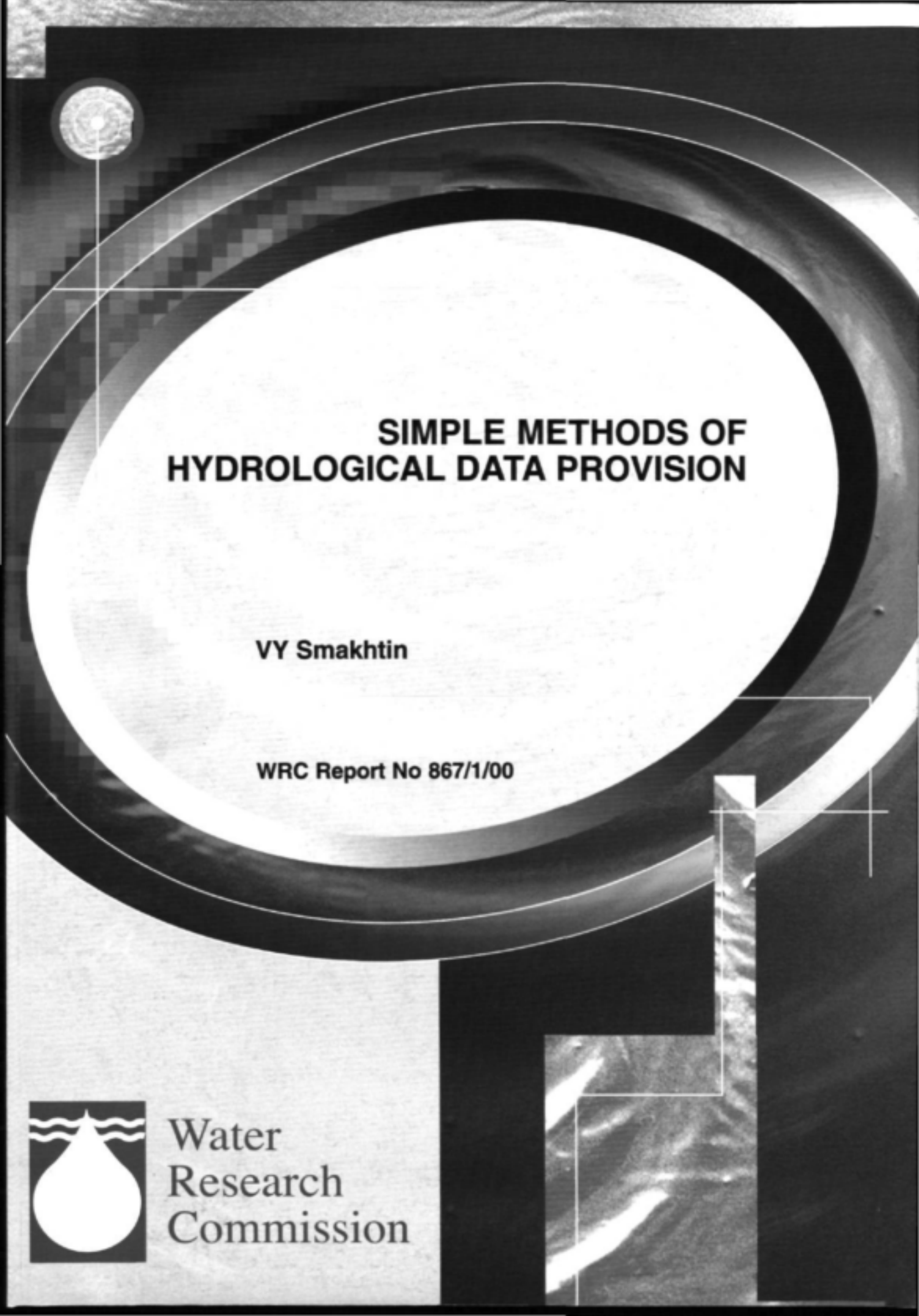

# SIMPLE METHODS OF HYDROLOGICAL DATA PROVISION

**VY Smakhtin**

**WRC Report No 867/1/00**

Water
Research
Commission

# SIMPLE METHODS OF HYDROLOGICAL DATA PROVISION

FINAL REPORT TO THE WATER RESEARCH COMMISSION ON THE PROJECT:

"INTEGRATED AND APPLICATION OF DAILY FLOW ANALYSIS AND SIMULATION APPROACHES WITHIN SOUTHERN AFRICA"

BY THE

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IWR Report No. 1/2000
WRC Report No. 867/1/00
ISBN No. 1 86845 662 5
ISBN Set No. 1 86845 657 9

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## ACKNOWLEDGEMENTS

The author gratefully acknowledges the following people who have directly or indirectly contributed to this Project.

- Prof Denis Hughes, a co-project leader, for valuable comments, suggestions and discussions throughout the course of the Project.
- Ms Deidre Watkins for permanent technical assistance and preparation of extensive graphical information behind the study
- Mr David Forsyth for computer support
- Mrs Juanita Mclean for administrative and secretarial support
- Ms Marion Toulouse and Ms Benedicte Masse, interns from the Ecole Nationale Superieure Agronomique de Rennes, France, for assistance with data preparation and analysis

Sincere thanks are extended to Mr Johan Wetzel and Ms Fransinah Sibanony of the Department of Water Affairs and Forestry for effective supply of streamflow data throughout the Project.

Rainfall data have been obtained from the Computing Center for Water Research (CCWR), University of Natal, Pietermaritzburg. (Special word of thanks to Mr Reinier de Vos, for technical assistance with data supply).

It is gratefully acknowledged that this Project would not have been possible without financial support of the Water Research Commission (WRC).

Thanks are extended to the following people who comprise the acting core of the Steering Committee for this Project:

Mr H Maaren (Chairman) : Water Research Commission
Dr. GC Green : Water Research Commission
Prof B Kelbe : University of Zululand
Mr B Wolf-Piggott : Department of Water Affairs and Forestry
Mr EA Nel : Department of Water Affairs and Forestry

A special word of thanks is due to Mr Hugo Maaren, for his permanent attention and wise guidance during the Project

## ABBREVIATIONS

| | |
|---|---|
| ADF | Average Daily Flow |
| API | Antecedent Precipitation Index |
| AVC | Average flow duration curve (Average Variability Curve) |
| BFI | Baseflow Index |
| CE | Coefficient of Efficiency |
| CPI | Current Precipitation Index |
| DWAF | Department of Water Affairs and Forestry |
| FDC | Flow Duration Curve |
| HVC | High Variability flow duration Curve |
| HYMAS | Hydrological Modeling Application System |
| IWR | Institute for Water Research |
| LEC | Lower Envelope flow duration Curve |
| LVC | Low Variability flow duration Curve |
| MAE | Mean Annual Evaporation |
| MAR | Mean Annual Runoff |
| MAP | Mean Annual Precipitation |
| MALF | Mean Annual Low Flow |
| MAHF | Mean Annual High Flow |
| MAM7 | Mean Annual 7-day Minimum Flow |
| Q95, Q75, etc | Discharges exceeded 95, 75% of the time, etc |
| REC50 | Median recession ratio |
| $R^2$ | Coefficient of determination |
| SE | Standard Error |
| $T_0$ | % of time with zero flow conditions |
| VTI | Variable Time Interval model |
| WR90 | An acronym for Surface Water Resources of South Africa 1990 (Midgley *et al*, 1994) |
| UEC | Upper Envelope flow duration Curve |
| SD50 | Mean of the annual series of maximum spell durations below the threshold flow of 50% of ADF |
| DEF50 | Mean of the annual series of maximum flow deficits below the threshold flow of 50% of ADF |
| 7Q2, 7Q10 | 7-day average minimum discharges with return periods of 2 and 10 years |

## EXECUTIVE SUMMARY

The assessment of water resources in South Africa has traditionally been based on monthly streamflow time series, which are now widely available in the country from various basin studies, system analysis reports commissioned by the Department of Water Affairs and Forestry, as well as from the Surface Water Resources of South Africa (WR90, Midgley, et al, 1994). However, flow information on a finer, daily time resolution is required in many areas of research and practice (river ecology and water quality studies, design of run-off-river abstraction schemes, etc). The primary source of daily streamflow data is observed flow records, but their direct use is often hampered by their insufficient quality. Also, the spatial availability of such records varies significantly in different parts of the country.

The conventional way of augmenting the availability daily streamflow records is the use of deterministic rainfall-runoff simulation methods. However, the costs and timing associated with many water projects do not always justify the use of such complex modelling techniques. Also, the comprehensive methods of streamflow generation may not necessarily result in a reliable output, since they normally require a large amount of input information, including the information, which may simply not be available in many data poor regions in Southern Africa. In such circumstances, the use of simpler and quicker estimation methods may be more justified and, at the same time, equally successful.

The development of such "pragmatic" methods of streamflow estimation and analysis was initiated in the Institute for Water Research of Rhodes University during the period of 1995-1996, through several research projects funded by the WRC. Hughes and Smakhtin (1996) developed and algorithm for patching and extending observed time series of daily streamflow. The algorithm was based on daily flow duration curves and the motivation for the developing the technique was initially related to the need for flow time series that were coincident in time. Smakhtin, *et al* (1997) further illustrated one possible extension of this method for generating continuous flow sequences at ungauged sites. The suggested methods were economic (in terms of input information required) and quick to run but at that stage a number of issues related to their application still had to be resolved.

The investigation of the use of flow duration curves and their application for generation of continuous time series of daily flows has thus become the focal point of this research. The necessity for further development of these techniques was also driven by the information requirements of increasing number of small water supply projects and by the developing concepts of environmental flow management. The application of such parsimonious hydrological estimation techniques was found very useful, in establishing ecological Instream Flow Requirements for many rivers in the country. It was therefore recommended to continue with the development of simple estimation methods based on flow duration curves in the next WRC project entitled "Integration and application of daily flow analysis and simulation approaches within Southern Africa".

The main objective of this Project, which was identified in the original proposal and which is specifically addresses in this Report was:

- To further develop simple methods of estimating daily flow indices and time series, partly by converting existing regionalized monthly flow data using relationships between monthly and daily flow duration curves

The present Report summarizes the results of research activities, which are related to the originally defined objective. These activities lead to what is further referred to in this Report as "the concept of pragmatic hydrological modeling".

This concept focuses on Flow Duration Curve (FDC) as a key characteristic of streamflow variability in natural and developed river catchments. The Report reviews recent advancement in the theory of FDCs, and describes major steps which need to be implemented if a FDC-based methods of time series generation are to be used as a substitute to more complex deterministic modeling techniques. The ultimate goal in pragmatic hydrological modeling concept is a continuous streamflow time series, while the calculation of representative FDCs is the prerequisite for it and the starting point. In general, the methodology of pragmatic hydrological time series modeling includes:

1. technique(s) by which to establish representative FDCs for different types of river catchments in natural conditions. "Natural" FDCs represent reference conditions of streamflow variability in a catchment, which existed prior to any catchment or water resources development.

2. technique(s) by which to adjust the "natural" FDCs to match with the current state or possible scenarios of catchment and/or water resources development. These techniques allow different catchment development scenarios to be simulated (which also represent one of the goals of conventional hydrological modeling).

3. technique(s) by which the established and adjusted FDCs may be transformed into actual continuous flow time series for any further analysis.

In order to use a FDC in the context of hydrological time series modeling, a representative curve should be established at a site of interest (and adjusted if necessary for development effects) prior to the generation of the actual continuous flow time series.

The three sets of techniques outlined above effectively represent the general structure of the pragmatic hydrological time series modeling concept, and are discussed in detail in the Report. First, the methods of FDCs calculation by means of hydrological regionalisation are described and procedures for FDCs estimation at ungauged sites are suggested. They include, amongst the others, the techniques, which may be used to formulate different scenarios of streamflow variability in ungauged river catchments.

The Report further presents the techniques for derivation of 1-day FDCs from monthly streamflow data. These techniques have emerged from the analysis of approximately 200 observed streamflow datasets from the entire country.

A special section discusses possible approaches for adjustment of FDCs for catchment land-use changes and water resources development effects.

A complete continuous daily streamflow time series at a site is generated by means of a non-linear spatial interpolation technique and established FDCs. The Report gives examples of the time series generation using exclusively the observed streamflow records, in cases when FDCs at a site were established by means of hydrological regionalization. The application of spatial interpolation technique for the restoration of natural daily streamflow time series in already modified catchments is also described.

During the course of the project, the original version of the spatial interpolation technique has been extended to be specifically applicable in cases when no daily streamflow data are available. The Report describes the major extension of the spatial interpolation algorithm, which includes the incorporation of the precipitation index concept. It illustrates, how daily streamflow time series at an ungauged site may be generated using available rainfall daily records only. Another section describes possible application of this method for generating monthly streamflow records.

A special Chapter deals with possible application of FDCs for low-flow estimation at ungauged sites. It explores the relationships between low-flow indices derived from the curve and low-flow indices, which describe other aspects of low-flow regime. The predictive formulae for various low-flow characteristics are suggested.

The research undertaken within the framework of this Project effectively results in the set of techniques, which could be used for the provision of very much needed daily streamflow information at any catchment in South Africa, southern Africa, or other data poor region. The set of techniques provided could be applied, for example for generation of streamflow time-series for quaternary catchments in the country (or combination of quaternary catchments), as well as for catchments of smaller, sub-quaternary scale.

The Report recommends proceeding with the development of pragmatic methods of hydrological estimation, which are specifically relevant in data poor regions. It is envisaged, for example, that such methods may form an integral part of the recently initiated sub-continent wide surface water resources survey in the SADAC region. The use of FDCs may also be relevant for the generation/estimation of other water resource characteristics (river stage, sediment load, habitat suitability, water quality parameters, hydropower energy output, etc.). A FDC based estimation methods have potential in producing inundation maps, evaluating tradeoffs among water quality management variables, in waste load allocation, optimal water resource allocation, estuarine management, economic appraisal of water resource management and engineering practices, etc.

# 1. INTRODUCTION

The assessment of water resources in South Africa has traditionally been based on monthly streamflow time series, which are now widely available in the country from various basin studies, system analysis reports commissioned by the Department of Water Affairs and Forestry, as well as from the Surface Water Resources of South Africa (WR90, Midgley, et al, 1994). However, flow information on a finer, daily time resolution is required in many areas of research and practice (run-off-river abstractions, water quality calculations, studies of river ecology etc). The primary source of daily streamflow data is observed flow records, but their direct use is often hampered by their insufficient quality. Also, the spatial availability of such records varies significantly in different parts of the country.

The conventional way of augmenting the availability daily streamflow records is the use of deterministic rainfall-runoff simulation methods. However, the costs and timing associated with many water projects do not always justify the use of such complex modelling techniques. Also, the comprehensive methods of streamflow generation may not necessarily result in a reliable output, since they normally require a large amount of input information, including the information, which may simply not be available in many data poor regions in Southern Africa. In such circumstances, the use of simpler and quicker estimation methods may be more justified and, at the same time, equally successful.

The development of such "pragmatic" methods of streamflow estimation and analysis was initiated in the Institute for Water Research of Rhodes University during the period of 1995-1996, through several research projects funded by the WRC. Hughes and Smakhtin (1996) developed and algorithm for patching and extending observed time series of daily streamflow. The algorithm was based on daily flow duration curves and the motivation for the developing the technique was initially related to the need for flow time series that were coincident in time. Smakhtin et al (1997) further illustrated one possible extension of this method for generating continuous flow sequences at ungauged sites. The suggested methods were economic (in terms of input information required) and quick to run but at that stage a number of issues related to their application still had to be resolved.

The investigation of the use of flow duration curves and their application for generation of continuous time series of daily flows has thus become the focal point of this research. The necessity for further development of these techniques was also driven by the information requirements of increasing number of small water supply projects and by the developing concepts of environmental flow management. The application of such parsimonious hydrological estimation techniques was found very useful, in establishing ecological Instream Flow Requirements for many rivers in the country. It was therefore recommended to continue with the development of simple estimation methods based on flow duration curves in the next WRC project entitled "Integration and application of daily flow analysis and simulation approaches within Southern Africa".

The main objective of this Project, which was identified in the original proposal and which is specifically addresses in this Report was:

- To further develop simple methods of estimating daily flow indices and time series, partly by converting existing regionalized monthly flow data using relationships between monthly and daily flow duration curves

The present Volume summarizes the results of research activities, which are related to the originally defined objective. These activities lead to what is further referred to in this Volume as "the concept of pragmatic hydrological modeling".

The Volume consists of 9 Chapters including this one. Chapter 2 describes the main principles of pragmatic hydrological time series modeling concept. It focuses on Flow Duration Curve (FDC) as a key characteristic of streamflow variability in natural and developed river catchments, reviews recent advancement in the theory of FDCs, and describes major steps which need to be implemented if a FDC-based methods of time series generation are to be used as a substitute to more complex deterministic modeling techniques

Chapter 3 deals with methods of FDCs calculation by methods of hydrological rationalization of based on observed streamflow data. It illustrates how FDCs for ungauged sites may be established and how FDCs may be used to formulate different scenarios of streamflow variability.

Chapter 4 presents the techniques for derivation of 1-day FDCs from monthly streamflow data. It summarizes the results, which have emerged from the analysis of approximately 200 observed streamflow datasets from the entire country.

Chapter 5 discussed possible approaches for adjustment of FDCs for catchment land-use changes and water resources development effects.

Chapter 6 describes how the established FDCs may be converted into a complete time series at a site using a non-linear spatial interpolation technique. The Chapter also gives examples of the time series generation using exclusively the observed streamflow records.

Chapter 7 describes the major extension of the spatial interpolation algorithm, which includes the incorporation of the precipitation index concept. It illustrates, how daily streamflow time series at an ungauged site may be generated in the absence of any streamflow data in the surrounding region, using only available rainfall daily records. A special section describes possible application of this method for generating monthly streamflow records.

Chapter 8 deals with possible application of FDCs for low-flow estimation at ungauged sites. It explores the relationships between low-flow indices derived from the curve and low-flow indices, which describe other aspects of low-flow regime. The Chapter suggests the predictive formulae for various low-flow characteristics.

Chapter 9 includes conclusions and recommendations for future research.

The list of references is given in the end of the Report.

## 2. A CONCEPT OF PRAGMATIC HYDROLOGICAL MODELING BASED ON FLOW DURATION CURVES

Continuous streamflow time-series are required for a variety of water engineering applications, water quality problems and river ecology studies. The conventional way of generating representative streamflow time series is through the use of deterministic rainfall runoff models. Flow time series represent only part of the overall data output which deterministic models normally provide, but these time series alone may satisfy the hydrological data requirements of many projects. Also, the application of complex and information consuming methods is not always appropriate, especially, in the data poor regions, where the use of more pragmatic techniques of data generation may be more justified and equally successful. In order to be competitive with more complex simulation methods, such "pragmatic" approaches need to be simple and economic (in terms of input information required), quick and easy to set up and run, and capable of generating hydrological time series for ungauged catchments and for different scenarios of catchment and/or water resources developments. On the other hand, they need to be scientifically sound and therefore - as much "physically based" as possible. This antagonism may be resolved if the focus is placed on some composite flow measure which

- may be calculated/estimated for any river catchment
- uniquely represents a catchment flow regime and reflects the effects of physiographic catchment factors and
- sensitive to changes in catchment hydrology.

The most obvious example of such a measure is a Flow Duration Curve (FDC). A FDC is a very informative way of displaying the complete range of discharges from low flows to flood events at any point in a river catchment. It is a cumulative distribution of river flows: a relationship between any given discharge value and the percentage of time that this discharge is equaled or exceeded, or in other words - the relationship between magnitude and frequency of streamflow discharges.

A FDC is constructed by reassembling the flow time series values in decreasing order of magnitude (ranking), assigning flow values to class intervals and counting the number of occurrences (time steps) within each class interval. Cumulated class frequencies are then calculated and expressed as a percentage of the total number of time steps in the record period. Finally, the lower limit of every discharge interval is plotted against the percentage points. Alternatively, all ranked flows are plotted against their rank, which is again expressed as a percentage of the total number of time steps in the record. The most convenient way of constructing a FDC is using the log-normal probability plot. This allows FDCs in some cases to be linearized and low- and high-flow ends of the curve to be more clearly displayed.

FDC may be constructed using different time resolutions of streamflow data: annual, monthly, and daily. However, the most commonly used data time resolutions are 1 day and 1 month. FDCs constructed on the basis of daily flow time series provide the most detailed way of examining duration characteristics of a river. FDCs constructed on the basis of daily flow time series are further referred to in this Report as "1-day FDCs", while those constructed on the basis of monthly flow time series – as "1-month FDCs".

FDCs may be calculated :

- on the basis of the whole available record period ("period of record FDC" (Vogel and Fennesey, 1994), or "long-term average annual FDCs" (FREND, 1989; Smakhtin *et al*, 1997));
- on the basis of all similar calendar months from the whole record period (e.g. all Januaries - "long-term average monthly FDC" (Smakhtin *et al*, 1997) or FDC of a monthly "window" (Mngodo, 1997)).

The first FDC type is referred to in this Report as "average annual FDC" (or simply "annual FDC") and the second - as "average monthly FDC" (or simply "monthly FDC"). FDCs may also be constructed using all similar seasons from the whole record period (long-term average seasonal FDCs (Smakhtin *et al*, 1997)), for a particular season (e.g. summer 1992) or particular month (e.g. January 1990)

The flows for the curve may be expressed in actual flow units, as percentages/ratios of MAR, MDF or some other "index flow", or divided by the catchment area. Such normalisation facilitates the comparison between different catchments, since it reduces the differences in FDCs caused by differences in catchment area or MAR. Consequently, the effects of other factors on the shape of FDCs (aridity, geology, anthropogenic factors) may be inspected. Additional details on FDC construction and interpretation have been provided by Searcy (1959); Chow (1964); Institute of Hydrology (1980); McMahon and Mein (1986).

The shape and general interpretation of any FDC depend on hydrometric errors and the particular period of record on which it is based. This has been directly or indirectly illustrated by (Searcy, 1959; Vogel and Fennessey, 1994; Hughes and Smakhtin, 1996; Mngodo, 1997, Smakhtin *et al*, 1997). FDCs are less sensitive to missing data, which in many cases can simply be ignored (Searcy, 1959; Mngodo, 1997).

The annual period-of-record FDC represents variability and exceedence probability of flow over the available (or selected) period. If the record period is sufficiently long, this interpretation is appropriate, since the FDC approaches a "limiting" cumulative flow distribution. Vogel and Fennessey (1994) suggested a different interpretation of a FDC. It considers FDCs for individual years and treats those annual FDCs in the way similar to a sequence of annual flow maxima or minima. This interpretation allows mean and median FDCs to be estimated. Such curves represent the exceedence probability of flow in a typical year and were demonstrated to be less sensitive to the length of the record period, especially in the area of low flows. This approach also allows confidence intervals and return periods to be assigned to FDCs. Other probabilistic and parametric representations of FDC have been suggested by Quimpo *et al* (1983), Mimikou and Kaemaki (1985), Fennessey and Vogel (1990), LeBoutillier and Waylen (1993).

FDCs are widely used in hydrological practice. Chow (1964) and Vogel and Fennessey (1994) refer to several early studies related to the theory and application of FDC. Searcy (1959) was possibly the first to summaries a number of FDC applications including the analysis of catchment geology on low flow, hydropower and stream water quality studies. Warnick (1984) illustrated the application of FDCs to hydropower feasibility studies for run-of-river operations. Male and Ogawa (1984) advocated the use of FDCs in the evaluation of the trade-offs among various characteristics involved in determination of the capacity of waste-water treatment plants including flow, flow duration, water quality requirements and costs. Alaouze (1989, 1991) developed the procedures based on FDC, for estimation of optimal release schedule from reservoirs, where each release has a unique reliability. Pitman (1993) and Mallory and McKenzie (1993) illustrated the use of FDCs in design of flow diversions. Estes and Osborn (1986) and Gordon *et al* (1992) illustrated the use of FDC for the assessment of river habitats in estimation of instream flow requirements. Hughes and Smakhtin (1996) suggested a non-linear spatial interpolation approach (based on FDCs) for patching and extension of observed daily flow time series, which has latter been extended to generation of flow time series at the ungauged sites (Smakhtin *et al*, 1997) and to restoration of natural streamflow sequences in regulated rivers (Smakhtin, 1998). Smakhtin *et al*, 1998a, b) suggest the use of FDCs as a tool for rainfall-runoff model calibration and for comparison of flow-time series simulated for different scenarios of development. Wilby *et al* (1994) used FDC to assess the effects of different climate scenarios on streamflow with particular reference to low-flows. Hughes *et al* (1996) developed an operating rule model which is based on FDCs and is designed to convert the original tabulated values of estimated ecological instream flow requirements for each calendar month into a time series of daily reservoir releases. Some of these applications have been developed further by Vogel and Fennessey (1995).

FDC illustrates the frequency distribution of flows in a stream with no regard to their sequence of occurrence. Consequently, although the FDCs are useful in their own right and are widely used in hydrological practice, the ultimate goal in pragmatic hydrological modeling concept is a continuous time series, while the calculation of representative FDC is the prerequisite for it and the starting point. It is therefore necessary to design a methodology, which would contain

1. technique(s) by which to establish representative FDCs for different types of river catchments in natural conditions. "Natural" FDCs would represent reference conditions of streamflow variability in a catchment, which existed prior to any catchment or water resources development. The knowledge of such conditions is often important in its own right. But "natural FDCs" are also required for step 2.

2. technique(s) by which to adjust the "natural" FDCs to match with the current state or possible scenarios of catchment and/or water resources development. This step would allow different catchment development scenarios to be simulated (which also represent one of the goals of conventional hydrological modeling).

3. technique(s) by which the established and adjusted FDCs may be transformed into actual continuous flow time series for any further analysis.

It is important to stress that in order to use a FDC in the context of hydrological time series modeling, a representative curve should be established at a site of interest (and adjusted if necessary for development effects) prior to the generation of the actual continuous flow time series (i.e. the first two steps outlined above are to be completed before step 3).

These three steps represent the general structure of the pragmatic hydrological time series modeling concept, and are discussed in detail in the following Chapters.

# 3. ESTIMATING DAILY FLOW DURATION CURVES FOR NATURAL CATCHMENT CONDITIONS BY METHODS OF HYDROLOGICAL REGIONALIZATION.

The shape of a FDC for any river catchment in natural conditions is determined by the rainfall pattern, catchment size and physiographic characteristics. The curve uniquely represents the pattern of streamflow variability in any catchment (either gauged or ungauged, natural or modified). In this sense, the FDC may be considered to be a "signature" of a river catchment.

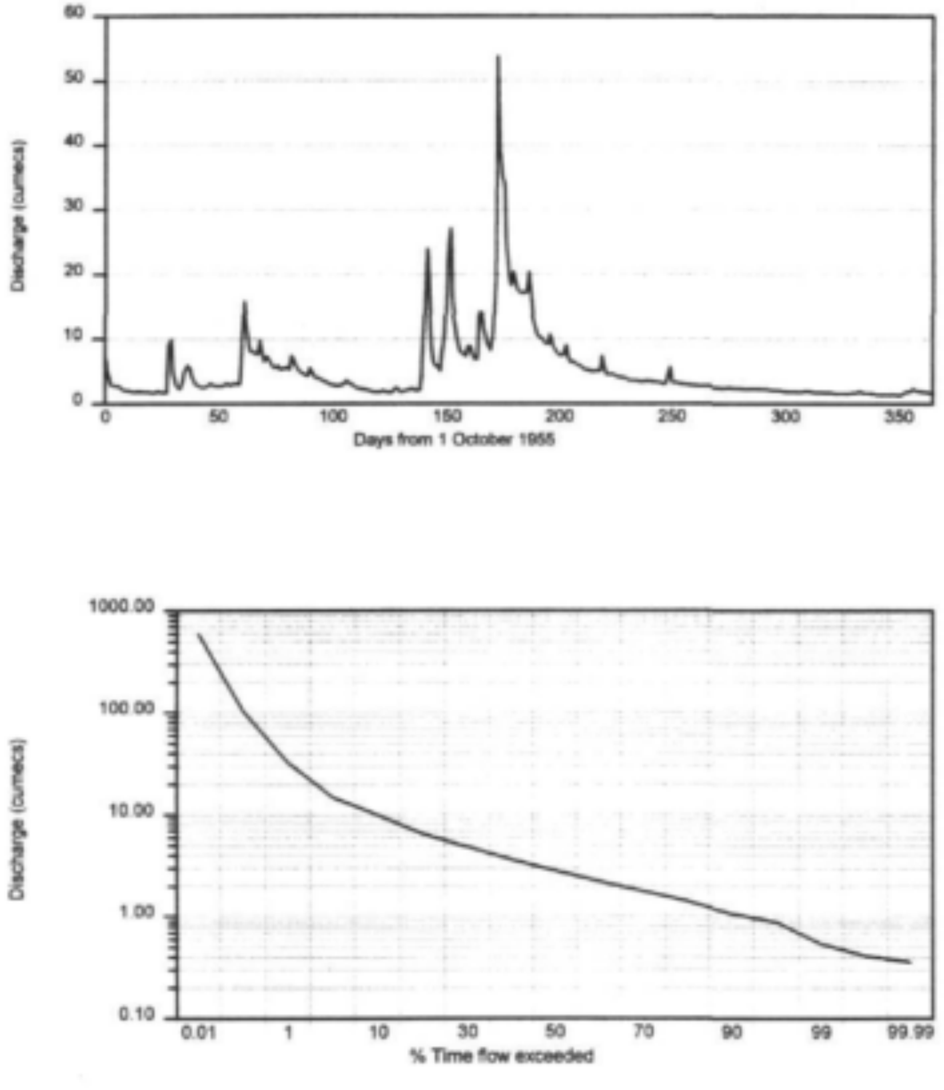


Figure 3.1 Example daily time series (top) and corresponding annual 1-day FDC (bottom) for perennial river (the Mtamvuna River at gauge T4H001)

For a gauged site, a representative FDC can be constructed directly from the observed time series provided the record is stationary. Perennial river with stable baseflow contribution would be characterized by the curve, which never crosses the time axis (a river never dries up) and normally has a gradual slope in a low-flow domain (Figure 3.1). On the contrary, a non-perennial river, which flows either seasonally or occasionally after infrequent rainfall events, will have a curve with a steep slope and may be characterized by extended zero-flow periods (Figure 3.2).

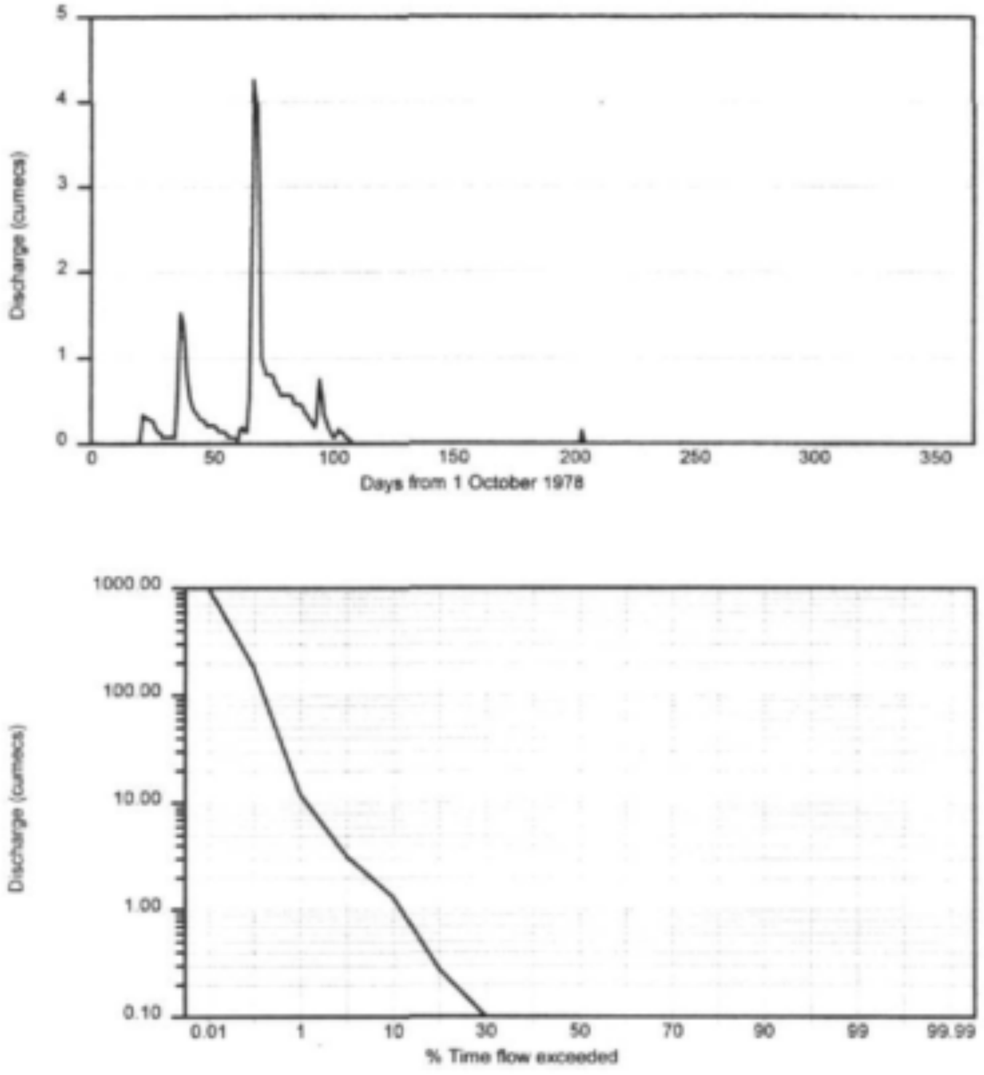


Figure 3.2 Example daily time series (top) and corresponding annual 1-day FDC (bottom) for intermittent river (the Selati River at gauge B7H008)

FDCs on Figures 3.1 and 3.2 are to illustrate the approximate "range of curves" which could be experienced in river catchments in natural conditions. Most of the curves in humid regions of South Africa are likely to repeat the general pattern of a FDC presented by Figure 3.1 (although the shape of the individual curves could be different). Streams flowing through arid and semi-arid areas (with exception of large rivers, crossing several different physiographic regions), on the contrary, would tend to have similar general pattern to that displayed by Figure 3.2. This opens possibilities for generalization of FDCs in physiographically homogeneous regions. Such generalization (rationalization) allows FDCs to be estimated for ungauged river catchments in a specified region.

Various approaches for the estimation of regional FDCs were reported. The first attempt to construct regional FDCs belongs to Lane and Lei (1949). They have designed the *variability index* - a measure of streamflow variability specifically related to FDC and calculated as the standard deviation of the logarithms of 5, 15, 25, ... 85 and 95 exceedence flow values. Lane and Lei determined the average value of variability index and corrections to this index, which are dependent on the physiography of the individual ungauged river catchment.

In many cases, the curves are approximated using some theoretical distribution function and regression relationships between distribution parameters and catchment characteristics are derived. Such approach was used in several states in USA (Singh, 1971; Dingman, 1978), in Philippines (Quimpo *et al*, 1983), Greece (Mimikou and Kaemaki, 1985), Northern Ireland (Wilcock and Hanna, 1987). Fennessey and Vogel (1990) used a different approach, approximating the lower half of 1-day annual FDCs using log-normal distribution and developing regression equation for distribution parameters with catchment characteristics. LeBoutillier and Waylen (1993) suggested probabilistic representations of a FDC combining the principles of order statistics and traditional flow frequency analyses. The model was applied to FDCs for rivers in British Columbia, Canada, where streamflows are generated from a number of distinct physical processes operating in highly variable environments.

Other sources suggest to use the assumption of the linearity a FDC in log-normal space, establish regional regression relationships with catchment characteristics for just two points on curve (one - from high flow domain and one - from low flows) and then draw the line through these two points (Institute of Hydrology, 1980; Nathan and McMahon, 1992).

The approach, which has been followed in this Report, is different. It implies that FDCs from available gauged catchments in a physiographically homogeneous region may be made comparable if standardized by some "index" flow (e.g. long-term mean). These standardized curves if plotted on one graph would normally demonstrate some scatter (due to different lengths of records, non-overlapping records and various data inaccuracies) and form a narrow domain of curves. Each FDC is represented by 17 flows at fixed percentage points (0.01%, 0.1%, 1%, 5%, 10%, 20%, 30%, 40%, 50%, 60%, 70%, 80%, 90%, 95%, 99%, 99.9%, and 99.99%). By averaging of the non-dimensional ordinates of all curves for each of the 17 percentage points, the average regional curve (AVC) may be calculated (Smakhtin *et al*, 1997).

The AVC represents only one possible option of a regional curve. Other options may include: the High Variability Curve (HVC- which represents the "most variable flow regime" in a region), the Low Variability Curve (LVC - representative of the "least variable flow regime"), upper and lower enveloping curves (UEC and LEC). HVC originates at the highest regional ordinate encountered at 0.01% exceedence level and ends at the lowest regional ordinate at 99.99% exceedence level. LVC, on the contrary, starts at the lowest regional ordinate encountered at 0.01% exceedence level and ends at the highest regional ordinate at 99.99% exceedence level. The three curves cross at 50% exceedence point. UEC and LEC are constructed by picking up correspondingly the highest and the lowest of ordinates at each exceedence level. The formulae for estimation of regional curves are given below.

*Average FDC (AVC):*

$$QAVCi = 1/\mathrm{n} \sum_{j=1}^{n} QPj,i \qquad \text{Eq. 3.1}$$

*Upper Enveloping Curve (UEC):*

$$QUECi = \max QPj,i \qquad \text{Eq. 3.2}$$

*Lower Enveloping Curve (LEC):*

$$QLECi = \min QPj,i \qquad \text{Eq. 3.3}$$

*High Variability Curve (HVC):*

$$\begin{aligned} QHVCi &= QAVCi\, Wi + QUECi\,(1- Wi) \quad (i = 1,2,..9) \\ QHVCi &= QAVCi\, Wi + QLECi\,(1- Wi) \quad (i = 10,11.., 17) \end{aligned} \qquad \text{Eq. 3.4}$$

*Low Variability Curve (LVC):*

$$\begin{aligned} QLVCi &= QAVCi\, Wi + QLECi\,(1- Wi) \quad (i = 1,2,..9) \\ QLVCi &= QAVCi\, Wi + QUECi\,(1- Wi) \quad (i = 10,11.., 17) \end{aligned} \qquad \text{Eq. 3.5}$$

Where: $j$ is the index of an individual FDC in a group, $i$ is the index of a percentage point on each curve ($i = 1,2.., 17$), $QPj,i$ is a standardised flow rate on the curve $j$ for a percentage point $i$. $QAVCi$, $QUECi$, $QLECi$, $QHVCi$, $QLVCi$ are standardised flow rates at percentage point $i$ on corresponding regional curves (AVC, UEC, LEC, HVC and LVC), $Wi$ are weighting factors which are given in Table 3.1.

Table 3.1. Weighting factors for 17 percentage points on FDC (for Eq.3.4 and 3.5)

| i | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| % | 0.01 | 0.1 | 1 | 5 | 10 | 20 | 30 | 40 | 50 | 60 | 70 | 80 | 90 | 95 | 99 | 99.9 | 99.99 |
| Wi | 0.0 | 0.125 | 0.25 | 0.375 | 0.5 | 0.625 | 0.75 | 0.875 | 1.0 | 0.875 | 0.75 | 0.625 | 0.5 | 0.375 | 0.25 | 0.125 | 0.0 |

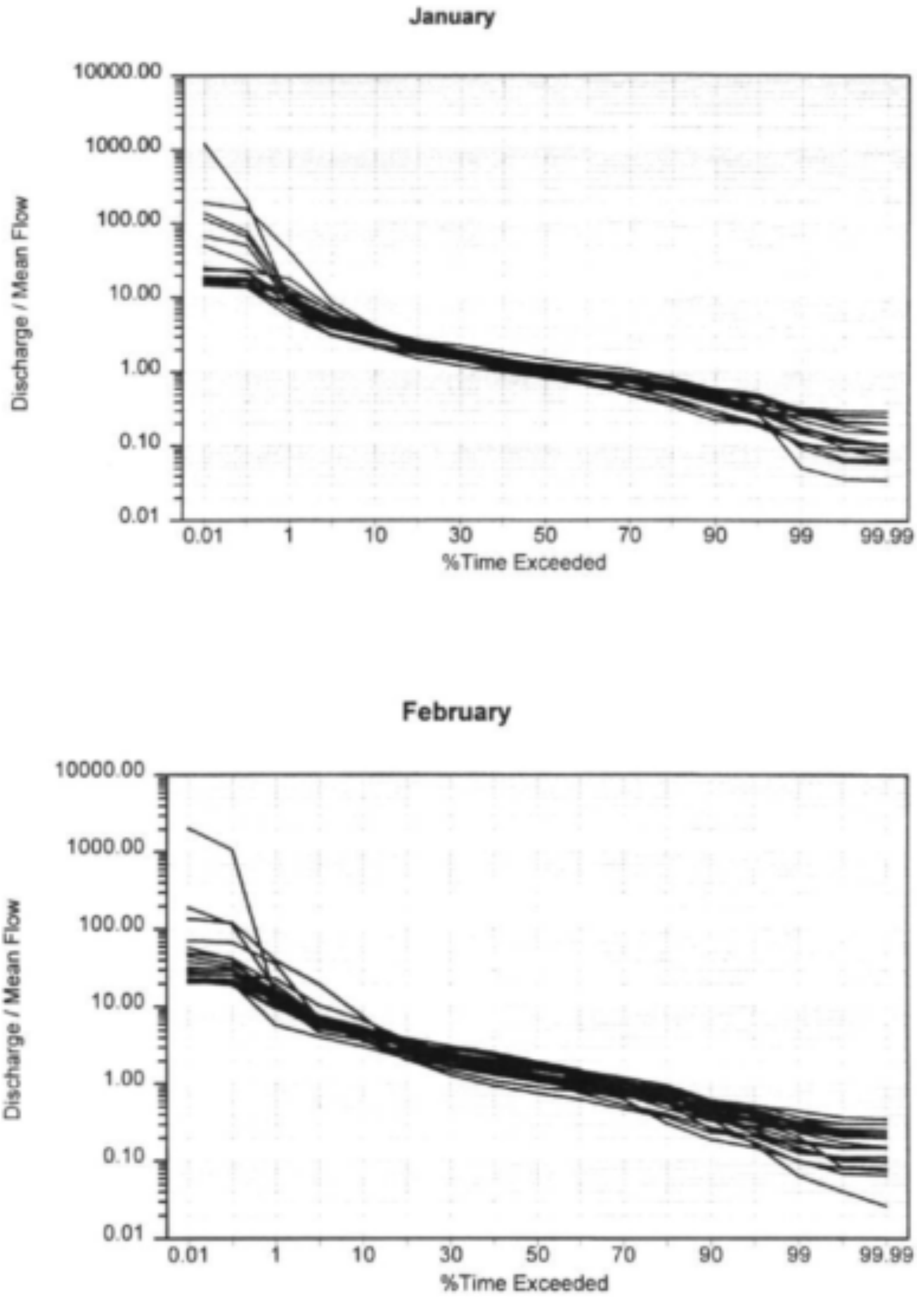
The ordinates of AVC, UEC and LEC are therefore estimated from the ordinates of the group of the original sstandardized FDCs, while the ordinates of HVC and LVC are derived from estimated AVC, UEC and LEC curves.

Once a required non-dimensional regional curve is established, a FDC for an ungauged site in the region may be estimated by multiplying back the non-dimensional ordinates of a regional curve by an estimate of the index flow. The index flow may be estimated either by means of regression equation or from regional maps. In South African conditions, the natural MAR for quaternary catchments available from (Midgley, *et al*, 1994) may be used as an index flow.

Figure 3.3 illustrates the group of 1-day FDCs (standardised by the mean daily flow) for all 12 months of the year for a number of gauged headwater catchments drawn predominantly from the upstream part of a large international Komati river basin, flowing through South Africa, Swaziland and Mozambique. The individual curves have been constructed for 21 gauging stations with an average observation period of approximately 25 years. With only a few exceptions, gauged catchment areas range from 50 to 700 km$^2$. The details of the streamflow gauges are given in Table 3.2.

Table 3.2 Details of the flow gauging stations used in regionalization

| Code | River | Area, km$^2$ | Available record |
|---|---|---|---|
| X2H005 | Nels | 642 | 1929-1996 |
| X2H008 | Queens | 180 | 1948-1996 |
| X2H010 | North Kaap | 126 | 1948-1996 |
| X2H011 | Elands | 402 | 1956-1997 |
| X2H012 | Dawsoni'sspruit | 91 | 1956-1996 |
| X2H013 | Crocodile | 1518 | 1959-1996 |
| X2H014 | Houtbosloop | 250 | 1958-1996 |
| X2H015 | Elands | 1554 | 1959-1996 |
| X2H022 | Kaap | 1639 | 1960-1996 |
| X2H024 | South Kaap | 80 | 1964-1996 |
| X2H025 | Houtbosloop | 25 | 1966-1992 |
| X2H026 | Beestekraalspruit | 14 | 1969-1992 |
| X2H027 | Blystanspruit | 78 | 1966-1992 |
| X2H030 | South Kaap | 57 | 1966-1992 |
| X2H031 | South Kaap | 262 | 1966-1996 |
| X2H034 | Ngodwane | 207 | 1971-1982 |
| X2H047 | Swartkoppiespruit | 110 | 1985-1996 |
| X2H072 | Nzikazi | 240 | 1989-1996 |
| X1H016 | Buffelspruit | 581 | 1970-1996 |
| X1H014 | Mlumati | 1119 | 1978-1992 |
| X1H021 | Mtsoli | 295 | 1975-1996 |


January

February

Figure 3.3 Standardized 1-day FDCs for 21 gauged streams in the upstream part of the Komati River basin.

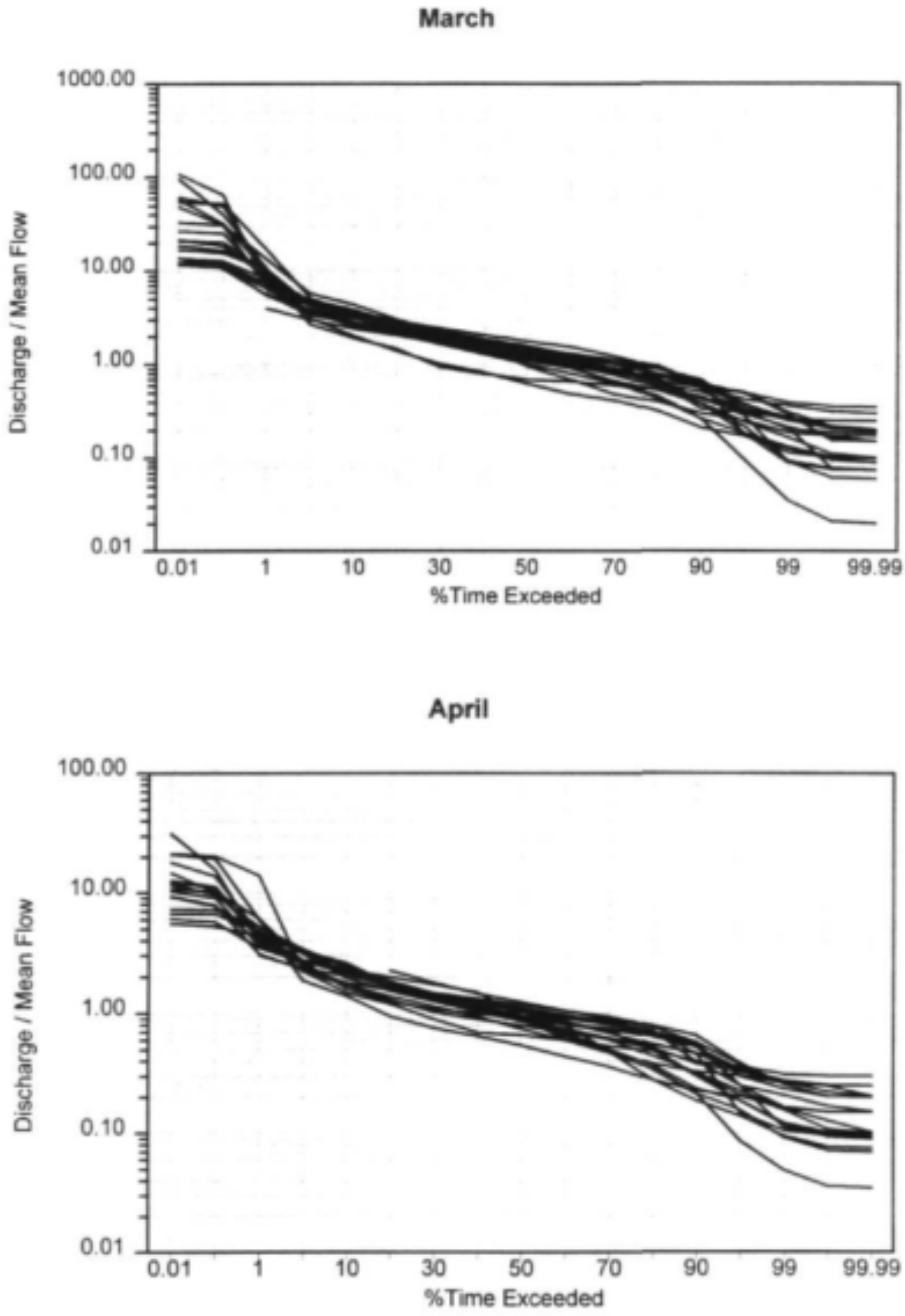
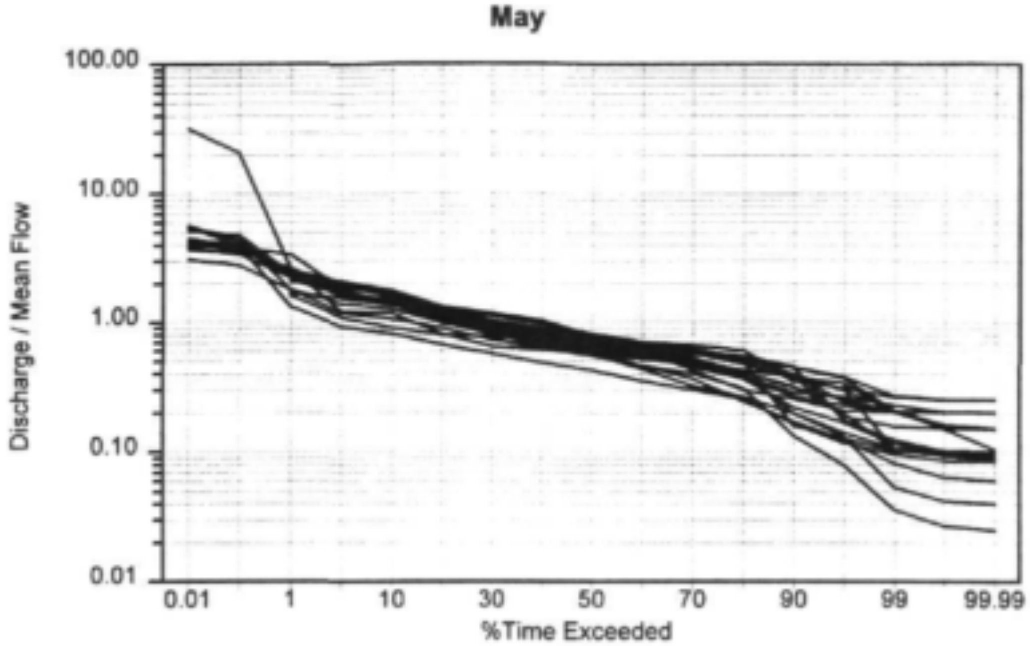


Figure 3.3 *(cont.)* Standardized 1-day FDCs for 21 gauged streams in the upstream part of the Komati River basin.



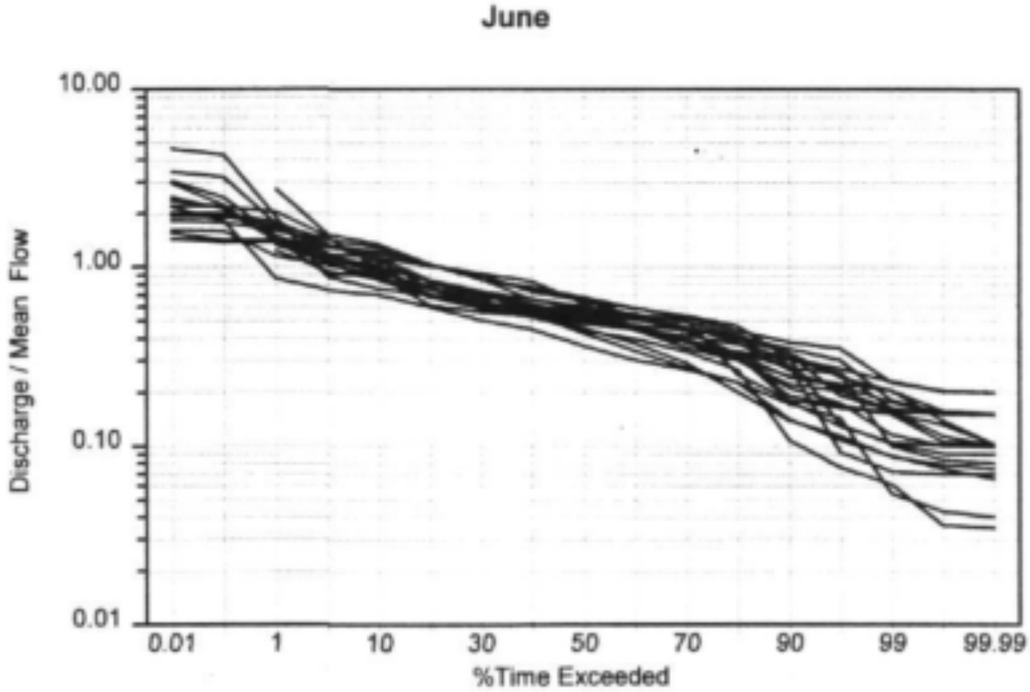
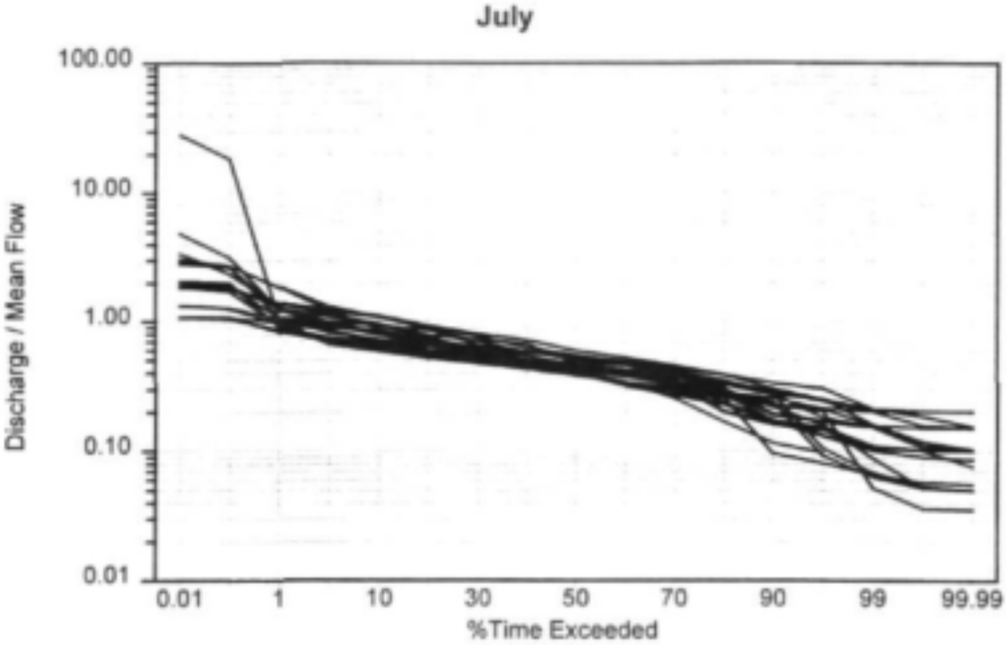


Figure 3.3 *(cont.)* Standardized 1-day FDCs for 21 gauged streams in the upstream part of the Komati River basin.



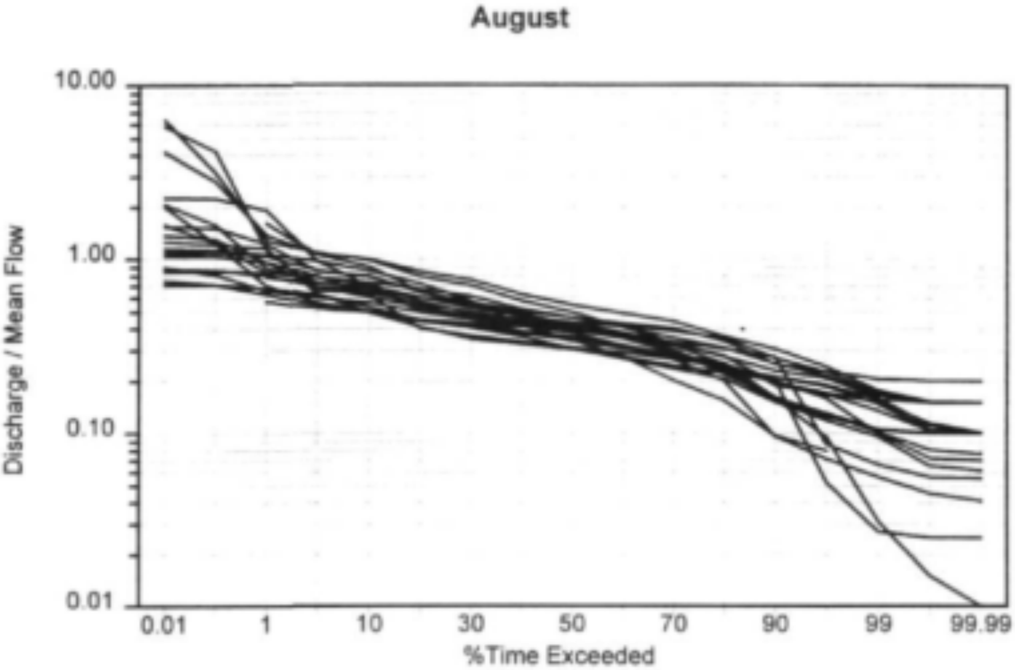
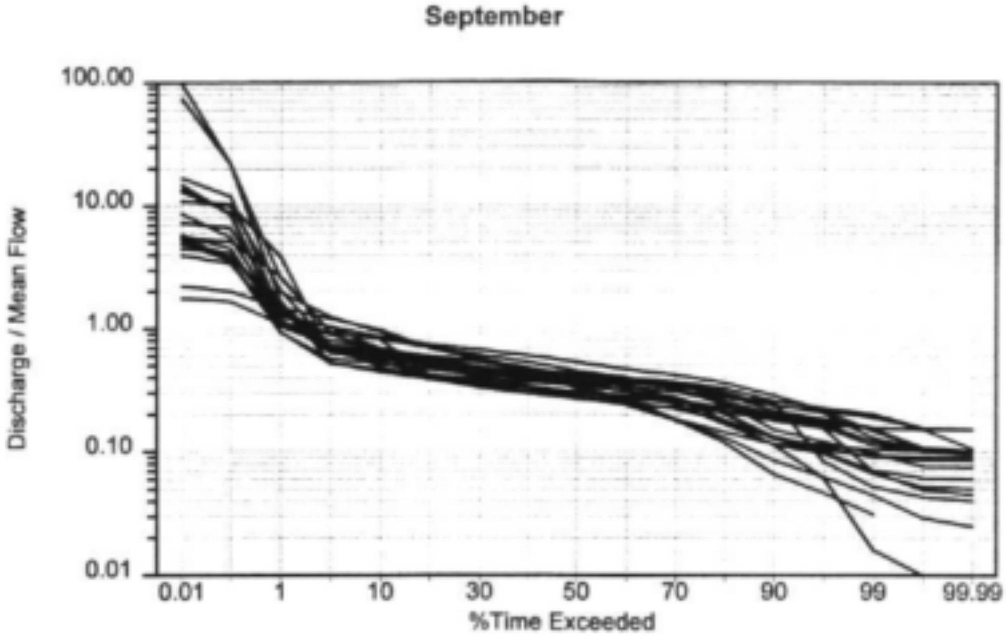


Figure 3.3 *(cont.)* Standardized 1-day FDCs for 21 gauged streams in the upstream part of the Komati River basin.



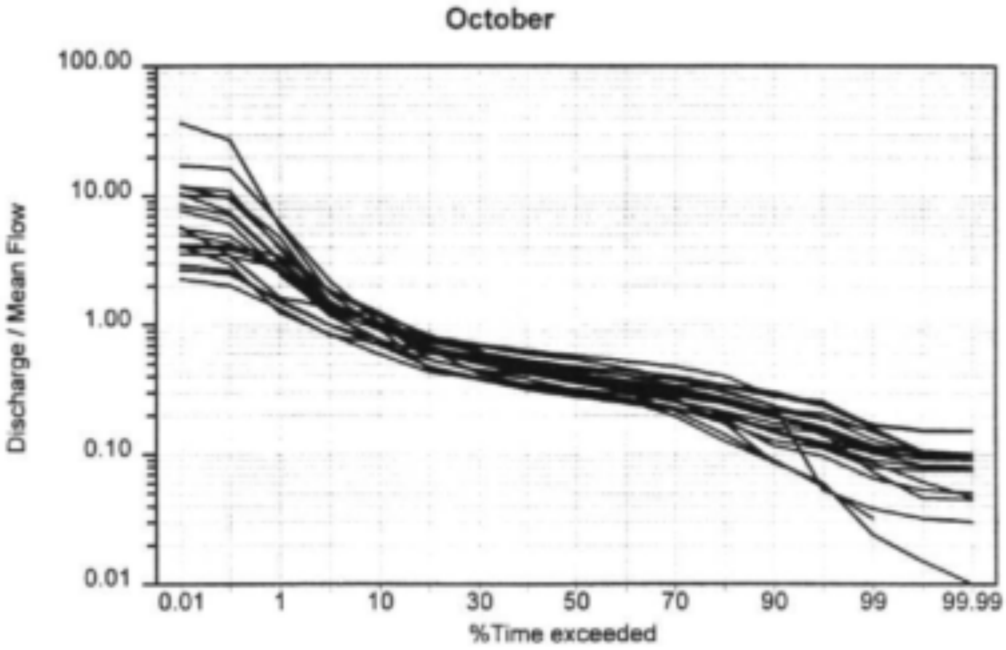
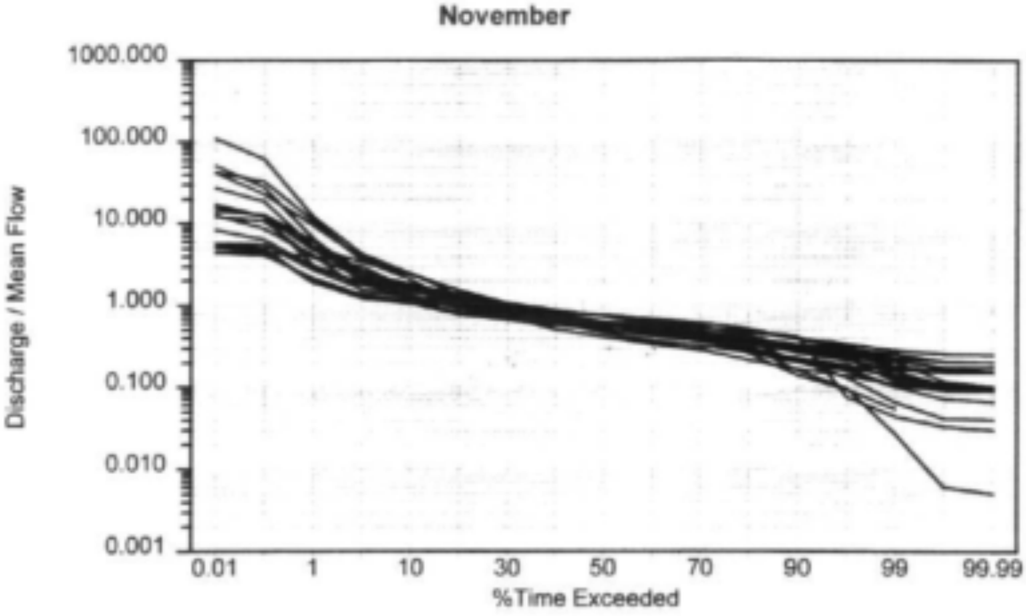


Figure 3.3 *(cont.)* Standardized 1-day FDCs for 21 gauged streams in the upstream part of the Komati River basin.



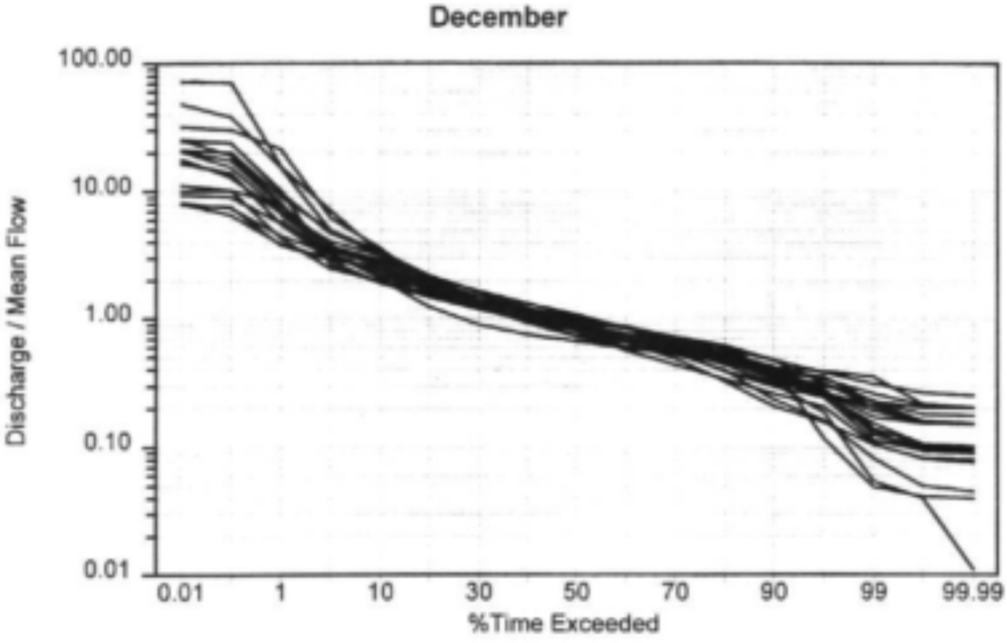


Figure 3.3 *(cont.)* Standardized 1-day FDCs for 21 gauged streams in the upstream part of the Komati River basin.

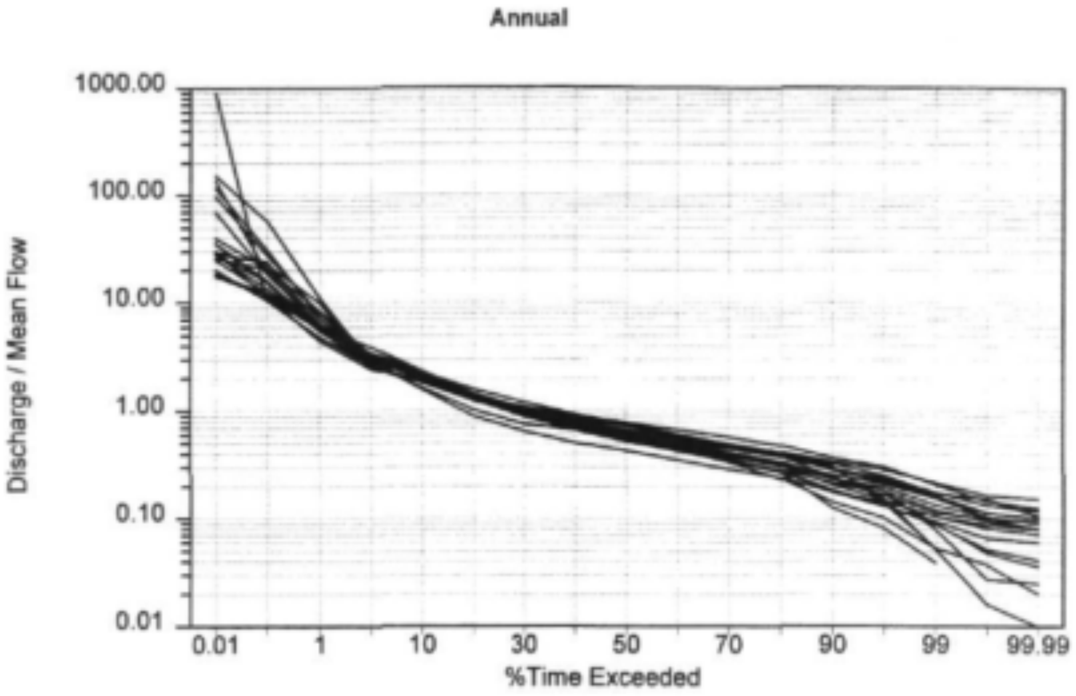


Figure 3.3 *(cont.)* Standardized 1-day FDCs for 21 gauged streams in the upstream part of the Komati River basin.

The biggest differences in all cases occur in the area of extreme low flows, exceeded more than 95% of the time and high flows exceeded less then 5% of the time. These differences are attributed to the inaccuracies of low and high flow measurements and are also partially due to the fact that observation periods on individual gauges don't entirely overlap and may cover different sequences of dry and wet years. Also some observation periods are short, and flows at the extreme high and low flow ends of curves are estimated by extrapolation, which creates additional uncertainty.

Figure 3.4 illustrates (for an arbitrarily selected month of April) five possible choices of composite regional curves - AVC, HVC, LVC, UEC and LEC, which have been calculated on the basis of 21 available "observed " curves. Composite curves effectively represent different "scenarios" of natural flow variability, which may be encountered in the region. It may be expected, that flow variability increases as the catchment area decreases. Consequently, in similar physiographic conditions, a smaller catchment would tend to have a curve of an HVC type, while a larger catchment's flow variability would be better represented by the LVC type. On the other hand, the variability of flow in similarly sized catchments of small tributaries, located in different parts of a larger catchment may be described by curves of UEC, AVC and LEC types, where UEC is likely to represent the most humid areas in the region and LEC - the most arid. The issue of assigning a most representative scenario curve to a particular ungauged river catchment in a specified region is not a trivial one and may require special expert attention.

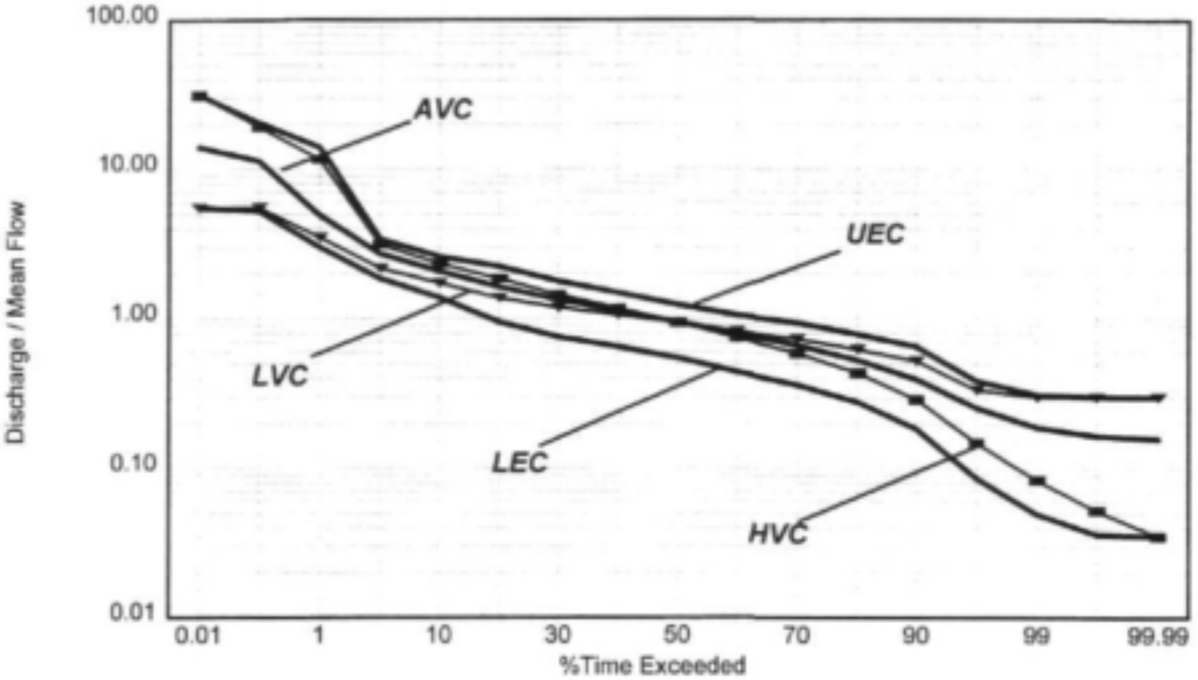


Figure 3.4. *Standardized composite regional FDCs in Komati basin for a month of April*

In practical terms, the average curve (AVC) is the most obvious and pragmatic choice and may be used as a representative regional "standard". The HVC and LEC types of flow variability represent the two most conservative scenarios which are expected to result in the most severe cost implications (if used in engineering practice: in designing a run-off-river water supply scheme, for example), or most stringent restrictions (if used in water quality calculations: for issuing effluent discharge permits), etc.

The regionalization technique described above has been illustrated using daily streamflow data, but the method is likely to be equally applicable for establishing 1-month FDCs. The limitations of the regionalization approach in South African context, relate to the difficulties in the definition of geographical boundaries of the "homogeneous" regions and to the fact that all observed flow data sets are normally affected (to a variable degree) by various catchment development effects and therefore may not be considered entirely representative of natural flow conditions.

# 4. ESTIMATING DAILY FLOW DURATION CURVES FOR NATURAL CATCHMENT CONDITIONS FROM MONTHLY STREAMFLOW DATA

Monthly streamflow volume time series data have been traditionally used in South Africa for management and development of water resources. Synthetic monthly data are also available for 1946 small and normally ungauged incremental drainage subdivisions ('quaternary catchments') throughout the entire country (Midgley *et al*, 1994). The average area of quaternary catchments is 650 km$^2$ but it varies from 80 -100 km$^2$ in humid regions to 2 000 km$^2$ in arid regions. The quaternary catchment monthly streamflow time series have been generated for natural (virgin) catchment conditions for a standard 70 year long period (1920-1990). Given a wide availability of monthly streamflow data in the country, a cost effective methodology may be developed which allows daily streamflow characteristics to be derived from synthetic monthly. It is logical in this context to investigate the possibilities of deriving FDCs representing daily flow regimes from synthetic monthly flow time series. In this Chapter, 1-day FDC for the whole year is referred to as 1-day annual FDC, while 1-day FDCs for each calendar month of the year are referred to as 1-day monthly FDCs.

Several studies have already attempted to address the problem of estimating 1-day FDCs from monthly data in South Africa. Pitman (1993) described a method, which allows monthly time series to be converted to a daily FDC using daily data at a single representative flow gauging station. The data were converted to non-dimensional parameters, which were assumed to be representative for a surrounding hydrologically homogeneous zone. The method was further developed by Schultz *et al.* (1995) to include the effects of development on streamflow. Smakhtin and Hughes (1995) and Smakhtin *et al* (1997) outlined several possible approaches to establish 1-day FDCs at ungauged sites including methods, which were using monthly flow data. However, previous studies attempted to approach the problem mostly on a conceptual background without much reference to the real data. Consequently, the problem of monthly to daily data conversion remains largely unresolved. Apart from the fact that it has a large potential for practical applications, it also represents a challenging and a non-trivial scientific issue.

This Chapter describes the pragmatic approach by which 1-day annual and 1-day monthly FDCs may be derived from synthetic monthly flow volume time series, which are available at a quaternary level of spatial resolution. The method is designed to be low-cost, straightforward and used for routine application. The problem of monthly-to-daily data conversion is approached from the empirical side: by analyzing the relationships between daily and monthly streamflow characteristics derived from observed flow records.

The most straightforward form of a relationship between the two curves at the same site (one based on daily time series and the other on monthly) is a *'ratio curve'*. To establish a ratio curve at a site, the two FDCs should be constructed using similar units (e.g. either aggregating daily discharges in each month into monthly flow volumes, or expressing monthly flow volumes as mean monthly discharges in m$^3$/s). The construction of an FDC is one of the program modules in HYMAS - Hydrological Modeling Application System - developed in the Institute for Water Research and used in a variety of hydrological analyses. The functionality of the HYMAS system has been described in many previous reports and papers. With HYMAS FDC construction procedure, curves may be constructed from daily and monthly streamflow data, for the whole period of record or any part thereof, for any of the 12 months of the year or for the whole year. The 17 fixed percentage points on the curve (0.01, 0.1, 1, 5, 10, 20, 30, 40, 50, 60, 70, 80, 90, 95, 99, 99.9 and 99.99% time of exceedence) with corresponding flow rates represent a duration-discharge table (DDT) - a discrete representation of an FDC which may be printed or written to a file for further display, analysis or adjustment using a spreadsheet package.

For any site in a river, the variability of daily flows is higher than that of monthly. In high-flow months, maximum daily average discharges are higher than the monthly average. In low-flow months minimum daily average discharges may be much lower than the monthly average. The implication for FDCs is that the1-day FDC generally has a larger slope than the 1-month FDC (Fig.4.1) Consequently, daily discharges are higher than monthly in the area of low probabilities of exceedence and lower then monthly in the area of high probabilities. This in its turn implies that the ratios of daily to monthly flows for the 17 fixed percentage points may be calculated and plotted against the percentage point values thus producing the '*ratio curve*' for a site. Similarly to FDCs themselves, such ratio curves may be established for each calendar month of the year or for the whole year (Fig. 4.2).

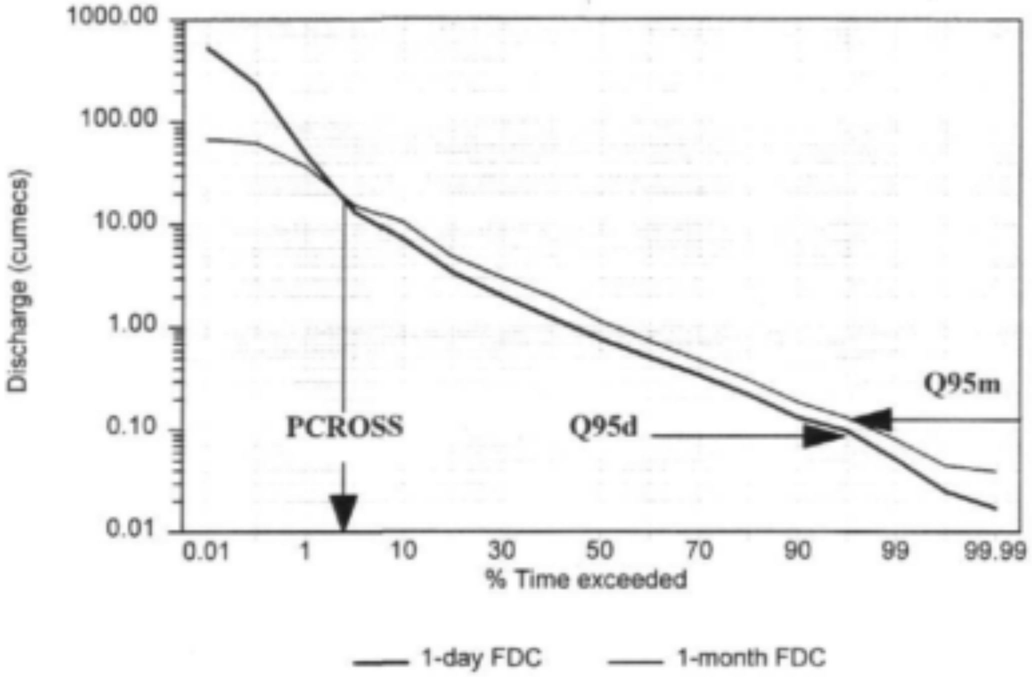


Figure 4.1 Annual 1-day and 1-month FDCs for the Mooi River at gauge T3H009 (catchment area 307 km$^2$) in the Eastern Cape showing daily and monthly Q95 flow values and the percentage point at which two curves cross (PCROSS)

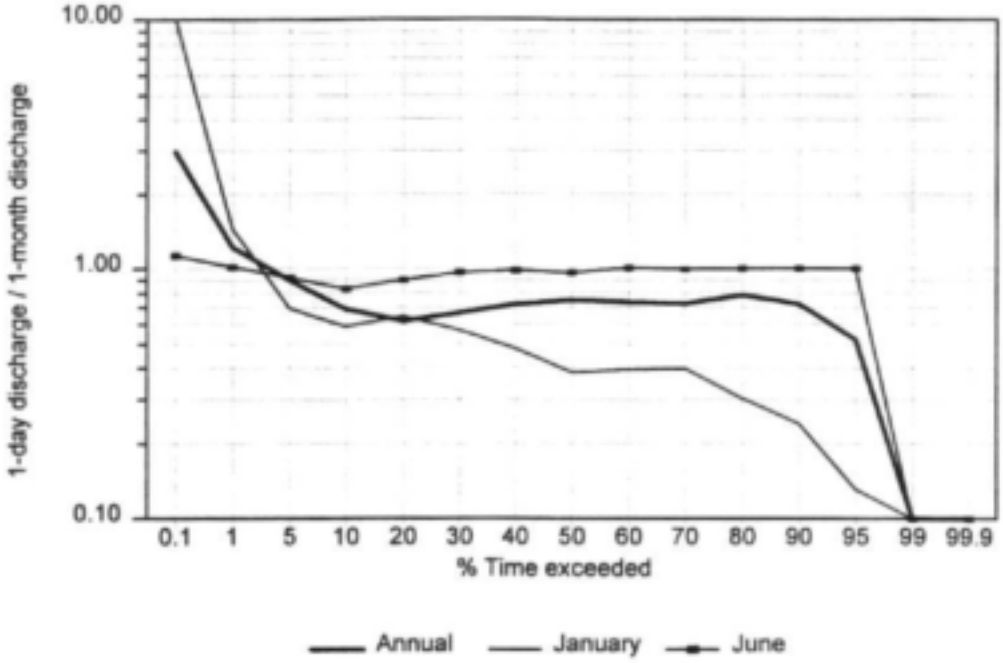


Figure 4.2. Ratio curves for the whole year (Annual), wet month (January) and dry month (June) for the White Mfolozi River at gauge W2H009 (catchment area 432 km$^2$) in Natal.

In a hydrologically homogeneous region, similar sized river catchments as well as different closely located sites on the same river are likely to experience similar variation of daily discharges within a month. Consequently, the similarity may also be expected between the non-dimensional ratio curves for such sites. Therefore, once a ratio curve is established at one site on a river (e.g. where observed daily records are available), it could be applied to other site(s) of interest along the same river (where synthetic monthly data are available) to convert 1-month FDCs to1-day FDCs. The "explicit ratio curve" method may be summarized as follows:

- In the vicinity of the site of interest identify a representative streamflow gauge(s) with good quality data. The size of the gauged catchment(s) should ideally be similar to that of the catchment upstream the site of interest.

- Construct both 1-day and 1-month FDCs using this gauge's data (for the whole year and/or for each calendar month)

- Calculate ratios of 1-day flows to 1-month flows for 17 fixed percentage points. These ratios may also be plotted against the percentage point values to visualize the resultant "ratio curve" for a site. If several representative flow gauges are identified in the adjacent area, the exercise should ideally be repeated for each gauge in order to calculate the average "ratio curve".

- The established "ratio curve" represents a conversion function from 1-month to 1-day FDC. It can now be used in combination with synthetic streamflow data in the area to establish 1-day FDC.

Smakhtin and Watkins (1997) have examined the applicability of this method in one of the headwater catchments in South Africa using multiple sites with observed data and calculating regional ratio curves. The effects of record length and data quality on the estimation of ratio curve have been examined. Smakhtin (1999) further illustrated the successful application of this method for calculation of natural FDCs in a large catchment using a single site. All calculations are conveniently performed using HYMAS computer package.

The problem associated with this method is similar to that described in the previous Chapter: the method described assumes that the relationship between 1-day and 1-month FDC is valid in a physiographically homogeneous region. The boundaries of such a region (and consequently, the geographical limits for the application of the established ratio curves) should be defined in each case. This is a tedious task, which is unlikely to be resolved with the existing scarcity of good quality daily flow records. 80 homogeneous hydrological zones outlined in Midgley *et al.* (1994) on the basis of synthetic monthly flow data may be used for such purpose as the first approximation. On the other hand, gauged catchments may cross several such zones, which complicates the matter. In practical terms, the nearest gauge with good quality data will be used to create ratio curves and then transfer them to other sites along the same river and/or to adjacent similar sized catchments (Smakhtin, 1999). In general, however, this method remains "site specific" and the more routinely applicable approach may be sought.

It is likely that for similar sized catchments (e. g. quaternary), a more general and universally applicable relationship(s) between 1-month and 1-day FDCs may be established. The study should then focus on relationships between similar flow indices extracted from 1-day and 1-month FDCs. More specifically, at least two different approaches may be suggested:

- Using the observed streamflow data sets from a number of flow gauges drawn from different parts of South Africa derive regression relationships of 1-day flows with 1-month flows at several fixed percentage points (e.g. 17, as above). Once such models are established, they may be applied to a 1-month FDC based on synthetic flow data to convert it into a 1-day curve;

- Assume the linearity of both 1-day and 1-month FDCs in a log-normal space. Establish the regression relationship for two 1-day flow indices (one from the high-flow end of the curve and one from the low-flow end) and construct the entire 1-day FDC as a straight line based on two points only. The assumption of FDC linearity is valid for many natural rivers and has been used for the calculation of FDCs elsewhere. In the study of the Institute of Hydrology (1980) the curves were derived from 5 and 95% flow values; Nathan and McMahon (1992) used 10 and 90% flow values (for intermittent streams the latter point was replaced by the percent of time with zero flows). South African rivers also frequently demonstrate linear (or close to linear) FDCs (Fig. 4.1).

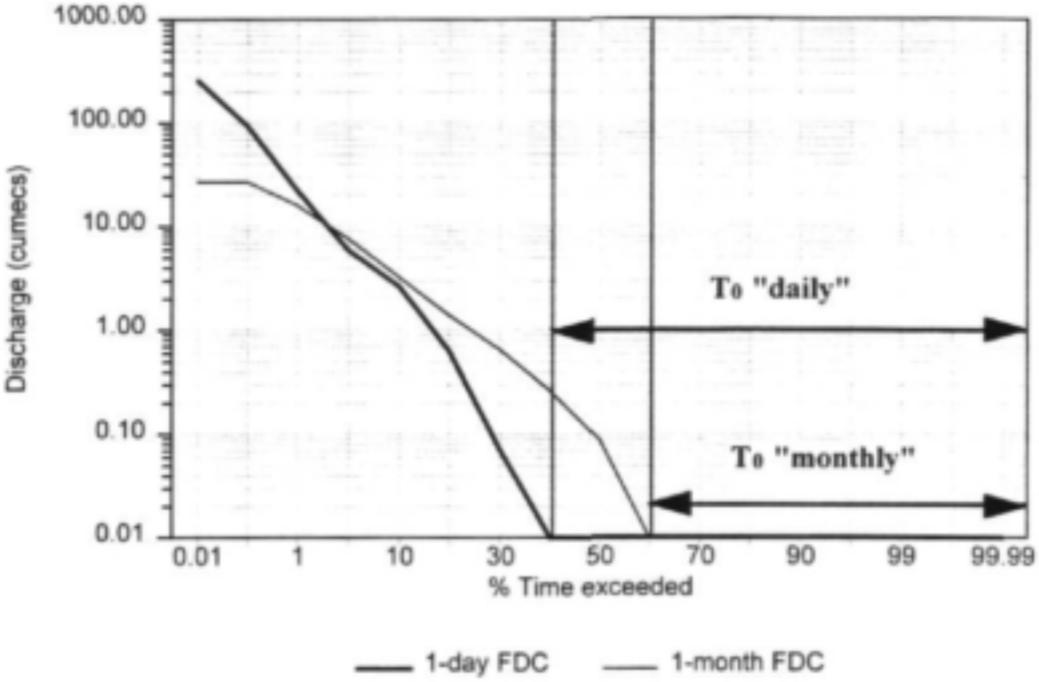


Figure 4.3. Annual 1-day and 1-month FDCs for the Koonap River at gauge Q9H002 (catchment area 1245 km$^2$) in the Eastern Cape illustrating the differences between daily and monthly percentage time with zero flow conditions ($T_0$).

The second approach, which uses only two points is more pragmatic and has been investigated in detail. This investigation has been based on observed stationary flow records from 200 gauging stations. The stations used are located upstream of all major impoundments or abstractions and have a mean record period of approximately 20 years. In some cases only part of the record period (pre-impoundment) has been used to ensure that only non-regulated flow regimes are considered. With a few exceptions, the areas of the catchments are < 1 000 km$^2$ , and are therefore similar to the range of quaternary catchment areas. The following information has been derived from observed streamflow time series for each gauge.

- *Daily and monthly flows exceeded 95% of the time throughout the year* (Q95 flows from 1-day and 1-month annual FDCs, Fig. 4.1);
- *The percentage of time with zero-flow conditions ($T_0$, %) from 1-day and 1-month annual FDCs*. $T_0$ may be read directly from the FDC graph at a point where the curve intersects the time axis (Fig. 4.3). This index is important for distinguishing between perennial and non-perennial streams.

- A smaller subset of 55 randomly selected flow gauges from different physiographic regions was used to construct the actual plots of i) 1-day and 1-month annual FDC and ii) 1-day and 1-month FDCs for each calendar month of the year. Altogether, the 13 graphs with pairs of curves have been constructed for each gauge. These graphs gave the full-scale view of the relationship between two curves on the month-by-month and annual basis. They have also been used for the estimation of another important characteristic - *the percentage point at which 1-day and 1-month FDCs cross* (PCROSS - Fig. 4.1).

The details of the gauges used, and some of the calculated indices for all gauges (e.g.1-day Q95 flow values and "daily" $T_e$) are listed in Smakhtin and Watkins (1997). The study has shown that the two curves normally cross between the 1% and 10% time exceedence points. With a few exceptions, this is valid for pairs of curves constructed for both the whole year and for individual calendar months. The attempts have been made to investigate the possible relationships of the PCROSS (for annual FDCs) with characteristics, which may be easily obtained from the Surface Water Resources of South Africa 1990 volumes (Midgley *et al.*, 1994). These characteristics included: catchment area, unit MAR, MAP, MAE and several combinations of those (e.g. MAP/MAE). PCROSS has not been found to be related to any of these parameters. On the other hand, the majority of cases studied indicate that the PCROSS may be approximated as a constant, which is equal to 5% (Fig. 4.4). This assumption may be feasible considering that the data sets used normally have measurement errors and observation periods, which are different in length, and not always overlapping. It also has to be taken into account that in the area of high flows some of 1-day FDCs are "truncated" which results from low discharge table limits of gauges (1-month curves are also affected by this limit, but to a lesser extent). This may also affect the accuracy of PCROSS calculation. The assumption of a constant PCROSS value has a convenient implication for the estimation of 1-day FDCs. It means that the first point for the 1-day FDC may be read directly from the 1-month FDC at the 5% exceedance level.

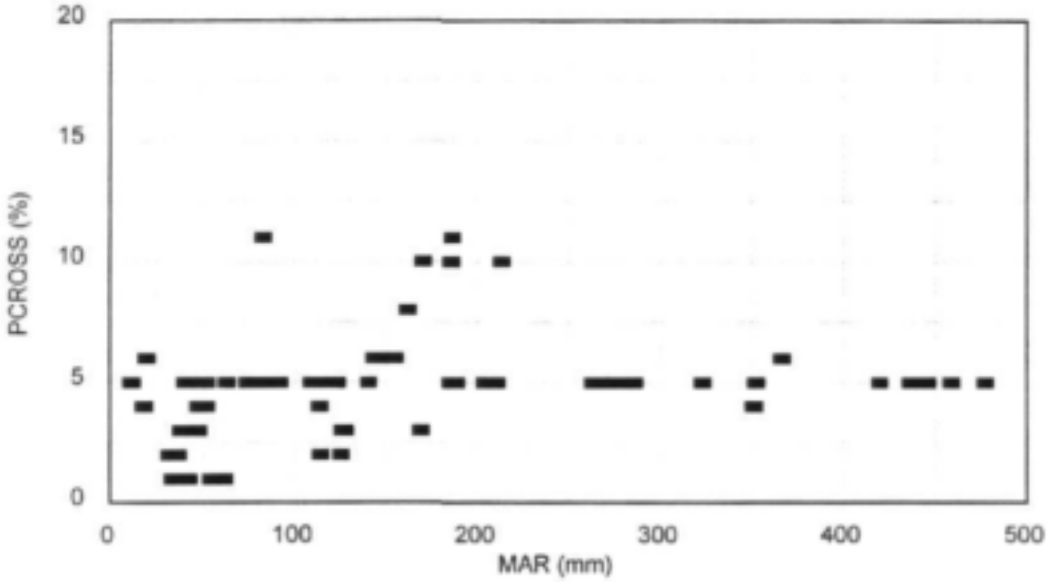


Figure 4.4. Scatter plot of the relationship between the percentage point at which 1-day and 1-month annual FDCs cross (PCROSS) and the MAR

The second point for the construction of 1-day FDC should be derived from the low-flow domain and will differ for perennial and non-perennial (intermittent, ephemeral) streams. For the purpose of this study, perennial streams are defined as those having non-zero Q95 value extracted from 1-month annual FDC. In accordance with this criteria, 126 rivers from the original data set of 200 have been classified as perennial and used to establish a relationship between "daily" and "monthly" Q95 flow values. The following simple linear regression equation has been derived:

$$Q95_d = 0.811 * Q95_m \qquad \text{Eq. 4.1}$$
$$(R^2 = 0.991; \quad SE = 0.006)$$

Where $Q95_d$ and $Q95_m$ are flow values exceeded 95% of the time and estimated correspondingly from 1-day and 1-month annual FDCs. This relationship is also illustrated in Figure 4.5.

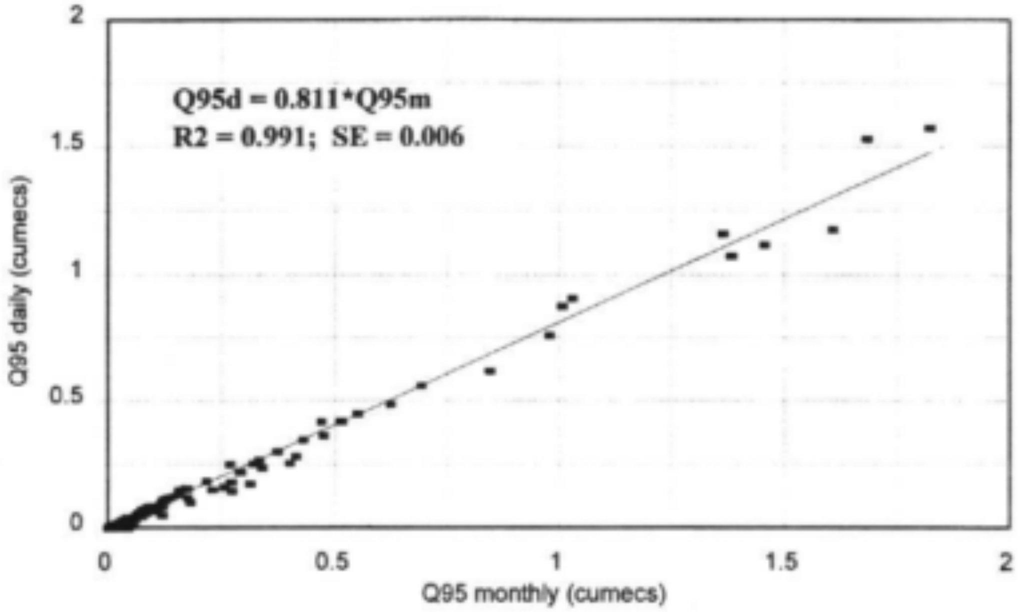


Figure 4.5 Relationship between Q95 flow values estimated from 1-day and 1-month annual FDCs

The rest of the data set has been classified as non-perennial rivers. These rivers have zero "monthly" Q95 values and Eq. 4.1 is not applicable. The focus should be shifted to the estimation of the time spent at zero-flow conditions ($T_0$). For non-perennial rivers, "monthly" $T_0$ > 5%. The corresponding "daily" $T_0$ values are even larger (Fig. 4.3). This is explained by the fact that in semi-arid and arid catchments a river may dry up completely for most of the low-flow month, while the average monthly discharge will remain non-zero. Both monthly and daily $T_0$ values increase with the increasing aridity of the area (e.g. decreasing MAP). The following relationship between "daily" and "monthly" $T_0$ values has been derived (also illustrated in Fig. 4.6):

$$T_{0,daily} = 8.08 + 1.10 * T_{0,monthly} \quad (R^2 = 0.937; \; SE = 5.81) \qquad \text{Eq. 4.2}$$

Once the required two points on the 1-day FDC for either perennial or non-perennial river are estimated as described above, the curve itself may be plotted. In practice, log-interpolation could be used to calculate flow values for other percentage points on the curve. For perennial rivers, the interpolation is performed using the following equation:

$$DQ_{j,d} = \exp\{ \ln DQ_{j,m} - \ln(Q95_m / Q95_d) * (\ln DT_j - 1.61) / 2.94 \} \qquad \text{Eq. 4.3}$$

where $DQ_{j,d}$ and $DQ_{j,m}$ are 1-day and 1-month flow values at the j percentage point $DT_j$, 1.61 is the natural log of the constant PCROSS (5%) and 2.94 equals to (ln95 - ln5). The already mentioned 17 fixed percentage points may be used to define the curve (in this case j = 1,2,..17). But Eq.4.3 may also be used to calculate flow values for any other percentage point(s) on the curve.

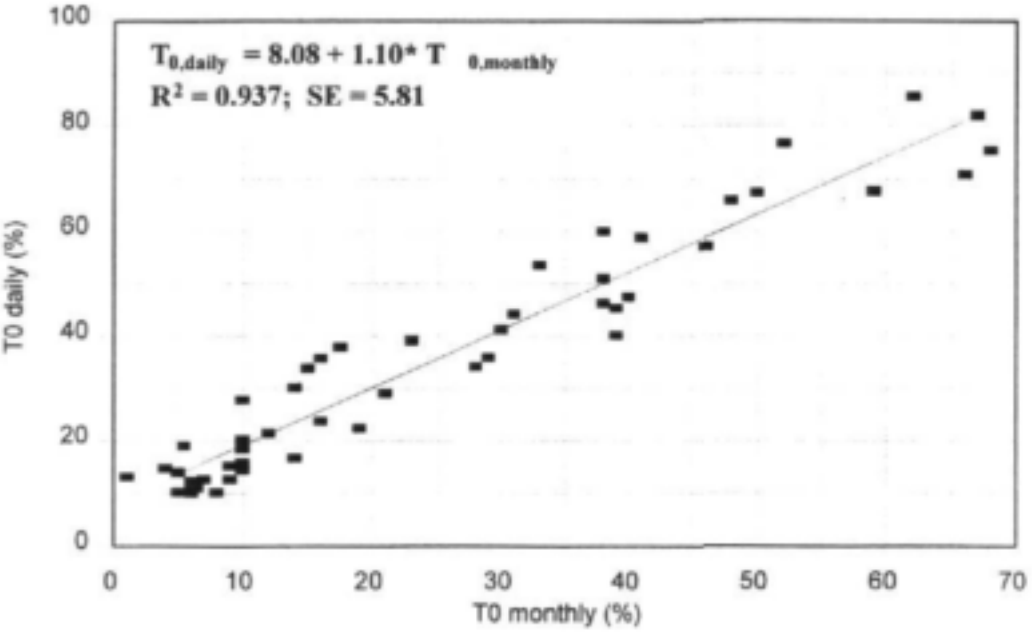


Figure 4.6 Relationship between $T_0$ values extracted from 1-day and 1-month annual FDCs for non-perennial rivers.

For non-perennial rivers, $T_0$ varies between rivers and the interpolation equation is different:

$$DQ_{j,d} = \exp\{ \ln DQ_{j,m} - \ln(Q_{m\,(1-To,d)} / Q_{d\,(1-To,d)}) * \ln(DT_j / 5) / \ln((1-T_{0,d}) / 5)\} \qquad \text{Eq. 4.4}$$

where $Q_{m\,(1-To,d)}$ and $Q_{d\,(1-To,d)}$ are 1-month and 1-day flow values exceeded 1 - $T_{0,d}$ per cent of the time. Naturally, $Q_{d\,(1-To,d)}$ is zero and a closest non-zero substitute value is required to use Eq. 4.4. The most convenient substitute is 1% of the MAR, converted to discharge units. This value may easily be calculated using the quaternary catchment information from Midgley *et al.* (1994). The study has shown that the "daily" values of ( 1 -$T_0$ ) and (1 - $T_{0.01\,MAR}$) in the majority of cases are almost indistinguishable. The final form of the interpolation equation for non-perennial rivers then becomes:

$$DQ_{j,d} = \exp\{ \ln DQ_{j,m} - \ln(Q_{m\,(1-To,d)} / (0.01*MAR)) * \ln(DT_j / 5) / \ln((1-T_{0,d}) / 5)\} \qquad \text{Eq. 4.5}$$

The suggested approach for 1-day FDCs estimation may be summarized as follows:

- Construct 1-month annual FDC for an identified quaternary catchment using the standard 70-year long synthetic monthly flow record;
- Estimate $Q95_m$ flow value. If it is non-zero, use Eq. 4.1 to calculate $Q95_d$ flow value and Eq. 4.3 to calculate 1-day flows for other percentage points.
- If $Q95_m$ flow value is zero, estimate $T_{0,m}$. Then use Eq. 4.2 to calculate $T_{0,d}$.
- Estimate 1% of the MAR from quaternary catchment data and convert it into discharge units. Use Eq. 4.5 to calculate non-zero 1-day flow values at all percentage points smaller than 1- $T_{0,d}$. Assign zero values to all flows exceeded more than 1- $T_{0,d}$ percent of the time.

All calculations required by the method, may, in principle, be carried out in a spreadsheet. But taking into account that calculated 1-day FDC may be and normally is required for further analysis and/or applications, the use of adequate professional software is preferable. The method may be computerized and linked to quaternary catchment synthetic monthly flow database supplied by Surface Water Resources of South Africa (Midgley, *et al*, 1994).

The method has so far focused on annual FDCs. The problem of conversion of 'monthly' to 'daily' curves for each of the 12 calendar months represents a separate issue. The analysis of graphs of FDC pairs produced for each calendar month for the subset of 55 streamflow gauges has in fact supported the statement of Midgley *et al* (1983) that "...at least for dry-season months of the year, the duration curves based on monthly values were, in most rivers of the more humid regions, more or less coincident with those based on daily values". On the other hand, Smakhtin and Watkins (1997) have shown that in wet months in humid catchments, the differences between 1-day and 1-month curves may be more pronounced than differences between two annual curves. Some rivers in the semi-arid and arid regions (e.g. Koonap in the Eastern Cape) demonstrate a different pattern, when the differences between two curves increase during wet months of the year. In general, the curves for particular months constructed on the basis of observed data often take a complex shape and are difficult to analyze.

One of the problems which arise in the case of individual calendar months' curves, relates to the length of record of many observed data sets. When an annual 1-month FDC is constructed on the basis of 20 years of data, the number of months used equals 240. This is sufficient to calculate the extremes at 1 and 99% directly from the record. Flow values for percentage points <1% and >99% are than calculated by an in-built extrapolation procedure. Given possible extrapolation errors, these estimates may not be accurate and this creates the uncertainty already at the level of annual FDCs

The problem is exacerbated when the sample is divided by 12. For example, to construct the FDC for January from a monthly flow record, which is 20 years long, only 20 values are available. This is just sufficient to define flows at 5 and 95% exceedance levels. The flows which are exceeded less and more % of the time will be calculated by means of extrapolation. If the record is shorter and/or months with missing data are present in the record, even 5 and 95% flow values are calculated by means of extrapolation. Consequently, the accuracy of calculations drops significantly. Alternatively, only gauges with records of at least 20 years long should be used, which reduces the number of good quality gauges available for analysis. Given the level of uncertainty involved, it is unlikely that such analysis will be completed with reasonable results and the more pragmatic alternative would be to apply the results already formulated for annual FDCs to curves for each calendar month.

The approaches described in this Chapter are designed as simple tools to generate 1-day FDCs at ungauged sites for which synthetic monthly flow volume data are available from elsewhere (e.g. synthetic data for quaternary catchments from Midgley *et al.* (1994). The methods are developed within the context of South African information environment. But, their main principle (establishing relationships between 1-day and 1-month streamflow characteristics) may equally successfully be applied in other regions, provided that a time series simulated by any monthly rainfall-runoff model or obtained from water balance calculations is available. The proposed scheme of monthly to daily data conversion may be particularly relevant for a developing country where the application of economical monthly rainfall-runoff models represents one of the few feasible options for assessment of surface water resources.

The established 1-day FDCs may have many direct practical applications. At the same time, the curves may be converted into the actual daily streamflow time series representing natural flow conditions in a river catchment. The suggested techniques are designed to contribute to the availability of much needed detailed streamflow time series information. The methods for conversion of established FDCs into a complete daily time series are described in the following Chapters.

# 5. ADJUSTING NATURAL FLOW DURATION CURVES FOR CATCHMENT DEVELOPMENT EFFECTS

Changing land-use and the state of the water resources development (such as direct water abstractions, commercial forestry plantations, upstream impoundments, etc.) modify the hydrological response of any catchment. The simulation of modified hydrological responses at different scenarios of catchment development is a common procedure, which at present is normally performed by means of deterministic rainfall-runoff modelling techniques (Chiew and McMahon, 1994; Hughes, 1997; Smakhtin and Watkins, 1997). In such cases, a rainfall-runoff model selected has first to be calibrated against observed flow data to ensure that the general pattern of flow variability in the simulated catchment is properly reproduced and to obtain the representative parameter values. After that, dependent on the scenario being simulated, the existing or planned direct abstractions/effluents to the stream are "removed" or "added" from/to the model parameter set, while other relevant parameters values (e.g. those related to vegetation cover) are modified to represent the state of the catchment (Schulze, 1995; Hughes, 1997). Such a modification should be based on a clear scientific evidence and/or experience of the modeller. Eventually the model is run with modified parameters to generate the flow time series representative of the simulated catchment development scenario.

On the other hand, any catchment or water resources developments are inevitably reflected in the shape of the flow duration curve. The effects of anthropogenic factors on streamflow may therefore be also built into the FDC (prior to the simulation of the actual continuous streamflow time series) to make it representative of the *current state* of catchment development. On the other hand, the established FDC for a catchment which is currently in the natural state, may be similarly adjusted to simulate the effects of different possible *future scenarios* of development on streamflow. This approach assumes that any "simulated" current state or future scenario doesn't change with time and, consequently, that the resultant curve is a reflection of a stationary flow time series. The adjustment of FDCs for different scenarios of catchment development therefore forms another step in the context of the pragmatic time series modelling.

The data on artificial influences in South Africa are not usually well documented. In some cases, information on direct water abstractions may exist as a time series with a monthly time step, but more often only monthly average data on abstractions are available at the best. Consequently, the general approach to FDC adjustment would require the combined use of 1-month FDCs for each of the 12 calendar months of the year together with average monthly distribution of abstractions and/or effluents. Once a 1-month FDC has been adjusted for artificial effects, it may be converted into 1-day FDC (e.g., using methods described in the previous Chapters).

The problem of incorporating development effects directly into a FDC has not been widely addressed. One generalised framework for possible solution suggested by Bullock *et al* (1994) may be used within the context of the proposed concept. It implies that once the individual artificial influences upstream of the site of interest have been quantified, a total monthly artificial influence (AI) for each calendar month may be calculated. For a given calendar month, AI is a constant and may be either positive or negative dependent on whether the artificial inflows in that month exceed the abstractions or vice versa. Using these monthly AI values, the FDC for each calendar month may be adjusted. Following the principle of 17 fixed percentage points used above, all flows at these points at each month's FDC should be adjusted by the constant AI value for this month.

If monthly AI values upstream of the site of interest are made up by direct ABSTRACTIONS and effluent discharges /return flows (INFLOWS) only, then flows at each $i$ percentage point on the modified FDC (MFDC) are calculated from natural FDC (NFDC) for each month $m$ as:

$$\mathrm{MFDC}_{m,i} = \mathrm{NFDC}_{m,i} + (\mathrm{INFLOWS}_m - \mathrm{ABSTRACTIONS}_m) \qquad \text{Eq.5.1}$$

A different case exists if a reservoir is located upstream of the site of interest. The natural flow regime immediately downstream is then often completely withdrawn. Further downstream, the flow regime is also often dominated by the reservoir releases (which entirely or partially constitute AI) and in such cases, the availability of the reservoir release data becomes critical. In general, the flow regime at a site downstream the reservoir is composed of the natural inflow from the unregulated part of the catchment downstream of the reservoir (but upstream of the site) and reservoir releases (RR), which depend on the reservoir operation rules. The flows at each $i$ percentage point on modified FDC at the site downstream of the reservoir may be calculated as:

$$\mathrm{MFDC(s)}_{m,i} = \mathrm{NFDC(s)}_{m,i} - \mathrm{NFDC(r)}_{m,i} + \mathrm{RR}_m \qquad \text{Eq. 5.2}$$

Where MFDC(s) and NFDC(s) are modified and natural FDCs at the site of interest, and NFDC(r) is a natural FDC at a reservoir site.

The alternative approach for FDC adjustment has been suggested by Schultz et al (1995). This method focuses on FDCs for each individual month of the year (e.g. January 1977) and includes the estimation of a set of non-dimensional parameters, which uniquely characterise each month's curve. Parameters are estimated from historical flow record of a representative flow gauge and include:

$$A_d = \frac{Qmax}{Qave} \qquad \text{Eq. 5.3}$$

$$C_d = \frac{Qmin}{Qave} \qquad \text{Eq. 5.4}$$

$$B_d = \frac{Qinf}{Qave} \approx 1 \qquad \text{Eq. 5.5}$$

$$t = \frac{T}{no.\,days\ per\ month} = \frac{Qave - Qmin}{Qmax - Qmin} \qquad \text{Eq 5.6}$$

Where Qave, Qmin and Qmax are daily average, minimum and maximum flow in a month, Qinf is an inflection point which is approximated by the ratio of monthly flow volume to a number of days per month, t = proportion of a number of days (T) in month consisting of quickflow.

It is assumed that for natural conditions, these parameters can be transferred to other sites of interest in a study area with similar hydrological response. If historical record is not representative of natural flow conditions, the parameters are first adjusted to be representative of these conditions. Thereafter the natural parameters can be transferred to other sites of interest where they can be further adjusted to account for various levels of development.

The effects of development are accounted for by substituting in equations 5.3 –5.6, the value of Qave, which is obtained for various types of development by converting the simulated monthly flow volume to average daily values. Further, by assuming that all water use abstractions and discharges occur uniformly through the month, these daily values are simply added or subtracted as appropriate, to the virgin values of Qmax and Qmin. Finally, the adjusted 1-day flow duration curves for each individual month are produced. Schultz et al (1995) supply some additional details on how to adjust non-dimensional parameters in cases of direct abstraction and effluent discharges and discuss adjustments, which need to be made in cases of upstream impoundments.

This elegant approach in it current form is however not directly applicable in the context of the pragmatic modeling approach, since it focuses on each individual month's FDC, while the pragmatic modeling concept requires typical calendar month's 1-day FDCs. However, there is a good potential for the modification of this approach to make it compatible with the pragmatic time series modeling concept. A more serious complication related to this method, however, is that it directly assumes that a monthly time series of artificial influences exists for a catchment of interest. This complication is not easy to resolve if such data don't exist and this implies that additional modifications to the original method will be required.

The approaches describe above deal mostly with adjustments of FDCs in cases of direct abstractions or effluents. The incorporation of the effects of catchment land-use changes in the shape of FDC represents even a more complex problem. The direction and magnitude of such effects may vary for different types of catchment land-use change and in different physiographic regions. Also, catchment land use types are likely to affect a FDC differentially over the range of flows. This latter consideration effectively applies to all possible cases of FDC adjustment for catchment development effects and is not catered for in methods described above. At the same time, given the limitations of available data on direct artificial influences in the country, it is not an easy task to formulate a valuable alternative method, which could provide a differential adjustment of FDC ordinates without introducing a large degree of uncertainty and a number of unjustified suppositions.

However, one of the cases, when a FDC may be adjusted differentially over the range of flows is the adjustment for forestry effects. In South Africa, commercial forestry is one of the primary land uses in river catchments. Intensive research has been conducted regarding the flow reduction due to afforestation. Scott and Smith (1997) and Scott *et al* (1998) suggested the empirical models which allow reductions in both total and low flows to be predicted in different physiographic regions using commercial plantation area, tree types and their ages. These studies have quantitatively illustrated, amongst the others, the more pronounced effect of forestry on low flows compared with that on mean flow values. In the context of these studies, the mean annual low flow (MALF) is approximated by the three times the mean of the driest 25% of monthly flow values in the standard 70 year long simulated monthly flow record of 1920-1990 available for each quaternary catchment in South Africa from Midgley *et al*, (1994). The driest 25% of monthly flows are 210 monthly flows out of the total 840 (in a 70-year long record) and the index may be expressed as:

$$\text{MALF} = \frac{1}{70} \sum_{i=1}^{210} Qi \qquad \text{Eq. 5.7}$$

Where, Qi is the monthly flow volume for each of the 210 driest months. This low-flow index (MALF) may be interpreted as the average amount of flow that one can expect during a three-month dry season (Scott *et al*, 1998).

The empirical formulae for mean flow (MAR) and mean low flow reduction due to forestry suggested by Scott and Smith (1997) are based on monthly flow records. In order to use their approach for FDC adjustment, the position of these two indices should first be identified on "natural" annual 1-month FDC for a site of interest. Once these positions (exceedence levels) are identified, the two flows may be adjusted using the suggested flow reduction models. These two flow indices, however are not entirely sufficient to define the entire shape of a modified FDC. Additional flow index from the high flow area may need to be specified. Similarly to MALF, it could be defined as the three times the mean of the wettest 25% of monthly flow values in the standard simulated monthly flow record and provisionally called mean annual high flow (MAHF). The flow reduction model for this index needs to be developed separately.

Once the flows are adjusted, they may be used as the three base points for the construction of the entire adjusted 1-month FDC (Fig. 5.1), where flows at the intermediate points could be calculated by interpolation. 1-day FDC may then be constructed using the relationships between 1-day and 1-month flow indices described in the previous Chapter.

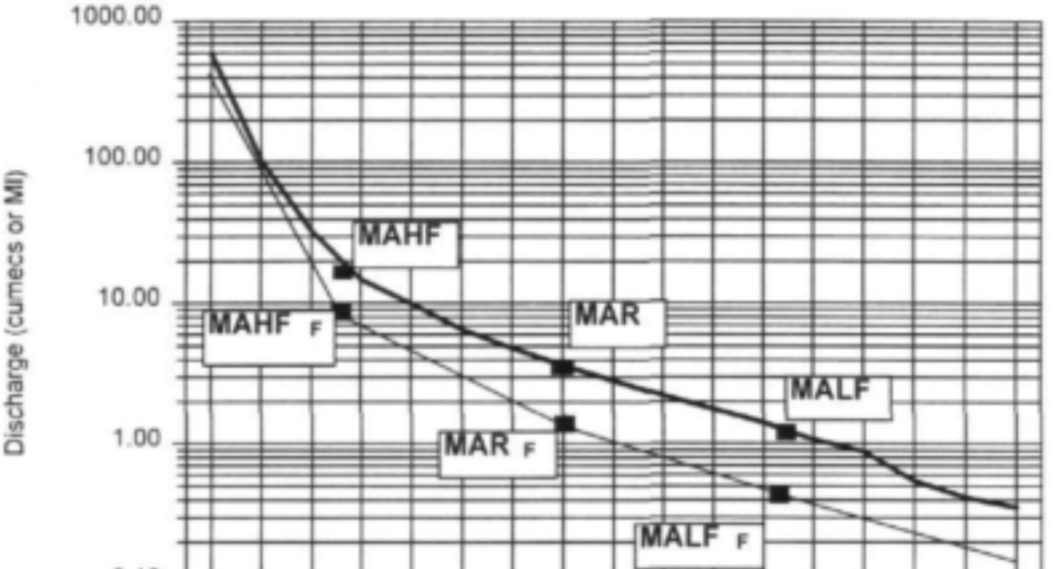


Figure 5.1 Illustration of 1-month FDC adjustment for forestry effects using three flow characteristics (index "F" indicates flows from FDC for afforested catchment).

The approach for FDCs adjustment in cases of other land-use changes or indirect effects on streamflow may in fact be similar to that described above. It should include identification of several (e.g. three) base points on the curve (either 1-day or 1-month) and adjustment of flows at these points. The flows at intermediate points may then be calculated by interpolation or extrapolation. This approach however may give only a crude estimate of adjusted FDC. Additional complication is that no simple models of flow reduction due to different land-uses (with the exception of forestry) have been developed so far in South Africa.

Another possible alternative for correction of annual 1-day includes the combined use of typical monthly flow distribution and a natural 1-month annual FDC. It may be formulated as follows:

- Construct 1-month annual FDC using available monthly flow data for natural condition (e.g. using quaternary catchment data)
- Calculate average monthly flow distribution using the same data with the output of 12 average monthly flow values.
- Locate these 12 flow values on 1-month annual natural FDC, estimating time of excedence for each.
- Calculate average artificial influences for each month. This may be performed using the procedures outlined in Midgley *et al.* (1994) (e.g. calculating monthly irrigation demands).
- Subtract estimated average monthly artificial flows from average monthly natural flows.
- Construct the adjusted 1-month annual FDC using 12 adjusted monthly flows. The flows for 17 fixed percentage points on the curve may be estimated by means of interpolation or extrapolation.
- Convert adjusted 1-month annual FDC into 1-day annual FDC using the technique described in the previous Chapter.

This approach assumes that percentage points for 12 monthly average flows remain the same for both natural and adjusted FDC. This may not always be the case and the pragmatic way of addressing this problem is to sort the 12 adjusted flows from highest to lowest and their corresponding percentage points from in the opposite direction in order to preserve the general shape of the curve.

The approaches for FDC adjustment for various development effects have been discussed mostly at the theoretical level and have so far not been intensively tested in different catchments. However, they all effectively demonstrate that the problem of FDC adjustment in the context of pragmatic time series modelling could be resolved and may form a challenging research direction.

# 6. CONVERSION OF FLOW DURATION CURVES INTO A COMPLETE CONTINUOUS FLOW TIME SERIES.

## 6.1 Spatial interpolation of observed flow records

The third major step in the pragmatic time series modeling approach (Chapter 2) is the generation of complete flow time series from established FDCs. This is, perhaps, the most attractive area of application of the proposed approach since , amongst the others, it is designed to generate daily flow time series at the ungauged sites without using sophisticated deterministic modelling techniques. The methods for FDCs conversion into a time series described in this Chapter stem from the original work by Hughes and Smakhtin (1996) who designed a simplified algorithm initially developed to patch and/or extend observed time series of daily streamflows. This algorithm attempts to account for possible non-linearities in streamflows at different sites, even within similar parts of the same basin, and is based on 1-day FDCs for each calendar month. The method is, however, equally applicable if only annual FDC is used.

The major assumption of the non-linear spatial interpolation algorithm in its original form (Hughes and Smakhtin, 1996) is that flows occurring simultaneously at sites in a reasonably close proximity to each other correspond to similar percentage points (probabilities) on their respective flow duration curves. The approach includes the following steps:

- *Source site selection for data transfer.* 'Source' sites are the sites with gauged flow records from where the data will be transferred to the 'destination' site of interest. Up to 5 candidate source flow gauging stations are identified in the vicinity of the destination site and the weights are assigned to each of the source sites. The weights are based on the degree of similarity between source and destination site flow regimes. Suitable source sites may be selected and weights may be quantified on the basis of spatial correlation analysis. However, in practice, especially in data poor regions, such selection and quantification is frequently either limited or obvious and the nearest gauges on the same river, its tributaries or adjacent streams will be used as source sites.

- *Generation of tables of discharge values.* Tables of discharge values are generated for each site (source and destination) and each month of the year for fixed percentage points on the corresponding FDC. For example, if two source sites are selected, the total number of sites involved in simulation is 3 and the total number of required discharge tables is 36. The algorithm uses 17 fixed percentage points from 0.01 to 99.99% and, consequently, each discharge table is made up of 17 flow values.

- *Data transfer from individual source gauges.* This is the major computational step during which the percentage point of each day's flow at each source site is identified and the flow value for the equivalent percentage point from the destination site's FDC is read off. The discharge tables are used to "locate" the flows on corresponding curves and log-interpolation is used between fixed percentage points. The procedure is repeated for each source site. The layout of the computational procedure is presented in Figure 6.1.

- *Final estimate of a destination daily discharge*. Weighted averaging of all flow estimates for the destination site (obtained using individual source flows) is performed. If the flow for any source site on that day is missing, it is ignored, and the final estimation is performed with the remaining set of individual flows (the weights are automatically adjusted).

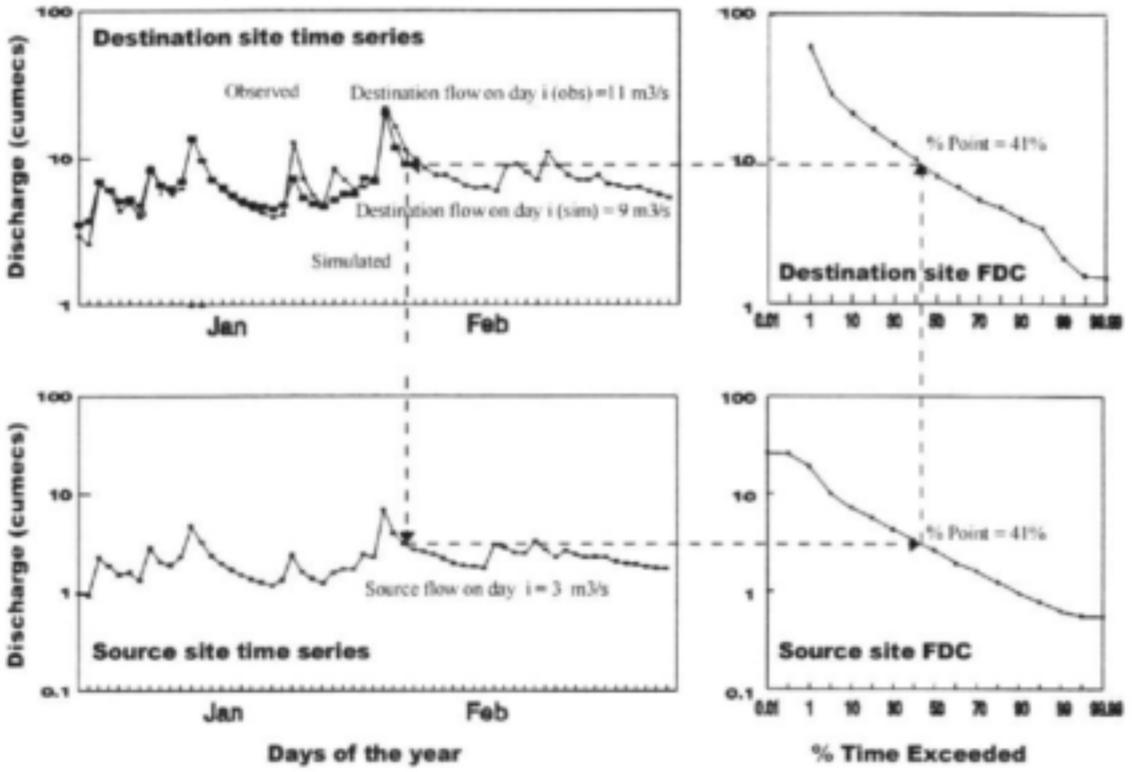


Figure 6.1 Illustration of daily flow data transfer from a single source to the destination site in the spatial interpolation approach

The first two steps are, in fact, preparatory and are performed only once. The last two form the bulk of the computational procedure and are performed for each day during the calculation period. Different gauged records may have different starting and ending dates. The starting date of the calculation period corresponds to the earliest starting date of the selected gauges, and the ending date corresponds to the latest of all ending dates. Hughes and Smakhtin (1996) provide other details of the computational procedure.

The algorithm has been incorporated into a time series 'model' that allows flows at a 'destination' site to be estimated from flows occurring at several 'source' sites. Parameters of this model are the site numbers of up to 5 source sites and weighting factors for each source site based on the degree of similarity between source and destination site's flow regime. The output of the model consists of the 'patched' and/or 'extended observed flow and a 'substitute' flow times series made up of completely estimated values regardless of whether the original observed flow was missing or not.

If the observed record at the destination site exists, this record (entirely or partially) may be used for the generation of discharge tables. The aim of the interpolation procedure is then likely to be the patching and/or extension of the available record at the destination site. Also, in this case, the 'model' described above may be 'calibrated' in a similar way as, for example, rainfall-runoff models are calibrated against observed data. The calibration may be performed by

- changing the selection of the source sites and their number and/or
- changing the weighting factors for each selected source site.

Technically the calibration is performed by the visual analysis of similarities between displayed source and destination site's flow time series and by calculation of several goodness-of-fit measures, namely, maximum, minimum and mean flows (Max, Min, Mean), standard deviation (SD), coefficients of determination ($R^2$) and efficiency (CE). The comparison between observed and generated time series is made for untransformed and log-transformed flows. The latter give a better indication of the quality of low-flow simulations. All these facilities are provided in HYMAS computer package.

## 6.2 Application to ungauged catchments using regional flow duration curves

If the generation of flow time series is intended at an ungauged destination site, the set of typical 1-day FDCs for each month of the year at this site should be established prior to the simulation of the actual time series by either

- regionalisation of FDCs based on available observed records from several adjacent gauges (Chapter 3) or
- conversion of 1-month FDCs into1-day FDCs (Chapter 4)

Once a FDC is established at the ungauged destination site of interest, the spatial interpolation algorithm may be applied to generate the actual continuous flow time series. However, no 'calibration' may be performed in the case of an ungauged catchment since no observed record at an ungauged destination site is available.

Figure 6.2 presents extracts of the daily flow time series simulated by means of spatial interpolation approach for the upper Sabie River at gauge X3H001 (gauged catchment area 174 km$^2$). The river is part of the Komati basin and the destination site FDCs are derived as described in Chapter 3. The regional curves used are represented by Low Variability Curve (LVC) and High Variability Curve (HVC ) illustrated by Figure 3.4 in Chapter 3. Two nearest streamflow gauges (X3H002 and X3H003) have been used as source sites (with equal weights). The time series are simulated for natural catchment conditions. The observed hydrograph illustrates the response of the catchment under the current state of catchment development.

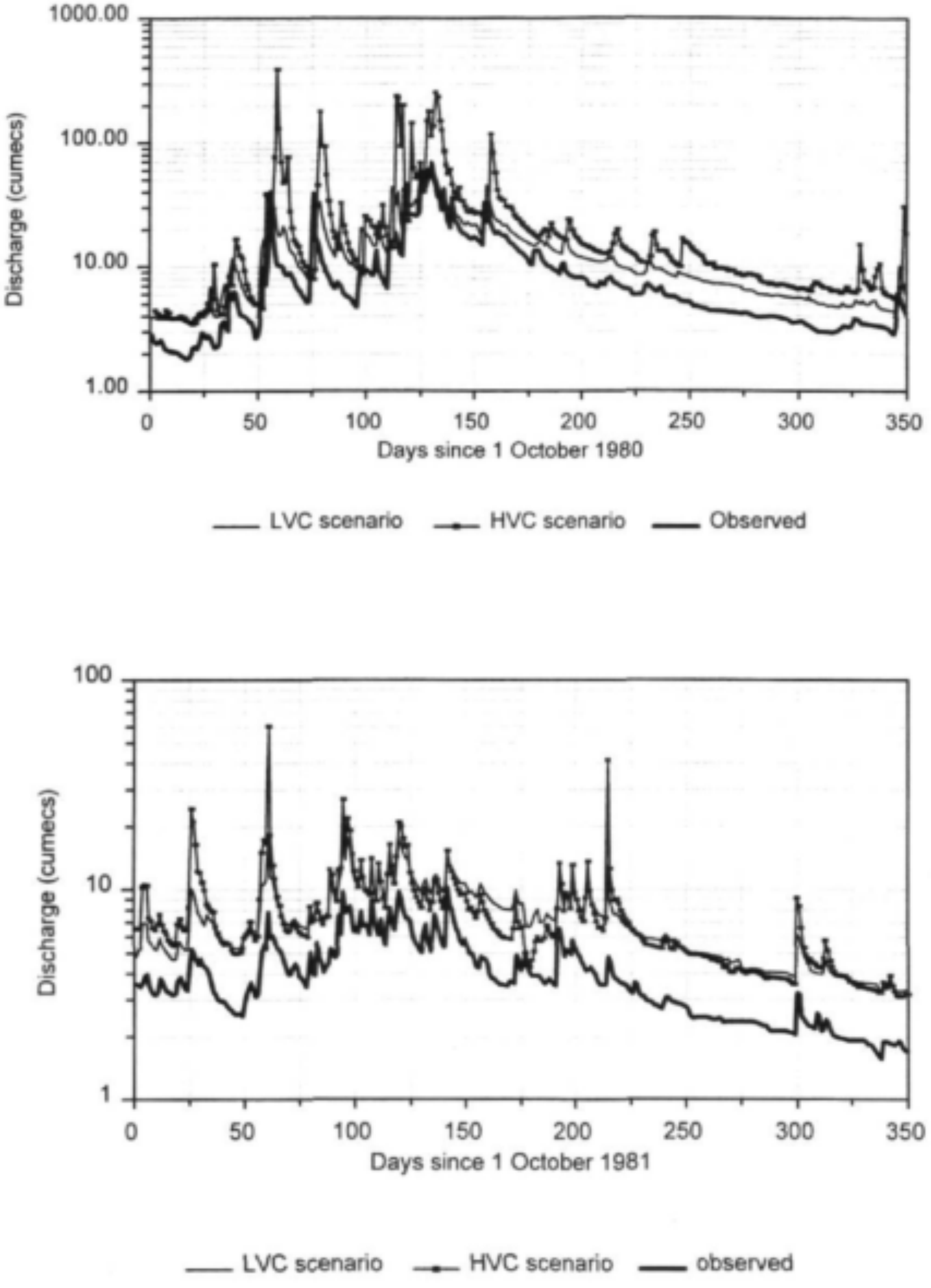


Figure 6.2 Observed and simulated daily hydrographs for the Sabie River at gauge X3H001 using two different FDC scenarios for two years of different wetness.

### 6.3 Generating natural daily flow time series in regulated river catchments

There is often a paucity of flow time series, which are representative of unmodified hydrological conditions in already modified catchments. At the same time, such time series are often in demand, for example, in river ecology studies, where it is important to know to what an extent the river flow regime has been modified compared to the natural one. Such studies may require the time series (often including particular, e.g. recent extremely dry year) for unmodified flow conditions downstream of already existing reservoir(s) or direct water abstraction(s) from the river.

The spatial interpolation algorithm may provide a quick solution to this problem. The prerequisite for the application of spatial interpolation technique is the existence of at least one source flow gauge upstream of the point of regulation (or abstraction) with records representing natural flow conditions. If the stream flow data generation is intended at the destination site downstream of a reservoir, two typical cases may exist: (i) flow record at the destination site exists and part of this record is affected by the upstream impoundment (normally the most recent part of the observation period); (ii) no natural flow record downstream of the reservoir exists.

*Case 1: Downstream site flow record is partially affected by upstream impoundment*

In this case, part of the destination site's record representing unmodified flow regime should be identified. The observations at the upstream source gauge(s) should extend into the period for which the flow generation at the destination site is intended. This case may be illustrated by the example in the Blyde River catchment. located to the west of the Kruger National Park boarder in South Africa. The gauge B6H005 (catchment area 2204 km$^2$) with record starting in 1958, is located downstream of the Blydepoort Dam which was constructed in 1974 (Fig. 6.3). No catchment or water resource developments occurred upstream this gauge until the construction of the dam. Therefore, the first part of the record at gauge B6H005 (1958 - 1974) represents the natural flow regime in the river, while the second part (from 1974 until present) reflects the modified flow. Tables of discharge values for fixed percentage points for each calendar month were therefore generated using the unmodified 15-year long flow period (1958 - 1973).

The suitable neighbouring source sites are B6H001 (catchment area 518 km$^2$), B6H003 ( 93 km$^2$) and B6H006 (43 km$^2$ ), shown in Figure 6.3. All source gauges record natural flow conditions. Consequently, the entire observation periods on these gauges ( from late 1950s until present) have been used to generate discharge tables.

Once the discharge tables for each calendar month at each site are calculated , the spatial interpolation technique was used to generate natural flows at gauge B6H005 for the entire observation period (1958 - 1996). The first source gauge (B6H001) is the closest to the destination site and is located on the same river. The visual inspection of observed time series revealed that of all three source gauges, the flow pattern at gauge B6H001 is the most similar to that at gauge B6H005 downstream. Therefore, it was assigned the largest weight (0.8), while the other two gauges were assigned smaller equal weights ( 0.1 each).

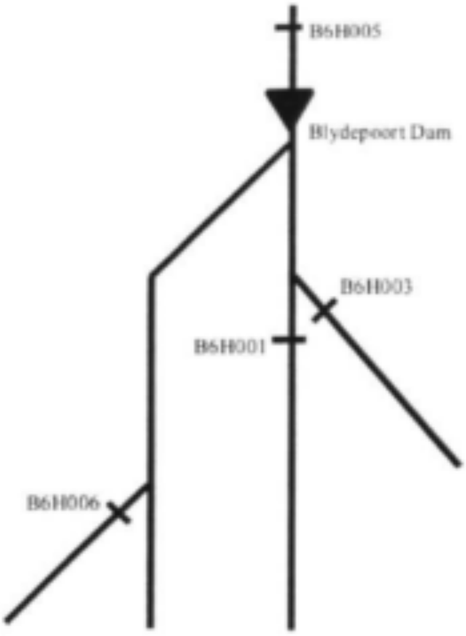


Figure. 6.3 A schematic layout of the streamflow gauging network in the Blyde River catchment (not to scale).

Table 6.1 Goodness-of-fit statistics for the pre-impoundment (1958 - 1973) and post-impoundment (1974 -1996) periods at gauge B6H005 on the Blyde River.

| Period | Time-Series | Untransformed flows | | | | | | Log-transformed flows | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Max, $m^3/s$ | Min, $m^3/s$ | Mean, $M^3/s$ | SD, $m^3/s$ | $R^2$ | CE | Max | Min | Mean | SD | $R^2$ | CE |
| 1958-1973 | Obs. | 318 | 0.06 | 6.72 | 13.7 | 0.90 | 0.90 | 5.76 | -2.76 | 1.04 | 1.38 | 0.86 | 0.86 |
| | Sim. | 296 | 0.08 | 6.47 | 13.1 | | | 5.69 | -2.56 | 0.97 | 1.38 | | |
| 1974-1996 | Obs. | 270 | 0.15 | 7.37 | 15.3 | 0.81 | 0.81 | 5.60 | -1.92 | 1.06 | 1.32 | 0.73 | 0.66 |
| | Sim. | 284 | 0.17 | 8.09 | 14.7 | | | 5.65 | -1.78 | 1.40 | 1.15 | | |

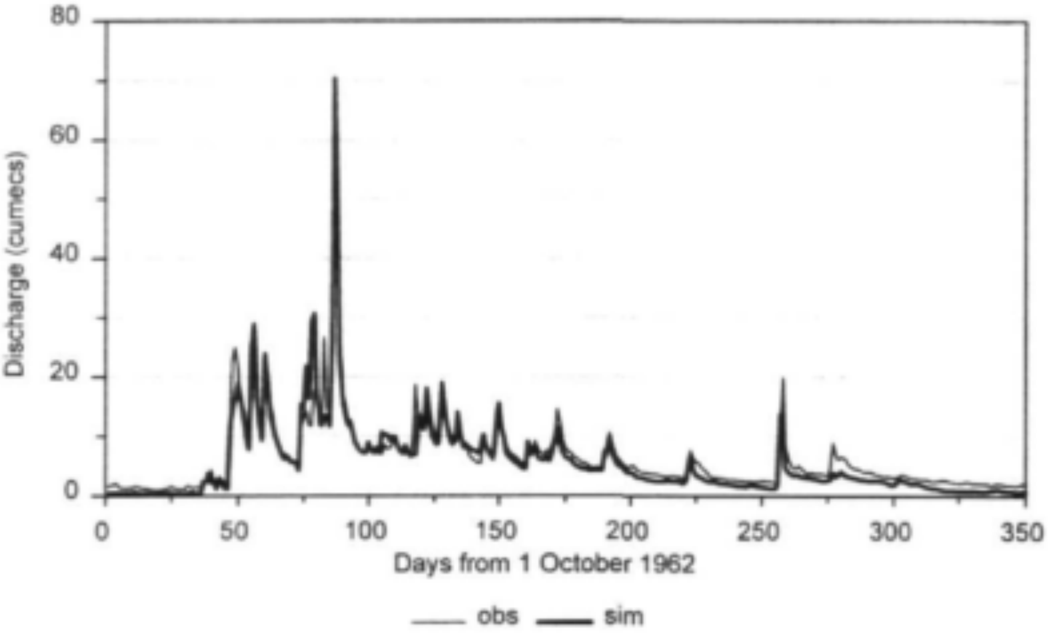


Figure 6.4 Observed and simulated daily streamflow hydrographs for the Blyde River at gauge B6H005 for one hydrological year during the pre-impoundment period.

The goodness-of-fit statistics between observed and generated flows are summarised in Table 1. High values of $R^2$ and CE for both untransformed and log-transformed flows during pre-impoundment period are indicators of a good simulation. Visual comparison of observed and simulated flows illustrated that during this period the flows in both wet and dry years (years with the annual total flow volume significantly higher or lower than the Mean Annual Runoff (MAR)) are simulated equally well. Figure 6.4 shows the extract from observed and simulated time series at gauge B6H005 for one arbitrarily selected wet hydrological year.

As may be expected, relative deterioration of the fit statistics (particularly for log-transformed flows) occurs in the post-impoundment period (Table 6.1). This is a direct consequence of comparing observed regulated and simulated natural daily flow sequences. The differences between the two are especially pronounced during dry years, when flow regulation becomes critical. Figure 6.5 compares the observed and simulated daily flow hydrographs during most of the driest 1991 hydrological year at gauge B6H005 and clearly illustrates the differences between the actual releases from the upstream Blydepoort Dam and the natural flow pattern restored by the simulation. The water is released to satisfy the requirements of the downstream users but possibly with little regard to instream flow ecology.

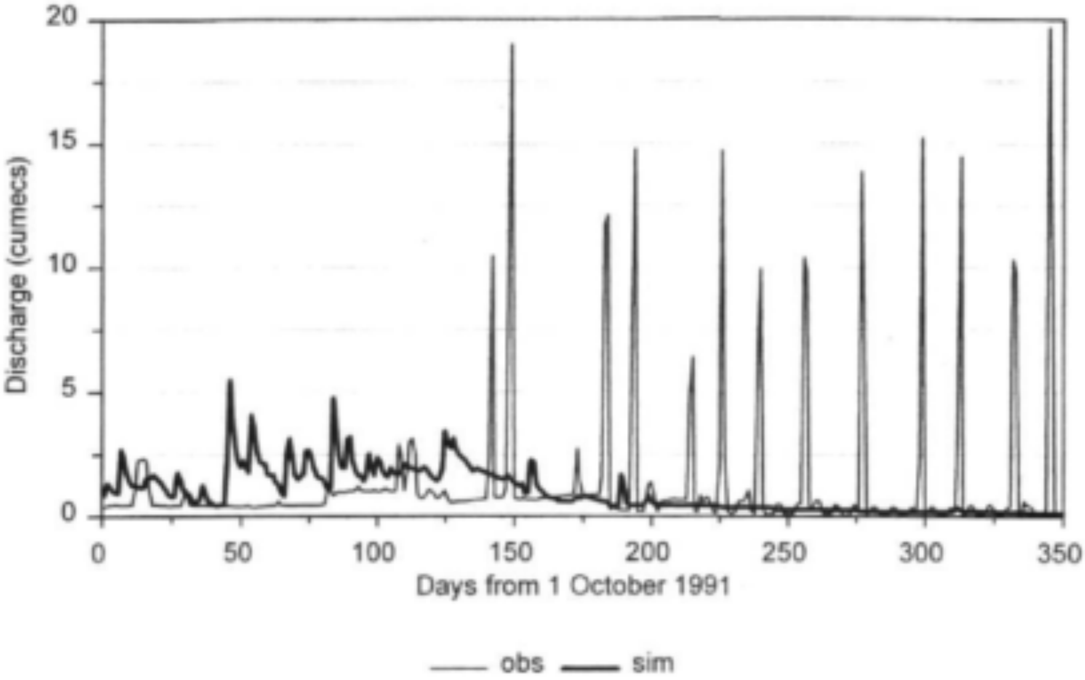


Figure 6.5 Observed regulated (reservoir releases) and simulated natural daily streamflow hydrographs for the Blyde River at gauge B6H005 for one dry hydrological year during post-impoundment period

*Case 2: No natural flow record exist downstream of the reservoir*

If no flow observations exist downstream of the reservoir during the pre-impoundment period, it is appropriate to use just one nearest upstream flow gauge with representatively long and unbroken observation record. In this case, the discharge tables for each month generated from such record are adjusted using an appropriate correction factor. The adjusted discharge tables then represent 1-day monthly FDCs at the destination site.

The correction factor may be calculated as the ratio between the catchment areas at the destination site and the upstream site with data. However, the streamflows at even closely adjacent sites are rarely linearly related to catchment area and the more valid alternative is to use the ratio of the MAR or Mean Daily Flow (MDF) values of the destination site of interest and selected upstream gauged site. The estimates of MAR (MDF) for ungauged sites may be obtained from quaternary catchment data (Midgley *et al*, 1994).

Figure 6.6 A map of the Bushmans River catchment showing the major streams, the location of streamflow gauges and Wagendrift Dam and quaternary subcatchment boundaries.

Generation of natural flow sequences for a regulated river reach in the absence of historical flow records downstream of the reservoir site may be illustrated by the example of the Bushmans River located in KwaZulu-Natal Province of South Africa to the east of the boarder with Lesotho. The layout of the streamflow gauging network in the Bushmans River catchment is shown in Figure 6.6. Only one gauge (V7H017, gauged catchment area 276 $km^2$) with good quality flow records starting in early 1970s and reflecting natural flow conditions exists upstream of the Wagendrift Dam constructed on the Bushmans River in 1963. The upstream catchment area at the dam site is 744 $km^2$. The releases from the dam are measured since the year of its construction at gauge V7H020 located immediately downstream of the dam. No flow records exist downstream of the dam site during the pre-impoundment period. Figure 6.6 also shows the boundaries of the quaternary subcatchments in the Bushmans River basin.

The FDC discharge tables at the upstream gauge V7H017 may be used to generate FDC discharge tables for natural flow conditions at the dam site using an appropriate correction factor. The MAR estimate at V7H017 is 118 MCM, while the MAR at the dam site is 222 MCM (the latter value is obtained from Midgley *et al* ( 1994) as the sum of the MARs of two quaternary subcatchments above the reservoir site (Fig. 6.6)). To calculate the FDC discharge tables at the dam site, the FDC discharge tables at V7H017 are corrected by the factor of 1.882 ($MAR_{DAM}$ / $MAR_{V7H017}$). Once the FDC discharge tables at the destination dam site are calculated, the spatial interpolation technique is applied to generate the continuous natural daily flow time series using V7H017 as a source gauge. The restored natural daily streamflow time-series at the dam site reflects the main features of the unmodified upstream flow regime and, if compared with observed flow downstream of the dam, clearly illustrates the changes in flow regime brought to the entire downstream river system by flow regulation (Fig. 6.7).

The method illustrated in *case 2* is effectively equivalent to simple rescaling of the flow time-series at the upstream gauge by a certain correction factor. This approach may be suitable if the source site is close to the destination one and is located on the same stream (like in the case of the Bushmans River). The upstream source site's high, medium and low flows may then be expected to increase downstream to the same proportion (which is reflected by the application of a constant correction factor). If there are no suitable upstream gauging stations, it would be more appropriate to establish the set of 1-day monthly FDCs for the destination site on the basis of natural records from several adjacent gauged catchments using regionalisation approach (as described in Chapter 3).

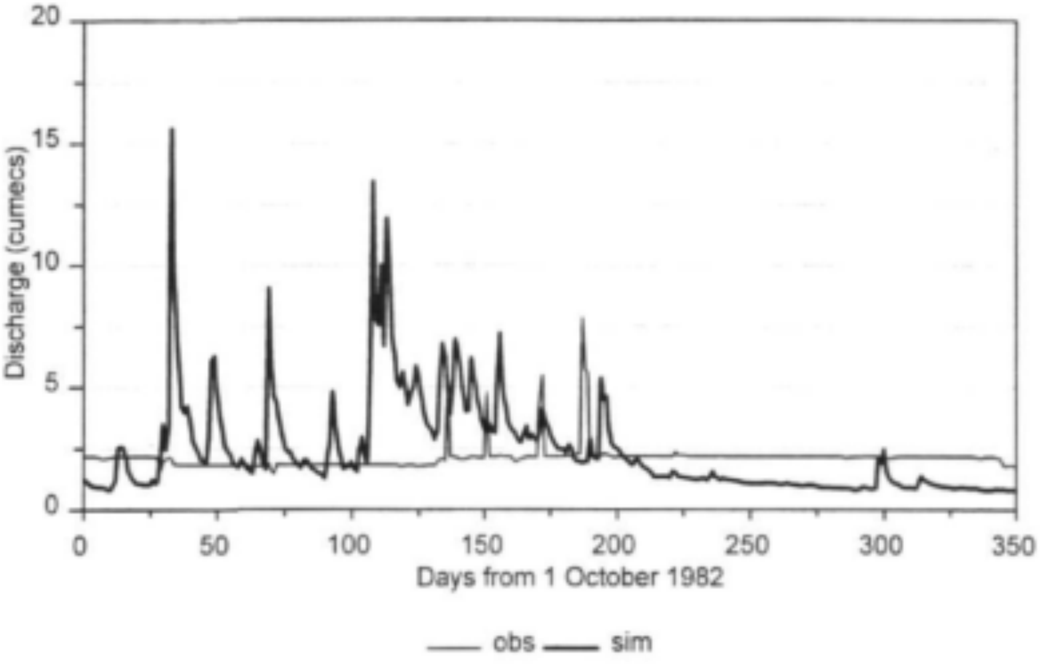


Figure 6.7 Observed regulated (reservoir releases) and simulated natural daily streamflow hydrographs for the Bushmans River at gauge V7H020 downstream of the Wagendrift Dam.

### 6.4. Generating natural daily flow time series using synthetic monthly flow records.

The method may be illustrated with the example of the Komati River catchment The anthropogenic influences in the catchment are numerous including various direct abstractions and catchment land-use changes (irrigated agriculture and commercial forestry being the dominant ones). Two major dams (Fig. 6.8) are located in the upstream parts of the catchment. Nooitgedacht Dam with capacity of 80 MCM and an upstream catchment area of 1569 km$^2$ was constructed in 1960. Vygeboom Dam with the same capacity and an upstream catchment area of 3131 km$^2$ was constructed in 1971.

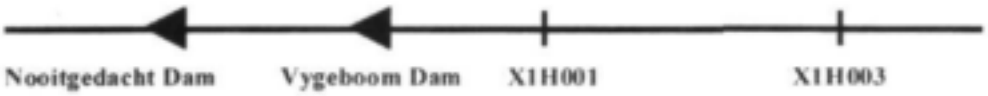


Figure 6.8 A schematic layout of the main Komati stream showing major dams and flow gauges (not to scale).

Daily flow records exist at the gauge X1H001 (gauged area 5499 km$^2$) since 1909 until present. This gauge is strategically located in the central part of the catchment (Fig. 6.8) and its record prior to the beginning of river regulation in 1960 is representative of natural daily flow variability in the main stream. The observed flow records at gauge X1H003 exist from 1959 till 1970 and are therefore affected by the construction of the upstream impoundments. Monthly flow time series for natural catchment conditions are available at a number of locations along the main river from Midgley *et al* (1994).

The explicit ratio curve method described in Chapter 4 and the flow record at X1H001 prior to 1960 have been used to establish natural 1-day FDCs. The calculated ratio curves may be applied to any location along the river, where monthly flow time series are available, to convert 1-month FDCs into 1-day FDCs, while the record at the source gauge X1H001 may be used to simulate a continuous daily streamflow time series at sites along the river by means of the spatial interpolation technique.

Since no records representing natural flow regime exist upstream or downstream gauge X1H001, only the indirect assessment of the quality of simulations is possible. The simulated daily flows may be accumulated into monthly, and compared with natural monthly flow time series available from Midgley *et al* (1994). Such a "verification" has been performed at site X1H003. It illustrates that monthly hydrographs obtained from these two sources compare favourably (Fig. 6.9). This may be considered as the indirect indication of a good simulation produced by the spatial interpolation technique.

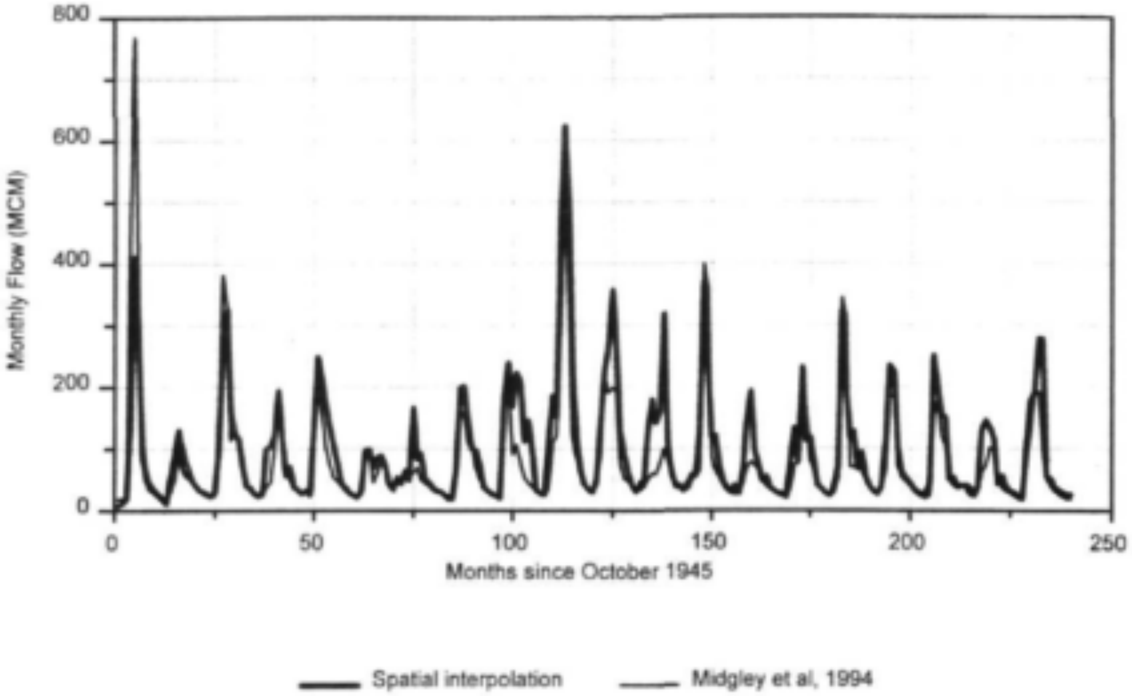


Figure 6.9 Natural monthly flows at gauge X1H003: accumulated from simulated daily discharges and reconstructed from Midgley *et al*. (1994)

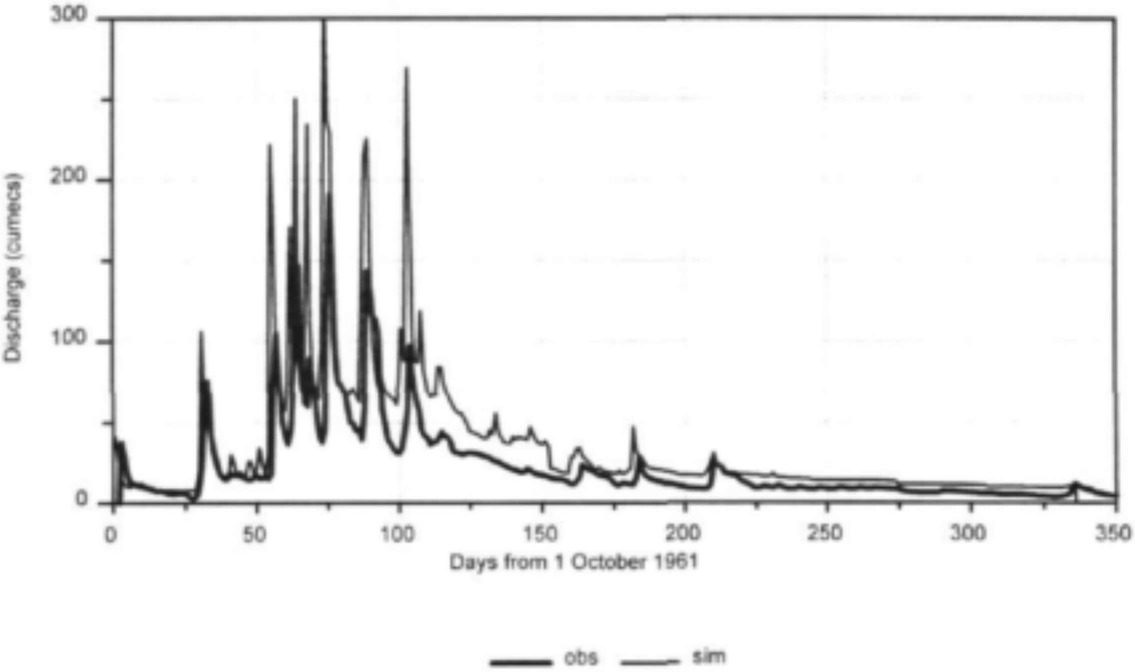


Figure 6.10 Observed (historical) and simulated natural daily hydrographs at gauge X1H003 for one hydrological year

The effects of upstream flow regulation along most of the main stream were minor until the beginning of 1970s, when the Vygeboom dam was constructed. It is therefore possible to compare simulated and observed daily hydrographs at gauge X1H003 during the previous decade. Figure 6.10 illustrates that the variability of simulated natural daily discharges generally follows the same pattern as that of the observed, but simulated natural flows are consistently higher than observed ones, which is possibly the consequence of the various upstream catchment land-use changes.

One obvious limitation of the approaches presented is that they are dependent on the availability and representativeness of the source gauge's flow data. For example, if the source natural flow record is not available for the most recent period, the generated destination natural flow record will also be similarly deficient. However, if this is not a critical issue in the context of a study for which the natural flows are required, and if the available record at the source gauge is sufficiently long (e.g. 20-25 years), the resultant destination site's daily time series will be suitable for the majority of hydrological analyses.

# 7. CONTINUOUS HYDROGRAPH SIMULATION USING DURATION CURVES OF RAINFALL CHARACTERISICS

## 7.1 A concept of a Current Precipitation Index and its use in daily flow time series generation

The procedures for FDC estimation at ungauged sites described in previous Chapters effectively represent the modifications to the original version of the non-linear spatial interpolation approach. These procedures essentially expand the area of the algorithm's application. However, its main limitation is that it is based entirely on observed flow records. The algorithm therefore inherits all the problems related to the quality and availability of such records. One of the most important requirements (and limiting factors) for the application of the spatial interpolation approach to either gauged or ungauged destination site is the existence of at least one nearby source flow gauge from where the data may be transferred (two or more source sites are, however, preferable if the simulated hydrograph is to have a minimum, or no, missing data). As has been illustrated by Smakhtin *et al* (1997), this may represent a serious problem in data deficient regions. Even if the required FDCs are established for the destination site (by any of the techniques already described), a suitable neighbouring source flow gauge may still not be available. The logical way to address this problem is to investigate the possibilities of incorporating more widely available (and normally longer) rainfall records into the structure of non-linear spatial interpolation method.

Rainfall records are to be used in the algorithm in cases when no source flow records are available. Consequently, both source flow time series and source FDC should be replaced by corresponding rainfall related measures. 'Rainfall duration curves' can certainly be constructed similarly to FDCs. However, their direct use in the algorithm is problematic, owing to the number of zero rain days in any rainfall record (Fig. 7.1). Zero daily rainfall does not imply zero flow. A rainfall duration curve, if constructed on the basis of the entire record and not just rain days, is a very steep one, indicating amongst the others, that it rains only for a very small percent of the time on average during a year (Fig.7.2). This percent obviously depends upon climatic conditions and may be relatively large in some humid regions.

In order to make rainfall records "work" within the framework of the spatial interpolation approach, one should define a continuous function of daily rainfall which would abruptly increase on rainy days and gradually decay during the dry periods and therefore resemble the general pattern of streamflow variability. The type of function sought is thus similar to that of the antecedent precipitation index (API). The API is an exponential decay function of precipitation which reflects the rate of soil moisture depletion during the period of no rainfall (Linsley *et al*, 1975). Soil moisture content affects the occurrence and magnitude of storm flow as well as the rate of groundwater recharge. Consequently, the API may be a good indicator of the continuous catchment outflow and, as such, has already been used in some previous API-type hydrological models for continuous hydrograph synthesis (e.g. Sittner *et al*, 1969). However, the API (or its modifications) is most frequently used in storm runoff prediction (Fedora and Beschta,1989; Ni-Lar-Win and Vandewiele, 1994).

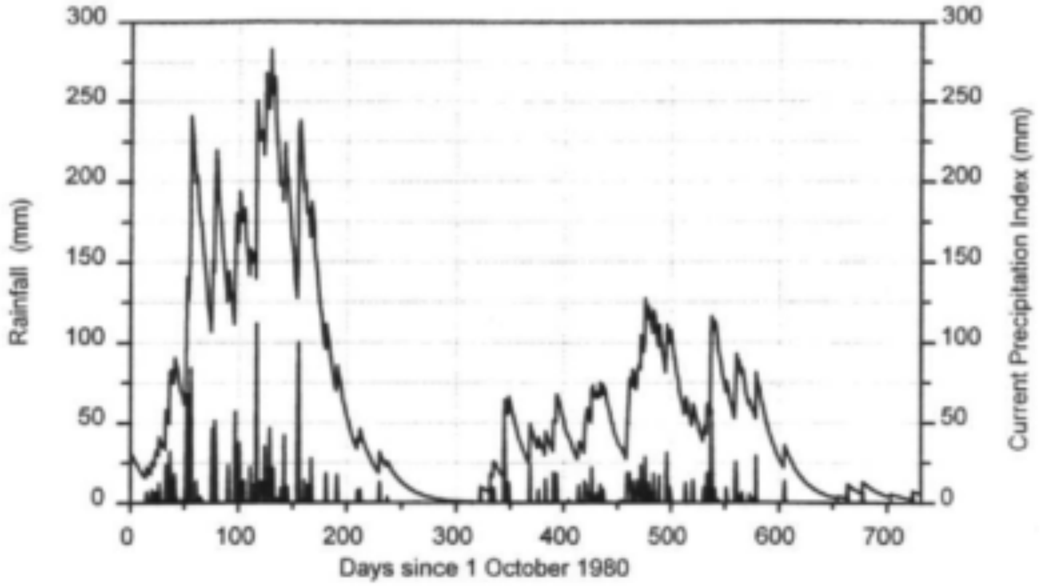


Figure 7.1 Example time series of daily rainfall and CPI at an individual rainfall gauge

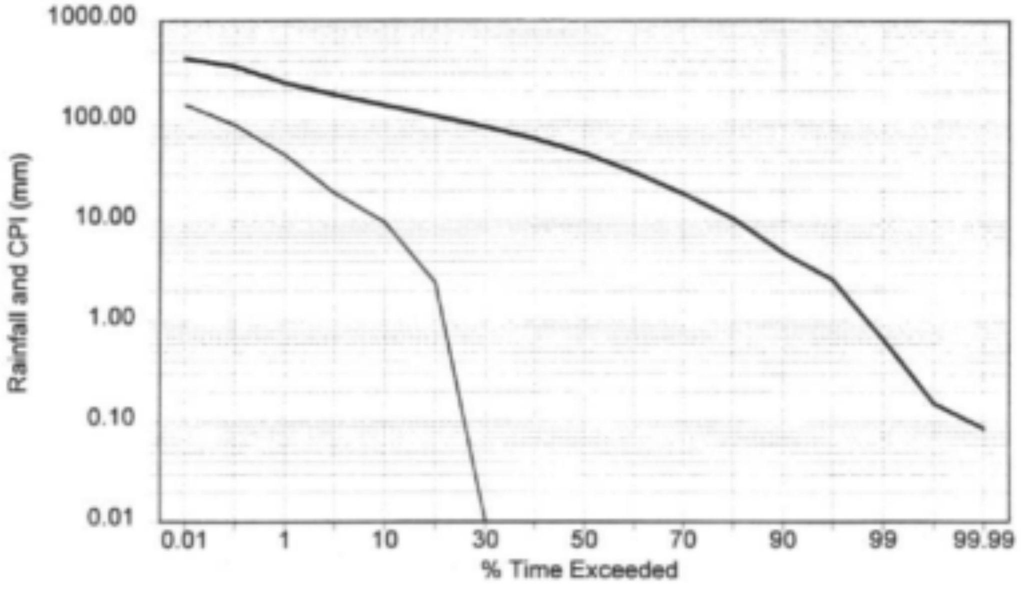


Figure 7.2 Typical form of the annual duration curves of daily rainfall and CPI

The original concept of the API needs to be slightly modified to be applicable in the context of the spatial interpolation approach. It should reflect not just for the antecedent catchment conditions for any day but also the current daily precipitation input. Such a modification effectively leads to what is referred to here as a Current Precipitation Index (CPI). The CPI for any day is calculated as:

$$CPI_t = CPI_{t-1} K + R_t \qquad \text{Eq. 7.1}$$

where $CPI_t$ is a Current Precipitation Index (mm) for day t, $R_t$ is the catchment precipitation for day t and K is the daily recession coefficient. On any day with no rain ($R_t = 0$) the CPI is equal to the CPI of the previous day multiplied by K (similarly to API). However, if it rains on any day, the daily rainfall depth is added to the CPI immediately. Consequently, the index in its current form does not represent only the antecedent wetness of the catchment, but also reflects the effects of the current precipitation.

To generate the continuous time-series of daily CPI values, its initial value ($CPI_0$) and recession coefficient need to be defined. The initial value however does not have any major effect on the resultant CPI time series, since several time series calculated with different initial values will converge within the first year of simulation. This value may generally be assumed to be equal to the long-term mean daily precipitation and calculated from available daily rainfall records.

The daily recession coefficient K normally varies from 0.85 to 0.98 (Linsley *et al,* 1975; Fedora and Beschta,1989 ) and it therefore fluctuates in a similar range as the baseflow recession constant (e.g. Klaasen and Pilgrim, 1975). It may, also, be treated as a parameter of the current 'model' and calibrated by comparing observed and simulated hydrographs in cases when observed data exist. On the other hand, K values will be required for ungauged catchments where no calibration is possible. In the current study, K is assumed to be equal to the median daily recession ratio of a stream (REC50). This characteristic represents the rate of baseflow recession and is estimated from the distribution of daily recession ratios (today's flow divided by yesterday's flow) calculated for all recession periods found in a record for those days when discharge is less than a long-term mean daily flow. This index is similar to the one described in the FREND (1989) study which provides the values of REC50 for a number of streams in the Europe. Smakhtin and Watkins (1997) list REC50 values for a number of South African streams. K values may also be estimated by means of regional regression models where K are dependent on catchment characteristics (topography, geology etc).

With an estimated K value, a continuous daily CPI time series may be generated for any rainfall station in a catchment and consequently, the required CPI duration curves may also be established. Figure 7.1 illustrates the time series of observed daily rainfall and corresponding calculated CPI time series at an individual rainfall station, while Figure 7.2 presents the duration curves calculated from these time series.

During a long dry period, the exponentially decaying CPI may reduce to unrealistically low values at which a catchment may be considered to be completely dry. It is therefore possible to replace all such negligible CPI values below a certain low threshold by zeros. In the current study this threshold was arbitrary assumed to be 0.1 mm and every CPI value below

0.1 mm was replaced by zero in the resultant CPI time series. This procedure was deemed necessary to create a more realistic CPI time series in which zero CPI values may correspond to zero river flows (e.g. in all non-perennial rivers).

Once the CPI time series and duration curve are calculated, it may be used in the spatial interpolation algorithm as a substitute for the source flows. The major assumption of the algorithm in this case becomes that both the CPIs occurring at rainfall sites in a reasonably close proximity to the destination site and destination site's flows themselves correspond to similar percentage points on their respective duration curves. The steps of the computational procedure outlined in the previous Chapter do not change and the layout of the process of daily flow generation undergoes only slight changes (as illustrated by Figure 7.3).

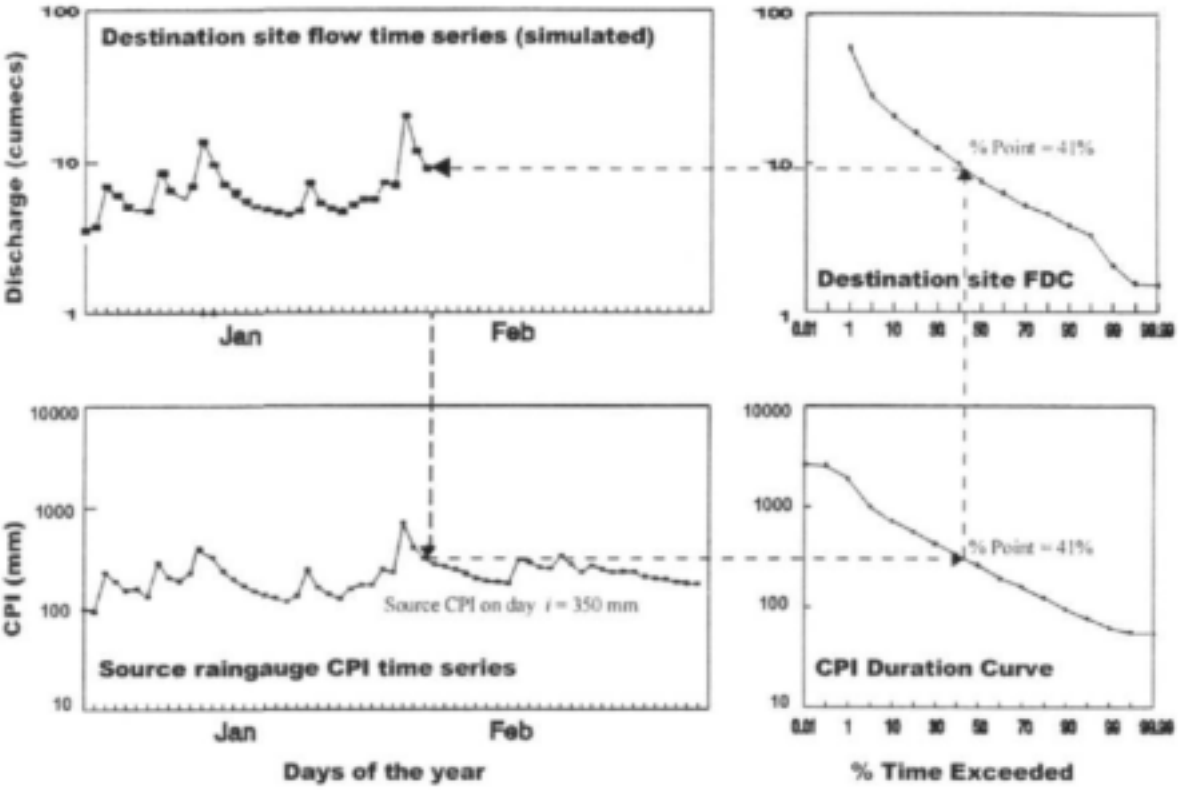


Figure 7.3 Illustration of daily streamflow generation using the spatial interpolation algorithm with the CPI source time series

### 7.2 Application of the method to South African catchments

The catchments selected have been drawn from different parts of the country and have already been used in some previous hydrological or water resource related studies (e.g. Smakhtin and Watkins, 1997). Two of them, (the Mac-Mac and Marite) are located in the headwater areas of the Sabie River, flowing through the Kruger National Park; one, the Sundays, is the tributary of the Thukela River in KwaZulu-Natal Province, one is located in the headwaters of the Mhlatuze River in the coastal area north of Durban and the other one is in the headwater part of the Koonap River catchment located in the semi-arid region of the Eastern Cape Province (Fig. 7.4). The exact geographical location of these catchments is however, largely irrelevant in the context of the proposed streamflow generation algorithm. On the other hand, the differences in the type of rainfall and flow regime as well as the amount and quality of available data are of primary importance. It may be expected *a priori* that lack of observed data would be the limiting factor to properly characterise the spatial variability of rainfall and, consequently, the spatial variability of the catchment wetness.

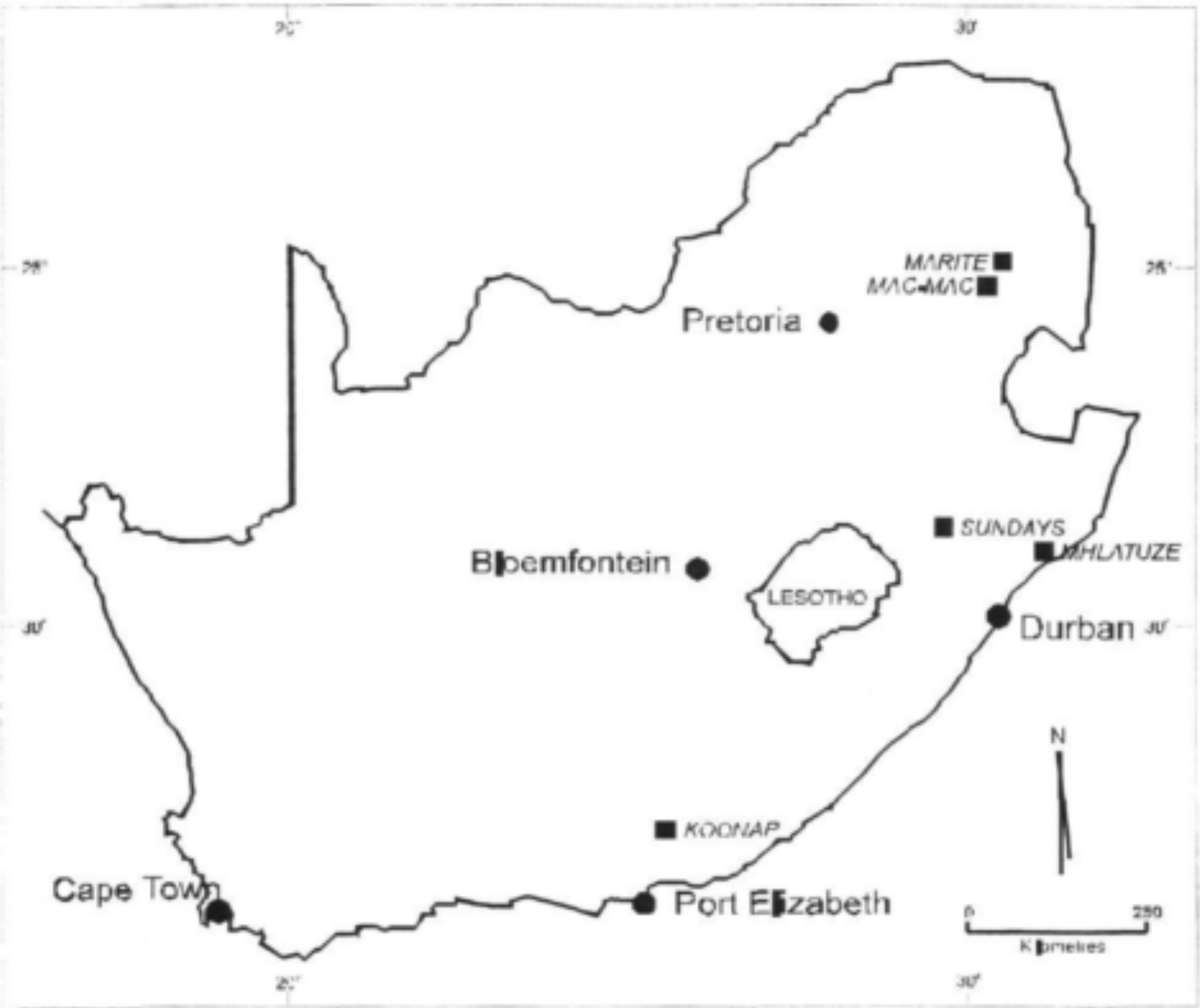


Figure 7.4 Location of the study catchments

The summary of available information for each selected catchment is given in Table 7.1. All selected catchments are gauged. This has been deemed necessary not for the sake of 'model calibration', but simply to compare the 'model' output with the observed streamflow data. Schematic maps of each catchment with indicated locations of rainfall stations and streamflow gauges are presented in Figure 7.4.

### *Mac-Mac River and Marite River*

These catchments are located in a mountainous region and receive relatively high summer rainfall which is primarily convective in nature. A strong orographic effect results in considerable variation in Mean Annual Precipitation (MAP) across each catchment (1200 - 1600 $mm.yr^{-1}$). At the same time, for the Mac-Mac catchment there are only 2 suitable rainfall stations which have consistent and largely overlapping record. Both are located in the high rainfall area zone, one station being outside the catchment boundary. Suitable rainfall stations in the Marite catchment are located around its centre. The streamflow records for both flow gauges are of reasonable quality, but Marite gauging station has a very low discharge measuring capacity.

### *Sundays River (flow gauge V6H004)*

The river originates at the altitude of about 1700 m above sea level. The Mean Annual Precipitation (MAP) exceeds 900 mm. More then 70% of the annual rain falls in the October to March period. Precipitation often occurs in the form of heavy localised thunderstorms. Two of the four suitable rainfall stations have records only till mid 1960s and consequently the later period is represented only by two stations located in the downstream part of the catchment. Streamflow record at gauge V6H004 is of good quality.

### *Mhlatuze River*

The catchment receives 850 $mm.yr^{-1}$ of rain, but no clear seasonal pattern appears to exist either in rainfall or streamflow. Many available rainfall stations have short records and were not considered. Three of the four selected rainfall stations lie around the boundaries of the catchment. The available data at streamflow gauge extend from 1964 to 1973, but contain long periods of missing data. These records do not appear to be very reliable and are affected by sedimentation problems upstream of the flow gauge.

### *Koonap River*

The catchment drains the mountainous area in the Eastern Cape province and experience on average about 700 $mm.yr^{-1}$ rainfall. It is the 'driest' catchment of all considered at this stage. Three rainfall stations with overlapping records are relatively evenly distributed with respect to the catchment boundary. Only a short flow record of good quality is available.

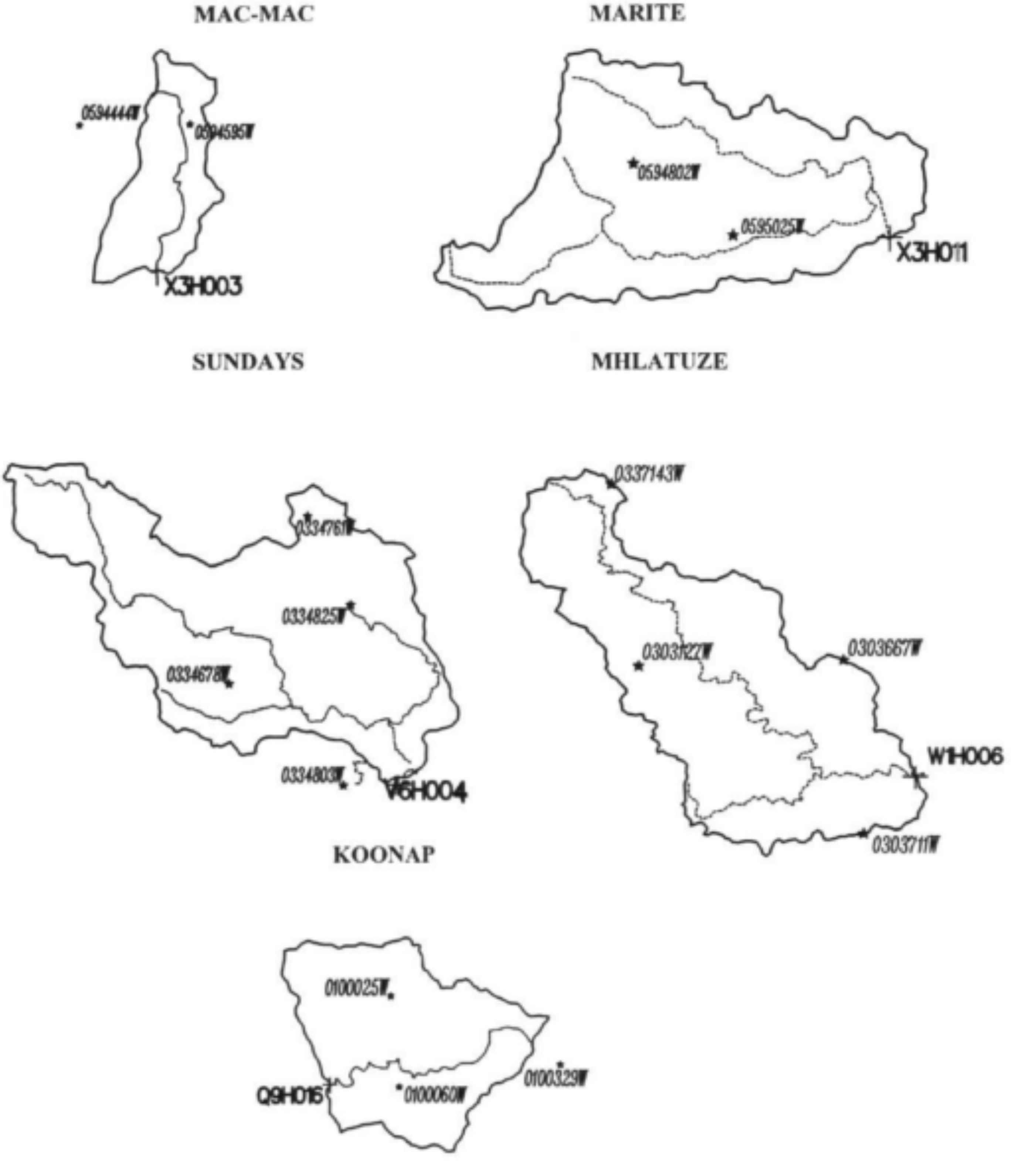


Figure 7.5 The schematic maps of the study catchments showing the location of rainfall stations and streamflow gauges (not to scale)

Figures 7.6 – 7.10 illustrate the correspondence between daily streamflow hydrographs observed and generated by the algorithm, as well as between annual FDCs constructed on the basis of observed and generated time series. Some measures of fit between observed and generated time series are presented in Table 7.2. They include maximum, minimum and mean flows, standard deviation (SD) and coefficients of determination ($R^2$) and efficiency (CE).

Table 7.1 Data availability in the study catchments

| **Catchment** | **Flow and rainfall gauge codes** | **Gauged area, km$^2$** | **Record period** |
|---|---|---|---|
| **Mac-Mac** | **X3H003** | **52** | **1948 - 1997** |
| | 0594595W | | 1914 - 1992 |
| | 0594444W | | 1940 - 1992 |
| **Marite** | **X3H011** | **212** | **1978 - 1997** |
| | 0594802W | | 1950 - 1997 |
| | 0595025W | | 1972 - 1997 |
| **Sundays** | **V6H004** | **658** | **1954-1997** |
| | 0334761W | | 1932 - 1963 |
| | 0334825W | | 1914 - 1992 |
| | 0334678W | | 1913 - 1967 |
| | 0334803W | | 1949 - 1997 |
| **Mhlatuze** | **W1H006** | **1272** | **1964 - 1973** |
| | 0337143W | | 1928 - 1993 |
| | 0303127W | | 1916 - 1994 |
| | 0303667W | | 1936 - 1980 |
| | 0303711W | | 1941 - 1993 |
| **Koonap** | **Q9H016** | **489** | **1982 - 1993** |
| | 0100025W | | 1960 - 1992 |
| | 0100060W | | 1960 - 1992 |
| | 0100329W | | 1960 - 1992 |

Table 7.2 Statistics of fit between observed daily flows and daily flows simulated by the CPI-based spatial interpolation algorithm and by the VTI deterministic daily model.

| Catchment and simulation period | Data | Mean, $m^3/s$ | SD, $m^3/s$ | Max, $m^3/s$ | Min, $m^3/s$ | $R^2$ | CE |
|---|---|---|---|---|---|---|---|
| Mac-Mac: X3H003 | Obs | 0.91 | 0.99 | 15.7 | 0.3 | | |
| 1979-1989 | Sim | 0.92 | 1.05 | 15.3 | 0.4 | 0.62 | 0.54 |
| | VTI | 0.78 | 1.03 | 23.3 | 0.3 | 0.78 | 0.51 |
| Marite: X3H011 | Obs | 1.7 | 2.44 | 28.9 | 0 | | |
| 1979-1989 | Sim | 1.57 | 1.91 | 28.8 | 0.01 | 0.64 | 0.64 |
| | VTI | 1.86 | 3.77 | 98.4 | 0.34 | 0.64 | 0.08 |
| Sundays: V6H004 | Obs | 3.3 | 7.53 | 93.6 | 0 | | |
| 1954-1964 | Sim | 2.93 | 5.64 | 71.1 | 0.02 | 0.58 | 0.58 |
| | VTI | 3.32 | 7.92 | 104 | 0 | 0.57 | 0.48 |
| Mhlatuze:W1H006 | Obs | 4.95 | 10.9 | 232 | 0 | | |
| 1964-1973 | Sim | 5.63 | 9.08 | 172 | 0 | 0.5 | 0.48 |
| | VTI | 4.94 | 10.6 | 166 | 0.02 | 0.49 | 0.45 |
| Koonap: Q9H016 | Obs | 0.53 | 3.06 | 102 | 0 | | |
| 1983-92 | Sim | 0.68 | 3.97 | 95.3 | 0 | 0.61 | 0.34 |
| | VTI | 0.53 | 3.93 | 98.2 | 0 | 0.74 | 0.63 |

The results of the "simulation" are also compared in Table 7.2 with those generated by the daily time step semi-distributed rainfall-runoff VTI model (Hughes and Sami, 1994), which represents a much more resource intensive alternative to generating flow time series. The VTI model incorporates two soil layers and includes the description of all major components of catchment hydrological cycle: interception, evapotranspiration, rainfall intensity controlled runoff, soil moisture redistribution and saturated surface runoff, a variety of surface-subsurface water interaction processes, catchment routing, channel transmission losses and flow routing. A modelled catchment is represented by a set of interlinked homogeneous subareas. The variability of some hydrological processes within each subarea is described by means of probability distribution functions of some model parameters. The average rainfall input for each subarea at each time step is determined by the inverse distance squared interpolation procedure which uses the information from the nearby rainfall stations, the coordinates of these stations and coordinates of subarea centre. The detailed description of the model is provided by Hughes and Sami (1994). The fit statistics in Table 7.2 are calculated for the indicated periods, for which the VTI model simulations were available.

It should be emphasized that no attempt has been made to "calibrate" the proposed "model" because i) calibration options are very limited (only rainfall stations weights and recession parameter value may be changed and ii) the method is intended for use at ungauged sites where no calibration is possible. Consequently, the results illustrate the performance of the approach under very stringent conditions. All rainfall stations in each catchment have been assigned equal weights (the sum of all individual station weights equals 1 in every catchment). The recession K value for each catchment was assumed to be equal to the median recession ratio value (REC50) of the nearest streamflow gauge listed in Smakhtin and Watkins (1997). The assigned K values varied in the range from 0.90 to 0.95.

Taking these stringent conditions into account, the results may generally be viewed as satisfactory and promising. In terms of fit statistics, the algorithm has performed almost as well as the more complex VTI model, although better VTI simulations were achieved for Mac-Mac and Koonap rivers as outlined in Table 7.2. (In the case of Marite River, the low CE value for the VTI simulations is most probably attributed to high simulated peaks, which in some years exceed the low measuring capacity of the gauge).

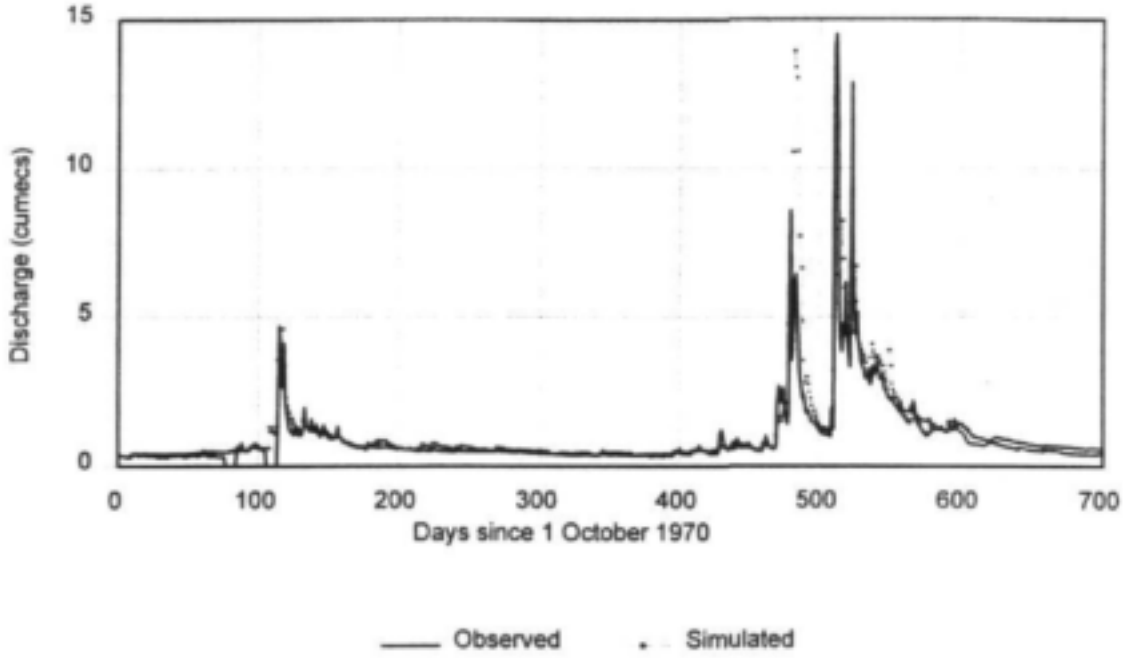
FDCs have been used for the assessment of the general quality of the simulations throughout the range of flows. Although a FDC does not represent a conventional measure of simulation quality control, it can help to visualize the differences and consequently to identify the deficiencies of any model's output. In three cases out of five, the curves match reasonably well through most of the flow range (Figs. 7.6, 7.7, 7.10). The FDCs for the observed and generated flows for the Sundays and Mhlatuze Rivers display the differences in the low-flow domain (Figs. 7.8 and 7.9). These differences may be attributed to the differences in the shape of CPI and flow duration curves for individual calendar months. A zero daily source CPI value in a certain month at a certain rainfall station could, in principle, correspond to a range of possible flows at the destination flow site. In the algorithm, the percentage point of the zero CPI value in each month always equals to the "first" fixed percentage point with zero CPI. Consequently, the estimated destination flow for that month is always the same. If the destination site FDC for that month has fewer (or no) zero values than the source duration curve, the destination flow may be overestimated. This happens in some cases in a low-flow domain and is reflected by Figures 7.8 and 7.9. This problem was identified by Hughes and Smakhtin (1996) in the original version of the spatial interpolation algorithm, but it was not of critical importance, since most of the rivers where the algorithm was applied were perennial. In the case of the Mhlatuze catchment, the rainfall gauge 0303711W has a very different rainfall pattern to that of the other three, and its CPI duration curves (especially in the wet months of December, January and February) is steeper than the corresponding destination FDCs. This leads to the overestimation of generated destination "low flows" (Fig. 7.9). A similar problem, although to a lesser extent, occurs with some other rainfall stations in Mhlatuze catchment and also in the Sundays River catchment (Fig. 7.8). Since the weights of all rainfall stations in each individual catchment were equal, no attempt has been done to "filter out" the undesirable rainfall stations. Such rainfall stations with records having a sequential pattern different to that of the gauged streamflow at the catchment outlet are most likely to be located, for example, outside the catchment boundary, or almost on the boundary (like 0303711W).

The other problem which affects the quality of the simulations in some of the cases considered (e.g. the Mhlatuze catchment) is the length of flow record and quality of the streamflow data which were used to construct the destination site FDCs. The longer the record, the more reliable and representative is the constructed FDC. FDCs for particular months, as opposed to the annual curve, are especially sensitive to the length of record and to the amount of missing data. The shorter the record and the more data are missing, the fewer data are available for the construction of FDCs. The alternative in such circumstances would be to use 1-day annual FDC for all 12 months of the year instead of 12 different curves for each month. This approach has been used as an experiment in several catchments and has been found to have the effect of slight reduction on flow variability. The discussed problem of the record length is only relevant when the FDCs are established on the basis of observed data. Since the algorithm is intended for application at ungauged sites, the destination FDCs will have to be calculated either by regional methods or from synthetic monthly time series as described in one of the previous Chapters.

One typical characteristic of the output daily flow time series is the presence of minor flow fluctuations which result from the nature of the source CPI time series (Fig. 7.1). Daily CPI values reflect even minor increases in catchment wetness which are consequently transferred to the resultant flow. In dry months of the year, such fluctuations caused by some minor rainfall events break the smooth recession limbs in the generated time series. This may represent an issue in cases where the representation of true recession characteristics is required. Minor increases in CPI may be filtered out by introducing certain daily rainfall thresholds below which the daily rainfall will not be added to the CPI. Tests have shown that daily rainfall of 2 mm is a suitable threshold in this regard.

The weights of source rainfall stations in each catchment were initially taken to be equal Although this seems to be an arbitrary approach, the subsequent experiments with different weights in several catchments have shown that changing the weights normally does not have a profound effect on the resultant destination time series. Assuming equal weights may be just a pragmatic way of specifying them in the absence of observed streamflow data against which to evaluate the results of simulation. A more logical approach, however, would probably be to assign Thiessen polygon weights to source rainfall stations.

The number of source rainfall stations to use in the algorithm is unlikely to be a serious issue. For catchments with areas smaller or similar to those used in the current study (predominantly less than < 1000 km$^2$), the choice would normally be limited to 1 - 5. More stations are often simply not available. Others may be unusable because of the short or non-overlapping records, suspect values or missing data. The use of just one rainfall station is not recommended since all the deficiencies of its data (e.g. missing data) are effectively transferred to the generated destination site flow time series. On the other hand, one gauge may not always be representative of the spatial variability of catchment rainfall even in small catchments. Figure 7.11 presents the extracts from the CPI time series of the two available rainfall stations in the Mac-Mac River and illustrates that the catchment wetness calculated using solely one or the other rainfall station may be very different. Figure 7.11 also shows how these individual CPI time series (if used individually) are translated into the resultant destination daily hydrograph. The best coincidence between observed and simulated flow time series at gauge X3H003 was obtained when the two source rainfall stations were used in the algorithm together (Fig. 7.6).



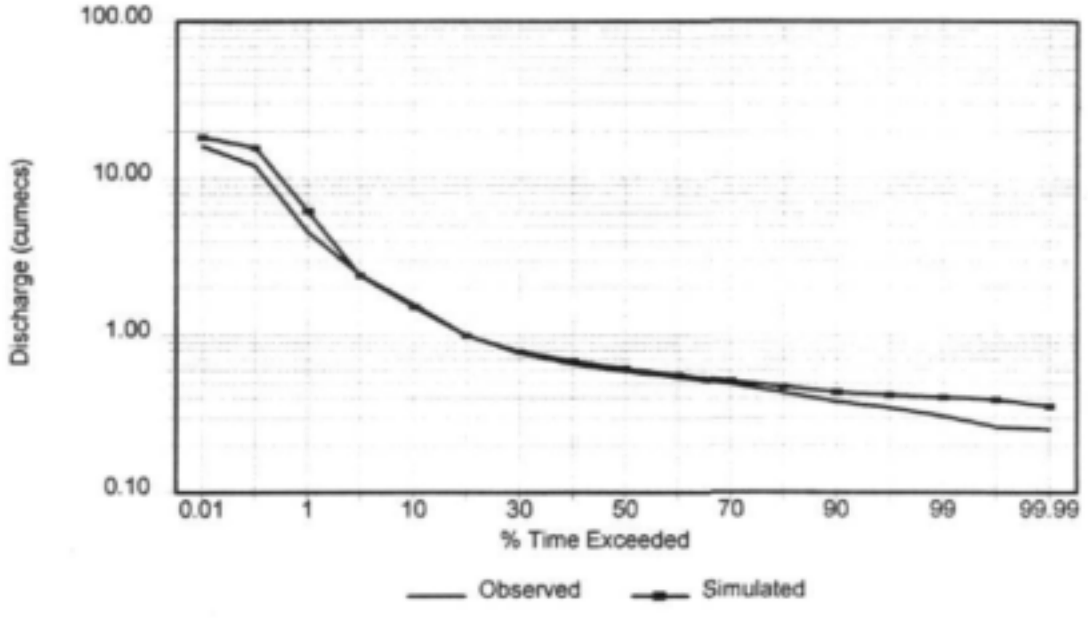
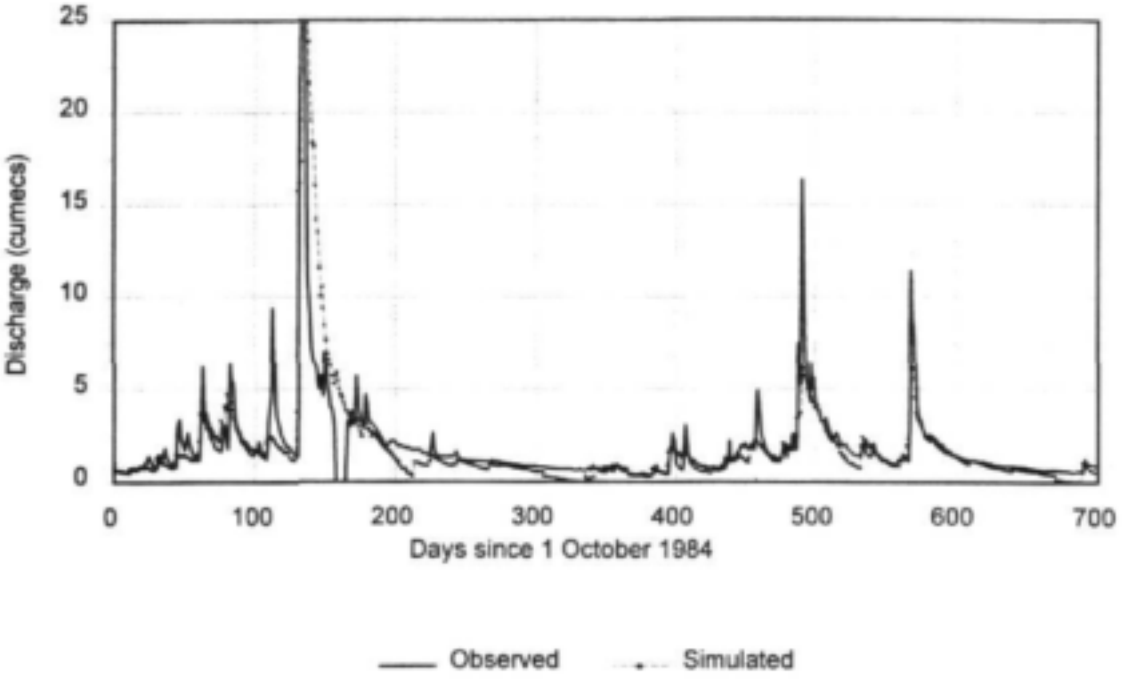


Figure 7.6 Observed and simulated daily hydrographs (top) and annual 1-day flow duration curves (bottom) for the Mac-Mac River at gauge X3H003



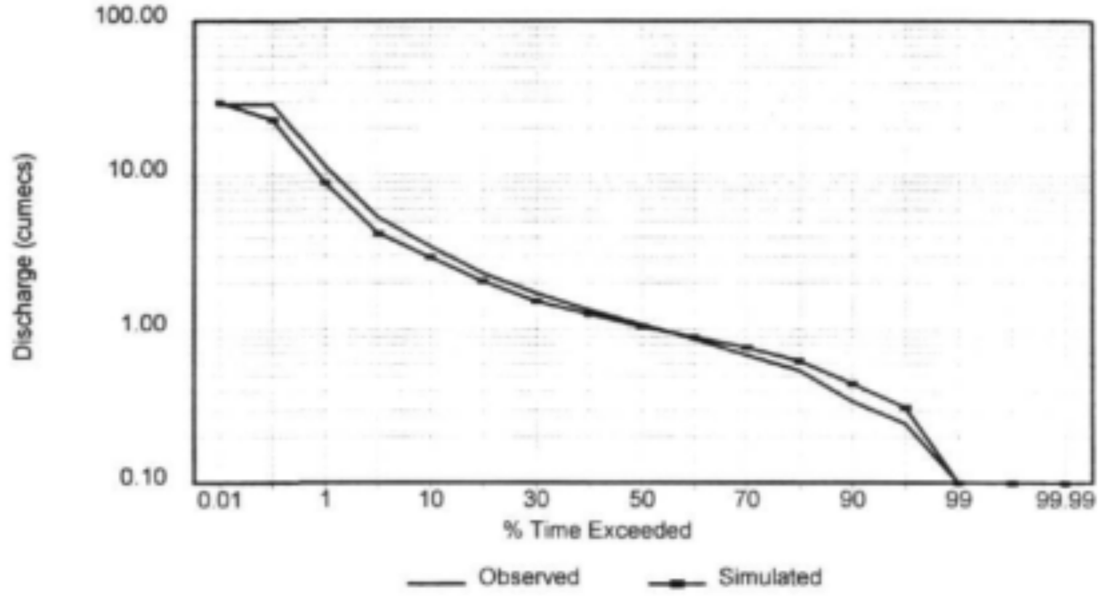
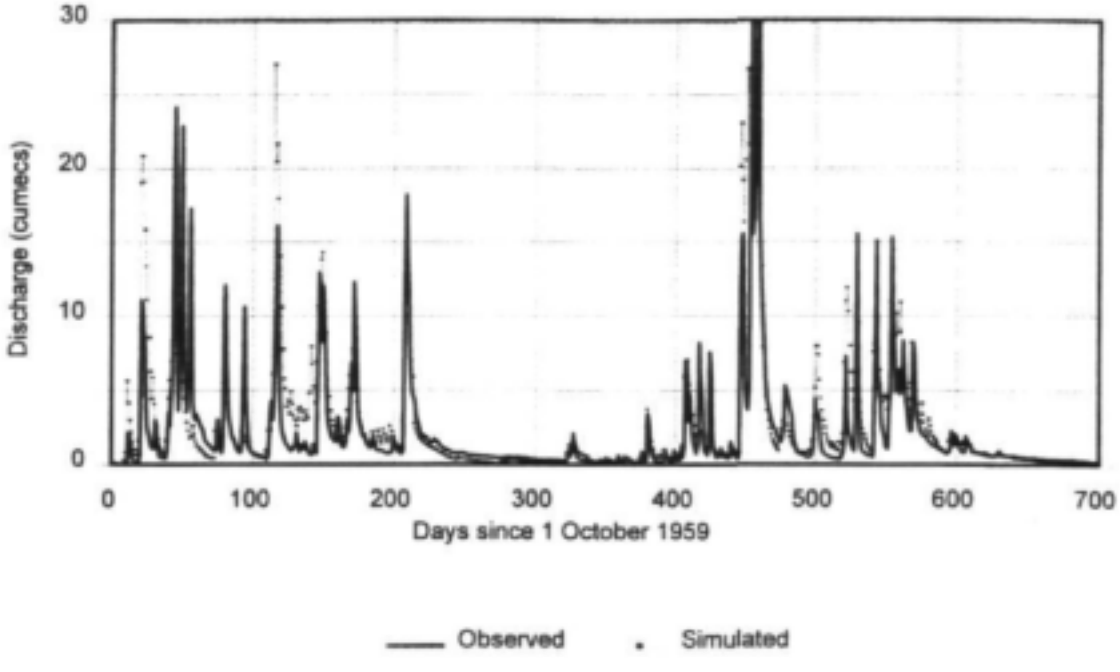


Figure 7.7 Observed and simulated daily hydrographs (top) and annual 1-day flow duration curves (bottom) for the Marite River at gauge X3H011



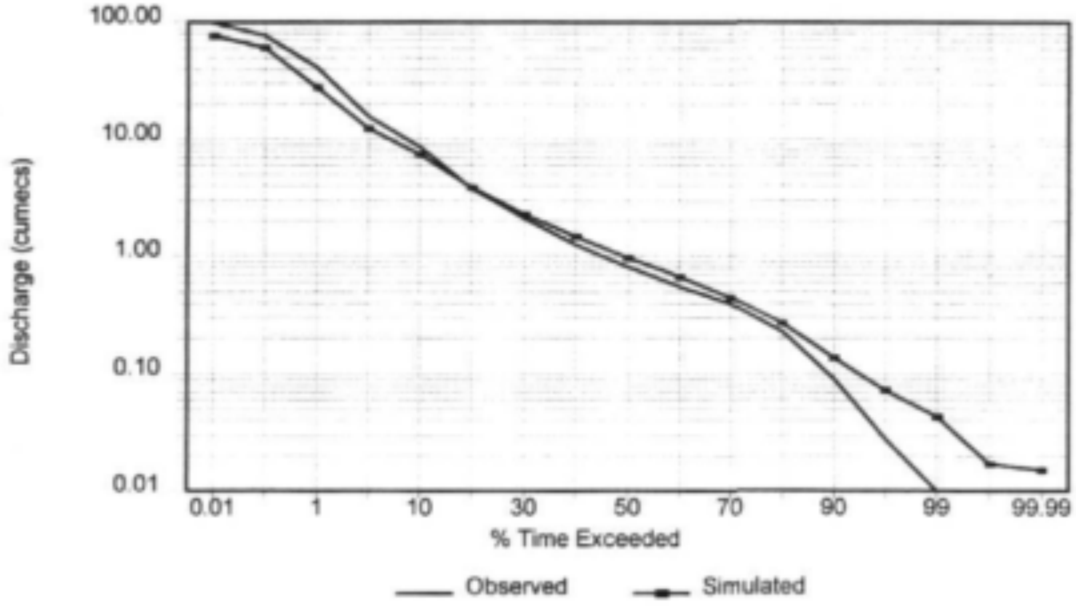


Figure 7.8 Observed and simulated daily hydrographs (top) and annual 1-day flow duration curves (bottom) for the Sundays River at gauge V6H004

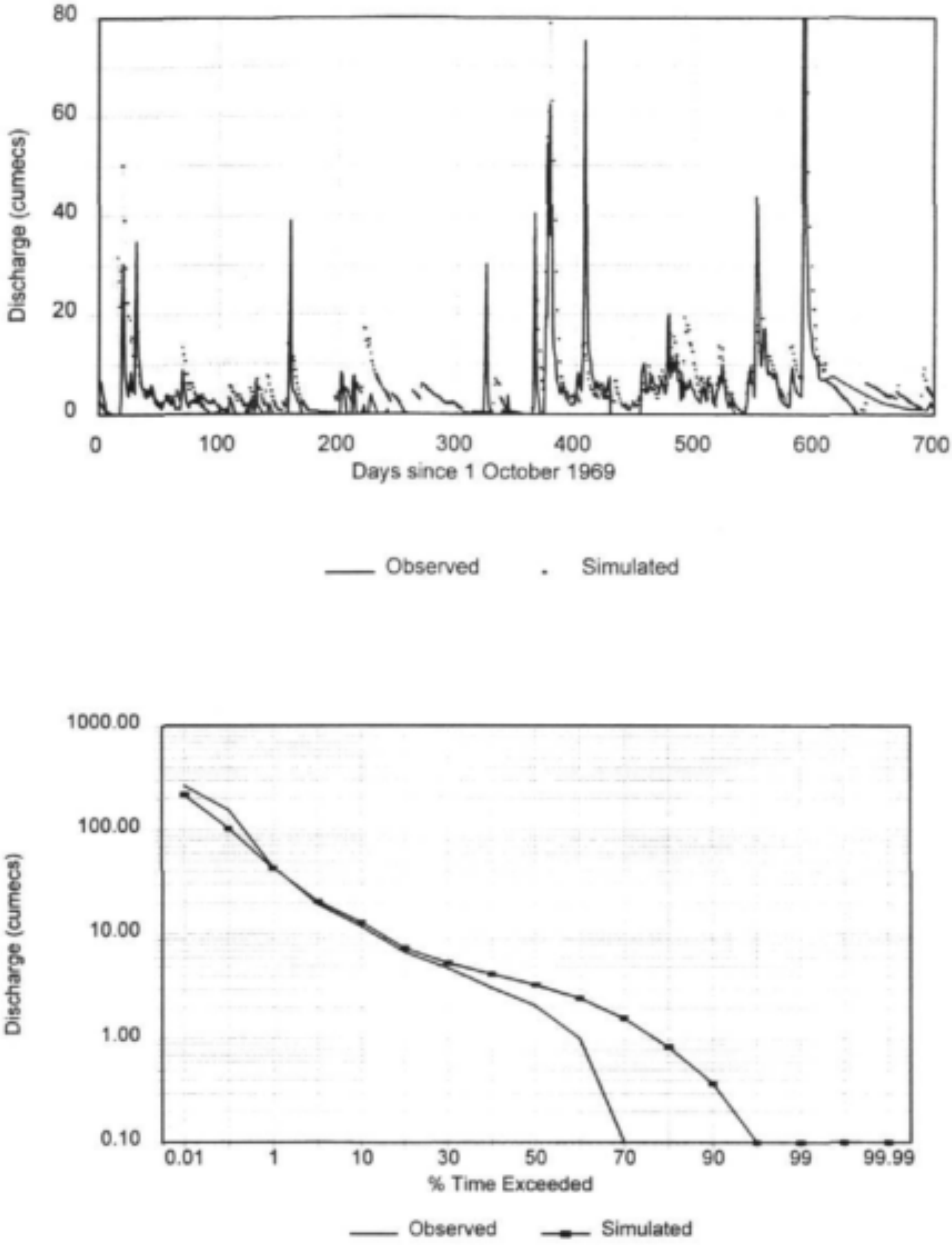
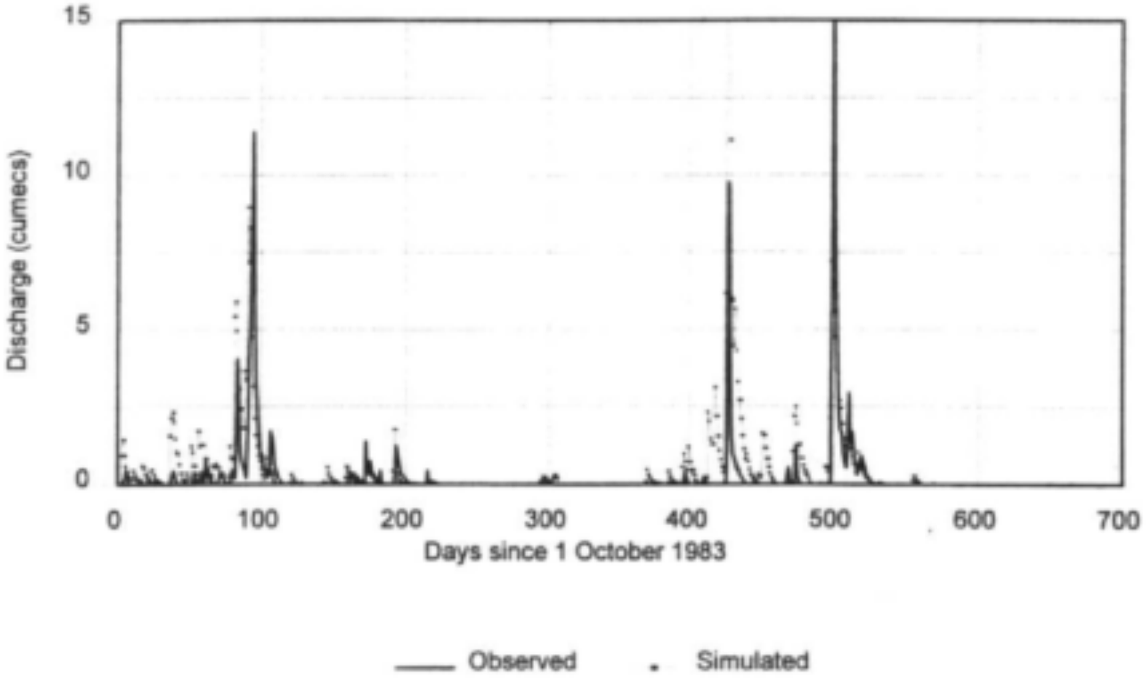


Figure 7.9 Observed and simulated daily hydrographs (top) and annual 1-day flow duration curves (bottom) for the Mhlatuze River at gauge W1H006



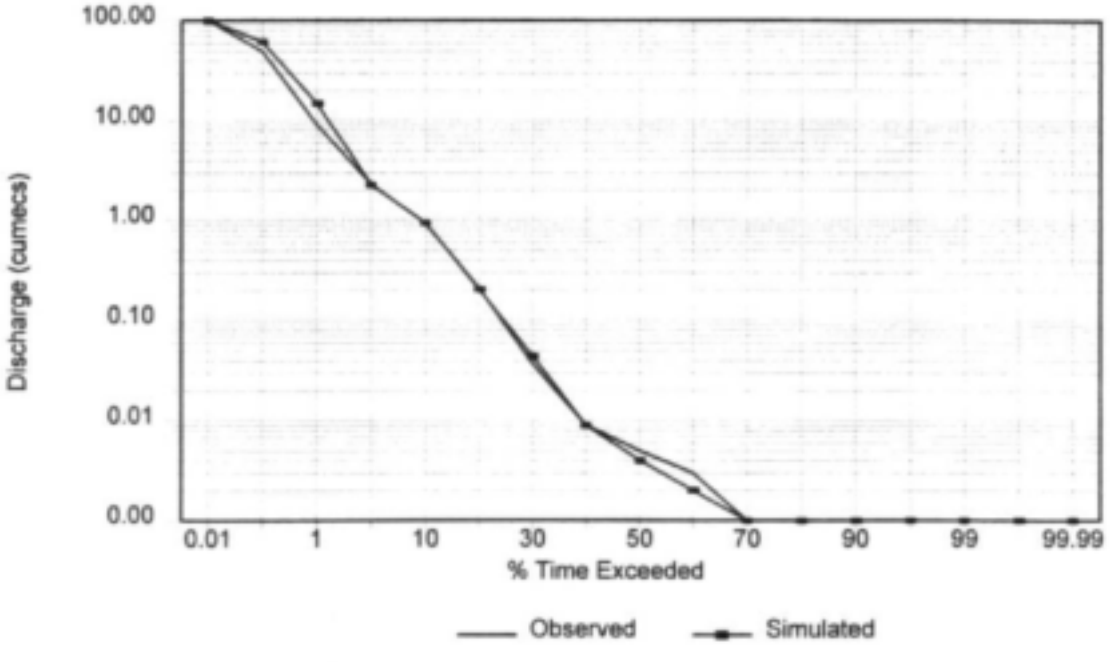


Figure 7.10 Observed and simulated daily hydrographs (top) and annual 1-day flow duration curves (bottom) for the Koonap River at gauge Q9H016

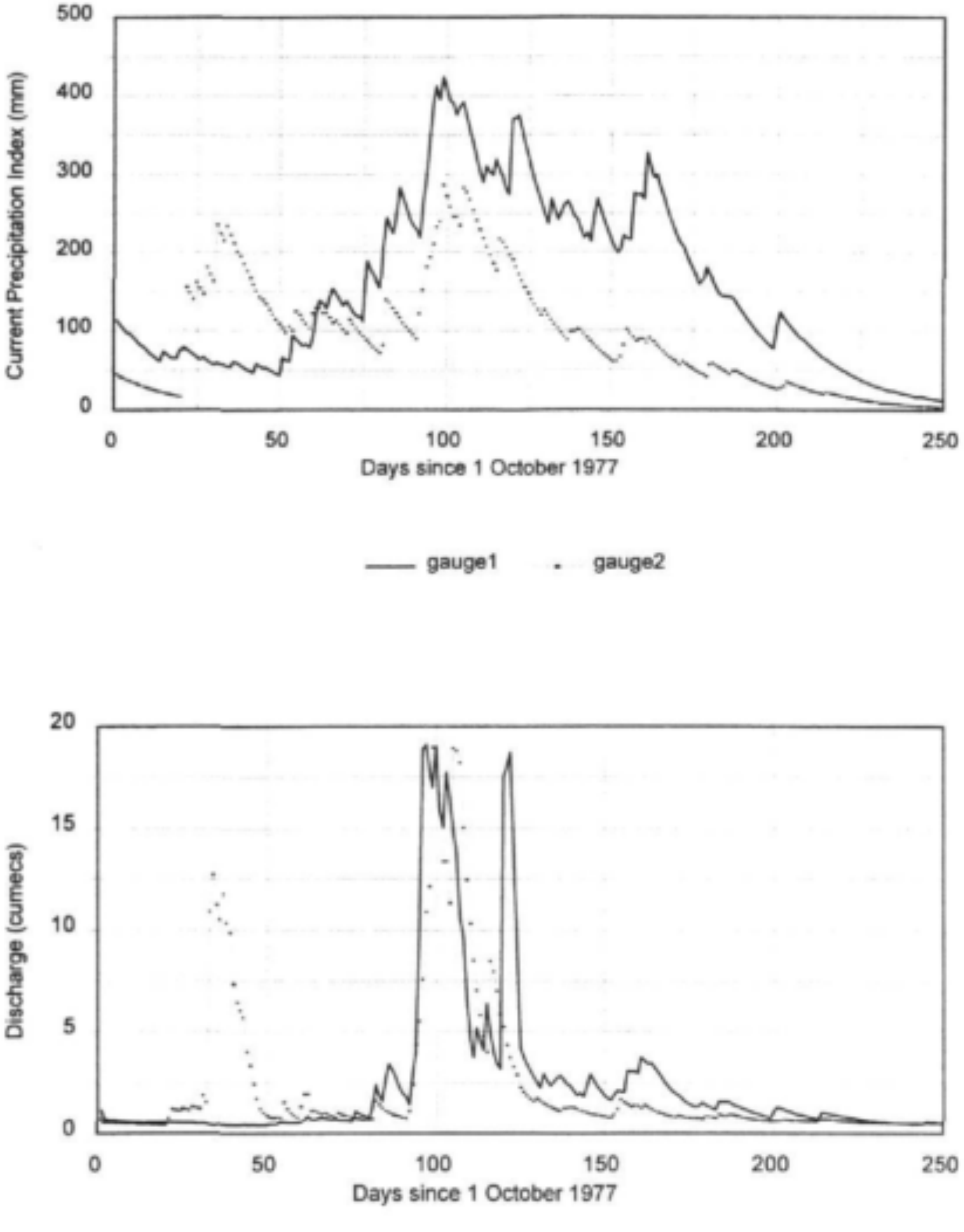


Figure 7.11. Extracts from the source CPI time series at two rainfall stations in the Mac-Mac River catchment (top) and corresponding daily hydrographs at gauge X3H003 generated using each station's data independently (bottom).

The discussion above suggests, amongst the others, that the suitability of the source rainfall data must be assessed using the criteria of record length, completeness, location with regard to being representative of catchment rainfall. It may also be suggested that Eq. 7.1 used to calculate CPI daily values from daily rainfall data may need some modifications related to the differences in catchment wetness dynamics at different levels of this wetness. It is possible, for example to introduce different K values in Eq. 7.1, which will be dependent on wetness thresholds. Such thresholds would effectively represent different catchment storages contributing to the output streamflow hydrograph. On the other hand, the advantage of the proposed approach is its simplicity and a limited number of "parameters". By introducing additional "parameters" into this "model", this advantage may be lost.

## 7.3 Continuous monthly hydrograph simulation using rainfall duration curves

The previous section dealt with continuous *daily* streaflow hydrograph simulation, using rainfall related index of catchment wetness (CPI). However, similar approach is also applicable for the simulation of continuous monthly flow records. In this case, the approach becomes even more straightforward. Calculating Current Precipitation Index (CPI) or any other continuous function of the catchment wetness is still possible on a monthly basis, but not necessary. Instead, monthly rainfall time series from the nearby rainfall gauges could be used directly to calculate duration curves of monthly rainfall. Monthly rainfall time series are derived from daily rainfall time series and consequently each month's value represents the cumulative rainfall during this month. If it rains at least for one day during a month, a monthly rainfall value will be non-zero. Consequently, there are much less zero rainfall values in a monthly rainfall time series. This implies that duration curve of monthly rainfall has a much more gradual slope than that of a daily rainfall. Such duration curve may therefore be used in the spatial interpolation algorithm directly and is to replace source CPI duration curve used in the daily version of the algorithm. The procedure for monthly streamflow data generation is virtually the same (Fig. 7.12), but the source site FDC is replaced by the rainfall duration curve constructed on the basis of monthly rainfall data.

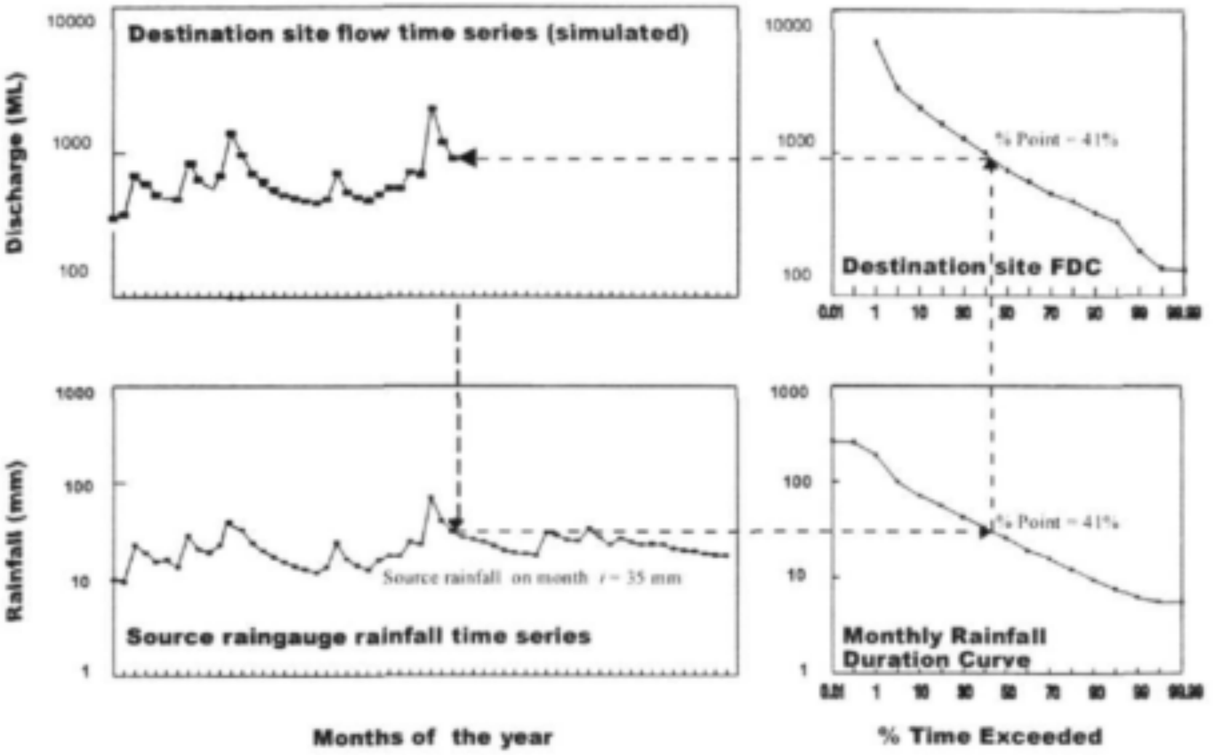


Figure 7.12 Illustration of monthly streamflow generation using the spatial interpolation algorithm with monthly rainfall duration curves

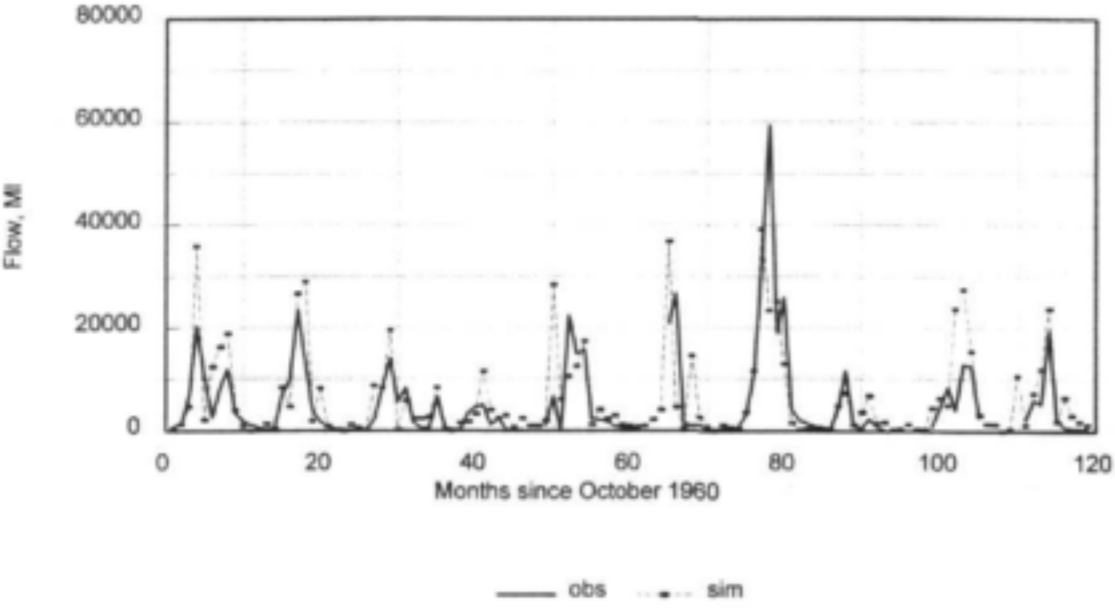


Figure 7.13 Observed and simulated (by rainfall-runoff conversion method) monthly hydrographs for Sundays River at gauge V6H004

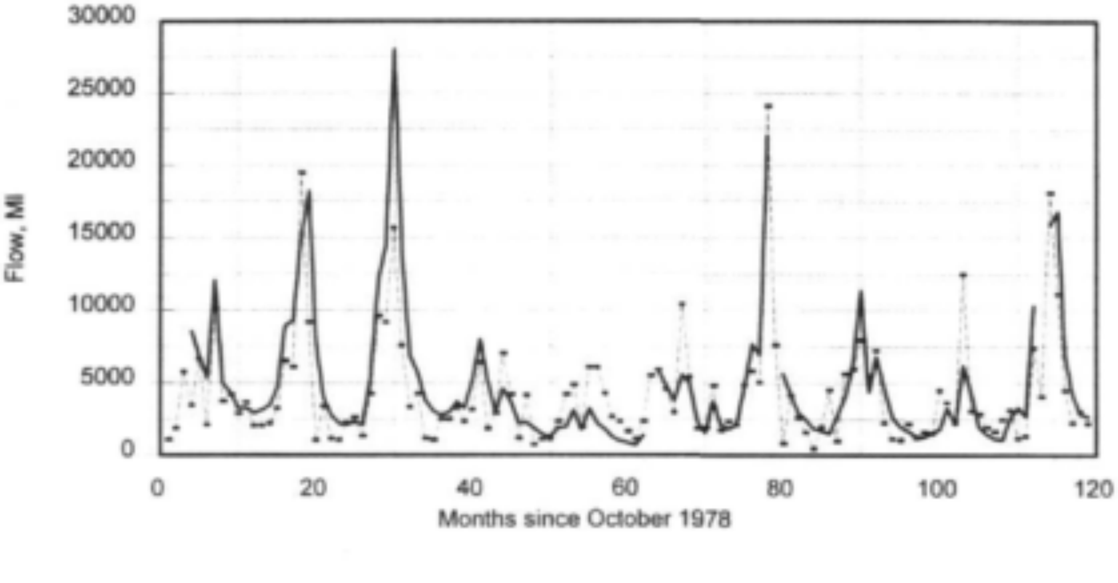


Figure 7.14 Observed and simulated (by rainfall-runoff conversion method) monthly hydrographs for Marite River at gauge X3H011

Figures 7.13 and 7.14 illustrate observed and simulated using the described rainfall-runoff conversion technique monthly hydrographs for two arbitrary selected catchments. The general pattern of monthly flow variability seems to be adequately reproduced by the method, although the variability of monthly flows in low-flow months is overestimated. This may be explained by the fact that the method in the suggested form doesn't take into account that catchment wetness in each month is also dependent on the rainfall in the previous month(s) and the monthly rainfall fluctuations are directly transferred to the resultant flow time series. The performance of the approach could possibly be improved if a smoothing procedure is applied to the source monthly rainfall time series. Alternatively, a concept of "monthly CPI" may be introduced. In this case, monthly CPI time series should be calculated for each source rain gauge similarly to daily CPI time series, but the recession coefficient will need a different interpretation.

Given the wide use of a monthly Pitman model in engineering practice in South Africa, it is unlikely that the method presented is competitive. At the same time, it could be used as a quick tool for monthly flow simulations in data poor countries outside South Africa (e.g. SADC countries) where the use of Pitman model is not an standard procedure.

The methods described in this Chapter are perceived as economical tools for generating continuous streamflow time series from observed rainfall records in a river catchment. They represent a major extension of the original non-linear spatial interpolation technique developed by Hughes and Smakhtin (1996). The methods are designed primarily for application at ungauged sites in data poor regions where the use of more complex and information consuming techniques of streamflow time series generation may not be justified.

Daily streamflow generation technique has been tested under stringent conditions, taking into account that no calibration would be possible in practical applications. The method has been found to perform satisfactory in these tests. Comparison of observed and generated hydrographs as well as FDCs and fit statistics have shown that the approach is capable of reproducing the general pattern of daily streamflow variability, although low flows and small events may be overestimated.

The performance of the method has been illustrated using the examples of predominantly small catchments (less than 1000 km$^2$). However, it is expected that the method, in principle, is applicable to large river catchments as well. In this case, the number of initially available rainfall stations with suitable data will be large and it may be appropriate to generate the weighted average catchment wetness first. Dependent on the type of data used, it could be daily or monthly weighted average wetness. It is also possible to split the large catchment into a set of "homogeneous" subareas and calculate weighted average wetness time series for each subarea. In this case the subareas will replace the source rainfall sites. On the other hand, the large catchments are more likely to have suitable streamflow source gauges which can be used for data transfer between the sites and the original version of the spatial interpolation algorithm (which uses streamflow data *only*) will apply.

# 8. ESTIMATION OF LOW-FLOW CHARACTERISTICS USING FLOW DURATION CURVES

Chapters 3 and 4 described how FDCs could be established for ungauged sites from either observed daily flow records in a specified region, or from simulated monthly flow time series. Once the curve is established, it becomes the only hydrological characteristic which describes the pattern of flow variability at a site. However there are many other flow characteristics (not directly obtainable from FDC) which need to be estimated at ungauged sites. The use of flow indices is a common approach in many water resources studies and particular attention is paid to various indices of low flow. This Chapter focuses on such low-flow characteristics and describes how they can be derived from a FDC.

Low flow in South Africa is normally perceived as a dynamic concept which is not easily tied to a single characteristic or estimation method. Some sources indicate that the wide variation in low-flow characteristics in the country makes the selection of a single, predefined design flow impractical (DWAF, 1995) implying that low-flow assessment may be done on a case- or site-specific basis. Overall, the choice of low-flow characteristic for a specific purpose is currently not restrictive and the suitability of existing and adopted elsewhere indices sometimes becomes a subject for separate studies.

Smakhtin and Watkins (1997) calculated the variety of low-flow characteristics from daily streamflow records at about 240 gauging stations in South Africa and constructed the maps of several low-flow characteristics to illustrate the general pattern of their spatial distribution in the country. The indices considered for this exercise represented different aspects of low-flow regime: flows of different time of exceedence, flows of different return periods, recession and baseflow characteristics, etc. The study has demonstrated that low-flow regimes exhibit a high degree of spatial variability and are very dependent on local physiographic factors. At the same time, many indices have demonstrate a similar spatial pattern, which implies that similar mechanisms have similar relative effects on a range of low-flow characteristics and suggested that strong correlation should exist between the indices describing different aspects of the low-flow regime. It also implies that it may be possible to establish some "primary" low-flow characteristic from which all (or most) other - "secondary" low-flow indices will be calculated.

In this study, all primary low-flow indices are estimated from the FDC. The study investigates the relationships between low-flow indices extracted from a 1-day annual FDC and several other types of low-flow characteristics representing different aspects of low-flow regime. All indices have been calculated using low-flow estimation software which forms part of the HYMAS package. The indices have been calculated for 240 gauging stations which time-series data represent stationary flow regimes. The stations used were located upstream of all major impoundments or abstractions and had a mean record period of 20 years. In some cases only part of the record period has been used (pre-impoundment period) to ensure that only non-regulated flow regimes are considered. The full range of calculated indices and tables containing calculated low-flow index values are presented in Smakhtin and Watkins (1997). The latter report also includes the detailed description of these indices and methods of their estimation. Only a brief summary of these indices is given in this Chapter.

The low-flow indices that could be extracted from a 1-day annual FDC are those which are exceeded more than 50% of the time. The following three indices have been initially considered:

- The flow exceeded 95% of the time (Q95). This index is used in some countries for licensing of surface water abstractions. It is also widely used for the assessment of effluent discharge limits to the receiving streams.

- The flow exceeded 75% of the time (Q75). In some southern African countries this is a primary design low-flow characteristic (Drayton, *et al*, 1980). It is also close to the concept of normal flow' used in SA Water Law. Smakhtin and Watkins (1997) have estimated Q75 and Q95 for a number of large South African catchments at the fine level of spatial resolution.

- The percentage of time with zero-flow conditions ($T_0$). Many rivers in South Africa have long zero-flow periods and this index, may be perceived as a measure of flow intermittency. $T_0$ may be read directly from the curve if it intersects the time axis (Chapter 4).

The emphasis has been placed on the first two indices. $T_0$ has been used mostly to select between perennial and non-perennial streams to specify subsets of data used in regression analysis. Dependent on the type of the secondary index being considered for relationship, Q95 and Q75 have been expressed either in $m^3/s$ or as a portion of long-term Average Daily Flow (ADF).

The following secondary low-flow indices have been considered:

- Flows estimated from the annual series of flow minima. They include the 7-day average flow with a return periods of 10 and 2 years ( 7Q10 and 7Q2) and the 7-day average Mean Annual Minimum (MAM7). The first two are used as designed low flows in the USA, while the latter is the alternative index used in the UK for abstraction licensing.

- BaseFlow Index (BFI). BFI represents the general baseflow response of a catchment, frequently used to study the effects of catchment geology on low flows, and is estimated as the volume of baseflow divided by the volume of total streamflow (the volume of baseflow may be calculated by digital filtering from continuous daily streamflow data)

- The median daily recession ratio (REC50). This characteristic represents the rate of baseflow recession and is estimated from the distribution of daily recession ratios (today's flow divided by yesterday's flow) calculated for all recession periods found in a record for each day when discharge is less than ADF. This index is similar to the one described in FREND (1989), may be considered as another way of studying the effects of catchment geology on low flows or serve as a criterion of rainfall-runoff daily model ability to simulate low flows (Smakhtin *et al*, 1997).

- Characteristics of continuous low-flow events (spells or runs). A low-flow spell is defined as an event when the flow is continuously below a certain specified threshold discharge. Each low-flow spell is characterised by the duration and the deficit which would be required to maintain the flow at a given threshold. Spell analysis normally deals with the annual time series of maximum durations/deficits, from which a number of spell indices may be extracted. The indices used in this study include the mean duration and deficit of spell maxima below 50% of ADF (SD50 and DEF50 correspondingly). SD50 has been expressed as the proportion of a number of days in a year (SD50/365), while DEF50 - as a % of the Mean Annual Runoff (MAR). The duration and deficit with return period of 10 years have also been initially considered, but it was found that their relationships with primary low-flow indices are very similar to those of SD50 and DEF50. Therefore these results are not specifically reported here.

The correlation graphs between indices extracted from the FDC and other low-flow characteristics are shown in Figures 8.1 – 8.4. The sample size used in all these cases was 208. The areas of the gauged catchments considered varied in the range from 2 to 10000 $km^2$, however, the majority of the catchments were in the range of 100-300 $km^2$. The location of streamflow gauges used in this study is shown on the map presented in Smakhtin and Watkins (1997) and also in Smakhtin et al (1995).

Figure 8.1 demonstrates a strong correlation between Q75 flow and all three low-flow characteristics estimated from the series of annual minima (MAM7, 7Q10 and 7Q2). Q75 is especially strongly correlated with MAM7 and 7Q2. Estimates for several perennial rivers have shown that MAM7, if placed on the 1-day long-term annual flow duration curve, is exceeded 80 to 91% of the time and 7Q2 - 83 to 93 % of the time. The values of MAM7 and 7Q2 for each particular stream are therefore normally close to each other. Both are also closer to Q75 then to Q95 and show slightly worse correlation with the latter (Figure 8.2).

On the other hand, 7Q10 is the index of more extreme low-flow conditions. On the flow duration curve it is normally exceeded 95-99.5% of the time (in the majority of cases tested - more than 99% of the time). It therefore exhibits better correlation with Q95 than with Q75 (Fig. 8.2). Consequently MAM7 and 7Q2 show better relationships with Q75, while 7Q10 is better predicted from Q95. This is illustrated in Table 1 which lists all the best established regression relationships of selected secondary low-flow indices with primary.

The correlation between baseflow and recession indices (BFI and REC50) and Q75 is illustrated by Figure 8.3 (the correlation graphs for Q95 are broadly similar). Unlike the "frequency" indices, these are not the actual flows and, although estimated from the streamflow time-series data, rather represent the generalised characteristics of the subsurface storage of a catchment. Consequently, their relationships with particular low-flow values are not that explicit. The characteristic feature of the correlation graphs is that a zero Q75 flow value corresponds to a variety of non-zero BFI and REC50.

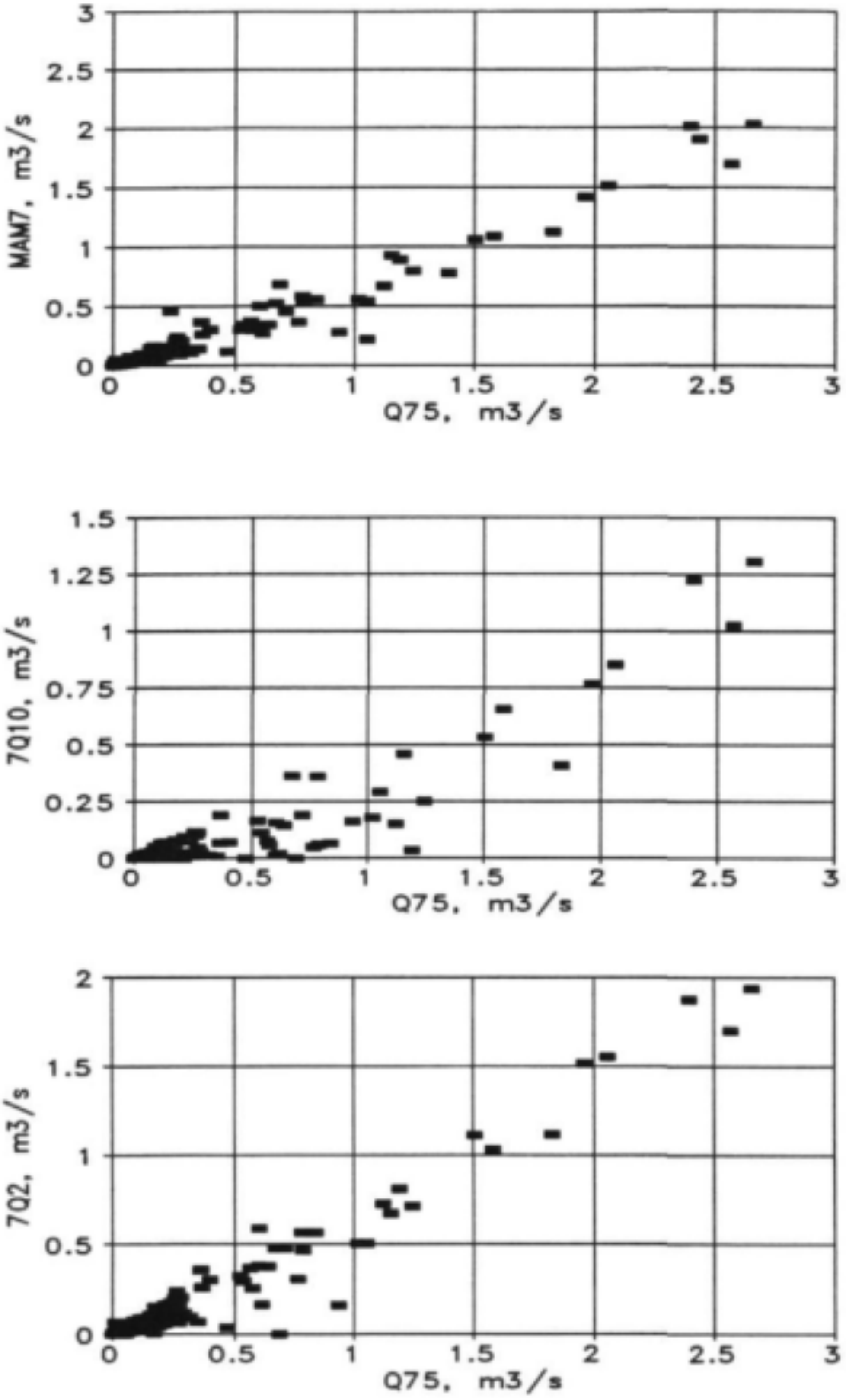


Figure 8.1 Scatter plots of the relationships between Q75 and low-flows of different frequency of occurrence.

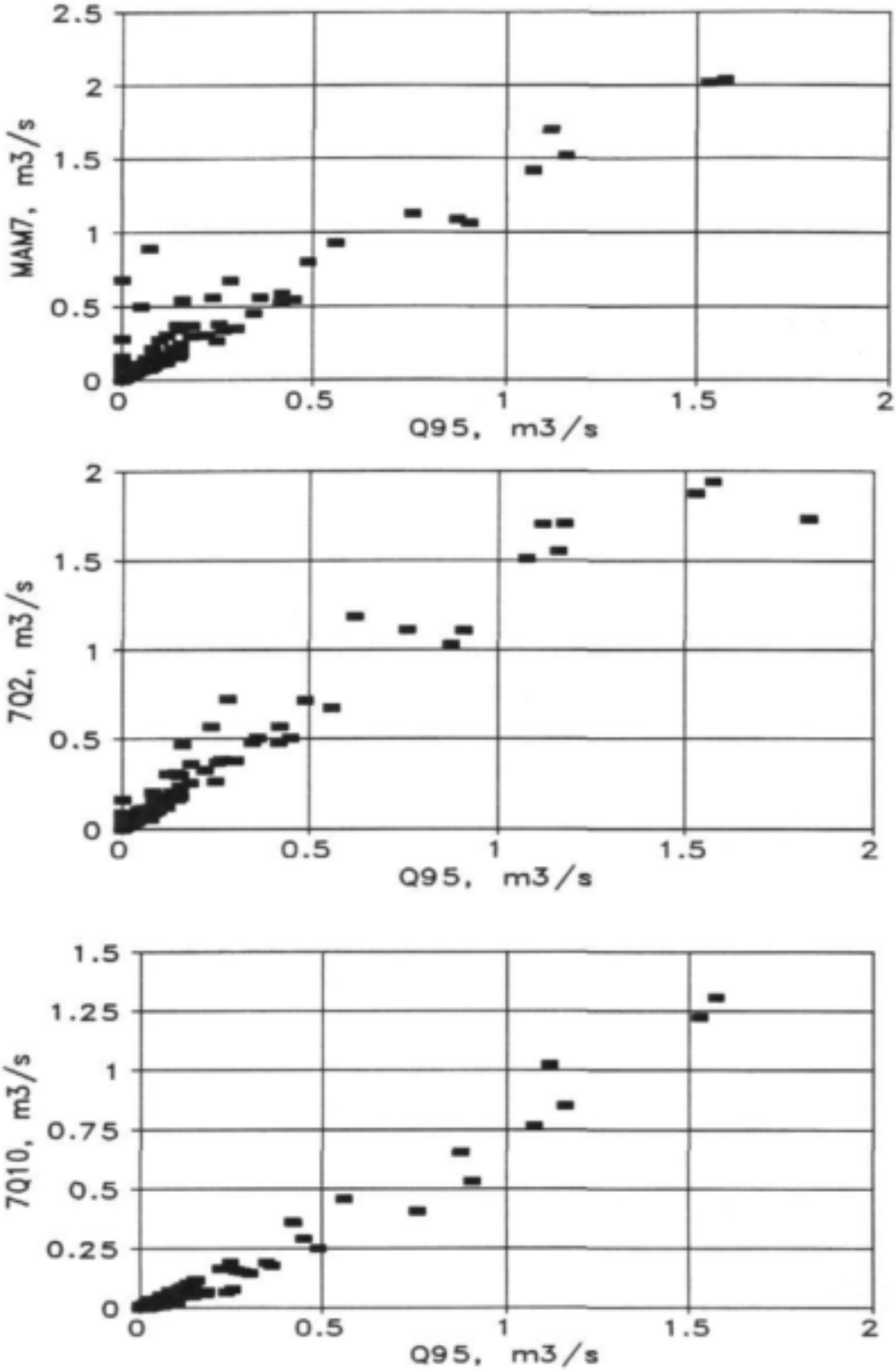


Figure 8.2 Scatter plots of the relationships between Q95 and low-flows of different frequency of occurrence

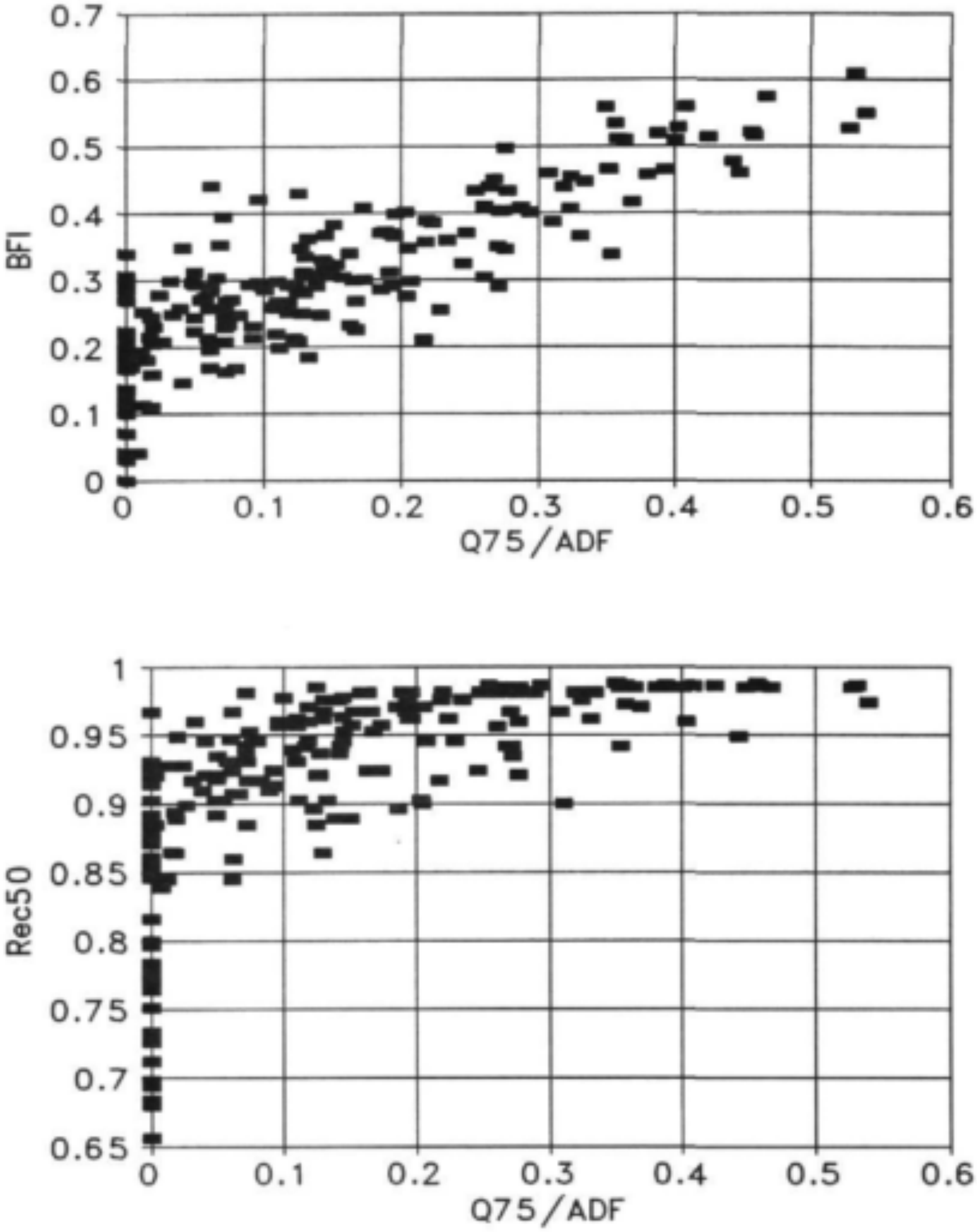


Figure 8.3 Scatter plots of the relationships between Q75, baseflow index (BFI) and median recession ratio (REC50)

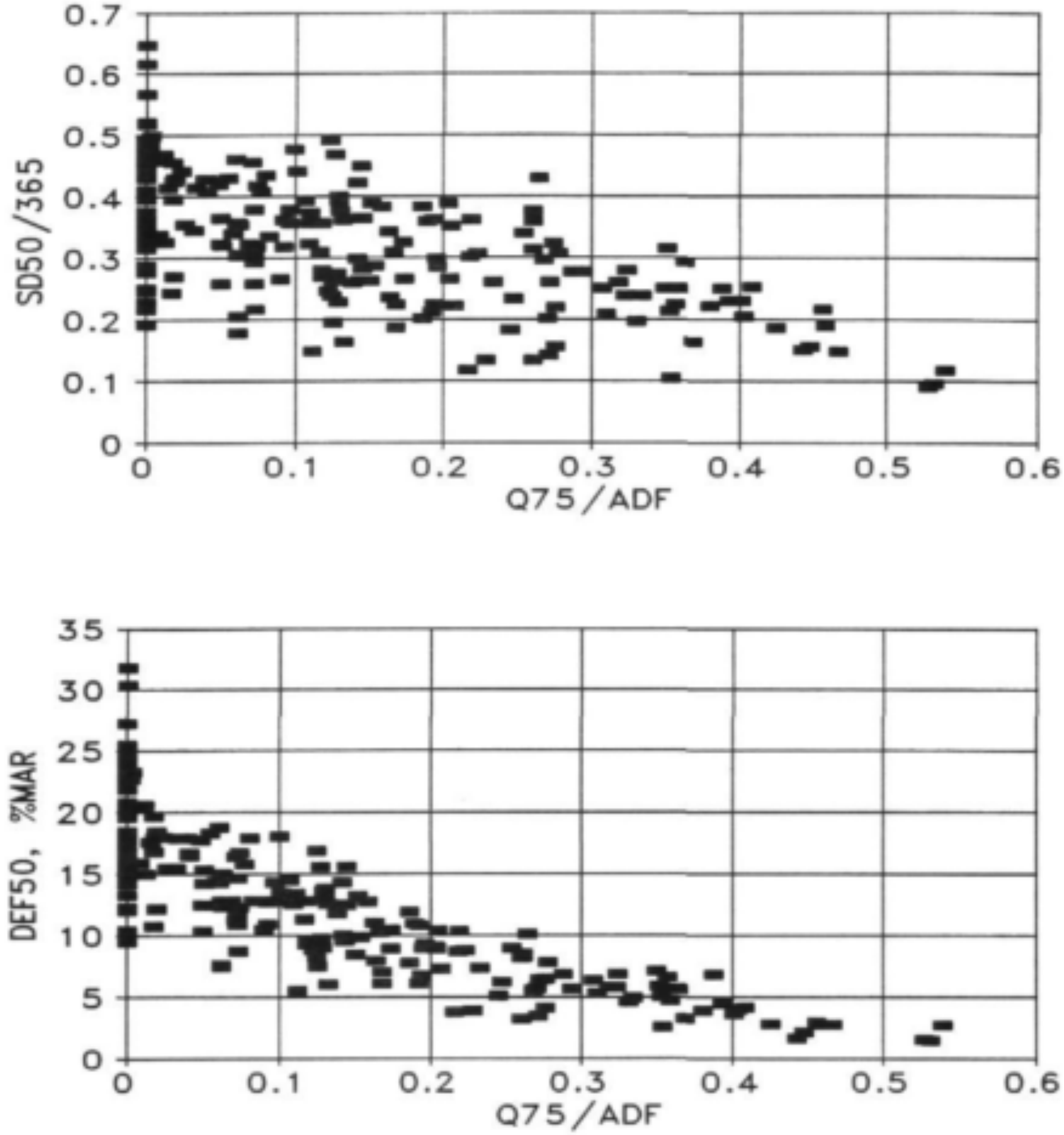


Figure 8.4 Scatter plots of the relationships between *Q75* and characteristics of continuous low-flow events below the threshold discharge of 50% ADF

Table 8.1 Relationships between low-flow indices

| Low-Flow Index | Regression model | $R^2$ | SE | Sample size |
|---|---|---|---|---|
| MAM7, $m^3/s$ | MAM7 = 0.691*Q75 | 0.966 | 0.061 | 208 |
| | MAM7 = 1.37*Q95 | 0.907 | 0.100 | 208 |
| 7Q2, $m^3/s$ | 7Q2 = 0.658*Q75 | 0.944 | 0.076 | 208 |
| | 7Q2 = 1.33*Q95 | 0.933 | 0.083 | 208 |
| 7Q10, $m^3/s$ | 7Q10=0.343*Q75 | 0.820 | 0.078 | 208 |
| | 7Q10=0.744*Q95 | 0.966 | 0.034 | 208 |
| BFI | BFI =0.229 + 0.62*(Q75/ADF) -0.002*$T_0$ | 0.777 | 0.068 | 208 |
| | BFI=0.279+ 0.856*(Q95/ADF) - 0.003*$T_0$ | 0.717 | 0.076 | 208 |
| | BFI = 0.20 + 0.712* (Q75/ADF) | 0.726 | 0.057 | 158 |
| REC50 | REC50 =0.957 - 0.0034*$T_0$ | 0.600 | 0.067 | 208 |
| SD50/365 | ln SD50 = -0.94 - 1.74*(Q75/ADF) | 0.431 | 0.271 | 208 |
| | ln SD50 = -1.04 -2.70*(Q95/ADF) | 0.334 | 0.293 | 208 |
| DEF50, %MAR | ln DEF50 = 2.88 -3.94*(Q75/ADF) | 0.786 | 0.278 | 208 |
| | ln DEF50 = 2.58 -5.8*(Q95/ADF) +0.005*$T_0$ | 0.720 | 0.317 | 208 |
| | ln DEF50 = 2.9 -4.0*(Q75/ADF) | 0.794 | 0.260 | 158 |

In the first case, this is partly related to the limitations of the digital filtering technique used to calculate BFI. Smakhtin, *et al* (1995) have found that digital filtering has a tendency to overestimate BFI especially for intermittent streams as it often creates excessive baseflow for isolated relatively short-term flood events. For the purpose of this study the intermittent streams may be defined as those having zero Q75 (and therefore, $T_0$ not less then 25%). However, this definition is rather arbitrary since baseflow overestimation by the filter may also occur (although to a lesser extent) in cases when $T_0$ is less than 25%. The coefficient of determination of the best regression relationships between BFI and solely either Q75 or Q95 does not exceed 0.65. In order to improve the regression relationship, all intermittent rivers may be excluded from the data set. In this case the sample size will be reduced to 158. Alternatively , $T_0$ may be included in regression model as a second independent variable. The results achieved using both options are only marginally different (Table 8.1). The relationships between BFI and Q75 are slightly better than that between BFI and Q95 possibly because Q75 (as well as BFI itself) is a better indicator of average baseflow response of a catchment than a more extreme Q95.

In the case of REC50, 60% of its variability is explained by $T_0$ along (Table 8.1), whereas the $R^2$ of the linear regression between REC50 and either Q75 or Q95 does not exceed 0.26. If all intermittent rivers (with $T_0$ more then 25%) are excluded from the data set, the $R^2$ of each REC50 individual relationship with primary low-flow indices are in the range of 0.32-0.42.

The major problem which may also partially explain the lack of correlation between REC50 and other indices, possibly relates to the method of estimation of REC50 itself. REC50 should represent the rate of baseflow recession. In the current procedure, the recession ratios are estimated for each (even isolated) recession day and for all days when discharge is less then ADF. For many streams, the minor flow fluctuations which occur on top of the main recession limb, and are formed by surface or quick subsurface flow, may effect the results of the estimation process and cause the underestimation of the final REC50 value. It may, therefore, be necessary to recalculate REC50 for every stream using only continuous recession limbs (e.g. longer then 8-10 days). This may result in REC50 values, which are more representative of actual baseflow recession in each stream. Also the analysis should only be done for streams with well defined recession properties and therefore only completely perennial streams should be included.

It should also be taken into account that the nature of relationship between flow recession and any particular low-flow index is much more complex than between actual low flow discharges of different magnitude. It is therefore possible that for establishing a better regression model, other primary indices will have more value. For example the Q90/Q50 ratio, which characterise the slope of the entire lower portion of the flow duration curve may have a more pronounced effect than any single flow index.

The correlation graphs of spell characteristics SD50 and DEF50 with Q75 are shown on Figure 8.4. The correlation of 10-year return period spell duration and deficit below 50% of ADF are broadly similar and so is the correlation of all spell characteristics with Q95. The best relationships achieved are listed in Table 8.1, which illustrates that spell duration can hardly be predicted from considered primary low-flow indices with reasonable accuracy. This is due to the fact that a low-flow spells may be interrupted by minor increases in flow (dry season freshes) and therefore is more dependent on variability of daily flows rather then on a single low-flow characteristic. This relationship should probably be investigated in more detail using seasonal flow duration curves and/or using characteristics of daily flow variability.

The satisfactory relationships have been established for spell deficits (Table 8.1). This may be due to the fact that low-flow discharges determine the magnitude of flow deviation from the specified threshold value during a dry spell. Also, the threshold flow itself is related to the primary indices used. Similarly good results have been obtained for spell deficit with a 10-year return period ($R^2$ are just above 0.72). Only marginal improvement has been achieved when the exercise was repeated for reduced set of perennial rivers (Table 8.1).

All results illustrated above have been obtained at the scale of the entire country. The data set used included streams with different types of low-flow regime. Better regression models may be established at the scale of smaller geographical regions where the physiographic conditions vary less significantly and which are consequently more hydrologically homogeneous.

Table 8.2. Relationships between low-flow indices in X drainage region

| Low-Flow Index | Regression model | $R^2$ | SE |
|---|---|---|---|
| MAM7, $m^3/s$ | $MAM7 = 0.647*Q75$ | 0.996 | 0.089 |
| 7Q2, $m^3/s$ | $7Q2 = 0.727*Q75$ | 0.997 | 0.081 |
| 7Q10, $m^3/s$ | $7Q10^{0.5} = 0.033 + 0.343*Q95^{0.5}$ | 0.868 | 0.120 |
| BFI | $BFI = 0.272 + 0.583*(Q75/ADF) - 0.003*T_0$ | 0.836 | 0.033 |
| REC50 | $REC50^{0.5} = 0.962 - 0.0016*T_0 + 0.07*(Q75/ADF)$ | 0.728 | 0.016 |
| SD50/365 | $SD50 = 0.437 - 0.56*(Q75/ADF) - 0.005*T_0$ | 0.725 | 0.039 |
| DEF50, %MAR | $DEF50 = 14.6 - 25.6*(Q75/ADF)$ | 0.890 | 1.05 |

Table 8.3. Relationships between low-flow indices in S and T drainage regions

| Low-Flow Index | Regression model | $R^2$ | SE |
|---|---|---|---|
| MAM7, $m^3/s$ | $MAM7 = 0.037 + 1.28*Q95$ | 0.985 | 0.066 |
| 7Q2, $m^3/s$ | $7Q2 = 1.329*Q95$ | 0.987 | 0.061 |
| 7Q10, $m^3/s$ | $7Q10 = 0.706*Q95$ | 0.983 | 0.039 |
| BFI | $BFI = 0.169 + 0.875*(Q75/ADF) - 0.003*T_0$ | 0.927 | 0.045 |
| REC50 | $REC50 = 0.957 - 0.005*T_0 + 0.08*(Q75/ADF)$ | 0.958 | 0.020 |
| SD50/365 | $SD50^{-1} = 0.007 + 0.0028*(Q95/ADF)$ | 0.600 | 0.001 |
| DEF50, %MAR | $\ln DEF50 = 2.72 - 5.73*(Q95/ADF) + 0.002*T_0$ | 0.901 | 0.140 |

Tables 8.2 and 8.3 list some of the regression models which have been established in the X drainage region (the Mpumalanga Province; sample size 23) and drainage regions S and T together (the Eastern Cape Province; sample size 15). Compared to the results obtained using the data set for the entire country, the improvement has been achieved in prediction of BFI, REC50, and spell characteristics. This is mostly explained by the fact that the majority of rivers in these regions are perennial and have well defined recession characteristics. Consequently, the values of secondary indices are more representative and less error prone.

Most of the relationships presented in Tables 8.1, 8.2, and 8.3 may be recommended for quick conversion of one type of low-flow characteristics into others. The conversion approach may be particular relevant for ungauged sites where a FDC (as a "source" of primary low-flow indices) may be established by techniques described in Chapters 3 and 4.

# 9. CONCLUSIONS AND RECOMMENDATIONS

*Achievement of the project objective*

The main aim of developing pragmatic methods of daily streamflow estimation has been maintained throughout the course of the Project. The Project appeared to be a unique research work in terms of producing the techniques which require limited amount of input information and are quick to apply, but at the same time are still capable of providing the daily streamflow information which is much needed for a variety of water research and water engineering applications. The suggested economic methods of hydrological data provision are specifically designed for conditions of limited information environment, like Southern Africa, and have a good potential for successful application in other similar data poor regions.

The two, perhaps, major achievements of the this Project include:

- The technique for estimating 1-day FDCs from widely available monthly streamflow data. This allows a quick estimation of 1-day FDCs at any location in Southern Africa, where monthly streamflow data are either of observed or simulated origin.

- The technique for daily streamflow time series generation using daily rainfall time series in cases when no reliable adjacent streamflow records is available.

The combined use of these two methods represents a powerful tool for daily streamflow data provision without application of more complex, information and time consuming deterministic daily rainfall-runoff modeling techniques. However, the suggested methods should not be viewed as a preferred option for hydrological streamflow data provision in all possible cases, nor were they designed with such an intention. These methods should rather be seen as a an addition to the tool box of hydrological engineering, which expand the choice of suitable techniques for time series generation and analysis. These methods are also not cast in concrete and have a potential for future development and detalisation. Some of the recommendations for future research are summarized below.

*Further developments of pragmatic modeling methods*

The suggested techniques by definition remain dependent on the quality of the input data. One aspect of these data is the length of the available record. While monthly flow records are available, or may be generated using Pitman monthly model for a standard record period of 1920-1990, the techniques for daily flow generation could so far produce the time series which is determined by the length of the input data record. In many cases, what is required in water resources assessment is the daily and monthly records which have the same length, the same start and end date and are compatible with each other in origin (one is derived from another). The methods which would generate a daily flow record compatible with simulated monthly may be designed using some form of disaggregation procedure which is applied to simulated monthly flow time series. This could be achieved either by some stochastic procedure (e.g. wavelets disaggregation), or through the combined analysis of limited (short record) observed data and simulated monthly time series data. The successful outcome of such studies could provide water resource engineers with compatible long-term daily flow record. This aspect of daily streamflow time series generation is recommended for the future research.

The techniques suggested in this Report effectively provide the possibility for calculating 1-day FDCs for each quaternary catchment in the country (or the combinations of quaternary catchments). One ambitious, but logical recommendation in this regard could be to extend the application of these techniques in order to generate natural long-term daily flow records for each quaternary catchment. It could be done either through the disaggregation of monthly flow records into daily (as suggested in the previous paragraph), or through consistent simulation of daily flow time series, using rainfall-to-runoff conversion techniques described in Chapter 7, for example. In either case, the product of such research is envisaged to be a GIS-based system which links spatial coverages of rivers and quaternary catchments in South Africa with the DWAF observed streamflow data base, national rainfall data base and WR90 synthetic monthly flow data base. The system should also include the described procedure for 1-day FDC estimation from monthly data and the spatial interpolation algorithm. This could provide a user with the possibility to select the site(s) of interest, identify nearest flow and rainfall stations, generate 1-day FDCs, set up and run the spatial interpolation algorithm with the simulated daily flow record as an output.

One aspect of pragmatic modeling approach, which relates to the adjustment of FDCs for catchment and water resources development, needs further insight. The possible approaches, which are suitable in this regard, have been identified. But they need to be accommodated in the framework of the pragmatic modeling concept and tested with real data. It is recommended that this research is to be continued.

*Implications for SADC Surface Water Resources Assessment.*

The WRC has recently sponsored a project to draft the terms of reference for a large-scale, SADC-wide Surface Water Resources Survey (similar to WR90 in South Africa, but of a broader scope). The methods suggested in this Report, may be accommodated in this surface water resources survey and bring a new insight into the whole issue of water resources assessment and analysis in Southern Africa. It is recommended that the methods described in this Report are considered in this regard and is envisaged that they will form an integral part of the planned surface water resources survey since they are specifically designed for the application in data poor regions, like Southern Africa.

*Application of Flow Duration Curves for quantification of other water resources characteristics.*

The methods discussed in this Report focus entirely on the estimation of either FDCs or corresponding streamflow time series. However, some of these methods may be slightly modified to be applicable for estimation/generation of other water resources related characteristics. A "water index" duration curve may be defined as the relationship between frequency of occurrence and magnitude of this index. In other words, such duration curve would illustrate (similarly to FDC) the percentage of time that a given water index value is equaled or exceeded during a specified period of time. (The term "water index" is used here as a general substitute for a variety of water resource characteristics, such as river stage, sediment load, habitat suitability, hydropower energy output, various water quality characteristics etc.) The general scheme for the construction of such duration curves of various "water indices" includes the establishment of a rating curve which describes the relationship between streamflow and water index. This rating curve is then combined with a FDC to produce the resultant water index duration curve. Such an approach is feasible for any water index which can be uniquely related to streamflow. Procedures for developing rating curves which describe the relationship between river stage and discharge are well documented, but other rating curves which describe the relationships between streamflow and, for example sediment load or habitat suitability, are not well defined. At the same time, establishing rating curves and subsequent derivation of corresponding duration curves may be very useful for water quality management, environmental management, hydropower and other water resources applications.

A FDC and related water index duration curves may have potential applications in producing inundation maps, evaluating tradeoffs among water quality management variable to best meet the site specific water quality standards, in waste load allocation, in optimal water resource allocation, in assessing damage caused by floods or benefits of flood control, etc. Such tools are not currently available in South Africa, but once developed, may appear to become invaluable in water resource management practices. Investigation of various applications of FDCs and water index duration curves for water resources management in South Africa is therefore strongly recommended as one of the future research directions.

### *Application of pragmatic modeling principles in estuarine research and management.*

The concept of pragmatic hydrological time series modeling has so far focused entirely on rivers. However its application may be extended to study the functioning of other water bodies, e.g. estuaries. The single most important factor which determines the structure and functioning of the resident biotic community and which for this reason is in the focus of the estuarine research, is the condition and behavior of an estuary mouth. Most estuaries along the South African coast may be classified as temporarily closed systems (estuarine mouth is either closed or open). The lengths of the closed and open phases are driven primarily by the interaction of river runoff, evaporation, seepage, and wave overwash events in the mouth region, of which river runoff (inflow to the estuary) is the most important factor. The majority of SA estuaries are also small systems with very limited data of any kind, but very often - with high conservation value. Such estuaries are managed on an ad-hoc basis without proper understanding of the system functioning.

Continuous observations on mouth conditions (open/closed) of different estuaries (for about 80 small estuaries, with daily or weekly time resolution) have been collected from different sources. These data are unique and have never been analysed in the context of developing predictive tools for estuarine management. Daily streamflow data for most of these estuaries are not available but could be generated using low-cost time series generation methods presented in this Report. It would then be possible to establish relationships between available observed records of estuary mouth conditions and characteristics of the generated streamflow time series. Such relationships may then be used to generate continuous time series of mouth conditions. Consequently it would be possible to predict the probability, frequency and duration of estuarine conditions (e.g. mouth opening/closure) in natural conditions and under different scenarios of upstream catchment development. By generalizing the relationships developed for individual estuaries it would be possible to design relationships applicable within certain groups of estuaries. The existing classifications of estuaries may be considered in this regard, but it is more likely that a more detailed /alternative grouping will be required to enhance the performance of predictive relationships. Group models are expected to be applicable for unexplored estuaries. The group models may also be tested on independent data set to ensure that they are capable of reproducing the estuarine regime in those estuaries where no/limited data are available.

Similar approach may be used to generate time series of other estuarine variables (e.g. salinity, sediments etc). The application of a time-series philosophy in the estuarine research would also lead to products which are directly relevant in the context of the Ecological Reserve for estuaries, which relies, amongst the others, on the proper quantification of the sensitivity of the estuary mouth. In general, such approaches will significantly expand the national information database for estuarine research and management. It is therefore recommended that a separate project is set up to specifically address these issues.

*Estimation of streamflow characteristics in small catchments (subquaternary scales).*

One aspect of hydrological analysis which is currently not properly addressed in South African engineering practice, relates to the development of techniques for streamflow estimation in catchments smaller then quaternary (subquaternary scale). For small catchments ( e.g. less than 100 km$^2$ ) neither monthly nor daily streamfow data are normally available in South Africa. The current practice often implies a straightforward weighting of quaternary flow characteristics and/or monthly time series by the ratio of the catchment areas of the subquaternary site and quaternary catchment. One of the critical aspects of this approach is that streamflows at even closely adjacent sites are rarely linearly related to catchment area. The unit mean runoff from various smaller parts within a larger catchment may be either higher or lower than that from the entire catchment ( e.g. due to large spatial gradients in rainfall). The variability of daily flows in a smaller catchment may be higher than that in a larger. Small streams, if not fed by permanent springs, may experience long zero-flow periods while the larger streams are more likely to have a permanent hydraulic connection with the main growndwater body. In general, the flow regime of a small stream is normally very dependent on small-scale variability of physiographic and meteorologic factors and simple fractioning of larger quaternary flows may lead to gross over- or underestimation of streamflow characteristics at subquaternary scales.

Scale problems in hydrology are predominantly investigated with regard to parameters of different mathematical models and not flow characteristics themselves. In South African context, it would be logical to make use of quaternary monthly flow data and to develop a technique by which daily flow characteristics can be estimated at subquaternary scales. Alternatively, it is also feasible to investigate the relationships between observed flow characteristics at subquaternary scales and corresponding physiographic parameters. However, the preliminary investigation has shown that observed “subquaternary” flow data which could be made available for such studies, is very limited and are of poor quality. These data may be represented at the best by the observed daily streamflow records from approximately 80 small gauged catchments with areas ranging from 3 to 220 km$^2$ drawn from different parts of the country.

The first attempts to identify relationships between subquaternary and quaternary flow characteristics directly remained largely inconclusive, which illustrates the profound effects of local physiographic anomalies and orographic gradients on streamflow generation in small catchments. For all gauged subquaternary catchments the areal weighted values of MAP and altitude as well as corresponding spatial MAP maxima have been estimated from the national 1' X 1' grid GIS coverages. The subsequent regression analysis has illustrated that a flow characteristic in a subquaternary catchment is related to the corresponding quaternary characteristic and ratios between subquaternary and quaternary MAPs, altitudes and catchment areas. However, these relationships were not significant. A brief combined analysis of FDCs at quaternary and subquaternary scales in a limited number of quaternary catchments has also shown no consistent relationship between the curves. This implies that attempts to develop reliable predictive tools for subquaternary flow estimation based solely on available flow data are unlikely to result in reliable products and a different approach needs to be sought. The scale dependency of flow characteristics generally represents a complex problem. It is recommended that this problem is investigated in more detail, possibly he combination of specialist workshops and subsequent research project.

## 10. REFERENCES

Chiew, F. & McMahon, T. (1994) Application of the daily rainfall-runoff model MODHYDROLOG to 28 Australian catchments. *J. Hydrol*. **153**: 383- 416

Dingman, S.L. (1978) Synthesis of flow-duration curves for unregulated streams in New Hampshire. *Water Resour. Bull*., **14(6)**: 1481- 1502.

Drayton, R.S, Kidd, C. H. R, Mandeville, A.N & Miller, J.B (1980) A regional analysis of floods and low flows in Malawi. *Institute of Hydrology, Rep. No 72*, Wallingford, UK, 79 pp

DWAF: Department of Water Affairs and Forestry (1995) Procedures to Assess Effluent Discharge Impacts.

Fedora, M.A. & Beschta, R.L. (1989) Storm runoff simulation using an antecedent precipitation index (API) model. *J. Hydrol.* **112**: 121-133.

Fennessey, N. & Vogel, R.M. (1990) Regional flow-duration curves for ungauged sites in Massachusetts. *J. Water Res. Plng. Mgmt*. **116**: 530-549.

FREND (1989): Flow Regimes From Experimental And Network Data. I: Hydrological Studies; II: Hydrological Data. Institute of Hydrology. Wallingford, UK, 345 pp.

Gustard, A., Bullock, A. & Dixon J.M. (1992) Low flow estimation in the United Kingdom. *Institute of Hydrology Rep*. **N 108:** 88 pp

Hughes, D.A., Murdoch, K.A. & Sami, K. (1994) A Hydrological Model Application System - a tool for integrated river basin management. In : Kirkby, C. and White, W.R. (Eds) *Integrated River Basin Development*, John Wiley & Sons, Chichester, UK, 397-406

Hughes, D.A. & Sami, K. (1994) A semi-distributed, variable time interval model of catchment hydrology - structure and parameter estimation procedures. *J.Hydrol.*. **155**: 265-291.

Hughes, D.A. & Smakhtin, V.Y. (1996) Daily flow time series patching or extension: a spatial interpolation approach based on flow duration curves. *Hydrol. Sci. J*. **41**: 851 - 871.

Hughes, D.A. (1997) Southern African "FRIEND" - The application of rainfall-runoff models in the SADC Region. *Water Research Commission Report* **No 235/1/97.** Pretoria, South Africa. 69 pp.

Institute of Hydrology (1980). Low Flow Studies (1 - 4) , Wallingford, UK.

Kelman, J. (1980) A stochastic model for daily streamflow. *J.Hydrol.* **47**: 235 -249.

Klaasen, B. & Pilgrim, D.H. (1975) Hydrograph recession constants for New South Wales streams. *Inst. Eng. Civ. Eng. Trans.*, **CE17**: 43-49.

Lall, U. & Olds, J. (1987) A parameter estimation model for ungauged streamflows. *J. Hydrol.* **92**: 245-262.

Lane, E.W. & Lei, K. (1949) Stream flow variability. *Proc. ASCE.*, **75**: 935-994.

LeBoutillier, D.W. & Waylen, P.R.(1993) Stochastic model of flow duration curves. *Water Resour. Res.* **29(10)**: 3535-3541.

Linsley, R.K., Kohler, M.A. & Paulhus, J.L.H. (1975). *Hydrology for Engineers*. McGraw-Hill.2-d edition. 482 pp.

Middelkoop, H. (1998) Statistical downscaling of discharge series from the Rhine basin for peak flow analysis under changed climate conditions. *Proc. Int. Conf. "Hydrology in Changing Environment", Exeter, UK.* **Vol 1**: 175 -190.

Midgley, D.C., Pitman W.V. & Middleton B.J. (1983) Addendum to Surface Water Resources of South Africa. Johannesburg , South Africa

Midgley, D.C., Pitman, W.V. & Middleton, B.J. (1994) Surface Water Resources of South Africa 1990. *Water Research Commission Report* **No 298/5.1/94**, Pretoria, South Africa.

Mimikou, M. & Kaemaki, S. (1985) Regionalization of flow duration characteristics. *J. Hydrol.*, **82**: 77-91.

Mngolo, R.J. (1997) Flow duration characteristics of Southern African rivers. *Acta Hydrotechnica 15/18 - Proc. of oral presentations: FRIEND=97. Ljubljana, Slovenia*: 49-63

Mohseni, O. & Stefan, H.G. (1998) A monthly streamflow model. *Water Resour. Res.* **34**: 1287-1298.

Nathan R.J. & McMahon T.A. (1992) Estimating low flow characteristics in ungauged catchments. *Water Resour. Manage.*, **6** 85-100.

Ni-Lar-Win & Vandewiele G.L. (1994) Conceptual daily rainfall runoff models using correlation analysis. *FRIEND: Flow Regimes from International Experimental and Network Data (Proc. Braunschweig Conference, Oct. 1993) IAHS Publ.* **No 221**: 343 - 348.

Pitman, W.V. (1993) Simulation of run-of-river schemes using monthly data. *Proc. Of the 6-th South African Nat. Hydrol. Symp.* Vol.1 445-452

Quimpo, R.G., Alejandrino, A.A. & McNally, T.A. (1983) Regionalised flow duration curves for Philippines. *J. Water Res. Plng. Mgmt., ASCE*, **109**: 320-330.

Schultz C.B., Middleton, B.J. & Pitman, W.V. (1995) Estimating daily flow information from monthly flow data. *Proc. 7th SA Natl. Hydrol. Symp.*, Grahamstown, South Africa, 4-6 September 1995

Schulze, R.E. (1995) Hydrology and Agrohydrology: A text to accompany the ACRU 3.00 agrohydrological modelling system. *Water Research Commission Report* **N TT69/95**, Pretoria, South Africa

Scott, D.F. & Smith, R.E (1997). Preliminary empirical models to predict reductions in annual and low flows resulting from afforestation. *Water SA*, **23**: 135-140.

Scott, D.F., Le Maitre, D.C. & Fairbanks, D.H.K. (1998) Forestry and streamflow reductions in South Africa: a reference system for assessing extent and distribution. *Water SA* **24**: 187-199.

Singh, K.P. (1971) Model flow duration and streamflow variability. *Water Resour. Res.*, **7(4)**: 1031-1036.

Sittner, W.T., Schauss, C.E. & Monro, J.C. (1969) Continuous hydrograph synthesis with an API-type hydrologic model. *Water Resour. Res.*, **5**: 1007 - 1022.

Smakhtin, V.Y. (1999) Generation of natural daily flow time-series in regulated rivers using a non-linear spatial interpolation technique. *Regulated Rivers: Research and Management.* **15**: 311-323

Smakhtin V.Y. & Hughes D.A. (1995) A pragmatic approach to patching or extending daily streamflow records - examples and potential value. *Proc. 7th SA Natl. Hydrol. Symp.* Grahamstown, South Africa, 4-6 September 1995

Smakhtin, V.Y., Hughes, D.A. & Creuse-Naudin, E. (1997) Regionalization of daily flow characteristics in part of the Eastern Cape, South Africa. *Hydrol. Sci. J.* **42**: 919 - 936.

Smakhtin, V.Y. & Watkins, D.A. (1997) Low Flow Estimation in South Africa. *Water Research Commission Report* **No 494/1/97**, Pretoria, South Africa.

Smakhtin, V.Y., Watkins, D.A. & Hughes, D.A. (1995) Preliminary analysis of low-flow characteristics of South African rivers. *Water SA*, **21**(3*)*: 201-210.

Smakhtin V.Y. & Masse B. (2000) Continuous daily hydrograph simulation using duration curves of precipitation index. *Hydrol. Processes* (in press).

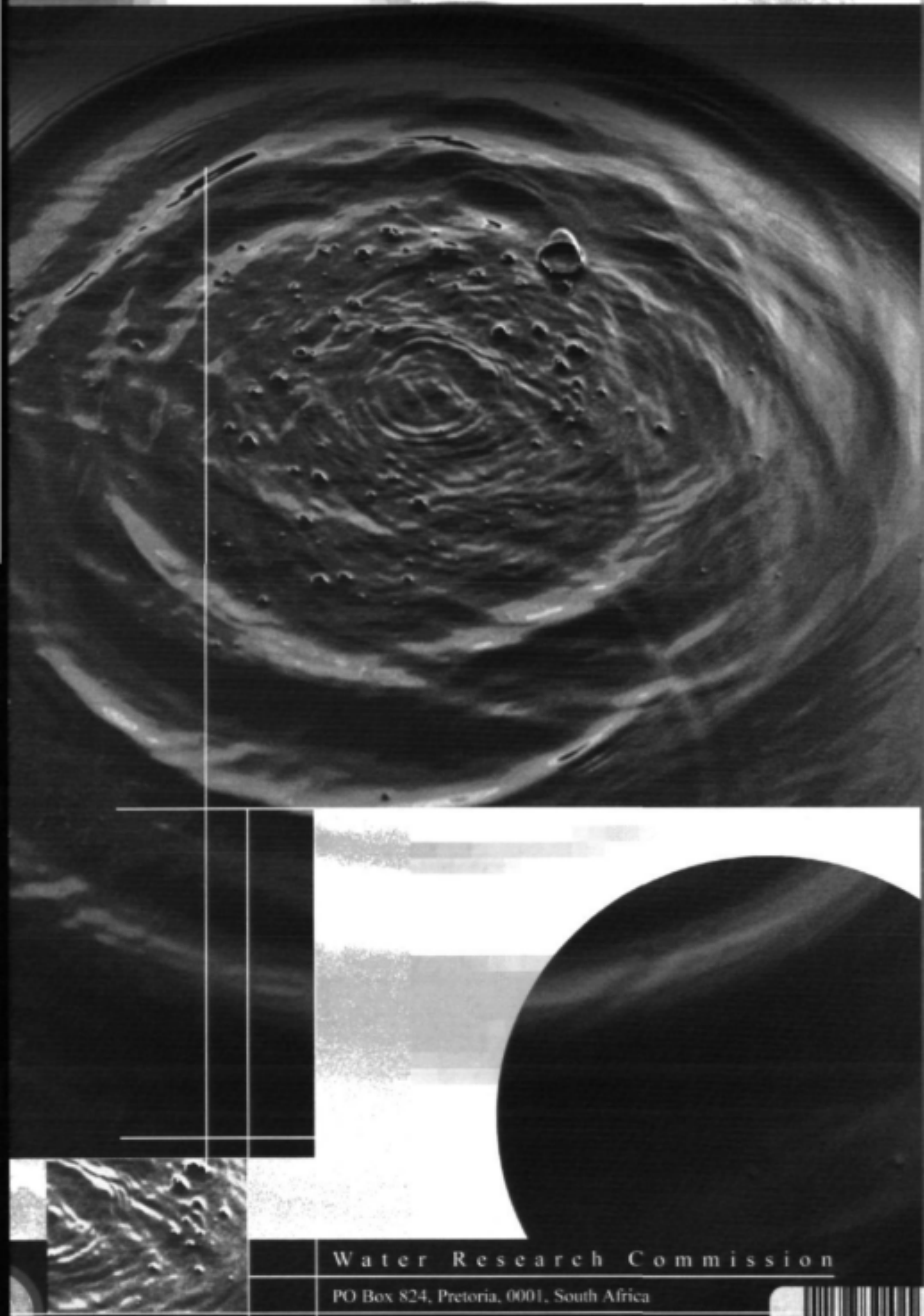
Torfs, P.J.J.F. (1998) Statistical disaggregation of hydrological time series using wavelets. *Proc. Int. Conf "Hydrology in Changing Environment", Exeter, UK.* **Vol 1**: 81 -89.

Vandewiele, G.L. & Atlabachew, E. (1995) Monthly water balance of ungauged catchments obtained by geographical regionalisation. *J.Hydrol.* **170**: 277-291.

Vogel R.M. & Fennessey N.M. (1994) Flow duration curves. I: A new interpretation and confidence intervals. *J. Water Resour. Plan. Manage*. **120**(4): 485 -504.

Vogel, R.M. & Fennessey, N.M. (1995) Flow duration curves II: A review of applications in water resources planning. *Water Res. Bull.*, **31**(6): 1029 - 1039

Wilcock, D.N. & Hanna, J.E. (1987) Derivation of Flow Duration Curves in Northern Ireland. *Proc. of Inst. Civil Engineers*. **83(2)**: 381-396



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