peak flow value of the drought flood specified in the IFR table ($m^3.s^{-1}$).
ElapsedFloodDays	Local variable	The number of days that have passed since the start of a flood release i.e. *ElapsedFloodDays* equals 0 on the first day of the flood (days).
EndOfDayFlow	Local variable	The flow required for the current day to produce the desired flood ($m^3.s^{-1}$).

HydrographSlope	Local variable	The slope of the triangular hydrograph used for determining the daily flood release ($m^3.s^{-1}.day^{-1}$).
MainDaysToPeakFlow	*DMainDaysToPeakFlow*	The days required before peak flow is reached for the maintenance flood specified in the IFR table (days).
MainFloodDuration	*DMainFloodDuration*	The duration of the maintenance flood specified in the IFR table (days).
MainFloodVolume	*DMainFloodVolume*	The volume of the maintenance flood specified in the IFR table (m^3).
MainInstantaneousFlow	*DMainInstantaneousFlow*	The monthly maintenance low-flow value specified in the IFR table ($m^3.s^{-1}$).
MainPeakFlow	*DMainPeakFlow*	The peak flow value of the maintenance flood specified in the IFR table ($m^3.s^{-1}$).
ReqRelease	Local variable	The quantity required to satisfy the requirements of the ecological reserve on a day. This variable is used for both low-flow and high-flow requests and forms the request quantity part of the water request (m^3).
StartOfDayFlow	Local variable	The flow from the previous day required to produce the desired flood ($m^3.s^{-1}$).

Table B3 Definitions of the variables employed by the *PIFRComplex* process

Variable name	Class name	Definition
AttenuationParameter	Local variable	The parameter used to lower the *MinRateOfRise* criterion as a month progresses ($m^3.s^{-1}$).
AvailableWater	Local variable	The storage volume in a dam that is available for use by water users, i.e. dead storage excluded (m^3).
BaseflowStatus	*DBaseflowStatus*	A flow value that gives some indication of the hydrological conditions existing in a catchment over the preceding 30 days (m^3).
CurrentDay	Local variable	The current day of the simulation. This value is utilised during the *PIFRComplex* process as part of the calculation of the *MinRateOfRise* value (days).
CurrentDayFlow	*DDamInflow*	The flow entering the dam from the main upstream river channel. For the purposes of this study, this flow value can be assumed to be supplied fully by the Bivane River. This point on the Bivane River, serves as the trigger point used for finding both the *BaseflowStatus* and the *RateOfRise* values ($m^3.s^{-1}$).
DaysInMonth	Local variable	The total number of days in the month in which *CurrentDay* is situated. This value is used in calculating the *AttenuationParameter* for the relevant month (days).
DroughtDaysToPeakFlow	*DDroughtDaysToPeakFlow*	The days required before peak flow is reached for the drought flood specified in the IFR table (days).
DroughtFloodDuration	*DDroughtFloodDuration*	The duration of the drought flood specified in the IFR table (days).
DroughtFloodVolume	*DDroughtFloodVolume*	The volume of the drought flood specified in the IFR table (m^3).

DroughtInstantaneousFlow	*DDroughtInstantaneousFlow*	The monthly drought low-flow value specified in the IFR table ($m^3.s^{-1}$).
DroughtPeakFlow	*DDroughtPeakFlow*	The peak flow value of the drought flood specified in the IFR table ($m^3.s^{-1}$).
DroughtRateOfRise	*DDroughtRateOfRise*	The rate of rise of the drought flood specified in the IFR table ($m^3.s^{-1}.day^{-1}$).
DroughtThreshold	*DDroughtMonthlyThreshold*	A monthly percentage value used to find the *ModDroughtFlow* value from the monthly duration curve (%).
FloodThreshold	Local variable	A value used together with *BaseflowStatus*, to determine whether a drought or maintenance flood should be released on a day ($m^3.s^{-1}$).
MainDaysToPeakFlow	*DMainDaysToPeakFlow*	The days required before peak flow is reached for the maintenance flood specified in the IFR table (days).
MainFloodDuration	*DMainFloodDuration*	The duration of the maintenance flood specified in the IFR table (days).
MainFloodVolume	*DMainFloodVolume*	The volume of the maintenance flood specified in the IFR table (m^3).
MainInstantaneousFlow	*DMainInstantanousFlow*	The monthly maintenance low-flow value specified in the IFR table ($m^3.s^{-1}$).
MainPeakFlow	*DMainPeakFlow*	The peak flow value of the maintenance flood specified in the IFR table ($m^3.s^{-1}$).
MainRateOfRise	*DMainRateOfRise*	The rate of rise of the maintenance flood specified in the IFR table ($m^3.s^{-1}.day^{-1}$).
MainThreshold	*DMainMonthlyThreshold*	A monthly percentage value used to find the *ModMainFlow* value from the monthly duration curve (%).
MaxThreshold	*DMaxMonthlyThreshold*	A monthly percentage value used to find the *ModMaxFlow* value from the monthly duration curve (%).
MinRateOfRise	Local variable	A minimum rate of rise required at the trigger point in order to cue the release of a maintenance high-flow event ($m^3.s^{-1}.day^{-1}$).

ModDroughtFlow	*DDroughtThresholdFlow*	The monthly drought flow value used for determining the daily low-flow request quantity ($m^3.s^{-1}$).
ModMainFlow	*DMainThresholdFlow*	The monthly maintenance flow value used for determining the daily low-flow request quantity ($m^3.s^{-1}$).
ModMaxFlow	*DMaxThresholdFlow*	The monthly maximum low-flow value used for determining the daily low-flow request quantity ($m^3.s^{-1}$).
PreviousDayFlow	Local variable	The previous day's flow at the trigger point ($m^3.s^{-1}$).
RateOfRise	Local variable	The rate of rise at the trigger point from day-to-day ($m^3.s^{-1}.day^{-1}$).
ReqRelease	Local variable	The quantity required to satisfy the requirements of the ecological reserve on a day. This variable is used for both low-flow and high-flow requests and forms the request quantity part of the water request (m^3).
ThresholdValue	Local variable	A percentage value used to raise the *FloodThreshold* above the *ModDroughtFlow* value (%).

Table B4 Definitions of the variables employed by the *PGenericOperatingRule* process

Variable name	Class name	Definition
AllocatedLowflowQuantity	Local variable	This value is only used during the *PParisDamOperatingRule* process. It is the quantity of water allocated to IFR site 2 after the water allocation procedure has been completed and is combined with *IrrigQuantity* to determine the quantity of water that must be released from Paris Dam to satisfy the environmental requirements (m^3).
AvailableWater	Local variable	This value differs for requests made from unallocated and allocated water. For requests from unallocated water, this value is the unallocated storage volume in a dam above dead storage. For requests from allocated water, this value is the quantity of water already allocated to the user making the water request (m^3).
CurrentStorage	Local variable	The storage of the dam at the beginning of the operational procedure for the day (m^3).
CurtailmentLevel	*DDamCurtailmentLevel*	The percentage of a user's request quantity that is likely to be satisfied. This value is dependent on the storage of the dam (%).
CurtRequestQuantity	Local variable	The quantity that remains after the request quantity of the user has received curtailment (m^3).
CurtRequestTotal	Local variable	The sum of a number of *CurtRequestQuantities* of equal priority users. If only one user of a specified priority exists, this value will equal the *CurtRequestQuantity* value (m^3).

DamOperationOption	*DDamOperationOption*	The option to specify whether a dam should be operated according to a curtailment structure or not: 1 = all requests made to the dam are subjected to the curtailment structure 2 = all requests made to the dam are automatically abstracted, provided the available storage is greater than or equal to the dead storage level.
DeadStorage	*DDamDeadStorage*	The volume of storage in a dam that cannot be abstracted. For Paris Dam, this is assumed as 10 % of the dam's full capacity (m^3).
Deficit	Local variable	This value is only used during the *PParisDamOperatingRule* process. It is the quantity of water that needs to be released from Paris Dam, over and above *IrrigQuantity* in order to satisfy the environmental requirements (m^3).
EqualPriorityRequestTotal	Local variable	The sum of a number of *RequestQuantities* of equal priority users. If only one user of a specified priority exists, this value will equal the *RequestQuantity* value (m^3).
IrrigQuantity	Local variable	This value is only used during the *PParisDamOperatingRule* process. It is the quantity of water allocated to the Pongola Irrigation scheme after the water allocation procedure has been completed (m^3).
ManagementLevel	*DDamManagementLevel*	A range of percentages of a dam's current storage that determine to what degree a user's request quantity is curtailed (%).
ReallocationQuantity	Local variable	The quantity that a user is allocated if sufficient storage does not exist in the dam above the dead storage level to supply the *CurtRequestQuantity*. If more than one user of equal priority exists, the *AvailableStorage* will be distributed proportionally among the users according to their respective *CurtRequestQuantities* (m^3).

RequestQuantity	Local variable	The quantity contained in a water request that is requested by a user from the dam on a day (m^3).
ThisWaterRequest	Local variable	The particular water request whose curtailment is currently being determined by the *PGenericOperatingRule* process.

Table B5 Definitions of the variables employed by the *PChannelOperatingRule* process

Variable name	Class name	Definition
AvailableWater	Local variable	This value is the unallocated storage volume in a channel above the *DroughtInstantaneousFlow* level (m^3).
CurrentDayFlow	*DCurrentDayFlow*	The average flow value for the day in the stretch of river from which water is being abstracted ($m^3.s^{-1}$).
CurtailmentLevel	*DChannelCurtailmentLevel*	The percentage of a user's request quantity that is likely to be satisfied. This value is largely dependent on the *CurrentDayFlow* value (%).
CurtRequestQuantity	Local variable	The quantity that remains after the request quantity of the user has received curtailment (m^3).
CurtRequestTotal	Local variable	The sum of a number of *CurtRequestQuantities* of equal priority users. If only one user of a specified priority exists, this value will equal the *CurtRequestQuantity* value (m^3).
DroughtInstantaneousFlow	*DDroughtInstantaneousFlow*	The monthly drought low-flow value specified by the IFR table ($m^3.s^{-1}$).
ManagementLevel	*DChannelManagementLevel*	A range of percentages of a channel's current storage between the *DroughtInstantaneousFlow* and *MainInstantaneousFlow* levels, that determines to what degree a user's request quantity is curtailed (%).
MainInstantaneousFlow	*DMainInstantaneousFlow*	The monthly maintenance low-flow value specified by the IFR table ($m^3.s^{-1}$).

ReallocationQuantity	Local variable	The quantity that a user is allocated if sufficient storage does not exist in the channel above the *DroughtInstantaneousFlow* level to supply the *CurtRequestQuantity*. If more than one user of equal priority exists, the *AvailableStorage* will be distributed proportionally among the users according to their respective *CurtRequestQuantities* (m^3).
RequestQuantity	Local variable	The quantity contained in a water request that is requested by a user from the channel on a day (m^3).
ThisWaterRequest	Local variable	The particular water request whose curtailment is currently being determined by the *PChannelOperatingRule* process.

Table B6 Definitions of the variables employed by the *PPongolaIrrigationSchemeReq* process

Variable name	Class name	Definition
FlowDeficit	*Local variable*	The difference between the values of *ReqIrrigationFlow* and *UpperPongolaWeirFlow* ($m^3.s^{-1}$).
MonthlyIrrigationVolume	*Local variable*	The monthly volume required by the Pongola Irrigation scheme (m^3).
ReqIrrigationFlow	*Local variable*	The daily flow value required by the Pongola Irrigation scheme and calculated from the value of *MonthlyIrrigationVolume* for the current month ($m^3.s^{-1}$).
ReqRelease	*Local variable*	The quantity required to satisfy the requirements of the Pongola Irrigation scheme on a day. This value is found by converting *FlowDeficit* to a volume (m^3).
UpperPongolaWeirFlow	*DChannelOutflow*	The flow occurring at the Upper Pongola weir, shown in Figure 5.2. The flow at this weir is compared to *ReqIrrigationFlow* to find the value of *FlowDeficit* ($m^3.s^{-1}$).