Low Flow Estimation in South Africa

VY Smakhtin • DA Watkins

Report to the Water Research Commission
by the
Institute for Water Research
Rhodes University

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LOW FLOW ESTIMATION IN SOUTH AFRICA

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"Classification and Hydrological Modelling of Low Flows in Southern Africa"

by the

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EXECUTIVE SUMMARY

1. INTRODUCTION

South Africa faces a number of problems related to the efficient utilisation of the country's scarce water resources. These problems exacerbate during the dry season of a year and drought periods. Rural water supply schemes fail, river ecosystems endure a severe stress, water pollution becomes critical and extremely difficult to manage etc. It is thus becoming increasingly important to improve the understanding of stream and catchment behaviour during periods of limited flow in both natural conditions and under various anthropogenic impacts, to investigate the applicability of existing low-flow estimation methods to South African conditions, to improve the availability of low-flow data and to link low-flow hydrology to the requirements of other aquatic sciences and water resources management.

In 1991 the Water Research Commission entered into an agreement with the Institute for Water Research (IWR) of Rhodes University to start a project on low-flow research at the beginning of 1993. The primary idea of this initiative was to advance the general level of low-flow hydrology in South Africa addressing the problem of low-flows on a national scale and on the scale of large river catchments.

2. PROJECT OBJECTIVES

The major project objectives stated in the original research proposal to the Water Research Commission and latter modified by the first Steering Committee meeting on the Project are summarised as follows.

- To examine the criteria currently used by the different hydrological and aquatic sciences to characterise low-flow regimes, and on this basis, to develop a methodology for the estimation and multipurpose analysis of low-flows in South Africa from available streamflow data;

- To construct a data base for the information on river low-flow regimes within southern Africa;

- To evaluate and possibly adapt a currently available daily rainfall-runoff model to specifically simulate low-flow conditions;

- To characterise and to determine changes in the low-flow regimes of selected major rivers within southern Africa.

It was envisaged that the Project would concentrate primarily on the use of available daily flow data to characterise low-flow regimes but the relationships with monthly flow data, commonly used in South Africa, would also be investigated. The project would also address the problem of low-flow estimation at ungauged sites and contribute to the general availability of daily flow data in the country.

3. LOW-FLOW HYDROLOGY AND DIFFERENT USER REQUIREMENTS

The study into low-flow problems in South Africa should begin with a clarification of the research subject, that is: what low-flow hydrology really is. The problem that existed from the very beginning (and that became quite clear at the national Low Flow Workshop held in Pretoria in February, 1993) is that the terms 'low flows' and 'low-flow hydrology' could mean different things to different interest groups. To many it may be considered as the flows occurring during the dry season, to others the length of time and the conditions occurring between events in erratic and intermittent semi-arid flow regimes. Yet others may be concerned with the effects of changes in the total flow regime of a river on sustainable water yield or riverine and riparian ecology. The latter may perceive 'low flows' as not only the flows occurring during a dry season, but as a reduction in various aspects of the overall flow regime. A recent tendency is to encourage specialists dealing with low-flow problems to communicate using common terminology. In the present report 'low flow' is defined in terms of the World Meteorological Organization as the "flow of water in a stream during prolonged dry weather" and only the portion of the hydrograph below the mean flow is considered. The problem of low flows is addressed in terms of various low-flow characteristics (measures and indices).

To attract the attention of a broad South African scientific community to the complex and diverse problem of low flows, the following initial steps were undertaken:

- A report on the present worldwide knowledge of low-flow estimation and analysis has been compiled. It included an examination of the various low-flow measures and indices currently and potentially used in hydrology, aquatic sciences, engineering practice and water resources management. This review was distributed among interested specialists so that they could assess the value of the various low-flow characteristics to their individual needs. The review was expanded at a latter stage and is included in the final report.

- A survey was conducted to define the community of current users of low-flow (and low-flow related) information in southern Africa, to clarify the requirements of these users and the need for improvements in data acquisition and other activities associated with low-flow problems. The survey has highlighted several issues regarding the possible directions of low-flow studies in South Africa. The results of the survey are summarised in the final report.

The report also includes a brief review of the physical low-flow generating processes and the direct and indirect anthropogenic impacts on low-flow regimes.

4. THE SOFTWARE FOR LOW-FLOW ESTIMATION.

The literature review and survey results outlined the methods which are in demand or of potential importance to most of the users of low-flow information. These methods have been computerised resulting in a flexible multipurpose computer software for analysing low-flow data and estimating low-flow characteristics. This software has been developed within the framework of a general IWR system - HYMAS (HYdrological Modelling Application Software). The procedures included in the system were designed to be applicable to a range of data sets with different origins (observed or simulated), size and time resolution (daily, monthly). The software for low-flow estimation provided the analytical base for further low-flow studies.

The package includes the following methods: i) flow duration curve construction along with the interactive facility to extract the required low-flow indices; ii) analysis of frequency, magnitude and duration of continuous low-flow events (low-flow spells or runs); iii) baseflow separation procedures; iv) calculation of recession properties of a stream; v) low flow frequency analysis.

A number of supporting routines for general flow time-series analysis have also been added to the HYMAS package. These include analysis of dry and wet annual flow periods, seasonal distribution of flow, residual flow diagrams illustrating changing flow conditions throughout the catchment and some others. The low-flow estimation software has been extended on a permanent basis throughout the course of the Project in terms of the variety of methods and improved in terms of the available on-screen options and graphical presentation.

5. LARGE SCALE ANALYSIS OF LOW-FLOW CHARACTERISTICS.

The software has been applied to daily data sets from approximately 240 streamflow gauging stations from different parts of the country to estimate various low-flow characteristics. These characteristics reflect different aspects of unregulated stationary low-flow regimes in South Africa (frequency, magnitude, duration, etc.) and form the core of the data base on recorded daily low-flow regimes.

Several different types of low-flow indices have been used to illustrate and examine the spatial variability of low-flow regimes throughout the country. A set of maps for several selected low-flow indices has been constructed. The preliminary analysis of low-flow characteristics demonstrated that many low-flow indices exhibit a similar spatial pattern and that for many practical purposes low-flow estimation based on one 'basic index' may suffice (since most of the low-flow indices are generally interrelated). It has also been shown that low-flows are extremely spatially variable. This implies that low-flow characteristics are very dependent on local physiographic factors and the problem of low flows in a South African context, should be addressed at a finer spatial resolution, such as the scale of a large catchment or a physiographically homogeneous region. It also implies that more flow data sets are required for low-flow characterisation to cater for the high level of spatial variability of low-flow regimes and therefore the problem of daily data generation becomes extremely important.

6. EVALUATION AND APPLICATION OF THE DETERMINISTIC DAILY MODEL IN LOW-FLOW STUDIES.

The in-house developed daily VTI model has been used in low-flow studies. It is a semi-distributed catchment model which incorporates sub-grid effects with a reasonably limited complexity of model algorithms and information requirements. Parameter estimation procedures allow parameters to be quantified in many cases from the physical catchment variables. The model conceptualises several different surface-subsurface interaction processes present under South African conditions, which are responsible for the maintenance of low flows: intersection of the regional groundwater table with the surface, lateral drainage from deep soil profiles, re-emergence of percolating water as springs from fracture systems in underlying bedrock.

To evaluate the model performance in the context of low-flows and to test the model's ability to simulate various aspects of low flows, a new set of criteria of model performance has been utilized in addition to the conventional fit statistics and flow duration curves. These conventional goodness-of-fit criteria normally focus on how well the simulated hydrograph shape, flood peaks and flow volumes match with the corresponding observed ones and therefore place more emphasis on storm runoff or the whole range of flows. The quality of low-flow simulation is not specifically addressed. The newly introduced criteria of model performance illustrate how well the model is able to predict streamflow recessions and baseflow volumes, continuous low-flow events below certain referenced discharges, frequency, magnitude and duration of extreme low-flow events and dry season freshes, etc. Many of these are rather subtle measures and are normally ignored in conventional assessment of simulations. However, they are of vital importance for ecological and water quality problems related to low flows. All criteria are conveniently calculated using the low-flow estimation software, included in the HYMAS computer package.

The model has been extensively applied to simulate satisfactorily long daily streamflow time series in present day and natural conditions in many catchments throughout South Africa. This allowed the basin-wide analysis of low-flow regimes to be performed at much finer spatial resolution than the quaternary subcatchment scale. In most of the cases the model was found to perform successfully. However, its application was sometimes limited by the lack of good quality input rainfall data and/or knowledge on the physiographic characteristics of the drainage basins. Additional complications arose when the model was applied to catchments with various anthropogenic effects, which were very difficult to quantify and for which the reliable information is frequently not available (direct abstractions, return flows, interbasin transfers, farm dams etc.). The application of the VTI model on a catchment-wide scale was also found to be a very time consuming approach.

7. SPATIAL INTERPOLATION OF OBSERVED STREAMFLOW RECORDS

Significant steps have been undertaken during the course of the Project to address the problem of the availability of daily data for low-flow and any other detailed hydrological analysis. The most important result is the spatial interpolation algorithm initially developed for the patching/extension of observed flow time series. The development of such a technique was dictated by the necessity to have the observed time series coincident in time for basin-wide low-flow analysis and by the requirement of an unbroken streamflow input time series for some applications of the VTI model.

The spatial interpolation algorithm makes use of available observed daily streamflow records and attempts to account for some of the non-linearities in the relationship between streamflow at different sites, by using 1-day flow duration curves for each month of the year and the assumption that flows occurring simultaneously at sites in a reasonably close proximity to each other, correspond to similar percentage points on their respective duration curves. The algorithm has been incorporated into a 'model' that allows flows at a 'destination' site (site of interest) to be estimated from flows occurring at one or several 'source' site(s). The output from the model consists of the 'patched' observed flow and the 'substitute' (simulated) flow time series. The latter represents a time series made up completely of estimated values regardless of whether the original observed flow was missing or not. This substitute flow time series may be compared with the original observed flows and with flows simulated by another model.

The 'patching model' has been applied to a number of catchments within southern Africa (Southern Cape, Sabie, Swaziland, Mooi, Tugela, Koonap, etc.). In most of the cases the resulting streamflow simulations were found to match well with the observed flows and compare favourably with those obtained using the VTI model. Despite some of the limitations of the spatial interpolation technique which are mostly related to the possibility of establishing satisfactorily representative flow duration curves for each month of a year, the approach was found to be very straightforward, efficient and easy to use.

8. DEVELOPMENT OF METHODS FOR CHARACTERISATION OF DAILY FLOW REGIMES AT UNGAUGED SITES.

Since the characterization of daily flow regimes from observed flow records is possible only at a limited number of sites and deterministic daily modelling is a resource intensive approach, there is a need for the use of simple methods for generating daily flow data. Such methods have been suggested and tested during the course of the Project. The first makes use of the regional annual and seasonal flow duration curves established on the basis of available observed records. The discharge values from the individual observed flow duration curves are divided by the mean daily flow and these standardised curves from several gauges within a hydrologically homogeneous region are superimposed. Their ordinates are averaged and a composite non-dimensional regional flow duration curve for a year and each season is calculated. The mean daily flow for an ungauged site in a region is estimated by means of the regression relationships with the catchment and physiographic parameters. Alternatively, it can be estimated using synthetic hydrological information presented in the results of the recently updated study on the Surface Water Resources of South Africa.

The second method converts flow duration curves based on monthly flow time series into flow duration curves based on daily discharges. The objective of this procedure is to establish a set of regional conversion parameters (annual and seasonal) using gauged flow data. This approach should allow daily flow duration curves to be established for many small and normally ungauged drainage subdivisions throughout South Africa (quaternary subcatchments) for which synthetic monthly flow volume time series are already available. Both approaches are therefore linked to the widely used information presented in the Surface Water Resources of South Africa and other sources of monthly streamflow data (e.g. basin studies and system analysis reports).

The established flow duration curve for an ungauged site is useful in its own right and may be used directly for various water resource assessment problems. Flow duration curves may also be further utilized to generate a complete time series of daily discharges at an ungauged site, by means of a spatial interpolation algorithm and the observed streamflow records in the vicinity of an ungauged site. In this sense the spatial interpolation technique represents a pragmatic alternative to the more sophisticated deterministic methods of daily flow time-series generation.

9. REGIONALISATION OF LOW-FLOW CHARACTERISTICS.

Regionalisation of low-flow characteristics is logically related to the regionalisation of daily flow duration curves. Once the regional annual or seasonal curves are established, the required low-flow indices can be obtained using the estimate of mean flow and any of the ordinates of the non-dimensional regional flow duration curves for high exceedence percentage points.

Two other approaches have also been tested during the Project. The first is the classical multiple regression method whereby a low-flow characteristic is estimated by means of the established relationship with catchment physiographic and climatic parameters. In the second method the relationship is established between a required daily low-flow index and some monthly low-flow characteristic (e.g. flow volume during the driest month(s) of a year). It has been demonstrated that both approaches are able to produce satisfactory results. However the lack of good quality observed daily flow records from which to estimate low-flow indices for regression analysis, appeared to be the critical issue, especially for the first approach.

10. BASIN-WIDE LOW FLOW STUDIES.

Catchment-wide analysis of low-flow regimes formed the main and the largest part of the project and almost all other developments and research initiatives described contributed to it. The major objective of catchment-wide low-flow studies was to characterize temporal changes in low-flow regimes as well as their spatial changes from the top to the bottom of a catchment in terms of several low-flow indices. Several catchments drawn from different parts of the country have been analyzed:

- The Sabie River catchment in the Mpumalanga Province;
- The Berg River catchment in the Western Cape;
- The Mooi River catchment (the tributary of the Tugela, KwaZulu-Natal);
- The Sundays River catchment (the tributary of the Tugela);
- The central part of the Tugela River catchment;
- The Mzimvubu catchment in the Eastern Cape;
- The Mzimkhulu catchment in the KwaZulu-Natal;
- The Olifants River catchment in the Northern Province.

Some preliminary work has also been initiated on several other catchments (the Buffalo and Fish rivers in the Eastern Cape Province, the Gamtoos and Gouritz rivers in the Southern Cape).

A range of techniques have been used for low-flow estimation in these catchments: from complex deterministic daily modelling to more straightforward regionalization methods. The first step in catchment low-flow studies was the detailed analysis of available observed flow records to identify the usable period of record, the necessity and possibility to patch/extend the time series, and to investigate temporal changes in low-flow regimes using selected low-flow indices. Each basin was then broken down into smaller subdivisions. These correspond either to the boundaries of gauged subcatchments, boundaries of quaternary subcatchments or smaller subareas (for the subsequent application of the VTI model). Selected low-flow indices have been estimated for each subdivision from either observed or simulated daily flow time series. Low- flows have normally been estimated for both present day and natural conditions. The GIS coverages of estimated low-flow characteristics at the adopted level of catchment discretization have been constructed to illustrate their spatial distribution within each catchment. The degree of changes in flow regimes from natural to present day conditions has been illustrated by means of 1-day annual flow duration curves. The results are also summarised in tables which contain estimated low-flow indices for each drainage subdivision.

11. RECOMMENDATIONS

The problem areas identified by the Project mostly relate to the availability of daily streamflow information rather than to the low-flow estimation techniques themselves. It has been demonstrated that it is generally possible to develop a picture of the low-flow conditions in large catchments through the combined use of observed and simulated data. At the same time, a good potential exists in simpler methods that make use of either existing synthetic monthly flow data or the regionalisation of observed daily flow data. The limitations of these simpler methods relate to the lack of techniques to account for the effect of abstractions/imports/effluents, rating table limitations and the non-stationarity of flow records on flow duration curves. A better understanding is also required of how to regionalise the relationships between monthly and daily flow duration curves. These directions are therefore recommended for future research.

The regionalisation of flow duration curves should be tested in other regions of South Africa. Research is also required into the regionalisation of other low-flow measures (low-flow frequency curves, spell frequency curves, etc.). This should facilitate the solution of low-flow estimation problems at the scale of small ungauged catchments. In general more research is necessary in the area of the development of the simple methods of daily flow estimation at the subquaternary catchment scale.

In order to improve the reliability of simulations by daily models, detailed data on direct water abstractions or imports of water are required. The data base of the time series of such abstractions would be very useful for many types of hydrological analysis. Other characteristics of anthropogenic impacts at least at the quaternary catchment level of spatial detail need to be documented at different historical levels.

It is recommended that the ability of any daily rainfall-runoff model to simulate low-flow regimes is tested in terms of several low-flow criteria in addition to the conventional goodness-of-fit criteria, since the latter do not always guarantee that a model reproduces low-flows satisfactorily.

It is also felt that there exists a necessity to develop an accessible inventory of all streamflow gauging stations in the country supplemented with some standard data on recorded flow regimes. The existing catalogues of gauges published by the DWAF at present are either out of date or contain information that is not complete and requires further clarification. The description of each gauge and its recorded flow regime would allow the interested users to determine *a priori* whether to request the data from DWAF or not. Such a description will require the joint efforts of the DWAF on the one hand, and a research institution, where the relevant expertise already exists, on the other. The description of each gauge should contain the technical details of the gauging structures and the characteristics of the recorded flow regime (annual flow time series, flow duration curve(s), seasonal distribution etc.).

The possibility of establishing a direct access to the DWAF streamflow database needs to be investigated. This access would allow the users to extract the required information in the same way as for example, rainfall data is now extracted from the CCWR database. It would free the DWAF from data extraction functions and allow the DWAF staff to concentrate on the maintenance and updating of the existing database.

Some of the techniques and information generated by the Project have been applied within the field of Instream Flow Assessment. This link should be strengthened and developed. For example, one of the research directions could be the development of appropriate techniques that could translate the Instream Flow Requirements into a time series of expected reservoir releases and therefore allow the suggested modified flow regimes to be illustrated and analyzed.

The logical extension of the low-flow studies would be to continue with the detailed investigation of low-flow processes in different parts of the country, paying more attention to the behaviour of the natural water systems (streams, wetlands) under drought conditions.

The Project presents a large amount of low-flow information for particular catchments and the general problem of such studies is how most effectively to convey the generated hydrological data to a potential user. It is suggested that the development of a nation-wide system of storing, updating, displaying and manipulating of hydrological information should be initiated. Such a system should combine the spatial and time-series components (e.g. through the use of ARC/VIEW) and should allow the distributed catchment characteristics and time-series data for the various basins to be accessed by interested users.

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1. INTRODUCTION

South Africa faces a number of problems related to the efficient utilisation of the country's scarce water resources. These problems are exacerbated during the dry season of a year - a period of low flows which forms an integral part of the hydrological regime of a river. During a period of low flows rural water supply schemes may fail, river ecosystems endure a severe stress, water pollution becomes critical and extremely difficult to manage. In the past more emphasis has been placed on water resource assessments for bulk water supply and the low-flow part of the continuous hydrograph has frequently been ignored because its contribution to total water availability was perceived as being less important. The contribution of daily flows below the median to total flow volume in semi-arid regions of the country (and/or large areas) can be less than 10%. However, in more humid areas (and/or smaller catchments) it may be as high as 50% which already constitutes a substantial resource. A recent shift towards more integrated management of water resources and an increased emphasis on the environmental requirements of rivers (which represent the sources of supply) attract a permanently growing attention to the low-flow part of a total streamflow hydrograph.

In broad terms 'low flow' may be defined as "flow of water in a stream during prolonged dry weather" (World Meteorological Organization, 1974). However, there does not seem to exist a clear cut-off point where low-flow conditions can generally be considered to start and therefore the terms 'low flows' and 'low-flow hydrology' could mean different things to different groups of scientists and managers. To many, 'low flows' may be considered as the flows occurring during the dry season, to others the length of time and the conditions occurring between events in intermittent semi-arid flow regimes. Yet others may perceive 'low flows' as a reduction in various aspects of the overall flow regime. Consequently, there is not enough clarity on how to define low flows or what low criteria to use for different purposes. The concept of 'normal flow' used in SA Water Law (the flow exceeded about 70% of the time during the critical irrigation period (Midgley et al, 1994)) is perceived mainly with regard to only one user group i.e. irrigation and does not cater for other users such as rural communities, waste disposal, the environment, etc. The government Water Supply and Sanitation Policy (1994) recommends that rural water supply schemes should ensure the availability of water for 98% of the time, meaning that the service should not fail more than one year in fifty, on average. Ecologically, critical low flows in South Africa are often evaluated in terms of their position in a lower portion of a flow duration curve (King et al, 1995). Procedures to Assess Effluent Discharge Impacts (DWAF, 1995) state that the wide variation in low-flow characteristics in the country makes the selection of a single, predefined design flow impractical and that assessing the effects of an effluent discharge may be done on a case- or site-specific basis. In general, 'low flow' in South Africa is normally perceived as a dynamic concept which is not easily tied to a single characteristic.

Consequently, the problem of low flows should be addressed in terms of various low-flow characteristics (indices) which describe different aspects of a low-flow regime of a river and therefore in many water related fields the preference is given to a complete representative streamflow time series from which a variety of such characteristics may be estimated.

Water resource assessment in South Africa has traditionally been based on monthly streamflow data time series. Monthly data are available from various Basin Study and System Analysis Reports commissioned by the Department of Water Affairs and Forestry (DWAF) as well as from widely used volumes of the Surface Water Resources of SA (the old version of 1981 and an updated version (WR90), Midgley et al, 1994). These volumes contain detailed synthetic information on monthly flow characteristics for each of the small drainage subdivisions in the country (quaternary subcatchments). The scale of these catchments varies from 30 km^2 to several hundred km^2, depending on their location. Low-flow estimation from monthly streamflow data is normally performed using regional Deficient Flow -Duration - Frequency curves, also presented in WR90.

However, flow information on a finer, daily time resolution is required in many areas of research and practice. The primary source of daily streamflow data is the observed flow records. The direct use of these records is frequently hampered by their insufficient quality. Also the spatial availability of such records varies significantly in different parts of the country. These two factors limit, in a South African context, the possibilities for the development and application of regional regression models widely used for low-flow assessment elsewhere (FREND, 1989; Gustard et al, 1992; Nathan and McMahon, 1992), put more emphasis on the application of daily streamflow simulation techniques and generally imply that different methods of low-flow assessment are required in different regions of the country.

The high variability of low-flow regimes throughout South Africa also implies that the problem of low flows in the country should preferably be addressed at a regional or catchment scale (Smakhtin et al, 1995). Catchment-wide low-flow assessment matches well with the integrated approach for catchment water resources planning and management.

It is therefore becoming increasingly important to improve the understanding of stream and catchment behaviour during periods of limited flow, to improve/develop techniques for daily streamflow time-series generation and low-flow assessment at different scales, to investigate the applicability of existing low-flow estimation methods from the time-series data to South African conditions, to improve the general availability of low-flow information and to strengthen the link of low-flow hydrology with the requirements of other aquatic sciences and water resources management.

In 1991 the Water Research Commission entered into an agreement with the IWR to start a project on low-flow hydrology. The main idea of this initiative was to advance the level of low-flow hydrology in South Africa, addressing the problem of low-flows on a national scale, as well as on the scale of several large river systems. The main objectives of the study were:

- To examine the criteria currently used in different water related areas to characterise low-flow regimes and to develop techniques for the estimation and analysis of low-flows in South Africa from available streamflow data;
- To construct a data base for the information on river low-flow regimes;
- To evaluate and adapt a currently available daily rainfall-runoff model(s) to specifically simulate low-flow conditions;
- To characterise and to determine changes in low-flow regimes of selected major rivers within southern Africa.

It was envisaged that the Project would concentrate primarily on the use of daily flow data to characterise low-flow regimes but the relationships with monthly flow data commonly used in South Africa would also be investigated. The Project would also address the problem of low-flow estimation at ungauged sites and therefore contribute to the general availability of daily streamflow data in the country.

The present report consists of two volumes. Volume I consists of 9 Chapters and 6 Appendices. Chapter 2 gives a review of processes and driving forces of low-flow hydrology, describes the existing techniques for low-flow estimation at gauged and ungauged catchments and discusses the user requirements for low-flow information in South Africa.

Chapter 3 includes the description of the software for low-flow estimation that has been developed and intensively used throughout the course of the Project. The software includes various low-flow estimation techniques which form part of the more general PC-based computer package HYMAS (HYdrological Modelling Application System) designed to set up and run hydrological models and analyze observed or simulated hydrological variables.

Chapter 4 presents the results of the analysis of various low-flow characteristics estimated from a large number of observed daily streamflow data sets on the scale of the whole country.

Chapter 5 describes the structure of a semi-distributed deterministic rainfall-runoff, Variable Time Interval (VTI) model and discusses the techniques for the assessment of its applicability in low-flow studies.

Chapter 6 describes the spatial interpolation technique that has been developed for the patching, extension and generation of daily streamflow time series and discusses its application to a number of catchments in southern African and its potential value for hydrological analyses.

Chapter 7 discusses the technique of disagregation of synthetic monthly streamflow data into daily and describes the application of a spatial interpolation technique for generation of daily streamflow time-series to ungauged locations.

Chapter 8 summarises the results of catchment-wide low-flow studies, presented in detail in Volume II.

Chapter 9 includes final conclusions and recommendations.

Appendix A1 includes the form of a questionnaire for the survey of user requirements for low-flow information. Appendices A2 to A6 contain a variety of low-flow characteristics estimated from about 250 unregulated observed daily flow records from different parts of the country and the maps illustrating the spatial variability of low-flow regimes in South Africa.

Volume II includes a number of Appendices which deal with basin-wide low-flow studies in several selected South African catchments/regions: the Sabie River catchment (Mpumalanga Province), the Berg River catchment (Western Cape Province), the Tugela River catchment (KwaZulu-Natal Province), the T drainage region in the Eastern Cape Province and the Olifants River catchment (Northern Province). The Appendices B1, C1, D1, E1, F1 describe step-by-step applications of various techniques used for low-flow assessment in these catchments and the detailed results of these applications.

Appendices B2, C2, D2, E2 and F2 contain the time series plots of annual flow totals and annual low-flow characteristics for streamflow gauges in the catchments used for detailed basin-wide low-flow studies and therefore illustrate the temporal variability of low-flow regimes in different parts of the study catchments.

The executive summary included at the beginning of the Report describes the objectives, achievements and conclusions of the Project in a more condensed format.

2. LOW-FLOW HYDROLOGY: PROCESSES, METHODS AND REQUIREMENTS

2.1 INTRODUCTION.

This Chapter intends to give a brief introduction to low-flow hydrology. The processes and factors affecting low-flows are first discussed with an emphasis on South African conditions. This is followed by the review of existing methods of low-flow estimation from available observed time series data and techniques for low-flow estimation at ungauged sites. The Chapter also presents the results of the survey on user requirements for low-flow information in South Africa conducted by the IWR in 1993.

2.2 NATURAL PROCESSES AND DRIVING FORCES OF LOW-FLOW HYDROLOGY.

A discussion of the factors affecting low flows should ideally begin with a definition of what 'low-flow hydrology' really is. However, the problem is that this term could mean different things to different interest groups. To many it may be considered as the flows occurring during the dry season, to others the length of time and the conditions occurring between events in erratic and intermittent semi-arid flow regimes. Yet others may be concerned with the effects of changes in the total flow regime of a river on sustainable water yield or riverine and riparian ecology. The latter may perceive 'low flows' as not only the flows occurring during a dry season, but as a reduction in various aspects of the overall flow regime. The discussion in this section on the factors affecting 'low flows' will be confined mostly to the processes operative during dry weather periods.

In a relatively simple sense, a river catchment can be perceived as a series of interlinked reservoirs of storage each of which has components of recharge, storage and discharge. Recharge to the whole system is largely dependent on precipitation, whereas storage and discharge are complex functions of catchment physiographic characteristics.

During low-flow conditions it is those processes that affect the release of water from storage and the fate of this discharge that are directly relevant. These processes are usually operative in the vicinity of the river channel zones rather than the full range of hydrological processes that operate over larger parts of catchments during periods of higher discharge. The latter of course also cannot be ignored as they control the catchments ability to absorb and store water during precipitation events for later release as low flows. However, the discussion of the full range of hydrological and hydrogeological processes involved is not within the scope of this Report.

In the southern African context, during prolonged periods when there is a minimal input from precipitation, lateral movement of water within the majority of a catchments hillslope and hilltop soils will be non-existent. Processes affecting levels of dry weather streamflow discharge are therefore confined to movement in the deeper subsurface environment.

The natural processes may be grouped into those affecting gains and losses to streamflow during dry weather. Anthropogenic effects on these processes and on the streamflow directly should be considered separately.

Gains to streamflow.

- In many cases the majority of natural gains to streamflow during low flow periods will be derived from releases from groundwater storage. This occurs where stream channels intersect the main phreatic surface or a perched water table. Rates of outflow will clearly depend upon the hydraulic gradient and the hydraulic conductivity of the subsurface material.

- A different example of groundwater re-emergence can occur where relatively slow moving groundwater drainage in fracture zones above the main water table has a significant lateral component which intersects the ground surface in the vicinity of channels (springs). This is most likely to occur in steeply sloping terrain and can account for prolonged baseflows following rainfall events in semi-arid areas even when the water table is well below the level of stream channels. Rates of such outflow will depend upon the fracture size and density as well as the relative importance of the lateral drainage component compared to the vertical component, which recharges the 'true' groundwater storage.

- Gains to low flows can also be derived from drainage of near surface valley bottom (or near channel) storages such as more permanently wetted channel bank soils, alluvial valley fills and wetland or natural vlei areas. These are areas where water becomes concentrated during and soon after precipitation events and therefore where adequate levels of storage are maintained during the dry season to allow lateral drainage into channels to continue.

  The water contained within these soil and alluvial storages is often referred to as 'groundwater', which can lead to conceptual misunderstandings. A distinction should really be made between this source and the 'true' groundwater body which exists below the phreatic surface. It is of course possible for these two water storages to be in direct hydraulic connection, as would be the case where the phreatic surface intersects the ground surface. The distinction is then more difficult to define. However, in many of the semi-arid environments of southern Africa this is not the case for most of the time and if the term 'groundwater' is to be used at all, it should possibly be referred to as 'perched' groundwater storage, alluvial water storage or channel bank water storage.

The relevance of these different 'gain' processes to the wide variety of climatic, topographic and geological conditions that exist in Southern Africa is difficult to determine. Identifying their relative importance on a regional basis or for a particular catchment is a logical step in low-flow analysis.

Losses to streamflow.

In many respects the processes involved in causing streamflow losses are the reverse of those causing gains with the addition of direct evaporation from channel water bodies. Losses to streamflow during dry weather periods may be summarised as follows.

- Direct evaporation from standing or flowing water in a channel, other open water bodies, wetlands or natural vlei areas.

- Seepage areas, where groundwater or channel bank soil water is draining into the channel will also be subject to evaporation and transpiration losses. This process may account for some of the diurnal variations observed in low-flow discharge records.

- Groundwater recharge from streamflow can be an important process where the phreatic surface lies below the channel. River channels often follow lines of structural weakness and surface fracturing, offering an ideal opportunity for the infiltration of low flows into the channel bed.

- Similarly, where unconsolidated alluvial material underlies the river channel, bed losses can be substantial, not only during low flows but also during the early stages of flood events. Such losses have been identified by a number of hydrologists working in semi-arid areas, but this research has been dominated by investigations of flood events and low-flow losses of this type have been relatively neglected.

- Losses to relatively dry soils forming the banks of streams can also be identified as a contributing factor which may be enhanced by the presence of dense riparian vegetation promoting evapotranspiration. This process may also contribute to the diurnal variation effect referred to earlier.

These processes are often referred to as 'transmission losses'. The relative importance of transmission losses within the various regions of Southern African are largely unknown. Localised information from a few well studied catchments is certainly available but a more generalised and widespread impression is currently lacking. The study of transmission losses in several major rivers of South Africa forms the core of another WRC project (McKenzie and Roth, 1994).

2.3 ANTHROPOGENIC IMPACTS ON LOW FLOWS.

Anthropogenic impacts on low-flow generating processes.

Natural gains and losses to low flows are both affected by various anthropogenic impacts which in South African context normally include:

- Groundwater abstraction within the sub-surface drainage area. This will clearly affect the level of phreatic surfaces and therefore the potential for groundwater re-emergence in stream channels. Localised reductions in the level of the water table may affect either hydraulic gradients or the length of channel that intersects the phreatic surface.

- Artificial drainage of valley bottom soils for agricultural or building construction purposes. This can lead to more rapid removal of water from valley bottom storage and a reduction in the sustainability of lateral drainage during dry weather.

- Changes to the vegetation regime in valley bottom areas through clearing or planting. They can modify the levels of evapotranspiration loss from riparian soils, thereby affecting gains or losses to bank or alluvial storage.

- Afforestation of a whole catchment or parts thereof. A number of studies have demonstrated that afforestation has had a major effect on low flows reducing low-flow volumes to a larger degree than those of annual flow. Afforestation, irrigation and groundwater abstraction are likely to be the most important indirect man-induced impacts on low flows in the South African context.

- A wide variety of other effects which may influence the amounts or rates of accumulation of water held in storage during rainfall and consequently the levels of storage during periods of limited rainfall. An example is the modification of land use over large parts of a catchment which may contribute to changes in the infiltration and/or evaporation characteristics, as well as modifications to the amount of groundwater recharge (urbanisation, dryland farming etc.)

Anthropogenic effects directly on streamflow.

Apart from indirect anthropogenic impacts on low-flow processes there are impacts which remove water directly from or add water to the stream channel.

- Direct river abstractions for industrial, agricultural or municipal purposes.

- Direct effluent flows into river channels from industrial or municipal sources.

- Irrigation return flows from agricultural fields. These are widely recognised as contributing to additional sub-surface drainage directly to the river channel or through "return" canals. Irrigation return flows may constitute a large proportion of a stream's water balance (10-40%). They are particularly important if the water for irrigation is imported from outside the catchment. The time lag associated with return flows remains largely unknown. Similar to effluent discharges from industrial and municipal sources, irrigation return flows can significantly affect the composition of low flows leading to deterioration of water quality and therefore limiting its availability for downstream users.

- Direct importation of water from outside the catchment via inter-basin transfer schemes and the use of channels as natural supply conduits.

- Construction of dams and the consequent regulation of a rivers flow regime. This regulation can either increase or decrease low-flow discharge levels depending on the operational management of the reservoir. It is necessary to distinguish between small impoundments such as farm dams where there is little or no control over the level of storage, and larger dams where artificial releases can be made. Taken together, artificial impoundments probably constitute the single most important direct impact on the low-flow regimes of rivers in southern Africa.

Due to the variety of direct impacts the low-flow regimes of many rivers in South Africa have been significantly modified. In many cases low flows have been effectively either removed from the streamflow hydrograph (due to various abstractions) or artificially generated (from irrigation return flows, releases of imported water from dams for downstream users). The origin of water in a stream during low-flow conditions should therefore be understood and taken into account when dealing with low flows.

2.4 REQUIREMENTS FOR LOW-FLOW RESEARCH AND INFORMATION.

The processes of low-flow generation and factors affecting them pose a number of questions the most obvious being:

- What are the relative contributions of the natural gain and loss processes in different regions of Southern Africa?

- What are the relative quantitative impacts of the various anthropogenic effects in different regions?

- How do the combined effects of the dominating processes and the anthropogenic impacts affect various aspects of low flow management including water utilization control, water quality control and conservation of aquatic ecology?

Similarly a number of questions arise with regards to information requirements of different water related areas and research directions of low-flow studies in South Africa.

- What are the best indices of low flow to use in different regions and for different purposes ?
- How sensitive are different indicators of low flows to the various effects and processes that have been identified ?
- What is the best way to represent changing low flow conditions at different spatial positions within a catchment and at different times ?
- What is the best way of generating selected indices for ungauged sites where no flow records are available ?
- How to generate indices for natural conditions when most of the observed records include at least some anthropogenic effects ?
- Should indices be selected which are not only applicable to low flows but can be used to quantitatively describe other aspects of rivers flow regimes ? (This question may become important where an overall assessment of regime changes due to anthropogenic effects is required. For example, ecological Instream Flow Requirement studies are concerned with more than just minimum flows).

All these questions clearly imply that a more closer look is required on the existing low-flow characteristics and methods of low-flow analysis.

2.5 LOW-FLOW MEASURES AND INDICES AND THEIR ESTIMATION FROM OBSERVED FLOW RECORDS.

Low-flow regime of a river can be analyzed in a variety of ways dependent on the type of data initially available and type of information required. Consequently there exist a variety of low-flow measures and indices. The term 'low-flow measure' used here, refers to the different methods that have been developed for analysing, often in graphic form, the low-flow regime of a river. The term 'low-flow index' is used predominantly to define particular values obtained from any low-flow measure. Sometimes, it is however rather difficult to distinguish between these two notions. For example, when a low-flow measure is not a "method" but just a variable, or when it is simply a single value, or condition. This section does not intend to give a comprehensive review of the literature on low-flow estimation techniques, but should rather be considered as a short summary of existing approaches to low-flow analyses. The detailed description of various methods of low-flow analyses may be found in several sources (Searcy, 1959; Vasak, 1977; Institute of Hydrology, 1980; FREND, 1989; Gustard et al, 1992; Stedinger et al, 1993; Tallaksen, 1995).

Mean Annual Runoff and Annual Flow Variability.

Mean annual runoff (MAR) is also often referred to as 'average annual flow' and 'mean annual flow'. It is estimated as the mean value of all annual flow totals in the available flow time series. It is one of the most fundamental hydrologic characteristics widely used for comparing the regime of different rivers, for evaluating available water resources, for estimating changes in historical flow sequences including those caused by human activity. MAR may be expressed in different ways. Normally it has the dimension of a flow volume (**m^3, km^3, or Ml**). For water balance purposes, e.g. for comparison between rainfall, evaporation, soil moisture storage and groundwater recharge, it is often expressed in **mm** as an average depth over the catchment area (annual flow volume divided by the catchment area). In this way it is also very useful for comparisons between catchments with different areas. For the later purpose, MAR is also expressed in **$m^3/s/km^2$ or $l/s/km^2$** to show the flow rate from a unit area of a catchment. Although not strictly a low flow measure, MAR is very useful since it may be perceived as an indicator of the "upper boundary" for low-flow hydrology.

The variability of annual flows around the MAR is normally described by the **coefficient of variation (CV)** of the annual flow series and by the **standard deviation**, which are common statistical parameters.

Median Flow

If a flow time series is ranked in a decreasing or increasing order of magnitude, the Median Flow (**MF**) represents the middle value and therefore half of the flows in the time series are larger and half are smaller than the median flow value. The MF value is determined only by the "middle" flow value in a ranked time series (in the case of an odd number of years in a series) or two "middle" flow values (in the case of an even number of years) and, unlike MAR, is independent on the other flow values in a time series. Since hydrological time-series data are often positively skewed, the median flow value is frequently smaller than MAR and may represent a "better" upper limit for low flows. The positive skewness of the data normally increases as the time resolution of the streamflow data decreases from annual to daily and therefore the gap between higher mean flow value and lower median flow value normally increases.

Average Daily Flow

Various low-flow indices are often expressed as a percentage of 'average daily flow' (**ADF**). This is a common index normally used in many daily flow data analyses and has a dimension of discharge. It is often obtained by dividing MAR volume by a number of seconds in a year ($31.536\ 10^6$). However, the average value is determined by all values in a time-series and therefore the ADF calculated from the annual data may be different from that estimated from daily data, where it is estimated by a simple averaging of all daily discharges in a record period. For many purposes it is necessary to estimate ADF for a short available record period or part of the longer record period, while MAR should normally be established only on the basis of long-term observations.

Absolute Minimum Flow

This is the lowest recorded instantaneous or mean daily discharge which indicates the maximum observed degree of streamflow depletion at the particular flow gauge in a catchment. The information content of this index varies with the length of record. Absolute minimum flow **(AMF)** may indicate that discharge falls to zero and in this sense it represents the 'lower boundary' of low-flow hydrology. Similar to MAR it may be expressed in different units.

Flow Duration Curve

In low-flow studies it is important to consider not only the flow magnitude but also the duration of low-flow periods. In many cases it is important to know the percentage of the period of record during which the river contains less (or more) than a given flow. Such a result can be read directly from the **flow duration curve (FDC)**.

In the case of daily flow data, the FDC may be obtained by reassembling the hydrograph ordinates (flow values) in decreasing order of magnitude, assigning flow values to class intervals and counting the number of days within each class interval. Cumulated class frequencies are then calculated and expressed as a percentage of the total number of days in the record period. Finally the cumulated percentages are plotted against the lower limit of every discharge interval. Alternatively, all recorded flows may be ranked and each rank expressed as a percentage of the total number of days in the record (using Weibull plotting position formula for example). In order to linearize FDCs a logarithmic scale is usually used for flows and a normal probability scale for percentage of time each flow is exceeded. The flows may be expressed in discharge units, volumetric units, mm of runoff or as percentages of MAR or ADF. The latter two options facilitate comparisons between catchments because it reduces differences in the location of FDCs on a plot, which are caused by differences in catchment area or MAR and thus the effects of other factors on the shape of FDCs may become evident (Fig. 2.1).

FDCs constructed on the basis of daily flow time series provide the most detailed way of examining duration characteristics of a river, but curves may also be constructed from annual, monthly and *m*-day averaged flow time series. In the latter case a moving average approach is used to construct a new time series of *m*-day or *m*-month averaged flows from initially available daily or monthly data.

FDCs may be constructed for each season of the year (e.g all summers and all winters), for each month of the year (e.g. all Januaries or all Septembers), for a particular season (e.g summer 1992) or particular month (January 1990) etc.

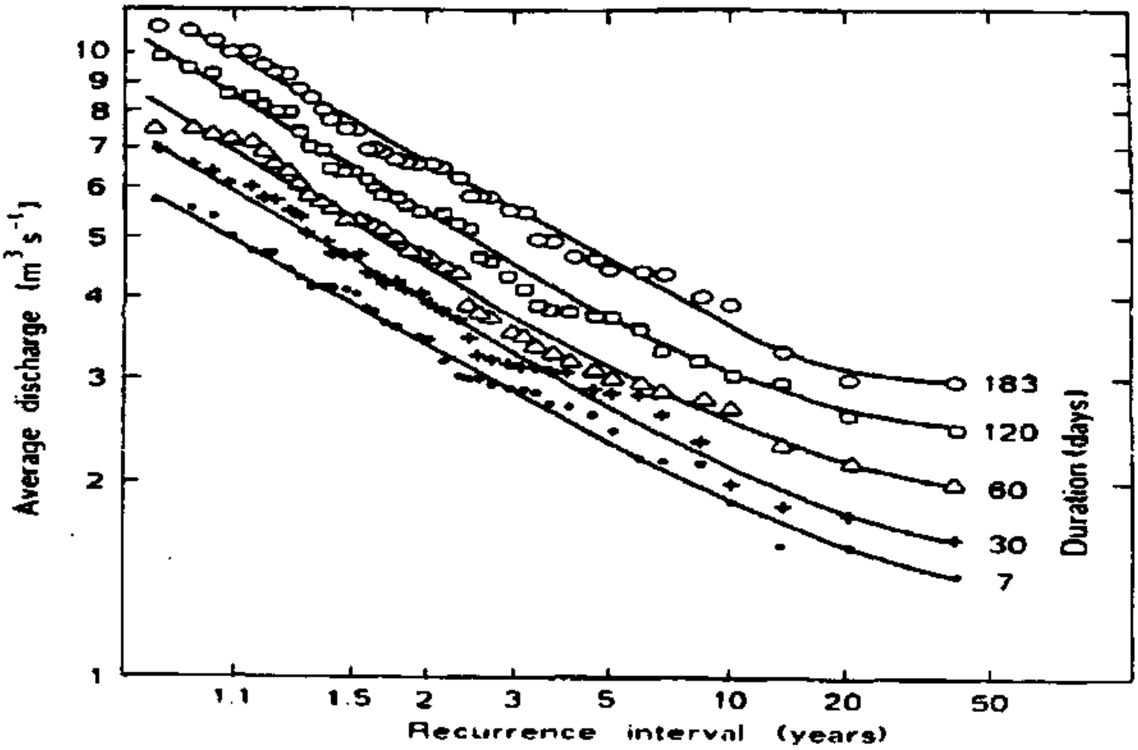


Figure 2.2. Example set of low-flow frequency curves (Reproduced from McMahon & Mein, 1986).

The slope of LFFC may also be considered as a low-flow index and represented by the difference between two flow values (normalised by the catchment area), one from high and another from low probability domains.

A knowledge of the **recurrence intervals (return periods)** of low-flow events, derived from LFFC, is important in reservoir storage-yield investigations and operation analysis, drought studies etc. Low-flow frequency indices are used in streamflow water quality studies. For example, in the USA and Canada the most widely-used index of low flow is **7-day 10-year low flow** which is defined as the lowest average flow that occurs for a consecutive 7-day period at a recurrence interval of 10 years (Characteristics of low flow, 1980). This index is mostly used in regulating waste disposal to streams. Some studies have used the **7-day 2-year low flow** as an index (Vasak, 1977). In Russia and Eastern Europe the most widely used indices are **1-day** and **30-day summer and winter low flows** (Yevstigneev, 1990; Vladimirov, 1970, 1976).

Dry Weather Flow (DWF) was defined by Hindley (1973) as **the average of the annual series of the minimum weekly (seven consecutive days) flows.** This index is used in the UK by several River Authorities for abstraction licensing and is better known as **Mean**

Annual 7-day Minimum flow (MAM7). The seven day period covered by DWF or other similar index is important for several reasons. Firstly, it eliminates the day to day variations in the artificial component of the river flow, notably the reduction in abstractions and effluent returns at weekends (Pirt & Simpson, 1983). Secondly, an analysis based on a time series of 7-day average flows is less sensitive to measurement errors. (The same considerations apply to indices extracted from FDCs).

Zero Flow Indices

In arid climates streamflow may frequently fall to zero and certain measures of zero-flow or "cease-to-flow" conditions are introduced in many cases. These are obviously duration measures. From FDCs **the percentage of time the stream is at zero-flow conditions** may be estimated. The **longest recorded period of consecutive zero-flow days** may give some idea of how severe the drought may be, but this measure is greatly dependent on the length of the record and thus contains a high degree of uncertainty. If the river regularly falls to zero-flow conditions, then common statistical methods may be introduced to estimate the **zero-flow period durations of different probabilities of exceedence**. In monthly streamflow analysis, such a measure as **zero-flow months as % of total months analyzed** may be of use (Görgens & Hughes, 1982).

Intervals of Consecutive Low Flows and Deficiency Volumes

All the measures described above still provide no information either about the length of continuous periods below any particular flow value of interest, or about the distribution of these periods throughout the period of record. They also give no idea of a deficit which is formed during a particular low flow event. However two streams with similar FDCs may have very different low-flow sequences: one may have a few long intervals below a given discharge, the other many short intervals below the same threshold. These differences may be of importance for dilution requirements in water quality control, abstraction policies, recreational planning, environmental impact assessment etc.

There exist different ways to overcome these limitations. It is possible, for example, to analyze the durations of the longest periods which are necessary to yield a specified small percentage of the annual flow volume (e.g. 1, 3, 5, 10% of MAR). These indices are similar to characteristics derived from FDC, but unlike FDC, time sequencing of discharges used in the analysis is not disturbed. Extracted from each year of record these intervals may be ranked and plotted in different ways to provide the information on consistency of low flows.

A large number of studies have used the truncation level approach (the theory of **runs**: Yevjevich, 1967) where continuous low-flow events (often interpreted simply as hydrological droughts) are *defined as periods during which streamflow* is lower than a certain threshold, the truncation level (Dracup et al, 1980; Chang and Stenson, 1990; Tlalka and Tlalka, 1987, Clausen and Pearson, 1995; Sen, 1980a,b; Moye and Kapadia, 1995). In this approach the three main low-flow characteristics are the **run duration, the severity (deficit or the negative run sums) and the magnitude (the intensity)** which is calculated as severity divided by duration. This approach is widely used when a certain minimum flow is required, e.g. for designing reservoirs to supply river flow, when permissions for river abstractions are considered or the like.

A detailed example of run theory application to low-flow and drought analysis from observed daily streamflow records is given by Zelenhasic and Salvai (1987). All important components of continuous low-flow events such as deficit, duration, time of occurrence, number of continuous events in a given time interval, the largest streamflow deficit and the largest duration in a given time interval are taken into account. The authors presented a stochastic model for analysis and interpretation of the most severe low-flow events.

One of the most well known methods was developed by the Institute of Hydrology, UK (1980). This approach has a slightly different terminology. Two important low-flow measures are considered: the length of a period during which the stream discharge is continuously less than a given threshold value - **spell duration,** and the total volume of flow that would be required to maintain the flow at a given threshold - **deficiency volume (or simply, a deficit as above)** (Fig. 2.3).

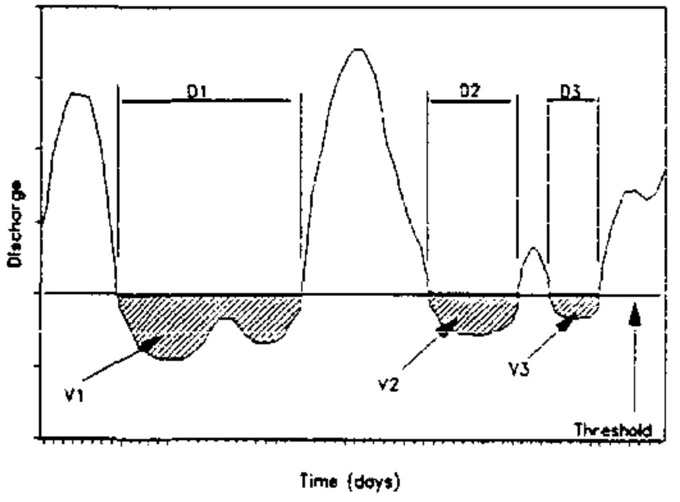


Figure 2.3. Definition of spell duration (D) and deficiency volume (V).

The threshold values are set corresponding to 5, 10, 20, 40, 60, 80% (or any other percent) of the mean annual discharge. From a given flow series of N years **the frequency of spells for a given duration** and **the number of spells greater than a given duration** may be calculated. These are then plotted against the duration of spells below a given threshold (usually in days) (Fig. 2.4). Similarly **the frequency of deficiency volume** and **the number**

of deficiency volumes greater than a given volume may be extracted and plotted against the values of deficiency volumes for given threshold (Fig. 2.5).

Duration and deficit of consecutive low-flow events may also be analyzed in many other ways (Midgley & Pitman, 1969; Natan & McMahon, 1992). For analysis of long term events the deficient flow periods may be defined as continuous events with annual runoff totals less than the MAR or as continuous events with monthly runoff totals less than mean monthly flow. Low-flow indices extracted from FDC may also be used as thresholds in spell analysis. For example, the plot may be constructed to show the distribution of spell durations when flow is continuously less then discharge exceeded T% of the time (e.g. Q50, Q75, Q90, Q95, etc.) (Fig. 2.6). The differences between streams at low-flow conditions may then be clearly seen.

Spell analysis is applicable not only to low flows but to the periods of high flow as well. It may also be useful for the study of even more specific events, like short-term freshers (small peaks caused by occasional rains during prolonged low-flow periods (important, for example, in determination of ecological Instream Flow Requirements).

The extension and typical application of spell analysis is the **Storage - Yield** (or storage - draft) **Diagrams (SYD)**. These diagrams allow the estimation of a reservoir storage which is necessary to provide a given yield at certain levels of reliability. This information is required for different purposes - domestic water supply, irrigation, power generation, dilution of industrial pollutants, fish migration etc - which are all dependent on the continuous availability of prescribed river discharges.

SYD is usually presented in a form which gives the proportion of years in which the yield (expressed as a percentage of MAR or ADF) is sufficient to empty the reservoir of given storage (expressed as a percentage of MAR, e.g. Kachroo, 1992; Domokos and Gilyen-Hofer, 1990; Gan et al, 1988). The reservoir storage can also be estimated as a function of yield and the frequency of occurrence. The storage required to maintain river flow at the prescribed flow throughout the year is the maximum of all individual deficiency volumes occurring during this year. To calculate a frequency of occurrence the series of annual maximum storages (one for each year of observations) is ranked in a decreasing or increasing order with a plotting position assigned to each value according to the rank and sample size. In order to estimate storages beyond the range of probabilities, given by the assigned plotting position, it is necessary to assume a theoretical distribution function. From the fitted distribution deficit storages may be estimated for return periods of any *N* years and for yields of certain percentage of MAR. The results give a storage-yield (storage-draft) diagram (Fig. 2.7). More details about storage-yield analysis may be found in McMahon and Mein (1986) and Midgley et al (1994).

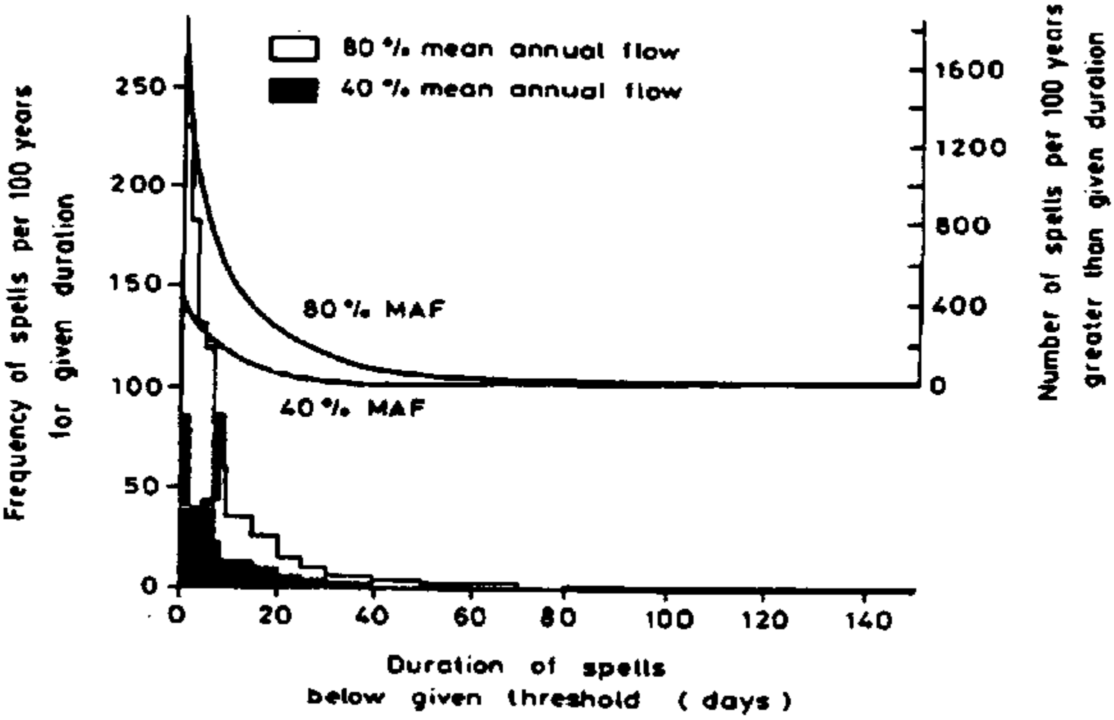


Figure 2.4. Frequency of low-flow spells. (Institute of Hydrology, UK, 1980)

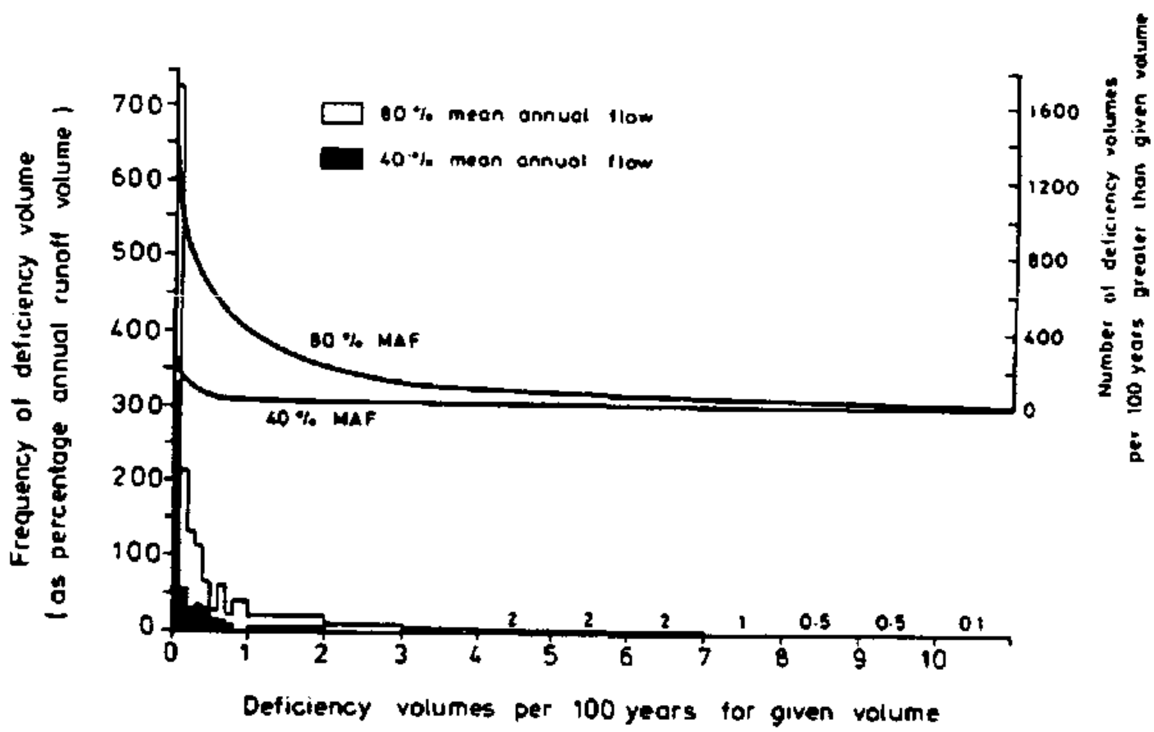


Figure 2.5. Frequency of low-flow deficit volumes. (Institute of Hydrology, UK, 1980)

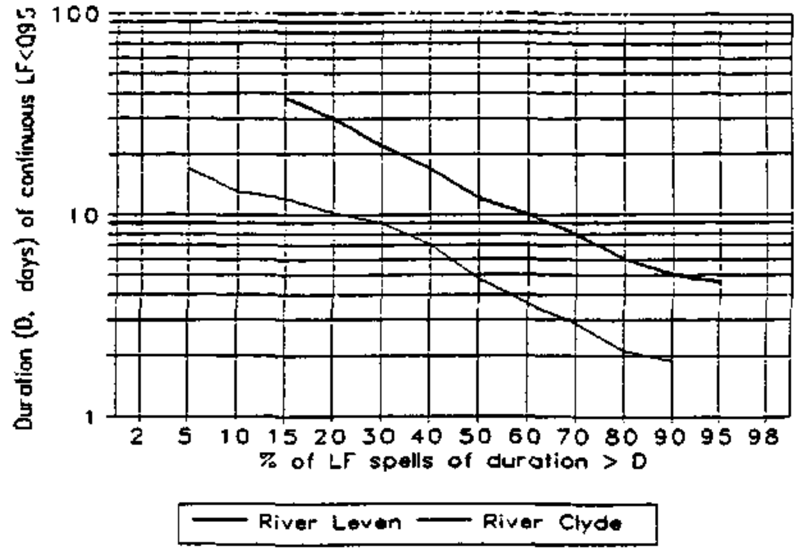


Figure 2.6. Frequency of low-flow spells on two British rivers. (Modified from Beran & Gustard, 1977)

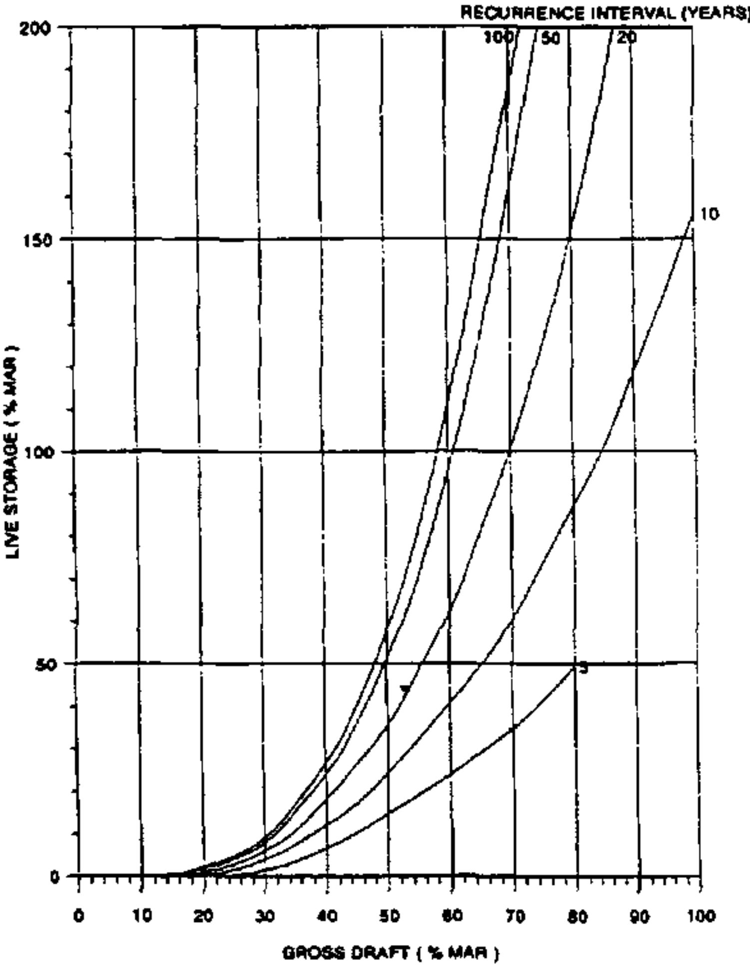


Figure 2.7. Example storage-yield diagram (reproduced from Midgley et al, 1994).

Base flow measures

Baseflow is an important component of streamflow hydrograph which comes from groundwater storage or other delayed sources (shallow subsurface storage, lakes etc). Baseflow may be generally characterised by its hydrograph which is derived from the total streamflow hydrograph by numerous **baseflow separation techniques**.

Base flow volume (BFV) shows the total (annual or event based) contribution of baseflow (the source of which may be groundwater flow and/or shallow subsurface flow) to the streamflow hydrograph.

Mean base flow discharge (MBFD) is defined as the average discharge under the separated baseflow hydrograph. Likewise total streamflow, baseflow may also be considered in terms of its average depth over the catchment area or flow rate per unit area.

The base flow index (BFI) concept was introduced by Lvovich (1972) and developed by the Institute of Hydrology, UK (1980) to describe the effect of geology on low flows. BFI is sometimes also referred to as 'reliability index' (e.g Beran & Gustard, 1977). It is a dimensionless ratio which is defined as the volume of baseflow divided by the volume of total streamflow (or alternatively, as the ratio between the average discharge under the separated baseflow hydrograph to the average discharge of the recorded hydrograph).

In catchments with high groundwater contribution to streamflow BFI may be close to 1, but it is equal to zero for ephemeral streams. In some cases, e.g. lake regions, baseflow may be of a different origin which makes hydrogeological interpretation of the BFI difficult.

BFV and BFI may be estimated for every year of record or for the whole period of observations. Common statistical procedures may be used to estimate baseflow characteristics of duration and frequency of interest.

Baseflow separation techniques. To estimate any of baseflow characteristics listed above one should first generate a baseflow hydrograph from the originally available total streamflow hydrograph. This is normally done by a number of baseflow separation methods (reviews of baseflow separation methods may be found in Dickinson et al.,1967, Hall, 1971 and many other sources). The majority of these methods concentrate on baseflow separation from a flood hydrograph (event based methods) and are eventually directed to the estimation of the surface runoff component of a flood. They may be grouped into two main types: those methods that assume that baseflow responds to a storm event concurrently with surface runoff, and those that account for the delaying effects of bank storage. The quantitative aspects of these techniques are rather arbitrary mostly due to the difficulties related to the estimation of timing and rate of baseflow rise and identification of the point on a storm hydrograph at which surface runoff is assumed to cease. In general, these methods are of rather little relevance to low-flow studies.

Other types of baseflow separation techniques are directed to generate baseflow hydrograph for a long term period - a year, several years or for the whole period of observations. These techniques normally make use of a certain kind of digital filter which allows daily streamflow time series to be disintegrated into two components: quickflow and baseflow. The most well known techniques of that kind are UK 'smoothed minima' method (FREND, 1989) and "recursive digital filter" (Nathan and McMahon, 1990) although other attempts to separate baseflow on a continuous basis have been reported (Sittner et al., 1969, Boughton, 1988). These techniques do not attempt to simulate actual baseflow conditions for each particular flood event but rather they are aimed at the derivation of objective indices related specifically to general baseflow response of a catchment (BFV, BFI).

Recession analysis

During dry weather periods water stored in a catchment is gradually removed by groundwater and soil water discharge into a stream and by evapotranspiration. A depletion of streamflow discharge during these periods is known as 'recession'. A flow recession is presented graphically by a **recession curve** - the decreasing portion of the streamflow hydrograph during a dry period.

A storm hydrograph usually comprises three components : overland flow, interflow and groundwater flow. Each component has characteristic recession rates. It is possible to distinguish these three components by plotting the logarithms of flow against time (Barnes, 1939; Fig. 2.8). A measure of each flow components' recession rate is known as **recession constant**. Recession constants calculated from daily flow data are normally in the range of: 0.2-0.8 for overland runoff, 0.7-0.94 for interflow, and 0.93 - 0.995 for baseflow (Klaassen and Pilgrim, 1975). The overlapping ranges reflect the fact that the distinctions between surface flow and interflow and between interflow and baseflow are not always clear.

In low-flow context baseflow is obviously the most important component and hence **baseflow recession constant** is of primary interest. This index in a simplified terms is a measure of the rate at which a groundwater store discharges in the absence of recharge, or in other words, the rate at which baseflow recedes in the absence of rain. In mathematical terms, recession constant constitutes a parameter in a simple exponential decline equation, known as **recession equation** (Toebes and Strang, 1964; FREND, 1989). Estimation of recession constant in its turn forms an integral part of baseflow estimation. If baseflow recession constant is known, the total flow during the baseflow period can be readily computed based on a single discharge measurement using recession equation (e.g. Potter and Rice, 1987).

The baseflow recession constant for a particular site may be estimated from the slope of a **master recession curve** which is defined as an envelope to various individual recession curves or as the most frequent depletion situation. The two most commonly used techniques for the construction of a master recession curve are "correlation method", "matching strip method".

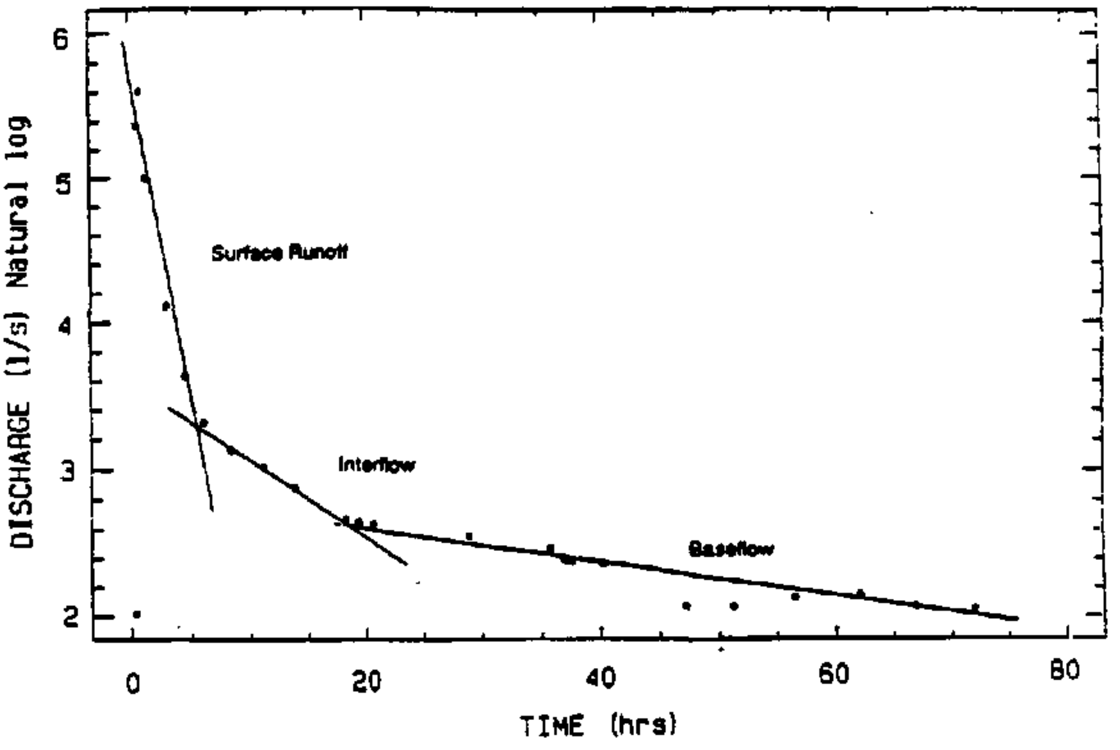


Figure. 2.8. Log-linear plot of runoff hydrograph showing the three components: surface flow, interflow and baseflow (Redrawn from Mulder and Kelbe, 1992)

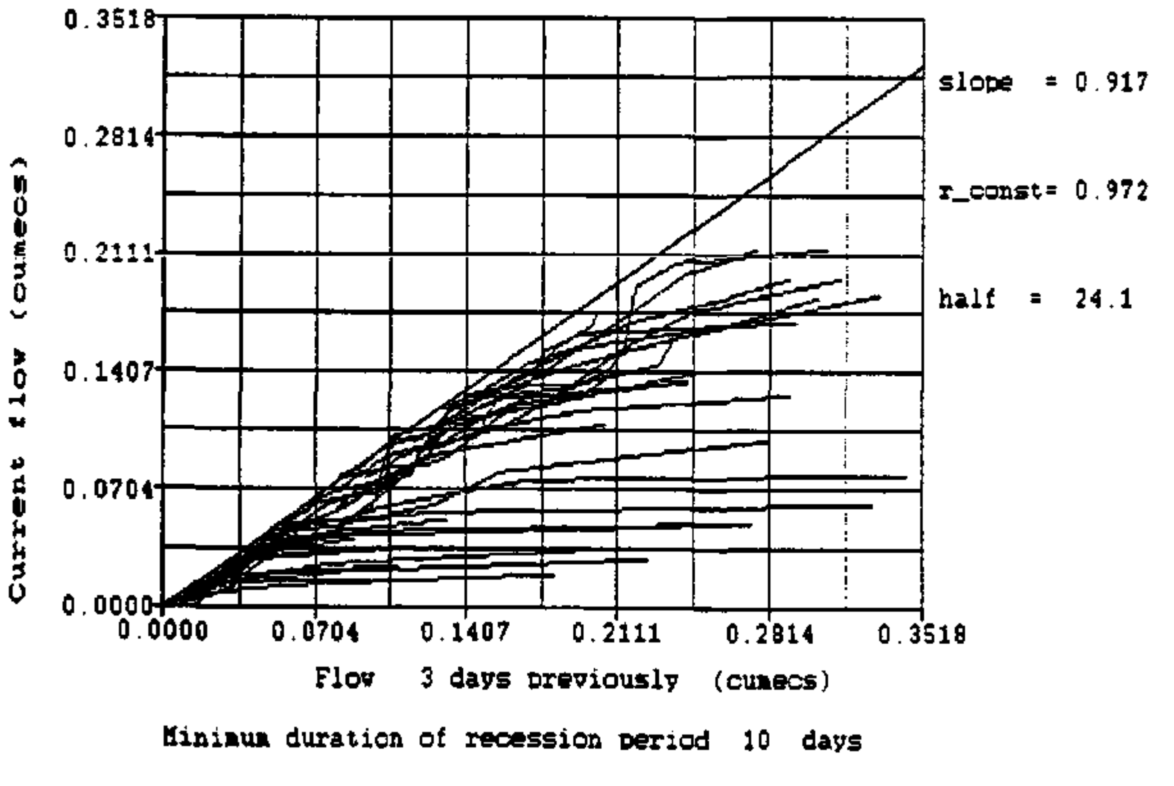


Figure. 2.9. Derivation of recession constant by 'correlation method', Diep River, South-Western Cape, SA (G2H012).

In the first approach the plot of 'current flow' ('today's flow') against the "flow *n* days ago" is constructed for all low-flow recession periods longer than *N* days. The envelope can be rather objectively defined if the number of individual recessions are large enough to show the region of their highest density (Fig. 2.9). Recession constant is easily calculated from recession equation if the slope of the master recession curve is known. The value of *n* is usually in the range of 1 - 5 days and the threshold value of *N* must be reasonably long to have a suitable number and duration of individual recessions (Institute of Hydrology, 1980; Beran and Gustard, 1977; Hall, 1968).

The matching strip method includes plotting individual recession curves on tracing paper and superimposing them on each other to construct a master recession curve. A reasonable result may be obtained simply by altering the vertical or horizontal scales of some individual curves (Nathan and McMahon, 1990). Alternative approaches for recession constant estimation have also been suggested (Petras, 1986; Bako and Hunt, 1988).

Most of the methods of recession analysis are rather subjective. Another approach is to deal with actual ratios of current flow to flow *n* days ago. This is calculated for every day when discharge is below the mean flow. All individual ratios are then ranked and cumulative frequency diagram is constructed to estimate, for example, a **recession ratio exceeded by 50% of recessions** - a straightforward index showing the average baseflow recession rate and assumed in some studies as a substitute for a 'true' recession constant (FREND, 1989).

The other useful measure of flow recession is the **"half-flow period"** (Martin, 1973) - the time required for the baseflow to halve (sometimes also referred to as a 'half-life'). Some authors consider it to be more physically meaningful than the recession constant and more "sensitive to differences in recession rates for slowly receding streams" (Nathan & McMahon, 1990).

The recession analysis is widely used in many areas of hydrological research, water resource planning and management. The usual applications are: short-term forecasting for irrigation, water supply, hydroelectric power plants and waste dilution, hydrograph analysis, regional low-flow studies etc.

Recession analysis (as well as baseflow estimation) has more than a century history in hydrology and it is virtually impossible to review it in full. Reasonably detailed reviews of recession analyses methods have been given by Hall (1968) and Tallaksen (1995).

Residual Flow Diagrams

Residual Flow Diagrams (RFD) provide a simplified catchment-wide picture of flow information. For a condition of interest (e.g. low flow, flood) they assess the quantity and quality of natural and artificial components of flow at any point along the river reach. The main advantage of these diagrams is a very convenient straightforward presentation of flow data, which allows a user to find information at the point of interest quickly. The main problem is that the RFD approach assumes that flow conditions under consideration exist simultaneously throughout the whole catchment. This may obviously not be the case, especially for large catchments. Nevertheless RFD may be beneficially used to present 'modelled' situations when, for example, low-flow conditions exist all over the catchment. Different low-flow indices derived from FDCs or LFFCs may be used for RFD. For convenience the flow plotted may be expressed in discharge, volume or percentage of MAR.

RFD may be of two types - **quantity diagrams** and **quality diagrams**. Quantity diagrams show the total quantity of water at any point in a stream by dividing this water into its natural and artificial components. The vertical axis represents distance downstream from the source, the horizontal axis is for natural and artificial flow data. The flow in a stream at every point along the distance is represented by the distance between natural and artificial flow lines In this format RFD are frequently used by UK National River Authorities (Pirt and Simpson, 1983; Fig. 2.10).

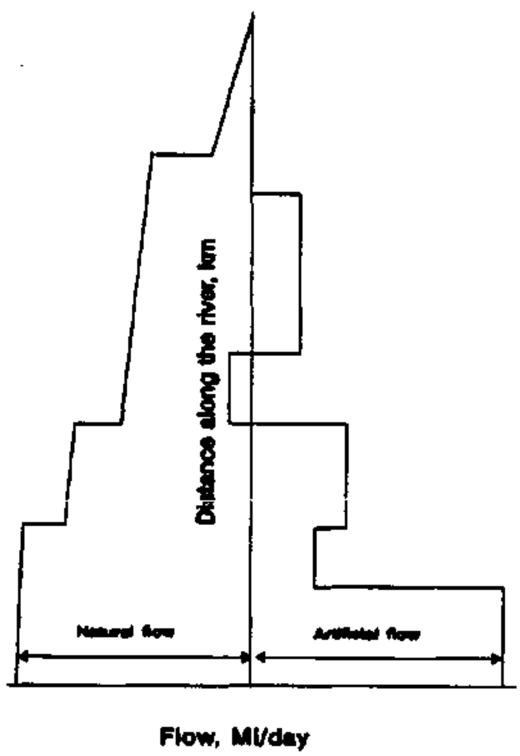


Figure. 2.10. Example of residual flow diagram. (A modified version from Pirt & Simpson, 1983).

If the data on artificial effluents of different types and abstractions are available for a stream under consideration - quality type RFDs may be constructed. They are still much the same shape as quantity diagrams but may additionally give some idea about the composition of water at any point in the stream. Alternative ways of presenting RFDs are also known from the literature (Task Committee, 1980; Domokos and Sass, 1990).

2.6. METHODS OF LOW-FLOW ESTIMATION FOR UNGAUGED CATCHMENTS.

Most of low-flow measures and calculation methods described above require adequate series of streamflow record which can only be provided for gauged catchments. Ungauged catchments pose a different problem. Possible approaches for low-flow estimation in ungauged catchments may loosely be classified into five groups.

1. Construction of regional relationships of particular low-flow characteristics with catchment physiographic parameters (regression models).

2. Construction of regional curves (flow duration curves, low-flow frequency curves etc.)

3. Use of catchments-analogues.

4. Regional mapping of low-flow characteristics.

5. Use of deterministic models to simulate required streamflow time series and estimation of low-flow characteristics from simulated (synthetic) series.

This separation is rather arbitrary and many regional low-flow estimation techniques incorporate elements of several approaches. Nathan et al (1988) described a system approach to follow while dealing with low-flow hydrology of ungauged catchments.

Regional Regression approach.

This is perhaps the most widely used technique in low-flow estimation at ungauged sites. It normally includes the three major steps:

- Selection of low-flow characteristic of interest. In some cases it is not a serious problem since many countries (USA, UK, Russia) have their "standard" low-flow statistics (design low-flows, prescribed low-flows etc.: Vladimirov, 1970; Characteristics of low flows, 1980; Gustard et al, 1992;) and it is clear what low-flow index (indices) needs to be estimated by regression model(s). In other cases the choice is not that obvious either due to different user requirements, or because of the limitations of existing streamflow database or because of the extreme spatial variability of low-flow river regimes (Australia, South Africa).

- Delineation of hydrologically homogeneous regions - actual regionalization. The regionalization of streamflow characteristics is based on the premise that catchments with similar geology, topography, vegetation and weather pattern would normally have similar streamflow regimes, e.g. if a continuous low-flow event (or a flood) happens in one catchment, it is likely to happen in a nearby one. This is however not always the case, since even two adjacent catchments may have rather different topography or other local anomalies. Hence it is possible to establish groups of similar catchments which may not necessarily be geographically contiguous. Consequently classification of catchments may be based either on standardised or non-dimentionalised flow characteristics estimated from available streamflow records in a region (King and Tharme, 1994; Haines et al, 1988, Hughes, 1987; Wiltshire, 1986) or on catchment physiographic and climatic parameters (Acreman and Sinclair, 1986) obtained from maps and hydrometeorological data (rainfall, evaporation). Application of regression technique to homogeneous sub-regions or groups is likely to improve the predictive ability of the final prediction equations. Grouping of catchments is usually performed by means of multivariate statistical analyses (e.g. Gordon et al, 1992, Burn and Boorman, 1993), or on the basis of cartographic information. Classification is normally required for large areas (countries, large regions/catchments) with varying physiographic conditions and may be skipped for smaller regions.

- Construction of regression model. This step in its turn includes selection of model type, estimation of regression parameters, assessment of estimation errors. Before usable regression relationships can be estimated, a certain amount of observed streamflow data should be available to adequately represent the variability of flow regimes in a region and to allow required flow characteristics to be estimated for the input in the regression analysis. The streamflow data used should represent natural flow conditions in the catchments: the derived relationships will most probably not work for flow regimes continually changing under man-induced impacts. Therefore, data selection is a very important step in regional analysis. It is also usually difficult to uncover true physical relationships using multivariate statistical procedures without prior knowledge of which basin characteristics should be included in the regression equation. Basin characteristics which are most commonly related to low-flow indices are: catchment area, rainfall parameters (most frequently - mean annual rainfall), channel and catchment slope, stream frequency and density, urbanization, lake and forest indices, various soil and geology indices, length of the main stream, catchment shape and elevation and some others. The "best" regression model is commonly estimated by means of stepwise regression approach when the model is derived one step - one independent variable - at a time (Haan, 1977, Gordon et al, 1992). Occasional attempts to apriory "fill" a future regression model with physical meaning have been reported (Vogel and Kroll, 1992). However, Nathan and McMahon (1992) correctly stated that regression models "...are in effect a 'black-box' solution to the problem... where only inputs and outputs have any real significance". In some cases the world-wide or local experience in constructing regional low-flow regression models may suggest the required set of independent physiographic parameters.

A number of regional models for low-flow estimation at ungaged sites have been developed in different parts of the world in the last several decades and the references are too numerous to mention. The results of regional regression analysis may range from "very poor" to "very good" depending on the quality and amount of streamflow data used, accuracy of independent catchment parameters estimation and amount of time spent on experimenting with different types of regression models. For example, Thomas and Benson (1970) found that average prediction errors in low-flow estimation may be at least twice as large as for flood estimation in the same catchment. At the same time the results of detailed regional low-flow studies in Australia seem very encouraging (Nathan and McMahon, 1992).

Regional prediction curves.

As opposed to estimation of a single low-flow characteristic for which regression model is available, this approach allows the range of low-flow indices to be estimated. Flow duration curves, low-flow frequency curves and low-flow-spell curves from a number of gauged catchments of varying size in a region can be converted to a similar scale, superimposed and averaged to develop a composite regional curve. To make curves from different catchments comparable all flows are standardised by catchment area, mean flow or "index" low-flow discharge.

A curve for ungauged site may then be constructed by multiplying back the coordinates of a regional curve by either catchment area or an estimate of the index low-flow depending on how the flows for the regional curve were standardized. The index flow is estimated either by means of regression equation or from regional maps.

Regional flow duration curves have been developed in a number of states in USA (Singh, 1971; Dingman, 1979), in Greece (Mimikou and Kaemaki, 1985), Philippines (Quimpo et al, 1983). The index flow used in many cases is Q50 (the median flow). Fennessey and Vogel (1990) used a different approach, approximating the lower half of daily flow-duration curves using log-normal distribution and developing regression equation for distribution parameters with catchment characteristics. In FREND (1989) low-flow studies observed daily flow duration curves have been grouped by Q95 flow value. Nathan and McMahon (1992) used the linearity of flow duration curve in log-normal space and defined the full curve for ungauged site by estimating only two flow values: 10% and 90% exceedence values (Q10 and Q90) estimated by means of regression models.

The principle of low-flow frequency curves construction and use is the same as in case of regional flow duration curves. Frequency curves are normally constructed using annual minima standardised by mean annual minimum flow. Various aspects of regional low-flow frequency curves are addressed in Vogel and Kroll (1990), Nathan and McMahon (1992), Pilon (1990), Tasker (1987), Tucci et al (1995).

Use of catchments-analogues.

If a regional relationship is not available and low-flow estimate is required for a single ungauged site the method of hydrologic analogy may be used. Only few measurements must be made at the site in an ungauged catchment during baseflow (low flow) conditions. These measured discharges are then related to concurrent discharges of a nearest gauged stream (with the analogous catchment properties) for which some basic low-flow measures, for example, low-flow frequency curve, has already been derived. The discharges from that curve are then transferred through the relation curve to obtain corresponding flows at the ungaged site (see for example Riggs, 1972). It should be noted however that the size of projects normally associated with small catchments may not justify the time and costs involved with short-term flow gauging. It is also not always a simple matter to identify a nearby gauged catchment from which it would be possible to confidently transpose low-flows.

Regional mapping.

Mapping of flow characteristics is based on a principle of existence of a "field" of flow and its relation with physiographic zonation of natural factors. A flow field is normally assumed to be contiguous, although this assumption is rather arbitrary since a field may have disruptions due to local factors the effect of which increase with the scale of study.

Flow maps are constructed using flow characteristics estimated from gauged data. The size of catchments used for mapping ideally should reflect the zonal type of flow regime. So very small rivers (where flow regime is normally a result of small-scale local factors) and very large rivers (flowing through several geographical zones) may not be selected for the purpose of mapping of flow characteristics. The choice of upper and lower threshold catchment areas is often rather arbitrary and may differ in different physiographic environments.

The most widely used approach in flow mapping is the construction of flow contour maps (Drayton et al, 1980; Vandewiele and Elias, 1995; Vladimirov, 1990, etc.). A flow characteristic estimated at any gauged location in a region is assumed to be representative for the whole catchment above the gauge. Therefore, calculated flow values are assigned to the centroids of gauged catchments. Flow contour lines are then constructed either manually by available computer packages. Automated contouring has advantages of efficiency and reproducibility, whereas manual contouring allows the exercise of potentially more accurate expert local knowledge, where it exist.

Alternatively regions are delineated with spatially homogeneous flow characteristics (Church et al, 1995; Arihood and Glatfelter, 1991), or interpolated grid data is used (Arnell, 1995).

The reliability of flow estimates obtained from maps depends upon a number of factors: the density of gauging network and quality of flow data used, variability of flow characteristic being mapped in time and space, the scale of the map and the contour interval, type of relief etc. At the same time, maps of flow characteristics provide an easy way of estimating required flows at ungauged sites, indicate the quantity of water resources available in a region, and may be a valuable water resource planning tool.

Deterministic modelling.

The alternative approach to low-flow estimation at ungauged sites is to utilise a time-series simulation method to generate a satisfactorily long length of streamflow data and to calculate a set of low-flow indices from the simulated series. A number of rainfall-runoff models of various types have been developed during the last decades and the references are too numerous to mention.

The difficulties with this method are associated with the reliability or representativeness of the model employed and the ability of the user to satisfactorily quantify the parameter values for the specific catchment under investigation. If the user has to rely upon calibrating the model against observed data, the constraints are similar to those that might apply to the regionalization approach described above. The question then concentrates on whether there exists enough faith in the ability to construct models which do not rely upon calibration to produce satisfactory results. These models would then require regional techniques for estimation of model parameter values which, especially in the case of a daily model, is a very difficult task even if the model is explicitly physically based.

However, the advantage of the modelling approach which makes it very attractive in many water related problems, is that, if an 'appropriate' model is used, it provides different users with a complete flow time-series from which various low-flow characteristics can be extracted. Another advantage is that various scenarios of water use development, land-use change and even climate change can be easily incorporated into the parameter set used to simulate the time-series and to examine their effects on the derived low-flow indices. Recent research in applied hydrological modelling indicates that in general terms, this approach is possible today.

2.7. THE SURVEY OF USER REQUIREMENTS FOR LOW-FLOW INFORMATION.

It is clear from the previous section that types of low-flow analysis are numerous and diverse and strongly depend upon the particular research or management task being solved. It is widely recognised in South Africa that surface water resources are limited whereas the population growth and consequent industrial and agricultural development permanently increase the pressure on the country's scarce water resources. The recognition of growing competing demands for water has lead to a dialogue between the different specialists involved in low-flow related problems, and has necessitated an understanding and appreciation of different points of view. The absence of any approved standard in low-flow analysis and estimation and/or interpretation of low-flow values also contribute to this dialogue.

In order to assess low-flow activities in the country from various perspective members of different scientific communities, engineers and managers were consulted by means of a survey. This approach has already been used previously in low-flow investigations elsewhere (USA: Task Committee on Low-Flow Evaluation.., 1980; Australia: McMahon, 1983) and was recommended by many concerned parties at the beginning of the Project.

The general objectives of the survey were:

- To define the community of current and potential users of low-flow and low-flow related information in southern Africa;
- To clarify the requirements of these users;
- To clarify the needs (if any) and ways for improvement in data availability and other activities associated with low-flow problems in the country.

The questionnaire was directed at different institutions in South Africa and several neighbouring countries - water authorities, engineering consultants, research groups and environmental bodies. The issues raised in the questionnaire were designed to cover a wide range of low-flow problems. They included aspects of the required resolution, types and areas of application of low-flow information, specific low-flow indices, typical problems faced when dealing with low flows etc. (the questionnaire form is presented in the APPENDIX A1). Of the 58 questionnaires sent out, 20 replies were received (34% return rate). Of the 20 respondents, 8 were researchers, 8 engineers and 4 university lecturers. These respondents represented 8 universities, 7 consulting agencies and 2 government departments (in South Africa and Namibia). Although the reply rate appeared to be relatively low compared to other similar surveys mentioned above, most of the replies were rather detailed and it was assumed that these respondents (and institutions) may be considered as a "representative sample" of the community of interested users. The results of the survey are summarised below according to the major groups of issues raised in the questionnaire. Every respondent had an option to indicate several possible answers (or add any additional comments), so the total reply rate for each particular question may exceed 100%.

Range of interests in low flow.

Most of the respondents indicated that their interest in low-flow problems is related to the assessment of environmental impacts (65%), water resources research (55%), water supply design and water quality management (50%). Specific areas of interest indicated were waste load allocation, river pollution by mining activities, estimation of groundwater recharge to lakes through the assessment of low flows for the contributing rivers, conservation of biotic diversity. The responses to this question were highly influenced by the functions performed by the particular respondent and/or institution.

Types of low-flow information required.

70% of the respondents required streamflow duration characteristics (annual or seasonal), low-flow frequency characteristics and recession rates, while 40% indicated that they required data on baseflow conditions and characteristics. Generally, most of the respondents felt that the duration, frequency and magnitude of low-flow events already cover the range of (either existing or required) low-flow characteristics. Both monthly and daily data are the most commonly used types of data time resolution with a slight preference for daily data in research field.

Specific low-flow indices/measures.

Specific low-flow characteristics used by respondents mostly include the flow of prescribed (or otherwise fixed) probability of exceedence (65 %) or flow of a particular return period (50 %). Some require knowledge on any baseflow characteristics (25 %). A few respondents recognised the potential of spell analysis for their purposes (however, it is not used because of the absence of a relevant software). Others mentioned 'minimum extractable flow to sustain viable irrigation schemes', a ratio of river flow/tidal prism, multi-year flow volume statistics, percentiles of daily flows, probability of no-flow conditions, return period of low flows of stated duration etc. The answer to this question was highly influenced by a degree of involvement of each respondent in low-flow problems and his/her exposure to the world's experience in low-flow studies. Some respondents left this question unanswered.

Application of low-flow data.

80% of the respondents use low-flow data for different kinds of analysis, 70% for management purposes, 55% in planning and 45% in design. Specific applications include the improvement and/or testing of prediction techniques, estimation of maintenance flows, and general understanding of the functioning of natural and disturbed river systems in stressed conditions.

Alternative methods used when low-flow information is not available.

70% of the respondents tend to use simple generalised relationships (if those are available), 65% use simulation approaches, and 40% consult outside experts. Fewer seem to prefer the "trial and error" approach or "rely on experience and engineering judgement" (10%). Short-term continuous measurements at the site of interest were also mentioned.

Problems experienced in low-flow hydrology at present.

Most of the respondents indicated the lack of gauging weirs and poor maintenance of existing ones, which usually results in unreliable and inaccurate data for any flow magnitude and for low flows in particular. Other respondents stressed the lack of acceptable and accepted statistical distributions for low-flow extremes. Some found defining low flows a problem. Some respondents were hesitant as to what flow criteria to use for their specific purposes. Some stressed the expected difficulties in defining regions with typical low-flow behaviour since low flows are not homogeneous and highly variable in arid and semi-arid regions. Many problems outlined by the respondents are related to man-induced impacts on low flows such as the influence of afforestation, irrigation, dams and water supply schemes. Some respondents indicated that a distinction needs to be made in the flow records between natural low flows and low flows influenced by abstraction and/or augmentation. The need for natural low-flow characteristics was emphasized.

Expectations.

Almost all respondents felt that the associated benefit from future low-flow studies could be the development of ways to improve water and water quality management during low flow events, an understanding of the low-flow limitations of a catchment during drought and improved statistical reliability in low-flow data. 65% of the respondents would like to have standard procedures for low-flow analysis. Many respondents stressed the necessity to develop regionalized relationships between low-flow characteristics and catchment or climatic parameters, while others preferred low flows to be addressed in terms of deterministic modelling (generation of usable flow time series data, enhancement of groundwater components of models etc.). Some respondents expressed the need for the 'establishment of regional low-flow indices' that would 'represent' low-flow regimes in an area and would be most frequently used in that area for most of the envisaged low-flow problems.

General comments.

The survey highlighted several important issues.

- One is that although most of the respondents are aware of the existing major groups (or categories) of low-flow measures, only a small proportion of these measures (usually the most straightforward) are actually used by design engineers, planners or even practising hydrologists. The problem is exacerbated by the fact that no guidelines exist in South Africa to suggest which low-flow indices are the best to use for different purposes. It appeared to be questionable whether indices that only apply to low flows should be selected or whether more flexible indices of streamflow behaviour would be of greater value. The general tendency seemed to be that a variety of low-flow indices should be examined in the South African context and recommended together with methods and facilities to estimate them.

- It has been recognised that non-hydrologists sometimes have difficulties in specifying their requirements for low-flow hydrology and that hydrologists should provide a link before general rules and/or recommendations can be established. The absence of common terminology appeared to be a serious problem.

- There appeared to be a necessity to base further low-flow studies on data with a daily time resolution although possible correlations with monthly data should be investigated since many specialists in South Africa use monthly data to perform their functions (the consequence of widely used Pitman monthly rainfall-runoff model and the well known volumes Surface Water Resources of South Africa, 1981, updated in 1994).

- There were requests to standardize the methods of low-flow analysis and prediction to a reasonable degree and there is therefore a perceived need for flexible multipurpose software for low-flow analysis. The development of a nation wide low-flow data base coupled with low-flow prediction methodology should be considered as one of the challenging aims of low-flow studies. This database should probably include a variety of calculated low-flow characteristics for all gauged catchments which will supply potential users with a set of indices to select from for their individual purposes. The database should ideally include the low-flow characteristics that represent both present and natural conditions and thus certain procedures to naturalise low-flow indices for disturbed catchments should be developed and implemented.

The questions asked in the questionnaire covered a diversity of low-flow aspects in southern Africa. At the same time these questions appeared to be rather general which made it difficult in several cases for respondents to properly formulate their answers. This generality to a certain degree reflected the desire of the Project team at that time to address as many low-flow problems in the country as possible. It was expected that the questionnaire would indirectly contribute to the clarification of the research priority of the Low Flow Project and in this respect the questionnaire has been successful. The clarification of user requirements however in many possible ways continued throughout the whole course of the Project.

2.8 LOW FLOWS AND INSTREAM FLOW REQUIREMENTS

From the survey results it became clear that one of the primary users of low-flow information in the country is the Instream Flow Assessment (IFA) process which includes the determination of the required nature of a river's modified flow regime. This regime is described in terms of month-by-month daily flow rates (known as Instream Flow Requirements - IFR) which should maintain the river in a prescribed ecological condition (and/or satisfactory status for downstream users) after any water resource development. The process normally involves a multidisciplinary team of specialists from aquatic ecologists to water engineers and is currently implemented in any river system where such water resource developments are planned.

The components of a flow regime which are considered important for the estimation of IFR include low flows, small increases in flow (freshes) and small and medium floods. Large floods which cannot be managed are normally ignored.

The Instream Flow Requirements have the following objectives:

- To establish low-flow and high-flow discharges for ecological river maintenance for each of the 12 calendar months of the year. Additional information that describes the required duration of high-flow events and the severity of low-flows (in terms of their percentage time exceedence) is often also included.

- To determine minimum flow requirements during drought years. These are also determined as a set of month-by month daily flow rates and are viewed as the flows which could prevent the irreversible damage to the river system during extreme droughts.

- To estimate the total water volume (ecological water demand) that will be required to be released to maintain the desired ecological state of the river after the water resource development has been implemented. This flow volume is normally expressed in both volumetric units and percentages of natural and present day MARs.

The IFA process requires the description of (preferably) natural flow regime and the streamflow time-series data with daily time resolution. IFR are estimated at several different sites below the proposed impoundment or other water resource development. It is therefore clear from the above that the estimation of IFR is a very information consuming process where the hydrological information (including low-flow data) is a basic need and at the same time a primary component for final recommendations. It is therefore important that the current Project contributes to the IFR estimation by the development of relevant analytical techniques and time-series generation methods.

3. DEVELOPMENT OF METHODS AND SOFTWARE FOR THE ESTIMATION OF LOW-FLOW CHARACTERISTICS

3.1 INTRODUCTION

The brief literature review of low-flow estimation methods and the survey results indicated that to meet the needs of different users of low-flow information, the range of existing estimation techniques should be considered and evaluated in terms of their accuracy and acceptability for South African conditions. Since the objectives of the Project also imply that a number of different flow data sets all over the country are to be processed to allow a variety of low-flow analysis to be performed, the attempt should be made to standardize low-flow estimation techniques to a reasonable degree.

Thus it became obvious that further work would be very dependent on the availability of a relevant software package which should:

- allow various techniques to be utilised in a readily accessible computer form;
- be applicable to flow data sets with different origins (either observed or simulated by an appropriate model), size and time resolution (daily or monthly);
- facilitate automatic estimation of various low-flow indices required by different users and needed to characterise low-flow regimes (as well as changes in low-flow regimes) of a large number of rivers in the country;
- allow the evaluation of selected daily model(s) ability to specifically simulate low-flows in natural and disturbed conditions.

It was taken into account that no appropriate software of this kind was available for these purposes in South Africa and that commercially available statistical and hydrological packages are either not designed to serve these purposes at all, or are in this or that way limited in their applications. It was expected that besides its usefulness for low-flow studies the software along as a product of the Project would find application in water management practices and water scheme design, would be appreciated by aquatic ecologists and other specialists involved in formulation of Instream Flow Requirements etc.

3.2 LOW-FLOW ESTIMATION SOFTWARE AS PART OF HYDROLOGICAL MODELLING APPLICATION SYSTEM (HYMAS).

The development of low-flow software was carried out within a more general computer system HYMAS (HYdrological Modelling Application System) which has been developed at the Institute for Water Research previously. HYMAS represents a flexible environment in which to set up and run hydrological models and to analyze observed and simulated hydrological variables (e.g. Hughes, et al.,1994). The system is written in 'C' code to make use of the features of modern high speed microcomputers and makes extensive use of computer graphic facilities. The general structure of HYMAS is presented in Figure 3.1.

The main HYMAS menu gives access to any of the estimation options and utilities included in the system (later include file management and editing, binary file listing, access to spreadsheet etc.). The system uses the concept of setup (project) file which has to be established by the user for any application. Project file contains the information on the location of data files required for the application as well as their status (file exists, number of files matching a wild card specification etc.) A project file can be created, edited, deleted or selected from already existing setup files (to repeatedly run a model and/or analyze its results).

Physiographic data generation is designed to create a file of physiographic variables (topography, soil, vegetation) for each selected subdivision in a catchment. Some physiographic variables are primary and can be estimated from maps, field experiments or literature sources, the other (secondary) are estimated from primary variables. The established physiographic file is then used to calculate model parameter values. Some of the parameters however have to be input directly. Facilities are available for parameter value editing (e.g. at the stage of model calibration) and changing in time (time slicing).

"Model execution" (Fig.3.1) is used to run a model. The input to a model normally consists of file(s) of time series data (rainfall, observed discharge, upstream inflow etc.) and a parameter file.

Time series modules include establishing time series input to models by converting original data files available in several different formats to a standard internal system format, generating time series graphs, plotting scattergrams of variable pairs (e.g. observed and simulated) and calculating comparative statistics, examining seasonal distribution of hydrological variables, plotting the actual daily hydrographs in wet, dry and intermediate years, analysing the variability of daily flows within particular months etc.

Low-flow estimation forms a large part of the whole system and contains several modules which are described in more detail in the following sections. Overall, HYMAS is a comprehensive system which allows a variety of hydrological analyses to be performed with a high degree off efficiency, which is very important for processing a large number of data sets. HYMAS has been distributed to several research institutions and consultancy companies in southern Africa and overseas.

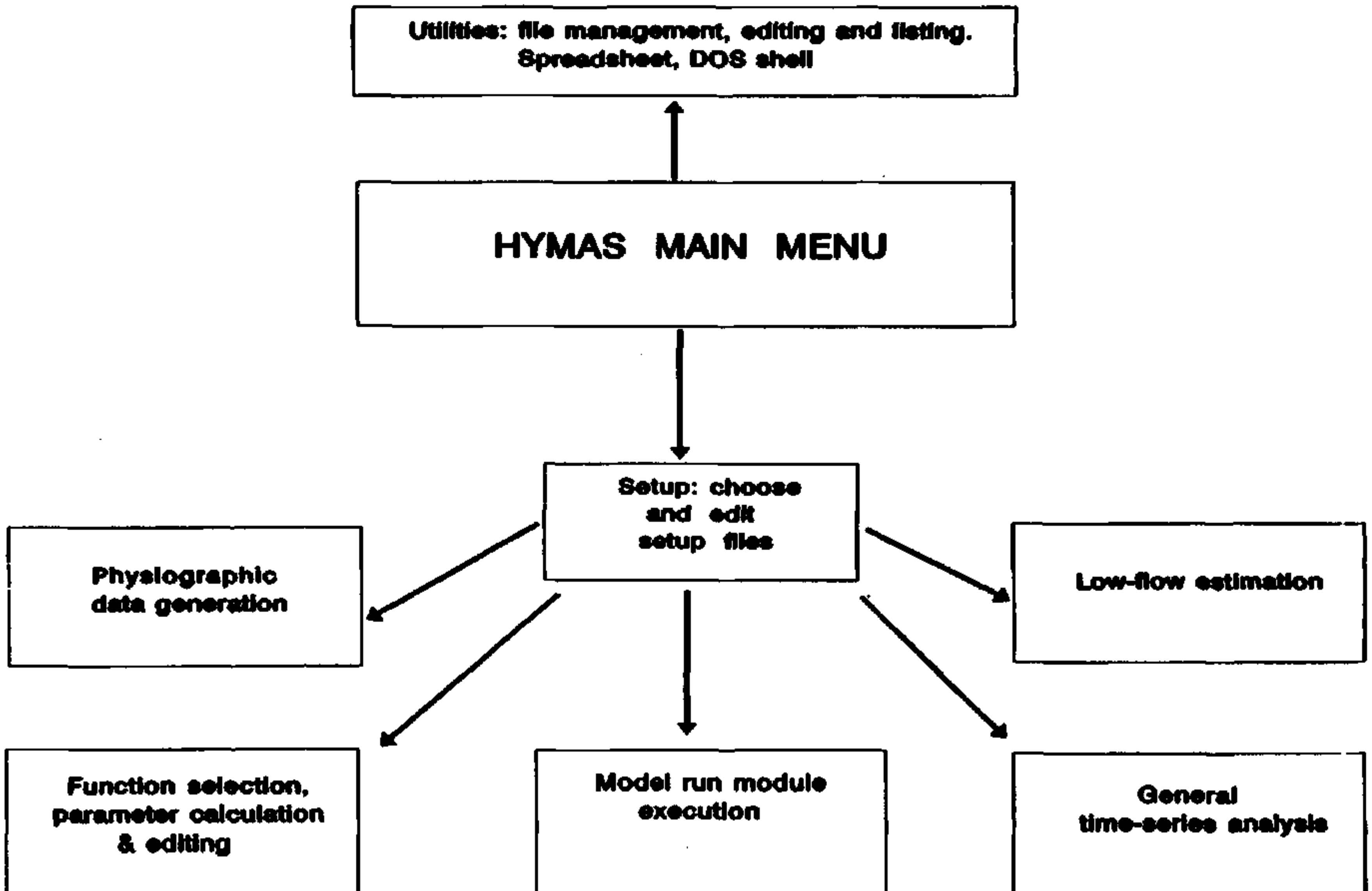


Figure 3.1 *General structure of HYdrological Modelling Application System (HYMAS).*

3.3 LOW-FLOW SOFTWARE : GENERAL.

The developed computer package for low-flow estimation and analysis includes the following methods: i) flow duration curve construction along with the interactive facility to extract the required low-flow indices; ii) analysis of frequency, magnitude and duration of consecutive low-flow events; iii) baseflow separation procedures; iv) calculation of recession properties of a stream; v) low-flow frequency analysis.

The software developed can give answers to a number of questions which normally arise when analysing the low-flow regime of a river. Some of them are:

- How long within a particular year, month, season (or on average within a year, month, season) a specified flow value is exceeded, or vice versa - what is a flow value of the specified time of exceedence ?

- For how long on average or within a particular year, month, season a river stops flowing (what is the time spent at zero flow conditions) ?

- What are the values of various low-flow indices relative to the corresponding mean flow ?

- How long do the consecutive low flow events below the specified flow value of interest last (in a month, season, year) ?

- How large the deficit can be built during consecutive low-flow events (in a month, season, year) ?

- What is the flow volume (as opposed to the deficiency volume) during the consecutive low-flow event(s) (in a month, season, year) ?

- What is the probability\return period of the drought of the specified magnitude or vice versa: what is the magnitude of the drought of the specified probability\return period?

- What is the probability\return period of the low-flow of specified magnitude and duration (and vice versa) ? What is the mean minimum flow for specified probability\return period (and vice versa) ?

- How fast the flow is receding in the absence of rain and what is the relative contribution of baseflow generated from subsurface stores to the total flow in a catchment ?

- What is the driest month (season), how variable are the flows during that month (season) and what is the proportion of its flow to the annual flow etc.

Some of the methods included in the package (like flow duration curves and spell analysis) are applicable to more than just low flows and can be used to analyze the aspects of the complete streamflow regime, the others are related to low flows directly. Low-flow estimation software has been described in several publications (Smakhtin and Hughes, 1993; Smakhtin, et al, 1995). A theory behind each of the methods used is summarized in Chapter 2 and the description of particular modules is given below.

3.4 FLOW DURATION CURVE.

A Flow Duration Curve (FDC) shows the percentage of the period of record during which a river contains less (or more) than a given flow. The program developed (SUMM_DT) allows FDCs to be constructed for data with daily, monthly or variable time resolution. The analysis can be carried out using the complete time series available or a shorter period within it. For example, FDCs may be constructed for each year of record or for two parts of the record, e.g. prior to and after the construction of a reservoir upstream of the gauge being analyzed. All months of the year can be selected from a tag list of months to construct annual FDC. Alternatively specific months (e.g. all Januaries in a record period) can be selected to construct typical FDCs for each month of a year. By the same token, typical seasonal FDCs can be obtained.

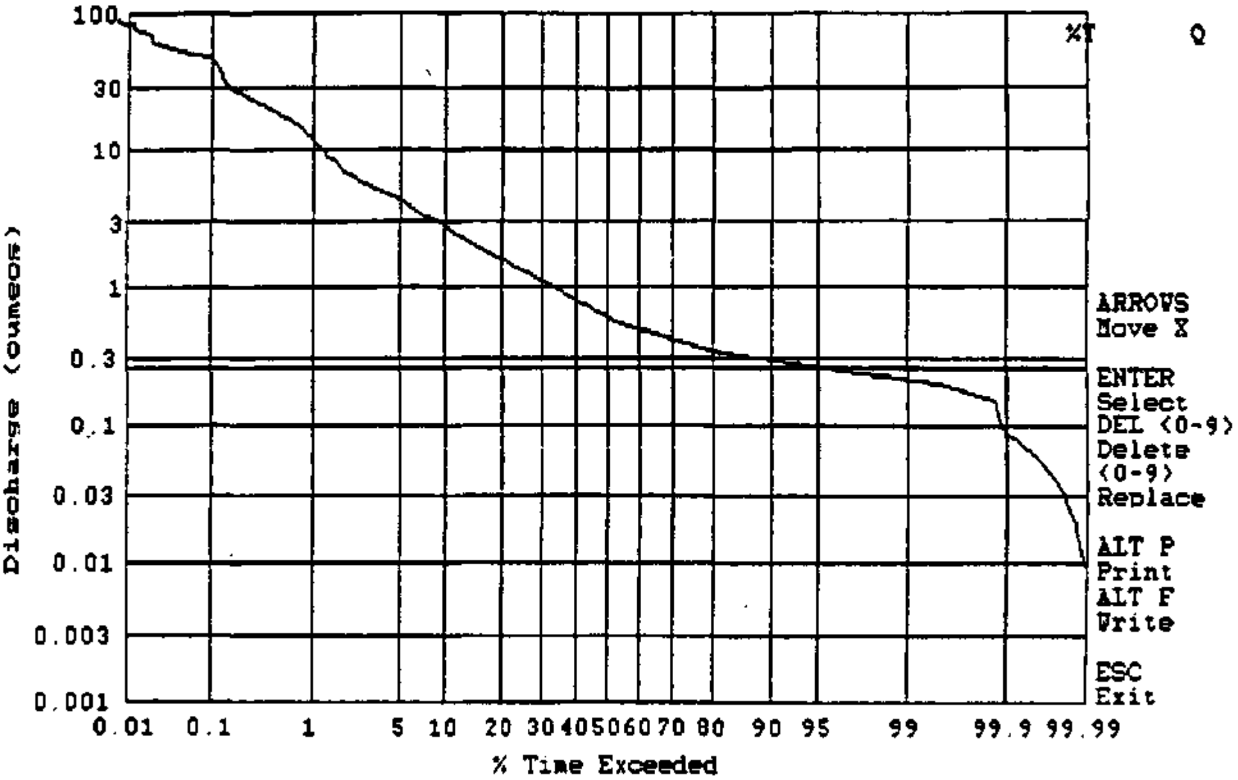
The moving average procedure may be applied to the original data to construct a new time series where each flow represents the average value during *n* consecutive days (in case of daily flow data) or *n* consecutive months (in case of monthly data). The desired *n* value can be selected from a tag list. This option allows the estimates of such indices as 7-day average flow exceeded 75% of the time or 30-day average flow exceeded 95% of the time (or other similar indices) to be made.

The flows for the curve may be expressed in the original data units (m^3/s, Ml) or as percentages of mean flow. The latter option facilitates the comparison of FDCs between catchments of different size which is very useful in regional studies..

The program allows the user to move to any point on the curve and determine the flow rate and percentage of time this rate is equalled or exceeded. The coordinates of the curve for 17 fixed percentage points can be printed or written to a text file for further analysis if required (e.g. using a spreadsheet package). The example computer screen is shown in Figure 3.2.

3.5. SPELL ANALYSIS.

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 its duration and deficit or deficiency flow volume, which would be required to maintain the flow at a given threshold. Spell analysis is effectively a frequency analysis of these two variables.



Discharge: 0.258 cumecs Percentage Time Exceeded: 95.00 %

Figure. 3.2. A computer screen with example annual 1-day flow duration curve.

The software includes two different methods of spell analysis. In the first the duration and number of spells below any selected threshold is calculated and the results are plotted on the screen in the form of a histogram and a cumulative frequency curve. A similar approach is followed for deficiency volumes. In this method all spells below a specified threshold are extracted from a streamflow series regardless of how many of them may be found in each particular year. The actual flow volume during continuous low-flow events can also be extracted on request of a user. That allows a 'spell regime' of a river to be analyzed in three different ways (as opposed to two in conventional spell analysis): in terms of duration of spells, their deficits and their actual flow volume during each event.The duration of spells is expressed in days or months (dependent on the data used) while flow deficits and actual flow volumes are expressed in % of MAR.

This first method gives an impression of spell variability, or how responsive the river is, and the cumulative spell frequency curves may be perceived as showing the probability that a low-flow sequence below selected threshold will last for a given duration (or longer, fig.3.2). The program also calculates the minimum, mean and maximum value for spell duration, deficit and flow volume, standard deviation for each variable and allows the spells in a particular range specified by the user to be examined in detail. The module is conveniently linked with the flow-duration curve from where the set of threshold discharges can be

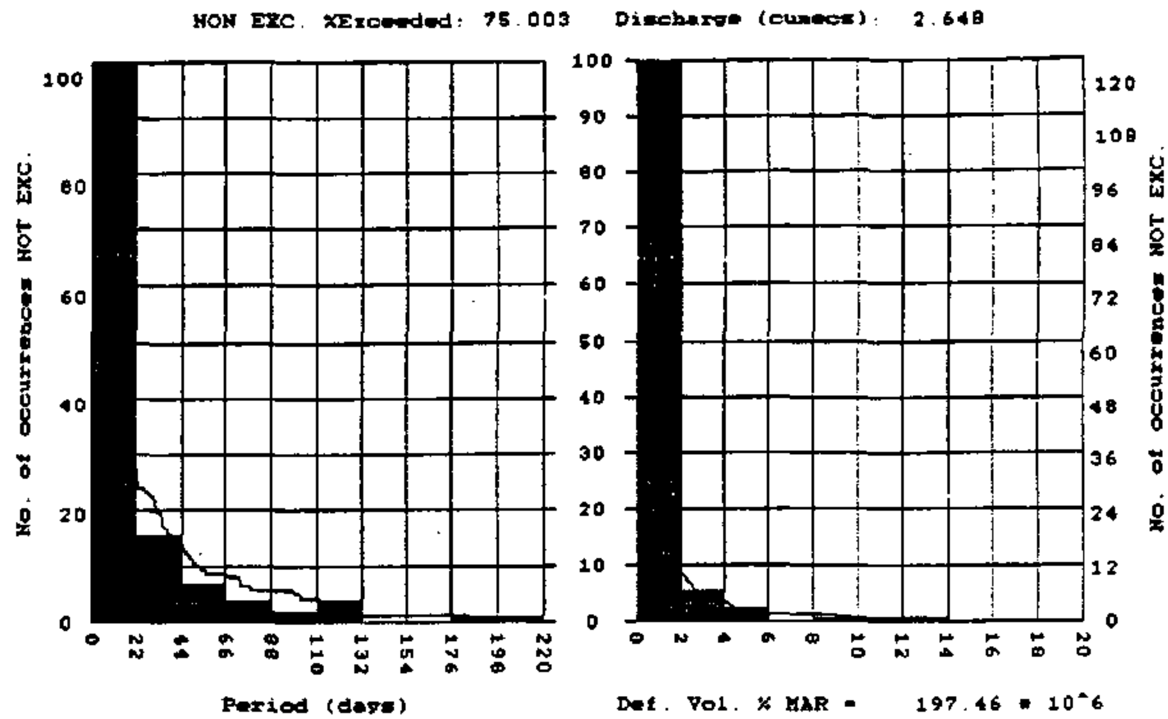


Figure 3.3. *Example computer screen with results of spell analysis for the Sabie river at gauge X3H006 (method 1). The threshold flow is Q75. Left diagram shows the frequency histogram and cumulative frequency curve for duration, the right one - for deficits.*

selected. The table of spell characteristics may be printed or written to a text file for further analysis.

This method may also be applied to analyze spell characteristics above any selected threshold. By the same token a number of spells above a threshold, their durations and flow volumes are extracted and plotted in a similar way. The user may toggle between 'non-exceedence' spells (spells below threshold flow) and 'exceedence' spells (spells above threshold flow). With respect to low flows this option may be useful for example; to analyze the characteristic duration and flow volume of 'freshes': short-lived peaks during a prolonged low-flow events and is of value from ecological point of view.

The second part of spell analysis (module SUMM_SP) deals with the annual series of maximum spell duration, deficiency volume and actual flow volume extracted from each year of record. The series is then used to estimate the probability and/or return period for an event of a specified magnitude or vice versa. The extracted values are assumed to be log-normally distributed and are plotted in log-normal scale (Fig.3.4). Some ordinary statistics

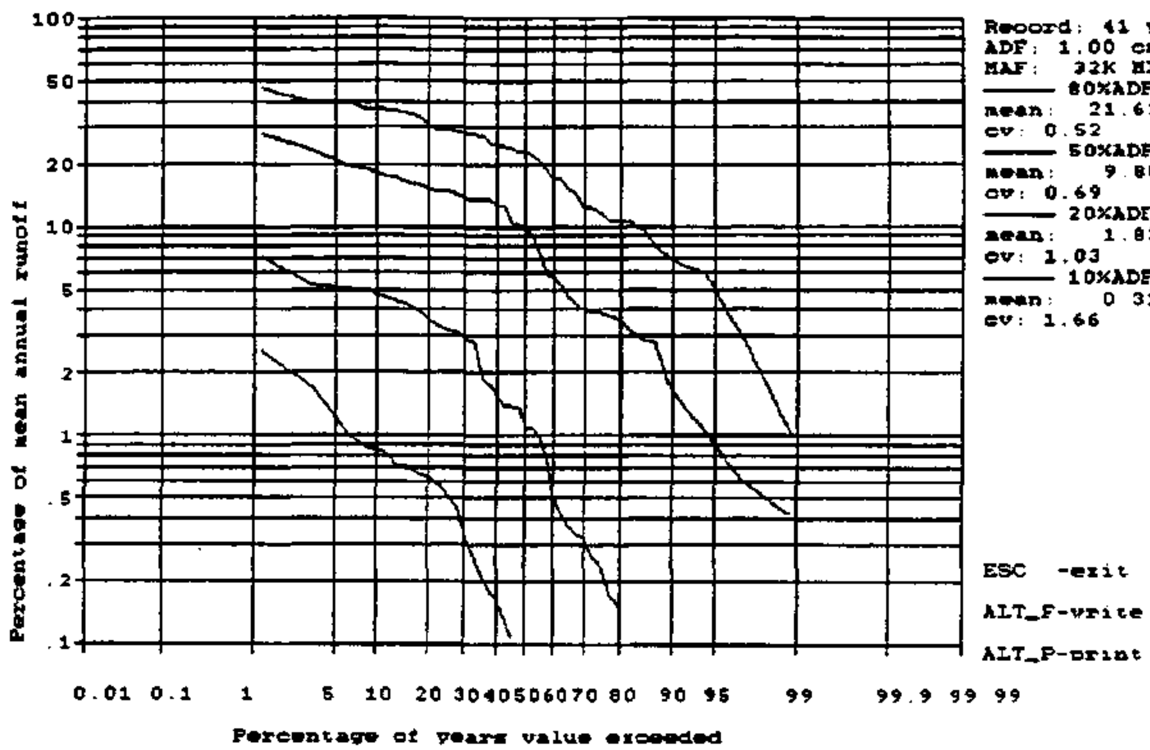


Figure 3.4. *Example computer screen with empirical probability curves of annual deficit maxima below thresholds of 80, 50, 20 and 10 % of Average Daily Flow (ADF; method 2) for the Klaaser River at gauge B7H004. The top curve represents the results for the threshold of 80% ADF, the bottom one - for 10% ADF. The mean and CVs for each deficit maxima series are shown in the top right corner in the same order as curves (from top to the bottom).*

are also displayed on the screen. The thresholds are selected from a menu of fixed values representing percentages of either mean daily (daily data) or mean monthly (monthly data) flow. The range of selection is from 100 to 1% of mean flow. The program allows up to 5 empirical frequency curves to be constructed on one screen. All extracted spell characteristics may be printed or written to a text file for further analysis.

Likewise flow duration curve, both types of spell analysis are applicable to daily and monthly data and the analysis may be carried out for specific months or seasons extracted from each year of the record, or for different continuous lengths of period within the complete record. One should however always bear in mind that the smaller the period of record used for the analysis and the lower the specified threshold flow, the smaller is the final number of spells which may be extracted for analysis. This is especially critical for the second method where only one spell from each year of record (with maximum duration or deficit, whichever is specified as the primary variable) is extracted.

The start date for analysis should preferably be selected coincident with the first day of the typically wettest month of a year to avoid the situation when a continuous low-flow event is split between two consecutive years. In the latter case (which is again especially dangerous for the second method described) the program will extract pairs of dependent values and the results of spell analysis are hardly useful.

3.6. RECESSION ANALYSIS.

Recession analysis is used to estimate the rate at which flow recedes in the absence of rain. The range of existing methods is very wide and continue to grow. For inclusion in the software package it is necessary first to select from the existing techniques, taking into account the possibility for automatization, since a number of techniques may not be easily computerised. Certainly such aspects as objectivity, accuracy of the estimates of recession properties and simplicity should also be considered.

Several methods of recession analysis were examined and two techniques readily amenable to automation have been selected: the correlation method and frequency method.

The flow recession is presented by a recession limb - the decreasing portion of streamflow hydrograph during a dry period. Thus for both methods, a number of recession periods is first derived from the original data. These periods are selected only from those portions of the hydrograph where the discharge is less then mean daily flow. Only "smooth" limbs are considered; recession periods interrupted by insignificant short-term increases in discharge are not included in the analysis.

The correlation method provides the estimates of the baseflow recession constant and involves plotting the current discharge against discharge several days ago for each day during every recession period selected. These points are then linked and the trace of every individual recession period is constructed. The number of traces represents the recession domain. The enveloping line drawn along the upper boundary of this domain represents the master line of recession. The slope of this line is used to calculate the recession constant from the exponential recession equation of the type

$$Q_t = Q_0 K^t \qquad (3.1)$$

where Q_t is the discharge at time t, Q_0 the initial discharge, and K is the recession constant. The recession constant K is thus a function of the slope of the correlation line (Q_t/Q_0) and the lag interval t

$$K = (Q_t/Q_0)^{1/t} \qquad (3.2)$$

and the correlation line is represented by a master line of recession.

Once the recession constant has been estimated, the time necessary for baseflow to decrease to any degree may be obtained. The program calculates the value of the half-flow period (HFP - time required for the baseflow to halve)

$$HFP = \ln(K)/\ln(0.5) \qquad (3.3)$$

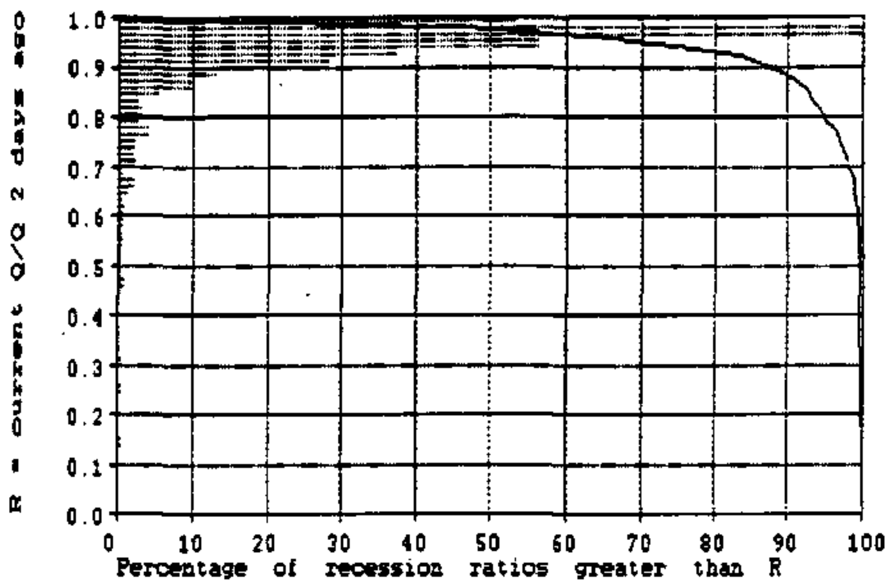
The values of K and HFP are displayed on the screen (see Fig.2.10, Chapter 2). The minimum duration of the recession period and the time lag between neighbouring discharges should be specified at the beginning of the program run. The length of the recession limb affects the number of recessions included in the analysis and generally should not be very large to allow for a reasonable number of recession limbs to be extracted from the flow record to satisfactorily define the recession domain on the plot. A series of test runs with different minimum durations of recession period for several rivers were conducted, and a value of 10 days was found suitable for most of the cases, but for flashy streams this value needs to be as small as 6-8 days. In each particular case the user is encouraged to experiment with different minimum durations of recession period.

The time interval between neighbouring discharges may have a significant effect on the accuracy of estimates, and generally several runs with different lags are required to obtain averaged results (Table 3.1). It can be seen from the last two comments that the correlation method remains rather subjective. Further complication is that for very slowly receding streams (recession constants in excess of 0.997) the application of this method was found to be very problematic due to the difficulties involved in the construction of a reliable master recession curve.

Table. 3.1. Recession properties for several SA rivers estimated with different lag intervals.

Station code	A6H011			G2H012			B7H004			K4H001		
Time lag (days)	2	3	4	2	3	4	2	3	4	2	3	4
Rec. constant	.992	.992	.990	.971	.972	.972	.996	.996	.996	.988	.988	.989
HFP (days)	84	84	68	24	24	24.5	166	167	167	56	56	61

The second method involves the calculation of ratios of the current discharge to the discharge n-days ago. Again the ratios are calculated for every day in each known recession period, and then ranked and assigned to class intervals to construct a frequency diagram and cumulative frequency curve (Fig. 3.5.). The ratio exceeded by 50% of recession ratios, derived from that curve, is perceived as a low-flow index showing the average expected rate of recession. The whole procedure is generally objective and it doesn't assume a particular mathematical form for the recession model. In order to produce a unique result from a given daily flow series the values of a minimum recession period and a time lag between neighbouring discharges should be set to 1. The table of values that make up the frequency diagram may be printed or written to a text file.



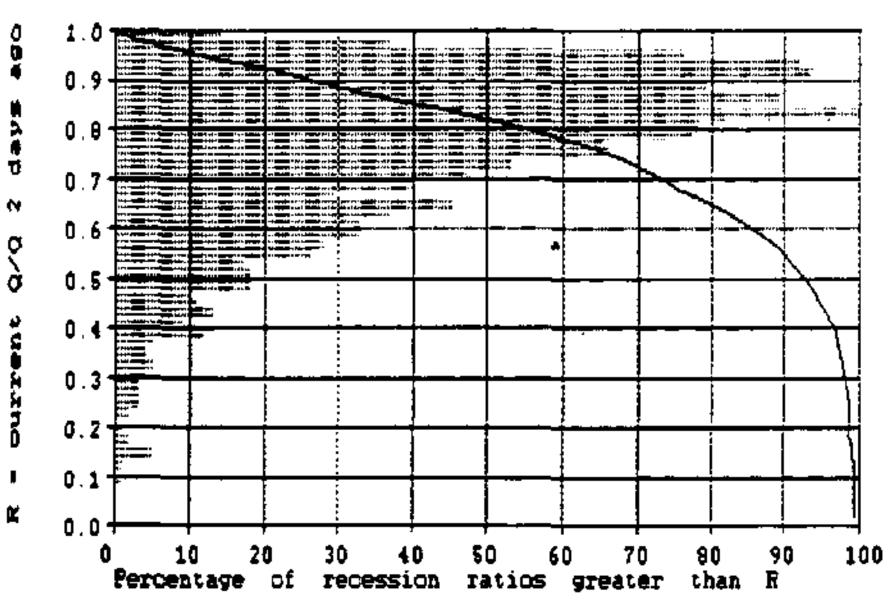


Figure 3.5 *Recession frequency graphs produced by 'ratio' method for: (top) the Ncibidwane River (V7H016) and (bottom) the Hoekraal River (K4H004).*

Although the derived recession index can hardly be equated with the baseflow recession constant, the procedure is rather straightforward, can give a rough estimate of an average baseflow recession rate, and is utilized also for the purposes of comparative analysis of observed and simulated low flows as an additional test of model performance in the lower portion of the hydrograph (e.g. Chapter 5). It also may be used for comparative analysis of recession properties of different streams as illustrated by Figure 3.5.

3.7 BASEFLOW SEPARATION.

Two baseflow separation techniques are incorporated into HYMAS low-flow estimation package. They are aimed at estimation of a long-term baseflow hydrograph and the derivation of a baseflow index (the volume of baseflow divided by the volume of total streamflow) which was reported to be closely related to other low-flow indices and catchment parameters (Chapter 2).

The first method makes use of a digital filter which separates "high-frequency" quickflow from the original streamflow. The difference between these two variables gives the estimate of "low-frequency" baseflow:

$$q_t = aq_{t-1} + 0.5(1+a)(Q_t - Q_{t-1}) \quad (3.4)$$

$$Q_{bt} = Q_t - q_t \quad (3.5)$$

where q - quickflow (high frequency signal), Q - original streamflow, Q_b - baseflow (low-frequency signal), a - filter parameter. The filter is commonly used in signal analysis, from where the terminology is taken. The filter parameter in the range of 0 - 1, should be specified for that procedure. A number of test runs on several rivers showed that acceptable results may be obtained using a filter parameter value of 0.995. It was recommended by Nathan and McMahon (1990) that the filter should be passed three times over the data - forward, backwards and forward again to obtain smooth results. It was noted however that in most of the cases one pass forward was enough to obtain meaningful baseflow hydrographs.

The second method (provisionally entitled 'rational method') is based on the results of the recession analysis. The recession estimation procedures supply this method with the set of nodal points in the original streamflow hydrograph - the ends of known recession periods - where the quickflow is assumed to be zero and thus discharge is generated only by baseflow. The "flat" areas below mean daily discharge (if those exist) in the original streamflow hydrograph are also assumed to be composed of baseflow only. The program interpolates between the determined non-zero baseflow values to obtain baseflow discharges for the other days.

The shorter the minimum specified duration of recession period, the more nodal points are originally involved in the separation procedure and thus the more efficient is the procedure itself. Trials have shown that in most cases physically meaningful baseflow hydrographs may be obtained if the minimum specified duration of the recession period is in the range of 6-8 days. The procedure may be further modified and probably improved if the days with the 50 percentile recession ratio (derived from recession analysis) are also used as nodal points.

In both methods the resultant baseflow is constrained so that it is not negative or greater than the original streamflow. Both techniques generally produce acceptable baseflow hydrographs (Fig. 3.6) and in most cases - comparable estimates of the baseflow index. The 'rational method' was developed in IWR as a pragmatic alternative to digital filtering which was found to have a tendency to overestimate baseflow, especially for highly intermittent streams (table 3.2) as it often creates excessive baseflow for isolated relatively short-lived flood events. The 'rational' method on the contrary may underestimate baseflow for the sluggish streams or streams with long flood events. Therefore, both methods may be used equally well for streams with frequent short-term floods; for streams with long-term floods the preference should be given to digital filter; in other cases the second method is acceptable. In certain cases it might be necessary to assume the results on the mid-way between the two estimates. One should however bare in mind that, as has already been mentioned, the separation techniques employed are not aimed to simulate actual baseflow conditions: this is the task for deterministic modelling. Therefore, for comparative analysis of "indexed" baseflow conditions of many streams in an area the use of only one separation technique for all datasets may be preferable.

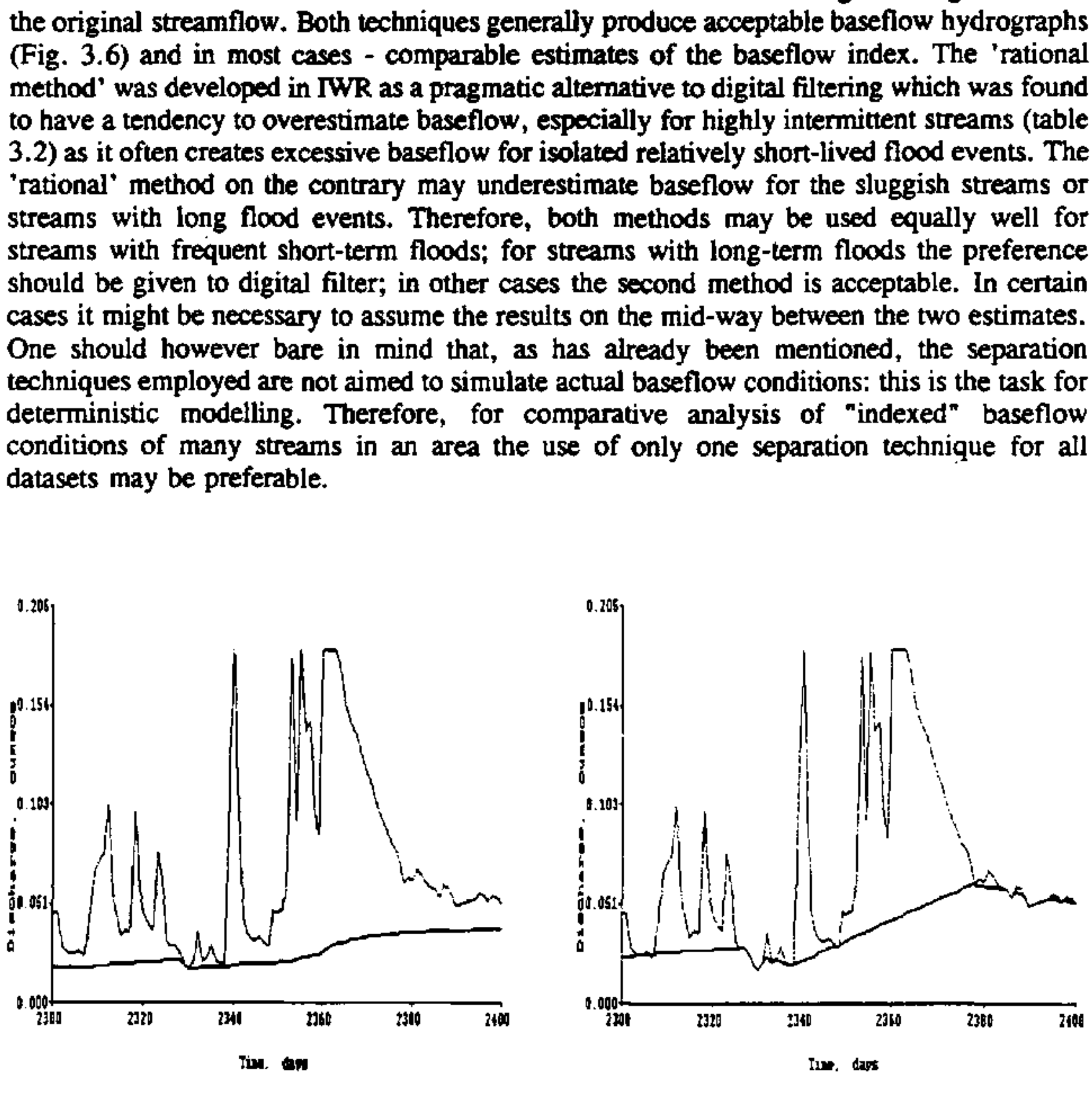


Figure 3.6. Examples of automated baseflow separation for the Groot-Nyl River at gauge A6H011. Digital filter (left) and 'rational method' (right).

Table 3.2. Estimates of baseflow (BFI) index by digital filter and the 'rational' method.

Station code	*BFI*, filter	*BFI*, rational
B6H003	0.402	0.345
B7H004	0.362	0.295
G1H012	0.297	0.159
G2H012	0.202	0.071
H1H007	0.210	0.117
H1H018	0.338	0.300
K4H001	0.214	0.152
V7H016	0.384	0.303

Whichever method of baseflow separation is used, the program will calculate and display the value of baseflow index, total streamflow volume and total baseflow volume for the specified period and mean baseflow discharge. The flow values which make up the separated baseflow hydrograph may be written to a binary output file for further analysis by any of HYMAS routines. The user is also offered a choice either to look at the results of separation or to return to the previous menu step. If the first option is selected the program displays the original streamflow hydrograph (cut at the value of mean flow to zoom in on the lower part of the hydrograph) and separated baseflow hydrograph and the user can browse the results to evaluate the quality of separation procedure. At any current screen the user may return to a display of a summary results of separation.

Baseflow separation techniques and recession analysis methods are linked together in one program module (SUMM_RE). The user will be asked whether to start with recession analysis or to separate baseflow. Whichever process is selected, the program will guide the user through the estimation process offering a number of prompts and messages.

3.8. LOW-FLOW FREQUENCY ANALYSIS.

Low-flow frequency analysis deals with a series of annual flow minima and is aimed at the estimation of extreme low-flows of certain average return periods. The results of frequency analysis are normally presented in a form of low-flow frequency curves (LFFCs).

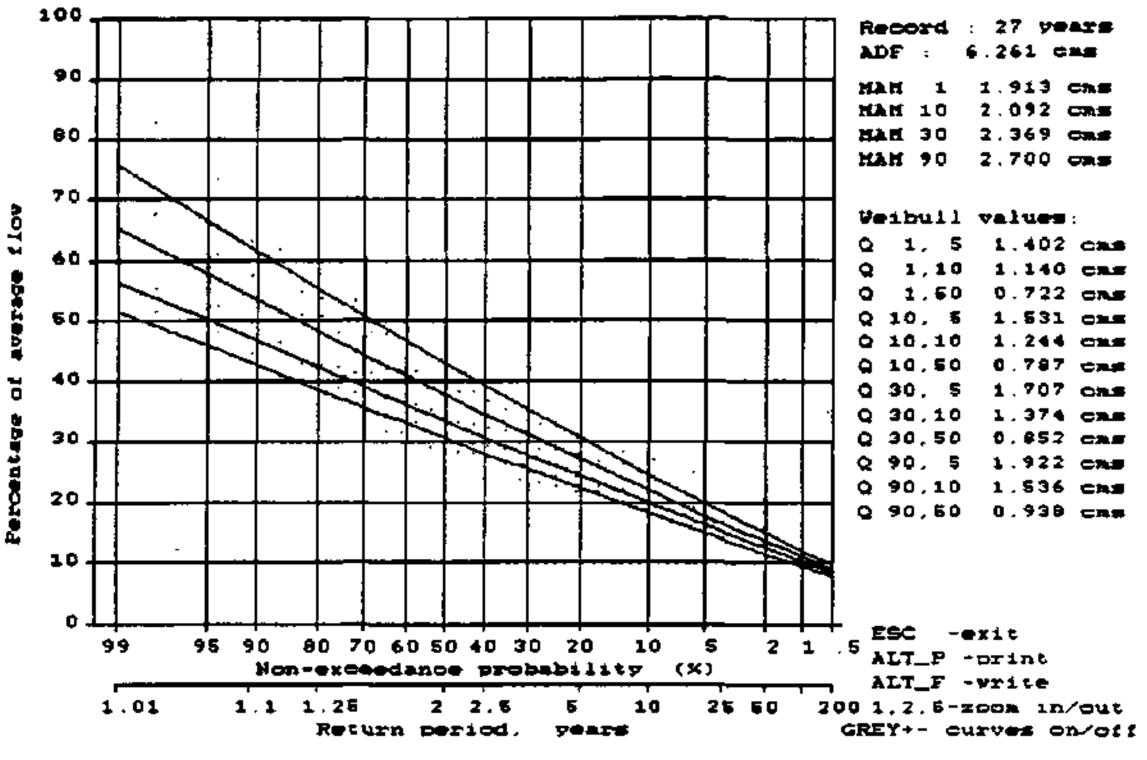


Figure 3.7. *Example computer screen with low-flow frequency curves for the Sabie River at gauge X3H006. Weibull distribution is fitted to minima averaged over 1, 14, 30 and 90 days. The top curve represents 90-day minima, the bottom one - 1-day minima. Mean Annual Minima (MAM) for each duration and other statistics are displayed to the right of the graph.*

The program module SUMM_FRQ allows LFFCs to be constructed for data with daily and monthly time resolution. All months of the year can be selected from a tag list of months to construct annual LFFC. Alternatively specific months (e.g. all Januaries in a record period) can be selected to construct LFFCs for each month of a year (in this case flow minima will be extracted only from the month(s) selected). By the same token, seasonal LFFCs can be obtained.

The extracted flow minima are expressed as percentage of average daily (average monthly) flow. The program ranks the minima (the largest extracted low flow being rank 1) and assigns a plotting position to each ranking in terms of probability of non-exceedence; the second scale is provided for return period. Ranked minima are then plotted against their plotting positions to give an empirical LFFC.

The moving average procedure may be applied to the original data to construct a new time series where each flow represents the average value during *n* consecutive days (in case of daily flow data) or *n* consecutive months (in case of monthly data). The flow minima are then extracted from a series of averaged flows. Minima of 1, 3, 5, 7, 10, 14, 30, 60, 90, 120 and 183 days or 1 to 6 months (dependent on the resolution of the data used) may be extracted. The desired averaging interval (*n* value) can be selected from a tag list. This option allows the estimates of such indices as 7-day average flow with return period of 10 years, or 30-day average flow with return period of 5 years (or other similar indices) to be made.

The program optionally fits the Weibull distribution to the data (fig.3.7). Two parameters of Weibull distribution are estimated by the method of probability weighted moments. The option exists to switch between empirical and theoretical curves.

It is possible to construct up to 5 LFFCs on one screen (for minima of different durations). The lower portion of the curve may be inspected at the increased scale if necessary. The program also calculates and displays the absolute minimum flow for a period in use, mean annual minimum (MAM) for each selected duration as well as flow values for several fixed return periods. All extracted minima of every selected duration and estimated low flows for several fixed return periods can be printed or written to a file for further analysis.

As in the case of spell frequency analysis the start date for analysis must be set up coincident with the beginning of the wettest month of a year to ensure that low-flow season is not split between two consecutive years.

3.9. SUPPORTING ROUTINES.

Plots of annual totals.

Among the frequently used supporting routines is the facility for plotting annual flow volumes as a time series (SUMM_CYC). The annual values are calculated from the original daily or monthly data and four different ways of plotting them can be selected:

- actual annual flows;
- normalised annual flows (divided by mean) ;
- differential mass flow curves (the cumulative deviation from the mean annual flow);
- normalised mass flow curves (the cumulative deviation from the mean annual flow divided by coefficient of variation of the annual flows).

This procedure applies to more than just low flows since it allows the representativeness of the data for stations with short periods of record to be tested, dry and wet periods in the record to be detected, fluctuations of annual flows for rivers with different variability to be compared etc.

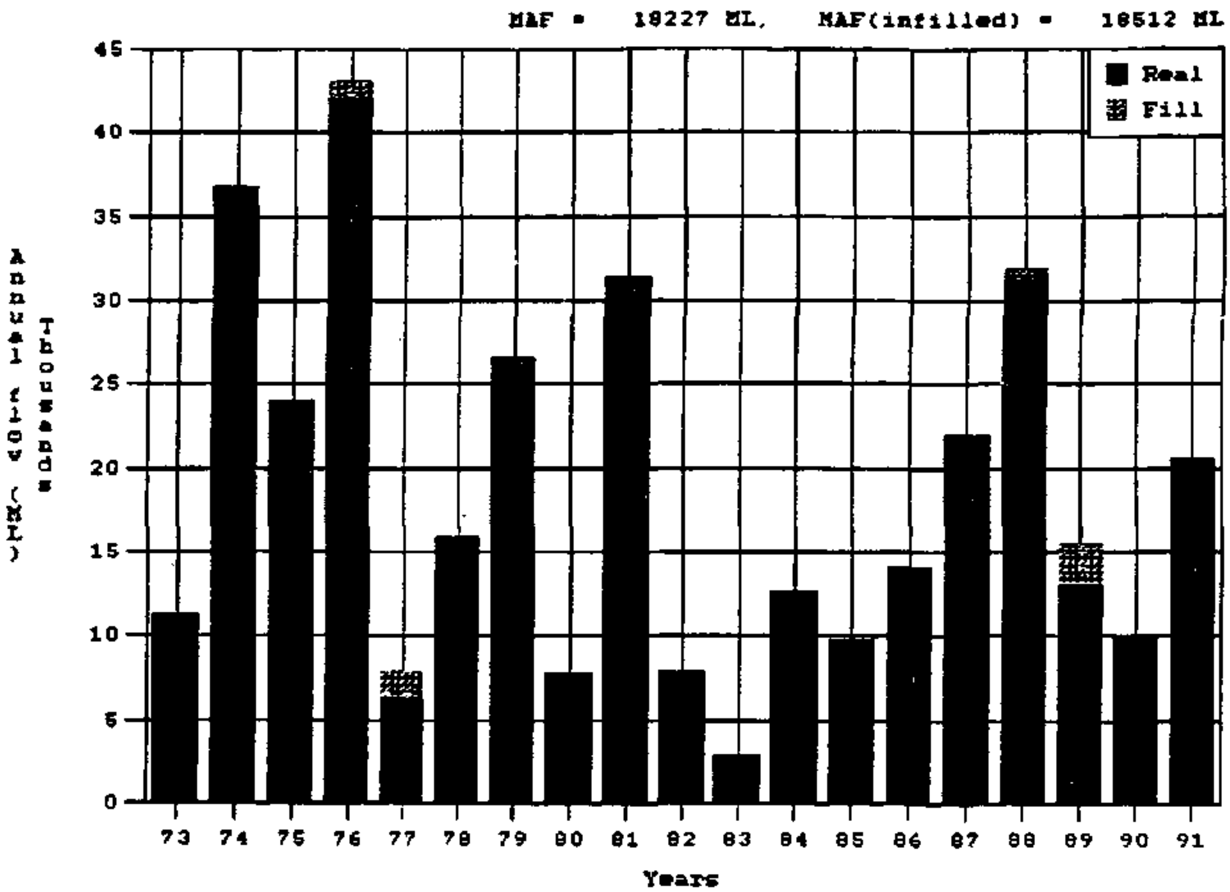


Figure 3.8 *Example computer screen illustrating one of the 4 available options for plotting annual total flows. The grey portions of bars indicate the amount of unmeasured flow.*

The procedure also gives the idea about the quality of the data. It calculates mean monthly flows and fills - either the missing month with the corresponding mean value (in the case of monthly data), or part of the month with a product of mean monthly flow and a fraction of missing days in that month (in the case of daily data). The results of this procedure are displayed on the screen showing "bad years" and the potential amount of "missing" (unmeasured) flow. This allows the user to decide what part of the record period is suitable for the required type of analysis (Fig.3.8).

Monthly flow distribution.

This module (SUMM_SZN) allows mean monthly flow totals to be plotted either in Ml or as percentages of MAR. It also calculates and plots coefficients of variation for each month's flow. The means and CV's can be calculated from the original daily or monthly data. This option is very useful for a quick estimation of the driest month or season, their actual volume and their contribution to total annual streamflow especially while working with a large number of gauging stations. It may also be used to determine the optimal start date for different types of low-flow frequency analysis described above.

Both modules (annual and monthly flow plotting) are applicable to monthly and daily data since the program automatically determines which type of data has been used. Both modules are also applicable to other hydrological variables - for example included in the output files of several different hydrological models which may be set up and run within the HYMAS environment.

Residual flow diagrams.

This module (FLOW_DG) provides a straightforward and yet very illustrative facility to examine flow quantity and composition in catchments with a large number of gauging stations and/or simulated sites and are perceived as another way of looking at the spatial variation of flow conditions within a large river system.

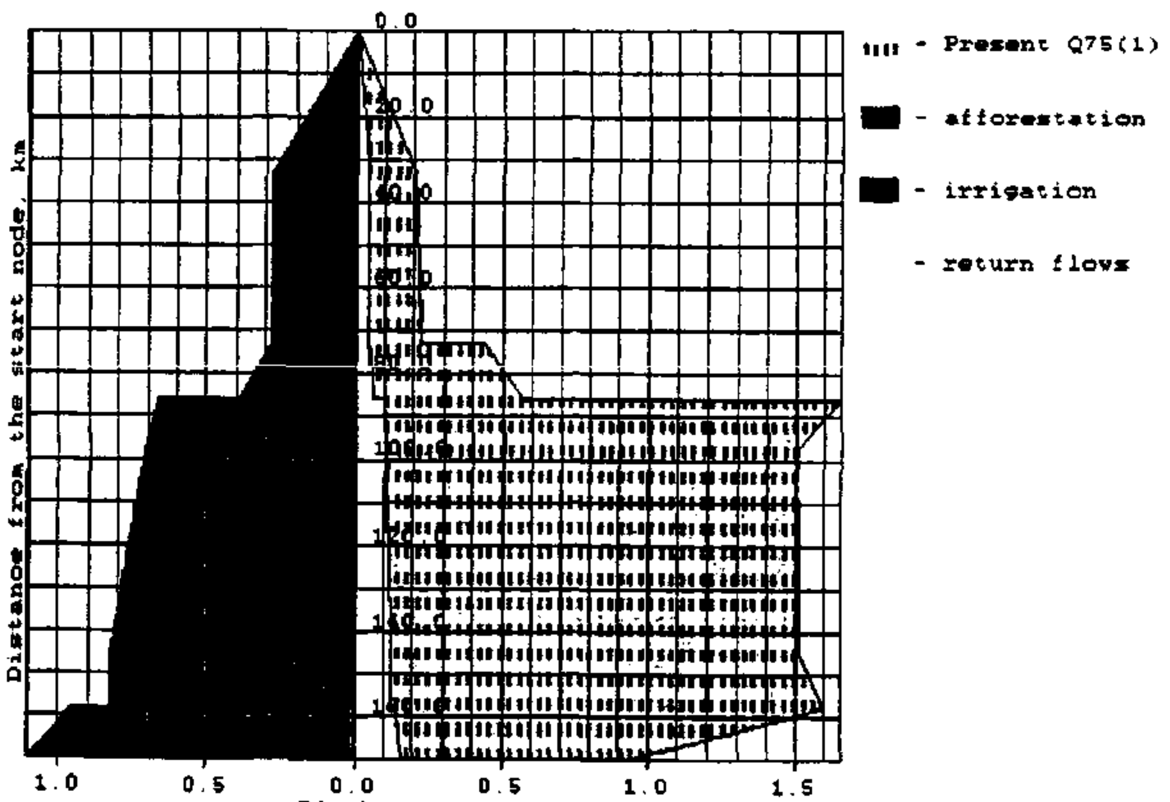


Figure 3.9 Example residual flow diagram.

Initially, a data file containing the same flow characteristic (for example, mean annual or mean monthly runoff, the flow during the driest month, any flow index extracted from flow duration curve etc.) for all gauged or simulated sites within a catchment is established. Values of the index can be entered for the present-day flow in the river, as well as for any known artificial influences (inflows or abstractions). Existing flow conditions in the main channel and contributions from tributaries are presented on the right-hand side of the central (distance) axis, and the cumulative artificial abstractions - on the left. The width of the diagram at any point along the vertical axis represents the natural flow at that point in the river system.

The flows may be expressed either in Ml or in m^3/s, the vertical axis may be marked either in kilometres from the source or in areas. The user may select any "flow route" in a specified river network and examine flow conditions in any part of selected route in more detail. Residual flow diagram module is a typical presentation graphic procedure and may be illustrated only poorly by black-and-white printout.

3.10. CONCLUSIONS.

The description of the software presented in this Chapter is still brief. More details can be found in the HYMAS manual which contains a step-by-step explanation of the operation of the system as a whole and of each of the options in particular. At the same time, the system is entirely menu driven and the use of most of the low-flow estimation routines is rather straightforward.

The software for low-flow estimation has appeared to be one of the first and the most important products of the Low Flow Project. It has been extensively used throughout the whole course of the Project being periodically updated and enhanced. The software has been applied to a number of low-flow indices to be extracted and tabulated. The results of this application are summarised in the following Chapter.

4. LARGE-SCALE ANALYSIS OF THE LOW-FLOW CHARACTERISTICS OF SOUTH AFRICAN RIVERS

4.1 INTRODUCTION.

The low-flow estimation methods described in the previous chapter have been applied to daily data from selected flow gauging stations in South Africa. This exercise was considered to be worthwhile for several reasons :

- To test the low-flow estimation software on different subsets of daily data representing flow regimes.
- To initiate the development of a low-flow database. The idea was that once started this database may eventually grow into a more flexible information system useful for different water related areas. The database will expand as data from more gauging stations are processed. It was expected that the initiation of such database would facilitate the transfer of low-flow data between different scientific groups in the country and other research projects which have a low-flow related component.
- To carry out a preliminary investigation of the spatial variability of low-flow characteristics to assist with the selection of an appropriate scale to use in low-flow studies. This has been done by constructing maps of several low-flow indices for the whole of the country and by examining variability of low-flow indices.

4.2 ESTIMATION OF LOW-FLOW INDICES.

River classification studies undertaken at the Freshwater Research Unit at the University of Cape Town (King and Tharme, 1994) made use of a set of 352 South African flow gauging stations situated upstream of all major impoundments and abstractions. The daily data for these stations have been acquired from the Department of Water Affairs and Forestry and converted to a format used by the HYMAS software. Each data set was previously tested for non-homogeneity at UCT. These tests were performed by plotting cumulative monthly flow for each flow gauge against cumulative monthly rainfall for the nearest representative rainfall gauge identified by Dent et al (1987). Where breaks in these double mass plots occurred which were obvious by visual assessment, the flow gauging stations concerned was either excluded from classification, or the data after the break were excluded where this was possible. The list of flow gauges and/or periods of record excluded was supplied by UCT

(A.Joubert, pers. com., 1993). All such non-homogeneous stations were similarly excluded from the calculations of low-flow indices in this study to ensure that the gauges used record reasonably natural flow and thus the low-flow indices extracted represent stationary flow regimes.

The remaining flow gauging stations had a mean record period of about 20 years. However, a number of them had short periods of record (less than 10 years). Recognizing that longer record periods are normally required to provide reliable estimates of low-flow indices, the shorter data sets were still considered useful, as the alternative would have been to reduce a number of flow gauges in some parts of the country to an unreasonable minimum.

However, to ensure that the low-flow estimates would be based on reasonably representative records, the annual flows for stations with short periods of record were compared with longer annual series from one of the nearby stations using the plots of annual flow totals described in the previous Chapter. The general idea of this analysis was to make sure that the short period of record available did not fall entirely within either a wet or dry flow cycle only. Some gauges were excluded from further use after this exercise but in most cases the examined data sets were demonstrated to be suitable for low-flow estimation. Stations with less then 10 years of record were still not used in estimations of low-flow frequency and spell frequency indices and gauges with less than 5 years of record, as a general rule, were not used at all. In total, 261 gauging stations were used in the estimation of low-flow indices. The data used were generally of good quality: in most cases - long records (or assumed to be sufficiently long in cases of 15 - 20 years of record) with few missing records. The nature of most of the low-flow indices and the software options allow missing records to be skipped instead of being patched.

A number of indices have been extracted *for each group of low-flow measures*. The indices extracted from the flow duration curves were within the range of 50 to 99% time exceedence (1-day flows exceeded 50, 60, 75, 90, 95 and 99% of the time). Since many rivers in SA have relatively long zero flow periods, the percentage of time at zero-flow conditions was also estimated as a measure of the degree of flow intermittency. Wherever the flow exceeded 90% of the time was non-zero, the ratio of Q90/Q50 was calculated as it may provide an estimate of the slope of the lower part of flow duration curve and represent the proportion of streamflow originating from subsurface stores, excluding the effects of catchment area. All annual 1-day low-flow indices extracted from flow duration curves are listed in APPENDIX A2.

Low-flow frequency curves (LFFCs) were constructed for each gauge with at least 10 years of observations for annual minima averaged over 1, 7, 10, 30 and 60 days. If a year contained more than 20 days with missing data, it was not included in the analysis. The estimated frequency indices were Mean Annual Minimum for each duration (MAM1, MAM7, MAM10, MAM30 and MAM60) and low-flow events (for each duration) with average return periods of 2, 5 and 10 years. (It was taken into account that these return periods are normally used in practical applications). The start date of analysis in each case corresponded to the beginning of the wettest month of the year to ensure that the dry period in each year is not split between two consecutive years (WMO, 1983). Such a "low-flow year" was normally 5 to 6 months out of phase with the hydrological year.

It was found that there was virtually no difference between 7-day and 10-day low-flow indices which goes well along the lines of some previous studies (Drayton et al, 1980). It was also discovered that the Weibull distribution generally fits well to annual minima of all selected durations. However, it tends to overestimate low flows with long recurrence intervals (for minima of shorter durations). Most of the indices extracted from Low Flow Frequency Curves are listed in APPENDIX A3. Some other low-flow frequency characteristics (also extracted but not listed in the APPENDIX A3) are available on request from IWR (see notes to APPENDIX A3).

The extracted low-flow spell indices describe the frequency of occurrence of spell maxima below threshold flows of 80, 50 and 20% of average daily flow (the duration of spells was expressed in days and the deficits in Ml, and percentage of MAR). The spell indices for each of the three thresholds are listed in the APPENDIX A4. They include: the mean of annual spell duration maxima, the mean of spell deficit maxima, duration of a spell with 5 year return period, deficit of a spell with 5 year return period, duration of a spell with 10 year return period, deficit of a spell with 10 year return period.

Estimated streamflow recession characteristics were: the 50 percentile recession ratio (REC50), recession constant (RCONST) and half-flow period (HFP). The theory behind each estimation method and some problems related to estimation techniques of recession characteristics are described in Chapter 3. Additionally a number of problems were encountered during the estimation process which relate to streamflow data itself.

First, in the number of cases the recession limbs were interrupted by frequently occurring flood events and/or dry season freshes. In such circumstances the number of recession limbs to adequately define "recession domain" was lacking and the estimation of baseflow recession constant was either impossible or unreliable. A number of such cases exist, for example, in drainage regions W and X (APPENDIX A5). Sometimes the method appeared to be not applicable simply because there was little or no baseflow and the record consisted of isolated flood events with no recession periods.

A number of cases have been discovered when the method can not be reliably applied because of the limited accuracy of flow measurements during low-flow season. It normally applies to small streams where flows during recession are very small. This results in a "steppy" decreasing hydrograph and consequently- in a lack of smooth recession limbs for the analysis.

In several cases the visual analysis of streamflow hydrograph revealed some unnatural patterns which may appear to be a result of some flow regulation. The estimated recession characteristics of such streams are not reliable.

Generally it was found that the estimation of baseflow recession constant by the correlation method is rather subjective and time consuming exercise and is very sensitive to the type of flow regime being analyzed and the quality of the data being used. Further research is necessary to specifically address the practical aspects of the estimation of recession properties of South African rivers.

Both baseflow separation techniques were tried for the derivation of a baseflow index and both were found to produce generally accepted baseflow hydrographs. However, as has already been mentioned in Chapter 3, digital filtering was found to have a tendency to overestimate the baseflow index especially for highly intermittent streams as it often created excessive baseflow for isolated relatively short-term flood events. The rational method, on the other hand, was found to underestimate baseflow for sluggish (slow response) streams or streams with long flood events. In general terms, both methods were found to work equally well for streams with frequent short-term floods. For streams with long duration floods preference should be given to the digital filter approach, otherwise the rational method is acceptable. There is no strict rule as to what method is the best to use in each particular case. It is therefore recommended to use both techniques, visualise the results of separation procedure and on that basis, decide which method has performed better. In certain cases it would be necessary to assume the final result as the mid-way between the two estimates.

It was taken into account that for comparative analysis of "indexed" baseflow conditions of a number of streams in the country the use of only one separation technique for all data sets is preferable. Thus final estimates of baseflow index for the majority of gauges were obtained using digital filter technique. The rational method was used for some ephemeral and intermittent streams where the estimates obtained by digital filtering were found to be unacceptably high. Baseflow indices are listed in APPENDIX A5 together with recession characteristics.

4.3 MAPPING OF LOW-FLOW CHARACTERISTICS.

Mapping of low-flow indices was performed using the commercially available SURFER (1990) software package to obtain a preliminary impression of the spatial variability of low flow indices and to see if they show any regional pattern on a country-wide basis. SURFER contains facilities to construct contour maps from irregularly spaced data. Several griding procedures are provided to create a regular grid of a specified density (SURFER Manual, 1990). An inverse distance weighting algorithm and kriging interpolation technique have been used for the purpose of this study.

Several types of low-flow indices have been selected for mapping. The indices selected represent different aspects of the low-flow regime (e.g. flow duration curve indices, frequency indices, spells, baseflow etc). A series of draft maps have been constructed for each low-flow index considered.

The problem of the catchment size is very important in mapping. The larger catchments would generally have larger flow characteristics and usually - more sustained low flows. In most of the low-flow studies carried out elsewhere the stations selected either for mapping or regression analysis were in the range of 1 - 1000 km2 (Australia, UK). However, in cases where the network of gauging stations is scarce, larger rivers are often forced into use. In Malawi low-flow studies (Drayton et al, 1980) the rivers used for low-flow estimation and mapping were up to 11800 km2. In the current study, all the major rivers (above 10000 km2) were excluded from the mapping procedure. Small and medium size catchments (with an area less than 1000 km^2) dominated the data set finally used for mapping purposes. The catchments with areas in the range 1000 - 10000 km^2 have been used mostly in the regions of scarce data if they were found to have stationary flow records and were not suspected to cause regional anomalies. The exclusion of more rivers lead to the reduction of the initially small data set and was found to result in physically less meaningful maps.

However, a number of experiments have been carried out with the reduced data sets. First, all the stations above 5000 km2 were removed from the mapping procedure and a new series of maps were drawn. Then all the rivers above 1000 km2 were removed and another series of maps were drawn. In both cases the resultant maps were found to be difficult to interpret from a physical point of view (as compared to the original set of maps where catchments with areas in the range 1000 - 10000 km^2 were retained) due to severe map distortions caused by the increased scarcity of data points in several areas. Additional data points (about 10) have nevertheless been removed from the original data set as it was suspected that they also caused distortions.

To make low-flow analysis more concise the most common procedure was applied: low-flow indices have been normalised either by MAR or by catchment area thus allowing rivers with different catchment areas to be compared.

In some cases isolated point values of low-flow indices were either significantly higher or lower than the surrounding point values. As no apparent physiographic reason could be ascertained they were removed from the mapping procedure to suppress minor anomalies and to try to preserve the general regional trends. The stations removed from mapping each low-flow index were not necessarily the same and thus the data sets used in each case are slightly different.

The resultant set of maps have been redrawn manually for better presentation. The approximate positions of the gauges used for mapping are shown on Figure 4.1 and on Figure A6.1 in APPENDIX A6.

When interpreting the maps a word of caution must be sounded and the results should be viewed as relative rather than absolute. Apart from the mathematical and technical aspects involved (mostly related to the SURFER package used at the first step of mapping), the individual station samples cover different lengths of record, different periods of records, are not evenly distributed in the areas of interest and are not equally representative of the

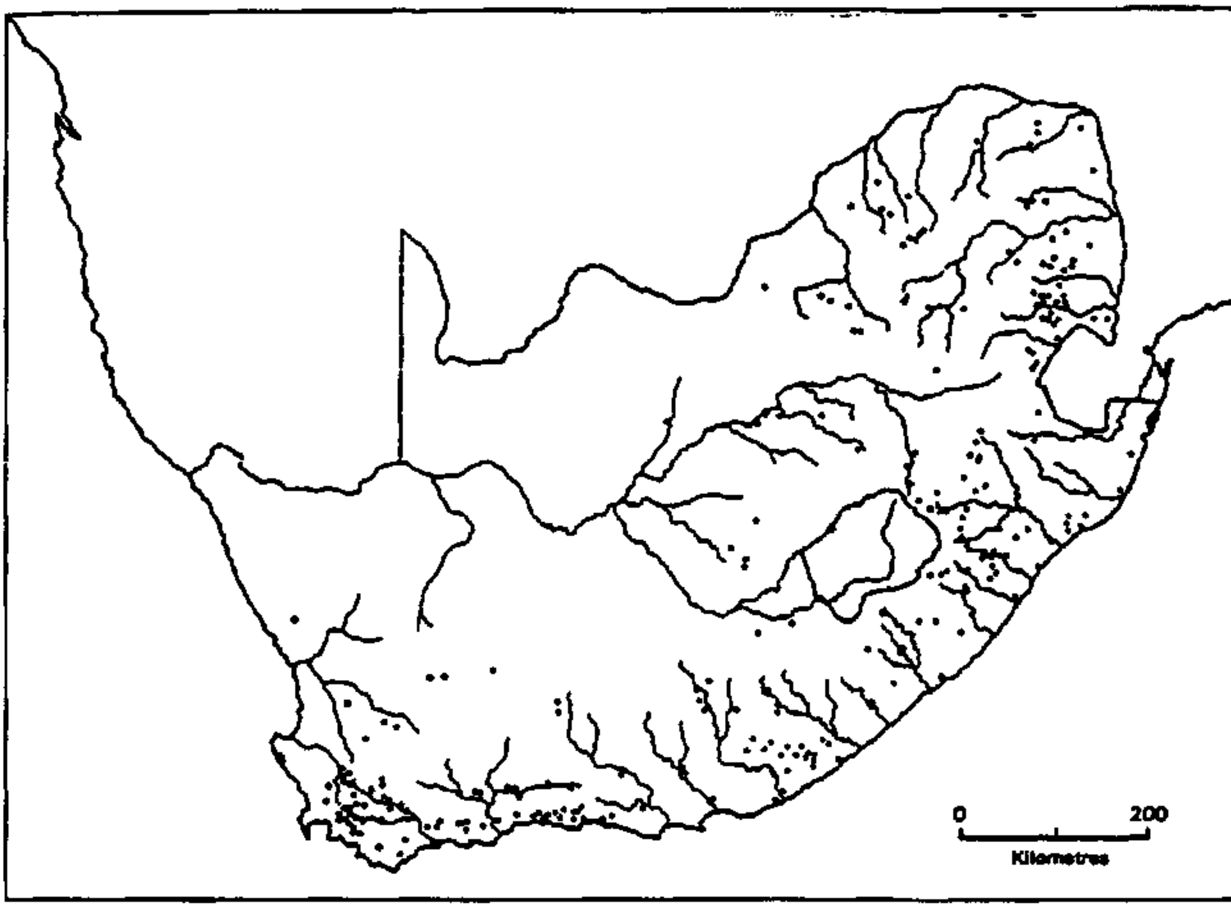


Figure 4.1 Flow gauging stations used for mapping of low-flow indices.

expected variety of the flow regimes in different areas. The contour lines are not reliable in areas of missing or scarce data. Large rivers that have been excluded from mapping, like the Tugela in KwaZulu-Natal, Olifants in the Northern and Mpumalanga Provinces and especially those like the Orange flowing through the driest parts of the country (even if they would be in virgin conditions), will obviously exhibit quite different low-flow characteristics.

Percentage time with zero flow was selected for mapping as one of the most basic measures of stream behaviour in the low-flow domain (Fig. A6.2, APPENDIX A6). The resultant map illustrates the problem of the applicability of the whole low-flow concept to different parts of SA. In most of the coastal regions and the Mpumalanga Province rivers cease to flow for not more than 10 to 20% of the time and it seems possible to apply the full range of other low-flow measures to study the stream and catchment behaviour during the dry season. The rivers in the areas with (arbitrary) 30 to 40% of the time spent at zero flow conditions (and higher) may be considered as highly intermittent and further low-flow studies cannot be considered worthwhile (if low flow is defined in terms of the World Meteorological

Organization (1974) as "flow of water in a stream during prolonged dry weather"). It should be noted that the spatial variability of time with zero flow follows very closely the spatial pattern of mean annual precipitation in SA (DWA, 1986). As a general rule, the lower the rainfall - the smaller the proportion of the rainfall reaching river systems - the greater the variability of river flows and the greater the time spent at zero flow conditions. Figure A6.2 seems to support the qualitative estimate by Alexander (1985) that only 25% of the rivers in SA are perennial with another 25% that flow periodically. The remaining 50% of the rivers (primarily the northern and southern interior) flow only after infrequent storms.

The distribution of 1-day flow equalled or exceeded 75% of the time (Q75) is obviously restricted to the regions with predominantly perennial streamflow regimes (Fig. A6.3, APPENDIX A6). These indices are quite stable in the Western Cape and along the whole southern coast where they vary over a range of 5 to 20% of the average daily flow (ADF). They increase to 30 to 35% of ADF in the coastal part of Natal while the highest values occur in the Mpumalanga Province (35 to 42% of ADF in drainage regions B4 and B6), with another local maximum of 25 to 35% in the north (drainage regions A6 and A9). The higher the value of Q75, the flatter the lower part of the flow duration curve and the greater the contribution to streamflow from subsurface stores. The spatial distribution of Q75 (as well as the distribution of other indices extracted from the flow duration curve), in general, follows very closely that of the baseflow index (Fig. A6.4, APPENDIX A6) which represents the relative degree of such contributions. Areas with baseflow index values below 0.2 are normally areas with poor subsurface contributions to streamflow and are well correlated with the areas where Q75 is close to or equal to zero. On the other hand the areas with the highest values of baseflow index usually yield the highest values of Q75 (and other similar indices).

The corresponding absolute values of Q75 are the highest in the Mpumalanga Province (0.3 to 0.4 mm) and in drainage regions A6 and A9 (0.2 to 0.3 mm). Relatively high flow values also occur along parts of the southern coast; 0.25 mm in region K1 and 0.3 to 0.31 mm in regions K7 and L8. The absolute value of Q75 is relatively stable in KwaZulu-Natal and varies over the range 0.05 to 0.15 mm.

It should be noted that analysis of the original data set used in the interpolation of the contours indicates that there is a high degree of variability even within one drainage region for the values of a single index. Most of the low flow indices seem to be very sensitive to local physiographic factors (soils, geology, etc.), the effects of which are smoothed in the maps presented by the use of a rather coarse grid density. In general, the spatial variability of the flow duration indices is very high throughout the country (Table 4.1).

The spatial distribution of some of the low flow frequency indices seems to be somewhat more complex than that of the flow duration indices although the general regional pattern in most parts of the country remains the same. The example provided for mean annual 10 day minimum flow (MAM10, expressed as percentage of ADF) is shown in Fig. A6.5 (APPENDIX A6).

Table.4.1. Spatial variability of several natural low-flow indices in SA.

Low-flow index[1]	Mean	St.Deviation	CV
Time with 0 Flow (%)	20.3	29.0	1.42
Q75 (% ADF)	12.7	13.5	1.06
Q90 (% ADF)	6.93	9.44	1.36
Q75 (mm)	0.081	0.117	1.45
Q90 (mm)	0.047	0.083	1.76
MAM1 (% ADF)	8.11	12.2	1.50
MAM30 (% ADF)	12.3	18.4	1.49
MAM1 (mm)	0.048	0.081	1.68
MAM30 (mm)	0.068	0.104	1.54
BFI	0.25	0.15	0.59
MMDEF50 (%MAR)	13.0	6.0	0.46
MMD50 (Days)	121	37.5	0.31

[1]ADF	- average daily flow;
BFI	- baseflow index;
MAM1,MAM30	- mean annual 1-day and 30-day minimum flows; calculated from a series of daily minima and 30-day averaged minima extracted from each of record;
Q75,Q90	- flows extracted from flow duration curve and exceeded correspondingly 75 and 90 % of time on average throughout a year;
MMDEF50	- mean of annual maximum deficits built during consecutive low-flow events below a referenced discharge of 50% of ADF;
MMD	- mean of annual maximum durations the river continuously stays below a referenced discharge of 50% of ADF;

MAM10 is relatively moderate in the Western Cape (6 to 11% of ADF, with absolute values in the range of 0.05 to 0.11 mm), somewhat smaller along most of the southern coast (4 to 8% of ADF or 0.05 to 0.08 mm), 8 to 16% of ADF in most of KwaZulu-Natal and the highest values of 18 to 32% of ADF (0.14 to 0.24 mm) in Mpumalanga Province. The pattern corresponds reasonably well with the baseflow index (Fig. A6.4, APPENDIX A6) throughout most of the country, emphasizing once again the effect of hydrogeological factors on low-flow extremes rather than the effect of meteorological conditions. The overall regional patterns of similar indices (mean annual 30 and 60-day minima) are predominantly the same.

Several indices characterising spells of low flows below selected (low) thresholds have also been plotted. The resultant draft maps of these indices appeared to be the most complex and difficult to interpret. The example maps for mean annual maximum duration of spells below 50% ADF (days) and mean annual maximum deficiency volume below the same threshold (expressed in percentage of MAR) are given in Figs. A6.6 and A6.7 (APPENDIX A6) respectively. Analysis of these maps as well as those for similar indices shows that the most responsive streams are those in the coastal parts of the southern Cape with the mean annual maximum spell duration in the range of 75 to 90 days and relatively small deficits (below 10% of MAR). One possible explanation is that rainfall here occurs as frequent falls with an all year round pattern (DWA, 1986). Along the KwaZulu-Natal coast the mean duration of spells slightly increases to 90 to 100 days with the mean deficits largely fluctuating in the same range of 6 to 10% of MAR. In general terms, the further from the coast, the larger the spell durations and the larger the deficiency volumes during continuous low flow periods.

The variability of spell indices is much higher in the Western Cape and most of the north-eastern parts of the country. For the threshold of 50% ADF, the mean maximum duration of spells in these regions varies from as little as 50 to 60 days to as large as 160 to 180 days, the corresponding range of mean annual maximum deficiency volumes being 6 to 22% of MAR. In many cases it is the rivers with the shortest spells (below any threshold) that usually yield the largest values of baseflow, flow duration and flow frequency indices, although the detailed picture is much more complex. It has been roughly estimated that most of South African rivers have mean maximum spells below 50% ADF of around one-third of the year with a mean maximum deficit of 13% MAR. In general, the indices of low-flow spells are the least variable compared to the other low flow characteristics (Table. 4.1).

4.4. CONCLUSIONS.

Mapping of low-flow characteristics showed that in general they exhibit a very high degree of spatial variability through the country. Even within the same drainage region for gauging stations with similar catchment areas and lengths of observation period, standardised low flow indices may differ greatly. This implies that low flow characteristics are very dependent on local physiographic factors and the problem of low flows should preferably be addressed at a finer resolution, such as the catchment scale. For example, attempts to regionalize low flows on a national basis (at least with the set of stations and quality of the data which were available for this analysis) may result in limited success.

Some of the low-flow indices demonstrate a similar spatial pattern. This implies that similar driving forces and mechanisms have similar relative effects on a range of indices of low flow. The correlation between various low-flow indices may therefore be expected to be strong. For example, the high rate of recession in a strongly seasonal stream will most likely produce large deficit volumes and long durations of continuous low-flows below a certain threshold flow. High values of baseflow index would in many circumstances mean that the stream has a strong groundwater component and therefore slow recession rates. Low relative values of Q75 and/or Q90 would almost certainly correspond to low values of mean annual minima of different durations and low baseflow index values. High percentage of time spent at zero flow conditions will signify "no low-flow" case etc. The correlation between various low-flow indices required separate investigation on the scale of a large catchment or physiographic region.

The assumption of high correlation between various types of low-flow indices would imply that the development of low-flow prediction methods, for example, on a regional level, could be based on some "basic" low flow index (for example 10 day average flow equalled or exceeded 75% of the time). The sensitivity of the index to local physiographic factors should then be the subject of detailed studies while the other low flow indices may be estimated by means of certain relationships with the 'basic' index.

The mapping exercise may be repeated if more flow data sets are used. In order to identify additional usable data sets available from DWAF further research should be concentrated on low-flows within several major river basins drawn from different parts of the country. This research is also expected to show how different low-flow characteristics vary due to local physical (topography, geology, soil, precipitation etc.) and anthropogenic factors. Low- flow studies for these catchments should include the data from all available flow gauges and address the issues of present and natural low flows. To investigate natural low-flow regimes in more detail, the indices extracted from stations affected by abstraction or other modifications to the flow regime should be naturalised. The use of deterministic modelling approach may prove invaluable in this respect.

5. APPLICATION OF DETERMINISTIC DAILY MODELLING IN LOW-FLOW STUDIES.

5.1 INTRODUCTION.

Catchment-wide analysis of low-flow characteristics requires the hydrological information at much finer spatial resolution than is normally provided by streamflow gauging. Therefore, the problem of estimation of flow characteristics at ungauged locations arise. The commonly used approaches for estimation of flow characteristics (including low flows) at ungauged sites have been described in Chapter 2. The first group of these methods make use of available observed flow records and attempts to regionalize required flow characteristics. The approach is widely used in the world and some attempts to apply it to southern African conditions are described in Volume II of the current Report. However, the assessment of low flows in South Africa by means of such an approach may meet with serious difficulties due to the scarcity of good quality observed records of a sufficiently long duration, and by land use changes and water resource developments which may introduce temporal trends into observed flow data (Pitman, 1978; Braune and Wessels, 1980).

The alternative approach to extend the area which can be characterised beyond adequately gauged sites, and also to simulate past natural and future flow and low-flow conditions, is deterministic time-series simulation. The extensive testing is required in this case to ensure that the selected model(s) can be reliably applied over the range of conditions prevailing in southern Africa for the purposes of simulating different aspects of low-flow regimes (duration, frequency, recessions, spells etc.).

Low-flow characteristics can vary widely according to the relative importance of several distinct surface-subsurface interaction processes. It is therefore important that the model employed be flexible enough to adequately conceptualise and simulate each of the processes involved. In South African context these include the generation of baseflow from the intersection of the regional groundwater table with the surface, the lateral drainage of deep soil profiles resulting in re-emergence from a saturated seepage face, as well as the re-emergence of percolating water as springs from fracture systems located above the regional groundwater body. The weathered and fractured bedrock zone between the soil and groundwater greatly influences these processes in semi-arid and in semi-mountainous catchments, however, it has traditionally been neglected by both surface and groundwater models. Some rainfall-runoff models which have attempted to describe the processes between the soil zone and groundwater have either tried to interface with existing finite element or finite difference groundwater models (whose parameters are difficult to quantify spatially in fractured aquifers with scarce hydraulic data; Chiew et al., 1992), or have been dependant on parameters which are not easily physically quantified (Arnold et al., 1993).

Surface-subsurface interaction algorithms to simulate the above mentioned baseflow generation processes have been incorporated into the semi-distributed deterministic Variable Time Interval (VTI) Model (Hughes and Sami, 1994). This model has been selected as a base simulation tool for the current low-flow studies and has been applied to a number of catchments in South Africa and neighbouring countries with a variety of physiographic conditions (Hughes et al, 1993; Hughes and Sami, 1994; Hughes, 1995; Smakhtin and Watkins, 1995; Sami et al, 1995). Due to the time resolution of available hydrolmeteorological input data and initial objectives of current low-flow studies the VTI model operates with a daily time step. This Chapter illustrates examples of the model application for several South African headwater catchments of different low-flow response in order to test the ability of the model algorithms to simulate different aspects of low-flows. The actual application of the model for simulation of daily time series for low-flow estimation in present day and natural conditions are described in Volume II of this Report.

5.2 THE VARIABLE TIME INTERVAL MODEL: GENERAL OVERVIEW.

The VTI model runs within HYMAS modelling system (Chapter 3). It is a semi-distributed physically based model which incorporates the following complex hydrological processes:

- potential evaporation
- interception
- rainfall intensity controlled runoff
- soil moisture redistribution and runoff
- evapotranspiration
- surface-subsurface water interactions
- catchment routing including depression and small dam components
- channel transmission losses
- channel flow routing

The model has a modular structure where each module (function) describes a separate component of the hydrological cycle. A modelled catchment is represented by a set of subareas where each subarea is relatively homogeneous in terms of catchment physiographic parameters (soils, vegetation, geology) and/or water use development (concentration of farm dams, forestry). The variability of hydrological processes within each subarea (sub-grid effects) is described by means of probability distribution functions of some model parameters. Most of the model parameters can be derived from easily obtainable physical catchment properties. The model operates with a time step equal to input data time resolution (normally 1 day) but switches to shorter time steps during significant flood events. The inverse distance squared interpolation procedure is employed to build the subarea average rainfall input data for each subarea using the information from the nearby rainfall gauging stations, coordinates of these stations and coordinates of subarea centres. Details on generating the rainfall input to the model may be found in HYMAS user manual available from the IWR.

The brief description of each model component is given below. The surface-subsurface interaction functions generating low-flow response of a catchment are described in more detail in section 5.3.

Potential evaporation.

Daily potential evaporation is estimated by distributing mean monthly pan evaporation values, corrected to open water surface evaporation, equally over the days of a month. Correction factor non-linearly related to rainfall depth is applied to reduce the potential evaporation on wet days and increase it on dry days. Losses from interception, depression and small dam storages as well as from saturated soil surfaces are assumed to occur at potential rate.

Interception.

The interception is described by a simplified Rutter model. Parameters of this model: proportion of vegetation cover, leaf area index and interception capacity are estimated from the proportion of a subarea under several broad vegetation classes. Seasonal variation in interception rates may be accounted for using a sine curve distribution of the proportion of vegetation classes with an amplitude defined by summer and winter values. The balance of rainfall and overflow from interception storage constitute throughfall.

Rainfall intensity controlled runoff.

The infiltration rate is calculated using an empirical Kostiakov equation as a function of the cumulative time incremented from the start of rainfall event and decremented between events. Spatial variation of infiltration rates within a subarea is described by a log-Normal distribution of infiltration parameters. The mean and standard deviation of each parameter are estimated from their relationships with soil properties. Seasonal variation in means is described using the sine curve approach with an amplitude specified by winter and summer values. The proportion of a subarea contributing to intensity controlled runoff at each time step is assumed to be equal to the proportion of the cumulative frequency distribution of infiltration rates lying below current rainfall intensity. Runoff rate is calculated assuming that the infiltration is exceeded by rainfall by differing degrees over the contributing area. The initial amount of calculated intensity runoff is then passed to soil moisture redistribution component where it is subjected to re-infiltration.

Soil moisture redistribution and runoff from saturated areas.

The total soil profile is divided into two layers, the upper layer being 15 cm deep and the lower one being the balance of the mean subarea soil depth. Mean soil depth is estimated from the proportion of a subarea with several fixed soil depth classes. Spatial variation in moisture content of a soil within a subarea in each soil layer is represented by Normal distribution. The mean soil moisture storage in each layer is calculated from the water balance equation and is expressed as a degree of saturation (relative moisture content).

Standard deviation is assumed to be linearly related to the degree of saturation. It reaches its maximum at an arbitrary specified value of relative moisture content and reduces to zero either side of that value. The proportion of each soil layer that is saturated is assumed to be equal to the are under cumulative distribution which exceeds a relative moisture content of 0.98. The proportion of each soil layer above field capacity is assumed to be the area under the distribution that exceed the ratio of field capacity to porosity. These proportions are then used to estimate the parts of each subarea which contribute correspondingly to runoff from source areas (saturated area runoff) and vertical drainage.

In order to account for the spatial position of source areas and vertical distribution of drainage areas in the soil profile the model employs the concepts of 'lateral distribution factor' (LDF) and 'vertical distribution factor' (VDF). The LDF is designed to account for the likelihood that saturated parts of the soil are concentrated in valley bottom areas and varies in the range between 0 and 1. It is incremented during each time step by an estimate of the lateral drainage rate in a soil as a function of lower layer moisture content, slope to valley soil depth ratio, catchment slope and soil parameters and decremented as a function of the amount of water draining from the upper to lower soil layer. High LDF values are produced for wetted soils with high lateral drainage potentials (humid areas) and low LDF values - for dry soils or slow drainage rates (arid and semi-arid areas).

The VDF varies in the same range as LDF. It is incremented in each time interval by the proportion of the upper layer draining to the lower and decremented by the proportion of the lower layer below field capacity. It therefore gradually decreases after storm events but increases as the upper soil zone becomes wet and promotes drainage at the start of an event. The estimates of LDF and VDF are applied to the estimates of the proportions greater then saturation and field capacity to produce the final saturated source area, as well as the amount of re-infiltration and drainage.

Three components of runoff are simulated here. These are: i) saturation excess runoff caused by rainfall on saturated areas; ii) saturated sub-surface flow re-emerging from saturated parts of the upper soil layer; iii) saturated lower soil layer sub-surface flow from the 'seepage face'. The 'seepage face' is estimated as the product of the saturated proportion of the lower soil layer and the LDF value. If the groundwater level intersects the surface, the largest of the two 'seepage faces' taken to be the total 'seepage face' is used to estimate saturated area runoff. The intensity controlled runoff and components i) and ii) above are subjected to a re-infiltration function based on the proportion of the upper soil layer that is not contributing to any form of surface runoff.

Finally the upper soil layer moisture content is incremented with that part of the rainfall that does not contribute to either intensity controlled or saturation excess runoff after re-infiltration. The module also includes checks to ensure that the conservation of mass principles are satisfied. For example, the combined areas contributing to surface runoff cannot exceed unity and no drainage occurs to the lower soil layer if its mean moisture content already exceeds saturation.

Actual evapotranspiration.

The total evapotranspiration is assumed to include three components: evaporation from the saturated proportion of the upper soil layer and evaporation from non-saturated parts of the upper and lower soil layers. First is assumed to occur at the potential rate. The remaining potential evaporation demand is split between non-saturated parts of two soil layers by means of empirical power function of seasonally varying crop factor. The actual evaporation from the upper soil layer is estimated as a function of residual potential evaporation demand, the proportion of the residual potential rate (non-linearly related to relative soil moisture content) and a non-saturated proportion of this layer. The actual evaporation from the lower layer is estimated by a similar relationship with a non-saturated proportion of this layer being replaced by a crop factor.

Catchment routing.

This module includes three components: the retention of runoff by depression and small dams and transformation of runoff through routing within the subarea. The total depth of runoff first satisfies depression storage and then small dam storage. Evaporation from dams occur at potential rate. The total surface area of dams is estimated as a power function of current stored volume. The total volume of dam storage is allowed to be reduced by a fixed daily draft. Seasonal variations in volumes of water abstracted from dams are described using a set of monthly weighting factors. Attenuation of the subarea runoff is calculated by means of non-linear storage routing function.

Channel transmission losses.

Before the calculation of transmission losses, runoff generated within a subarea is added to that generated from upstream subareas. Kostiakov infiltration equation is used to estimate initial channel infiltration rate and then two weighting factors are applied to that initial estimate. The first represents an infiltration decay factor to account for a declining hydraulic gradient below the surface as the channel loss storage is incremented. This factor is estimated as a power function of the ratio of the currently available channel loss storage to the its maximum. The second weighting factor is introduced to account for variations in flow infiltration area with upstream inflow. The final volume of channel transmission losses at each time interval is calculated as a product of initial infiltration rate, two weighting factors, flow infiltration area and the time step. Checks are carried out to ensure that no more is lost than is available and that the available loss storage is not exceeded.

Channel routing.

The channel flow from one subarea to the next downstream is attenuated using the same non-linear form of storage-routing function as for catchment routing. An additional parameter specifies time shift between runoff generated in any subarea and its appearance as a contribution to flow at the outlet of the whole catchment.

5.3 THE VARIABLE TIME INTERVAL MODEL: SURFACE-SUBSURFACE WATER INTERACTION FUNCTIONS.

Four functions link surface and groundwater in the VTI model. They allow the following surface-subsurface interaction processes to be simulated:

- drainage from a lower soil layer into a percolating storage which conceptually represents water in transit to the water table;
- the re-emergence of percolating water as springs above the regional water table due to structural controls or a geological impedance;
- piezometric surface dynamics resulting from changes in aquifer storage due to increments from percolating storage, lateral transfers and borehole abstraction;
- groundwater seepage from the intersection of the water table with the surface.

As has been described above, the soil profile is divided into two layers whose moisture contents are represented by Normal distributions. This accounts for spatial variations within a subarea resulting from redistribution, macropore flow, soil depth and soil texture. The part of the sub-area which may potentially contribute to groundwater recharge is assumed equivalent to the proportion of the lower soil zone distribution in excess of field capacity. To account for the spatial position of such areas, lateral and vertical distribution factors are calculated for each time step (LDF and VDF already mentioned above). The proportion of the soil at greater than saturation and field capacity is modified by these distribution factors to estimate a soil saturated seepage face and recharge area.

Recharge is calculated as:

$$\text{Recharge} = LFC * KG * 0.5 * dt \qquad (5.1)$$

where LFC is the proportion of the lower layer above field capacity, with corrections for LDF and VDF. The rate of half the saturated hydraulic conductivity KG, is used to represent vertical drainage under partially saturated conditions. The saturated hydraulic conductivity is calculated as:

$$KG\ (\text{mm h}^{-1}) = TM\ /\ DEPTH * S * 1000/24 \qquad (5.2)$$

where DEPTH is aquifer thickness (m) and S - storage coefficient (storativity). The use of storativity to adjust KG accounts for the fact that some of the potential recharge area may be underlain by unfractured rock or rock not hydraulically connected to the main groundwater body. This adjustment has been found to be particularly necessary in fractured rock situations, where the opportunity for drainage from even saturated soils is limited by the occurrence of surface fractures.

Water leaving the lower soil layer as recharge increments the percolating groundwater store (PSTORE). Water in PSTORE is considered to be evenly distributed throughout the area above the water table (Fig. 5.1). Water is transferred from PSTORE either as increments to the water table, transfers to adjacent sub-area PSTORE's, or as springflow directly into the stream channel. The fraction of PSTORE which may re-emerge as springs (PROP) is determined by the proportion that lies above the groundwater drainage vector (DVECT) line which intersects the sub-area surface (Fig. 5.1). DVECT represents the resultant of the lateral and vertical components of percolation. For example, drainage through an unconsolidated layer would be represented by a large vector slope (e.g. > 20), whereas lateral flow over a gently dipping impermeable horizon would have a low vector slope. For springs to occur the drainage vector must therefore be less than the mean catchment slope.

The rate of emergence depends on the PROP fraction, the degree of saturation in PSTORE and KG.

$$\text{Re-emergence (mm)} = \text{PROP} * \text{PSTORE/TOTAL} * \text{KG} * \text{dt} \tag{5.3}$$

where TOTAL is the maximum storage of PSTORE defined as the product of PSTORE geometry during that time step and the storativity.

Losses from PSTORE to adjacent sub-areas are determined using a similar approach as for re-emergence, however, KG is corrected by an anisotropy factor (ANTY):

$$\text{Transfer (mm)} = \text{PTRANS} * \text{KG} * \text{dt} / \text{ANTY} \tag{5.4}$$

where ANTY is calculated by

$$\text{ANTY} = 90^{\circ}/\text{Tan}^{-1}(\text{DVECT}) \tag{5.5}$$

The fraction of water which may be transferred (PTRANS) from PSTORE is defined by the area above DVECT when the origin of DVECT is at the current groundwater depth minus PROP (Fig. 5.1). Consequently, if the groundwater depth is above the surface PTRANS is equal to zero.

Since KG is calculated from transmissivity (eq. 5.2), it relates to horizontal conductivity. To take into account lower conductivities in the vertical direction in structured formations, the anisotropy adjustment factor corrects KG according to the lateral flow component during percolation. Transfers to other sub-areas can be sub-divided into two components determined by two outflow distribution vectors defined by the user. The two directions of groundwater outflow can be either into adjacent sub-areas or external to the catchment.

Increments to the aquifer are calculated from the fraction of PSTORE which lies below DVECT (PGWATER):

$$\text{Inflow (mm)} = \text{PGWATER} * \text{PSTORE/TOTAL} * \text{KG/ANTY} * \text{dt} \tag{5.6}$$

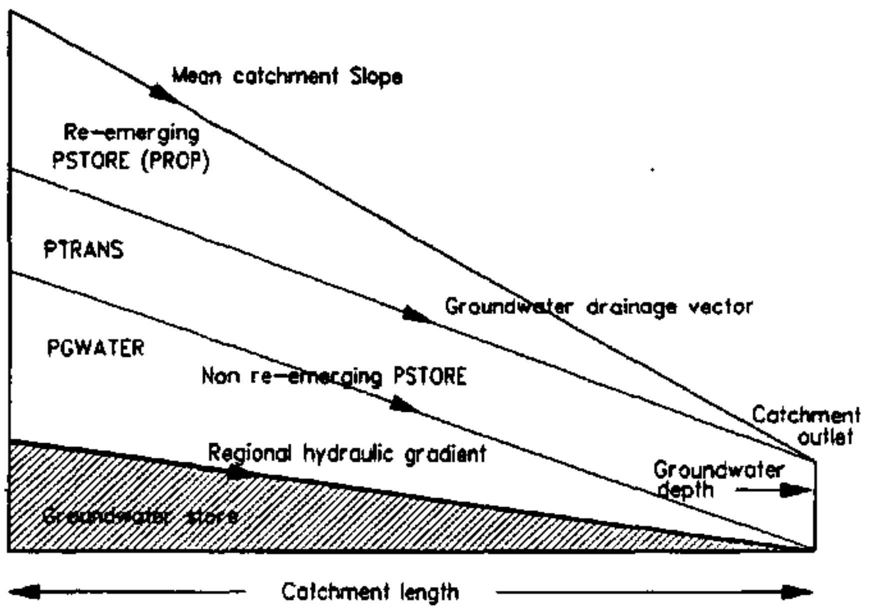


Figure 5.1. *Conceptualized distribution of groundwater storage in the VTI model relative to the catchment slope, drainage vector and regional hydraulic gradient parameters.*

Drainage out of aquifer storage can occur as flow to other sub-areas, groundwater abstraction or as baseflow if the water table intersects the surface. The seepage rate is calculated using Darcy's equation, with the saturated 'seepage face' set equal to the length of the intercept between lines representing the hydraulic gradient and the catchment slope (Fig. 5.1). The conductivity is assumed to be the mean of KG and the soil hydraulic conductivity while the gradient varies exponentially between the mean channel and catchment slopes according to the length of the seepage face.

Groundwater transfers between sub-areas also use Darcy's equation:

$$\text{Outflow} = T_{adj} * \text{HGRAD} * \text{WIDTH} * dt \tag{5.7}$$

where T_{adj} is the adjusted transmissivity, incremented to account for increasing flow rates as the saturated depth of the aquifer increases. The transmissivity parameter TM is incremented as the water table rises above the depth defined by the rest water level parameter RWL:

$$T_{adj} = \text{TM} + (\text{TM/DEPTH} * \text{S/SMAX} * (\text{RWL} - \text{GWD})) \tag{5.8}$$

where SMAX is an upper limit to storativity, defined as 0.2 and GWD is the current groundwater depth. The weighting of TM by S relative to SMAX is designed to have different effects under various hydrogeologic regimes. In unconsolidated unconfined aquifers S/SMAX will be high, consequently the adjustment to TM will become increasingly significant as the water table rises and the area conducting flow increases. Under confined conditions, however, a rising piezometric surface does not result in a significant increase in the cross-sectional area of flow. As confined aquifers have low storativities the S/SMAX ratio would be low, the transmissivity adjustment would be low.

The hydraulic gradient term HGRAD in eq. 5.7 also increases as the water table rises, being close to zero at RWL and rising exponentially to a maximum defined by the regional groundwater gradient parameter when the piezometric surface intersects the surface.

5.4 CRITERIA OF A DAILY MODEL PERFORMANCE IN LOW-FLOW DOMAIN.

No single simulated hydrological time series can be identical in all respects to the measured realization of a process which a model attempts to represent. However for a model to be considered reliable and acceptable it is required that model output is sufficiently close to observed data. The degree to which a model output corresponds with observed data is determined by a variety of goodness-of-fit measures. These measures range from purely subjective, visual assessment of simulation results to objective statistical criteria of the differences between observed and simulated values.

The method of assessing a model should depend on the type of a model and the purpose of simulation. Single event models focus on flood simulation whereas continuous models are designed to simulate satisfactorily long flow time sequences which can then be used for calculation of required flow characteristics and overall assessment of water resources. The visual comparison between observed and simulated hydrographs is normally undertaken as a first step in assessing a model performance. Visual analysis of simulation results normally focus on how well the simulated hydrograph shapes, flood peaks and overall runoff volumes match with corresponding observed ones. It therefore often indirectly underestimates the importance of low-flows in the model output or provides relatively little information on the success of low-flow regime simulations. Objective goodness-of-fit criteria (often referred to as "objective functions") usually include some form of generalization of residuals (the differences between corresponding observed and simulated values for the calibration period). Green and Stephenson (1986) listed 21 different objective functions which have been used for assessing the performance of different models in the last decades. Many of them are either biased towards high flows and thus have reduced emphasis on the quality of low-flow simulations. In order to remove this bias the logarithmic flow transformations may be used. This approach ensures the equality in comparison through the whole range of flows experienced and provides general assessment of a whole simulated time series with an emphasis on medium to low flows. It is therefore often used as a valid pragmatic low-flow simulation assessment option.

However, in certain cases, for example, for estimation of instream flow requirements or stream assimilative capacity determination more subtle criteria of model performance may be necessary. Low-flow estimation methods described in Chapter 2 can serve as such criteria. In this case in addition to conventional goodness-of-fit criteria the model simulations are evaluated by means of comparison of observed and simulated daily flow duration curves, hydrograph recession rates, the frequency and duration of low-flow spells below a reference discharge, the frequency, magnitude and duration of dry season freshes, and total baseflow volumes. The following sections illustrate how these criteria are applied for the evaluation of the VTI model results in several South African catchments.

5.5. THE STUDY CATCHMENTS.

Three different examples have been selected to illustrate the application of the VTI model to specifically simulate low-flow conditions. Two catchments are located in the Sabie river system, one is part of the Diep river of the Southern Cape and the other one is part of the Tugela river system in KwaZulu-Natal.

Sabie1 (gauge X3H001) and Sabie 11 (gauge X3H011).

The Sabie catchments are located in a mountainous region of Eastern Transvaal. They receive relatively high summer rainfall and are largely afforested by commercial timber plantations. Rainfall is primarily convective in nature. A strong orographic effect results in considerable variation in MAP across each catchment (1000-1600 mm).

Sabie1 is underlain by shales and quartzites in its headwater mountain region and by highly soluble dolomites and shales in its lower reaches. A significant tract of alluvium is also present. Soils are well to excessively drained but are significantly deeper on dolomites. Hydrological processes vary with geology across the catchment. A line of perennial springs and waterfalls is associated with the resistant quartzite layers high up the slopes. Significantly less surface runoff is generated from the dolomite regions. However, baseflow is sustained by the intersection of the water table with the surface as a valley bottom spring line. A re-emergence of bank storage from the alluvium is also thought to occur.

Sabie11 is underlain mostly by porphyritic granites. The topography is sharply dissected with steep slopes. Soils are well to excessively drained and are greater than 1 metre in depth. Baseflow is maintained by the re-emergence of groundwater from these valley bottom aquifers.

Diep (gauge K4H003).

The Diep river catchment is located in the Outeniqua mountains of the southern Cape and is covered by natural bush and managed forest plantations (see also Chapter 6 for more details). Precipitation originates from the advection of moist maritime air or from the passage of cold fronts. In general, rain events are of low intensity and long duration. The MAP is approximately 700-900 mm, however, a complex pattern of orographic effects and rain shadows makes it difficult to quantify. The area is underlain by quartzite, shale and tillite. Soils are relatively shallow and sandy in nature. Subsurface piping plays a significant role in their hydrologic response. Baseflow is maintained by structurally controlled springs on the hillslopes.

Mooi (gauge V2H002)

The Mooi River drains the Drakensberg escarpment, is underlain primarily by sandstones and mudstones and covered by highland sourveld. These rocks have a low permeability thus percolation to groundwater is restricted. This results in frequent surface saturation, reflected as vleis and wetlands. The MAP varies from 800-1300 mm across the catchment. Precipitation occurs predominantly in the summer months. Soils are deep and of a clay loam to clay texture but with high infiltration rates and permeabilities.

5.6 SIMULATION RESULTS.

A visual comparison of observed and simulated hydrographs (Figs. 5.2 - 5.5) demonstrates that the model is capable of generating excellent simulations of daily runoff in terms of hydrograph shape. This is supported by the fit statistics presented in Table 5.1. Diep exhibits the least successful calibration. This is strongly related to the difficulties experienced in quantifying rainfall input to the model. A low coefficient of efficiency for Sabie11 is attributed to simulated peaks which exceed the gauging weir capacity. Overall, it could be concluded that the simulations were successful over a range of catchment types. This conventional model assessment, however, does not place sufficient emphasis on how well the model simulates surface-subsurface interactions and their impact on low flows. It also provides limited information on the temporal distribution of low flows.

Table 5.1 Comparative statistics for simulated catchments.

Catchment	Sabie1		Sabie11		Mooi		Diep	
Period of simulation	1979-1989		1979-1989		1972-1982		1962-1976	
Area (km^2)	174		212		937		71	
Simulated maximum (m^3/s)	36.5		98.4		184.		73.47	
Observed maximum (m^3/s)	36.0		28.90[1]		306.90		45.55	
R^2	0.81		0.67		0.68		0.67	
R^2 (log)	0.87		0.83		0.85		0.64	
CE	0.77		0.07		0.67		0.55	
CE (log)	0.86		0.82		0.79		0.61	
	Obs.	Sim.	Obs.	Sim.	Obs.	Sim.	Obs.	Sim.
Mean flow (m^3/s)	1.81	1.83	1.84	1.88	9.45	10.1	0.28	0.33
Mean flow (m^3/s) (log)	0.35	0.34	0.23	0.21	1.44	1.72	-2.13	-1.97

1 Gauging weir capacity

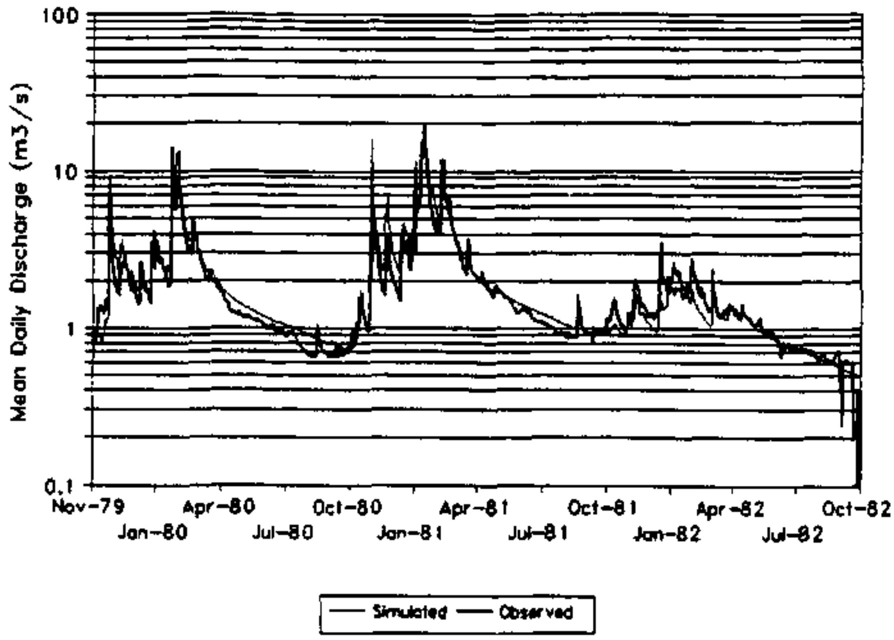


Figure 5.2. *Observed and simulated hydrographs for Sabie 1, 1979-82.*

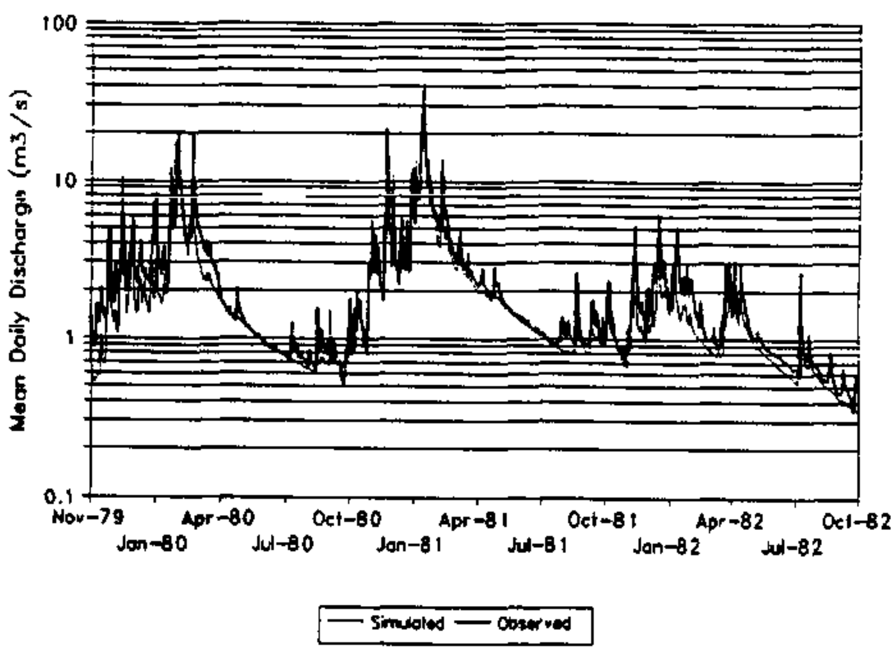


Figure 5.3. *Observed and simulated hydrographs for Sabie 11, 1979-82.*

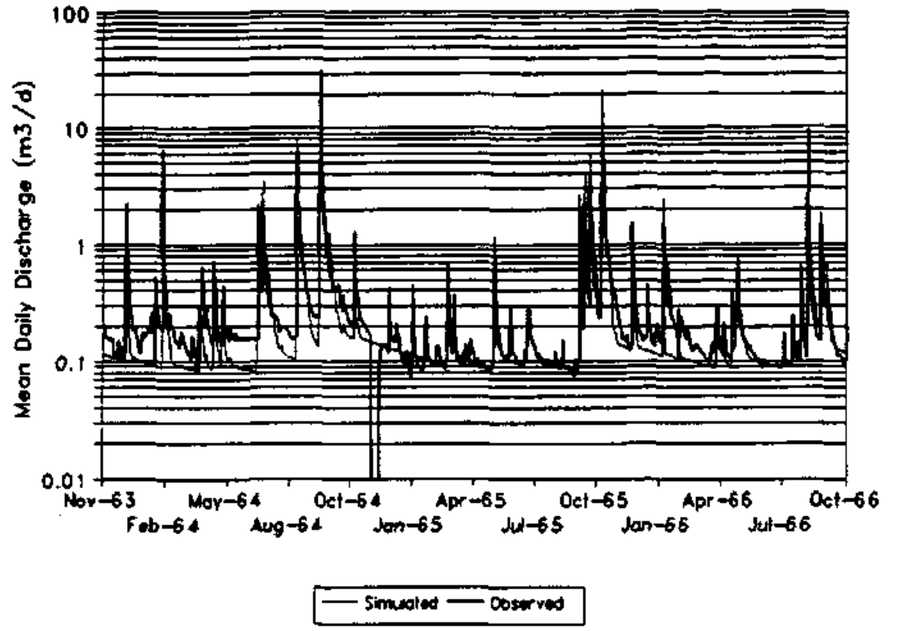


Figure 5.4. *Observed and simulated hydrographs for Diep, 1963-66.*

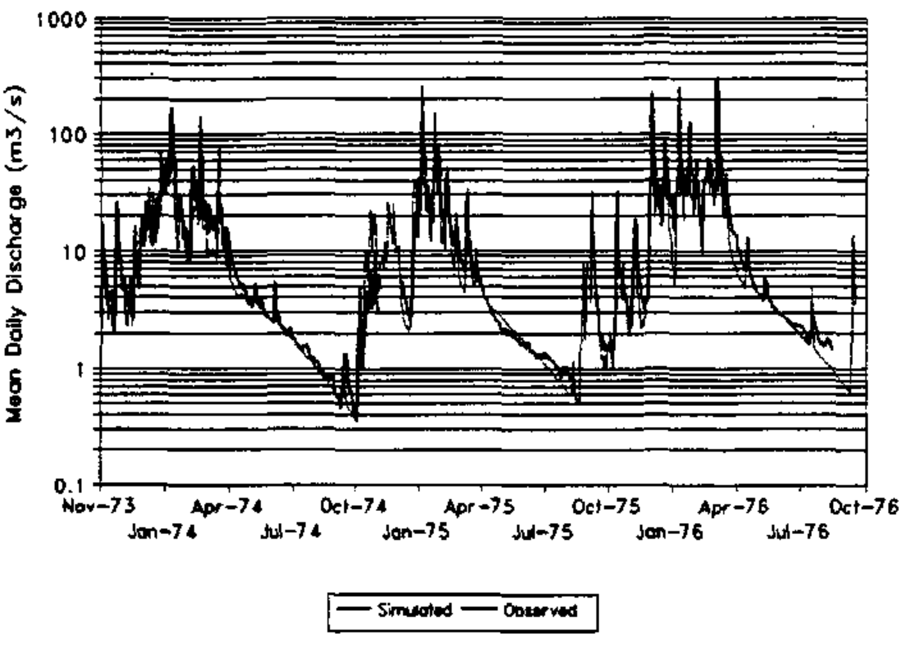


Figure 5.5. *Observed and simulated hydrographs for Mooi, 1973-76.*

Low-flow generation processes are predominant during hydrograph recessions. Therefore an analysis of recessions should highlight the success with which a model simulates these processes. The example distributions of recession ratios (the ratios of present day discharge to discharge during the preceding day when discharge is below mean daily flow Chapter 2 and 3), are shown in Figure 5.6. The percentage of observed recession ratios below arbitrary threshold of 0.94 are 9%, 29%, 46% and 47% respectively for Sabie1, Sabie11, Mooi and Diep (N = 1511, 1654, 1598, 2829). The corresponding figures for simulated runoff are 3%, 10%, 29% and 16% (N = 2261, 2096, 2065, 4012). Klaassen & Pilgrim (1975) found the range of recession constants to be 0.2-0.8 for surface runoff, 0.7-0.94 for interflow and 0.93-0.995 for groundwater. Recession ratios normally fluctuate within the same ranges. An example of simulated soil baseflow recession ratios (Fig. 5.7) shows that they vary within the correct range, with more than 70% lying between 0.7-0.94. Thus the deficiency of ratios below 0.94 cannot be attributed to a systematic conceptual error in the model. It may, however, indicate an insufficient duration or frequency of simulated soil water baseflow and surface runoff dominated recession. A low frequency of such events is exhibited by the lack of small scale flow variations and minor events in the simulated hydrographs (Figs. 5.2 - 5.5) and is reflected by the much larger number of recession days in the simulated data (higher number of recession ratio values). Since these minor events are characterised by rapid decays of their recession limbs, their undersimulation is the primary cause of the paucity of low recession ratios. Other fluctuations in observed low response affecting recession ratios can be attributed to variations in river abstraction.

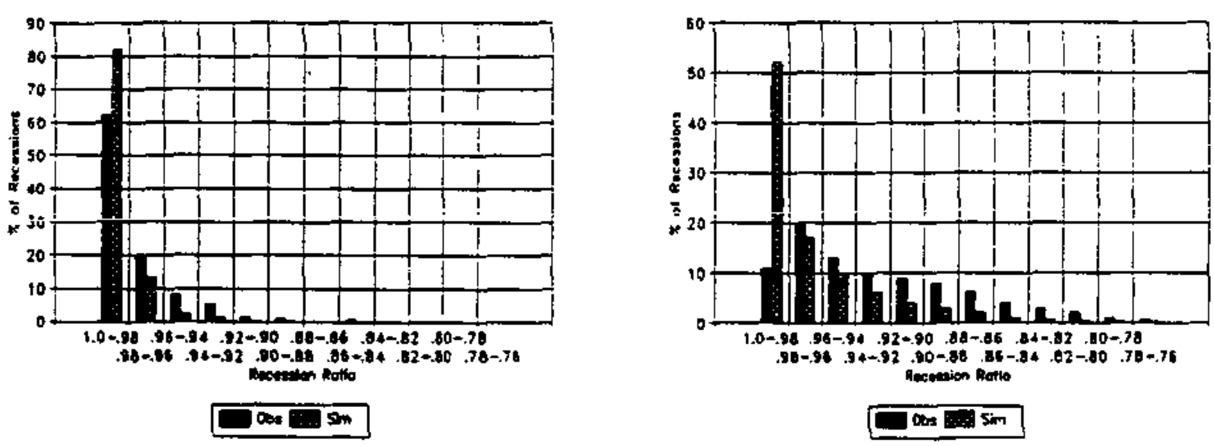


Figure 5.6. Distribution of recession ratios for observed and simulated runoff for Sabie1 (left) and Diep (right).

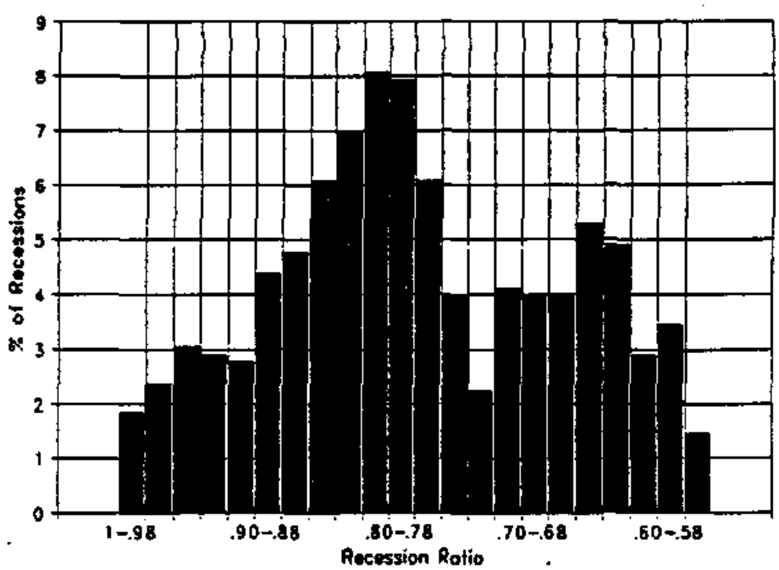


Figure 5.7. Distribution of soil baseflow recession ratios in the Diep catchment.

The poor simulation of minor flow fluctuations can be observed in seasonal hydrographs (Fig.5.8). An exception occurs in Mooi where two simulated events have no corresponding observed data. Winter freshes are poorly reproduced in Sabie1 but are better simulated in Mooi. This is attributed to differences in the role of subsurface runoff in the hydrological regime of each catchment and the model's conceptualisation of these processes. Subsurface runoff in the model is driven by mean soil moisture content, small inputs of rainfall to sub-area would have a minor impact on mean soil moisture, especially where soils are deep, and would therefore be poorly reflected as increased runoff generation. Similar rainfall inputs, however, would generate substantially more runoff in a regime where saturation or infiltration excess runoff play a dominant role. Sabie1 has a hydrological regime strongly driven by subsurface processes, whereas Mooi has a predominantly surface driven regime. Therefore, Sabie1 shows a poorer simulated response to small events and dry season freshes are frequently not simulated.

Another way of comparing the observed and simulated flow regimes is by means of baseflow separation techniques referred to in Chapters 2 and 3. The baseflow index (BFI), the ratio of baseflow to total flow, was determined from hydrograph separation using a digital filter. Results are shown in Table 5.2. They indicate that Sabie1 is the most baseflow driven catchment and Diep is the least. The larger errors in simulated BFI for Sabie11 and Diep indicate that the simulated origin of runoff may be faulty, such that runoff from subsurface sources is overestimated.

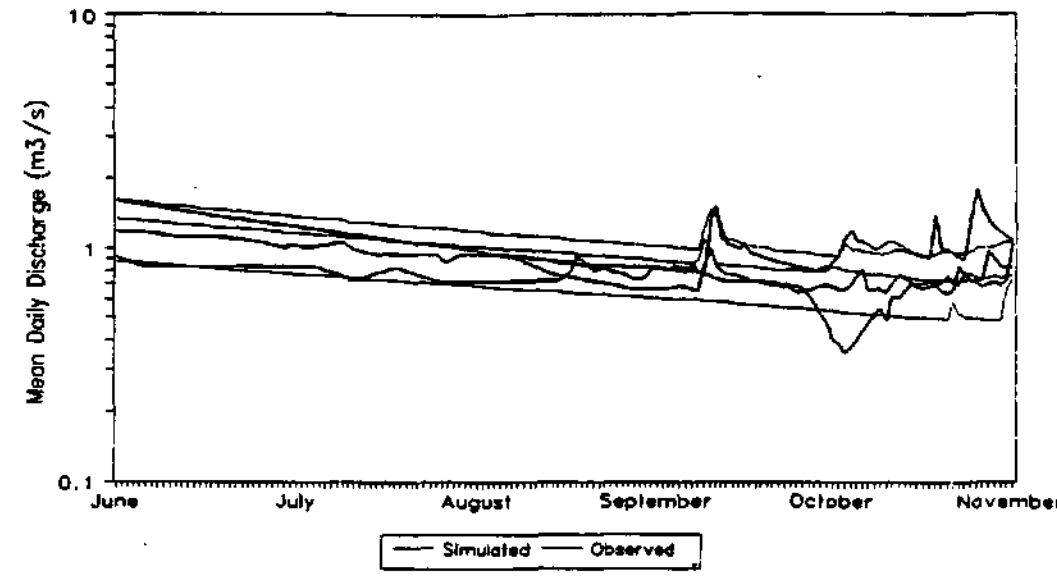


Figure 5.8a. Examples of simulated and observed dry season flow for three years in Sabie1.

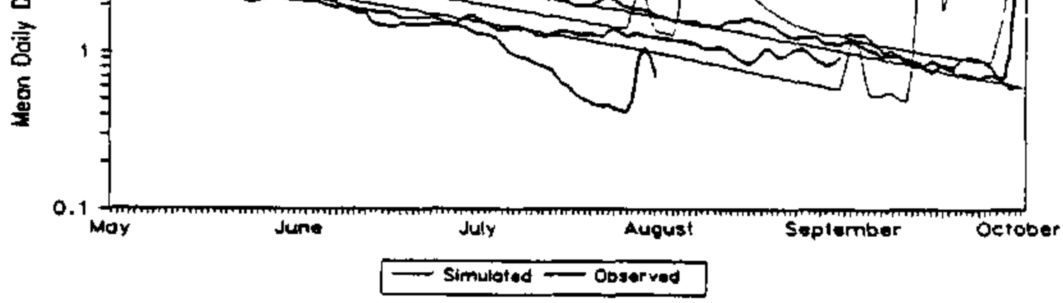


Figure 5.8b. Examples of simulated and observed dry season flow for three years in Mooi.

Table 5.2. Baseflow characteristics of Sabie1, Sabie11, Mooi and Diep.

	Sabie1		Sabie11		Mooi		Diep	
	Obs.	Sim.	Obs.	Sim.	Obs.	Sim.	Obs.	Sim.
Baseflow index	0.58	0.61	0.47	0.55	0.33	0.34	0.31	0.36
Baseflow index % error	5.2		17.0		3.0		16	
Mean daily baseflow (m^3/s)	1.05	1.12	0.88	1.07	3.07	2.83	0.09	0.12

Hence, the calibration may be 'correct for the wrong reasons'. Alternatively, it may indicate that the runoff response from subsurface pathways does not react rapidly enough to rainfall and does not contribute to storm hydrographs.

The rate of response of subsurface pathways can be evaluated from the distribution of recession ratios. All four catchments also exhibit surpluses of simulated recession ratios above 0.98. Although this also may be partly attributable to poor simulation of minor events resulting in prolonged periods where low flows are controlled by groundwater, it implies that the groundwater baseflow function decays too slowly. For example, 934 out of 1511 recessions in Sabie1 are greater than 0.98, while the corresponding figure for simulated data is 1910 out of 2261 recession days. If the extra 750 recession days can be attributed to periods where minor flow events were not simulated and all simulated recessions during such time were groundwater controlled and these are subtracted from the simulated recession figure, then 226 excess recessions remain above 0.98, demonstrating that the rate of simulated groundwater recession is too slow. This can be attributed to a conceptual limitation of the groundwater intersection function, which simulates the re-emergence of groundwater from a regional water table. It therefore does not account for baseflow contributions from perched aquifers which may recede at a much higher rate after storm events. This may be especially significant in alluvial systems where bank storage, recharged during high flow events, results in localised ridges of higher hydraulic conductivity (Sklash & Farvolden, 1979) which contribute to baseflow as flow recedes. The hydraulic characteristics of such a system are likely to be considerably different than the regional aquifer. For example, hydraulic gradients near the river bank are likely to be much higher than the channel gradient (assumed to represent the regional gradient), and hydraulic conductivities are likely to be much higher than those of the underlying bedrock. It is therefore necessary to incorporate the dynamics of such systems into the surface-subsurface interaction functions if low-flow simulations are to be improved.

To assess the ability of the model to simulate the frequency of occurrence of low flows of differing extremity observed and simulated daily flow duration curves can be compared. These have been standardised by dividing daily flow by mean daily flow (Fig. 5.9). Sabie11 is not shown since it is almost identical to Sabie1. With the exception of Diep, where low flows appear to be overstimulated, it would appear that an adequate simulation has been achieved. Flow duration curves are widely used for the assessment of the general quality of the simulations and in many cases may give more (or additional) information than the

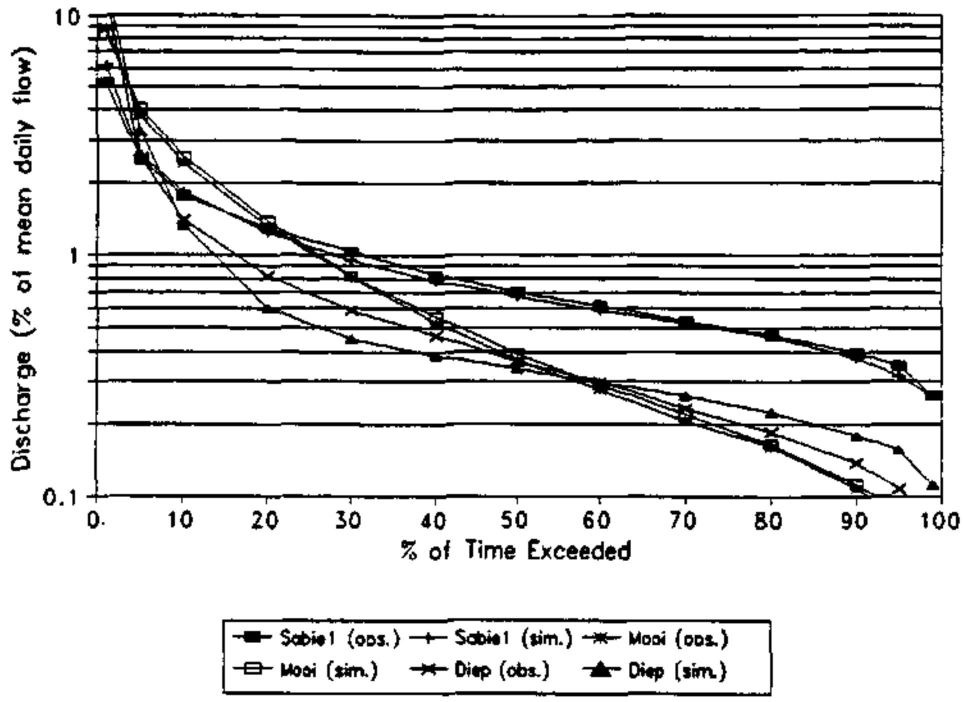


Figure 5.9. Standardised flow duration curves for Sabie1, Mooi and Diep.

conventional fit statistics. However, duration curves are sequence independent, hence provide little information on the temporal continuity of flows below a specified threshold. For ecological and water quality purposes an appreciation of the lengths of flow spells below a specified threshold flow value may appear to be more important.

Durations of observed and simulated spells below Q75 (flow exceeded 75% of the time) are shown in Figure 5.10. Simulated flows appear to generate too few short duration spells and too many long duration spells. This is attributed to the lack of small scale flow variations in the simulated hydrographs, which often break up long spells into several shorter ones. Since the length of spells may be critical for ecological functions, the difficulty of simulating small scale flow fluctuations may be a significant deficiency in the simulation approach. Only in the Mooi are spells adequately simulated. This success may be a consequence of the greater seasonality of the rainfall rather than the success of the model since few flow fluctuations or events can be observed in the dry winter months. Alternatively it may be related to the larger catchment size, which cause many of the smaller events generated in the headwater regions to be attenuated.

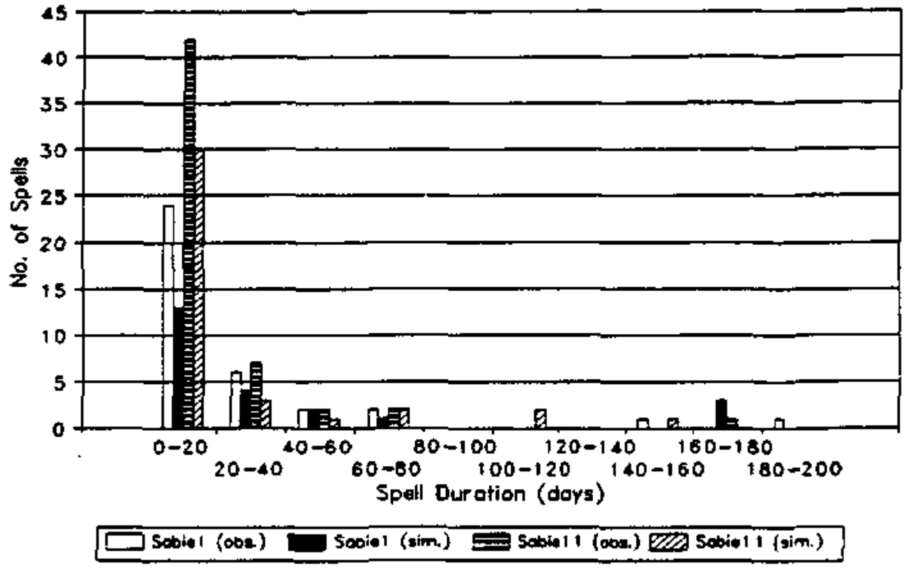


Figure 5.10a. *Frequency and duration of observed and simulated spells below Q75 in Sabie 1 and Sabie 11.*

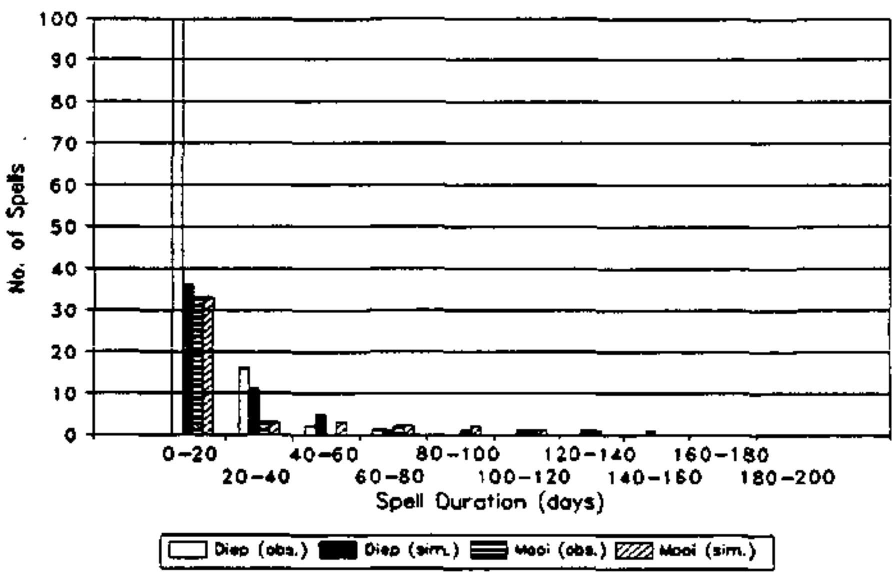


Figure 5.10b. *Frequency and duration of observed and simulated spells below Q75 in Mooi and Diep.*

Table 5.3 Duration of spells below a threshold of 75%, 50% and 40% of average daily flow (ADF) with a return period of 5 years and associated flow deficits below these threshold.

Threshold		Sabie1		Sabie11		Mooi		Diep	
		obs.	sim.	obs.	sim.	obs.	sim.	obs.	sim.
75% of ADF	Duration (d)	198	224	171	208	181	163	91	178
	Deficit flow (Ml)	10427	11699	12416	14316	83446	69233	1279	2501
50% of ADF	Duration (d)	121	167	116	138	133	150	83	136
	Deficit flow (Ml)	2282	3698	3880	4608	40268	35976	607	1024
40% of ADF	Duration (d)	64	109	69	117	128	139	77	123
	Deficit flow (Ml)	915	1269	1718	2529	28762	24934	393	588

For management purposes it is necessary to forecast expected durations and flow deficits of critical low flows. Although the simulation periods are rather short for meaningful statistical analyses, these have been performed for 5 year return period of low-flow spells to illustrate some of the differences which occur between observed and simulated flows. Table 5.3 shows the expected duration of spells below thresholds of 75%, 50% and 40% of long-term mean daily flow and the flow deficits which would have to be overcome to maintain flow at these thresholds. The simulations commonly overestimate the duration of spells. The best results are obtained for Mooi where observed and simulated spell durations are within 20 days of each other. This success can be attributed to the lack of minor flow fluctuations and the strong seasonality of the Mooi regime.

5.7 CONCLUSIONS.

Apart from the VTI model description, this Chapter has also concentrated on the possibility of using low-flow estimation methods as the criteria of model performance in the low-flow context. For all simulated catchments described in the Chapter good visual fits were obtained between observed and simulated hydrograph peaks and shapes. Conventional fit statistics (mean, standard deviation, coefficient of determination (R^2), coefficient of efficiency (CE)), were also favourable in all the catchments considered. This is an indication of successful simulations which would normally be acceptable for most of the water resource problem.

However, when the simulations were interpreted using the low-flow analytical methods the utility of the simulations is less than would appear initially. An analysis of recession rates suggests that too few fluctuations in the long term recession response were simulated due to a poor simulation of small dry season events and an inability to simulate fluctuations in low flows resulting from variations in daily river abstraction. The model was found to adequately reproduce soil water baseflow recessions, although groundwater recessions appeared to be undersimulated. Conceptual deficiencies were identified in the model which could affect the distribution of simulated recession rates in catchments driven primarily by subsurface processes and those where a rapid groundwater response plays a significant role. In the latter case simulated groundwater contributions may not decay rapidly enough.

A *comparison of observed and simulated 1-day flow duration curves (another conventional* technique widely used for model results evaluation) suggests that in most cases considered the range, frequency and severity of low flows were well simulated. This would also normally be treated as a reflection of good simulations. However, an analysis of the duration of low-flow spells below several arbitrary selected threshold flows indicated that the model overestimates the duration of these spells. This occurred due to the undersimulation of freshes which break up extended dry season low-flow spells.

The outlined problems with daily flow simulations do not intend to impose criticism on the general quality of the results produced by the VTI (or other similar daily) model. These results would still be considered to be very good in terms of conventional fit criteria. However, the ability of a daily model to reproduce specific aspects of the low-flow regime may be of critical importance for ecological or water quality purposes. The findings reported in this Chapter suggest that for those purposes the model simulations need to be evaluated by a variety of low-flow performances indicators not commonly considered by water engineers before being utilised for water quality or ecological applications.

6. DEVELOPMENT OF AN ALTERNATIVE TECHNIQUE TO PATCH, EXTEND AND GENERATE DAILY TIME SERIES FOR BASIN-WIDE LOW-FLOW ANALYSIS

6.1 INTRODUCTION.

The observed streamflow information forms the basis for any water resource assessment. The approach adopted in the current study is the detailed spatial characterisation of low-flows on a catchment scale from daily data. For such basin-wide low-flow analysis it is important that daily flow regimes are adequately measured at a number of sites which ideally are evenly distributed within the basin. However, in the South African context, there are a number of problems related to analysing basin wide daily flow regimes and determining spatial variations from the available observed data.

- Many of the available time series have gaps due to missing data.
- The time series from different sites within the basins are rarely coincident in time and may represent different sequences of dry and wet climatic conditions.
- The time series at any site may be non-stationary due to time variant land use effects or water abstraction patterns.
- Critical points of interest within the basin may not be represented by a gauging site.

There are several possible approaches that could be adopted to address these problems, but they are not necessarily independent or mutually exclusive and it is likely that no single approach will adequately or optimally address all problems. Some approaches (or combinations) may be more appropriate in certain situations than others. Some of the possible approaches and their advantages and disadvantages are briefly outlined below.

- Use available monthly streamflow time series (observed and/or simulated, for example by the Pitman monthly rainfall-runoff model) and develop a disaggregation method to determine daily flow characteristics. This has the advantage of adding value to the extensive work that has already been completed on the regionalisation of monthly flow characteristics in South Africa. However, the best that may be achieved is a characterisation of the frequency distribution of daily flows within a month, while it would be more difficult to generate realistic time sequences of daily flows. This disadvantage may be restrictive where several sites within a single basin are being considered together and the time coincidence of certain flows (peaks, for example) is important.

- A similar alternative to the previous case is to use a monthly simulation model to generate a monthly time series. This approach could be useful where information is required at the sub-'quaternary' catchment scale and the Surface Water Resources of South Africa provide guidelines for quantifying parameter values of the widely used Pitman model (Pitman and Kakebeeke, 1991) at ungauged sites. One further advantage is that it should be possible to incorporate non-stationarity due to time variant water use patterns into the simulated time series. However, the same disadvantages related to the application of any disaggregation method referred to in the item above would apply. A further disadvantage is that the successful application of the model relies upon the availability of adequately representative observed rainfall (and possibly evaporation) data.

- Use a daily time series simulation model, for example, the VTI model described in the previous Chapter. The assumed approach would be to establish the model parameter values for all gauged sites within the basin through calibration and validation studies and then to transfer parameter values to ungauged sites of interest. Such an approach has most of the advantages of the monthly simulation approach, but suffers from the distinct disadvantage that the calibration of a daily model frequently requires greater resources of time and effort to achieve a satisfactory simulation. The requirement of adequate rainfall and evaporation input data assumes even greater significance in daily modelling. Daily modelling has been used within South Africa with varying degrees of success (Hughes and Sami, 1994; Schulze 1991). The results of the application of the VTI daily model in several countries in the whole southern Africa are presented in a recently completed southern Africa FRIEND project (Hughes, 1997)

- Develop some form of spatial interpolation approach that uses the available observed streamflow records. The simplest example of such an approach might be straightforward weighting of observed streamflow at a gauged site (or sites) by the ratio of the catchment areas of the site of interest and the gauged site(s). One of the critical aspects of such an approach is that streamflows at even closely adjacent sites are rarely linearly related to catchment area. The larger the catchments and the greater the distance separating them, the greater the probability that the streamflows are the result of different meteorological events or runoff generation processes, reducing the likelihood of success of simple spatial interpolation methods. This is particularly true in the South African context where many rainstorms are convective in origin and of small spatial extent. Some of the problems associated with this type of approach are related to the possible existence of trends, or non-stationarity, in the actual streamflow at the required site or at the stations used for interpolation. It may therefore be necessary to naturalise all streamflow records before the interpolation process is started; not an easy task in most cases. Additional problems could result if some of the available observed records have truncated peak flows due to limited range stage-discharge relationships. This is particularly relevant to the South African situation where many streamflow monitoring sites are based on weirs or flumes which are not calibrated for the full range of observed peak flows. Despite the limitations, such approaches are simple to use and could be valuable tools if the interpolation algorithms satisfactorily account for non-linearities in the relationship between streamflows at different sites.

This Chapter outlines one possible approach that falls into the latter category and that was developed to patch missing data and extend observed records. The motivation for developing the technique was related to the need for time series that are coincident in time. These could then be used to determine representative measures of flow characteristics for a number of sites within a single basin. Coincident time series could also be useful as upstream inputs to a daily rainfall-runoff model applied to the middle or lower reaches of a basin.

6.2 SPATIAL INTERPOLATION ALGORITHM

In an attempt to account for some of the non-linearities in streamflows at different sites, even within similar parts of the same basin, the spatial interpolation algorithm has been based on the daily flow duration curves for each month of the year. The first step in the procedure is to generate tables of discharge values for each site and month of the year for 17 percentage points of the flow duration curves (DTQ_i, where i = 1 to 17 corresponding to 0.01, 0.1, 1, 5, 10, 20, 30, 40, 50, 60, 70, 80, 90, 95, 99, 99.9 and 99.99%). Up to five possible 'source' stations are then identified and each assigned weights (W_j, j = 1 to 5) associated with the degree of similarity between these flow regimes and the 'destination' site (the one to be patched or extended). An estimate of the streamflow on any day at the 'destination' site is then made by identifying the percentage point position (DP_j) on the duration curve table (for the relevant month) of the streamflows on the same day at the 'source' sites (QS_j) and reading off the flow value (QD_j) for the equivalent percentage point from the 'destination' site's duration curve table. The procedure is illustrated in Figure 6.1 for a single 'source' site.

Each estimate of the 'destination' site flow value (QD_j) is then multiplied by the 'source' site weight (W_j) and the sum of these values divided by the sum of the weights. If any of the 'source' sites have missing data then these are ignored for those periods.

$$QD = \Sigma(QD_j * W_j) \;/\; \Sigma W_j \qquad \text{Eq.6.1}$$

For 'source' streamflows lying between the 17 defined percentage points of the duration tables (DTQ_i), logarithmic interpolation is used to define the position. Thus :

$$DP_j = EXP\{(lQS_j - lDTQ_{j,i}) \;/\; (lDTQ_{j,i+1} - lDTQ_{j,i})\} \qquad \text{Eq.6.2}$$

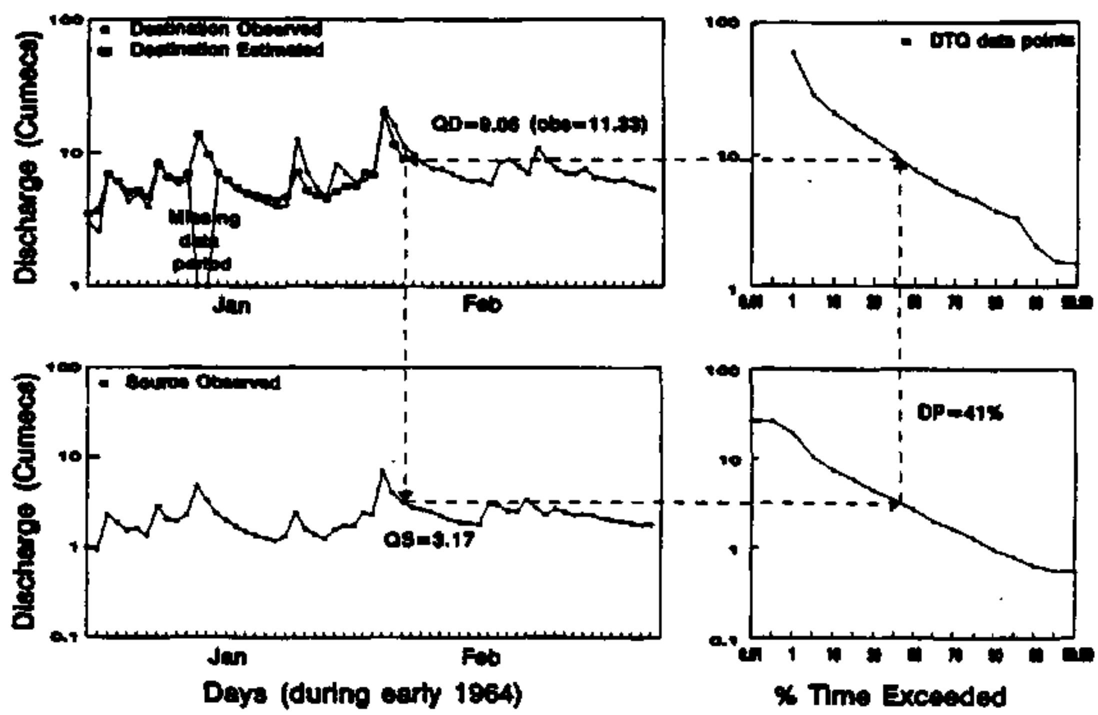


Figure 6.1. *Illustration of the patching algorithm for a Swaziland catchment with a single source station. The upper left diagram shows the estimated values for the whole of January for the destination station.*

$$QD_j = DP_j * EXP\{(lDTQ_{s,i} - lDTQ_{s,i-1}) + lDTQ_{s,i}\} \quad \text{Eq.6.3}$$

where DP_j is the duration table percentage point position,
$lDTQ_{j,i}$ the natural log of the closest duration table flow value less than QS_j,
$lDTQ_{s,i}$ the natural log of the flow value at the same percentage point in the 'source' site duration table,
and i-1 refers to the percentage point one step higher than i

While occurring very infrequently, special cases exist if the 'source' flow is either greater than the flow exceeded 0.01% of the time or less than the flow exceeded 99.99% of the time. In the former case QD_j is estimated as $QS_j * DTQ_{s,1} / DTQ_{j,1}$ and in the latter as $DTQ_{s,17}$. A further special case exists where the duration curve of a 'source' station is flat between two of the data table points (denominator of equation 6.2 = 0). The position (DP_j) is assumed to lie halfway between the two points.

The use of several 'source' sites is an attempt to account for the fact that a 'destination' site time series may be the result of several influences, which may not be reflected in a single 'source' site time series. In addition, part of an individual 'source' site time series may be missing and the use of several will decrease the number of missing values in the estimated 'destination' series.

The algorithm forms the main part of a time series 'model', one of several that are included in the HYMAS software package. In the case of this 'patching' model the 'parameters' for each 'destination' site are the catchment area, the site number of up to five 'source' sites and their weighting factors. The output from the model consists of the raw observed flow data (including missing data periods), the 'patched' observed flow (no missing data) and what is referred to here as the 'substitute' flow time series. This represents a time series made up of completely estimated values regardless of whether the original observed flow was missing or not. The first two flow values are expressed as $m^3 s^{-1}$ as well as $m^3 s^{-1} km^{-2}$. The purpose of 'substitute' series is to allow the patching process algorithm and associated choice of 'source' sites and weights to be evaluated by comparing them with the original observed data in a similar way that simulated series are compared with observed in conventional modelling approaches.

The selection of suitable 'source' sites and the quantification of weights could be based on a detailed spatial correlation analysis, but in practice, the choice is frequently limited and/or obvious. The graphical display facilities allow observed series to be visually compared to assist in the selection of 'source' sites and the model is quick and simple to run such that the best weighting factors to use can be determined through trial-and-error type calibration.

It is therefore possible to apply this approach to a group of stations and compare the results with those obtained by other methods. In the context of this Chapter, the results are compared with those generated from calibrating the VTI model operating with a daily time step. As obvious from the Previous Chapter, the VTI model represents a much more resource intensive alternative to generating extended time series.

6.3 EXAMPLES FROM SOUTHERN AFRICA

Six groups of catchments, drawn from different regions within Southern Africa (Fig. 6.2), are used to illustrate the potential of the patching algorithm and to identify some of the limitations of the method. The results are illustrated using a standard set of measures of fit between the observed and estimated (by the patching algorithm and the VTI model) daily streamflow series. The fit statistics used are the mean, standard deviation and coefficients

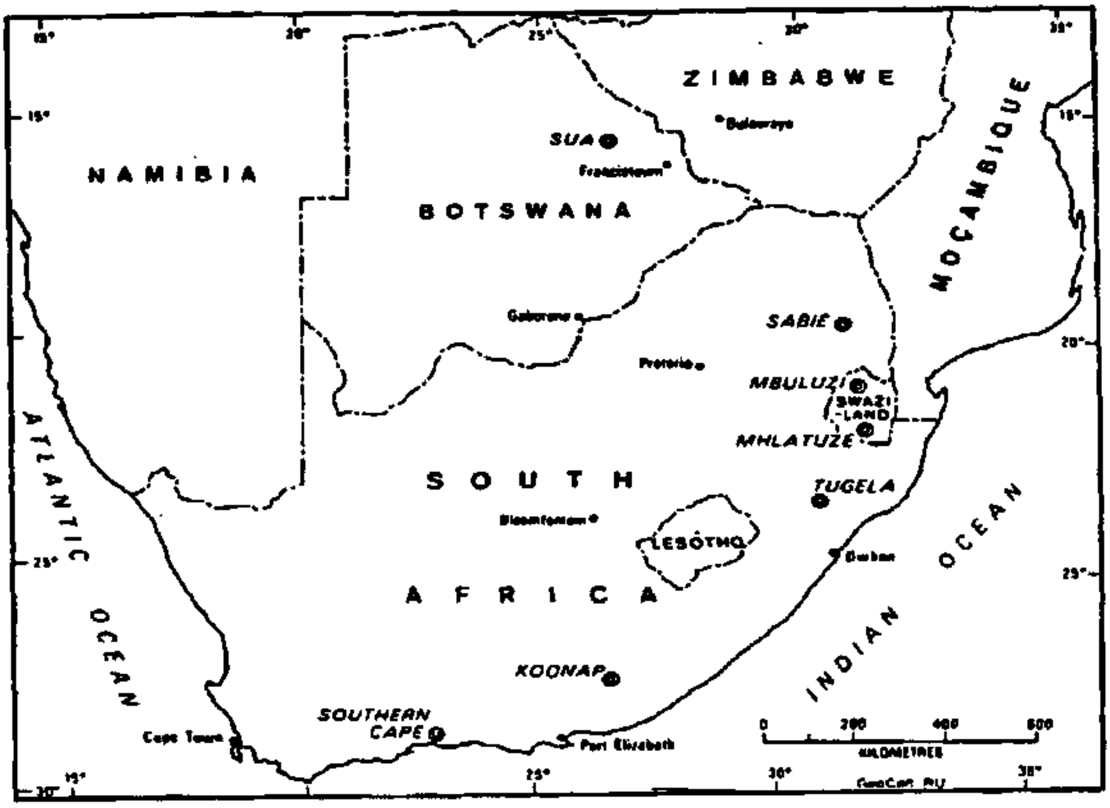


Figure 6.2. Location of catchment groups within southern Africa.

of determination (R^2) and efficiency (CE) based on un-transformed data as well as natural log transformed data. In some cases, short lengths of comparative time series data as well as duration curves are used to further illustrate specific points.

Southern Cape Catchments.

Four gauged catchments are located within the Southern Cape Coastal Lakes region, situated between George and Knysna (a distance of some 50 km) in the eastern part of the Western Cape Province of South Africa. They are bounded to the north by the steeply sloping Outeniqua Mountains and drain into a system of inter-connected lakes separated from the sea by relic sand dunes. The four catchments are closely adjacent to each other but the gauges are located at different distances from the headwater areas in the mountains (Fig. 6.3). The Karatara gauge is located in the headwater areas and dominated by steep mountain slopes

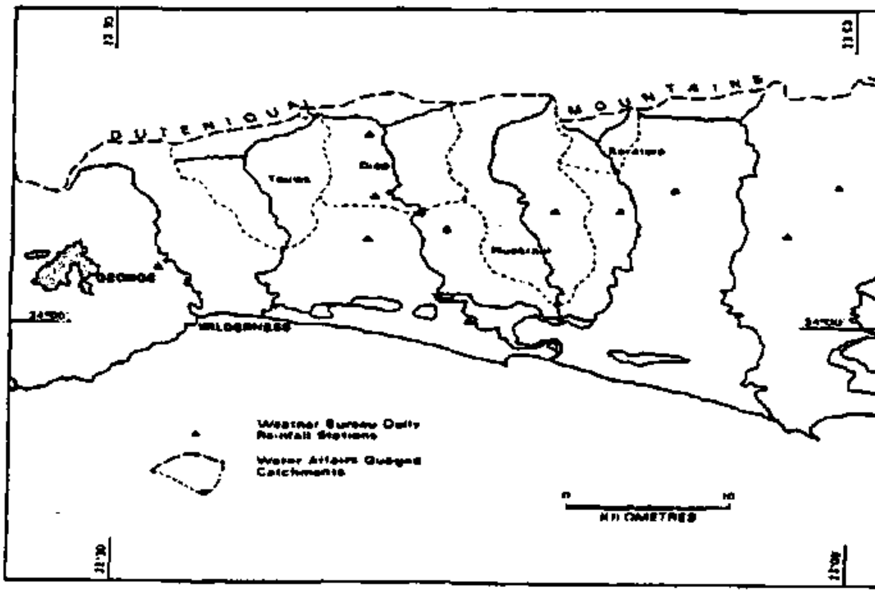


Figure 6.3. Location of the southern Cape catchments.

covered with natural 'fynbos' bush. The gauged part of the Diep catchment includes the foothills zone, dominated by a mixture of managed pine plantations and indigenous deciduous forest. The Touw catchment is gauged at a lower point and includes part of the coastal plateau area where the landuse consists of mixed forestry and agriculture (pasture and cultivation with some irrigation). The Höekraal catchment is gauged close to the coastal lakes and represents the full range of characteristics found within the region.

The available flow records start during the 1960's and extend to the present day, however none of the gauging stations are able to measure the full range of flows experienced. The Höekraal gauge is the worst, being a low level causeway structure. Rainfall data are available at some 12 stations either within, or close to, the catchments. However, some parts of the catchments are poorly represented, particularly in the more remote mountain areas. The observed flow records are expected to be non-stationary to a certain degree, due to changing patterns of water use related to agricultural practices. However, these influences are relatively minor, except within the Höekraal catchment and are difficult to detect within the natural climatic variations.

Table 6.1 lists the period used for the analyses for each catchment and the statistics of comparison for the simulations based on calibrating the VTI model and those based on the estimation of the complete series using the patching algorithm. The VTI model was not applied to the Höekraal catchment. Figure 6.4 shows the observed annual 1-day flow duration curve as well as the equivalent curves for the two simulated data series for the Touw catchment. Equivalent diagrams for the other catchments are broadly similar. It is apparent from the table that in terms of un-transformed flow values the patching algorithm has not been as successful as the VTI model simulations. Figure 6.4 illustrates that this is partly due to excessive over-estimation of the higher flows (< 1% exceedence equivalent to about 30 days in a 9 year time series), however, a detailed examination of the complete time series suggests that some high flows are simulated when none occur in the observed record and some observed high flows are under-simulated. The same applies to the simulations based on the VTI model, but to a lesser extent and this accounts for the somewhat better fit statistics. The latter result can be partly attributed to the inadequacy of the rainfall input.

Table 6.1 Comparative statistics for the Southern Cape catchments.

Catchment	Area (km^2)	Time period	Model	Untransformed				Ln transformed			
				Mean, m^3/s	SD, m^3/s	R^2	CE	Mean	SD	R^2	CE
Karatara -K4H002	22	1963-1971	Obs.	0.35	1.18			-2.19	1.21		
			VTI	0.34	1.08	0.50	0.45	-2.13	1.18	0.60	0.56
			Patch	0.40	1.40	0.53	0.32	-1.93	1.15	0.76	0.70
Diep -K4H003	71	1962-1976	Obs.	0.28	1.31			-2.13	1.00		
			VTI	0.33	1.53	0.67	0.55	-1.97	0.90	0.64	0.61
			Patch	0.36	2.41	0.44	-0.93	-2.07	1.05	0.57	0.48
Touw -K3H005	80	1970-1978	Obs.	0.37	1.38			-1.91	1.12		
			VTI	0.38	1.24	0.56	0.54	-1.90	1.07	0.40	0.30
			Patch	0.37	1.95	0.54	0.08	-1.99	1.02	0.67	0.65
Höekraal -K4H001	110	1960-1991	Obs.	0.42	0.73			-1.83	1.45		
			VTI	Has not been simulated							
			Patch	0.45	0.88	0.55	0.34	-1.68	1.38	0.66	0.63

In the Touw example, none of the available raingauges are within the catchment and it is clear that some observed flow events occur at times when there is no observed rainfall to account for the increase in streamflow. Although the rainfall is not generally very spatially variable, there can be quite large differences during individual events (Hughes and Wright, 1988). The implication is that during some events, even closely adjacent and similar catchments such as the Diep and Touw do not experience similar relative sized streamflows. The statistics based on log transformed data, reflecting the models performance with respect to moderate to low flows, are usually better for both estimation approaches and overall the patching model is an improvement on the VTI model. This is partly due to over-simulation, by the VTI model, of the flows less than the 95% exceedence level (about 330 days in a 9 year series). The Touw (Fig. 6.4) is an extreme example and is possibly caused by relatively small pumped abstractions from behind the flow measuring weir which are known to occur but are not quantified and therefore not incorporated into the simulations. In the other catchments the VTI model also tends to generate somewhat more sustained dry weather flows than occur in reality, whereas the patching algorithm reproduces these flows more accurately.

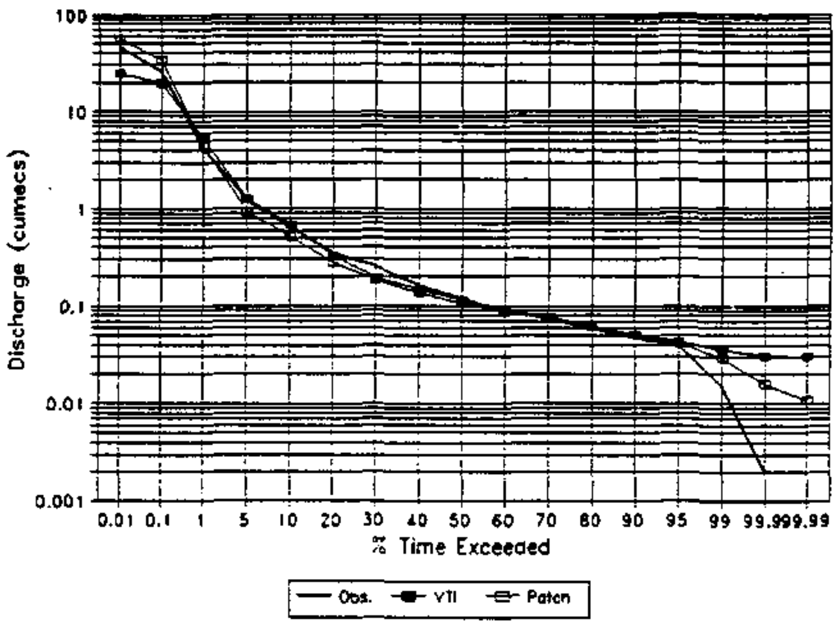


Figure 6.4. 1-day annual flow duration curves (observed and simulated) for the Touw catchment based on data for 1970 to 1978.

The annual duration curve for the Höekraal is more or less flat from the 1% to the 0.01% point due to the severe limitations of the gauging structure. However, 1 day in each month of the complete observed time series (approximately 860 days for each calendar month)represents greater than 0.1% exceedence and therefore the 0.1 and 0.01% points have to be estimated by extrapolation of the curve. If the maximum recorded flow occurs quite frequently in some months the extrapolation procedure generates a flat curve right up to 0.01%. In contrast, if such flows occur less often in other months the curve is still quite steep in the 5% to 0.1% part and extrapolation gives a 0.01% value which could be substantially higher than the maximum recorded flow. The patching algorithm can therefore produce estimated flows for some months which are greater than the gauge limits. This illustrates the problem of gauging structure limitations as well as that of adequately defining

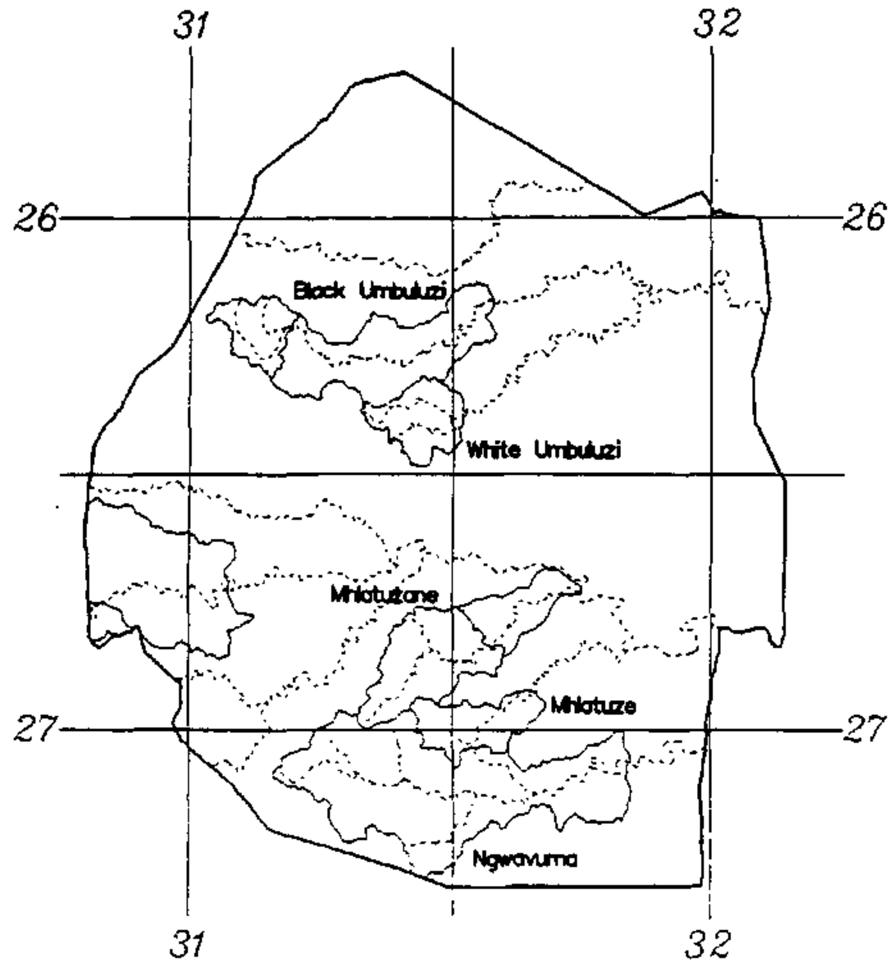


Figure 6.5. Location of the Swaziland catchments.

the full extent of the duration curves in the absence of a long enough time series. In fact, to define the 0.01% point accurately, a 329 year record is required - clearly a requirement unlikely to be satisfied. It may therefore be necessary to critically examine the upper extremes of the calender month duration curves before using them, particularly in situations where the period of record is relatively short.

Swaziland Catchments.

Two groups of Swaziland catchments have been included in the analysis; the first is situated in the northern part of Swaziland (Fig. 6.5) to the north of Manzini and east of Mbabane. Two gauging stations are located on the Black Umbuluzi above Mnjoli Dam and one within the White Umbuluzi to the south. The Black Umbuluzi headwaters are in the Highveld region and the river flows through the Upper and Lower Middleveld through steeply sloping topography towards the flatter Western Lowveld. The upper catchment is situated within the Highveld region, while the lower gauging station is lower down the river within the Lower Middleveld. The gauged catchment of the White Umbuluzi drains the Upper and Lower Middleveld and shares its northern boundary with the middle to lower parts of the Black Umbuluzi.

A total of three raingauges are available for both the Black and White Umbuluzi. Two of the Black Umbuluzi gauges are located near the southern and eastern borders of the upper catchment, while the third is near the outlet of the lower catchment. The three White Umbuluzi gauges are located on the southern and eastern boundaries of the catchment. In general terms there is a gradient in mean annual rainfall from about 1100 mm in the Highveld to less than 800 mm in the Lowveld. It is unlikely that the available data are able to adequately define the variability of rainfall on a daily basis. The results provided for the VTI model simulations in Table 6.2 suggest that this is particularly true for the White Umbuluzi and a detailed examination of the rainfall, observed and simulated streamflow time series suggests that some major runoff events occur at times when very little rainfall is recorded at the raingauges on the boundary of the catchment.

The time series patterns of streamflow at the two Black Umbuluzi gauges are similar and it is reasonable to suggest that a large proportion of the runoff at the lower site is generated in the mid to upstream areas represented by the upper gauged catchment, where two raingauges are available. This may account for the relatively better VTI model results for the Black than for the White Umbuluzi. It could also partly explain why the patching algorithm works quite successfully within the Black Umbuluzi (upper used to patch the lower and vice versa), but does not work as well when an attempt is made to patch the White Umbuluzi using the time series of the two Black Umbuluzi catchments.

Figure 6.6 illustrates the relative patterns of streamflow response at the gauging sites for 3 months of the wet season in 1970, while Figure 6.7 compares the observed response at the White Umbuluzi site with the simulations by the two models. One of the characteristics of the White Umbuluzi appears to be a less sustained baseflow response (days 60 to 110) relative to the other sites, which is not reproduced very well by either of the two models. Owing to the flatter recessions after the main event (days 50 to 60), the secondary events close to days 75 and 95 are at relatively high positions on the two Black Umbuluzi duration curves. The consequence of the steeper recession on the White Umbuluzi is that the patching algorithm tends to overpredict the secondary events for this catchment.

The second group of catchments are close to the southern border of Swaziland and include two gauges on the Mhlatuzane River and one each on the Mhlatuze and Ngwavuma Rivers (Fig. 6.5). All of these rivers rise within the Upper and Lower Middleveld (where the upper Mhlatuzane and Mhlatuze gauges are located) and drain to the Western Lowveld (where the lower Mhlatuzane and Ngwavuma gauges are located). The amount of rainfall data available for calibrating the VTI model is as limited as for the northern group of catchments and must be at least partly responsible for the poor coefficient of efficiency values resulting from the

Table 6.2 Comparative statistics for the Swaziland catchments.

Catchment	Area (km^2)	Time period	Model	Untransformed				Ln transformed			
				Mean, m^3/s	SD, m^3/s	R^2	CE	Mean	SD	R^2	CE
Upper Black Umbuluzi	166	1971-1982	Obs.	2.18	2.52			0.35	0.90		
			VTI	2.31	3.41	0.60	0.28	0.41	0.83	0.73	0.72
			Patch	2.52	2.99	0.72	0.58	0.54	0.82	0.81	0.76
Lower Black Umbuluzi	722	1971-1982	Obs.	7.65	8.65			1.73	0.72		
			VTI	6.97	9.42	0.61	0.50	1.63	0.69	0.81	0.80
			Patch	7.73	9.10	0.65	0.60	1.74	0.72	0.79	0.78
White Umbuluzi	223	1965-1971	Obs.	0.79	3.00			-1.05	1.01		
			VTI	0.83	2.17	0.17	0.07	-0.93	0.94	0.54	0.49
			Patch	0.72	1.81	0.33	0.33	-1.04	1.01	0.63	0.60
Upper Mhlatuzane	365	1972-1983	Obs.	1.33	2.53			-0.29	0.96		
			VTI	1.36	2.45	0.26	0.05	-0.15	0.88	0.55	0.51
			Patch	1.10	2.82	0.40	0.15	-0.53	0.97	0.85	0.78
Lower Mhlatuzane	526	1972-1983	Obs.	1.41	3.07			-0.24	0.98		
			VTI	1.64	3.31	0.35	0.11	0.06	0.76	0.51	0.41
			Patch	1.79	3.58	0.56	0.36	0.00	1.03	0.82	0.73
Mhlatuze	215	1972-1983	Obs.	0.83	1.44			-0.68	0.95		
			VTI	0.87	1.60	0.36	0.09	-0.61	0.98	0.47	0.35
			Patch	0.95	1.32	0.46	0.40	-0.54	0.92	0.83	0.81
Ngwavuma	1305	1971-1982	Obs.	3.56	7.51			0.73	0.92		
			VTI	3.26	7.12	0.26	0.07	0.67	0.84	0.50	0.45
			Patch	3.31	5.99	0.40	0.38	0.76	0.81	0.75	0.75

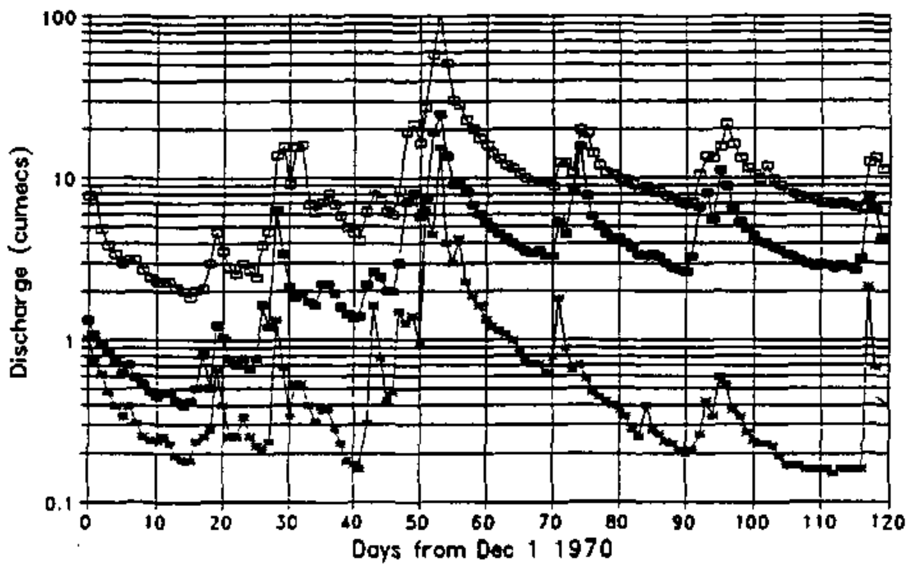


Figure 6.6. Time series plots of observed flow data for the Upper and Lower Black Umbuluzi and the White Umbuluzi for the wet season of the 1970 hydrological year.

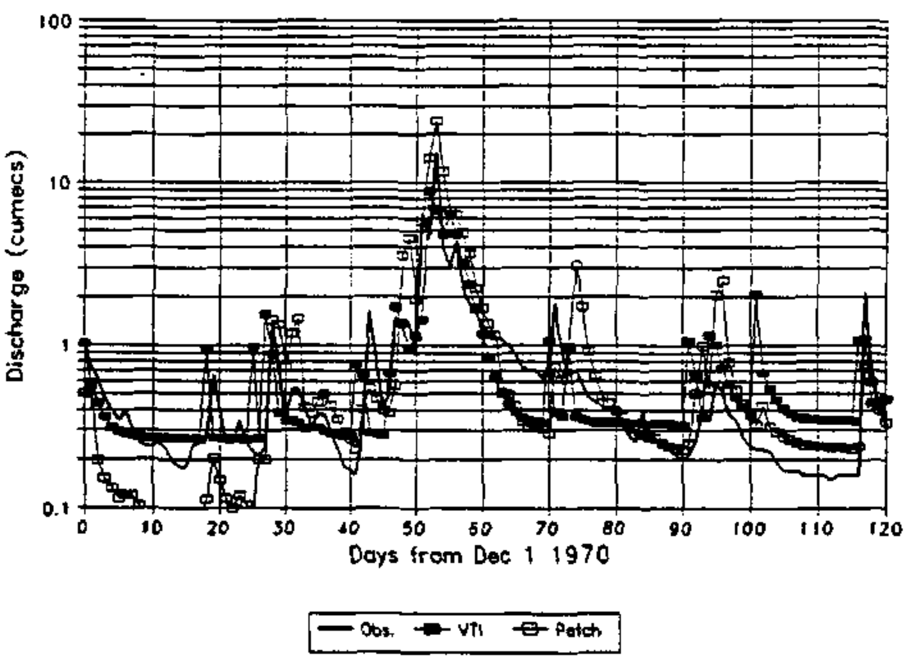


Figure 6.7. Observed and simulated hydrographs (VTI model and patching) for the White Umbuluzi for the wet season of the 1970 hydrological year.

VTI model application (Table 6.2). The VTI model generates a reasonably representative series of streamflows (observed and simulated duration curves are closely similar), but individual events are not modelled very successfully. The patching algorithm generates overall better results, particularly with respect to the one-to-one fit for individual days, despite the fact that some of the means and standard deviations are not as close to the observed as the VTI simulations.

Sabie catchments

The Sabie River basin is located in the Eastern Transvaal province, flows into the Limpopo River and falls within the summer rainfall region of South Africa. The upstream areas, situated in a mountainous region, receive relatively high rainfall (1000 - 1600 mm a^{-1}) and are largely afforested by commercial timber plantations. The downstream reaches flow through the Kruger National Park where the mean annual rainfall decreases to about 600 mm. The majority of the flow gauges are located in the upstream parts of the Sabie catchment where most of the runoff is generated, while the lower parts are rather poorly gauged. The quality of available flow records is not always good and most of the stations have missing data and low discharge table limits during at least part of their record periods. The description of the Sabie catchment and details of the gauging stations may be found in Volume II of the current Report.

The objective of the application of the algorithm to the Sabie catchment was to extend the short records on gauges X3H021 and X3H015 strategically located in the central and downstream reaches and to patch the poor flow records at gauge X3H008 on the Sand River - the largest northern tributary of Sabie.

The calibration of the VTI model in the Sabie catchment has been based on data for 1978 to 1989 and wherever the VTI simulation results were available the comparison between observed and the two models has been based on the same standard period. In general terms, the three closest gauges have been used as source stations for the patching method, with weighting factors largely related to the distances separating them from the destination stations and no attempt at calibrating the weights has been made at this stage.

The results for gauge X3H001 are broadly similar for both approaches, with the VTI model somewhat better in the low-flow domain. For gauge X3H006 the patching procedure appears to yield slightly better results than the VTI model which is partly due to the fact that the model simulates peaks in excess of the measuring limit (exceeded 0.1% of the time) while patching does not. The model also frequently overestimates intermediate sized events (Fig. 6.8). Low to moderate flows are reproduced equally well by both approaches as illustrated by the flow duration curves in Figure 6.9. Relatively high values for the selected statistical criteria indicate a good performance of the algorithm at gauge X3H004, while for gauge X3H011, the patching procedure generates better results than the VTI model for the untransformed flows, but is less effective for low-flow representation.

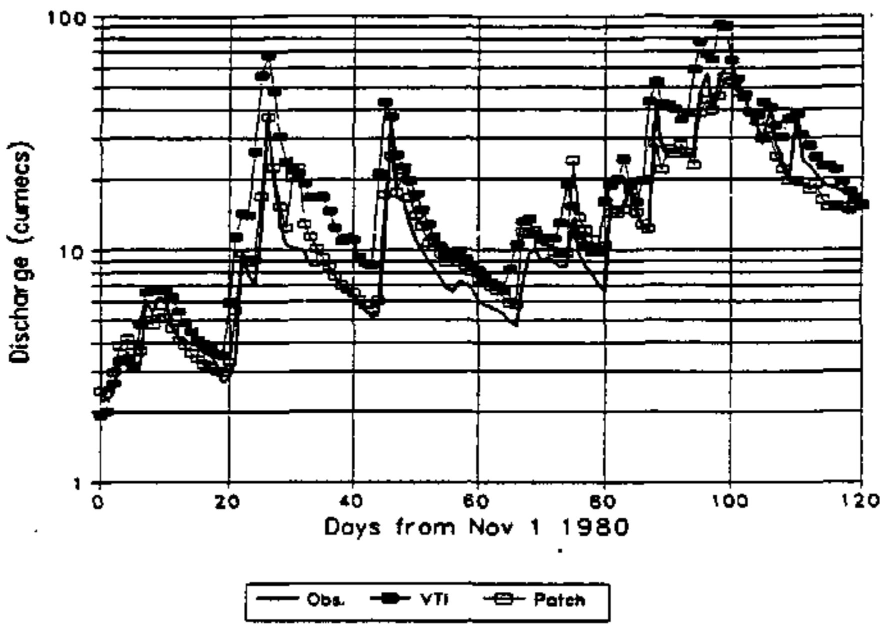


Figure 6.8. Observed and simulated (VTI model and patching) time series for the early part of the 1980 hydrological year at gauge X3H006 in the Sabie catchment.

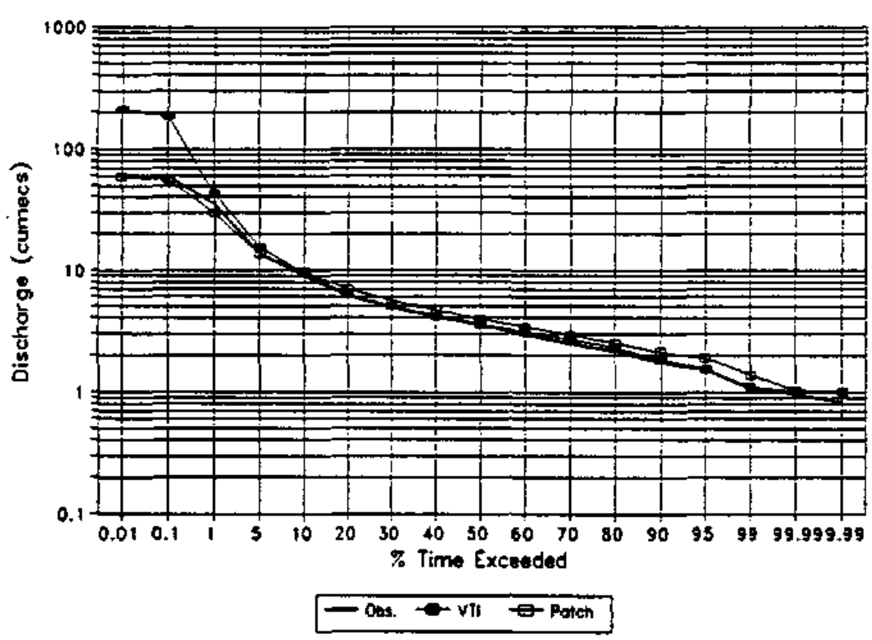


Figure 6.9. 1-day annual flow duration curves (observed and simulated) for the Sabie catchment at X3H006 based on data for hydrological years 1978 to 1988.

Table 6.3 Comparative statistics for the Sabie catchments[1]

Catchment	Area (km^2)	Time period	Model	Untransformed				Ln transformed			
				Mean, m^3/s	SD, m^3/s	R^2	CE	Mean	SD	R^2	CE
Sabie, X3H001	174	1978-1989	Obs.	1.71	1.84			0.31	0.60		
			VTI	1.77	2.16	0.83	0.76	0.29	0.66	0.86	0.84
			Patch	1.64	2.17	0.83	0.76	0.17	0.75	0.72	0.51
Sabie, X3H006	766	1978-1989	Obs.	5.00	5.86			1.32	0.68		
			VTI	5.23	8.11	0.73	0.45	1.34	0.68	0.70	0.67
			Patch	5.34	5.28	0.92	0.92	1.44	0.62	0.91	0.88
Nordsand, X3H004	151	1948-1993	Obs.	0.52	1.42			-1.81	1.55		
			VTI	Simulation has not been completed							
			Patch	0.54	1.62	0.74	0.65	-1.74	1.40	0.76	0.76
Marite, X3H011	212	1978-1989	Obs.	1.87	2.42			0.25	0.79		
			VTI	1.86	3.77	0.64	0.08	0.21	0.76	0.83	0.82
			Patch	1.41	2.23	0.84	0.80	-0.12	0.93	0.79	0.49
Sabie, X3H021	2407	1990-1993	Obs.	6.51	9.94			1.24	1.06		
			VTI	6.14	9.97	0.55	0.55	1.12	1.17	0.78	0.73
			Pat.1	4.33	14.55	0.63	0.12	0.59	1.02	0.75	0.36
			Pat.2	5.59	14.89	0.58	0.35	0.79	1.15	0.84	0.69
Sabie, X3H015	5713	1987-1993	Obs.	9.92	13.49			1.62	1.21		
			VTI	Simulation has not been completed							
			Patch	8.94	12.8	0.78	0.77	1.48	1.21	0.84	0.82
Sand, X3H008	1064	1967-1992	Obs.	2.07	3.47			-0.24	1.58		
			VTI	Simulation has not been completed							
			Patch	1.86	3.45	0.71	0.68	-0.40	1.59	0.70	0.66

[1] Statistics for the VTI model are given as they were in August 1995. The calibration of the VTI model for the Sabie catchment has latter continued. The final results are presented in Volume II.

The record period at X3H021 is too short (Oct. 1990 to July 1993) to allow representative flow duration curves for each month to be constructed. Consequently the patching algorithm generally appears to underestimate flows throughout the whole range and results in a relatively low CE value. It is also possible that the rainfall characteristics over the incremental catchment area, between X3H021 and the upstream stations used for patching, are different from those over the upstream parts of the catchment. The VTI model does not suffer from these limitations and that results in its slightly better overall performance.

Station X3H015 also has a relatively short record (1987 - 1993) and the discharge table limit is exceeded approximately 0.8% of the time. For the period used the results appear to be acceptable given that all the source stations have relatively poor quality records and are located far away from the site. The VTI model had not been applied to that part of the catchment at the time of writing.

Station X3H008 is the only one available on the Sand River. Its record contains many missing data periods and the discharge table limit is very low and exceeded about 3% of the time. The algorithm gives reasonable results bearing in mind the limitations of the available data. The source gauges in this case were X3H011 and B7H004 - located just north of the Sand River sub-catchment. Although gauge B7H004 is beyond the boundaries of the whole Sabie basin, it was accepted as being reasonably representative of the upper portions of the Sand river sub-catchment. The fact that the patching algorithm produces a relatively good fit to the untransformed observed values indicates that the simulated record also has limitations with respect to the representativeness of high flows. At the time of writing, the application of the VTI model to this site had not been successful.

Central Tugela catchments

The Tugela catchment is situated in the KwaZulu-Natal Province, has its source in the Drakensberg Mountains and flows eastward to the Indian Ocean near Durban. The total catchment area exceeds 29000 km^2 and the mean annual runoff is about 4000 10^6 m^3. The density and quality of the daily flow records in the middle reaches of the Tugela are very limited; all the major tributaries are not gauged at their outlets and only two stations (V6H007 and V6H002) exist on the Tugela itself (Fig. 6.10).

Gauge V6H007 has a short record. Gauge V6H002 is situated just downstream of V6H007 and has recorded flow from as early as 1927. However, the record prior to 1978 was found to be unreliable (Vaal Augmentation Planning Study Report, 1994), while the latter observations have an error band of up to 30%. Low flows in particular were found to be overestimated at V6H002 since it recorded higher flows during the dry months (April-August) than gauge V5H002, located downstream at the outlet of the whole Tugela catchment, and much higher flows than gauge V6H007 upstream. The other adjacent upstream gauges have reasonably long and reliable flow records, with high discharge table limits and rarely missing data. Nevertheless, the distances between these upstream stations

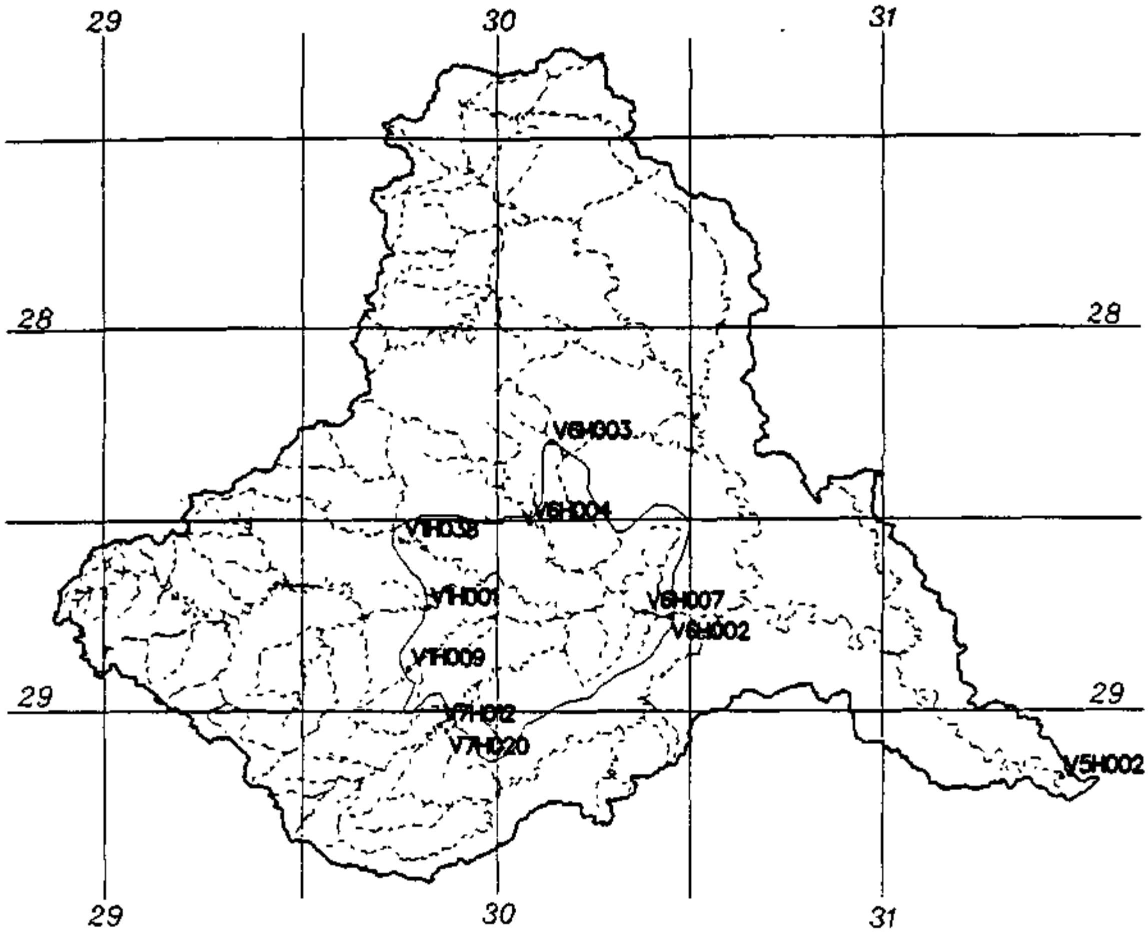


Figure 6.10 Location of the Tugela catchments.

and gauges V6H007 andV6H002 are large and flow sequences are expected to be quite different. This creates some difficulties for the selection of the source stations for extending discharge series at V6H007 and simulating flow series at V6H002.

It is logical to try and extend the record at V6H007 using data from V6H002. However, since V6H002 frequently has missing data the resultant substitute flow at V6H007 will not be complete and other source gauges should be used as well. It is suggested that the immediate upstream gauges probably have an approximately equal effect on the substitute runoff at the destination site, V6H007. Several combinations of source stations and weights have been tried and the best results (Fig. 6.11) produced by using 4 upstream gauges (V6H004, V1H038, V1H001, V1H020) together with the downstream gauge V6H002 (all having equal weights).

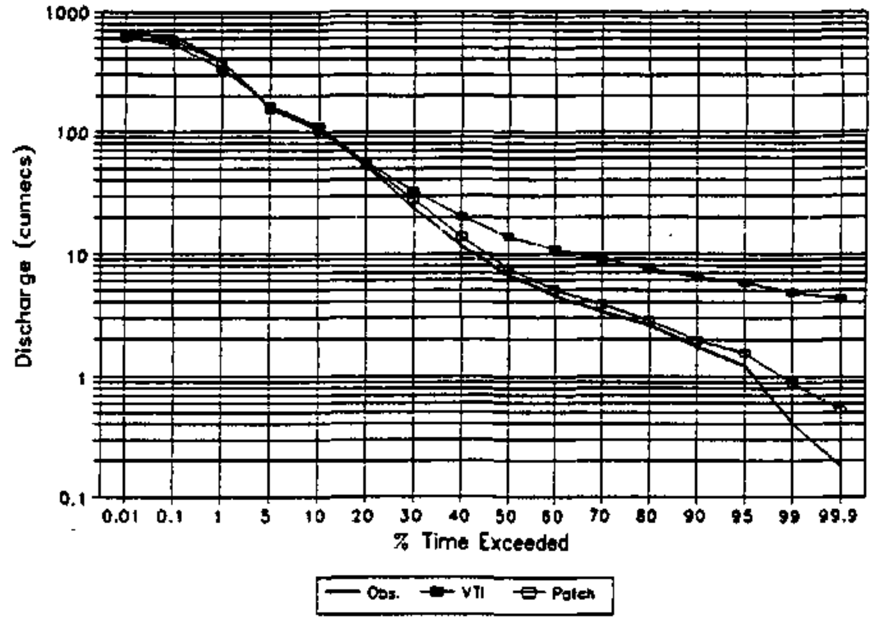


Figure 6.11. 1-day annual flow duration curves (observed and simulated) for gauge V6H007, Tugela River based on data for hydrological years 1982 to 1987.

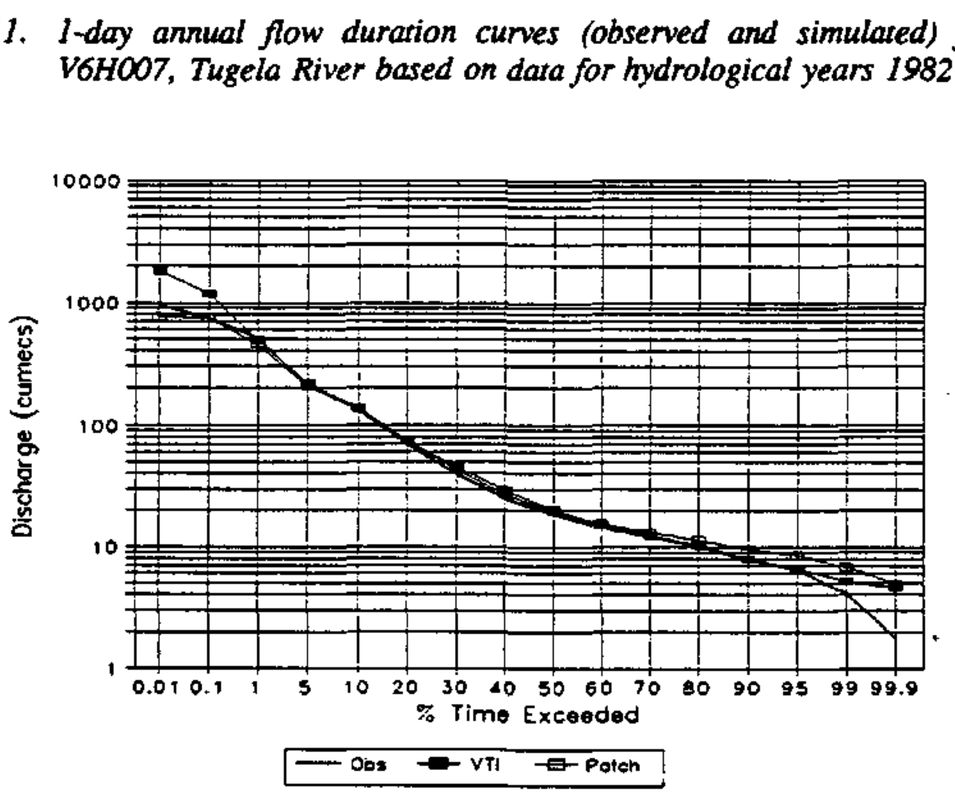


Figure 6.12. 1-day flow annual duration curves (observed and simulated) for gauge V6H002, Tugela River based on data for hydrological years 1978 to 1988.

Table 6.4 Comparative statistics for the central Tugela catchments

Catchment	Area (km^2)	Time period	Model	Untransformed				Ln transformed			
				Mean, m^3/s	SD, m^3/s	R^2	CE	Mean	SD	R^2	CE
Tugela, V6H007	12498	1982-1987	Obs.	36.03	72.74			2.30	1.58		
			VTI	40.98	65.47	0.81	0.80	2.99	1.10	0.91	0.66
			Patch	31.83	57.53	0.88	0.86	2.27	1.54	0.94	0.93
Tugela, V6H002	12862	1978-1988	Obs.	51.85	88.28			3.22	1.09		
			VTI	49.20	77.99	0.74	0.74	3.21	1.07	0.81	0.81
			Patch	50.34	78.16	0.89	0.89	3.27	1.03	0.86	0.85
Wasbank, V6H003	312	1954-1964	Obs.	1.35	4.12			-0.89	1.38		
			VTI	1.39	3.05	0.23	0.15	-1.26	2.49	0.29	-0.79
			Patch	1.31	3.17	0.20	0.09	-0.82	1.42	0.46	0.34
Sundays, V6H004	658	1954-1964	Obs.	3.38	7.64			-0.01	1.59		
			VTI	3.32	7.92	0.57	0.48	0.05	1.50	0.70	0.68
			Patch	3.25	7.97	0.37	0.18	-0.12	1.69	0.52	0.39

The record at V6H007 is too short to be useful on its own for patching V6H002. The same combination of source stations and weights as for V6H007 has been used to generate substitute flow at V6H002 (with gauge V6H007 replacing V6H002 as a source site) and the results also appear to be good (Fig. 6.12). However, given that the observed data are known to overestimate real flows, the patched and extended time series is similarly deficient.

The VTI model has been applied to the incremental area between gauge V6H002 and all immediate upstream gauges (Fig. 6.10) for a period of 1978 to 1988. The missing data periods at each of the upstream gauges have been previously patched from one of the adjacent stations to ensure continuous records of upstream inflow to the model. The resulting statistics for V6H007 are favourable, although medium to low flows are overestimated (Fig. 6.11) which was expected since the model was calibrated mainly against the record at V6H002 which as has already been noted, overestimates flow.

A good example of a problem area exists in the catchments gauged by V6H003 and V6H004 (Fig. 6.10). The application of the VTI model to both catchments produced rather poor results, largely as a consequence of a lack of observed rainfall data in the vicinity of the catchments. The application of the patching algorithm to both gauges has also resulted in limited success. The problem is attributed to the fact that the temporal distribution of rainfall events in both catchments and the resultant flow sequences are very different. At the same time these two flow gauges are located in that part of Tugela catchment which is very poorly gauged. The selection of source stations is very limited and the two stations can only be patched from each other.

Koonap Catchments.

These catchments are situated in the Eastern Cape Province of South Africa and drain the mountainous areas of the Winterberg, eventually flowing into the Great Fish River. The upper areas are represented by station Q9H016 and experience on average about 800 mm rainfall a year. Rainfall over the lower areas is about 550 mm a^{-1} and a lower gauging station occurs at Q9H002. The majority of the area is covered by grassland used for grazing purposes. There are numerous small farm dams and localised irrigation is practised in many of the valley bottom areas. The downstream increase in aridity coupled with the existence of irrigation abstractions and channel transmission losses to alluvial material has the effect of ensuring that the lower gauging site has a much higher percentage of zero flow days (71% - based on the annual duration curve) compared to the upper site (15%) (Fig.6.13).

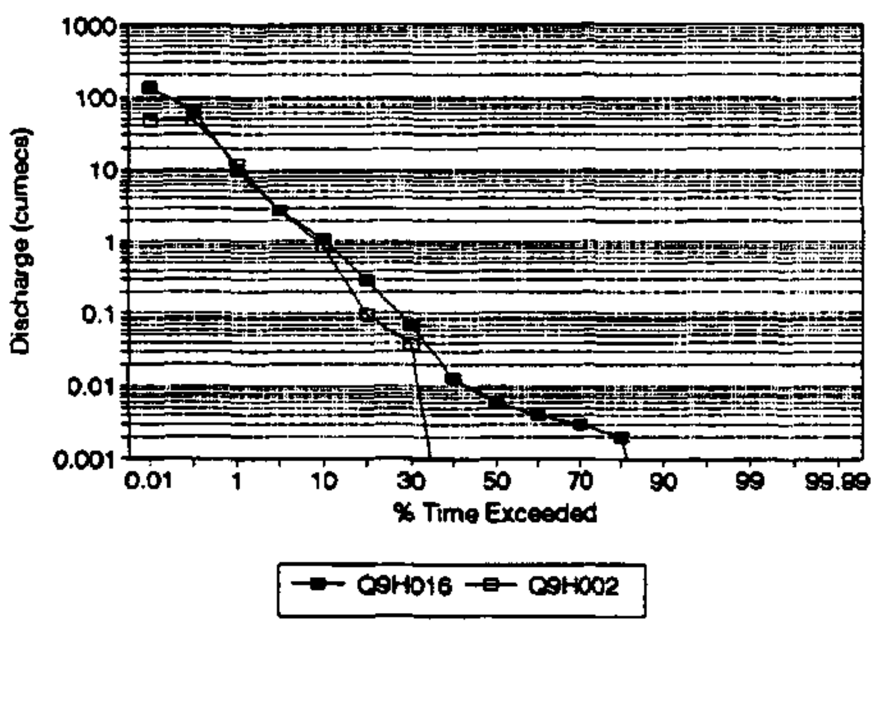


Figure 6.13 Observed flow duration curves at two flow gauges in the Koonap catchment.

The VTI model was applied by dividing the total catchment down to Q9H002 into 12 sub-areas, five of which are above Q9H016 and the results are summarised in Table 6.5. Given the relative complexity of the hydrology of this catchment, the model appears to have performed reasonably well. The results of applying the patching algorithm (Table 6.5) are broadly similar to the VTI model results, with different statistics favouring different approaches but in general terms the patching approach has worked better for the lower gauging station and the VTI model better for Q9H016. The latter conclusion is largely based on the one-to-one correspondence between observed and simulated untransformed flows and can be partly attributed to the nature of the duration curves. When the lower station is used to patch the upper, a zero flow day at the source station could correspond to a fairly wide range of possible flows at the upper station. However, in the absence of further information, the estimated destination flow will always be the same for each month of the year. When the upper station is used to patch the lower, the same problem does not occur as a wide range of source flows above zero will correspond to a zero destination flow, the same for observed and simulated. The conclusion must be that, in similar situations, an upstream gauge may be successfully used to patch a lower station, but caution must be exercised if the reverse is to be attempted. The use of additional gauging sites, outside the basin but in similar upstream locations, could solve the problem if they are available.

Table 6.5 Comparative statistics for the Koonap catchments.

Catchment	Area (km^2)	Time period	Model	Untransformed				Ln transformed			
				Mean, m^3/s	SD, m^3/s	R^2	CE	Mean	SD	R^2	CE
Upper, Q9H016	489	1980-1990	Obs.	0.61	3.29			-3.45	2.73		
			VTI	0.53	3.93	0.74	0.63	-3.11	2.13	0.67	0.49
			Patch	0.76	4.82	0.84	0.54	-3.63	3.04	0.45	0.42
Lower, Q9H002	1245	1980-1990	Obs.	0.58	3.02			-1.12	2.13		
			VTI	0.63	3.60	0.63	0.48	-1.12	2.15	0.42	0.29
			Patch	0.55	2.88	0.81	0.80	-1.53	2.43	0.57	0.30

Botswana Catchments.

Two rivers flowing into the endoreic area of Sua Pan, part of the Makgadikgadi Pan system of semi-arid east central Botswana have been used to assess the usefulness of the patching algorithm in arid catchments. The topography is very flat with vegetation cover consisting of sparse to moderately dense bush. Rainfall is of the order of 420 - 480 mm a^{-1} with most falling between November and March. Hughes (1995) demonstrated that the application of rainfall-runoff models to these catchments is difficult due to inadequate representation of the spatial and temporal variability of the rainfall input and the difficulties associated with

Table 6.6 Comparative statistics for the Botswana catchments.

Catchment	Area (km^2)	Time period	Model	Untransformed				Ln transformed			
				Mean, m^3/s	SD, m^3/s	R^2	CE	Mean	SD	R^2	CE
Mosetse	1026	1970-1975	Obs.	1.21	8.18			0.48	2.55		
			VTI	1.17	7.03	0.46	0.42	-0.66	2.23	0.31	0.22
			Patch	1.58	11.02	0.30	-0.33	2.39	1.21	0.17	0.02
Mosetse	1026	1970-1987	Obs.	0.71	5.41			0.27	2.27		
			VTI	0.31	2.78	0.14	0.12	-1.07	2.28	0.10	-0.72
			Patch	0.77	6.68	0.27	-0.23	1.71	1.72	0.20	-0.02
Mosupe	819	1970-1987	Obs.	0.21	1.58			0.11	1.69		
			VTI	Has not been simulated							
			Patch	0.19	1.49	0.23	0.02	-0.64	3.02	0.07	-2.41

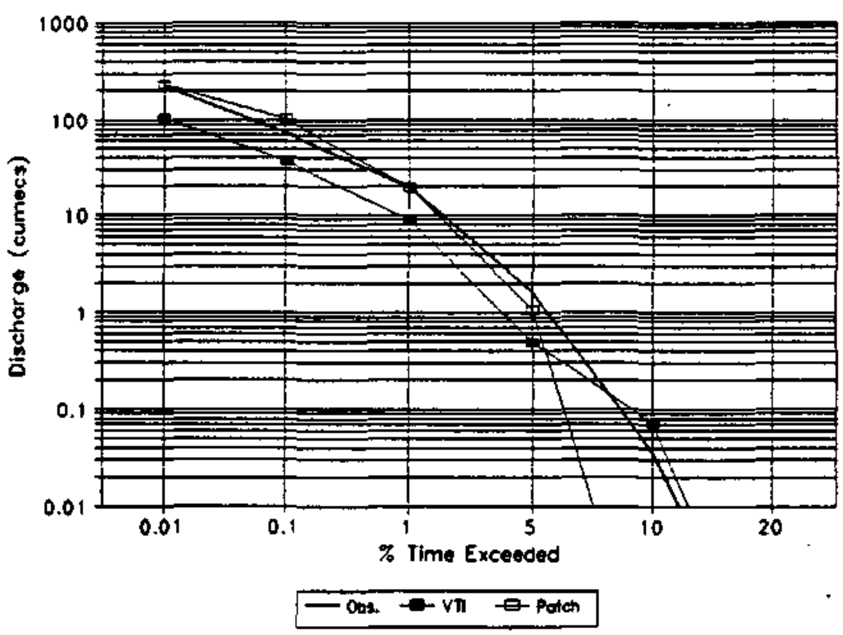


Figure 6.14. 1-day flow annual duration curves (observed and simulated) for the Mosetse River, Botswana.

representing some of the channel runoff processes. Table 6.6 illustrates this point for the Mosetse catchment, where despite achieving a reasonable fit over a calibration period of 5 years using the VTI model, the statistics for the complete 17 year period were not acceptable.

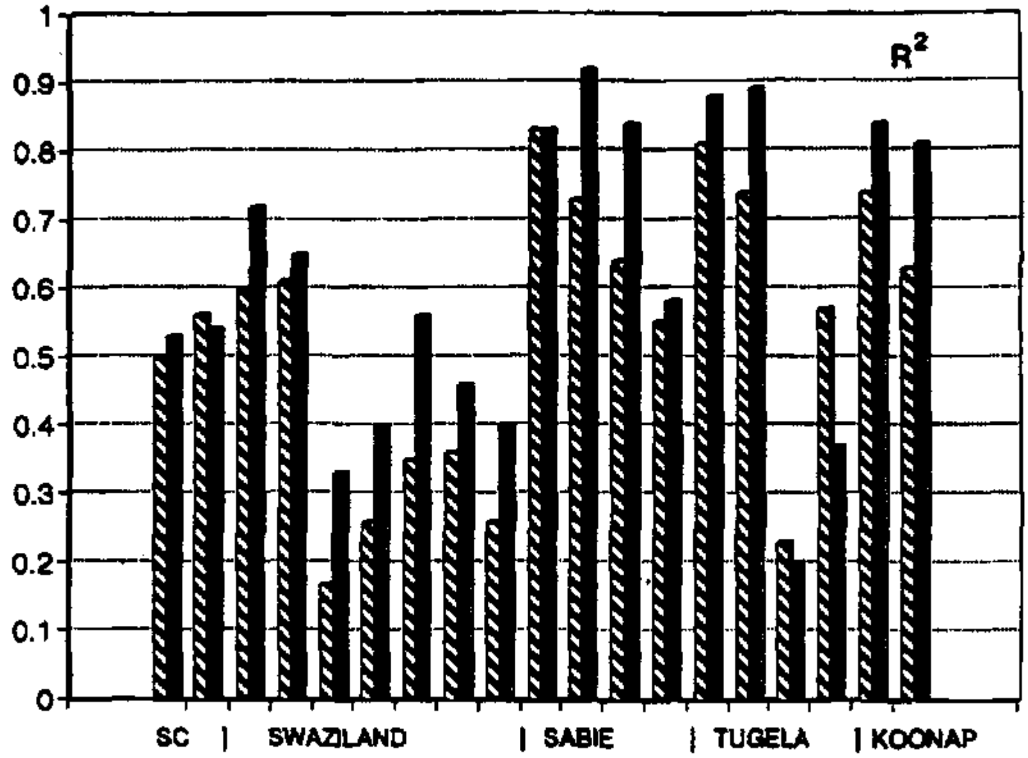
While the patching approach does not appear to have performed any better from the point of view of one-to-one correspondence, the simulated means and standard deviations are an improvement on the VTI model results. Figure 6.14 also illustrates that, except for some of the 'low flows', the patching algorithm has generated a time series that is somewhat more representative with respect to most of the range of flows than the VTI model.

6.4 CONCLUSIONS.

In general terms, the patching algorithm has performed at least as well as the VTI model. This has been illustrated by the tables presented in this Chapter and is also supported by Fig. 6.15 which gives a general overview of the patching algorithm perfomance in terms of coefficients of determination and efficiency (Fig. 6.15 presents the results only for catchments where both the VTI and 'patching model' simulations were available and coefficients of efficiency were positive). This is an important conclusion given the large disparity between the effort required to apply the two techniques.

The patching algorithm is a simple approach with a limited 'parameter space'; there are normally few 'source' gauges available to choose from and it does not take a great effort to quantify optimum weighting factors. After 'calibrating' the choice of 'source' gauges and associated weights, the approach either provides satisfactory answers (e.g. Tugela) or it does not (e.g. Wasbank) and the reasons why are normally clear. In contrast, relatively complex deterministic models have a large 'parameter space' and high information requirements, which if not adequately met, may either produce poor results or, at best, confuse the calibration procedure. The larger 'parameter space' suggests that greater resources are required to achieve a satisfactory result and it is not always clear when an optimum result has been achieved. When deterministic models do not produce satisfactory results, the reasons may be related, *inter alia*, to inadequate input rainfall data, inadequate catchment description data, poor calibration procedures or inadequate model formulation. Any or all of these may be contributing and to differing degrees, while in the simpler patching algorithm, the reason is simply the lack of suitable 'source' time series.

Although the patching algorithm was initially established to patch and extend observed records, it appears that it also has some potentially additional value. There are, however, a number of issues that have to be addressed if the patching algorithm is to realise its true potential as a simple tool for daily streamflow estimation. Most of these issues relate to being able to establish satisfactorily representative 1-day duration curves for each month of the year. For example, if the destination site record is short and only covers a sequence of dry years, the duration curves will not represent the full range of flows that otherwise would occur over a longer period of observations. If these are then used with longer period source records, the resultant extended record will inevitably underestimate the destination sites flow regime. The opposite (overestimation) could possibly apply if the destination site record only



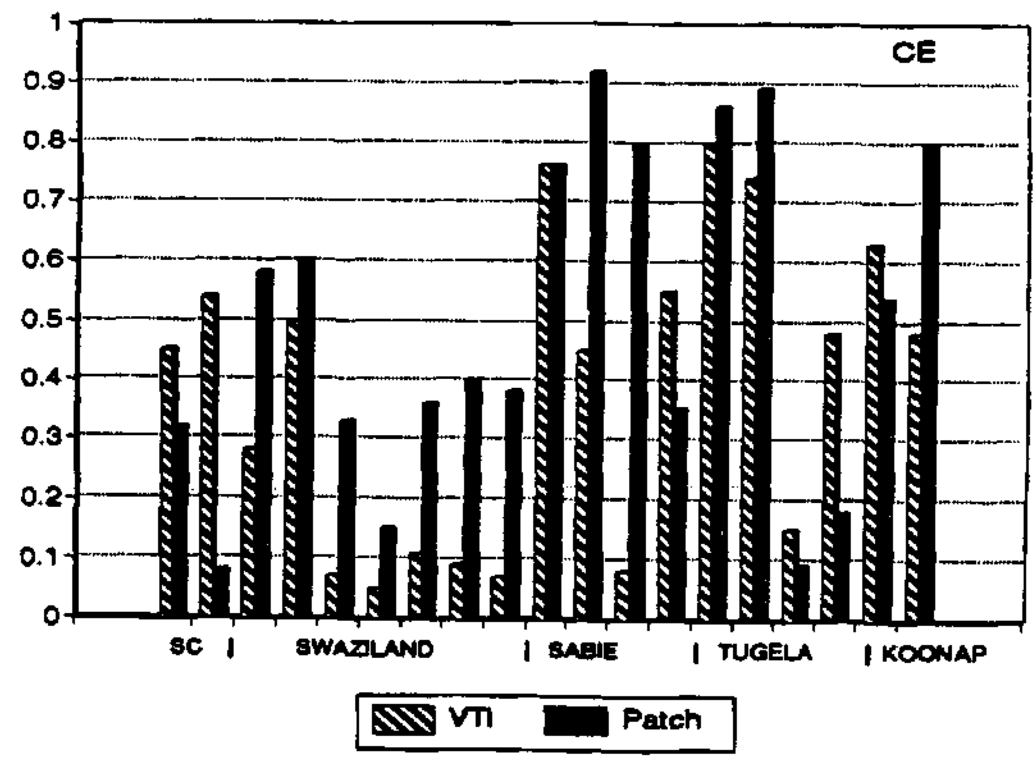


Figure 6.15 *Comparison of VTI and 'patching' model performances based on the coefficient of determination (R^2) and efficiency (CE).*

covers a sequence of wet years. Therefore, some of the problems experienced with the patching approach were related to the length of the observed record available to define the duration curves and others to the quality of the observed data, particularly with respect to high flow measurement. Although not addressed in detail, a further problem arises where a high degree of non-stationarity exists within the observed flow data caused by changing patterns of land-use or artificial water abstractions.

For the patching algorithm to be considered a useful tool, all these issues need to be resolved and techniques developed to correct, or adjust, the duration curves of both source and destination stations to account for errors, under-representation or non-stationarity in the observed flows. The natural extension of such techniques would be procedures to establish representative duration curves at ungauged sites and use suitable surrounding observed data to simulate time series where no observed data exist. Such representative duration curves could possibly be derived through regionalisation of curves constructed from existing observed daily flow data.

Monthly time-step modelling techniques have been used extensively for simulating monthly flow volumes at ungauged sites in the southern African region. If a suitable technique to translate duration curves based on monthly flow volumes to daily duration curves could be established, then the proposed patching algorithm could be used together with a limited amount of observed daily flow data to generate daily time series at ungauged sites. The initial steps to implement the latter approach are described in the following Chapter.

7. APPLICATION OF THE SPATIAL INTERPOLATION ALGORITHM FOR GENERATING DAILY TIME SERIES AT UNGAUGED SITES FROM MONTHLY FLOW DATA.

7.1 INTRODUCTION.

To extend the area of application of the spatial interpolation algorithm described in the previous Chapter to ungauged sites an 'inverse problem' should be solved first. It requires the establishment of 'typical' 1-day flow duration curves for each of the 12 calendar months of the year at an ungauged site before the actual daily flow time series can be generated. In the South African context, this problem may be approached by developing a conversion procedure to derive 1-day flow duration curves from flow duration curves based on monthly flow volume time series which are already available at many locations throughout the country.

The problem of such conversion has already been addressed in South Africa in several studies (e.g. Pitman, 1993; Schultz et al, 1995). 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 dimensionless parameters which were assumed to be representative for a surrounding hydrologically homogeneous region. The method was further developed by Schultz et al (1995) to include the effects of development on streamflow. Although the method generally seems feasible, the hypothesis that 'conversion parameters' are representative for the surrounding area was not tested. These studies indicate that none of the existing approaches would be likely to be generally applicable and that any of them should be intensively tested over a range of flow conditions prevailing in South Africa before they can be reliably applied.

7.2 THE ESTABLISHMENT OF REGIONAL RATIO CURVES.

The approach which is proposed and initially tested in this Chapter is based on the relationship between flow duration curves based on monthly flow volumes and flow duration curves based on daily discharges. The most straightforward form of such a relationship may be what is referred here as a 'ratio curve'. The first step in the analysis is to construct 1-month and 1-day FDCs for every gauge in a selected catchment (or physiographic region) using similar units (either converting daily discharges to Ml or expressing monthly flow volumes as mean monthly discharges in m^3/s). The ratios of daily to monthly flows for the

17 fixed percentage points are then calculated for each gauge and plotted against the percentage point values thus producing the 'ratio curve' for a site.

An attempt is then made to group and regionalize these ratio curves. The working hypothesis of this approach is that ratio curves for any site within a hydrologically homogeneous region might be expected to be equally similar. This is largely based on the premise that the within-month variation of daily flows is similar. The desired result is therefore a set of ratio curves (regional conversion parameters) that can be applied to catchments within a homogeneous region to convert the coordinates of any 1-month FDC (derived, for example, from simulated monthly flow data) to the ordinates of a 1-day FDC.

The boundaries of homogeneous regions may be established through the analysis of a number of calculated ratio curves in an area. On the other hand, hydrological zones defined in Surface Water Resources of South Africa 1980 or 1990 may serve as an initial basis for this study (if the later hypothesis can be demonstrated to work, it may add value to the extensive amount of research already undertaken). The approach has initially been tested using the observed flow data in the upper part of the Sabie catchment which according to Surface Water Resources of SA (1981) falls into one hydrological zone (Z4). Streamflow data for gauges X3H001, X3H002, X3H003, X3H006 and X3H011 have been used (see also Volume II).

Figure 7.1 illustrates a typical pattern of differences between annual flow duration curves based on monthly and daily flow data. The two curves normally cross between the 1% and 10% time exceedence points, 1-day flow duration curves being steeper. In the area of high flows, some of the 1-day flow duration curves are truncated due to the low discharge table limits of gauges. Monthly duration curves are also affected by this limit, but to a lesser extent. In such cases it would be important to correct the high flow end of 1-day flow duration curves before the calculation of flow ratios for each of the 17 fixed percentage points. This correction can be done using simulated daily flow sequences for 'truncated' gauges instead of observed ones (if such simulations are available). In this case the error of peak discharge estimates obviously cannot be assessed and the assumption has to be made that simulated peaks are reasonably representative of high flow conditions in a catchment if FDCs based on observed and simulated data match well throughout the rest of the flow range.

However, the availability of simulated daily data is not a typical case. Alternatively the upper parts of "truncated" flow duration curves should be ignored as being unreliable and any further analysis of the high flow area should be based on only the sites with "non-truncated" flow duration curves. This obviously reduces the number of data points on which further generalization can be made but represents a pragmatic approach to the use of unsatisfactory data.

In the area of 90-95% time exceedence, daily abstraction patterns and/or the time during which zero-flow conditions occur may have a substantial effect. In the upper Sabie region all the streams are perennial and zero-flow days, if any, are attributed to the effect of short-

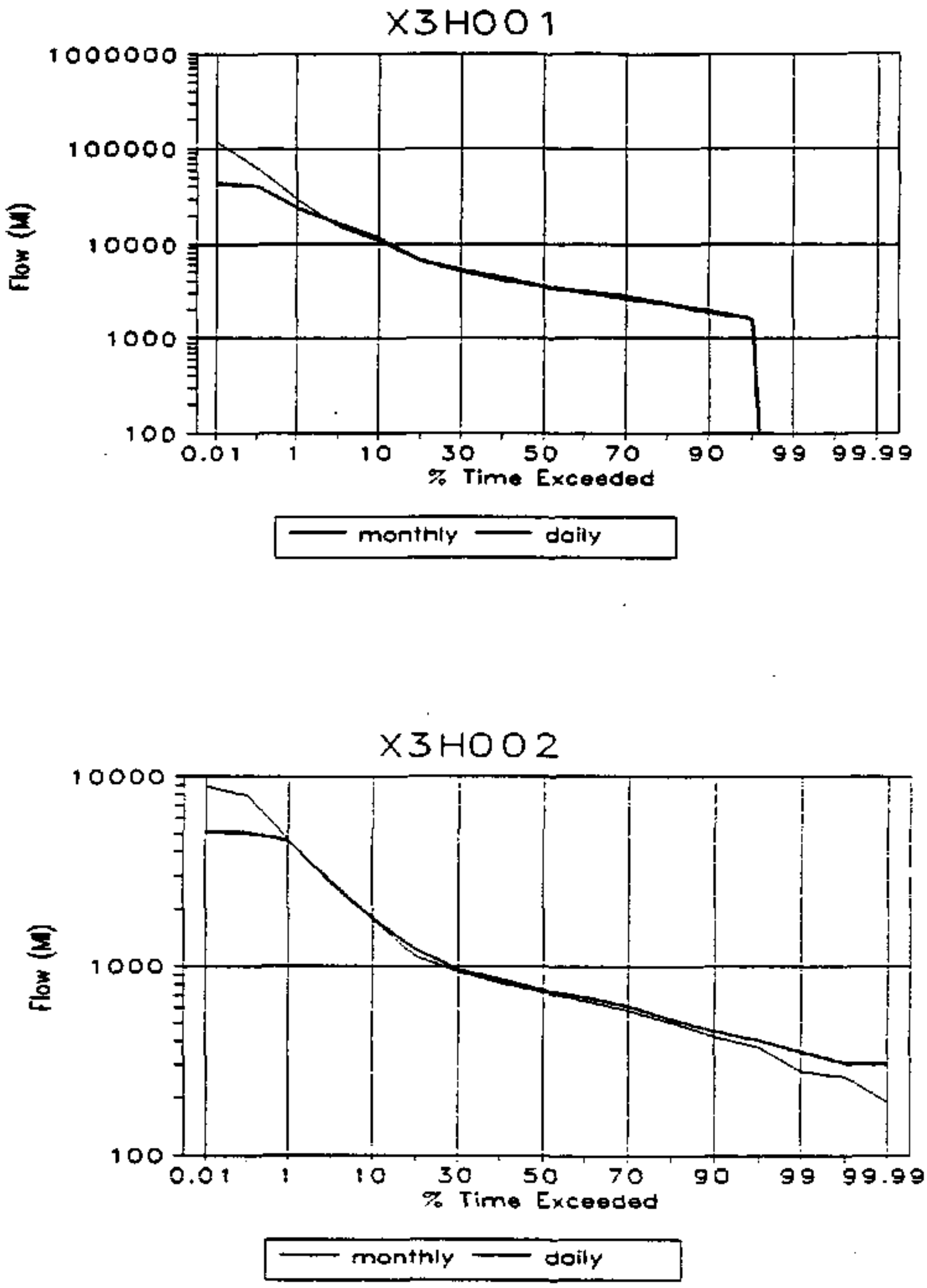


Figure 7.1 *Typical examples of annual flow duration curves in the Sabie catchment based on monthly and daily streamflow time series.*

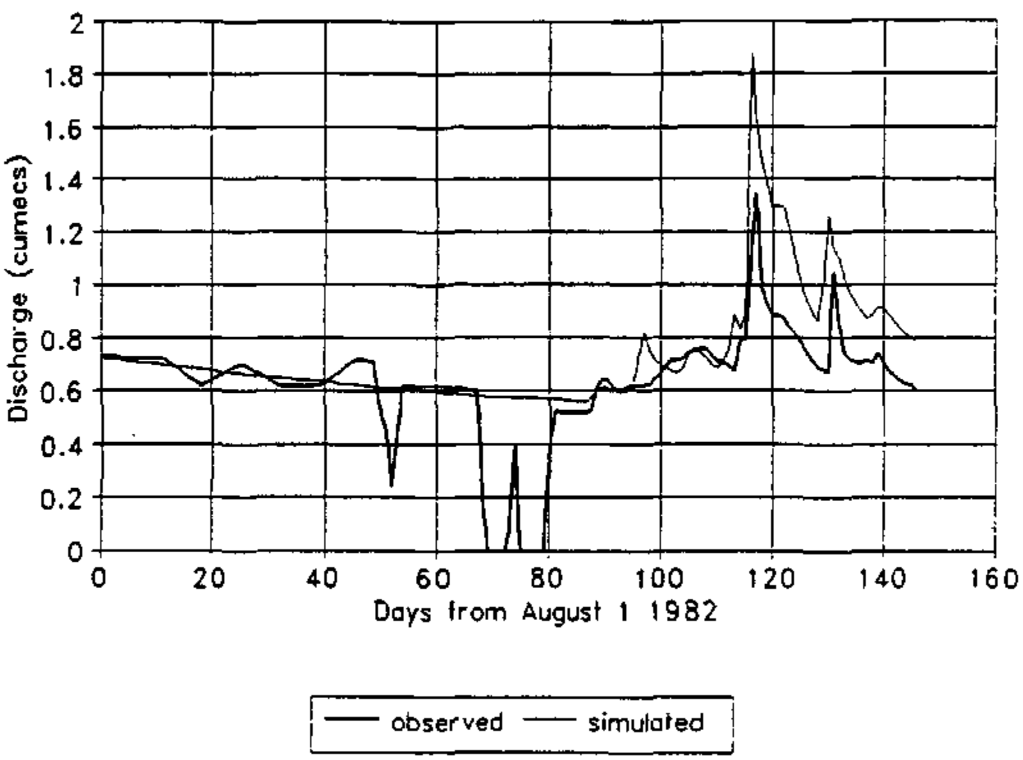


Figure 7.2. Observed and simulated by the VTI model daily flows at gauge X3H001.

term abstractions. This effect is very clear for the gauge X3H001. Figure 7.2 demonstrates the pattern of short-term abstractions at this gauge and compares it with a daily hydrograph simulated using the VTI model. It is possible to assume that in the absence of such abstractions, the flow duration curve for the gauge under consideration would follow the same pattern as that for other gauges (e.g. X3H002 and X3H003) not affected by abstractions and in close proximity to X3H001. This assumption allows the regional pattern of FDCs to be preserved.

The ratios of daily to monthly flows for 17 percentage points have been calculated to derive the resultant 'ratio curve' for each gauge (Figure 7.3). For almost all selected gauges the estimated ratios of daily to monthly flows are quite similar and only slightly less than 1 for percentage points from 1% to 99% The ratios in the area of extreme low flows (>99% time exceedence) and extreme high flows (< 1% time exceedence) are more variable. The worst example is demonstrated by gauge X3H002 exhibiting the lowest ratios in the high-flow area.

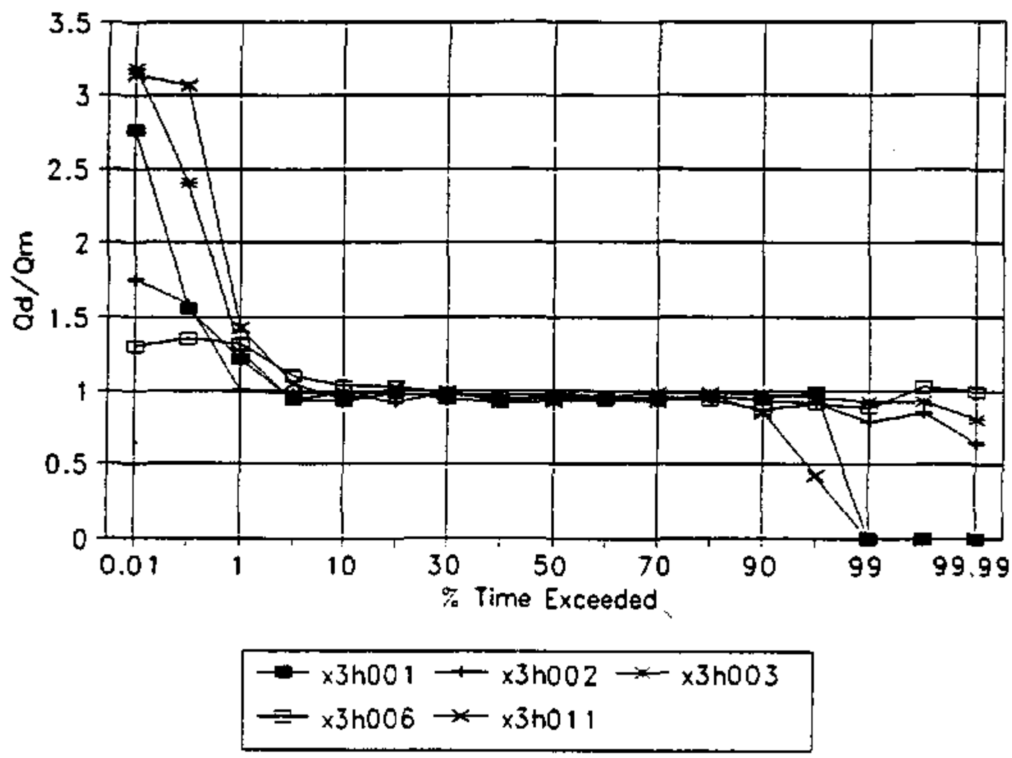


Figure 7.3. *Ratio curves for flow gauges in the Sabie catchment calculated on the basis of annual flow duration curves.*

It is also important to note that flow ratio values in the area of very high and very low percentage points are normally calculated on the basis of extrapolated flow values. This is performed automatically when using the HYMAS flow duration curve construction program. Given possible extrapolation errors in both 1-month and 1-day flow estimates, these calculated flow ratios may not be reliable. For example, in case of annual flow duration curves based on 10 years (120 months) of monthly data the limiting percentage points for which flow values are still calculated are 0.8 and 99.2%. Therefore, flows at 0.1, 0.01, 99.9 and 99.99% are extrapolated values. If a 1-day flow duration curve is constructed on the basis of 10 years of data (total of 3650 days) the last calculated values will be flows at 0.027 and 99.97% time of exceedence and only daily flows at 0.01 and 99.99% are extrapolated values. If 30 years of data are available - all 17 flow values for the 1-day flow duration curve can be calculated but the problem with monthly data remains.

To widen the limits where flows for 1-month FDC are actually calculated, a series of 30-day average flows has been used as a substitute to actual monthly flow time series. For a 10-year period there are 3620 values (365*10 - 30) of 30-day average discharges as opposed to only 120 actual monthly flows. That effectively means that flow values for 1-month flow duration curves are estimated on the basis of almost 302 years of monthly data instead of only 10. This approach essentially increases the limits of the calculated flow values used to construct 1-month flow duration curve for the whole year. At the same time, curves constructed using 30-day average flows and calendar months' flows are very similar throughout most of the flow range. Figure 7.4 shows seasonal (summer and winter) flow ratio curves for gauge X3H006, calculated on the basis of 1-day to 30-day average flows and on the basis of 1-day to actual 1-month flows.

The previous discussion refers to FDCs based on flows for all months of the year (annual FDCs). The translation of 'monthly' to 'daily' curves for each calender month has to be addressed separately. The problem of too short a record to adequately define the extremes

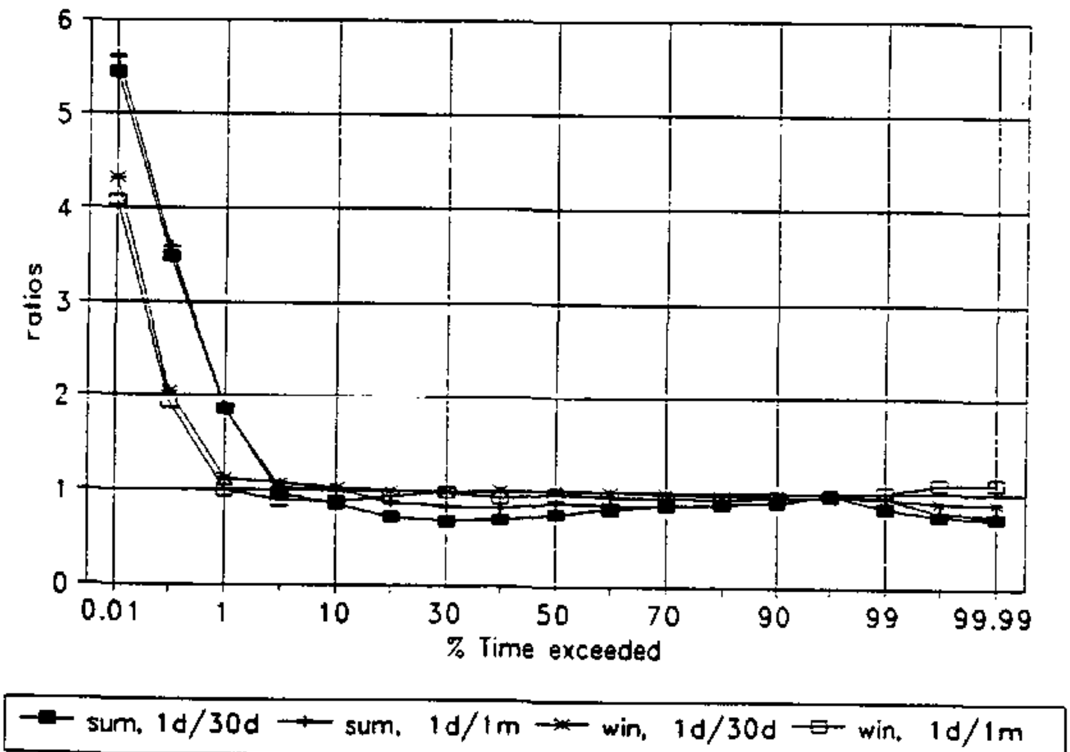


Figure 7.4. Seasonal flow ratio curves for gauge X3H006 calculated using ratios of 1-day to 30-day average flow and 1-day to 1-month flow.

of flow duration curves is obviously exacerbated when the number of data points to use is divided by 12. In this case a moving average approach does not work since there is only one 30-day average flow value in each particular month. The alternative is to establish 4 seasonal flow ratio curves (for summer, autumn, winter and spring) instead of 12 typical flow ratio curves for each calender month of the year. These curves have been calculated for all selected gauges and a set of average ratio curves has been derived (Fig. 7.5). It has been found that the major differences exist between summer and winter flow ratio curves, while flow ratio curves for intermediate seasons are mostly the same and very similar to annual flow ratio curve. The ratios for summer are higher than for winter in the high flow area and lower almost through the whole other range of flows.

All previous tests have been conducted using observed or simulated flow time series representing present day development conditions in the region and the applicability of the conversion parameters (ratio curves) for virgin flow conditions needs to be assessed. Daily flow time series for virgin flow conditions have been simulated for most of the gauges in the

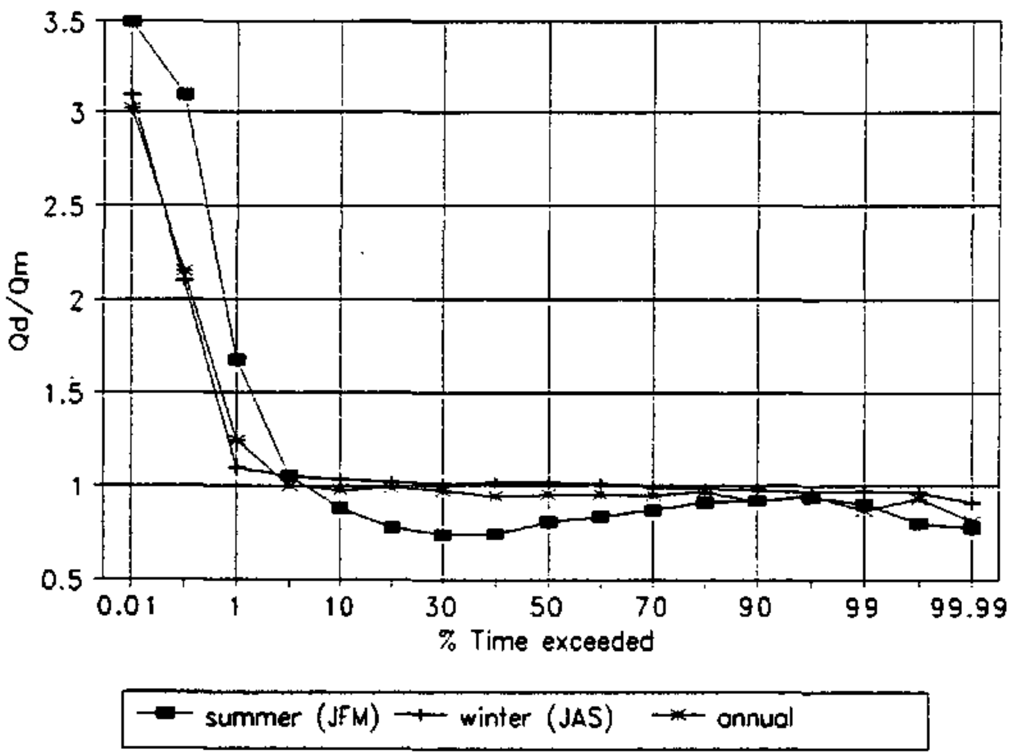


Figure 7.5. Averaged seasonal and annual flow ratio curves for the upper Sabie catchment (summer: January, February, March, winter : July, August, September).

Sabie catchment for a 30 year period (from 1962 to 1992) using the VTI model. The simulated flow data for several flow gauges have been used to derive flow ratio curves for virgin flows which are compared to ratio curves representing present day development conditions. In most of the cases the ratio curves for virgin and present day conditions appeared to be similar (Fig. 7.6). The implication is that once a regional set of ratio curves is established on the basis of present day flow data, it can be used to convert virgin 1-month flow duration curves into virgin 1-day flow duration curves with a high degree of confidence. The reverse is also true. It however should be noted that the effect of minor abstractions is not reproduced by simulated flow time series in present day conditions and only major effects of forestry are accounted for. Therefore, the latter conclusion is valid only for the upper Sabie area and would not likely to apply where duration curves are affected differentially over the range of flows. Additional research is necessary to address this point in more detail.

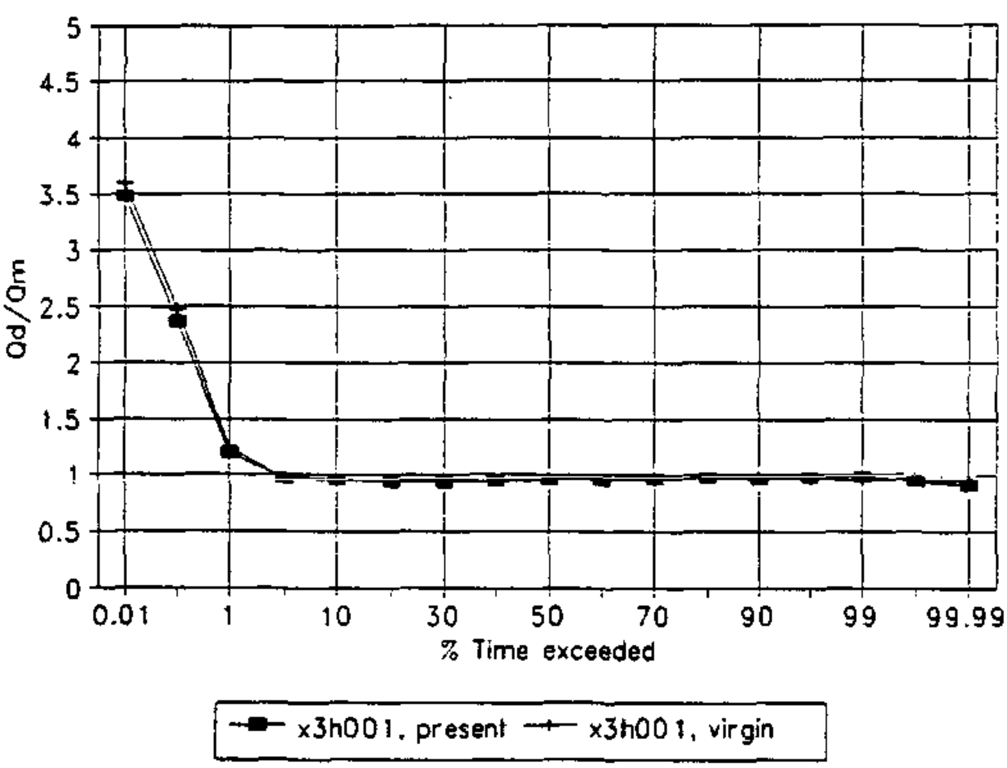


Figure 7.6. *Annual flow ratio curves for present day and virgin flow conditions at gauge X3H001.*

7.3 APPLICATION FOR GENERATING DAILY FLOW SEQUENCES AT UNGAUGED SITES

To extend the 'patching' model application to ungauged sites, a set of representative 1-day flow duration curves (either for each month of the year, or for each season) should be established at this site. Such representative flow duration curves can be established using the approach described in the previous section. A set of regional seasonal ratio curves derived on the basis of existing flow data may serve as conversion parameters which can be applied to each month's typical flow duration curve (constructed on the basis of monthly data) to establish a required set of 1-day flow duration curves at the ungauged site under consideration. 12 typical flow duration curves (based on monthly data) are calculated either using the available quaternary catchment flow data or monthly flow volume data simulated by the Pitman model specifically at a site of interest.

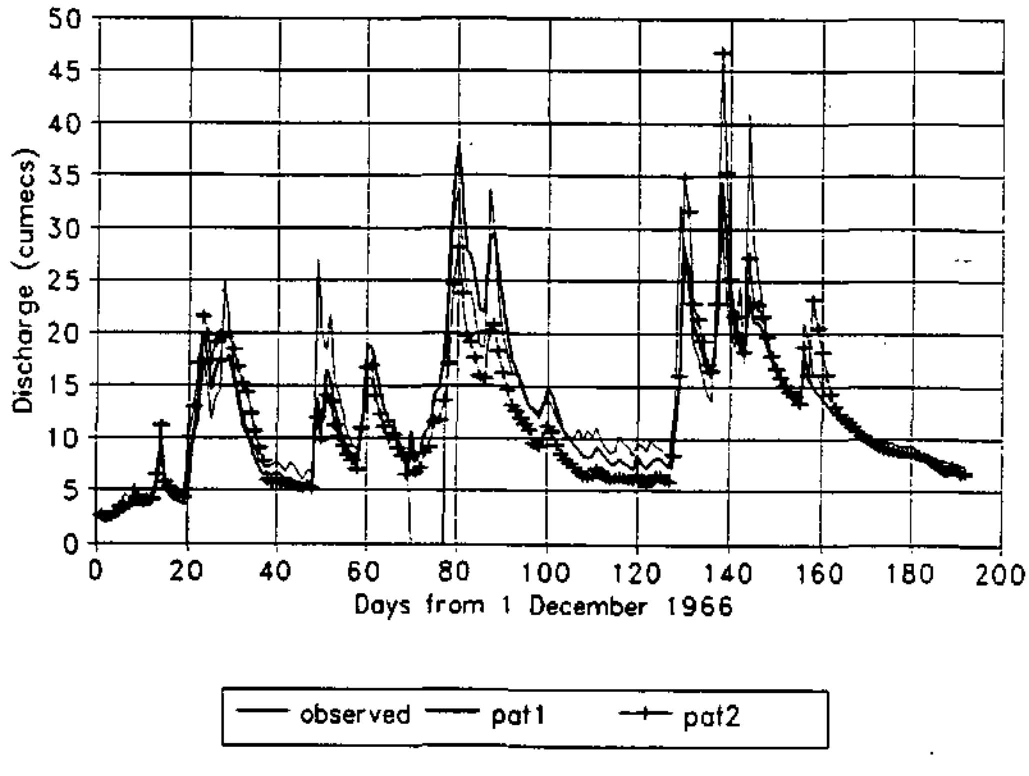


Figure 7.7. Observed daily flow time series at gauge X3H006 and simulated by the original version of the model (pat1) and using the 'ratio curve' approach (pat2).

Only slight modifications to the initial version of the 'patching' model described in Chapter 6 have been necessary to allow its application to ungauged sites to be made. The whole process of generating daily flow time series at a site where only monthly flow data are available can be split into several steps.

1. Identify up to 5 possible 'source' flow gauging stations and assign weights to each of them based on the degree of similarity between 'source' and 'destination' site flow regimes.

2. Using available daily flow data at selected 'source' sites, generate tables of discharge values for each month of the year for 17 percentage points of flow duration curves.

3. Using available monthly data at the 'destination' site, generate tables of discharge values for each month of the year for 17 percentage points of flow duration curves.

4. Convert each month's flow duration curve at the 'destination' site based on monthly data into flow duration curve based on daily data, using the regional set of 'flow ratio' curves. Apply the summer ratio curve to summer months, the winter ratio curve to winter months and the annual ratio curve to other months of the year.

5. Identify the percentage point position of each day's flow at the source site on its duration curve table (for a relevant month). Read off the flow value for the equivalent percentage point from the finally established 'destination' site 1-day flow duration curve table. For 'source' streamflows lying between the 17 defined percentage points of the duration tables use logarithmic interpolation to define the position. Repeat the procedure for each 'source' site.

6. Multiply each estimate of the 'destination' site flow value by the 'source' site weight; divide the sum of these values by the sum of the weights. Ignore missing data periods for any 'source' site.

Steps 1,2, 5 and 6 have, in fact, remained unchanged since the original version of the model was released. Steps 3 and 4 are optional and are activated only in cases when the model is applied to an ungauged site. If patching or extension of the available daily flow time series at the destination site are required, the original version of the model applies.

The approach has been tested at all flow gauging stations initially selected for analysis and also at gauges X3H007 and X3H004. Gauge X3H007 is located in the same hydrological zone but has not been used for calculation of the ratio curves for a region. Gauge X3H004 is located just outside this zone. The results are compared with those generated by the initial version of a 'patching' model and are illustrated in Table 7.1 using a standard criteria of fit between observed and estimated daily streamflow series. The fit statistics used for untransformed flows are the maximum and mean flow value, standard deviation of daily flows and coefficients of determination (R^2) and efficiency (CE). Comparison of log-transformed values is based on coefficients of determination and efficiency and a minimum flow. In most of the cases the period used was from 1962 to 1992, for gauge X3H011 the period was 1978 - 1992. Several preliminary conclusions can be reached about the performance of the proposed approach at this stage:

1. The means and standard deviations of the flow time series generated by the 'ratio curve' method match quite well with the corresponding values of observed time series. The general pattern of the observed daily flows is thus satisfactorily reproduced by the proposed approach. Figure. 7.7 illustrates the example simulations by both models at gauge X3H006.

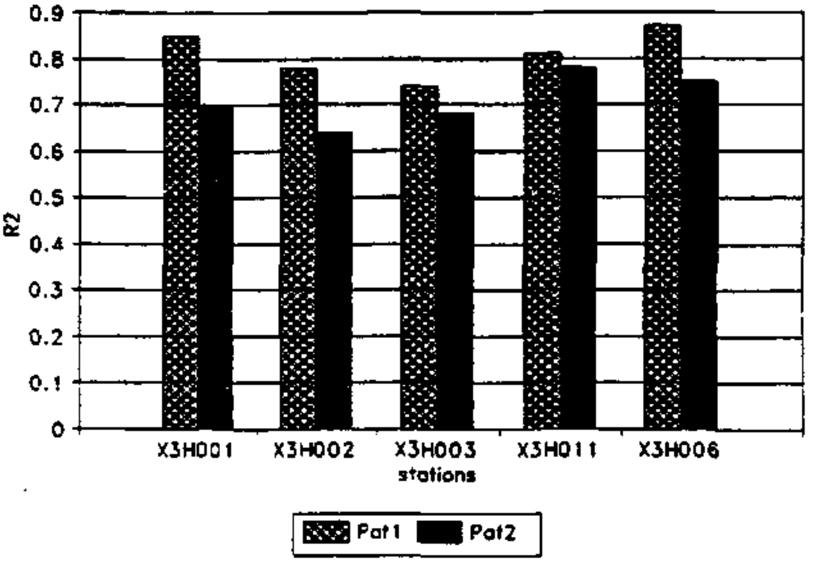
2. The regional ratio curve approach allows the higher peak flows for 'truncated' gauges (X3H006) to be generated as opposed to the original version of the 'patching model'. Although no comparison can be made in such cases between observed and simulated high flows, it may be assumed that the simulated peaks fall within the possible range of high flows in a catchment, since the regional pattern of daily flow variation is likely to be reproduced by the regional ratio curves. The simulation of the higher peak flows for "truncated" flow gauges however is only possible if the source site(s) selected are non-truncated themselves.

3. Since the ratio curves used have been estimated by the simple averaging of corresponding percentage points' ratios for all selected flow gauges, and the range of ratio values in the high flow area are quite large (Fig. 7.3), it is inevitable that simulated peaks for a particular gauge may be either overestimated or underestimated. This causes a slight deterioration of the resultant general fit statistics (R^2 and CE) as compared to the results obtained using the original version of the patching model (Fig. 7.8).

4. Fit statistics based on log-transformed data do not demonstrate any deterioration compared with the original version of the model. This, coupled with a good fit between means and standard deviations, implies that moderate to low flows are simulated as good as by the original version of the model.

5. A reasonable representation of daily flow time series may be obtained for sites situated in the same hydrological zone but not used to derive the set of regional ratio curves (e.g. gauge X3H007).

6. Problems arise when ratio curves established for one hydrological zone are used to generate flow time series outside this zone. The example is the unfavourable fit statistics for gauge X3H004. The record at gauge X3H004 may be affected by the large dam (DaGama) and irrigation upstream. However, analysis of flow data for gauge X3H004 for a period prior to dam construction (1948 - 1972) has shown that its calculated ratios are essentially smaller for almost all percentage points than regional ratio values and thus poor fit statistics are inevitable.



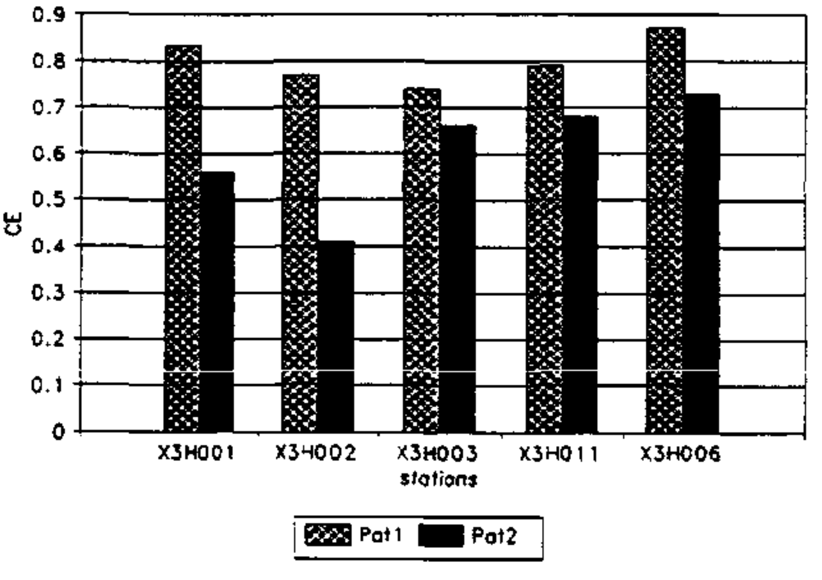


Figure 7.8. *Fit statistics (R^2 and CE) between observed flow time series and simulated by the original version of the 'patching model' (pat1) and using the 'ratio curve' approach (pat2).*

Table 7.1 Comparative statistics for flow gauges in the Sabie catchment

River	Data type	Untransformed					Log transformed		
		Max, m^3/s	Mean, m^3/s	SD, m^3/s	R^2	CE	Min	R^2	CE
Sabie, X3H001	Obs.	43.8	1.87	2.14			-6.9		
	Pat1	48.1	1.88	2.23	0.85	0.83	-9.2	0.64	0.62
	Pat2	76.9	1.88	2.59	0.70	0.56	-9.2	0.63	0.62
L.Sabie, X3H002	Obs.	3.42	0.33	0.30			-6.9		
	Pat1	3.27	0.34	0.30	0.78	0.77	-3.17	0.69	0.66
	Pat2	9.08	0.34	0.39	0.64	0.41	-3.0	0.69	0.67
MacMac, X3H003	Obs.	15.7	0.82	0.86			-1.41		
	Pat1	16.1	0.81	0.83	0.74	0.74	-6.37	0.75	0.72
	Pat2	17.9	0.79	0.85	0.68	0.66	-1.35	0.82	0.82
Marite, X3H011	Obs.	28.9	1.79	2.40			-6.91		
	Pat1	28.9	1.45	2.11	0.81	0.79	-9.21	0.49	-0.47
	Pat2	27.2	1.39	1.48	0.78	0.68	-9.21	0.45	-0.12
Sabie, X3H006	Obs.	60.0	6.07	6.90			-0.19		
	Pat1	60.0	5.96	6.51	0.87	0.87	-1.98	0.82	0.80
	Pat2	151	5.92	6.97	0.75	0.73	-0.14	0.84	0.83
White Waters, X3H007	Obs.	2.26	0.28	0.40			-6.91		
	Pat1	2.30	0.28	0.38	0.79	0.78	-9.21	0.68	0.66
	Pat2	7.94	0.29	0.44	0.62	0.51	-5.70	0.68	0.65
N.Sand, X3H004	Obs.	28.2	0.70	1.59			-6.91		
	Pat1	32.0	0.96	2.40	0.65	0.14	-9.21	0.74	0.68
	Pat2	81.3	1.30	4.0	0.46	-3.03	-4.68	0.72	0.47

* Pat1 - generated using daily flow durations curves at the destination sites (original model)
* Pat2 - generated using the approach described in this Chapter

7.4 CONCLUSIONS.

The approach described in this Chapter is designed as a simple tool to generate daily flow time series at an ungauged site for which monthly flow volume data are already available (quaternary scale) or may be obtained through the application of the Pitman monthly model (subquaternary scale). Initial tests of the proposed technique in the Sabie catchment have demonstrated that satisfactory daily flow simulations may be achieved. However, the choice of good quality data sets which may be used to establish the regional ratio curves is normally rather limited and even reasonably natural, stationary flow regimes (like those in the Sabie catchment) are affected by short-term direct water abstractions which distort the shape of 1-day flow duration curves and may affect the resultant ratios especially in the low-flow area. In these cases the general pattern of flows under present day conditions but excluding short-term effects may be traced by manual extrapolation of 1-day flow duration curves in the area of extreme low flows.

The computer technique which has been used to construct flow duration curves is rather sensitive to the length of record. This is especially true for monthly data where extrapolation into the area of both high and low flows may cause large errors and severely affect the resultant ratios. To solve this problem at the stage of establishing regional ratio curves, actual monthly flow time series have been replaced by 30-day average flow series. This has allowed more reliable estimates of extreme flows to be made before calculating ratios at both ends of the exceedence time scale. However, the problem may still remain at the stage of actual application of the proposed technique since only 70 years of monthly flow data (840 flow values) are available for quaternary subcatchments and thus ratios in extreme flow areas will still be calculated by extrapolation.

The 1-day and 1-month FDCs compared in this preliminary study represent the available period of observations at each flow gauge. For most of the gauges in South Africa this period is normally limited to 20-30 years. The ratio curves are thus being established on the basis of a relatively short record period. On the other hand, the simulated monthly flow volume data for quaternary catchments have a standard length of 70 years (from 1920 to 1990). It is therefore indirectly assumed in this study that 1-month FDCs constructed on the basis of a 70-year long period are similar to those constructed on the basis of a shorter period actually available. The validity of this assumption however, needs to be investigated separately and should form one of the directions of future research.

In this study the set of ratio curves has been derived and the approach has been tested on a limited number of gauges in one small region and it is premature to draw firm conclusions about the performance of the approach. Its validity should be investigated in different physiographic regions using a larger set of gauged data. However, even initial tests imply that the existing subdivision of the country into hydrological zones, outlined in Surface Water Resources of South Africa (either in the earlier - 1981 , or the latest - 1994 version) may not be satisfactory for the establishment of regional sets of ratio curves. This issue is illustrated by the example of gauge X3H002 which falls in the same hydrological zone as the other gauges used for the purpose of this study, but exhibits a quite different flow regime. The existing zones have been delineated on the basis of similar flow deficiency curves. The approach described in this Chapter considers all the range of flows experienced in a stream and indirectly concentrates on seasonal variability of daily flows. It implies that a different grouping of catchments will be necessary.

The alternative to the proposed approach is to try to group/regionalize 1-day flow duration curves themselves at available flow gauges. This technique, the first results of its application and implications for low-flow estimation are discussed in Volume II of the current Report, using the example of the T drainage region in South Africa.

8. CATCHMENT LOW-FLOW STUDIES

8.1 INTRODUCTION

This Chapter presents a summary of the catchment low-flow studies which are described in detail in Volume II of the current Report. The catchment-wide analysis of low-flow regimes formed the main and the largest part of the Project and almost all other developments and research initiatives described previously were contributing to it. The major objective of the catchment-wide low-flow studies was to characterize temporal changes in the low-flow regimes and their spatial variability from the top to the bottom of a catchment in terms of several low-flow indices. Catchments selected for low-flow studies were drawn from different parts of the country and are characterised by different physiographic conditions, a variety of low-flow generating mechanisms, different spatial availability and quality of observed flow records, and differing degrees of artificial impacts on water resources. The following catchments have been considered:

- The Sabie River catchment in the Mpumalanga Province;
- The Berg River catchment in the Western Cape;
- Several parts of the Tugela River basin (in the KwaZulu-Natal) :
    - The Mooi River catchment;
    - The Sundays River catchment;
    - The central part of the Tugela catchment;
- Two major catchments in the T drainage region of South Africa:
    - The Mzimvubu catchment;
    - The Mzimkhulu catchment;
- The Olifants River catchment in the Northern Province.

Some preliminary research has also been done on several other catchments (the Buffalo and Fish rivers in the Eastern Cape Province, the Gamtoos and Gouritz rivers in the Southern Cape).

The first step in the catchment low-flow studies was the detailed analysis of the available observed flow records to identify the usable period of record, the necessity and possibility to patch/extend the time series, to illustrate the temporal changes in the low-flow regimes at the available streamflow gauges. Two types of graphs have been constructed for each streamflow gauge. The first is a plot of the annual flow totals calculated from the original daily flow data. It shows the hydrological years of different wetness, years with major gaps in the record due to missing data and allows for the detection of trends in the annual flows. The second is a graph illustrating the temporal changes in three different low-flow indices: flows exceeded 75 and 95% of the time (Q75 and Q95 extracted from a flow duration curve for each year) and the baseflow index (BFI).

Each basin was then subdivided into smaller drainage units. The boundaries of these units correspond either to the boundaries of gauged subcatchments, or smaller subareas (for the subsequent application of the VTI model). In some cases (e.g. the Mzimvubu and Mzimkhulu catchments) the already existing quaternary subcatchment subdivisions have been adopted. A range of techniques have been used for low-flow estimation in these catchments: from complex deterministic daily modelling to the more straightforward regionalization methods.

Several low-flow indices (normally Q75 and Q95) have been estimated for each subdivision from either observed or simulated daily flow time series. Low-flows, in most of the cases, have been estimated for both present day and natural conditions. The GIS coverages of estimated low-flow characteristics have been constructed to illustrate their spatial distribution within each catchment. The degree of changes in the flow regimes from natural to present day conditions have been illustrated by means of 1-day annual flow duration curves. The results are also summarised in tables which contain estimated low-flow indices for each drainage subdivision.

8.2 THE SABIE CATCHMENT

The maximum gauged catchment area of the Sabie river is 5713 km². The upstream parts of the catchment are afforested by commercial pine plantations and are characterised by large scale irrigation development, while the downstream parts are located within the Kruger National Park. Taking into account the importance of the river from an environmental point of view, the catchment has been set up for simulation completely. It has been broken down into several smaller drainage subdivisions (projects) which corresponded to the gauged subcatchments. Each project in its turn has been subdivided into smaller homogeneous subareas. Altogether there are 9 projects and 70 subareas within the entire catchment. Such a discretisation allows the low-flow estimation to be performed at a much finer spatial resolution than that of the quaternary subcatchments. The Variable Time Interval (VTI) model has been calibrated for each project against the available observed daily data in order to establish representative model parameter values. The calibration was attempted for a period 1978-1988, although other calibration periods have been used in the downstream projects, where only short records exist. In most of the cases the calibration exercise appeared to be successful. Using the calibrated model, 40 years of daily flow time series at present day and virgin conditions for all subdivisions in the entire catchment were simulated. The 7-day average Q75 and Q95 flows were estimated from the simulated series for each subdivision. The spatial distribution of these characteristics is illustrated by the GIS coverages. The latter are supplemented by tables which contain estimated low-flow values. The degree of changes in the low-flow regimes in each project are illustrated by the comparison of 1-day annual flow duration curves at present and virgin conditions.

The detailed description of the model calibration and subsequent low-flow estimation is presented in Appendix B1 in Volume II. Plots of the annual flow totals and low-flow indices for streamflow gauges in the Sabie catchment are presented in Appendix B2.

8.3 THE BERG CATCHMENT

Similarly to the Sabie catchment, low flows in the Berg catchment have been investigated using the VTI daily model. The VTI model has been set up and calibrated for the largest gauged area of the catchment (4012 km^2). The objective of the simulation approach was to provide daily flow sequences at a range of locations in the catchment using the calibrated model. Altogether there were 5 projects and 33 subareas in the entire catchment. This subdivision allowed for the estimation of low flows on a subquaternary level of spatial resolution. Calibration was attempted for a period 1978-1988. The calibration procedure was met with serious difficulties, mostly related to the absence of adequate data on numerous water abstractions and interbasin transfers and to the high spatial variability of rainfall data in some projects. Although successful calibration was achieved in the outlet of most of the projects, the model appeared to overestimate low-flows in some individual subareas. 30-years long daily flow time series at present day and virgin conditions have been simulated. Q75(7) and Q95(7) low-flow indices have been extracted from the simulated time series for each subdivision in the catchment. The results are summarised in the tables and GIS coverages which illustrate the spatial distribution of the low-flow characteristics in the catchment. The degree of changes in the low-flow regimes are illustrated using 1-day annual flow duration curves for present and virgin conditions. Due to the high degree of catchment alterations and water resource developments, the Berg river catchment appeared to be one of the most complex catchments used in the course of the Project for daily flow simulation and low-flow estimation.

The detailed description of the model calibration and subsequent low-flow estimation is presented in Appendix C1 in Volume II. Plots of the annual flow totals and low-flow indices for streamflow gauges in the Berg catchment are presented in Appendix C2.

8.4 THE TUGELA CATCHMENT

For the characterisation of low-flows, the Tugela catchment (total area over 29 000 km^2) was subdivided into several major subcatchments. Each subcatchment included one of the main Tugela tributaries or parts of the main river catchment area (Mooi, Sundays, central Tugela, Buffalo, etc.). The availability of streamflow information required for detailed spatial low-flow estimation in many parts of the Tugela basin were limited. Therefore, the spatial resolution of the catchment discretisation varied, and, the estimation techniques varied similarly. Three different approaches for low-flow estimation have been used: i) the VTI daily model; ii) the 'patching' model and iii) the regional regression model for the derivation of daily low-flow characteristics from monthly data.

The VTI model was applied to the three main parts of the Tugela river catchment: i) the Mooi river catchment; ii) the Sundays river catchment and iii) the central part of the Tugela river. The patching model was applied, as an alternative, for low-flow estimation in the Mooi river catchment. Regional regression method was used for the entire Tugela catchment and was based on the streamflow data from a subset of gauges recording relatively natural flow regimes.

For the application of the VTI model, the Mooi River catchment (maximum gauged catchment area 1976 km²) has been subdivided into 4 projects and 21 subareas (subquaternary level of discretization). The calibration of the model was attempted for different periods depending on the available flow records. The model generally performed satisfactory although extreme low-flows in some cases were slightly overestimated. The representative 32-year long daily streamflow time-series at present and virgin conditions were simulated and Q75(7) and Q95(7) flow indices were extracted from the simulated time series for each subdivision.

The patching model allowed for the estimation of low-flows to be performed from extended historical records and only at the gauged locations in the catchment. However, it performed exceptionally well and low-flows have been especially well predicted.

The Sundays river catchment was subdivided into 3 projects and 29 subareas. The VTI model calibration was attempted for a period 1954-1964. The calibration exercise resulted in limited success due to the inadequate rainfall input data. However, low flows appeared to be only slightly oversimulated in some parts of the catchment. The standard set of low-flow indices have been estimated from a 32-year long simulated daily streamflow time-series. No attempt was made to simulated the streamflow time series in this catchment under natural conditions.

The central part of the Tugela river catchment was simulated as one project which included 11 subareas. The calibration of the VTI model was attempted for a period of 1978-1988. The calibration appeared to be satisfactory. The results of the calibration, however, are significantly affected by the boundary conditions - inflows from the upstream gauges. Since these inflows represent the historical records, no streamflow simulation in natural conditions was attempted and only present day low-flow conditions were assessed from the simulated 32-year long daily time series using the standard set of low-flow indices.

The attempt was made to relate a Q75(7) flow index with a mean monthly flow during the driest month of a year and the coefficient of variation of these 'driest' monthly flows. The data from 22 gauging stations recording relatively natural flow regimes were used for this analysis. The log-regression model was established which explained 97% of the variability of Q75(7). Since the model was established using the data from catchments with areas ranging from 21 to 1644 km², such models are likely to be applicable for low-flow estimation in the Tugela catchment at both quaternary and subquaternary scales.

The detailed description of the application of various techniques for daily data generation and subsequent low-flow estimation is presented in Appendix D1 in Volume II. Plots of the annual flow totals and low-flow indices for streamflow gauges in the Tugela catchment are presented in Appendix D2.

8.5 THE T DRAINAGE REGION

In all previous cases the approach for basin-wide low-flow estimation has been based primarily on the application of the deterministic modelling technique. In the case of the T drainage region, the approach followed, was completely different. It belongs to a family of classical regionalisation techniques and is aimed at the regionalisation of 1-day flow duration curves. The method adopted to establish regional flow duration curves included the following major steps: i) construction of non-dimensional flow duration curves for each flow gauge by dividing discharges from a curve by mean daily flow and ii) the superposition of all individual flow duration curves on one plot to derive an average regional non-dimensional flow duration curve. These steps have been performed for the whole year, wettest months, driest months and intermediate months of the year which have been identified by the analysis of the seasonal distribution at all available 17 gauged sites in the region.

Once the set of regional flow duration curves had been established, the actual flow duration curve for an ungauged site was calculated by multiplying back the non-dimensional ordinates of a corresponding regional FDC by the estimate of the mean daily flow. This estimate may be obtained by means of a regional regression model which would relate the mean daily flow with the physiographic and climatic characteristics of the drainage basins. Alternatively it could be calculated from the estimates of MAR presented in Surface Water Resources of South Africa (Midgley et al, 1994). Both approaches have been tested and the latter was found to be preferable.

Since a flow duration curve gives only a "summary" of a flow regime at a site, and in many cases a complete time series of daily flows is required to perform other types of hydrological analysis, a method was also described by which an established regional FDC can be used to generate synthetic hydrographs at ungauged sites. This method is based on the application of the spatial interpolation approach (patching model) described in Chapter 6 of the current report.

The results of the regionalization approach were also used to calculate Q75 and Q95 low-flow indices for each quaternary subcatchment in two major river basins in the region - the Mzimvubu and the Mzimkhulu catchments for both present day and natural conditions.

The approach applied in the T drainage region was designed as a simple tool to establish 1-day annual and seasonal flow duration curves at ungauged sites using observed streamflow data, and to translate these curves into a complete time series of daily discharges. The method is logically linked to the extensive database of synthetic flow characteristics presented in the Surface Water Resources of South Africa (Midgley et al, 1994) and was demonstrated to yield satisfactory estimates of annual FDC at ungauged locations in the region.

Although the proposed method was found to result in insufficient accuracy for generating high flow events, it demonstrated a much better performance in reproducing a general pattern of flow regimes and low-flow conditions at several test flow gauges. Most of the problems experienced may simply be attributed to the luck of good quality streamflow data which is the typical case in many regions of South Africa. Some of those problems are related to the length of the observed record available to define the duration curves and estimate mean daily discharge, others relate to the quality of high flow measurements.

Overall, the initial tests of the proposed technique have shown that satisfactory daily flow simulations at an ungauged site in the region may be achieved even without the application of more sophisticated rainfall-runoff modelling methods, which in their turn, may experience problems related to the scarcity or poor quality of daily rainfall data, inadequate data on water abstractions etc (e.g. as occurred in the case of the Berg River and the Sundays river catchments).

The detailed description of the regionalisation technique used for establishing the regional set of flow duration curves and for daily data generation as well as the results of low-flow estimation in the Mzimvubu and Mzimkhulu catchments are presented in Appendix E1 in Volume II. Plots of the annual flow totals and low-flow indices for streamflow gauges in the T drainage region are presented in Appendix E2.

8.6 THE OLIFANTS CATCHMENT

The problem of low flows in the Olifants river catchment (the total catchment area 54 575 km^2) has been addressed by means of regional estimation methods. First, the attempt was made to establish the regional regression relationships of selected low-flow characteristics with the physiographic and climatic parameters of the drainage basins. The approach is widely used in the world low-flow studies and the possibility of its application in South African conditions could not be ignored. Two different variations of the regression approach have been tested. In the first, the regression was attempted without *a priori* groupings of catchments into smaller, relatively homogeneous 'clusters'. In the second, the regression was attempted at the scale of smaller drainage subregions. The attempt to establish regression relationships within 'flow groups' emanating from the river classification studies undertaken at UCT (King and Tharme, 1994) has also been made. Some satisfactory preliminary results have been achieved using log-regression models.

The second technique applied was the regionalisation of daily flow duration curves (the similar approach was followed in the case of the T drainage region). However, the shape of the non-dimensional curves constructed on the basis of observed data appeared to be more variable than in the case of the T drainage region. Therefore, the attempt was made to group them, and on that basis, to establish the boundaries of geographically contiguous regions where the simple averaging of the observed flow duration curves can be justified. To increase the number of catchments included in the regional analysis both regionalization techniques used additional observed daily data from catchments adjacent to the Olifants River Basin.

The preliminary results of the application of the regionalization techniques in the Olifants river catchments are summarised in Appendix F1 in Volume II. Plots of the annual flow totals and low-flow indices for streamflow gauges in the Olifants river catchment are presented in Appendix F2.

8.7 OTHER CATCHMENTS.

Several other catchments have been considered for basin-wide low-flow analysis during the Project. Although the time constraints did not allow the problem of low flows in these catchments to be addressed in detail, the analysis of available data and some other preliminary investigations have been performed.

The Fish River catchment (Eastern Cape).

The Fish river was initially selected for low-flow studies in the Eastern Cape Province. The area of the catchment exceeds 29000 km². There are about 35 flow gauges on the streams and a number of measuring structures on various irrigation canals. 10 streamflow gauges measure flow in the Fish river itself.

After preliminary analysis of the available data it became clear that low-flow studies for this catchment are hardly feasible. Low-flow indices (Q75) estimated from 1-day annual flow duration curves constructed from available records for most of the gauged tributaries in the Fish River system are equal to zero. Some of these tributaries flow only 30-40% of the time during a year, the others are "more perennial" but zero flow conditions still occur for about 20-30% of the time. The earlier records (before 1970's - e.g. at gauges Q1H001, Q7H002) demonstrate that the Fish River itself used to be an ephemeral stream flowing only 40-50% of the time during a year. After the construction of the Orange-Fish transfer scheme, the river became perennial and the flow regime changed completely. At present the Fish River and its major tributaries like the Little Fish, Tarka and some other streams represent nothing more than canals delivering water mostly for irrigation purposes.

The best that can probably be achieved is the characterisation of the percentage of time at zero-flow conditions throughout the catchment, or the description of the seasonal 'low-flows' which are not low flows in the true meaning of the word. On the other hand, monthly flow data would seem more suitable for the analysis of 'low-flow' regimes in such catchments with prolonged dry periods. The Fish River was therefore found to be an inappropriate choice for the low-flow studies and was excluded from a list of initially proposed catchments. Nevertheless, some low-flow indices (Q75(1), Q75(30) and % time with zero-flow conditions) have been estimated from available daily data.

The Buffalo River catchment (Eastern Cape).

The daily data for the 8 available gauges in the catchment have been analyzed in terms of the annual flow totals and annual low-flow indices (Q75, Q95, BFI). The approach similar to that described in Chapter 7 was applied to establish a relationship between 1-day and 1-

month flow duration curves. The curves have been constructed for a year, each season and each calendar month for 6 gauges with satisfactorily long records. These results should form a basis for further analysis together with a similar output from the Sabie and Tugela River catchments.

The Southern Cape catchments.

The Gouritz and Gamtoos River catchments were initially considered for low-flow studies. The data for 30 streamflow gauges in the Gouritz and 11 streamflow gauges in the Gamtoos catchments have been analyzed in terms of annual flow totals and standard annual low-flow indices. However, the same considerations as in the case of the Fish river apply to these catchments. Low flows are generated only in some downstream (coastal) parts of both catchments. In the upstream reaches of the catchments, the rivers are dry up to 50% of the time during the year and detailed daily low-flow studies are hardly relevant.

9. CONCLUSIONS AND RECOMMENDATIONS.

9.1 ACHIEVEMENT OF THE PROJECT OBJECTIVES.

The main aim of developing improved low-flow estimation techniques and analysing low-flow regimes in selected river basins has been maintained throughout the course of the Project. Reference to the original objectives and the perceptions of the authors as to the extent to which these objectives have been achieved are summarised below.

- To examine the criteria used by different hydrological and aquatic sciences to characterise low-flow regimes and to develop a methodology for estimation and multipurpose analysis of low-flows in South Africa from available streamflow data;

This objective has been achieved by the extensive literature review and survey of the requirements for low-flow information. The literature review should give an interested user compressed, but detailed, information on existing low-flow measures and indices and actually serve as an introduction to present day low-flow hydrology. The computer techniques for analysis and estimation of various low-flow characteristics have been developed as part of a more general PC based HYMAS software package (HYdrological Modelling Application System). The software for low-flow estimation has appeared to be one of the first and the most important products of the Low Flow Project. It has been designed to work with data of different quality, time resolution and formats and allows a variety of low-flow analyses to be efficiently performed. It has been extensively used throughout the course of the whole Project and facilitated the achievement of other Project objectives. The software is available from the IWR together with the HYMAS software package. It is expected that it will be of benefit to the individuals and groups who work in different water related areas and has already been applied to a number of real water resources problems. The feedback from the users would be of great value for the project team in the future, in terms of creating a practical context for software improvement and further development.

- *To construct a data base for the information on river low-flow regimes within southern Africa.*

A number of observed streamflow records representing unregulated stationary flow regimes in different parts of the country have been examined within the course of the Project. Several appendices to the current report contain a number of estimated low-flow characteristics which are expected to be of direct practical value for many different users. The project team in the last two years has been receiving a number of requests from interested individuals for these type of data. The estimated low-flow characteristics form the core of the national low-flow database which could be expanded as additional time series in other locations in the country (observed as well as simulated) are processed.

- To evaluate and adapt a currently available daily rainfall-runoff model to specifically simulate low-flow conditions;

The in-house developed daily VTI model has been selected for the purpose of low-flow studies. The model has been applied to a number of catchments in South Africa and has proved to be a useful tool for daily time series generation. At the same time there exist some limitations as to the extent to which such deterministic simulation methods may be applied. Those include insufficiently available quality and amount of rainfall data, especially in catchments with highly spatially variable rainfall, the lack of good quality streamflow data against which to calibrate a model, the lack of knowledge on physiographic characteristics of the drainage basins which leads to a situation when the calibration may be good for the wrong reason and the absence of reliable data on abstractions and land-use in many catchments. Since low flows constitute the most sensitive part of daily streamflow hydrographs, the reliability of their estimation is greatly dependent on the quality of simulations.

In order to test the model's ability to simulate various aspects of low-flows, a set of new criteria of model performance has been utilised in addition to conventional fit statistics and flow duration curves. These criteria illustrate how well the model is able to predict streamflow recessions and baseflow volumes, continuous low-flow events below certain referenced discharges, frequency and magnitude of extreme low-flow events, etc. Many of those appeared to be rather subtle measures and are normally ignored by water scientists and engineers. However, they are of vital importance for ecological and water quality problems related to low flows.

- To characterise and determine changes in low-flow regimes of selected rivers within southern Africa.

The work in this direction constituted the major part of the Project. Several catchments have been selected for detailed studies from different parts of the country. They vary in size, physiographic conditions, low-flow generating mechanisms, the degree of anthropogenic influence and the amount and quality of available streamflow data. Those catchments were: Sabie, Berg (the Western Cape), several major tributaries of the Tugela River, Mzimvubu, Mzimkhulu, Olifants (the Northern province). Some preliminary analysis has also been done on the Buffalo and Fish rivers (Eastern Cape), Gamtoos and Gouritz rivers. All available observed daily flow records for these catchments have been analyzed in terms of several low-flow characteristics in order to identify temporal changes in low-flow regimes. The results of such analysis are presented in the appendices showing plots of annual flow totals and low-flow indices. These appendices effectively represent the inventory of recorded flow regimes in selected catchments with the emphasis on low flows. The VTI model has been extensively used in catchment-wide, low-flow studies for the purpose of generating representative daily streamflow time series for present day and natural conditions at different locations within these catchments and low-flow indices have been estimated from simulated series. In some catchments regionalization techniques have been successfully applied for low-flow estimation as an alternative to deterministic daily modelling.

9.2 ADDITIONAL PRODUCTS.

The references to the original objectives of the project do not entirely cover all the achievements of the project. The Project appeared to be a unique research undertaking in terms of the analysis of a large number of observed daily streamflow records. The possibility of a direct utilization of streamflow data for catchment-wide hydrological analysis has been overestimated at the planning stage of the project. On the other hand, the general lack of simple techniques for daily data improvement and/or generation had been underestimated.

Since the Project concentrated mostly on the use of daily data, these aspects have become critical to the success of the study and therefore, certain steps have had to be undertaken to address the problem of the availability of daily data for low-flow or any other detailed hydrological analysis. The most important result appeared to be the developed spatial interpolation algorithm for patching/extension of observed frow time series. This algorithm, often referred to in the report as the "patching model", is based on flow duration curves for each month of the year and allows a record at a site of interest to be patched or extended by a straightforward manipulation of other record(s) at the nearby gauge(s). The algorithm has been tested in many parts of southern Africa and used throughout the course of the Project.

The developed technique has good potential for the generation of a complete time series of daily flows and therefore, low-flow estimation at an ungauged site. Possible ways of daily flow time-series generation relate to the utilisation of already existing synthetic monthly streamflow time series for quaternary and tertiary catchments in the country. The possibility of converting monthly flow duration curves into daily flow duration curves and translating the latter into a complete daily flow time series has been investigated during the Project. Another method which has also been applied is the regionalization of observed daily flow duration curves. The established regional annual and seasonal daily flow duration curves are useful in their own right in many water resource applications but they can be similarly used to generate a continuous daily hydrograph at an ungauged site. The application of spatial interpolation technique has proved to be efficient and in this sense, it may represent a pragmatic alternative to more sophisticated deterministic modelling approaches. It also appeared to be the first attempt at using simple methods of daily flow estimation in a South African context. Although not specifically addressed in the current report, the technique may be further developed as a simple tool for the naturalisation of existing historical flow records.

The approaches for regionalization of low-flow characteristics have also been applied during the Project. Those make use of a multiple regression method whereby a low-flow characteristic is estimated by means of a relationship with catchment and climatic parameters or some monthly low-flow characteristic.

9.3 RECOMMENDATIONS FOR FUTURE RESEARCH

- The problem areas identified by the Project mostly relate to the availability of daily streamflow data rather than to low-flow estimation techniques themselves. It has been demonstrated that it is generally possible to develop a picture of the low-flow conditions in large catchments through the combined use of observed and simulated data. However, daily flow simulation may be very time consuming. At the same time, good potential exists in simpler methods that either make use of existing synthetic monthly flow data or regionalizations of observed daily flow data. In the context of the techniques developed and tested during the Project, it is necessary to account for the effects of abstractions/effluents, rating table limits and non-stationarity of records on daily flow duration curves. A better understanding is also required of how to establish and regionalize the relationships between monthly and daily flow duration curves. These directions are therefore recommended for future research.

- The regionalization of flow duration curves should be tested in other regions of the country. At the same time, research is required in regionalisation of other low flow measures (low-flow frequency curves, spell frequency curves etc.). This would facilitate the solution of low-flow estimation problems at the scale of small catchments. This could be relevant, for example, for the successful design of small water supply schemes in rural areas. In general, more research is necessary in the direction of the development of simplified methods of low-flow estimation at the subquaternary catchment scale.

- One of the problems that may limit the application of deterministic daily rainfall-runoff modelling methods in South Africa (as well as other estimation techniques) is the frequent absence of reliable data on abstractions/interbasin transfers. Basin studies and System analysis reports normally contain some data of that kind but these data are not always appropriate/sufficient for daily rainfall-runoff modelling. In general these data at present are not well documented. It would therefore be desirable to construct a national database of abstractions points and abstraction flow time series data. The participation of local DWAF centres may prove invaluable in this respect. Other characteristics of anthropogenic impacts (forestry, irrigation) at least at the quaternary catchment level of spatial detail need to be documented at different historical levels.

- A good performance of a daily rainfall-runoff model in terms of conventional goodness-of-fit criteria does not necessarily guarantee that a model satisfactory reproduces various aspects of a low-flow regime. It is recommended that the ability of any daily rainfall-runoff model to simulate low-flow regimes is tested in terms of several low-flow criteria as has been illustrated in the Report with the case of the VTI model. Such an approach would allow conclusions to be made about the efficiency of a model and its suitability for different water resource problems.

- The data requirements of the Project were substantial and a consequently a great deal of resources were required from the DWAF to supply the project with the data. In this context there appears to be a necessity to develop an accessible inventory of all streamflow gauging structures in the country supplemented with some standard data on recorded flow regimes. The existing catalogues of gauges published by the DWAF at present are either out of date or contain information that is not complete and require further clarification. The description of each gauge and its corresponding recorded flow regime would allow the interested users to determine *a priori* whether to request the data from DWAF or not. Such a description will require the joint efforts of the DWAF on one hand, and a research institution, such as the Institute for Water Research of Rhodes University, where the relevant expertise for time series analysis already exist - on the other. The description of each gauge should contain the details of gauging structures and discharge tables which could be supplied by the DWAF. The details about particular flow characteristics, plots of annual time series, flow duration curves, seasonal distribution, etc could be supplied by the IWR. During the course of the Project the initial steps have effectively been done in this direction: standard plots of annual flow totals and low-flows characteristics have been constructed for each flow gauge in the catchments considered. However those have been aimed at the illustration of low-flow regimes and may serve only as a minor part of the future gauge description. Similar description of recorded flow regimes has been undertaken in the UK (Dr. A.Bullock, pers. com.). Preliminary discussions with the DWAF staff have demonstrated that there exists an interest in a joint undertaking of a project of that kind (Mr.S.van Biljoen, Mrs.V.Mynhardt, pers. com.). The alternative solution could be the establishment of a direct access to the DWAF streamflow database. This access would allow the users to extract required information in the same way as for example, rainfall data is now extracted from the CCWR database. It would free the DWAF staff from data extraction functions and allow the existing database maintenance and updating to be concentrated on. It is understood that the DWAF is currently investigating the options and implications of such direct access (Mr.F.Cornelius, Mr B.Haasbroek, pers.com.)

- One of the major users of low-flow information in South Africa is the Instream Flow Assessment Process which deals with the estimation of ecologically relevant flows (normally in the modified streams). The Project has generated a number of routines for low-flow estimation which are currently used by aquatic ecologists. However, the search for ecologically important low flows in different parts of the country continues. The logical extension of low-flow studies would be to forge the link with ongoing environmental studies of Instream Flow Requirements. One example research direction could be the development of appropriate techniques that translate the IFR information into a time series of expected reservoir releases and therefore allow the suggested modified flow regime to be illustrated and analyzed.

- The logical extension of the Project would be to continue with the detailed investigation of low-flow processes in different parts of the country, paying more attention to the behaviour of the natural water systems (streams, wetlands) under drought conditions.

9.4 TECHNOLOGY TRANSFER

The most important research products of the completed Project have been presented in several publications. Smakhtin et al (1995) described low-flow estimation software and the results of large scale analysis of low-flow regimes in SA. Hughes and Smakhtin (1996) discussed the spatial interpolation algorithm, examples of it application in southern Africa and its potential value for hydrological analysis. Smakhtin et al (1996) described the regionalisation method developed and applied for daily flow time series generation and low-flow estimation in the T drainage region. The results of the Project have also been presented at several local and international conferences. A number of research papers which contain the most recent achievements of the Project are currently in preparation and are expected to be submitted for publication in local and international journals in the near future. They describe the experience in basin-wide low-flow estimation in selected South African catchments and suggest methods of estimation of daily flow characteristics from available synthetic monthly streamflow data.

During the course of the Project a number of analytical routines have been added to the HYMAS software package. That significantly enhanced the HYMAS capabilities as a tool for general time series analysis. HYMAS has been successfully used during the Luvuvhu (1995) and Sabie-Sand (1996) IFR workshops to supply various specialists involved in IFR formulation with relevant hydrological information. The routines developed during the course of the project were the most intensively used parts of the whole system during these workshops.

Several overseas institutions expressed an interest in low-flow estimation software and the spatial interpolation algorithm for daily data patching/ extension/generation. Since these modules form an integral part of the HYMAS package, the latter has been made available for these institutions, namely Global Runoff Data Centre (Koblenz, Germany), National High School of Agronomy (Rennes, France), Technical University of Denmark (Lyngby, Denmark).

After the completion of two major IWR projects (Low Flows and Southern Africa FRIEND) the HYMAS package became a very comprehensive, multipurpose and flexible computer system for hydrological analysis. It is a unique system of that kind in South Africa which is designed to work with a variety of original data formats and to provide solutions to a variety of water resource problems. The HYMAS User Manual, which also describes how to use the low-flow software, is available from the IWR. However, it is also suggested that a training course on the HYMAS system is organised for potential users in South Africa in the nearest future. This would promote the research products of the IWR, bring together the expertise of different specialists involved in modelling/time series analysis and also provide necessary feedback for the system developers. The operation of low-flow estimation software and general time-series analysis routines may form the bulk of such course.

The expertise gained and results that emerged from the Low Flow Project may form the basis for the solution of a variety of practical problems related to low flows. Such problems (should they emerge) may be discussed in the form of a workshop that the Institute for Water Research is prepared to organize. The IWR is also ready to service any requests for data generated during the Project that may arise.

The ideal form of conveyance of generated information to a potential user would be through the development of an approach that combines the spatial and time-series components, for example, through the use of ARC\VIEW. The CCWR has recently initiated the development of such an approach. A new project starting in the IWR in 1997 and entitled "The integration and application of daily flow analysis and simulation approaches within southern Africa" has the general objective of improving the availability and accessibility of daily flow information for use in various fields of water resources decision making and management. It is envisaged that cooperation with the CCWR and other inerested institutions/research groups in this respect will lead to the development of a spatial interface for accessing distributed low-flow and other daily flow indices and time-series for particular basins.

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11. ABBREVIATIONS

ADF	: Average Daily Flow
AMF	: Absolute Minimum Flow - the lowest flow value in the record
BFI	: Base Flow Index - the ratio of baseflow volume to total streamflow volume; calculated by baseflow separation techniques for a year or several years of daily flow record
BFV	: Base Flow Volume
CCWR	: Computing Centre for Water Research
CE	: Coefficient of Efficiency - a measure of 1:1 correspondence between observed and predicted flow values
CV	: Coefficient of Variation
DTL	: Discharge Table Limit - a limit to which the streamflow discharge may be measured at a gauging structure
DWA	: Department of Water Affairs (before the 1990s)
DWAF	: Department of Water Affairs and Forestry
FDC	: Flow Duration Curve
HFP	: Half Flow Period, a measure of streamflow recession - the time (days) required for the baseflow to halve
HYMAS	: HYdrological Modelling Application Software package
IFA	: Instream Flow Assessment process
IFR	: Instream Flow Requirements
IWR	: Institute for Water Research of Rhodes University
LFFC	: Low-Flow Frequency Curve

MAM	: Mean Annual Minimum flow; calculated from a series of minima extracted from each year of daily flow record
MAMn	: Mean Annual n-day average Minimum flow; calculated from a series of n-day average minima extracted from each year of daily flow record
MAP	: Mean Annual Precipitation
MAR	: Mean Annual Runoff
MBFD	: Mean Base Flow Discharge - the mean of daily baseflow values
MCM	: Million Cubic Meters
MMD50	: Mean of annual maximum durations the river continuously stays below a referenced discharge of 50% of ADF
MMDEF50	: Mean of annual maximum deficits built during consecutive low-flow events below a referenced discharge of 50% of ADF
Q50, Q75, Q95, etc.	: Flows extracted from a flow duration curve and exceeded 50, 75, 95% (etc.) of the time
Q75(n), Q95(n), etc.	: Flows extracted from a flow duration curve (constructed on the basis of n-day average flows) and exceeded 75, 95% (etc.) of the time
RCONST	: Recession Constant, a measure of flow recession and a parameter in the exponential recession equation
REC50	: 50 percentile recession ration estimated from a distribution of ratios of current discharge to the discharge n days previously.
RFD	: Residual Flow Diagram - a diagram illustrating changing flow conditions at different positions within a catchment
SYD	: Storage-Yield Diagram - a diagram for the estimation of a reservoir storage which is necessary to provide a given yield at required level of assurance
UCT	: University of Cape Town
VTI	: Variable Time Interval Model

VAPS	: Vaal Augmentation Planning Study
WRC	: Water Research Commission
WR90	: Surface Water Resources of South Africa 1990 (Midgley et al, 1994)

APPENDIX A1

The form of the Questionnaire for the survey of user requirements for low-flow information conducted by the IWR in 1993.

QUESTIONNAIRE

1. Name (optional)________________________________
2. Present occupation________________________________
3. Affiliation or company________________________________
4. Address , telephone________________________________

____

5. Indicate the area of your current or past interest in low flows.

- ○ water resources research
- ○ water supply design
- ○ assessment of environmental impacts
- ○ water quality management
- ○ water supply management
- ○ ecological research
- ○ others (specify________________________________)

Please supply the details if possible________________________________

____

____

____

6. What time resolution of low-flow information is important to you or your organisation?

○ Daily ○ Monthly ○ Annual ○ Other (specify____________________)

Please specify whether you use this information directly, to construct data of other durations, or both.________________________________

____

7. What categories of low-flow information are likely to be of value to your organisation ?

- ○ Streamflow duration characteristics
- ○ Recessions
- ○ Low-flow frequency characteristics
- ○ Baseflow data
- ○ Other (specify________________________________)

8. Do you use any specific low-flow indices and/or measures ?

- ○ Flow of prescribed (or fixed) probability of exceedence
- ○ Flow of a particular return period
- ○ Any baseflow indices
- ○ Other(specify________________________________)

9. What sort of low-flow criteria you would consider to be of potential use in low flow hydrology and/or related aquatic studies ?

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10. When dealing directly or indirectly with low flows, do you require information on aquatic aspects others than streamflow quantity and quality ?

○ flow velocity ○ groundwater ○ hydraulic conductivity
○ riparian vegetation ○ channel morphology ○ bedload material
○ evaporation ○ rainfall ○ other (specify____________)

Please indicate where necessary how (if at all) in your opinion your specified characteristics are related to low flows.____________________________

____

____

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____

11. How do you use the information on low flows ?

○ analysis ○ design ○ prediction
○ management ○ planning ○ other

Please specify further if necessary and give more details where possible

____

____

____

____

12. What do you do if the necessary information is not available or insufficient ?

○ use "trial and error" approach ○ consult different experts
○ use generalised or regional relations ○ simulate
○ other(specify____)

If possible, give examples of particular cases, or probable alternatives that you would use in case of necessity.

13. What would you advise to improve the link of low flow hydrology with other aquatic sciences and requirements of practice ?

- ◯ establish standard procedures for low-flow measurements and analysis
- ◯ define the terms properly
- ◯ organise interdisciplinary seminars and workshops
- ◯ other (specify____

____

____)

14. What sort of low-flow problems from your experience and professional point of view are typical, specifically for

a) your country____

____

____

____

b) southern Africa____

____

____

____?

15. What benefits would you expect from future low-flow studies ?

- ◯ an understanding of low-flow limitations of a watershed during drought
- ◯ improved statistical reliability in low-flow data
- ◯ better knowledge regarding the impacts of aquifer activities on streamflow
- ◯ development of ways to improve water quality management during low-flow events
- ◯ other(specify____

____

____)

16. Any other remarks you want to add:___________________________

____

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APPENDIX A2

Annual 1-day low-flow indices extracted from a flow duration curve

The indices listed are Average Daily Flow (ADF), the % of time with zero flows (T_0), flows exceeded 50, 60, 75, 90, 95 and 99 % of the time on average throughout a year (Q50, Q60, Q75, Q90, Q95, Q99) and the ratio of Q90/Q50 which approximates the slope of the lower part of the Flow Duration Curve.

Low-flow indices and mean flow are estimated for the period of record indicated for each gauge. The start date in most of the cases is coincident with the beginning of the hydrological year. The 'end year' indicated is either the year for which data was available from DWAF in October 1993, or the year prior to the construction of any impoundments in a catchment upstream of the gauge.

The percentage of time with zero flows was set to zero (the stream was assumed to be "100 % perennial") if the actual calculated value of T_0 was less than 1 %.

The ratio Q90/Q50 was calculated only if both (Q90 and Q50) were non-zero values.

Station Code	River	Start Year	End Year	Catchment area (km^2)	ADF, m^3/s	T_0, %	Q50, m^3/s	Q60, m^3/s	Q75, m^3/s	Q90, m^3/s	Q95, m^3/s	Q99, m^3/s	Q90/Q50
1	2	3	4	5	6	7	8	9	10	11	12	13	14
A2H029	Edenvalespruit	1962	1992	129	0.093	30	0.012	0.005	0.0	0.0	0.0	0.0	
A2H032	Selonsrivier	1963	1992	522	0.160	80	0.0	0.0	0.0	0.0	0.0	0.0	
A2H039	Waterkloof-Bo	1971	1992	3.6	0.029	2	0.010	0.009	0.006	0.003	0.002	0.0	0.300
A2H050	Krokodilrivier	1973	1991	148	0.265	1.06	0.119	0.098	0.072	0.051	0.029	0.0	0.429
A2H053	Sterkstroom	1973	1992	88	0.308	1.26	0.124	0.087	0.048	0.017	0.012	0.0	0.137
A3H001	Klein-Maricorivier	1906	1939	1 165	0.173	43.2	0.006	0.0	0.0	0.0	0.0	0.0	
A4H002	Mokolorivier	1948	1991	1 777	1.65	9.68	0.597	0.372	0.158	0.004	0.0	0.0	0.007
A4H008	Sterkstroom	1964	1991	504	1.76	8.62	0.371	0.206	0.720	0.004	0.0	0.0	0.011
A5H004	Palalarivier	1962	1991	629	2.34	5.70	0.603	0.378	0.167	0.037	0.0	0.0	0.061
A6H011	Groot-Nylrivier	1966	1991	73	0.183	0.0	0.072	0.046	0.025	0.007	0.004	0.002	0.097
A6H012	Olifantspruit	1966	1991	120	210.0	8.6	0.033	0.018	0.005	0.0	0.0	0.0	
A6H018	Rasloopriver	1973	1991	12	0.037	0.0	0.014	0.010	0.010	0.010	.0.009	0.005	0.714
A6H019	Hessie se water	1973	1991	16	0.044	1.95	0.026	0.0020	0.012	0.006	0.005	0.0	0.231
A6H020	Middelfonteinspruit	1973	1991	43	0.079	11.1	0.017	0.014	0.008	0.0	0.0	0.0	
A6H021	De Westpruit	1973	1991	16	0.039	77.8	0.0	0.0	0.0	0.0	0.0	0.0	
A6H022	Hartbeeslaagte	1973	1991	1.7	0.011	86.6	0.0	0.0	0.0	0.0	0.0	0.0	
A9H001	Luvuvhurivier	1931	1951	915	3.31	0.0	2.052	1.632	1.157	0.749	0.560	0.417	0.365
A9H002	Mutshindudirivier	1931	1991	96	1.14	0.0	0.714	0.576	0.402	0.205	0.119	0.026	0.287
A9H004	Mutalerivier	1932	1991	320	3.03	0.0	1.603	1.254	0.840	0.387	0.236	0.083	0.241
B1H001	Olifantsrivier	104	1951	3 904	4.21	4.7	0.522	0.375	0.174	0.028	0.004	0.0	0.0536
B1H002	Spookspruit	1956	1992	252	0.185	0.0	0.036	0.026	0.017	0.010	0.007	0.002	0.278
B2H001	Bronkhorstspruit	1904	1951	1 594	1.085	2.14	0.403	0.270	0.133	0.037	0.013	0.0	0.092
B3H001	Olifantsrivier	1938	1991	16 553	4.77	9.96	0.938	0.630	0.237	0.002	0.0	0.0	0.002
B4H001	Watervalrivier	1960	1992	188	0.72	0.0	0.425	0.340	0.241	0.159	0.123	0.080	0.374
B4H009	Dwarsrivier	1966	1992	448	0.61	1.5	0.163	0.111	0.072	0.041	0.031	0.0	0.252
B5H002	Olifantsrivier	1948	1977	31 416	23.8	0.0	7.283	4.631	1.631	0.384	0.176	0.018	0.053

Station Code	River	Start Year	End Year	Catchment area (km^2)	ADF, m^3/s	T_0, %	Q50, m^3/s	Q60, m^3/s	Q75, m^3/s	Q90, m^3/s	Q95, m^3/s	Q99, m^3/s	Q90/Q50
1	2	3	4	5	6	7	8	9	10	11	12	13	14
B6H001	Blyderivier	1911	1992	518	5.26	0.0	3.60	3.09	2.40	1.75	1.53	1.07	0.486
B6H002	Treurrivier	1909	1939	97	2.18	0.0	0.463	0.366	0.271	0.183	0.154	0.106	0.395
B6H003	Treurrivier	1959	1992	92	1.42	0.0	0.598	0.483	0.369	0.281	0.248	0.172	0.470
B7H003	Selatirivier	1948	1972	84	0.205	6.67	0.035	0.019	0.009	0.004	0.0	0.0	0.114
B7H004	Klaserierivier	1950	1992	136	0.997	1.68	0.412	0.269	0.145	0.076	0.045	0.0	0.184
B7H008	Selatirivier	1956	1992	832	1.30	67.7	0.0	0.0	0.0	0.0	0.0	0.0	
B7H009	Olifantsrivier	1960	1991	42 472	23.9	0.0	6.637	4.355	2.290	1.120	0.764	0.177	0.169
B7H010	Ngwabitsrivier	1960	1992	318	0.53	45.3	0.024	0.0	0.0	0.0	0.0	0.0	
B7H014	Selatirivier	1973	1992	83	0.25	16.8	0.018	0.013	0.005	0.0	0.0	0.0	
B9H001	Shisharivier	1960	1991	648	0.143	92.9	0.0	0.0	0.0	0.0	0.0	0.0	
C1H008	Watervalrivier	1973	1991	2 212	5.17	44.2	1.83	0.0	0.0	0.0	0.0	0.0	
C2H026	Middelvleispruit	1957	1992	26	0.012	31.9	0.005	0.003	0.0	0.0	0.0	0.0	
C2H027	Kocksoordspruit	1957	1991	4	0.002	82.6	0.0	0.0	0.0	0.0	0.0	0.0	
C2H028	Rietfonteinspruit	1957	1992	31	0.029	30.5	0.006	0.003	0.0	0.0	0.0	0.0	
C2H065	Leeudoringspruit	1970	1992	860	0.209	41.2	0.007	0.0	0.0	0.0	0.0	0.0	
C2H067	Sandspruit	1971	1992	1 895	0.081	85.9	0.0	0.0	0.0	0.0	0.0	0.0	
C3H003	Hartsrivier	1927	1992	10 990	1.51	53.3	0.0	0.0	0.0	0.0	0.0	0.0	
C4H002	Vetrivier	1940	1972	17 599	8.39	17.9	0.791	0.515	0.194	0.0	0.0	0.0	
C5H007	Renosterspruit	1923	1991	348	0.192	76.8	0.0	0.0	0.0	0.0	0.0	0.0	
C5H008	Rietrivier	1958	1986	593	0.379	85.8	0.0	0.0	0.0	0.0	0.0	0.0	
C5H012	Rietrivier	1954	1990	2 372	1.046	67.5	0.0	0.0	0.0	0.0	0.0	0.0	
C6H003	Valsrivier	1967	1992	7 765	5.647	49.9	0.002	0.0	0.0	0.0	0.0	0.0	
C6H004	Valsrivier	1969	1990	856	0.354	57.2	0.0	0.0	0.0	0.0	0.0	0.0	
C7H003	Heuningspruit	1947	1992	914	0.481	82.2	0.0	0.0	0.0	0.0	0.0	0.0	
C8H003	Corneliusrivier	1954	1990	806	1.39	15.3	0.203	0.107	0.026	0.0	0.0	0.0	
C8H005	Elandsrivier	1963	1992	696	3.06	2.90	0.622	0.374	0.188	0.075	0.023	0.0	0.121

Station Code	River	Start Year	End Year	Catchment area (km^2)	ADF, m^3/s	T_0, %	Q50, m^3/s	Q60, m^3/s	Q75, m^3/s	Q90, m^3/s	Q95, m^3/s	Q99, m^3/s	Q90/Q50
1	2	3	4	5	6	7	8	9	10	11	12	13	14
C8H012	Vaalbankspruit	1971	1992	386	0.310	29.0	0.014	0.009	0.0	0.0	0.0	0.0	
C8H022	Wilgerivier	1961	1973	15 466	13.2	3.4	2.784	2.011	1.055	0.433	0.076	0.0	0.155
D1H011	Kraairivier	1965	1991	8 688	19.5	2.13	4.895	3.112	1.397	0.465	0.155	0.0	0.095
D2H012	Klein-Caledonrivier	1975	1991	518	0.885	12.6	0.230	0.147	0.064	0.0	0.0	0.0	
D2H020	Caledonrivier	1982	1992	8 339	7.78	55.8	0.0	0.0	0.0	0.0	0.0	0.0	
D4H003	Swartbasrivier	1941	1947	181	0.006	99.0	0.0	0.0	0.0	0.0	0.0	0.0	
D5H003	Visrivier	1927	1991	1 509	0.441	94.8	0.0	0.0	0.0	0.0	0.0	0.0	
D5H013	Sakrivier	1958	1980	13 087	0.942	89.9	0.90	0.0	0.0	0.0	0.0	0.0	
E1H006	Jan Disselsrivier	1971	1991	160	1.238	0.0	0.388	0.282	0.179	0.109	0.083	0.046	0.281
E2H002	Doringrivier	1923	1992	6 903	9.46	0.0	1.706	0.796	0.318	0.116	0.072	0.006	0.068
E2H007	Leeurivier	1970	1991	265	2.079	10.1	0.046	0.014	0.006	0.0	0.0	0.0	
G1H002	Vier en twintig	1963	1970	187	3.88	1.35	1.884	1.290	0.835	0.623	0.489	0.0	0.331
G1H003	Franschhoekrivier	1949	1992	46	0.735	10.9	0.236	0.125	0.037	0.0	0.0	0.0	
G1H007	Bergrivier	1951	1977	713	14.4	13.2	5.265	2.870	0.936	0.0	0.0	0.0	
G1H008	Klein-Bergrivier	1954	1992	395	2.16	0.0	0.579	0.286	0.135	0.058	0.031	0.002	0.100
G1H009	Brakkloofspruit	1964	1991	5.7	0.012	5.12	0.0	0.0	0.0	0.0	0.0	0.0	
G1H010	Knolvleispruit	1964	1992	10	0.014	81.0	0.0	0.0	0.0	0.0	0.0	0.0	
G1H011	Watervalsrivier	1964	1991	27	0.434	8.41	0.138	0.068	0.022	0.003	0.0	0.0	0.022
G1H012	Watervalsrivier	1964	1992	36	0.440	12.3	0.133	0.062	0.014	0.0	0.0	0.0	
G1H014	Zachariashoekrivier	1964	1992	2.8	0.039	0.0	0.011	0.008	0.0051	0.005	0.0041	0.004	0.455
G1H015	Kasteelkloofspruit	1964	1989	1.9	0.049	2.81	0.014	0.009	0.006	0.0031	0.003	0.0	0.214
G1H016	Kasteelkloofspruit	1964	1992	3.3	0.09	0.0	0.031	0.020	0.013	0.009	0.008	0.007	0.290
G1H017	Zachariashoekspruit	1964	1989	1.7	0.021	15.5	0.005	0.003	0.002	0.0	0.0	0.0	
G1H018	Bakkerskloofspruit	1964	1992	3.4	0.073	1.35	0.017	0.009	0.004	0.002	0.002	0.0	0.118
G1H019	Banghoekrivier	1968	1991	25	0.107	76.7	0.0	0.0	0.0	0.0	0.0	0.0	
G1H021	Klein-Bergrivier	1968	1992	19	0.489	0.0	0.234	0.176	0.121	0.080	0.066	0.033	0.342

Station Code	River	Start Year	End Year	Catchment area (km^2)	ADF, m^3/s	T_0, %	Q50, m^3/s	Q60, m^3/s	Q75, m^3/s	Q90, m^3/s	Q95, m^3/s	Q99, m^3/s	Q90/Q50
1	2	3	4	5	6	7	8	9	10	11	12	13	14
G1H028	Vier-en-twintig	1972	1990	183	1.69	83.1	0.0	0.0	0.0	0.0	0.0	0.0	
G2H008	Jonkershoekrivier	1947	1992	20	0.728	19.1	0.185	0.090	0.013	0.0	0.0	0.0	
G2H012	Dieprivier	1965	1992	244	0.348	51.0	0.0	0.0	0.0	0.0	0.0	0.0	
G3H001	Kruisrivier	1970	1992	647	0.389	35.9	0.036	0.009	0.0	0.0	0.0	0.0	
G4H006	Kleinrivier	1963	1991	600	0.918	7.32	0.104	0.004	0.0031	0.003	0.0	0.0	
G4H008	Klein-Jakkalsrivier	1964	1991	1.5	0.023	14.6	0.010	0.006	0.003	0.0	0.0	0.0	
G4H009	Jakkalsrivier	1964	1991	2	0.012	47.4	0.002	0.0	0.0	0.0	0.0	0.0	
G4H013	Klein-Jakkalsrivier	1965	1991	2.1	0.028	26.9	0.009	0.004	0.0	0.0	0.0	0.0	
G4H014	Botrivier	1967	1991	252	0.64	2.63	0.158	0.085	0.031	0.010	0.004	0.0	0.063
G5H006	Klein-Sandrifrivier	1956	1991	3.2	0.027	0.0	0.015	0.014	0.012	0.010	0.008	0.007	0.666
G5H008	Soutrivier	1964	1991	382	0.155	70.9	0.0	0.0	0.0	0.0	0.0	0.0	
H1H007	Witrivier	1950	1992	84	3.774	0.0	0.918	0.605	0.271	0.136	0.111	0.055	0.148
H1H012	Holslootrivier	1963	1976	146	2.185	0.27	0.505	0.324	0.218	0.144	0.114	0.089	0.285
H1H013	Koekedourivier	1965	1992	53	0.714	0.0	0.195	0.118	0.059	0.036	0.027	0.010	0.1846
H1H017	Elandsrivier	1978	1992	61	2.361	4.13	0.720	0.497	0.338	0.268	0.252	0.0	0.372
H1H018	Molenaarsrivier	1969	1992	113	4.167	0.0	1.634	1.194	0.728	0.513	0.456	0.318	0.314
H2H001	Hexrivier	1927	1991	697	2.946	0.0	0.989	0.779	0.586	0.351	0.253	0.054	0.355
H2H005	Rooi-Elkskloofrivier	1969	1992	15	0.204	0.0	0.090	0.071	0.054	0.038	0.031	0.025	0.422
H3H001	Kingnarivier	1925	1947	593	0.331	95.7	0.0	0.0	0.0	0.0	0.0	0.0	
H3H004	Keisierivier	1965	1992	14	0.022	85.6	0.0	0.0	0.0	0.0	0.0	0.0	
H3H005	Keisierivier	1965	1992	76	0.017	85.7	0.0	0.0	0.0	0.0	0.0	0.0	
H4H005	Willem Nelsrivier	1950	1981	24	0.183	0.0	0.077	0.062	0.045	0.030	0.022	0.010	0.390
H4H009	Hoeksrivier	1967	1990	18	0.042	94.2	0.0	0.0	0.0	0.0	0.0	0.0	
H4H012	Waterkloofspruit	1969	1991	14	0.022	78.1	0.0	0.0	0.0	0.0	0.0	0.0	
H6H003	Riviersonderend	1932	1969	497	6.194	3.46	2.140	0.822	0.077	0.014	0.006	0.0	0.007
H6H006	Elandsrivier	1964	1974	56	0.363	50.3	0.0	0.0	0..0	0.0	0.0	0.0	

Station Code	River	Start Year	End Year	Catchment area (km^2)	ADF, m^3/s	T_0, %	Q50, m^3/s	Q60, m^3/s	Q75, m^3/s	Q90, m^3/s	Q95, m^3/s	Q99, m^3/s	Q90/Q50
1	2	3	4	5	6	7	8	9	10	11	12	13	14
H6H008	Riviersonderend	1964	1992	38	1.892	0.0	0.562	0.397	0.237	0.147	0.118	0.092	0.262
H6H010	Waterkloofrivier	1964	1992	15	0.067	0.0	0.047	0.042	0.036	0.020	0.011	0.010	0.426
H7H001	Breerivier	1912	1940	9 829	40.7	17.1	7.937	6.206	3.300	0.0	0.0	0.0	
H7H003	Buffeljagsrivier	1949	1991	450	1.77	3.78	0.384	0.235	0.109	0.024	0.010	0.0	0.0625
H7H007	Grootkloofrivier	1968	1992	24	0.308	0.0	0.187	0.152	0.109	0.070	0.052	0.028	0.374
H9H004	Kruisrivier	1969	1990	50	0.409	0.0	0.186	0.150	0.113	0.082	0.072	0.054	0.441
H9H005	Kafferkuilsrivier	1969	1991	228	1.503	14.4	0.218	0.117	0.029	0.0	0.0	0.0	
J1H015	Bokrivier	1974	1991	8.8	0.107	0.0	0.052	0.041	0.028	0.018	0.016	0.015	0.346
J1H016	Smalblaarrivier	1974	1991	30	0.089	30.5	0.015	0.008	0.0	0.0	0.0	0.0	
J2H005	Huisrivier	1955	1991	253	0.219	11.1	0.021	0.010	0.004	0.0	0.0	0.0	
J2H006	Boplaasrivier	1955	1992	225	0.024	49.6	0.002	0.0	0.0	0.0	0.0	0.0	
J2H007	Joubertrivier	1967	1991	25	0.032	33.0	0.008	0.0	0.0	0.0	0..0	0.0	
J3H012	Grootrivier	1973	1991	688	0.336	12.6	0.036	0.024	0.009	0.0	0.0	0.0	
J3H013	Perdepoortrivier	1966	1991	29	0.257	0.0	0.164	0.141	0.115	0.093	0.082	0.066	0.567
J3H016	Wilgerivier	1967	1991	32	0.029	4.91	0.013	0.010	0.006	0.003	0.002	0.0	0.231
J3H017	Kandelaarsrivier	1967	1992	348	0.115	59.0	0.0	0.0	0.0	0.0	0.0	0.0	
J3H018	Wynandsrivier	1969	1991	137	0.231	5.9	0.103	0.077	0.043	0.010	0.0	0.0	0.0971
J3H020	Meulrivier	1976	1993	35	0.055	34.9	0.010	0.004	0.0	0.0	0.0	0.0	
J4H003	Weyersrivier	1965	1991	95	0.583	8.92	0.157	0.113	0.062	0.008	0.0	0.0	0.051
J4H004	Langtourivier	1967	1992	99	0.212	10.3	0.055	0.039	0.019	0.0	0.0	0.0	
K1H001	Hartenbosrivier	1937	1969	144	0.169	75.5	0.0	0.0	0.0	0.0	0.0	0.0	
K1H002	Brandwagrivier	1958	1990	3.80	0.041	14.3	0.018	0.016	0.011	0.0	0.0	0.0	
K3H001	Kaaimansrivier	*1961*	1991	47	0.459	1.74	0.133	0.016	0.077	0.043	0.025	0.0	0.323
K3H002	Rooirivier	1961	1991	1.04	0.013	34.7	0.002	0.0	0.0	0.0	0.0	0.0	
K3H003	Maalgaterivier	1961	1991	145	0.81	4.06	0.174	0.115	0.059	0.010	0.003	0.0	0.057
K3H004	Malgasrivier	1961	1991	34	0.537	0.0	0.135	0.096	0.060	0.037	0.028	0.016	0.274

Station Code	River	Start Year	End Year	Catchment area (km²)	ADF, m³/s	T_0, %	Q50, m³/s	Q60, m³/s	Q75, m³/s	Q90, m³/s	Q95, m³/s	Q99, m³/s	Q90/Q50
1	2	3	4	5	6	7	8	9	10	11	12	13	14
K3H005	Touwsrivier	1969	1991	78	0.381	0.0	0.103	0.087	0.064	0.046	0.039	0.027	0.447
K4H001	Hoekraalrivier	1959	1991	111	0.432	3.61	0.145	0.085	0.044	0.027	0.011	0.0	0.186
K4H002	Karatararivier	1962	1991	22	0.301	0.0	0.072	0.056	0.040	0.025	0.018	0.011	0.347
K4H003	Dieprivier	1961	1991	72	0.286	0.0	0.092	0.076	0.055	0.038	0.030	0.018	0.413
K5H002	Knysnarivier	1961	1991	133	0.803	0.0	0.327	0.275	0.216	0.165	0.147	0.103	0.505
K6H001	Keurboomsrivier	1961	1991	165	0.308	9.0	0.049	0.036	0.018	0.003	0.0	0.0	0.013
K6H002	Keurboomsrivier	1974	1981	764	2.405	0.0	1.404	1.186	0.904	0.653	0.553	0.290	0.465
K7H001	Bloukransrivier	1961	1991	57	0.892	0.0	0.313	0.265	0.204	0.137	0.105	0.071	0.438
L1H001	Soutrivier	1917	1976	3 938	0.448	94.9	0.0	0.0	0.0	0.0	0.0	0.0	
L6H001	Heuningkliprivier	1926	1992	1 290	0.538	92.9	0.0	0.0	0.0	0.0	0.0		
L8H001	Harlenspruit	1965	1992	52	0.38	0.0	0.095	0.057	0.025	0.010	0.006	0.003	0.105
L8H002	Waboomspruit	1970	1992	21	0.356	0.0	0.144	0.113	0.077	0.044	0.032	0011	0.306
N2H009	Volkersrivier	1978	1986	536	2.427	6.17	2.418	1.401	0.124	0.004	0.0	0.0	0.002
P4H001	Kowierivier	1969	1993	576	0.768	40.1	0.018	0.0	0.0	0.0	0.0	0.0	
Q1H001	Groot-Visrivier	1918	1970	9 091	2.416	92.2	0.0	0.0	0.0	0.0	0.0	0.0	
Q1H009	Klein-Brakrivier	1968	1974	1 211	0.034	99.0	0.0	0.0	0.0	0.0	0.0	0.0	
Q3H004	Paulsrivier	1975	1991	872	0.227	10.23	0.084	0.041	0.014	0.0	0.0	0.0	
Q4H003	Vlekpoortrivier	1974	1991	1 300	0.109	30.2	0.014	0.008	0.0	0.0	0.0	0.0	
Q6H003	Baviaansrivier	1980	1991	814	0.238	24.6	0.007	0.005	0.002	0.0	0.0	0.0	
Q9H002	Koonaprivier	1933	1992	1 245	1.277	60.1	0.0	0.0	0.0	0.0	0.0	0.0	
Q9H013	Kaprivier	1979	1992	46	0.079	628	0.0	0.0	0.0	0.0	0.0	0.0	
Q9H016	Koonaprivier	1981	1992	489	0.484	33.9	0.004	0.002	0.0	0.0	0.0	0.0	
Q9H017	Blinwaterrivier	1965	1992	226	0.176	34.2	0.007	0.003	0.0	0.0	0.0	0.0	
Q9H019	Balfourrivier	1972	1992	76	0.313	4.36	0.076	0.048	0.023	0010	0.003	0.0	0.132
R1H001	Tyumerivier	1928	1980	238	0,749	35.8	0.162	0.041	0.0	0.0	0.0	0.0	
R1H005	Keiskammarivier	1948	1981	482	1.367	0.0	0.644	0.469	0.284	0.136	0.094	0.037	0.211

Station Code	River	Start Year	End Year	Catchment area (km^2)	ADF, m^3/s	T_0, %	Q50, m^3/s	Q60, m^3/s	Q75, m^3/s	Q90, m^3/s	Q95, m^3/s	Q99, m^3/s	Q90/Q50
1	2	3	4	5	6	7	8	9	10	11	12	13	14
R1H006	Rabularivier	1948	1965	100	0.196	3.67	0.072	0.051	0.034	0.021	0.013	0.0	0.292
R1H007	Mtwakurivier	1948	1965	33	0.064	0.0	0.033	0.027	0.020	0.013	0.010	0.006	0.394
R1H014	Tyumerivier	1957	1991	70	0.632	0.0	0.304	0.244	0.171	0.105	0.075	0.029	0.345
R1H015	Keiskammarivier	1969	1981	2 350	4.348	3.8	1.345	0.97	0.474	0.067	0.005	0.0	0.05
R2H001	Buffedrivier	1947	1991	29	0.251	0.0	0.087	0.059	0.036	0.017	0.010	0.005	0.195
R2H005	Buffelsrivier	1947	1992	411	1.237	8.2	0.334	0.248	0.114	0.010	0.0	0.0	0.030
R2H006	Mgqakweberivier	1957	1991	119	0.282	40.1	0.086	0.064	0.040	0.022	0.011	0.0	0.256
R2H008	Quencwerivier	1947	1991	61	0.222	21.5	0.022	0.011	0.004	0.0	0.0	0.0	
R2H012	Mgqakweberivier	1961	1991	15	0.133	1.2	0.038	0.029	0.017	0.010	0.006	0.0	0.263
S3H002	Klaas Smitrivier	1977	1992	796	0.211	63.6	0.0	0.0	0.0	0.0	0.0	0.0	
S3H004	Swart-Keirivier	1964	1991	1413	0.520	27.8	0.009	0.004	0.0	0.0	0.0	0.0	
S3H006	Klaas Smitrivier	1964	1991	2 170	0.781	39.2	0.011	0.002	0.0	0.0	0.0	0.0	
S6H002	Kubusrivier	1947	1969	49	1.275	8.8	0.322	0.213	0.077	0.009	0.0	0.0	0.028
S6H003	Toiserivier	1964	1986	215	0.45	6.61	0.117	0.083	0.048	0.012	0.0	0.0	0.1026
T1H004	Basheerivier	1956	1973	4 908	16.6	1.87	5.117	3.386	1.961	1.519	1.073	0.0	0.293
T2H002	Mtatarivier	1957	1983	1 199	8.12	0.0	3.140	2.087	1.246	0.683	0.487	0.059	0.327
T3H002	Kiwirarivier	1949	1980	2 101	7.91	3.09	2.185	1.440	0.884	0.517	0.277	0.0	0.237
T3H004	Mzintlavarivier	1947	1991	1 029	2.636	1.09	1.227	0.915	0.576	0.311	0.180	0.0	0.253
T3H005	Tinarivier	1951	1975	2 597	14.7	1.62	5.806	4.199	2.438	1.276	0.911	0.0	0.220
T3H008	Mzimvuburivier	1962	1990	2 471	6.953	1.73	1.884	1.136	0.765	0.332	0.144	0.0	0.176
T3H009	Moorivier	1964	1991	307	3.633	0.0	0.755	0.495	0.269	0.128	0.094	0.049	0.170
T4H001	Mtamvunarivier	1951	1992	715	4.974	0.0	2.814	2.205	1.585	1.065	0.875	0.523	0.378
T5H002	Bisirivier	1934	1959	867	5.035	0.0	3.238	2.63	2.058	1.455	1.158	0.912	0.449
T5H003	Polelarivier	1949	1993	140	1.873	0.0	0.643	0.424	0.243	0.114	0.068	0.010	0.177
R5H004	Mzimkulurivier	1949	1993	545	7.45	0.0	2.414	1.727	1.054	0.594	0.448	0.182	0.246
T5H005	Nkonzorivier	1966	1992	100	0.68	0.0	0.351	0.260	0.177	0.097	0.059	0.012	0.276

Station Code	River	Start Year	End Year	Catchment area (km^2)	ADF, m^3/s	T_o, %	Q50, m^3/s	Q60, m^3/s	Q75, m^3/s	Q90, m^3/s	Q95, m^3/s	Q99, m^3/s	Q90/Q50
1	2	3	4	5	6	7	8	9	10	11	12	13	14
T6H001	Mntafufurivier	1969	1979	108	0.657	2.0	0.458	0.346	0.214	0.132	0.077	0.0	0.296
U1H005	Mkomazirivier	1963	1993	1 744	20.2	0.0	6.781	4.938	3.195	1.797	1.176	0.284	0.265
U1H006	Mkomazirivier	1962	1992	4 349	29.7	0.0	12.27	8.854	5.623	3.638	2.848	1.410	0.296
U2H001	Mgenirivier	1948	1992	937	5.126	0.0	2.536	1.954	1.505	1.085	0.906	0.191	0.428
U2H006	Karkloofrivier	1954	1991	2.94	0.0	1.212	0.903	0.604	0.363	0.265	0.135	0.300	
U2H007	Lionsrivier	1954	1992	2.48	0.0	1.222	0.984	0.714	0.468	0.346	0.097	0.383	
U2H011	Msunderivier	1957	1992	176	1.417	1.18	0.627	0.492	0.319	0.179	0.138	0.0	0.285
U2H012	Sterkrivier	1960	1992	438	1.776	0.0	0.709	0.494	0.295	0.122	0.075	0.005	0.172
U2H013	Mgenirivier	1960	1992	299	2.397	0.0	1.022	0.763	0.526	0.323	0.220	0.088	0.316
U3H002	Mdlotirivier	1950	1976	356	1.819	0.0	1.097	0.906	0.671	0.495	0.417	0.256	0.451
U4H002	Mvotirivier	1949	1992	316	1.087	1.4	0.555	0.420	0.276	0.137	0.084	0.0	0.247
U4H003	Hlimibitwarivier	1956	1974	49	0.088	6.69	0.029	0.022	0.011	0.004	0.0	0.0	0.138
U6H002	Mlazirivier	1981	1991	105	0.474	0.0	0.317	0.261	0.159	0.102	0.079	0.047	0.322
U7H001	Zwatenirivier	1962	1991	16	0.076	1.17	0.044	0.036	0.025	0.015	0.011	0.0	0.341
U7H007	Lovurivier	1965	1991	114	0.514	0.0	0.249	0.185	0.120	0.055	0.026	0.010	0.221
V1H001	Tugelarivier	1951	1971	4 176	32.6	0.0	10.44	6.825	4.71	2.63	1.83	0.941	0.252
V1H002	Tugelarivier	1931	1970	1689	9.583	0.0	8.751	5.849	3.168	1.744	1.279	0.829	0.199
V1H009	Bloukransrivier	1954	1992	196	0.586	20.2	0.050	0.029	0.007	0.0	0.0	0.0	
V1H010	Klein-Tugelarivier	1964	1992	782	10.10	14.9	4.310	2.690	0.690	0.0	0.0	0.0	
V1H029	Geluksburgspruit	1968	1992	21	0.129	23.7	0.012	0.007	0.002	0.0	0.0	0.0	
V1H031	Sandspruit	1972	1992	162	0.470	14.1	0.031	0.015	0.005	0.0	0.0	0.0	
V1H034	Khomberivier	1974	1992	51	0.932	30.6	0.247	0.162	0.0	0.0	0.0	0.0	
V1H041	Mlambonjarivier	1976	1992	434	5.91	0.0	2.837	1.966	1.192	0.701	0.549	0.345	0.247
V2H001	Mooirivier	1947	1976	1976	18.67	0.0	6.229	4.286	2.437	0.943	0.618	0.113	0.151
V2H005	Mooirivier	1972	1992	260	3.44	0.0	1.347	0.974	0.639	0.405	0.300	0.178	0.301
V2H006	Klein-Mooirivier	1972	1992	188	1.814	0.0	0.502	0.343	0.200	0.099	0.061	0.026	0.197

Station Code	River	Start Year	End Year	Catchment area (km^2)	ADF, m^3/s	T_0, %	Q50, m^3/s	Q60, m^3/s	Q75, m^3/s	Q90, m^3/s	Q95, m^3/s	Q99, m^3/s	Q90/Q50
1	2	3	4	5	6	7	8	9	10	11	12	13	14
V2H007	Hlatikulurivier	1972	1992	109	0.951	0.0	0.317	0.226	0.155	0.101	0.076	0.040	0.319
V3H002	Buffelsrivier	1933	1990	1 518	5.206	1.41	1.964	1.234	0.617	0.222	0.100	0.0	0.113
V3H003	Ngaganerivier	1929	1961	850	3.625	0.0	1.060	0.660	0.350	0.132	0.064	0.009	0.125
V3H005	Slangrivier	1947	1986	676	3.301	1.6	0.511	0.335	0.198	0.091	0.045	0.0	0.178
V3H007	Ncandurivier	1948	1992	129	1.175	1.94	0.289	0.184	0.090	0.029	0.011	0.0	0.100
V3H009	Hornrivier	1961	1992	148	0.606	2.86	0.094	0.057	0.024	0.006	0.004	0.0	0.064
V5H002	Tugelarivier	1959	1970	28 920	95.79	0.0	32.9	21.8	10.9	5.97	4.101	2.153	0.181
V6H003	Wasbankrivier	1954	1992	312	1.137	5.54	0.275	0.196	0.125	0.059	0.0	0.0	0.215
V6H004	Sondagsrivier	1954	1992	658	2.952	5.06	0.593	0.402	0.212	0.065	0.0	0.0	0.110
V7H018	Kleinboesmansrivier	1972	1992	119	0.61	0.0	0.165	0.116	0.071	0.038	0.026	0.009	0.230
W1H004	Mlalazirivier	1948	1977	20	0.124	6.6	0.053	0.037	0.016	0.005	0.0	0.0	0.094
W1H006	Mhlatuzerivier	1964	1973	1 272	4.876	26.6	2.240	1.106	0.0	0.0	0.0	0.0	
W1H010	Matigulurivier	1965	1992	455	1.676	1.72	0.617	0.461	0.274	0.076	0.034	0.0	0.123
W1H018	Manzamnyrivier	1981	1990	10	0.065	1.15	0.034	0.026	0.014	0.008	0.005	0.0	0.235
W1H019	Siyayarivier	1983	1990	9	0.055	0.0	0.020	0.015	0.010	0.006	0.004	0.002	0.300
W1H025	Mlalazisystroom	1959	1991	20	0.016	16.0	0.005	0.004	0.002	0.0	0.0	0.0	
W2H002	Swart-Mofolozirivier	1947	1964	3 468	9.467	2.57	3.678	2.360	1.176	0.435	0.222	0.0	0.118
W2H006	Swart-Mfolozirivier	1965	1992	1 648	5,794	1.68	2.490	1.821	1.124	0.473	0.282	0.0	0.190
W2H009	Wit-Mfolozirivier	1971	1982	432	1.709	0.0	0.498	0.345	0.218	0.123	0.101	0.044	0.246
W3H011	Mkuzerivier	1970	1991	5 027	4.132	11.6	1.272	0.846	0.451	0.0	0.0	0.0	
W3H014	Mpaterivier	1969	1991	48	0.120	15.7	0.026	0.016	0.006	0.0	0.0	0.0	
W4H004	Bivanerivier	1950	1992	948	5.219	0.0	2.460	1.739	1.020	0.526	0.362	0.117	0.214
W4H008	Brakaloot	1972	1983	3.5	0.021	10.1	0.015	0.011	0.007	0.0	0.0	0.0	
W5H001	Jessievalespruit	1910	1991	15	0.032	24.4	0.009	0.005	0.002	0.0	0.0	0.0	
W5H006	Swartwaterrivier	1950	1992	180	1.092	0.0	0.475	0.291	0.144	0.062	0.043	0.009	0.131
W5H007	Usuturivier	1950	1992	531	1.80	1.06	0.363	0.188	0.083	0.030	0.017	0.0	0.083

Station Code	River	Start Year	End Year	Catchment area (km^2)	ADF, m^3/s	T_0, %	Q50, m^3/s	Q60, m^3/s	Q75, m^3/s	Q90, m^3/s	Q95, m^3/s	Q99, m^3/s	Q90/Q50
1	2	3	4	5	6	7	8	9	10	11	12	13	14
W5H008	Bonnie Brook	1951	1993	118	0.313	1.60	0.137	0.102	0.070	0.034	0.016	0.0	0.248
W5H011	Mpuluzirivier	1963	1992	910	1.216	0.0	0.349	0.251	0.158	0.086	0.054	0.006	0.246
X1H003	Komatirivier	1939	1970	8 614	28.72	0.0	17.52	14.66	11.29	6.765	4.368	1.514	0.386
X1H014	Mlumatirivier	1968	1992	1 119	5.236	0.0	2.006	1.447	0.787	0.301	0.159	0.050	0.150
X2H002	Witrivier	1927	1941	176	0.404	18.5	0.292	0.194	0.056	0.0	0.0	0.0	
X2H005	Nelsrivier	1930	1968	642	3.342	0.0	2.463	1.957	1.192	0.375	0.071	0.031	0.152
X2H008	Queensrivier	1948	1992	180	0.670	0.0	0.314	0.223	0.116	0.047	0.032	0.012	0.150
X2H010	Noordkaaprivier	1948	1992	136	1.011	0.0	0.625	0.501	0.362	0.237	0.182	0.086	0.3792
X2H011	Elandsrivier	1956	1993	402	1.667	0.0	0.872	0.697	0.540	0.268	0.149	0.049	0.307
X2H012	Dawsoni'sspruit	1956	1992	91	0.339	0.0	0.147	0.123	0.093	0.072	0.058	0.035	0.490
X2H013	Krokodilrivier	1959	1992	1 518	5.66	0.0	3.447	2.700	1.829	1.076	0.758	0.403	0.312
X2H014	Houtbosloop	1958	1992	250	1.704	0.0	1.188	0.997	0.781	0.554	0.419	0.303	0.466
X2H015	Elandsrivier	1959	1992	1 554	6.755	0.0	4.413	3.499	2.570	1.606	1.117	0.706	0.364
X2H024	Suidkaaprivier	1964	1993	80	0.557	0.0	0.409	0.340	0.260	0.169	0.132	0.100	0.413
X2H025	Houtbosloop	1966	1992	25	0.322	0.0	0.197	0.169	0.129	0.094	0.081	0.058	0.477
X2H026	Beestekraalspruit	1966	1992	14	0.143	0.0	0.081	0.068	0.052	0.036	0.028	0.013	0.444
X2H027	Blystaanspruit	1966	1992	78	0.732	0.0	0.407	0.336	0.257	0.184	0.152	0.103	0.452
X2H028	Kantoorbosspruit	1966	1992	5.7	0.037	0.0	0.024	0.019	0.015	0.010	0.008	0.005	0.417
X2H030	Suidkaaprivier	1966	1992	57	0.508	0.0	0.395	0.339	0.268	0.186	0.153	0.095	0.471
X2H031	Suidkaaprivier	1966	1992	262	0.919	0.0	0.532	0.414	0.283	0.131	0.081	0.027	0.246
X3H001	Sabierivier	1948	1992	174	1.551	1.50	1.054	0.880	0.602	0.154	0.049	0.0	0.146
X3H002	Klein-Sabierivier	1963	1992	55	0.331	1.24	0.252	0.220	0.176	0.129	0.109	0.0	0.512
XH003	MacMacrivier	1948	1992	52	0.93	0.0	0.607	0.554	0.480	0.396	0.356	0.299	0.652
X3H004	Nordsandrivier	1948	1970	200	1.068	0.0	0.413	0.284	0.162	0.075	0.048	0.01	0.182
X3H006	Sabierivier	1958	1992	766	6.259	0.0	4.13	3.53	2.66	1.93	1.574	1.056	0.467
X3H007	White Watersrivier	1963	1991	46	0.275	1.44	0.136	0.098	0.054	0.021	0.008	0.154	0.039

Station Code	River	Start Year	End Year	Catchment area (km^2)	ADF, m^3/s	T_0, %	Q50, m^3/s	Q60, m^3/s	Q75, m^3/s	Q90, m^3/s	Q95, m^3/s	Q99, m^3/s	Q90/Q50
1	2	3	4	5	6	7	8	9	10	11	12	13	14
X3H008	Sandrivier	1967	1992	1 064	1.973	6.35	0.705	0.493	0.252	0.046	0.0	0.0	0.065

APPENDIX A3

Low-Flow frequency indices

The indices listed are Average Daily Flow (ADF), mean annual 1, 10 and 30 day average minimum (MAM1, MAM10, MAM30), 1, 10 and 30-day average minimum flow with a return period of 2 years ($1Q_2$, $10Q_2$ and $30Q_2$) and 1, 10 and 30-day average minimum flow with a return period of 10 years ($1Q_{10}$, $10Q_{10}$ and $30Q_{10}$).

Similar indices have been estimated for durations of 7 and 60 days. In addition, flows with return periods of 5, 25 and 50 years have been estimated. These indices are not listed in the APPENDIX but are available on request from IWR. (It should be noted however, that in most cases, flows with large return periods are equal to zero).

The start date of the analysis in each case was coincident with the first day of the wettest month of the year to ensure that the low-flow season is not split between two consecutive years. The period of record used is normally the same as that in the APPENDIX A2. The number of OK years listed in column 3 are the number of years that do not have more than 20 days of missing data. If the number of OK years are less than 10, no frequency analysis was performed (these cases are marked as ***).

All flows are given in m^3/s.

Station Code	Rivers	No. of OK years	Catchment area, km^2	ADF	MAM1	$1Q_2$	$1Q_{10}$	MAM10	$10Q_2$	$10Q_{10}$	MAM30	$30Q_2$	$30Q_{10}$
1	2	3	4	5	6	7	8	9	10	11	12	13	14
A2H029	Edenvalespruit	28	129	0.095	0.001	0.000	0.000	0.002	0.000	0.000	0.003	0.000	0.000
A2H032	Selonsrivier	22	522	0.162	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
A2H039	Waterkloof-Bo	17	3.6	0.028	0.003	0.003	0.000	0.004	0.004	0.001	0.005	0.005	0.002
A2H050	Krokodilrivier	17	148	0.272	0.035	0.034	0.005	0.052	0.055	0.031	0.073	0.068	0.051
A2H053	Sterkstroom	9	88	0.308	***								
A3H001	Klein-Maricorivier	30	1165	0.171	0.003	0.000	0.000	0.004	0.000	0.000	0.007	0.000	0.000
A4H002	Mokolorivier	39	1777	1.668	0.128	0.040	0.000	0.158	0.085	0.000	0.242	0.117	0.000
A4H008	Sterkstroom	25	504	1.789	0.060	0.000	0.000	0.084	0.026	0.000	0.129	0.046	0.000
A5H004	Palalarivier	33	629	2.317	0.141	0.052	0.000	0.161	0.067	0.000	0.219	0.133	0.000
A6H011	Groot-Nylrivier	24	73	0.073	0.002	0.001	0.000	0.002	0.001	0.000	0.003	0.001	0.000
A6H012	Olifantspruit	23	120	0.208	0.003	0.002	0.000	0.004	0.003	0.000	0.006	0.003	0.000
A6H018	Rasloopivier	16	12	0.035	0.007	0.008	0.000	0.009	0.009	0.005	0.011	0.010	0.007
A6H019	Heanie se water	19	16	0.044	0.008	0.006	0.000	0.011	0.008	0.000	0.014	0.012	0.002
A6H020	Middelfonteinspruit	18	43	0.079	0.004	0.001	0.000	0.005	0.001	0.000	0.006	0.002	0.000
A6H021	De Wetspruit	17	16	0.038	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
A6H022	Hartbeeslaagte	16	1.7	0.011	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
A9H001	Luvuvhurivier	19	915	3.316	0.957	0.617	0.487	1.007	0.672	0.460	1.113	0.846	0.470
A9H002	Mutshindudirivier	41	96	1.099	0.286	0.254	0.057	0.312	0.301	0.076	0.351	0.327	0.093
A9H004	Mutalerivier	44	320	2.892	0.524	0.447	0.037	0.570	0.567	0.067	0.657	0.650	0.137
B1H001	Olifantsrivier	42	3904	4.237	0.054	0.000	0.000	0.081	0.005	0.000	0.151	0.051	0.000
B1H002	Spookspruit	27	252	0.192	0.007	0.007	0.001	0.010	0.010	0.002	0.016	0.014	0.004
B2H001	Bronkhorstspruit	33	1594	1.091	0.038	0.019	0.000	0.061	0.038	0.002	0.098	0.075	0.004
B3H001	Olifantsrivier	12	16553	4.851	0.397	0.036	0.000	0.493	0.050	0.000	0.821	0.121	0.000
B4H005	Watervalsrivier	22	188	0.714	0.123	0.106	0.044	0.167	0.173	0.080	0.204	0.199	0.097

Station Code	Rivers	No. of OK years	Catchment area, km^2	ADF	MAM1	$1Q_2$	$1Q_{10}$	MAM10	$10Q_2$	$10Q_{10}$	MAM30	$30Q_2$	$30Q_{10}$
1	2	3	4	5	6	7	8	9	10	11	12	13	14
B4H009	Dwarsrivier	13	448	0.610	0.046	0.031	0.015	0.054	0.040	0.016	0.068	0.050	0.018
B5H002	Olifantsrivier	25	31416	24.053	1.554	0.590	0.019	1.649	0.788	0.019	2.031	1.088	0.087
B6H001	Blyderivier	39	518	5.366	1.964	1.798	1.190	2.038	1.873	1.244	2.146	1.951	1.322
B6H002	Treurrivier	24	97	2.175	0.183	0.179	0.109	0.189	0.180	0.112	0.204	0.192	0.124
B6H003	Treurrivier	28	92	1.424	0.250	0.244	0.185	0.269	0.260	0.192	0.299	0.285	0.216
B7H003	Selatirivier	8	84	0.206	***								
B7H004	Klaserierivier	34	136	1.003	0.072	0.042	0.006	0.095	0.060	0.014	0.129	0.093	0.028
B7H008	Selatirivier	29	832	1.314	0.000	0.000	0.000	0.000	0.000	0.000	0.002	0.000	0.000
B7H009	Olifantsrivier	17	42472	23.827	1.321	0.706	0.096	1.539	0.900	0.231	2.076	1.009	0.436
B7H010	Ngwabitsrivier	16	318	0.537	0.008	0.000	0.000	0.009	0.000	0.000	0.018	0.000	0.000
B7H014	Selatirivier	12	83	0.248	0.004	0.000	0.000	0.004	0.000	0.000	0.006	0.001	0.000
B9H001	Shisharivier	19	648	0.146	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
C1H008	Watervalrivier	11	2212	5.190	1.161	0.000	0.000	1.249	0.000	0.000	1.608	0.000	0.000
C2H026	Middelvleispruit	18	26	0.013	0.000	0.000	0.000	0.001	0.000	0.000	0.003	0.000	0.000
C2H027	Kockscortdspruit	23	4	0.019	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
C2H028	Rietfonteinspruit	23	31	0.029	0.000	0.000	0.000	0.001	0.000	0.000	0.005	0.000	0.000
C2H065	Leeudoringspruit	21	860	0.210	0.000	0.000	0.000	0.001	0.000	0.000	0.001	0.000	0.000
C2H067	Sandspruit	18	1895	0.083	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
C3H003	Hartsrivier	57	10990	1.367	0.008	0.000	0.000	0.016	0.000	0.000	0.025	0.000	0.000
C4H002	Vetrivier	9	17599	8.390	***								
C5H007	Renosterspruit	55	348	0.181	0.000	0.000	0.000	0.000	0.000	0.000	0.001	0.000	0.000
C5H008	Rietrivier	38	593	0.381	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
C5H012	Rietrivier	28	2372	1.025	0.003	0.000	0.000	0.003	0.000	0.000	0.006	0.000	0.000
C6H003	Valsrivier	21	7765	5.764	0.000	0.000	0.000	0.001	0.000	0.000	0.001	0.000	0.000

Station Code	Rivers	No. of OK years	Catchment area, km^2	ADF	MAM1	$1Q_2$	$1Q_{10}$	MAM10	$10Q_2$	$10Q_{10}$	MAM30	$30Q_2$	$30Q_{10}$
1	2	3	4	5	6	7	8	9	10	11	12	13	14
C6H004	Valsrivier	12	856	0.354	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
C7H003	Heuningspruit	41	914	0.483	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
C8H003	Corneliusrivier	20	806	1.399	0.118	0.000	0.000	0.018	0.001	0.000	0.038	0.008	0.000
C8H005	Elandsrivier	12	696	3.091	0.037	0.016	0.000	0.056	0.038	0.000	0.086	0.055	0.004
C8H012	Vaalbankspruit	16	386	0.312	0.003	0.000	0.000	0.004	0.000	0.000	0.006	0.003	0.000
C8H022	Wilgerivier	10	15466	12.843	0.208	0.031	0.000	0.222	0.054	0.000	0.372	0.225	0.000
D1H011	Kraairivier	18	8688	19.520	0.643	0.092	0.000	0.835	0.297	0.006	1.303	0.567	0.050
D2H012	Klein-Caledonrivier	13	518	0.839	0.022	0.000	0.000	0.033	0.014	0.000	0.067	0.032	0.000
D2H020	Caledonrivier	7	8339	7.780	***								
D4H003	Swartbasrivier	5	181	0.006	***								
D5H003	Visrivier	62	1509	0.442	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
D5H013	Sakrivier	12	13087	0.991	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
E1H006	Jan Disselsrivier	14	160	1.250	0.073	0.072	0.001	0.087	0.088	0.025	0.103	0.100	0.047
E2H002	Doringrivier	54	6903	9.461	0.096	0.084	0.009	0.112	0.094	0.016	0.142	0.114	0.037
E2H007	Leeurivier	12	265	2.072	0.001	0.002	0.000	0.003	0.002	0.000	0.004	0.003	0.000
G1H002	Vier en twintig	3	187	3188	***								
G1H003	Franschhoekrivier	26	46	0.741	0.006	0.000	0.000	0.008	0.000	0.000	0.015	0.000	0.000
G1H007	Bergrivier	14	713	13.701	0.252	0.160	0.160	0.292	0.160	0.160	0.437	0.350	0.160
G1H008	Klein-Bergrivier	31	395	2.130	0.024	0.013	0.000	0.040	0.031	0.002	0.059	0.049	0.007
G1H009	Brakkloofspruit	17	5.7	0.012	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
G1H010	Knolvleispruit	24	10	0.014	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
G1H011	Watervalsrivier	24	27	0.434	0.004	0.001	0.000	0.005	0.002	0.000	0.007	0.003	0.000
G1H012	Watervalsrivier	20	36	0.437	0.002	0.000	0.000	0.002	0.000	0.000	0.005	0.001	0.000
G1H014	Zachariashoekrivier	25	2.8	0.039	0.004	0.004	0.004	0.004	0.004	0.004	0.005	0.004	0.004

Station Code	Rivers	No. of OK years	Catchment area, km^2	ADF	MAM1	$1Q_2$	$1Q_{10}$	MAM10	$10Q_2$	$10Q_{10}$	MAM30	$30Q_2$	$30Q_{10}$
1	2	3	4	5	6	7	8	9	10	11	12	13	14
G1H015	Kasteelkloofspruit	24	1.9	0.049	0.003	0.003	0.002	0.003	0.003	0.002	0.003	0.003	0.002
G1H016	Kasteelkloofspruit	21	3.3	0.090	0.008	0.008	0.007	0.009	0.008	0.007	0.009	0.009	0.007
G1H017	Zachariashoekspruit	23	1.7	0.021	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001
G1H018	Bakkerskloofspruit	24	3.4	0.073	0.002	0.002	0.001	0.002	0.002	0.001	0.003	0.002	0.001
G1H019	Banghoekrivier	16	25	0.105	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
G1H021	Klein-Bergrivier	13	19	0.486	0.061	0.056	0.026	0.078	0.070	0.041	0.096	0.089	0.065
G1H028	Vier-en-twintig	14	183	1.718	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
G2H008	Jonkershoekrivier	34	20	0.727	0.003	0.000	0.000	0.006	0.000	0.000	0.011	0.001	0.000
G2H012	Dieprivier	24	244	0.353	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
G3H001	Kruisrivier	19	647	0.389	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
G4H006	Kleinrivier	26	600	0.917	0.003	0.003	0.000	0.003	0.003	0.000	0.003	0.003	0.000
G4H008	Klein-Jakkalsrivier	24	1.5	0.023	0.001	0.001	0.000	0.002	0.001	0.000	0.002	0.001	0.000
G4H009	Jakkalsrivier	27	2	0.012	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
G4H013	Klein-Jakkalsrivier	26	2.1	0.028	0.000	0.000	0.000	0.000	0.000	0.000	0.001	0.000	0.000
G4H014	Botrivier	24	252	0.633	0.003	0.001	0.000	0.010	0.008	0.001	0.021	0.012	0.003
G5H006	Klein-Sandrifrivier	18	3.2	0.027	0.006	0.007	0.000	0.010	0.010	0.007	0.012	0.011	0.008
G5H008	Soutrivier	27	382	0.157	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
H1H007	Witrivier	33	84	3.770	0.103	0.110	0.033	0.119	0.118	0.059	0.147	0.134	0.085
H1H012	Holslootrivier	12	146	2.214	0.128	0.121	0.075	0.143	0.129	0.085	0.157	0.145	0.092
H1H013	Koekedourivier	19	53	0.719	0.023	0.023	0.005	0.031	0.032	0.020	0.040	0.039	0.024
H1H017	Elandsrivier	2	61	2.600	***								
H1H018	Molenaarsrivier	9	113	4.210	***								
H2H001	Hexrivier	21	697	2.994	0.353	0.338	0.066	0.378	0.370	0.078	0.414	0.437	0.090
H2H005	Rooi-Elskloofrivier	22	15	0.208	0.041	0.040	0.025	0.044	0.043	0.026	0.047	0.047	0.026

Station Code	Rivers	No. of OK years	Catchment area, km^2	ADF	MAM1	$1Q_2$	$1Q_{10}$	MAM10	$10Q_2$	$10Q_{10}$	MAM30	$30Q_2$	$30Q_{10}$
1	2	3	4	5	6	7	8	9	10	11	12	13	14
H3H001	Kingnarivier	15	593	0.344	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
H3H004	Keisierivier	19	14	0.022	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
H3H005	Keisierivier	22	76	0.017	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
H4H005	Willem Nelsrivier	29	24	0.185	0.019	0.019	0.005	0.027	0.025	0.012	0.033	0.030	0.016
H4H009	Hoeksrivier	18	18	0.040	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
H4H012	Waterkloofspruit	20	14	0.227	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
H6H003	Riviersonderend	25	497	6.315	0.012	0.011	0.000	0.017	0.013	0.000	0.028	0.015	0.000
H6H006	Elandsrivier	9	56	0.364	***								
H6H008	Riviersonderend	24	38	1.891	0.105	0.106	0.083	0.126	0.120	0.091	0.171	0.144	0.102
H6H010	Waterkloofrivier	16	15	0.068	0.021	0.026	0.009	0.024	0.027	0.010	0.027	0.031	0.010
H7H001	Breerivier	9	9829	***									
H7H003	*Buffeljagsrivier*	*23*	*450*	*1.805*	*0.043*	*0.015*	*0.000*	*0.050*	*0.021*	0.000	*0.102*	0.045	0.015
H7H007	Grootkloofrivier	16	24	0.310	0.056	0.053	0.034	0.065	0.058	0.038	0.089	0.080	0.046
H9H004	Kruisrivier	20	50	0.413	0.064	0.062	0.046	0.072	0.070	0.055	0.089	0.079	0.061
H9H005	Kafferkuilsrivier	16	228	1.530	0.003	0.000	0.000	0.005	0.000	0.000	0.016	0.005	0.000
J1H015	Bokrivier	14	8.8	0.105	0.020	0.019	0.019	0.022	0.019	0.019	0.023	0.019	0.019
J1H016	Smalblaarrivier	16	30	0.089	0.001	0.000	0.000	0.001	0.000	0.000	0.002	0.000	0.000
J2H005	Huisrivier	30	253	0.222	0.003	0.000	0.000	0.005	0.003	0.000	0.006	0.004	0.000
J2H006	Boplaasrivier	27	225	0.024	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
J2H007	Joubertrivier	27	25	0.032	0.000	0.000	0.000	0.001	0.000	0.000	0.001	0.000	0.000
J3H012	Grootrivier	23	688	0.341	0.004	0.000	0.000	0.004	0.000	0.000	0.007	0.003	0.000
J3H013	Perdepoortrivier	17	29	0.260	0.070	0.063	0.046	0.092	0.088	0.070	0.103	0.095	0.080
J3H016	Wilgerivier	15	32	0.029	0.001	0.000	0.000	0.001	0.001	0.000	0.003	0.003	0.000
J3H017	Kandelaarsrivier	18	348	0.118	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000

Station Code	Rivers	No. of OK years	Catchment area, km^2	ADF	MAM1	$1Q_2$	$1Q_{10}$	MAM10	$10Q_2$	$10Q_{10}$	MAM30	$30Q_2$	$30Q_{10}$
1	2	3	4	5	6	7	8	9	10	11	12	13	14
J3H018	Wynandsrivier	14	137	0.234	0.004	0.000	0.000	0.008	0.001	0.000	0.017	0.014	0.000
J3H020	Meulrivier	14	35	0.055	0.000	0.000	0.000	0.000	0.000	0.000	0.001	0.000	0.000
J4H003	Weyersrivier	9	9.5	0.583	***								
J4H004	Langtourivier	22	99	0.592	0.005	0.000	0.000	0.010	0.000	0.000	0.026	0.000	0.000
K1H001	Hartenbosrivier	23	144	0.143	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
K1H002	Benekerivier	10	3.8	0.042	0.009	0.010	0.003	0.012	0.013	0.007	0.014	0.014	0.009
K3H001	Kaaimansrivier	17	47	0.466	0.051	0.055	0.027	0.061	0.065	0.033	0.079	0.071	0.041
K3H002	Rooirivier	8	1.04	0.013	***								
K3H003	Maalgaterivier	20	145	0.814	0.011	0.000	0.000	0.020	0.004	0.000	0.053	0.014	0.000
K3H004	Malgasrivier	28	34	0.542	0.027	0.026	0.010	0.040	0.033	0.018	0.063	0.042	0.026
K3H005	Touwsrivier	22	78	0.384	0.037	0.036	0.016	0.045	0.040	0.028	0.055	0.049	0.032
K4H001	Hoekraalrivier	9	111	0.430	***								
K4H002	Karatararivier	21	22	0.300	0.019	0.019	0.008	0.023	0.024	0.011	0.030	0.030	0.015
K4H003	Dieprivier	24	72	0.288	0.037	0.032	0.013	0.043	0.039	0.018	0.052	0.049	0.020
K5H002	Knysnarivier	25	133	0.836	0.130	0.131	0.074	0.161	0.163	0.103	0.201	0.200	0.130
K6H001	Keurboomsrivier	28	165	0.310	0.006	0.000	0.000	0.009	0.006	0.000	0.014	0.008	0.000
K6H002	Keurboomsrivier	8	764	2.405	***								
K7H001	Bloukransrivier	16	57	0.901	0.106	0.116	0.009	0.133	0.132	0.077	0.166	0.165	0.088
L1H001	Soutrivier	13	39338	0.465	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
L6H001	Heuningkliprivier	36	1290	0.545	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
L8H001	Harlemspruit	17	52	0.378	0.005	0.004	0.000	0.008	0.006	0.002	0.017	0.011	0.004
L8H002	Waboomsrivier	22	21	0.355	0.039	0.033	0.013	0.049	0.041	0.017	0.071	0.053	0.025
N2H009	Volkersrivier	5	536	2.420	***								
P4H001	Kowierivier	19	576	0.775	0.000	0.000	0.000	0.001	0.000	0.000	0.003	0.000	0.000

Station Code	Rivers	No. of OK years	Catchment area, km^2	ADF	MAM1	$1Q_2$	$1Q_{10}$	MAM10	$10Q_2$	$10Q_{10}$	MAM30	$30Q_2$	$30Q_{10}$
1	2	3	4	5	6	7	8	9	10	11	12	13	14
Q1H001	Groot-Visrivier	69	9091	3.286	0.004	0.000	0.000	0.024	0.000	0.000	0.358	0.000	0.000
Q1H009	Klein-Brakrivier	5	1211	0.034	***	0							
Q3H004	Paulsrivier	13	872	0.230	0.039	0.037	0.000	0.050	0.066	0.000	0.065	0.075	0.000
Q4H003	Vlekpoortrivier	14	1300	0.098	0.000	0.000	0.000	0.000	0.000	0.000	0.003	0.000	0.000
Q6H003	Baviaansrivier	12	814	0.241	0.001	0.000	0.000	0.002	0.000	0.000	0.003	0.001	0.000
Q9H002	Koonaprivier	50	1245	1.288	0.000	0.000	0.000	0.001	0.000	0.000	0.002	0.000	0.000
Q9H013	Kaprivier	9											
Q9H016	Koonaprivier	10	489	0.508	0.000	0.000	0.000	0.000	0.000	0.000	0.001	0.001	0.000
Q9H017	Blinkwaterrivier	27	226	0.178	0.004	0.000	0.000	0.005	0.000	0.000	0.007	0.001	0.000
Q9H019	Balfourrivier	20	76	0.320	0.008	0.007	0.000	0.012	0.010	0.001	0.020	0.016	0.005
R1H001	Tyumerivier	38	238	0.740	0.006	0.000	0.000	0.014	0.000	0.000	0.025	0.000	0.000
R1H005	Keiskammarivier	19	482	1.498	0.093	0.078	0.013	0.148	0.106	0.031	0.205	0.138	0.057
R1H006	Rabularivier	11	100	0.200	0.013	0.012	0.000	0.017	0.017	0.001	0.022	0.023	0.007
R1H007	Mtwakurivier	15	33	0.065	0.013	0.012	0.005	0.014	0.013	0.005	0.018	0.016	0.008
R1H014	Tyumerivier	36	70	0.623	0.090	0.081	0.035	0.109	0.100	0.050	0.133	0.123	0.061
R1H015	Keiskammarivier	17	2530	3.409	0.081	0.009	0.000	0.127	0.035	0.000	0.212	0.084	0.000
R2H001	Buffelsrivier	42	29	0.252	0.016	0.013	0.004	0.019	0.016	0.005	0.026	0.022	0.006
R2H005	Buffelsrivier	22	411	1.240	0.079	0.007	0.000	0.105	0.059	0.000	0.139	0.107	0.000
R2H006	Mgqakweberivier	26	119	0.282	0.015	0.013	0.000	0.021	0.019	0.000	0.029	0.026	0.000
R2H008	Quencwerivier	41	61	0.224	0.002	0.000	0.000	0.004	0.000	0.000	0.006	0.000	0.000
R2H012	Mgqakweberivier	25	15	0.134	0.008	0.008	0.003	0.010	0.010	0.005	0.013	0.011	0.005
S3H002	Klaas Smitsrivier	10	796	0.205	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
S3H004	Swart-Keirivier	19	1413	0.534	0.001	0.000	0.000	0.002	0.000	0.000	0.006	0.000	0.000
S3H006	Klaas Smitsrivier	21	2170	0.802	0.001	0.000	0.000	0.003	0.000	0.000	0.006	0.000	0.000

Station Code	Rivers	No. of OK years	Catchment area, km^2	ADF	MAM1	$1Q_2$	$1Q_{10}$	MAM10	$10Q_2$	$10Q_{10}$	MAM30	$30Q_2$	$30Q_{10}$
1	2	3	4	5	6	7	8	9	10	11	12	13	14
S6H002	Kubusrivier	12	49	1.412	0.044	0.017	0.000	0.055	0.020	0.000	0.073	0.041	0.000
S6H003	Toiserivier	16	215	0.455	0.015	0.007	0.000	0.025	0.017	0.000	0.037	0.026	0.000
T1H004	Bashearivier	10	4908	16.363	1.360	1.488	0.596	1.493	1.512	0.798	1.989	1.700	1.074
T2H002	Mtatarivier	19	1199	8.130	0.724	0.624	0.171	0.826	0.713	0.276	1.003	0.841	0.395
T3H002	Kiwirarivier	5	2101	7.910	***								
T3H004	Mzintlavarivier	33	1029	2.658	0.256	0.203	0.040	0.313	0.254	0.065	0.409	0.344	0.127
T3H005	Tinarivier	7	2597	14.700	***								
T3H008	Mzinvuburivier	22	2471	6.979	0.332	0.258	0.017	0.384	0.305	0.048	0.505	0.441	0.077
T3H009	Mooirivier	26	307	3.646	0.096	0.080	0.035	0.116	0.098	0.042	0.154	0.128	0.053
T4H001	Mtamvuarivier	27	715	5.010	1.029	0.940	0.615	1.116	1.031	0.691	1.252	1.170	0.783
T5H002	Bisirivier	25	867	5.044	1.445	1.378	0.817	1.550	1.500	0.871	1.714	1.643	0.963
T5H003	Polelarivier	34	140	1.894	0.082	0.078	0.001	0.110	0.104	0.026	0.140	0.136	0.040
T5H004	Mzimkulurivier	32	545	7.467	0.493	0.417	0.234	0.567	0.503	0.325	0.685	0.586	0.402
T5H005	Nkonzorivier	31	100	0.688	0.107	0.107	0.008	0.117	0.111	0.021	0.138	0.121	0.041
T6H001	Mntafufurivier	2	108	0.657	***								
U1H005	Mkomazirivier	20	1744	20.106	1.464	1.485	0.260	1.682	1.707	0.374	2.104	2.084	1.015
U1H006	Mkomazirivier	26	4349	29.485	3.103	3.144	1.607	3.365	3.459	1.719	3.866	3.996	2.220
U2H001	Mgenirivier	36	937	5.155	0.973	0.958	0.474	1.097	1.109	0.541	1.264	1.248	0.683
U2H006	Karkloofrivier	27	339	2.947	0.296	0.317	0.093	0.353	0.380	0.172	0.419	0.454	0.213
U2H007	Lionsrivier	31	358	2.494	0.403	0.437	0.159	0.470	0.480	0.200	0.554	0.571	0.296
U2H011	Msunduzerivier	5	176	1.417	***								
U2H012	Sterkrivier	20	438	1.778	0.115	0.825	0.011	0.146	0.116	0.015	0.188	0.142	0.040
U2H013	Mgenirivier	32	299	2.407	0.275	0.291	0.131	0.312	0.323	0.166	0.365	0.356	0.193
U3H002	Mdlotirivier	18	356	1.842	0.473	0.440	0.299	0.533	0.479	0.376	0.583	0.543	0.413

Station Code	Rivers	No. of OK years	Catchment area, km^2	ADF	MAM1	$1Q_2$	$1Q_{10}$	MAM10	$10Q_2$	$10Q_{10}$	MAM30	$30Q_2$	$30Q_{10}$
1	2	3	4	5	6	7	8	9	10	11	12	13	14
U4H002	Mvotirivier	36	316	1.087	0.181	0.150	0.021	0.196	0.165	0.033	0.219	0.191	0.040
U4H003	Hlimbitwarivier	10	49	0.087	0.006	0.002	0.000	0.007	0.004	0.000	0.010	0.006	0.000
U6H002	Mlazirivier	8	105	0.474	***								
U7H001	Zwatenirivier	14	16	0.077	0.016	0.014	0.006	0.018	0.016	0.007	0.020	0.017	0.009
U7H007	Lovurivier	17	114	0.517	0.066	0.052	0.010	0.076	0.062	0.014	0.091	0.076	0.017
V1H001	Tugelarivier	18	4176	33.592	1.729	1.625	0.654	1.938	1.733	0.870	2.455	2.381	1.319
V1H002	Tugelarivier	35	1689	9.846	1.555	1.227	0.636	1.764	1.322	0.755	2.129	1.660	0.969
V1H009	Bloukransrivier	36	196	0.588	0.002	0.000	0.000	0.003	0.000	0.000	0.010	0.001	0.000
V1H010	Klein-Tugelarivier	22	782	10.097	0.626	0.000	0.000	0.726	0.000	0.000	1.010	0.004	0.000
V1H029	Geluksburgspruit	10	21	0.135	0.004	0.000	0.000	0.005	0.001	0.000	0.008	0.003	0.00
V1H031	Sandspruit	16	162	0.477	0.003	0.000	0.000	0.005	0.000	0.000	0.008	0.002	0.000
V1H034	Khomberivier	6	51	0.930	***								
V1H041	Mlambonjarivier	9	434	5.900	***								
V2H001	Mooirivier	30	1976	19.032	1.633	0.939	0.035	1.997	1.187	0.122	2.688	1.927	0.240
V2H005	Mooirivier	20	260	3.479	0.312	0.328	0.126	0.359	0.377	0.167	0.428	0.427	0.219
V2H006	Klein-Mooirivier	16	188	1.842	0.071	0.067	0.014	0.085	0.074	0.020	0.110	0.092	0.035
V2H007	Hlatikulurivier	17	109	0.972	0.082	0.077	0.030	0.096	0.092	0.049	0.118	0.108	0.062
V3H002	Buffelsrivier	43	1518	5.235	0.223	0.128	0.014	0.288	0.163	0.020	0.432	0.287	0.083
V3H003	Ngaganerivier	27	850	3.589	0.122	0.044	0.009	0.146	0.067	0.013	0.217	0.150	0.022
V3H005	Slangrivier	26	676	3.385	0.095	0.090	0.001	0.110	0.102	0.007	0.133	0.131	0.027
V3H007	Ncandurivier	35	129	1.190	0.030	0.012	0.001	0.038	0.021	0.002	0.058	0.033	0.005
V3H009	Hornrivier	27	148	0.603	0.010	0.005	0.000	0.014	0.006	0.000	0.021	0.010	0.002
V5H002	Tugelarivier	7	28920	95.800	***								
V6H003	Wasbankrivier	32	312	1.141	0.050	0.000	0.000	0.078	0.063	0.000	0.114	0.091	0.001

Station Code	Rivers	No. of OK years	Catchment area, km^2	ADF	MAM1	$1Q_2$	$1Q_{10}$	MAM10	$10Q_2$	$10Q_{10}$	MAM30	$30Q_2$	$30Q_{10}$
1	2	3	4	5	6	7	8	9	10	11	12	13	14
V6H004	Sondagsrivier	28	658	2.876	0.057	0.040	0.000	0.080	0.055	0.000	0.129	0.096	0.005
V7H018	Kleinboesmansrivier	15	119	0.616	0.019	0.019	0.003	0.029	0.031	0.014	0.041	0.039	0.023
W1H004	Mlalazirivier	19	20	0.133	0.010	0.004	0.000	0.014	0.005	0.000	0.019	0.006	0.000
W1H006	Mhlatuzerivier	4	1272	4.880	***								
W1H010	Matigulurivier	12	455	1.689	0.063	0.040	0.006	0.102	0.063	0.021	0.162	0.105	0.027
W1H018	Manzamnyamarivier	3	10	0.065	***								
W1H019	Siyayarivier	4	9	0.055	***								
W1H025	Mlalazisystroom	18	20	0.016	0.002	0.001	0.000	0.003	0.002	0.000	0.004	0.002	0.000
W2H002	Swart-Mfolozirivier	8	3468	9.470	***								
W2H006	Swart-Mfolozirivier	12	1648	5.856	0.579	0.479	0.069	0.713	0.724	0.167	0.874	0.905	0.203
W2H009	Wit-Mfolozirivier	8	432	1.700	***								
W3H011	Mkuzerivier	5	5027	4.130	***								
W3H014	Mpaterivier	18	48	0.122	0.002	0.000	0.000	0.004	0.001	0.000	0.007	0.002	0.000
W4H004	Bivanerivier	25	948	5.278	0.494	0.476	0.161	0.578	0.506	0.190	0.701	0.609	0.259
W4H008	Brakaloot	9	3.5	0.020	***								
W5H001	Jessievalespruit	44	15	0.032	0.006	0.001	0.000	0.007	0.001	0.000	0.008	0.002	0.000
W5H006	Swartwaterrivier	31	180	1.100	0.085	0.057	0.016	0.095	0.067	0.021	0.119	0.086	0.027
W5H007	Usuturivier	7	531	1.800	***								
W5H008	Bonnie Brook	36	118	0.315	0.045	0.043	0.000	0.052	0.049	0.005	0.061	0.066	0.016
W5H011	Mpuluzirivier	19	910	1.215	0.095	0.092	0.013	0.107	0.110	0.025	0.134	0.134	0.044
X1H003	Komatirivier	30	8614	27.897	6.661	8.111	0.772	7.385	8.292	1.249	8.699	0.326	1.805
X1H014	Mlumatirivier	13	1119	5.305	0.401	0.175	0.030	0.574	0.467	0.063	0.732	0.693	0.105
X2H002	Witrivier	13	176	0.393	0.032	0.000	0.000	0.043	0.000	0.000	0.067	0.000	0.000
X2H005	Nelsrivier	34	642	3.389	0.810	0.680	0.023	0.917	0.811	0.039	1.100	1.014	0.059

Station Code	Rivers	No. of OK years	Catchment area, km^2	ADF	MAM1	$1Q_2$	$1Q_{10}$	MAM10	$10Q_2$	$10Q_{10}$	MAM30	$30Q_2$	$30Q_{10}$
1	2	3	4	5	6	7	8	9	10	11	12	13	14
X2H008	Queensrivier	36	180	0.671	0.076	0.460	0.000	0.094	0.057	0.009	0.121	0.074	0.016
X2H010	Noordkaaprivier	32	126	1.014	0.353	0.345	0.053	0.376	0.358	0.097	0.407	0.367	0.166
X2H011	Elandsrivier	32	402	1.675	0.298	0.238	0.094	0.354	0.295	0.122	0.431	0.381	0.174
X2H012	Dawsoni'sspruit	31	91	0.339	0.070	0.068	0.041	0.077	0.074	0.052	0.089	0.086	0.061
X2H013	Krokodilrivier	21	1518	5.700	0.968	1.002	0.371	1.195	1.114	0.437	1.462	1.308	0.549
X2H014	Houtbosloop	23	250	1.706	0.556	0.563	0.328	0.592	0.567	0.370	0.631	0.614	0.419
X2H015	Elandsrivier	20	1554	6.822	1.583	1.507	0.961	1.747	1.700	1.075	1.981	1.841	1.197
X2H024	Suidkaaprivier	26	80	0.555	0.198	0.178	0.097	0.215	0.201	0.103	0.234	0.231	0.106
X2H025	Houtbosloop	22	25	0.323	0.091	0.082	0.066	0.098	0.091	0.070	0.105	0.103	0.076
X2H026	Beestekraalspruit	20	14	0.143	0.036	0.035	0.019	0.039	0.038	0.021	0.042	0.041	0.024
X2H027	Blystaanspruit	20	78	0.732	0.166	0.183	0.102	0.181	0.195	0.116	0.196	0.207	0.126
X2H028	Kantoorbosspruit	19	5.7	0.037	0.011	0.011	0.005	1.013	0.012	0.005	0.014	0.013	0.006
X2H030	Suidkaaprivier	16	57	0.510	0.225	0.217	0.102	0.242	0.236	0.116	0.259	0.256	0.119
X2H031	Suidkaaprivier	22	262	0.915	0.173	0.159	0.000	0.217	0.202	0.028	0.256	0.244	0.048
X3H001	Sabierivier	39	174	1.572	0.456	0.569	0.000	0.507	0.589	0.012	0.551	0.626	0.027
X3H002	Klein-Sabierivier	27	55	0.331	0.130	0.116	0.001	0.164	0.150	0.090	0.180	0.176	0.100
X3H003	Mac-Macrivier	42	52	0.932	0.400	0.401	0.313	0.416	0.417	0.318	0.435	0.437	0.336
X3H004	Nordsandrivier	37	200	0.902	0.086	0.051	0.005	0.102	0.061	0.010	0.127	0.080	0.017
X3H006	Sabierivier	27	766	6.261	1.913	1.811	1.232	2.092	1.937	1.360	2.369	2.119	1.540
X3H007	White Watersrivier	19	46	0.277	0.031	0.017	0.000	0.039	0.020	0.000	0.048	0.033	0.003
X3H008	Sandrivier	8	1064	1.970	***								

APPENDIX A4

Low-flow spells (duration and deficit volumes)

The APPENDIX contains the characteristics of continuous low-flow events. Each such event (low-flow spell (run)) is characterised by its duration and deficit volume. The indices listed are durations and deficits of continuous low-flow events below referenced discharges of 80, 50 and 20% of Average Daily Flow (ADF). For each referenced discharge the following characteristics are given :

- Mean Maximum Duration (MMDT), estimated as the mean of all extracted duration maxima (one from each year of observation);
- Mean Maximum Deficit (MMDEF), estimated as the mean of all extracted deficit maxima (one from each year of record); MMDEF is expressed in Ml and % of MAR;
- Duration and deficit volume with a return period of 5 years; deficit is expressed in Ml and % MAR;
- Duration and deficit volume with a return period of 10 years; deficit is expressed in Ml and %MAR;

The start date of the analysis in each case was coincident with the first day of the wettest month of the year to ensure that the low-flow season is not split between two consecutive years. The period of record used is normally the same as that in the APPENDIX A2. The number of OK years listed in column 3 of APPENDIX A3 equally applies for the spell analysis. Therefore if the number of OK years is less than 10, no analysis was performed (these cases are marked as ***).

Station Code	Events below 80% ADF						Events below 50% ADF						Events below 20% ADF					
	MMDT days		5 year return period		10 year return period		MMDT days		5 year return period		10 year return period		MMDT days		5 year return period		10 year return period	
		MMDEF	DT days	DEF	DT days	DEF		MMDEF	DT days	DEF	DT days	DEF		MMDEF	DT days	DEF	DT days	DEF
		MI		MI		MI		MI		MI		MI		MI		MI		MI
		%MAR		%MAR		%MAR		%MAR		%MAR		%MAR		%MAR		%MAR		%MAR
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
A2H029	172	944	247	1575	273	1699	150	517	235	946	250	1024	103	142	162	254	236	385
		31.6		52.7		56.8		17.3		31.6		34.2		4.75		8.49		12.9
A2H032	199	2158	266	2917	274	3034	190	1298	252	1741	272	1891	182	499	236	650	270	751
		42.4		57.2		59.6		25.5		34.2		37.1		9.79		12.8		14.8
A2H039	171	206	221	284	240	372	142	82.0	187	109	221	184	36	7.00	45	9.00	129	28.0
		22.9		31.6		41.4		9.11		12.2		20.5		0.82		1.02		3.11
A2H050	146	1558	198	2587	222	2920	95	546	143	1134	208	1445	15	41.0	13	19.0	53	227
		18.1		30.1		34.0		6.36		13.2		16.8		0.48		0.22		2.65
A2H053	***																	
A3H001	194	2080	239	2743	254	2945	180	1192	231	1683	249	1801	155	402	225	642	230	669
		38.7		51.0		54.8		22.2		31.3		33.5		7.47		11.9		12.4
A4H002	158	13454	254	26325	284	28882	130	6729	244	14837	267	17002	95	1855	214	4629	246	5777
		25.7		50.2		55.1		12.8		28.3		32.4		3.54		8.82		11.01
A4H008	153	14421	259	27245	290	31472	156	9282	264	17992	300	20069	124	2932	230	5.55	250	6958
		25.6		48.3		55.8		16.5		31.9		35.6		5.20		9.14		12.3
A5H004	177	2184	277	40440	306	41757	166	12012	273	22976	295	23710	114	3140	211	6260	241	7691
		29.9		55.3		57.1		16.4		31.4		32.5		4.30		8.57		10.5
A6H010	197	847	298	1372	325	1603	188	490	288	821	320	964	157	149	263	294	320	357
		36.7		59.5		69.5		21.3		35.6		41.8		6.48		12.8		15.5
A6H012	179	2079	247	3248	294	3458	161	1179	241	1876	280	2347	127	359	212	679	256	842
		31.6		49.4		52.6		17.9		28.5		35.7		5.47		10.3		12.8

Station Code	Events below 80% ADF						Events below 50% ADF						Events below 20% ADF					
	MMDT days		5 year return period		10 year return period		MMDT days		5 year return period		10 year return period		MMDT days		5 year return period		10 year return period	
		MMDEF MI / %MAR	DT days	DEF MI / %MAR	DT days	DEF MI / %MAR		MMDEF MI / %MAR	DT days	DEF MI / %MAR	DT days	DEF MI / %MAR		MMDEF MI / %MAR	DT days	DEF MI / %MAR	DT days	DEF MI / %MAR
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
A6H018	148	185	215	268	303	480	108	61.0	166	87	289	203	8	1.00	4	1.00	14	2.00
		16.6		24.1		43.3		5.53		7.88		18.3		0.11		0.12		0.18
A6H019	114	223	212	371	261	635	80	90.0	176	149	254	342	23	10.0	27	9.00	63	35.0
		16.1		26.8		45.9		6.47		10.7		24.7		0.73		0.65		2.51
A6H020	189	707	278	1174	299	1258	161	334	261	604	286	682	85	65.0	161	133	184	155
		28.5		47.3		50.6		13.4		24.3		27.5		2.62		5.35		6.25
A6H021	239	610	310	783	334	868	236	377	306	485	334	542	225	144	297	193	311	202
		51.5		66.2		73.3		31.8		41.0		45.8		12.2		16.3		17.0
A6H022	162	118	283	210	291	216	158	72	278	128	286	133	171	32.0	278	52.0	286	53.0
		34.9		61.9		63.7		21.4		37.9		39.1		9.30		15.2		15.6
A9H001	135	14935	238	24817	265	42861	91	5918	187	11643	248	22761	42	1106	66	1367	179	6088
		17.9		29.7		51.3		7.08		13.9		27.2		1.32		1.63		7.28
A9H002	125	4926	192	7344	231	11409	78	1751	142	3708	208	5285	20	177	75	442	31	124
		14.2		21.2		32.9		5.05		10.7		15.2		0.51		1.27		0.36
A9H004	151	16737	243	29494	256	35819	112	7103	199	12017	238	19311	35	806	57	723	127	2698
		18.4		32.4		39.3		7.80		13.2		21.2		0.88		0.79		2.96
B1H001	152	38170	239	62121	252	68394	149	22294	227	35475	243	40950	129	6742	215	12521	238	14615
		28.6		46.5		51.2		16.7		26.6		30.7		5.05		9.37		10.9
B1H002	150	1563	237	2295	257	3086	132	772	192	1199	244	1654	84	150	162	241	211	393
		25.8		37.9		50.9		12.7		19.8		27.3		2.47		4.00		6.50
B2H001	110	6156	187	11149	219	15624	90	3047	151	4436	207	8189	49	6.24	92	1083	108	1749
		17.9		32.4		45.4		8.86		12.9		23.8		1.81		3.15		5.08

Station Code	Events below 80% ADF						Events below 50% ADF						Events below 20% ADF					
	MMDT days		5 year return period		10 year return period		MMDT days		5 year return period		10 year return period		MMDT days		5 year return period		10 year return period	
		MMDEF	DT days	DEF	DT days	DEF		MMDEF	DT days	DEF	DT days	DEF		MMDEF	DT days	DEF	DT days	DEF
		MI		MI		MI		MI		MI		MI		MI		MI		MI
		%MAR		%MAR		%MAR		%MAR		%MAR		%MAR		%MAR		%MAR		%MAR
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
B3H001	107	30526	171	55975	203	65593	118	19127	187	33085	202	36688	67	4187	109	6256	163	12079
		20.0		36.6		42.9		12.5		21.6		24.0		2.74		4.09		7.90
B4H005	132	3489	187	5226	195	6660	87	1121	138	1822	176	2859	9	29.0	14	47.0	34	105
		15.3		22.9		29.2		4.91		7.98		12.5		0.13		0.21		0.46
B4H009	119	3840	180	6285	196	7018	102	1887	148	3192	173	3449	69	372	113	664	123	818
		19.7		32.2		36.0		9.68		16.4		17.7		1.91		3.40		4.19
B5H002	185	244398	249	353472	264	407023	160	123235	193	188214	256	244619	101	3133	181	66607	187	66829
		32.2		46.6		53.7		16.3		24.8		32.3		4.10		8.78		8.81
B6H001	143	21842	203	34148	216	40531	79	4931	138	9216	173	12433	0	0.00	0	0.00	0	0.00
		12.9		20.2		24.0		2.91		5.45		7.35		0.00		0.00		0.00
B6H002	197	22889	243	29180	283	33140	180	11574	235	15618	242	16593	132	2055	193	3223	201	3800
		33.4		42.6		48.3		16.9		22.8		24.2		3.00		4.70		5.54
B6H003	157	9599	196	12470	215	13519	131	3714	165	5181	179	5628	18	63.0	35	118	56	231
		21.4		27.8		30.1		8.27		11.5		12.5		0.14		0.26		0.51
B7H003	***																	
B7H004	141	6835	190	9966	207	11581	103	3099	155	4860	170	5746	64	578	118	1156	139	1524
		21.6		31.5		36.6		9.80		15.4		18.2		1.83		3.65		4.82
B7H008	139	11937	270	23762	315	28587	158	8563	281	15908	319	18133	160	3469	280	6339	319	7179
		28.8		57.3		69.0		20.7		38.4		43.8		8.37		15.3		17.3
B7H009	162	207481	222	319555	255	338655	137	102938	196	158630	219	191573	84	20835	139	33515	171	48811
		27.6		42.5		45.1		13.7		21.1		25.5		2.77		4.46		6.50

Station Code	Events below 80% ADF						Events below 50% ADF						Events below 20% ADF					
	MMDT days		5 year return period		10 year return period		MMDT days		5 year return period		10 year return period		MMDT days		5 year return period		10 year return period	
		MMDEF Ml / %MAR	DT days	DEF Ml / %MAR	DT days	DEF Ml / %MAR		MMDEF Ml / %MAR	DT days	DEF Ml / %MAR	DT days	DEF Ml / %MAR		MMDEF Ml / %MAR	DT days	DEF Ml / %MAR	DT days	DEF Ml / %MAR
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
B7H010	177	5876	248	9033	316	11666	161	3406	246	5590	316	7256	144	1216	243	2170	292	2680
		34.7		53.3		68.9		20.1		33.0		42.8		7.17		12.8		15.8
B7H014	169	2524	323	5187	335	5450	157	1442	308	3192	333	3344	168	553	316	1190	333	1266
		32.2		66.2		69.6		18.4		40.7		42.7		7.06		15.2		16.2
B9H001	164	1640	302	3030	328	3285	164	1022	302	1894	328	2050	162	405	302	757	327	818
		35.8		66.1		71.7		22.3		41.3		44.7		8.84		16.5		17.8
C1H008	132	44796	215	76411	285	101755	120	26316	212	47446	264	59047	115	10161	211	18912	263	23541
		27.4		46.1		62.2		16.1		29.0		36.1		6.21		11.6		14.4
C2H026	108	73.0	173	137	245	192	90	38.0	161	80.0	226	113	54	11.0	119	22.0	159	34.0
		18.4		34.8		48.6		9.55		20.3		28.5		2.66		5.57		8.59
C2H027	161	20.0	263	34.0	285	37.0	161	13.0	263	21.0	284	23.0	161	5.00	263	9.00	284	9.00
		34.6		57.6		62.3		22.0		36.0		38.9		8.80		14.4		15.6
C2H028	137	226	210	355	261	514	118	120	181	201	261	308	85	35.0	159	61.0	235	106
		24.9		39.2		56.7		13.3		22.1		34.0		3.85		6.74		11.7
C2H065	177	2420	266	3532	300	4238	173	1446	253	2146	299	2598	157	494	237	837	279	924
		36.6		53.4		64.0		21.9		32.4		39.2		7.46		12.6		14.0
C2H067	93	523	188	1061	295	1679	91	320	186	657	285	1018	101	142	229	326	286	408
		20.0		40.5		64.1		12.2		25.1		38.8		5.42		12.4		15.6
C3H003	188	16630	239	21614	278	24198	178	9706	232	12697	265	14995	156	3326	212	4913	230	5326
		39.0		50.7		56.8		22.8		29.8		35.2		7.80		11.5		12.5
C4H002	112	24745	202	45710	232	52698	104	14464	202	28414	235	33063	100	5634	197	11161	229	13003
		23.5		43.4		50.0		13.7		27.0		31.4		5.35		10.6		12.3

Station Code	Events below 80% ADF						Events below 50% ADF						Events below 20% ADF					
	MMDT days		5 year return period		10 year return period		MMDT days		5 year return period		10 year return period		MMDT days		5 year return period		10 year return period	
		MMDEF	DT days	DEF	DT days	DEF		MMDEF	DT days	DEF	DT days	DEF		MMDEF	DT days	DEF	DT days	DEF
		MI		MI		MI		MI		MI		MI		MI		MI		MI
		%MAR		%MAR		%MAR		%MAR		%MAR		%MAR		%MAR		%MAR		%MAR
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
C5H007	146	1779	212	2595	236	2940	147	1130	217	1710	238	1857	146	448	216	682	238	750
		30.9		45.1		51.0		19.6		29.7		32.2		7.78		11.9		13.0
C5H008	122	3157	217	5660	233	6129	119	1933	217	3524	233	3831	122	793	213	1400	236	1553
		26.3		47.2		51.1		16.1		29.4		31.9		6.61		11.7		12.9
C5H012	127	7431	223	13529	238	14487	127	4694	222	8438	237	9013	123	1823	211	3202	237	3587
		26.6		48.5		51.9		16.8		30.2		32.3		6.53		11.5		12.9
C6H003	183	70062	250	96646	270	103720	189	44698	253	60557	268	63540	179	16933	236	23316	253	23896
		38.5		53.2		57.1		24.6		33.3		35.0		9.31		12.8		13.2
C6H004	185	4287	251	5977	279	6712	175	2612	243	36.70	276	4160	172	1013	239	1459	274	1637
		38.4		53.5		60.1		23.4		32.8		37.2		9.06		13.1		14.7
C7H003	165	5478	277	9222	296	9813	167	3455	269	5579	296	6129	163	1352	258	2132	293	2450
		35.9		60.2		64.4		22.7		36.6		40.2		8.87		14.0		16.1
C8H003	165	14056	247	22021	277	25603	155	7921	226	12535	272	15069	113	2255	195	3947	217	4849
		31.9		50.0		58.0		18.0		28.4		34.1		5.11		8.94		11.0
C3H005	116	21900	165	31664	191	37814	111	12500	162	18580	189	22594	88	3306	129	5817	157	6662
		22.5		32.5		38.8		12.8		19.1		23.2		3.39		5.97		6.84
C9H012	172	3454	249	5089	262	5381	166	2050	243	3024	255	3320	154	711	212	1097	250	1267
		35.1		51.7		54.7		20.8		30.7		33.7		7.22		11.1		12.9
C3H022	172	211346	217	278237	255	318442	158	114367	207	156543	224	173663	114	28130	153	45505	172	51405
		32.1		42.3		48.4		17.9		23.8		26.4		4.27		6.91		7.81
D1H011	125	134504	189	201814	200	238746	107	69325	171	107226	192	139691	76	17907	113	27186	149	35738
		21.9		32.8		38.8		11.3		17.4		22.7		2.91		4.42		5.81

Station Code	Events below 80% ADF						Events below 50% ADF						Events below 20% ADF					
	MMDT days	MMDEF MI %MAR	5 year return period		10 year return period		MMDT days	MMDEF MI %MAR	5 year return period		10 year return period		MMDT days	MMDEF MI %MAR	5 year return period		10 year return period	
			DT days	DEF MI %MAR	DT days	DEF MI %MAR			DT days	DEF MI %MAR	DT days	DEF MI %MAR			DT days	DEF MI %MAR	DT days	DEF MI %MAR
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
D2H012	131	6028	181	8113	215	12116	110	3089	176	4430	214	7468	75	820	124	1196	209	2871
		2218		30.7		45.8		11.7		16.8		28.2		3.10		4.52		10.9
D2H020	***																	
D4H003	***																	
D5H003	110	3349	169	5159	215	6562	109	2084	169	3223	215	4101	109	832	169	1288	215	1640
		24.0		37.0		47.1		15.0		23.1		29.4		6.00		9.24		11.8
D5H013	126	8422	262	17443	312	21208	135	5749	255	10888	311	13203	138	2347	252	4318	279	4730
		27.0		55.8		67.8		18.4		34.8		42.2		7.51		13.8		15.1
E1H006	146	9735	224	13574	232	15277	133	4929	182	6610	191	6993	69	721	92	1026	108	1321
		24.7		34.4		38.7		12.5		16.8		17.7		1.83		2.60		3.35
E2H002	167	97512	218	131140	243	143456	151	53286	204	73743	217	80401	126	16813	177	23042	200	26943
		32.7		44.0		48.1		17.9		24.7		27.0		5.64		7.72		9.03
E2H007	184	25008	238	32083	256	34660	176	14858	230	191500	250	21122	164	5533	214	7294	234	7934
		38.3		49.1		53.0		22.7		29.3		32.3		8.47		11.2		12.1
G1H002	***																	
G1H003	148	6536	194	8822	222	9936	133	3571	186	5027	192	5496	99	1048	171	1979	146	1562
		28.0		37.8		42.5		15.3		21.5		23.5		4.49		8.47		6.69
G1H007	132	108912	183	148796	198	173184	112	55134	156	78636	184	93917	86	15144	117	18640	173	30264
		25.2		34.4		40.1		12.8		18.2		21.7		3.51		4.31		7.00

Station Code	Events below 80% ADF						Events below 50% ADF						Events below 20% ADF					
	MMDT days		5 year return period		10 year return period		MMDT days		5 year return period		10 year return period		MMDT days		5 year return period		10 year return period	
		MMDEF Ml / %MAR	DT days	DEF Ml / %MAR	DT days	DEF Ml / %MAR		MMDEF Ml / %MAR	DT days	DEF Ml / %MAR	DT days	DEF Ml / %MAR		MMDEF Ml / %MAR	DT days	DEF Ml / %MAR	DT days	DEF Ml / %MAR
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
G1H008	147	18912	198	25973	233	30970	129	10079	184	13800	205	15873	103	2844	150	4259	185	4817
		28.2		38.7		46.1		15.0		20.5		23.6		4.23		6.34		7.17
G1H009	165	119	206	168	244	179	157	69	206	99.0	232	104	120	19.0	185	29.0	199	36.0
		31.8		44.8		47.6		18.4		26.4		27.8		5.14		7.86		9.61
G1H010	228	214	287	266	302	282	225	132	279	166	300	175	216	51.0	267	63.0	284	67.0
		49.2		61.3		65.0		30.4		38.2		40.2		11.8		14.5		15.5
G1H011	137	3641	189	5016	229	6003	117	1948	158	2766	196	3340	95	590	141	907	171	1159
		26.6		36.7		43.9		14.2		20.2		24.4		4.31		6.63		8.47
G1H012	136	3735	179	4999	227	5970	126	2132	166	2854	205	3488	96	636	141	931	166	1163
		27.1		36.3		43.3		15.5		20.7		25.3		4.62		6.75		8.43
G1H014	184	376	243	491	248	512	171	193	224	251	237	262	74	19.0	101	27.0	129	35.0
		30.3		39.7		41.4		15.6		20.3		21.2		1.54		2.22		2.80
G1H015	183	504	226	619	238	656	156	252	193	321	209	347	92	47.0	133	72.0	150	78.0
		32.8		40.3		42.7		16.4		20.9		22.6		3.06		4.68		5.07
G1H016	160	761	222	1071	231	1126	133	355	190	528	216	598	68	46.0	101	73.0	118	82.0
		26.8		37.7		39.6		12.5		18.6		21.1		1.61		2.57		2.89
G1H017	180	213	235	276	246	295	166	115	205	145	228	155	139	28.0	179	38.0	197	40.0
		32.5		42.0		44.8		17.4		22.1		23.6		4.30		5.85		6.05
G1H018	186	819	226	981	254	1118	157	423	198	542	221	611	106	101	148	151	173	170
		35.5		42.5		48.4		18.3		23.5		26.5		4.38		6.52		7.35
G1H019	124	894	166	1195	201	1434	117	526	159	714	197	890	105	190	137	248	194	352
		26.9		36.0		43.1		15.8		21.5		26.8		5.71		7.45		10.6

Station Code	Events below 80% ADF						Events below 50% ADF						Events below 20% ADF					
	MMDT days		5 year return period		10 year return period		MMDT days		5 year return period		10 year return period		MMDT days		5 year return period		10 year return period	
		MMDEF Ml %MAR	DT days	DEF Ml %MAR	DT days	DEF Ml %MAR		MMDEF Ml %MAR	DT days	DEF Ml %MAR	DT days	DEF Ml %MAR		MMDEF Ml %MAR	DT days	DEF Ml %MAR	DT days	DEF Ml %MAR
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
G1H021	112	2352	155	3218	190	4435	85	949	120	1629	153	1906	31	70.0	52	126	69	185
		15.4		21.0		29.0		6.20		10.6		12.4		0.46		0.82		1.21
G1H028	186	21958	235	27770	253	30071	177	13069	226	16692	240	17754	169	5007	219	6483	236	6987
		40.5		51.3		55.5		24.1		30.8		32.8		9.24		12.0		12.9
G2H008	99	4454	134	6187	144	6340	89	2466	120	3415	134	3660	73	768	102	1067	124	1290
		19.4		27.0		27.7		10.8		14.9		16.0		3.35		4.66		5.63
G2H012	205	4798	258	6072	277	6386	207	3033	256	3766	272	4003	193	1132	245	1444	264	1549
		43.1		54.5		57.4		27.2		33.8		36.0		10.2		13.0		13.9
G3H001	187	4676	243	6038	260	6390	190	2923	240	3680	261	3874	168	1031	200	1242	215	1279
		38.1		49.2		52.1		23.8		30.0		31.6		8.40		10.1		10.4
G4H006	186	10853	247	14742	263	15342	182	6740	243	9025	253	9511	167	2476	227	3394	239	3594
		37.5		51.0		53.0		23.3		31.2		32.9		8.56		11.7		12.4
G4H008	160	199	218	279	230	291	132	100	187	146	204	154	83	21.0	140	37.0	145	42.0
		27.5		38.6		40.3		13.8		20.1		21.4		2.94		5.13		5.83
G4H009	152	107	233	171	256	189	150	67.0	219	101	246	113	140	24.0	205	37.0	224	40.0
		29.2		46.6		51.7		18.2		27.6		30.8		6.60		10.1		11.0
G4H013	169	279	225	379	240	408	144	151	209	221	210	235	106	43.0	156	67.0	167	74.0
		31.9		43.3		46.6		17.2		25.3		26.9		4.91		7.68		8.40
G4H014	170	6418	234	8876	253	9703	153	3550	214	5025	227	5394	127	1099	179	1426	200	1726
		32.1		44.5		48.6		17.8		25.2		27.0		5.50		7.14		8.65
G5H006	120	89.0	209	157	224	164	55	14.0	110	25.0	133	33.0	1	0.00	1	0.00	2	0.00
		10.6		18.7		19.6		1.62		2.99		3.93		0.03		0.05		0.06

Station Code	Events below 80% ADF						Events below 50% ADF						Events below 20% ADF					
	MMDT days		5 year return period		10 year return period		MMDT days		5 year return period		10 year return period		MMDT days		5 year return period		10 year return period	
		MMDEF MI / %MAR	DT days	DEF MI / %MAR	DT days	DEF MI / %MAR		MMDEF MI / %MAR	DT days	DEF MI / %MAR	DT days	DEF MI / %MAR		MMDEF MI / %MAR	DT days	DEF MI / %MAR	DT days	DEF MI / %MAR
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
G5H008	129	1325	267	2902	329	3355	128	819	267	1812	328	2020	115	297	218	562	283	722
		26.8		58.6		67.8		16.5		36.6		40.8		5.99		11.4		14.6
H1H007	106	24268	137	31623	154	35583	94	12910	126	16938	144	20708	76	3604	97	4486	127	6272
		20.4		137		29.9		10.9		14.3		17.4		3.03		3.77		5.28
H1H012	195	24266	240	29227	265	33596	174	12583	222	15595	258	18559	126	2595	152	3314	180	4158
		34.8		41.9		48.1		18.0		22.3		26.6		3.72		4.75		5.96
H1H013	143	5791	193	8012	225	9604	122	2906	163	4137	195	4735	71	587	102	875	121	1143
		25.6		35.4		42.4		12.8		18.3		20.9		2.59		3.86		5.05
H1H017	***																	
H1H018	***																	
H2H001	152	22194	211	32235	227	35214	132	10196	193	14780	211	18228	57	1180	103	2436	113	3085
		23.5		34.1		37.3		10.8		15.7		19.3		1.25		2.58		3.27
H2H005	192	1679	253	2205	267	2720	157	663	225	912	248	1303	27	21.0	52	32.0	100	122
		25.6		33.6		41.5		10.1		13.9		19.9		0.32		0.49		1.86
H3H001	143	3395	226	5376	240	5715	143	2118	226	3360	240	3571	143	846	226	1344	240	1427
		31.3		50.0		52.7		19.5		31.0		32.9		7.80		12.4		13.2
H3H004	119	176	213	317	230	341	123	114	213	198	228	212	121	45.0	207	77.0	215	81.0
		25.8		46.4		49.9		16.7		28.9		31.0		6.58		11.3		11.8
H3H005	71	82.0	128	151	290	342	70	51.0	128	94.0	290	214	69	20.0	128	37.0	290	85.0
		15.3		28.1		63.6		9.49		17.5		39.7		3.75		6.95		15.9

Station Code	Events below 80% ADF: MMDT days	Events below 80% ADF: MMDEF (MI / %MAR)	Events below 80% ADF: 5 year return period DT days	Events below 80% ADF: 5 year return period DEF (MI / %MAR)	Events below 80% ADF: 10 year return period DT days	Events below 80% ADF: 10 year return period DEF (MI / %MAR)	Events below 50% ADF: MMDT days	Events below 50% ADF: MMDEF (MI / %MAR)	Events below 50% ADF: 5 year return period DT days	Events below 50% ADF: 5 year return period DEF (MI / %MAR)	Events below 50% ADF: 10 year return period DT days	Events below 50% ADF: 10 year return period DEF (MI / %MAR)	Events below 20% ADF: MMDT days	Events below 20% ADF: MMDEF (MI / %MAR)	Events below 20% ADF: 5 year return period DT days	Events below 20% ADF: 5 year return period DEF (MI / %MAR)	Events below 20% ADF: 10 year return period DT days	Events below 20% ADF: 10 year return period DEF (MI / %MAR)
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
H4H005	88	731	110	946	134	1159	67	299	90	403	99	477	13	15.0	18	19.0	30	32.0
		12.6		16.3		19.9		5.13		6.92		8.20		0.26		0.33		0.55
H4H009	129	367	183	521	210	597	127	225	178	318	202	360	120	85.0	176	126	186	132
		28.2		40.0		45.9		17.3		24.4		27.6		6.60		9.70		10.2
H4H012	168	272	248	402	258	420	165	168	244	249	251	257	152	62.0	214	88.0	243	99.0
		36.2		53.6		55.9		22.4		33.2		34.2		8.29		11.7		13.2
H6H003	129	51593	176	69344	202	80653	119	29827	160	14056	186	46727	106	10281	148	14380	168	16678
		25.9		34.8		40.5		15.0		20.6		23.5		5.16		7.22		8.38
H6H006	***																	
H6H008	81	8837	100	10865	138	15781	71	4474	95	6051	137	8887	50	909	74	1442	91	1591
		14.8		18.2		26.5		7.50		10.1		14.9		1.52		2.42		2.67
H6H010	115	238	162	444	221	560	43	56.0	100	165	126	185	9	2.00	9	2.00	30	6.00
		11.2		20.9		26.3		2.64		7.77		8.69		0.12		0.11		0.29
H7H001	161	394881	198	486651	210	514255	148	21411	192	278302	208	292226	100	53034	145	77567	156	90006
		31.0		38.2		40.4		16.8		21.9		23.0		4.17		6.09		7.07
H7H003	81	8681	115	12630	125	14133	65	4267	87	6079	115	7916	49	1186	68	1831	79	2126
		15.3		22.2		24.8		7.50		10.7		13.9		2.08		3.22		3.74
H7H007	51	638	76	905	88	1147	38	246	47	329	63	503	11	16.0	18	25.0	22	43.0
		6.53		9.26		11.7		2152		3.36		5.15		0.16		0.26		0.44
H9H004	79	1481	115	1960	148	2917	57	529	76	771	82	8.72	17	23.0	31	34.0	40	51.0
		11.4		15.1		22.4		4.07		5.92		6.70		0.18		0.26		0.39

Station Code	Events below 80% ADF						Events below 50% ADF						Events below 20% ADF					
	MMDT days		5 year return period		10 year return period		MMDT days		5 year return period		10 year return period		MMDT days		5 year return period		10 year return period	
		MMDEF Ml / %MAR	DT days	DEF Ml / %MAR	DT days	DEF Ml / %MAR		MMDEF Ml / %MAR	DT days	DEF Ml / %MAR	DT days	DEF Ml / %MAR		MMDEF Ml / %MAR	DT days	DEF Ml / %MAR	DT days	DEF Ml / %MAR
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
H9H005	112	10639	139	14301	186	19050	98	5856	138	8861	185	11702	82	1938	131	3408	157	3877
		22.1		29.6		39.5		12.1		18.4		24.3		4.02		7.06		8.04
J1H015	163	727	210	1053	230	1125	137	283	203	481	214	520	43	8.00	87	16.0	111	20.0
		21.9		31.7		33.8		8.50		14.5		15.6		0.23		0.47		0.60
J1H016	191	1039	247	1283	254	1380	171	563	219	773	238	806	122	169	167	241	207	303
		36.9		45.5		49.0		20.0		27.4		28.6		6.00		8.55		10.8
J2H005	155	2112	252	3588	293	3892	144	1179	249	1896	267	2295	117	355	195	604	252	769
		30.1		51.2		55.5		16.8		27.1		32.7		5.07		8.61		11.0
J2H006	123	183	211	320	268	380	123	112	204	187	271	229	118	47.0	196	80.0	252	104
		23.9		41.8		49.6		14.6		24.4		29.9		6.17		10.42		13.6
J2H007	129	238	223	430	278	536	134	150	220	263	274	310	98	46.0	192	93.0	213	107
		23.3		42.1		52.4		14.7		25.8		30.4		4.51		9.07		10.5
J3H012	123	2551	188	4282	262	5520	129	1643	178	2245	260	3305	105	506	130	611	204	1069
		23.9		40.2		51.8		15.4		23.0		31.0		4.75		5.73		10.0
J3H013	112	888	154	1335	192	1661	57	169	87	275	124	446	1	1.00	1	1.00	1	1.00
		10.8		16.3		20.3		2.07		3.35		5.45		0.01		0.01		0.02
J3H016	128	182	187	265	220	326	97	81.0	146	137	193	162	47	12.0	84	22.0	95	30.0
		19.9		29.0		35.7		8.89		15.0		17.8		1.36		2.42		3.33
J3H017	123	967	209	1597	286	2270	118	583	191	944	272	1349	120	239	186	368	285	563
		26.1		43.1		61.2		15.7		25.5		36.4		6.43		9.93		15.2
J3H018	98	1238	140	1928	185	2451	74	573	117	1008	143	1157	38	120	81	245	90	327
		16.8		26.1		33.2		7.76		13.7		15.7		1.62		3.31		4.43

Station Code	Events below 80% ADF							Events below 50% ADF						Events below 20% ADF					
	MMDT days		5 year return period		10 year return period		MMDT days		5 year return period		10 year return period		MMDT days		5 year return period		10 year return period	
		MMDEF MI %MAR	DT days	DEF MI %MAR	DT days	DEF MI %MAR		MMDEF MI %MAR	DT days	DEF MI %MAR	DT days	DEF MI %MAR		MMDEF MI %MAR	DT days	DEF MI %MAR	DT days	DEF MI %MAR
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
J3H020	134	447	234	804	269	895	115	246	209	451	223	497	56	51.0	101	92	108	101
		25.7		46.3		51.6		14.2		26.0		28.6		2.93		5.27		5.80
J4H003	101	3439	136	5027	179	6208	93	1887	130	2961	168	3226	63	504	87	736	125	1072
		18.4		26.9		33.2		10.1		15.9		17.3		2.70		3.94		5.74
J4H004	119	1331	159	1985	183	2211	97	677	142	1064	165	1196	67	184	110	297	121	378
		20.6		30.7		34.2		10.5		16.5		18.5		2.85		4.60		5.85
K1H001	141	1366	216	2135	267	2484	167	1004	251	1505	267	1622	164	396	234	572	246	589
		30.3		47.4		55.2		22.3		33.4		36.0		8.79		12.7		13.1
K1H002	73	127	93	165	138	247	52	45.0	73	58.0	85	137	13	8.00	5	1.00	77	54.0
		9.72		12.6		18.9		3.46		4.45		10.5		0.64		0.10		4.12
K3H001	86	2059	113	2938	128	3213	68	895	97	1391	108	1514	34	131	54	198	67	351
		14.0		20.0		21.9		6.09		9.47		10.3		0.89		1.35		2.39
K3H002	***																	
K3H003	91	4320	118	6363	147	7160	79	2240	115	3579	134	3991	56	566	72	734	94	1088
		16.8		24.8		27.9		8.73		14.0		15.6		2.21		2.86		4.24
K3H004	72	2167	91	2813	114	3473	54	936	70	1243	75	1340	36	192	47	251	57	337
		12.7		16.5		20.3		5.48		7.27		7.84		1.12		1.47		1.97
K3H005	107	2099	152	3403	181	3730	82	852	128	1389	144	1756	37	97.0	62	165	69	201
		17.3		28.1		30.8		7.04		11.5		14.5		0.80		1.37		1.66
K4H001	***																	

Station Code	Events below 80% ADF						Events below 50% ADF						Events below 20% ADF					
	MMDT days		5 year return period		10 year return period		MMDT days		5 year return period		10 year return period		MMDT days		5 year return period		10 year return period	
		MMDEF MI / %MAR	DT days	DEF MI / %MAR	DT days	DEF MI / %MAR		MMDEF MI / %MAR	DT days	DEF MI / %MAR	DT days	DEF MI / %MAR		MMDEF MI / %MAR	DT days	DEF MI / %MAR	DT days	DEF MI / %MAR
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
K4H002	74	1216	97	1545	60	566	83	743	93	883	41	102	55	126	55	126	64	229
		1219		16.4		5.99		7.87		9.34		1.07		1.33		1.31		2.42
K4H003	102	1396	145	2167	196	2100	77	550	107	782	152	1231	23	43.0	41	78.0	53	138
		15.4		23.9		30.8		6.06		8.61		13.5		0.47		0.86		1.52
K5H002	69	2506	93	3825	122	4826	49	846	61	1233	82	1523	10	26.0	18	52.0	29	95.0
		9.51		14.5		18.3		3.21		4.68		5.78		0.10		0.20		0.36
K6H001	136	2512	205	3998	238	4489	124	1402	190	2146	205	2511	94	379	147	648	159	682
		25.7		40.9		45.9		14.3		22.0		25.7		3.88		6.63		6.98
K6H002	63	5865	90	8549	110	11250	50	1940	63	2475	101	4692	4	33.0	3	31.0	11	54.0
		7.66		11.2		14.2		2.53		3.23		6.13		0.04		0.04		0.07
K7H001	60	2654	83	3774	92	4637	49	1104	60	1521	79	2016	19	98.0	36	140	45	313
		9.33		13.3		16.3		3.88		5.35		7.09		0.34		0.49		1.10
L1H001	161	5175	250	7993	282	9053	161	3232	250	4977	282	5656	157	1261	240	1927	282	2262
		35.3		54.5		61.8		22.0		34.0		38.6		8.60		13.1		15.4
L6H001	184	6876	255	9573	282	10619	183	4270	255	5975	289	6793	176	1642	219	2066	282	2649
		40.0		55.7		61.8		24.9		34.8		40.0		9.56		12.0		15.4
L8H001	***																	
L8H002	56	992	75	1539	84	1742	43	422	58	693	71	781	23	65.0	40	160	49	167
		8.86		13.8		15.6		3.77		6.20		6.98		0.58		1.43		1.49
N2H009	***																	

Station Code	Events below 80% ADF						Events below 50% ADF						Events below 20% ADF					
	MMDT days	MMDEF MI %MAR	5 year return period		10 year return period		MMDT days	MMDEF MI %MAR	5 year return period		10 year return period		MMDT days	MMDEF MI %MAR	5 year return period		10 year return period	
			DT days	DEF MI %MAR	DT days	DEF MI %MAR			DT days	DEF MI %MAR	DT days	DEF MI %MAR			DT days	DEF MI %MAR	DT days	DEF MI %MAR
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
P4H001	84	4072	140	7127	215	10993	79	2367	125	3954	195	6333	82	948	141	1866	210	2347
		16.3		28.5		44.0		9.47		15.8		25.3		3.79		7.46		9.38
Q1H001	117	26249	214	48547	228	51850	115	16102	214	30342	228	32392	116	6529	216	12250	233	13180
		25.3		46.9		50.0		15.5		29.3		31.3		6.30		11.8		12.7
Q1H009	***																	
Q3H004	109	1218	184	1596	234	3201	75	554	106	912	220	1851	47	134	96	199	129	352
		16.8		22.0		44.2		7.64		12.6		25.6		1.85		2.75		4.86
Q4H003	97	587	164	1068	207	1326	83	317	120	494	206	807	67	102	107	150	164	270
		19.2		34.9		43.3		10.4		16.2		26.4		3.33		4.89		8.84
Q6H003	141	2241	213	3417	262	4309	123	1206	203	2023	228	2363	117	435	186	719	228	939
		29.5		45.0		56.7		15.9		26.6		31.1		5.73		9.46		12.4
Q9H002	121	10382	194	17087	210	18200	115	6211	181	9985	207	11335	109	2336	170	3786	202	4357
		25.6		42.1		44.8		15.3		24.6		27.9		5.75		9.32		10.7
Q9H013	***																	
Q9H016	176	6004	239	8258	296	10268	173	3654	237	5112	257	5585	163	1359	234	2005	248	2154
		37.5		51.6		64.2		22.8		31.9		34.9		8.49		12.5		13.5
Q9H017	110	1204	169	1873	253	28.3	105	690	169	1092	249	1620	102	231	186	377	208	541
		21.4		33.3		50.0		12.3		19.4		28.8		4.11		6.71		9.63
Q9H019	122	2194	186	3485	198	3887	116	1239	183	1961	192	2287	93	376	147	563	180	802
		21.8		34.6		38.6		12.3		19.5		22.7		3.73		5.58		7.95

Station Code	Events below 80% ADF						Events below 50% ADF						Events below 20% ADF					
	MMDT days		5 year return period		10 year return period		MMDT days		5 year return period		10 year return period		MMDT days		5 year return period		10 year return period	
		MMDEF Ml %MAR	DT days	DEF Ml %MAR	DT days	DEF Ml %MAR		MMDEF Ml %MAR	DT days	DEF Ml %MAR	DT days	DEF Ml %MAR		MMDEF Ml %MAR	DT days	DEF Ml %MAR	DT days	DEF Ml %MAR
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
R1H001	110	4979	145	6571	188	8239	101	2807	137	3859	164	5092	77	907	117	1480	157	2006
		21.3		28.2		35.3		12.0		16.5		21.8		3.89		6.34		8.60
R1H005	96	7280	146	10612	165	13821	81	3430	124	5082	150	6731	43	581	71	990	112	1547
		154		22.5		29.3		7.26		10.8		14.2		1.23		2.10		3.27
R1H006	122	1243	164	1765	197	1876	97	560	157	841	163	988	49	96.0	66	104	70	147
		19.8		28.1		29.8		8.91		13.4		15.7		1.53		1.66		2.33
R1H007	116	300	152	440	158	509	76	108	132	214	155	247	23	6.00	47	8.00	67	21.0
		14.6		21.4		24.8		5.28		10.4		12.0		0.29		0.41		1.03
R1H014	103	2941	141	4080	152	5541	74	1117	110	1556	129	2687	23	95.0	40	94.0	66	330
		15.0		20.8		28.2		5.68		7.92		13.7		0.48		0.48		1.68
R1H015	138	26458	209	39760	219	43543	118	13492	159	21482	184	22140	77	3273	129	5427	148	8343
		24.6		37.0		41.0		12.6		20.0		20.6		3.04		5.05		7.76
R2H001	117	1598	158	2310	189	2665	96	758	149	1165	161	1458	54	140	81	223	107	295
		20.1		29.1		33.5		9.53		14.7		18.3		1.76		2.80		3.72
R2H005	138	9105	194	13109	217	15614	116	4257	158	6440	188	7743	65	962	116	1865	161	2520
		23.3		33.5		39.9		10.9		16.5		19.8		2.46		4.77		6.44
R2H006	135	2000	184	2939	205	3085	109	889	148	1419	173	1641	49	135	69	181	121	372
		22.5		33.0		34.6		9.99		15.9		18.4		1.52		2.03		4.17
R2H008	167	2309	226	3249	236	3445	166	1387	222	1970	234	2252	126	396	208	691	225	838
		32.7		46.1		48.8		19.7		27.9		31.9		5.61		9.79		11.9
R2H012	129	941	176	1300	195	1431	100	409	136	576	149	709	54	70.0	73	98.0	102	165
		22.3		30.9		34.0		9.70		13.7		16.8		1.67		2.33		3.92

Station Code	Events below 80% ADF						Events below 50% ADF						Events below 20% ADF					
	MMDT days		5 year return period		10 year return period		MMDT days		5 year return period		10 year return period		MMDT days		5 year return period		10 year return period	
		MMDEF Ml / %MAR	DT days	DEF Ml / %MAR	DT days	DEF Ml / %MAR		MMDEF Ml / %MAR	DT days	DEF Ml / %MAR	DT days	DEF Ml / %MAR		MMDEF Ml / %MAR	DT days	DEF Ml / %MAR	DT days	DEF Ml / %MAR
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
S3H002	141	1947	206	2826	212	2967	137	1167	203	1730	211	1843	120	414	159	560	169	596
		30.1		43.7		45.9		18.0		26.7		28.5		6.41		8.66		9.22
S3H004	122	4276	201	7104	232	8502	115	2529	181	4101	217	4927	107	897	178	1623	210	1735
		25.4		42.2		50.5		15.0		24.4		29.3		5.33		9.64		10.3
S3H006	127	6543	216	11812	241	13007	130	4204	229	7540	242	8063	115	1463	198	2628	209	2792
		25.9		46.7		51.4		16.6		29.8		31.9		5.78		10.4		11.0
S6H002	140	11438	192	16559	259	23904	130	6360	182	9861	259	14427	91	1659	138	2699	214	4769
		25.7		37.2		53.7		14.3		22.2		32.4		3.73		6.06		10.7
S6H003	162	4045	206	5345	229	5895	143	2075	198	2983	212	3114	75	384	130	651	149	782
		28.2		37.3		41.1		14.5		20.8		21.7		2.68		4.54		5.46
T1H004	117	106451	174	139106	183	160995	98	47939	152	70714	172	86765	53	6895	69	10880	82	13211
		19.5		27.0		31.0		9.29		13.7		16.8		1.34		2.11		2.56
T2H002	126	54686	182	80797	211	88895	105	25270	163	43436	189	46741	61	4218	107	6056	144	11436
		21.3		31.5		34.7		9.86		16.9		18.2		1.64		2.36		4.46
T3H002	133																	
T3H004	133	16290	188	27107	225	29826	110	7282	163	12698	183	15741	43	890	74	1336	127	2996
		19.4		32.3		35.6		8.69		15.2		18.8		1.06		1.59		3.58
T3H005	***																	
T3H008	158	60059	216	86931	255	101072	136	29471	186	44791	230	56676	95	6573	144	10207	185	15259
		27.3		39.5		45.9		13.4		20.4		25.8		2.99		4.64		6.93

Station Code	Events below 80% ADF						Events below 50% ADF						Events below 20% ADF					
	MMDT days		5 year return period		10 year return period		MMDT days		5 year return period		10 year return period		MMDT days		5 year return period		10 year return period	
		MMDEF Ml %MAR	DT days	DEF Ml %MAR	DT days	DEF Ml %MAR		MMDEF Ml %MAR	DT days	DEF Ml %MAR	DT days	DEF Ml %MAR		MMDEF Ml %MAR	DT days	DEF Ml %MAR	DT days	DEF Ml %MAR
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
T3H009	172	36635	208	46671	231	50415	152	19219	191	24312	209	27639	112	4670	161	7625	175	8332
		31.9		40.6		43.9		16.7		21.2		24.0		4.06		6.63		7.25
T4H001	133	26722	190	37765	197	45998	95	9105	128	13828	167	19000	14	328	26	406	43	735
		16.9		23.9		29.1		5.76		8.75		12.0		0.21		0.26		0.47
T5H002	154	25493	195	37914	235	48273	92	6560	146	11759	200	19715	3	37.0	3	8.00	16	140
		16.0		23.8		30.4		4.12		7.39		12.4		0.02		0.01		0.09
T5H003	168	16957	204	21187	218	23173	143	8122	186	11148	200	11917	86	1541	117	1994	142	3149
		28.4		35.5		38.8		13.6		18.7		20.0		2.58		3.34		5.27
T5H004	176	69243	215	84340	237	94264	154	33666	193	44011	210	47877	89	5535	127	8183	153	10102
		29.4		35.8		40.0		14.3		18.7		20.3		2.35		3.47		4.29
T5H005	149	4423	193	6077	215	6887	114	1774	157	2359	188	3561	34	181	49	180	110	821
		20.4		28.0		31.8		8.18		10.9		16.4		0.84		0.83		3.79
T6H001	76	2629	111	4162	115	4978	45	1022	64	1559	78	1830	24	134	41	286	45	392
		9.35		14.8		17.7		3.64		5.54		6.51		0.48		1.02		1.40
U1H005	166	173467	208	207930	235	255341	140	80814	172	104809	189	122928	71	11594	101	15713	133	23559
		27.4		32.8		40.3		12.8		16.5		19.4		1.83		2.48		3.72
U1H006	162	232801	196	287341	214	341257	131	101633	172	137694	200	167663	63	12322	97	16874	136	33479
		25.0		30.9		36.7		10.9		14.8		18.0		1.33		1.81		3.60
U2H001	131	25868	198	41872	237	52844	101	9184	154	15610	193	22199	10	251	16	270	32	743
		15.9		25.8		32.5		5.65		9.60		13.7		0.15		0.17		0.46
U2H006	164	22773	213	32802	234	35821	128	9638	169	14049	198	16879	48	957	84	1849	105	2581
		24.5		35.4		38.6		10.4		15.1		18.2		1.03		1.99		2.78

Station Code	Events below 80% ADF						Events below 50% ADF						Events below 20% ADF					
	MMDT days		5 year return period		10 year return period		MMDT days		5 year return period		10 year return period		MMDT days		5 year return period		10 year return period	
		MMDEF MI %MAR	DT days	DEF MI %MAR	DT days	DEF MI %MAR		MMDEF MI %MAR	DT days	DEF MI %MAR	DT days	DEF MI %MAR		MMDEF MI %MAR	DT days	DEF MI %MAR	DT days	DEF MI %MAR
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
U2H007	150	14863	201	20088	226	25567	101	5394	127	6970	194	12067	26	441	28	270	69	846
		18.9		25.5		32.5		6.86		8.86		15.3		0.56		0.34		1.08
U2H011	***																	
U2H012	150	13245	203	18885	229	20255	113	5736	163	8054	190	10416	63	1072	104	1567	127	2494
		23.6		33.7		36.1		10.2		14.4		18.6		1.91		2.79		4.45
U2H013	168	19059	214	24709	244	30023	132	7832	171	11493	196	14072	48	858	70	1020	128	2531
		25.1		32.6		40.0		10.3		15.1		18.5		1.13		1.34		3.33
U3H002	104	6715	141	9870	149	11277	60	1870	104	3217	111	3390	6	41.0	3	18.0	11	71.0
		11.6		17.0		19.4		3.22		5.54		5.83		0.07		0.03		0.12
U4H002	167	7617	224	12063	247	12884	124	3063	183	5776	218	6428	45	358	85	619	146	1372
		22.2		35.2		37.6		8.94		16.9		18.8		1.04		1.81		4.00
U4H003	122	555	196	773	204	1048	87	227	114	350	123	376	52	52.0	104	101	114	106
		20.2		28.2		38.2		8.27		12.8		13.7		1.88		3.69		3.86
U6H002	***																	
U7H001	107	336	141	494	174	581	72	112	116	188	141	289	13	4.00	23	4.00	57	21.0
		13.9		20.4		24.0		4.61		7.79		11.9		0.17		0.16		0.88
U7H007	130	2845	212	5230	234	5768	95	1196	161	2027	204	3233	36	175	54	209	139	760
		17.4		32.1		35.4		7.33		12.4		19.8		1.07		1.28		4.66
V1H001	184	329353	220	392846	237	423721	164	164817	208	203918	213	231007	106	27705	136	35641	142	47810
		31.1		37.1		40.0		15.6		19.3		21.8		2.62		3.36		4.51

Station Code	Events below 80% ADF						Events below 50% ADF						Events below 20% ADF					
	MMDT days		5 year return period		10 year return period		MMDT days		5 year return period		10 year return period		MMDT days		5 year return period		10 year return period	
		MMDEF (MI / %MAR)	DT days	DEF (MI / %MAR)	DT days	DEF (MI / %MAR)		MMDEF (MI / %MAR)	DT days	DEF (MI / %MAR)	DT days	DEF (MI / %MAR)		MMDEF (MI / %MAR)	DT days	DEF (MI / %MAR)	DT days	DEF (MI / %MAR)
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
V1H002	121	52315	164	79481	182	85593	96	20832	138	34076	153	38403	27	1399	48	1765	62	3609
		16.9		25.6		27.6		6.71		11.0		12.4		0.45		0.57		1.16
V1H009	182	6768	226	8746	247	9464	171	3814	213	5119	240	5599	131	1088	172	1508	214	1828
		36.5		47.2		51.0		20.6		27.6		30.2		5.87		8.13		9.85
V1H010	139	78088	201	120163	227	136100	118	40713	187	68238	211	80417	80	11783	126	18950	162	24048
		24.5		37.7		42.7		12.8		21.4		25.3		3.70		5.95		7.55
V1H029	155	1253	203	1752	220	1886	151	749	198	1061	202	1146	125	228	169	303	199	447
		29.4		41.1		44.3		17.6		24.9		26.9		5.36		7.11		10.5
V1H031	162	4871	229	7373	256	7853	167	3071	229	4442	249	4793	139	983	193	1546	237	1715
		32.4		49.1		52.2		20.4		29.6		31.9		6.54		10.3		11.4
V1H034	***																	
V1H041	***																	
V2H001	155	156577	216	227179	235	257369	137	78622	201	123212	221	143858	79	15231	148	27649	178	38758
		26.1		37.9		42.9		13.1		20.5		24.0		2.54		4.61		6.46
V2H005	167	28601	194	33970	201	38980	140	13050	178	17133	192	20835	67	1512	97	2324	108	3105
		26.1		31.0		35.5		11.9		15.6		19.0		1.38		2.12		2.83
V2H006	156	15867	198	21306	216	22867	130	7623	174	10595	184	11988	100	1825	145	2671	166	3540
		27.3		36.7		39.4		13.1		18.2		20.6		3.14		4.60		6.09
V2H007	146	7240	194	9519	211	11025	125	3374	173	4751	203	5852	72	478	106	720	122	896
		23.6		31.1		36.0		11.0		15.5		19.1		1.56		2.35		2.92

Station Code	Events below 80% ADF: MMDT days	Events below 80% ADF: MMDEF Ml / %MAR	5 year return period: DT days	5 year return period: DEF Ml / %MAR	10 year return period: DT days	10 year return period: DEF Ml / %MAR	Events below 50% ADF: MMDT days	MMDEF Ml / %MAR	5 year return period: DT days	5 year return period: DEF Ml / %MAR	10 year return period: DT days	10 year return period: DEF Ml / %MAR	Events below 20% ADF: MMDT days	MMDEF Ml / %MAR	5 year return period: DT days	5 year return period: DEF Ml / %MAR	10 year return period: DT days	10 year return period: DEF Ml / %MAR
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
V3H002	152	42373	199	57811	221	65464	130	21189	174	30164	203	38881	81	4445	121	7687	146	9485
		25.7		35.0		40.0		12.8		18.3		23.6		2.69		4.47		5.75
V3H003	158	31613	209	43081	233	52755	138	16179	194	23203	219	29019	89	3352	137	5358	162	6008
		27.9		38.1		46.6		14.3		20.5		25.6		2.96		4.73		5.31
V3H005	171	34260	237	49805	273	56840	168	20036	233	28811	262	32602	127	5173	167	8080	233	11027
		32.1		46.7		53.3		18.8		27.0		30.5		4.85		7.57		10.3
V3H007	174	11705	231	16361	241	17410	149	5921	188	8258	218	9457	99	1393	145	2317	173	2780
		31.2		43.6		46.4		15.8		22.0		25.2		3.71		6.17		7.41
V3H009	171	6050	218	7953	270	10158	156	3396	203	4535	257	6252	110	853	159	1405	168	1513
		31.8		41.8		53.4		17.9		23.8		32.9		4.48		7.39		7.96
V5H002	***																	
V6H003	150	9291	186	11220	211	12890	130	4510	172	5694	204	6928	78	874	113	1268	133	2123
		25.8		31.2		35.8		12.5		15.8		19.3		2.43		3.53		5.90
V6H004	155	26556	200	35482	216	40195	138	13740	183	19756	196	21631	97	3302	143	5171	170	6453
		28.4		38.0		43.0		14.7		21.1		23.1		3.53		5.53		6.90
V7H018	146	4918	205	7206	222	7819	113	2203	146	3117	197	4151	74	430	110	782	130	882
		25.3		37.1		40.2		11.3		16.0		21.4		2.22		4.02		4.54
W1H004	116	809	182	1411	221	1607	83	380	148	643	179	944	53	101	103	202	140	272
		19.2		33.6		38.2		9.04		15.3		22.5		2.39		4.79		6.47
W1H006	***																	

Station Code	Events below 80% ADF						Events below 50% ADF						Events below 20% ADF					
	MMDT days	MMDEF	5 year return period		10 year return period		MMDT days	MMDEF	5 year return period		10 year return period		MMDT days	MMDEF	5 year return period		10 year return period	
			DT days	DEF	DT days	DEF			DT days	DEF	DT days	DEF			DT days	DEF	DT days	DEF
		Ml		Ml		Ml		Ml		Ml		Ml		Ml		Ml		Ml
		%MAR		%MAR		%MAR		%MAR		%MAR		%MAR		%MAR		%MAR		%MAR
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
W1H010	105	9204	144	12270	198	19344	86	4218	119	6554	144	8124	41	767	64	1129	113	2369
		17.3		23.0		36.3		7.92		12.3		15.3		1.44		2.12		4.45
W1H018	***																	
W1H019	***																	
W1H025	102	88.0	180	151	220	202	96	48.0	175	85.0	199	118	58	10.0	98	18.0	178	31.0
		17.1		29.6		39.5		9.32		16.7		23.1		1.90		3.56		6.10
W2H002	***																	
W2H006	106	29669	146	42335	186	61258	82	12458	127	21752	138	27600	34	1690	53	2518	123	6039
		16.1		22.9		33.2		6.75		11.8		14.9		0.92		1.36		3.27
W2H009	***																	
W3H011	***																	
W3H014	93	650	148	1169	176	1294	94	396	147	702	173	871	66	104	102	169	147	278
		16.9		30.4		33.6		10.3		18.3		22.6		2.70		4.39		7.21
W4H004	140	34926	205	52766	235	61230	109	14958	168	24398	190	32698	53	2015	101	3792	127	5244
		21.0		31.7		36.8		9.00		14.7		19.6		1.21		2.28		3.15
W4H008	***																	

Station Code	Events below 80% ADF						Events below 50% ADF						Events below 20% ADF					
	MMDT days	MMDEF	5 year return period		10 year return period		MMDT days	MMDEF	5 year return period		10 year return period		MMDT days	MMDEF	5 year return period		10 year return period	
			DT days	DEF	DT days	DEF			DT days	DEF	DT days	DEF			DT days	DEF	DT days	DEF
		Ml / %MAR		Ml / %MAR		Ml / %MAR		Ml / %MAR		Ml / %MAR		Ml / %MAR		Ml / %MAR		Ml / %MAR		Ml / %MAR
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
W5H001	124	219	223	398	253	501	112	123	199	225	235	293	84	35.0	151	59.0	194	100
		22.0		40.0		50.2		12.4		22.6		29.4		3.56		5.87		10.1
W5H006	157	9010	214	13649	261	15539	132	4351	196	6969	215	8085	84	908	151	1769	180	2130
		26.1		39.5		44.9		12.6		20.2		23.4		2.62		5.11		6.16
W5H007	***																	
W5H008	145	2077	221	3328	238	4355	112	870	185	1503	226	2403	43	139	78	180	155	531
		20.9		33.5		43.8		8.76		15.1		24.2		1.40		1.81		5.34
W5H011	171	10910	225	15006	246	18657	146	5273	197	7616	232	9478	88	899	161	1449	164	2188
		28.5		39.2		48.7		13.8		19.9		24.7		2.35		3.78		5.71
X1H003	146	135058	209	217597	256	302110	84	39176	132	65448	189	135200	11	2679	24	4375	44	12322
		15.4		24.7		34.3		4.45		7.44		15.4		0.30		0.50		1.40
X1H014	123	32377	192	53524	224	63440	96	14145	142	21153	192	36759	33	1939	69	4144	94	5998
		19.4		32.0		37.9		8.46		12.7		22.0		1.16		2.48		3.59
X2H002	118	2771	211	5178	217	5306	95	1456	158	2556	192	3040	72	467	136	922	160	1065
		22.4		41.8		42.9		11.8		20.7		24.6		3.77		7.45		8.60
X2H005	126	17750	188	29182	204	36298	82	7008	152	12557	189	19254	35	1440	65	1887	134	4982
		16.6		27.3		34.0		6.56		11.8		18.0		1.35		1.77		4.66
X2H008	140	4515	205	7194	237	9087	119	2215	161	3825	232	5377	58	369	107	712	139	1073
		21.3		34.0		42.9		10.5		18.1		25.4		1.74		3.36		5.07
X2H010	135	4804	214	8140	251	10607	91	1504	158	2783	189	3462	7	32.0	13	42.0	25	107
		15.0		25.5		33.2		4.70		8.71		10.8		0.10		0.13		0.34

Station Code	Events below 80% ADF: MMDT days	Events below 80% ADF: MMDEF Ml / %MAR	5 year return period: DT days	5 year return period: DEF Ml / %MAR	10 year return period: DT days	10 year return period: DEF Ml / %MAR	Events below 50% ADF: MMDT days	Events below 50% ADF: MMDEF Ml / %MAR	5 year return period: DT days	5 year return period: DEF Ml / %MAR	10 year return period: DT days	10 year return period: DEF Ml / %MAR	Events below 20% ADF: MMDT days	Events below 20% ADF: MMDEF Ml / %MAR	5 year return period: DT days	5 year return period: DEF Ml / %MAR	10 year return period: DT days	10 year return period: DEF Ml / %MAR
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
X2H011	144	9620	190	14128	225	18065	102	3604	172	6113	197	7747	23	310	28	329	72	719
		18.2		26.8		34.2		9.82		11.6		14.7		0.59		0.62		1.36
X2H012	166	2211	207	3358	231	3634	118	682	179	1243	203	1396	11	15.0	11	10.0	36	39.0
		20.7		31.4		34.0		6.38		11.6		13.1		0.14		0.09		0.36
X2H013	125	27854	191	40449	215	56562	87	10382	144	16237	191	26803	22	717	37	1242	71	2478
		15.5		22.5		31.4		5.76		9.01		14.9		0.40		0.69		1.38
X2H014	149	7062	212	10724	227	13104	69	1464	129	2647	182	3948	2	8.00	0	0.00	0	0.00
		13.1		19.9		24.4		2.72		4.92		7.34		0.02		0.00		0.00
X2H015	132	30383	200	48233	219	60606	81	8396	145	14764	160	24219	7	170	7	101	19	267
		14.1		22.4		28.2		3.90		6.86		11.3		0.08		0.05		0.12
X2H024	120	2056	165	3759	239	5690	54	483	101	753	158	1873	3	3.00	0	0.00	15	9.00
		11.8		21.5		32.5		2.76		4.31		10.7		0.02		0.00		0.05
X2H025	159	1623	203	2100	226	2839	84	368	126	600	134	855	2	2.00	0	0.00	0	0.00
		16.0		20.6		27.9		3.61		5.90		8.40		0.02		0.00		0.00
X2H026	158	798	219	1145	233	1292	107	254	145	381	187	478	5	4.00	4	1.00	10	5.00
		17.7		25.3		28.6		5.61		8.43		10.6		0.10		0.02		0.11
X2H027	176	4615	209	6130	227	7561	115	1362	172	2331	193	3098	7	18.0	12	21.0	23	36.0
		20.0		26.6		32.8		5.90		10.1		13.4		0.08		0.09		0.16
X2H028	137	171	191	231	240	340	75	47.0	108	66.0	160	112	5	1.00	2	0.00	21	3.00
		14.6		19.7		29.0		4.04		5.60		9.58		0.09		0.01		0.23
X2H030	100	1422	131	1982	202	3508	33	247	65	407	92	757	2	2.00	0	0.00	1	0.00
		8.84		12.3		21.8		1.53		2.53		4.71		0.02		0.00		0.00

Station Code	Events below 80% ADF: MMDT days	Events below 80% ADF: MMDEF MI / %MAR	5 year return period: DT days	5 year return period: DEF MI / %MAR	10 year return period: DT days	10 year return period: DEF MI / %MAR	Events below 50% ADF: MMDT days	MMDEF MI / %MAR	5 year return period: DT days	5 year return period: DEF MI / %MAR	10 year return period: DT days	10 year return period: DEF MI / %MAR	Events below 20% ADF: MMDT days	MMDEF MI / %MAR	5 year return period: DT days	5 year return period: DEF MI / %MAR	10 year return period: DT days	10 year return period: DEF MI / %MAR
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
X2H031	130	4626	216	7471	241	11070	91	1827	156	3374	197	5069	26	205	53	345	93	461
		1610		25.9		38.4		6.33		11.7		17.6		0.71		1.20		1.60
X3H001	161	9131	232	16604	285	23805	91	3397	177	7691	223	11400	26	553	40	931	120	2285
		18.4		33.5		48.0		6.85		15.5		23.0		1.11		1.88		4.61
X3H002	123	1068	234	2409	263	2842	35	150	98	307	119	443	2	11.0	1	3.00	4	12.0
		10.2		23.1		27.2		1.44		2.94		4.24		0.11		0.03		0.12
X3H004	171	7727	230	11064	266	14017	142	3745	209	5980	265	7947	72	668	143	1252	184	2268
		27.2		38.9		49.3		13.2		21.0		27.9		235		4.40		7.97
X3H006	140	26528	202	44214	231	51929	68	5502	120	10141	143	13604	1	10.0	0	0.00	2	7.00
		13.4		22.4		26.3		2.79		5.14		6.89		0.00		0.00		0.00
X3H007	136	1818	194	2524	252	3808	104	818	151	1200	203	1683	56	156	104	285	157	430
		20.8		28.9		43.6		9.37		13.7		19.3		1.79		3.26		4.93
X3H008	***																	

APPENDIX A5

Recession and baseflow characteristics

The indices listed are the Recession Ratio exceeded by 50 % of recession ratios (REC50, the index which represents the average rate of flow recession), the baseflow recession constant (RCONST) determined by correlation method, the half-flow period (HFP) and BaseFlow Index (BFI). Also listed are the minimum specified duration of recession period (days) used to extract smooth contiguous recession limbs below Average Daily Flow (ADF) from a streamflow record (column 5), and the number of extracted recession limbs (column 6). The time lag between neighbouring discharges was in the range of 3 to 5 days.

A low value of REC50 (less than 0.8) in most of the cases indicates a fast receding stream and consequently, a small or baseflow contribution. In such cases most of the indices are equal to 0.

Comments included in column 9 describe the problems related to the estimation of the baseflow recession constant by the correlation method.

S - short recession limbs interrupted by frequently occurring floods or dry season freshes. The consequence is the lack of recession limbs to define the recession domain. The estimation or RCONST is either impossible or not reliable.

M - measurement accuracy problems. Normally applies to small streams where flows during the recession are very small. This results in a "steppy" decreasing hydrograph and consequently a lack of smooth recession limbs for the analysis (often goes together with S).

R? - the visual analysis of streamflow hydrograph reveals some unnatural patterns which may be a consequence of stream Regulation.

DP- other Data Problems, for example, a short record period with large gaps due to missing data or highly intermittent stream with isolated flood peaks, and so on. In such cases all indices are either not estimated at all or are not reliable.

Baseflow index in the majority of cases is estimated by the digital filter. However, for intermittent streams the rational method is used.

All indices are estimated for the whole available period of record indicated for each gauge in APPENDIX A2. The start date of analysis in all cases is coincident with the beginning of observations.

Station Code	Rivers	Catchment area (km^2)	REC50	Min. rec. prd., days	No of rec. limbs	RCONST	HFP (days)	Comments	BFI
1	2	3	4	5	6	7	8	9	10
A2H029	Edenvalespruit	129	0.861	6	153	0.962	17.7		0.286
A2H032	Selonsrivier	522	0.623	5	112				0.0
A2H039	Waterkloof-Bo	3.6	0.903			0.942	11.6	S,M	0.401
A2H050	Krokodilrivier	148	0.935	6	126	0.980	35		0.403
A2H053	Sterkstroom	88	0.946	6	116	0.980	34		0.356
A3H001	Klein-Maricorivier	1 165	0.850	6	159	0.971	23		0.178
A4H002	Mokolorivier	1 777	0.96	10	179	0.990	70		0.421
A4H008	Sterkstroom	504	0.946	6	330	0.980	34		0.349
A5H004	Palalarivier	629	0.981	10	256	0.993	94		0.395
A6H011	Groot-Nylrivier	73	0.942	6	152	0.971	23		0.438
A6H012	Olifantspruit	120	0.928	10	81	0.990	69		0.278
A6H018	Rasloóprivier	12	0.942					S,M	0.452
A6H019	Hessie se water	16	0.921	5	104	0.932	9.9	S,M	0.498
A6H020	Middelfonteinspruit	43	0.960	6	140	0.987	53		0.285
A6H021	De Wetspruit	16	0.797						0.0
A6H022	Hartbeeslaagte	1.7	0.506					S,M	0.0
A9H001	Luvuvhurivier	915	0.988	6	192	0.993	94		0.559
A9H002	Mutshindudirivier	96	0.985	10	279	0.987	53		0.467
A9H004	Mutalerivier	320	0.985	10	315	0.995	140	R?	0.433
B1H001	Olifantsrivier	3 904	0.921	10	200	0.992	125		0.146
B1H002	Spookspruit	252	0.924	10	193	0.976	29.1		0.213

Station Code	Rivers	Catchment area (km^2)	REC50	Min. rec. prd., days	No of rec. limbs	RCONST	HFP (days)	Comments	BFI
1	2	3	4	5	6	7	8	9	10
B2H001	Bronkhorstspruit	1 594	0.896	8	110	0.962	17.7		0.213
B3H001	Olifantsrivier	16 553	0.892	8	153	0.968	21.2		0.244
B4H005	Watervalrivier	188	0.981	10	92	0.990	71		0.447
B4H009	Dwarsrivier	448	0.946	10	48	0.976	29		0.267
B5H002	Olifantsrivier	31 416	0.931	10	61	0.955	15.2		0.30
B6H001	Blyderivier	518	0.988	6	222	0.998	278		0.522
B6H002	Treurrivier	97	0.985	6	170	0.995	140		0.291
B6H003	Treurriver	92	0.985	6	212	0.998	279		0.406
B7H003	Selatirivier	84	0.921	10	20	0.961	20		0.143
B7H004	Klaserierivier	136	0.953	6	136	0.978	301		0.367
B7H008	Selatirivier	832	0.914	6	47	0.976	29	S	0.07
B7H009	Olifantsrivier	42 472	0.96	10	99	0.986	48		0.289
B7H010	Ngwabitsrivier	318	0.914	6	60	0/986	47		0.207
B7H014	Selativrivier	83	0.949	10	43	0.972	24		0.231
B9H001	Shisharivier	648	0.531						0.0
C1H008	Watervalrivier	2 212	0.967						0.0
C2H026	Middelvleispruit	26	0.769					S,M,R?	0.34
C2 H027	Kocksoortdspruit	4						S,M	0.151
C2H028	Rietfonteinspruit	31	0.783					S,M,R?	0.306
C2H065	Leeudoringspruit	860	0.854	6	111	0.971	23		0.106
C2H067	Sandspruit	1 895	0.764						0.0
C3H003	Hartsrivier	10 990	0.751						0.0

Station Code	Rivers	Catchment area (km^2)	REC50	Min. rec. prd., days	No of rec. limbs	RCONST	HFP (days)	Comments	BFI
1	2	3	4	5	6	7	8	9	10
C4H002	Vetrivier	17 599						DP	
C5H007	Renosterspruit	348	0.769					R?	0.0
C5H008	Rietrivier	593	0.694					R?	0.0
C5H012	Rietrivier	2 372	0.776					R?	0.0
C6H003	Valsrivier	7 765	0.846	6	194	0.971	55.6		0.04
C6H004	Valsrivier	856	0.769	3	152	0.935	10		0.03
C7H003	Heuningspruit	914	0.549						0.0
C8H003	Corneliusrivier	806	0.889	10	281	0.985	47		0.205
C8H005	Elandsrivier	696	0.924	6	345	0.981	35		0.196
C8H012	Vaalbankspruit	386	0.854	6	182	0.971	23		0.113
C8H022	Wilgerivier	15 466	0.946	10	209	0.987	53		0.168
D1H011	Kraairivier	8 688	0.942	10	181	0.986	47		0.246
D2H012	Klein-Caledonrivier	518	0.931	6	187	0.985	46		0.254
D2H020	Caledonrivier	8 339	0.51						0.0
D4H003	Swartbasrivier	181						DP	0.0
D5H003	Visrivier	1 509						DP	0.0
D5H013	Sakrivier	13 087	0.733						0.0
E1H006	Jan Disselsrivier	160	0.963	10	95	0.985	47		0.308
E2H002	Doringrivier	6 903	0.960	10	517	0.981	35		0.248
E2H007	Leeurivier	265	0.885	10	63	0.981	35		0.171
G1H002	Vier en twintig	187	0.974	10	40	0.985	47		0.304
G1H003	Franschhoekrivier	46	0.921	6	341	0.990	69.7		0.312

Station Code	Rivers	Catchment area (km^2)	REC50	Min. rec. prd., days	No of rec. limbs	RCONST	HFP (days)	Comments	BFI
1	2	3	4	5	6	7	8	9	10
G1H007	Bergrivier	713	0.907	6	242	0.962	18		0.304
G1H008	Klein-Bergrivier	395	0.907	6	383	0.981	35		0.288
G1H009	Brakkloofspruit	5.7	0.680					S,M,R?	0.114
G1H010	Knolvleispruit	10	0.684					S,M,R?	0.134
G1H011	Watervalsrivier	27	0.935	10	125	0.971	24		0.294
G1H012	Watervalsrivier	36	0.917	10	133	0.985	47		0.298
G1H014	Zachariashoekrivier	2.8	0.921					S,M,R?	0.348
G1H015	Kasteelkloofspruit	1.9	0.917	4	312	0.926	9.0	S,M,R?	0.314
G1H016	Kasteelkloofspruit	3.3	0.946	10	50	0.962	18	S,M	0.326
G1H017	Zachariashoekspruit	1.7	0.882					S,M,R?	0.342
G1H018	Bakkerskloofspruit	3.4	0.903	6	190	0.952	14		0.271
G1H019	Banghoekrivier	25						DP	0.0
G1H021	Klein-Bergrivier	19	0.981	6	230	0.990	70		0.371
G1H028	Vier-en-twintig	183	0.035					R	0.0
G2H008	Jonkershoekrivier	20	0.864	6	441	0.985	47		0.215
G2H012	Dieprivier	244	0.885	6	146	0.971	24		0.204
G3H001	Kruisrivier	647	0.921	6	140	0.967	21		0.134
G4H006	Kleinrivier	600	0.921	6	212	0.971	23		0.170
G4H008	Klein-Jakkalsrivier	1.5	0.892					S,M	0.340
G4H009	Jakkalsrivier	2	0.80					S,M	0.297
G3H013	Klein-Jakkalsrivier	2.1	0.871					S,M	0.293
G4H014	Botrivier	252	0.903	6	209	0.980	35		0.296

Station Code	Rivers	Catchment area (km^2)	REC50	Min. rec. prd., days	No of rec. limbs	RCONST	HFP (days)	Comments	BFI
1	2	3	4	5	6	7	8	9	10
G5H006	Klein-Sandriftriver	3.2	0.949					S,M	0.478
G5H005	Soutrivier	382	0.928	6	69	0.971	23		0.10
H1H007	Witrivier	84	0.939	6	657	0.981	35		0.208
H1H012	Holslootrivier	146	0.977	6	138	0.981	35		0.291
H1H013	Koekedourivier	53	0.917	6	209	0.995	139		0.247
H1H017	Elandsrivier	61	0.981	6	58	0.993	131		0.282
H1H018	Molenaarsrivier	113	0.974	10	154	0.990	71		0.339
H2H001	Hexrivier	697	0.974	10	84	0.980	35		0.369
H2H005	Rooi-Elskloofrivier	15	0.985	6	217	0.993	100		0.440
H3H001	Kingnarivier	593						DP	0.0
H3H004	Keisierivier	14						DP	0.0
H3H005	Keisierivier	76	0.726						0.0
H4H005	Willem Nelsrivier	24	0.924	6	229	0.980	35		0.324
H4H009	Hoeksrivier	18						DP	0.0
H4H012	Waterkloofspruit	14	0.515						0.0
H6H003	Riviersonderend	497	0.928	6	352	0.981	35		0.253
H6H006	Elandsrivier	56	0.854	6	48	0.909	7.3		0.241
H6H008	Riviersonderend	38	0.921	10	202	0.971	23		0.209
H6H010	Waterkloofrivier	15	0.974	10	100	0.982	39		0.550
H7H00	Breerivier	9 829	0.942	5	370	0.962	18		0.230
H7H003	Buffeljagsrivier	450	0.845	10	124	0.964	19		0.169
H7H004			0.825	6	218	0.962	18		0.140

Station Code	Rivers	Catchment area (km^2)	REC50	Min. rec. prd., days	No of rec. limbs	RCONST	HFP (days)	Comments	BFI
1	2	3	4	5	6	7	8	9	10
H7H007	Grootkloofrivier	24	0.942	6	344	0.990	70		0.338
H9H004	Kruisrivier	50	0.960	10	156	0.990	70		0.346
H9H005	Kafferkuilsrivier	228	0.889	10	159	0.976	28		0.158
J1H015	Bokrivier	8.8	0.985	6	131	0.971	23	M,R?	0.410
J1H016	Smalblaarrivier	30	0.903	6	104	0.952	14		0.200
J2H005	Huisrivier	253	0.894	6	186	0.980	35		0.245
J2H006	Boplaasrivier	225	0.860					S,M,R?	0.223
J2H007	Joubertrivier	25	0.879					S,M,R?	0.269
J3H012	Grootrivier	688	0.899	10	52	0.952	14		0.208
J3H013	Perdepoortrivier	29	0.985					DP	0.462
J3H016	Wilgerivier	32	0.900					S,DP	0.275
J3H017	Kandelaarsrivier	348	0.776	6	92	0.962	18	R?	0.137
J3H018	Wynandsrivier	137	0.896	6	230	0.971	23		0.286
J3H020	Meulrivier	35	0.712					DP	0.208
J4H003	Weyersrivier	95	0.931	6	391	0.990	70		0.210
J4H004	Langtourivier	99	0.910	6	199	0.962	18		0.293
K1H001	Hartenbosrivier	144	0.885						0.0
K1H002	Benekerivier	3.80	0.942			0.966	20	S,M	0.290
K3H001	Kaaimansrivier	47	0.953	10	215	0.990	69		0.226
K3H002	Rooirivier	1.04	0.680					S,M	0.124
K3H003	Maalgaterivier	145	0.885	6	491	0.990	70		0.163
K3H004	Malgasrivier	34	0.903	10	198	0.990	69		0.199

Station Code	Rivers	Catchment area (km^2)	REC50	Min. rec. prd., days	No of rec. limbs	RCONST	HFP (days)	Comments	BFI
1	2	3	4	5	6	7	8	9	10
K3H005	Touwsrivier	78	0.953	10	112	0.994	119		0.268
K4H001	Hoekraalrivier	111	0.892	6	364	0.962	18		0.215
K4H002	Karatararivier	22	0.903	6	484	0.971	23		0.184
K4H003	Dieprivier	72	0.967	10	205	0.987	53		0.312
K5H002	Knysnarivier	133	0.956	10	209	0.990	71		0.304
K6H001	Keurboomsrivier	165	0.931	10	198	0.992	87		0.274
K6H002	Keurboomsrivier	764	0.963	6	277	0.990	70		0.355
K7H001	Bloukransrivier	57	0.946	10	160	0.990	70		0.255
L1H001	Soutrivier	3 938						DP	0.0
L6H001	Heuningkliprivier	1 290						DP	0.0
L8H001	Harlemspruit	52	0.939	10	144	0.985	47		0.283
L8H002	Waboomsrivier	21	0.917	10	114	0.990	70		0.210
N2H009	Volkesrivier	536	0.882	10	90	0.981	36		0.134
P4H001	Kowierivier	576	0.931	6	191	0.980	35		0.166
Q1H001	Groot-Visrivier	9 091						DP	0.0
Q1H009	Klein-Brakrivier	1 211						DP	0.0
Q3H004	Paulsrivier	872	0.967	6	101	0.992	82	DP	0.283
Q4H003	Vlekpoortrivier	1 300	0.857	6	106	0.967	20		0.222
Q6H003	Baviaansrivier	814	0.839	6	123	0.978	31		0.04
Q9H002	Koonaprivier	1 245	0.769						0.0
Q9H013	Kaprivier	46	0.885	6	38	0.952	14		0.125
Q9H016	Koonaprivier	489	0.698	6	56	0.914	7.7		0.118

Station Code	Rivers	Catchment area (km^2)	REC50	Min. rec. prd., days	No of rec. limbs	RCONST	HFP (days)	Comments	BFI
1	2	3	4	5	6	7	8	9	10
Q9H017	Blinkwaterrivier	226	0.892	6	100	0.971	23		0.191
Q9H019	Balfourivier	76	0.917	10	78	0.980	35		0.268
R1H001	Tyumerivier	238	0.889						0.0
R1H005	Keiskammarivier	482	0.946	10	105	0.975	28		0.297
R1H006	Rabularivier	100	0.924	10	123	0.977	30		0.300
R1H007	Mtwakurivier	33	0.90	6	57	0.943	12		0.387
R1H014	Tyumerivier	70	0.967	10	216 0	0.996	70		0.35
R1H015	Keiskammarivier	2 530	0.931	10	161	0.987	53		0.219
R2H001	Buffelsrivier	29	0.942	10	188	0.985	47		0.329
R2H005	Buffelsrivier	411	0.913	10	79	0.980	35		0.230
R2H006	Mgqakweberivier	119	0.937	10	127	0.981	36		0.247
R2H008	Quencwerivier	61	0.894	10	102	0.987	51	R?	0.110
R2H012	Mgqakweberivier	15	0.937	10	140	0.985	46		0.250
S3H002	Klaas Smitsrivier	796	0.656						0.0
S3H004	Swart-Keirivier	1 413	0.777						0.0
S3H006	Klaas Smitsrivier	2 170	0.816						0.0
S6H002	Kubusrivier	49	0.935	6	189	0.990	70		0.257
S6H003	Toiserivier	215	0.939	10	105	0.986	48		0.259
T1H004	Basheerivier	4 908	0.960	5	219	0.990	71		0.251
T2H002	Mtatarivier	1 199	0.967	10	119	0.990	71		0.323
T3H002	Kiwirarivier	2 101	0.962	10	152	0.990	70	DP	0.193
T3H004	Mzintlavarivier	1 029	0.976	10	247	0.995	139		0.356

Station Code	Rivers	Catchment area (km²)	REC50	Min. rec. prd., days	No of rec. limbs	RCONST	HFP (days)	Comments	BFI
1	2	3	4	5	6	7	8	9	10
T3H005	Tinarivier	2 597	0.962	10	61	0.990	70		0.272
T3H008	Mzimvuburivier	2 471	0.957	10	187	0.993	94		0.267
T3H009	Mooirivier	307	0.952	10	97	0.996	177		0.233
T4H001	Mtamvunarivier	715	0.981	10	167	0.995	139		0.440
T5H002	Bisirivier	867	0.986	10	151	0.996	184		0.560
T5H003	Polelarivier	140	0.962	10	188	0.993	105		0.312
T5H004	Mzimkulurivier	545	0.976	10	132	0.998	302		0.307
T5H005	Nkonzorivier	100	0.981	10	95	0.997	210		0.304
T6H001	Mntafufurivier	108	0.967	10	33	0.993	105	DP	0.250
U1H005	Mkomazirivier	1 744	0.981	10	178	0.990	71		0.304
U1H006	Mkomazirivier	4 349	0.981	10	194	0.997	209		0.372
U2H001	Mgenirivier	937	0.986	10	124	0.995	140		0.401
U2H006	Karkloofrivier	339	0.971	10	108	0.996	160		0.347
U2H007	Lionsrivier	358	0.981	10	154	0.995	139		0.409
U2H011	Msunduzerivier	176	0.981	10	130	0.995	144		0.349
U2H012	Sterkrivier	438	0.967	10	102	0.996	193		0.299
U2H013	Mgenirivier	299	0.981	10	177	0.995	139		0.388
U3H002	Mdlotirivier	356	0.971	10	162	0.993	100		0.417
U4H002	Mvotirivier	316	0.986	10	201	0.997	209		0.433
U4H003	Hlimbitwarivier	49	0.885	6	89	0.962	18		0.283
U6H002	Mlazirivier	105	0.981	6	97	0.990	71		0.445
U7H001	Zwatenirivier	16	0.962	6	189	0.987	53	S	0.365

Station Code	Rivers	Catchment area (km^2)	REC50	Min. rec. prd., days	No of rec. limbs	RCONST	HFP (days)	Comments	BFI
1	2	3	4	5	6	7	8	9	10
U7H007	Lovurivier	114	0.976	10	10	0.990	71		0.359
V1H001	Tugelarivier	4 176	0.977	10	101	0.990	71		0.320
V1H002	Tugelarivier	1 689	0.981	10	138	0.990	71		0.467
V1H009	Bloukransrivier	196	0.845	6	409	0.976	28		0.112
V1H010	Klein-Tugelarivier	782	0.931	10	99	0.990	70		0.352
V1H029	Geluksburgspruit	21	0.865	6	123	0.962	18		0.181
V1H031	Sandspruit	162	0.845	6	207	0.981	35		0.189
V1H034	Khomberivier	51	0.928	6	76	0.976	28	DP	0.181
V1H041	Mlambonjarivier	434	0.981	10	86	0.990	71		0.364
V2H001	Mooirivier	1 976	0.967	10	108	0.990	70		0.335
V2H005	Mooirivier	260	0.971	10	198	0.997	198		0.370
V2H006	Klein-Mooirivier	188	0.962	10	178	0.995	153		0.297
V2H007	Hlatikulurivier	109	0.981	10	201	0.997	203		0.340
V3H002	Buffelsrivier	1 518	0.971	6	120	0.997	205		0.292
V3H003	Ngagancrivier	850	0.957	6	156	0.993	101		0.296
V3H005	Slangrivier	676	0.931	10	183	0.990	71		0.212
V3H007	Ncandurivier	129	0.946	10	144	0.996	165		0.270
V3H009	Hornrivier	148	0.91	10	135	0.992	85		0.257
V5H002	Tugelarivier	28 920	0.963	10	102	0.995	140		0.316
V6H003	Wasbankrivier	312	0.931	10	153	0.994	117		0.258
V6H004	Sondagsrivier	658	0.939	10	230	0.993	94		0.229
V7H018	Kleinboesmansrivier	119	0.942	10	87	0.993	92		0.263

Station Code	Rivers	Catchment area (km^2)	REC50	Min. rec. prd., days	No of rec. limbs	RCONST	HFP (days)	Comments	BFI
1	2	3	4	5	6	7	8	9	10
W1H004	Mlalazrivier	20	0.864	6	201	0.984	44		0.310
W1H006	Mhlatuzerivier	1 272	0.832	6	70	0.971	23		0.193
W1H010	Matigulurivier	455	0.924	10	102	0.990	69		0.232
W1H018	Manzamnyamarivier	10	0.875	6	44	0.973	25	S	0.281
W1H019	Siyayarivier	9	0.884	6	40	0.964	18	S	0.261
W1H025	Mlalazisystroom	20	0.763					S,M	0.430
W2H002	Swart-Mfolozirivier	3 468	0.874	10	19	0.943	12		0.239
W2H006	Swart-Mfolozirivier	1 648	0.962	10	70	0.990	70		0.291
W2H009	Wit-Mfolozirivier	432	0.942	6	246	0.990	69		0.277
W3H011	Mkuzerivier	5 027	0.986	10	80	0.990	70		0.272
W3H014	Mpaterivier	48	0.918	6	234	0.989	61		0.223
W4H004	Bivanerivier	948	0.981	10	201	0.993	94		0.366
W4H008	Braksloot	3.5	0.860					S,M	0.369
W5H001	Jessievalespruit	15	0.860					S,M	0.441
W5H006	Swartwaterrivier	180	0.976	10	221	0.990	71		0.361
W5H007	Usuturivier	531	0.947	10	89	0.991	75		0.218
W5H008	Bonnie Brook	118	0.962	10	150	0.994	112		0.386
W5H011	Mpuluzirivier	910	0.976	15	88	0.997	209		0.281
X1H003	Komatirivier	8 614	0.985	10	162	0.990	70	DP	0.465
X1H014	Mlumatirivier	1 119	0.889	6	152	0.981	35	S,DP	0.306
X2H002	Witrivier	176	0.889	5	120	0.950	13	S,DP	0.291
X2H005	Nelsrivier	642	0.973	5	344	0.994	115	S,DP	0.535

Station Code	Rivers	Catchment area (km^2)	REC50	Min. rec. prd., days	No of rec. limbs	RCONST	HFP (days)	Comments	BFI
1	2	3	4	5	6	7	8	9	10
X2H008	Queensrivier	180	0.957	6	437	0.990	69	S,M,DP	0.408
X2H010	Noordkaaprivier	126	0.986	10	164	0.993	105	M,R?	0.512
X2H011	Elandsrivier	402	0.976	10	138	0.990	69	M,R?	0.455
X2H012	Dawsons'spruit	91	0.981	10	133	0.996	179		0.404
X2H013	Krokodilrivier	1 518	0.981	10	134	0.995	139		0.406
X2H014	Houtbosloop	250	0.986	10	185	0.995	139		0.517
X2H015	Elandsrivier	1 554	0.985	6	383	0.990	70		0.458
X2H024	Suidkaaprivier	80	0.985	10	111	0.995	140		0.575
X2H025	Houtbosloop	25	0.985	10	80	0.995	133		0.509
X2H026	Beestekraalspruit	14	0.985	6	190	0.991	80		0.510
X2H027	Blystaanspruit	78	0.988	6	345	0.998	294		0.467
X2H028	Kantoorbosspruit	5.7	0.960					S,M	0.529
X2H030	Suidkaaprivier	57	0.985	6	232	0.995	130	S	0.527
X2H031	Suidkaaprivier	262	0.967	6	275	0.990	70		0.460
X3H001	Sabierivier	174	0.986	6	382	0.991	82	S,DP	0.519
X3H002	Klein-Sabierivier	55	0.986	5	378	0.996	190	S,DP	0.610
X3H003	Mac-Macrivier	52	0.986					S,M,DP	0.612
X3H004	Noordsandrivier	200	0.957	6	410	0.990	70		0.382
X3H006	Sabierivier	766	0.986	10	141	0.995	139		0.514
X3H007	White Watersrivier	46	0.962	6	297	0.993	98		0.399
X3H008	Sandrivier	1 064	0.937	6	243	0.990	69	DP	0.240

APPENDIX A6

Maps of selected low-flow characteristics

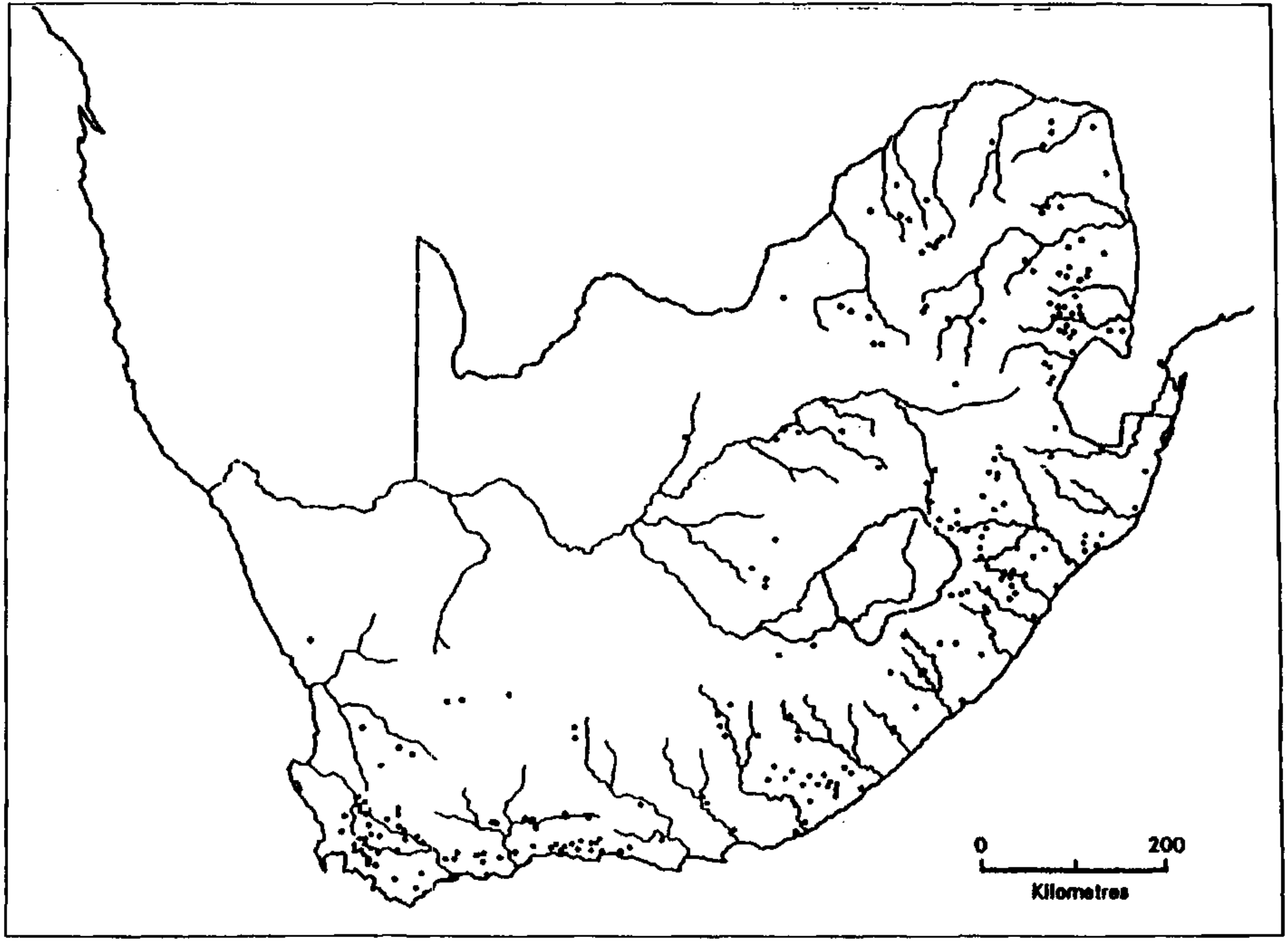


Figure A6.1 Flow gauging stations used for mapping of low-flow indices.

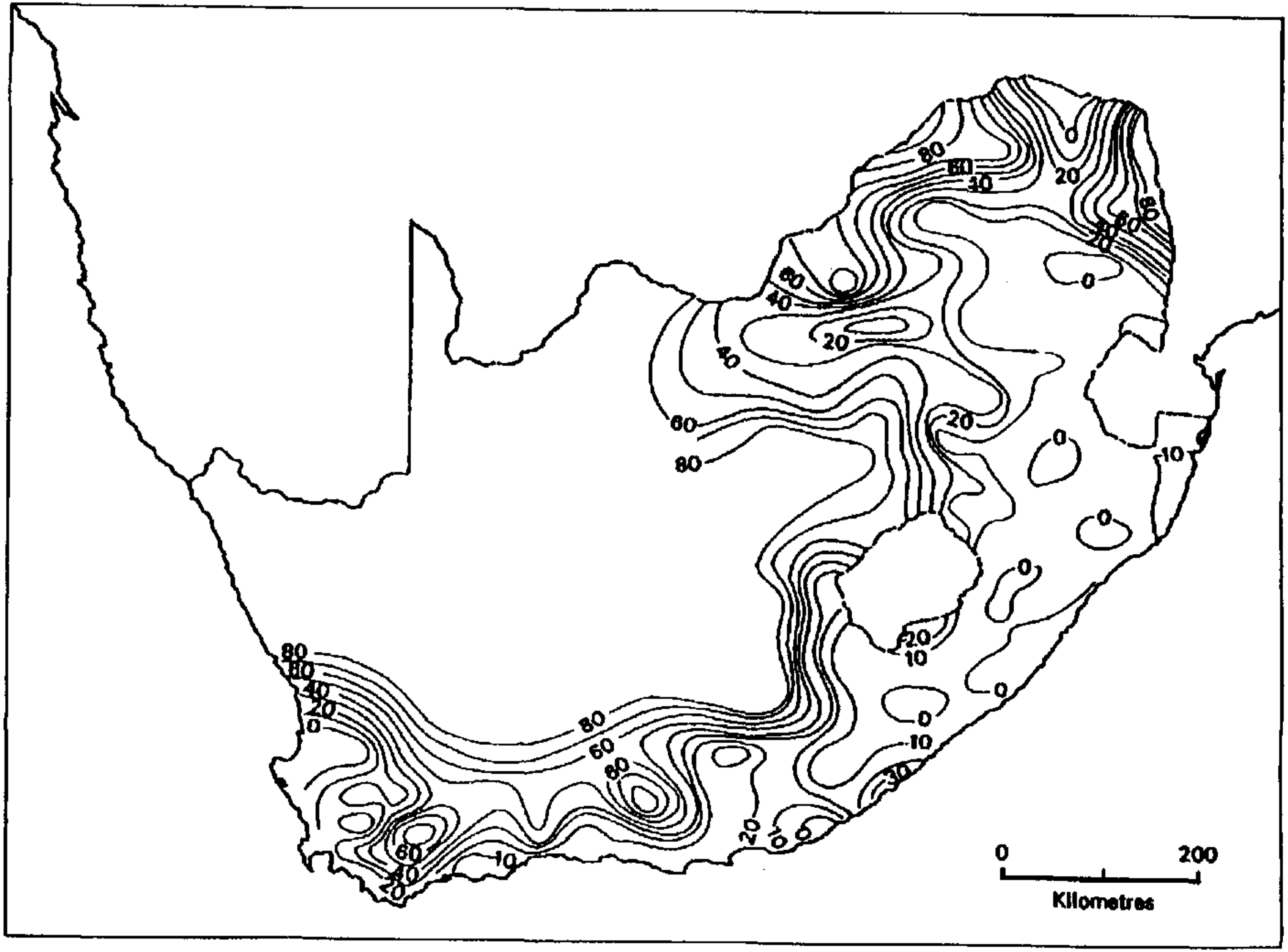


Figure A6.2 Spatial distribution of the percentage of time with zero flows

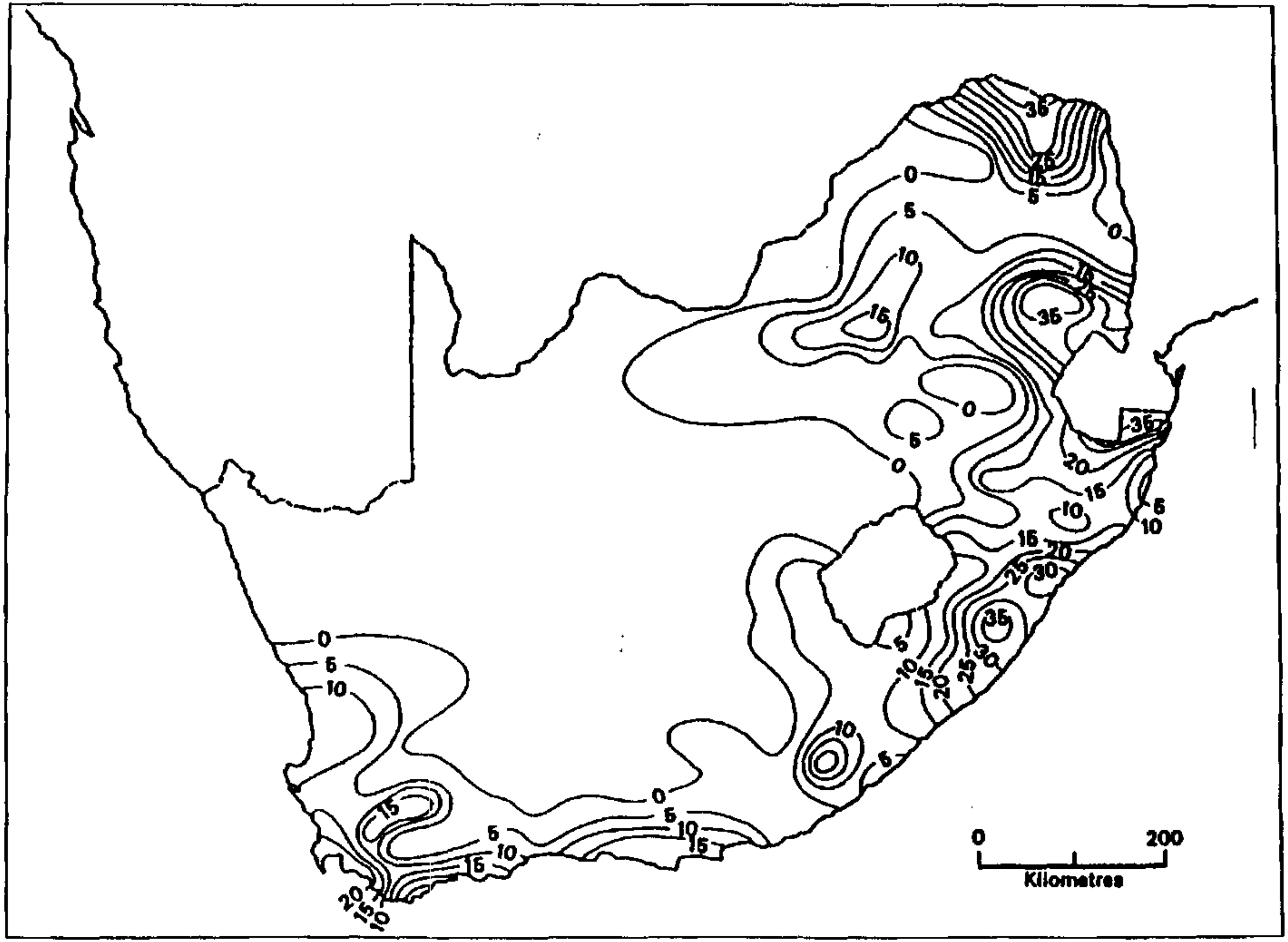


Figure A6.3 Spatial distribution of 1-day 75-percentile flow (percentage of ADF).

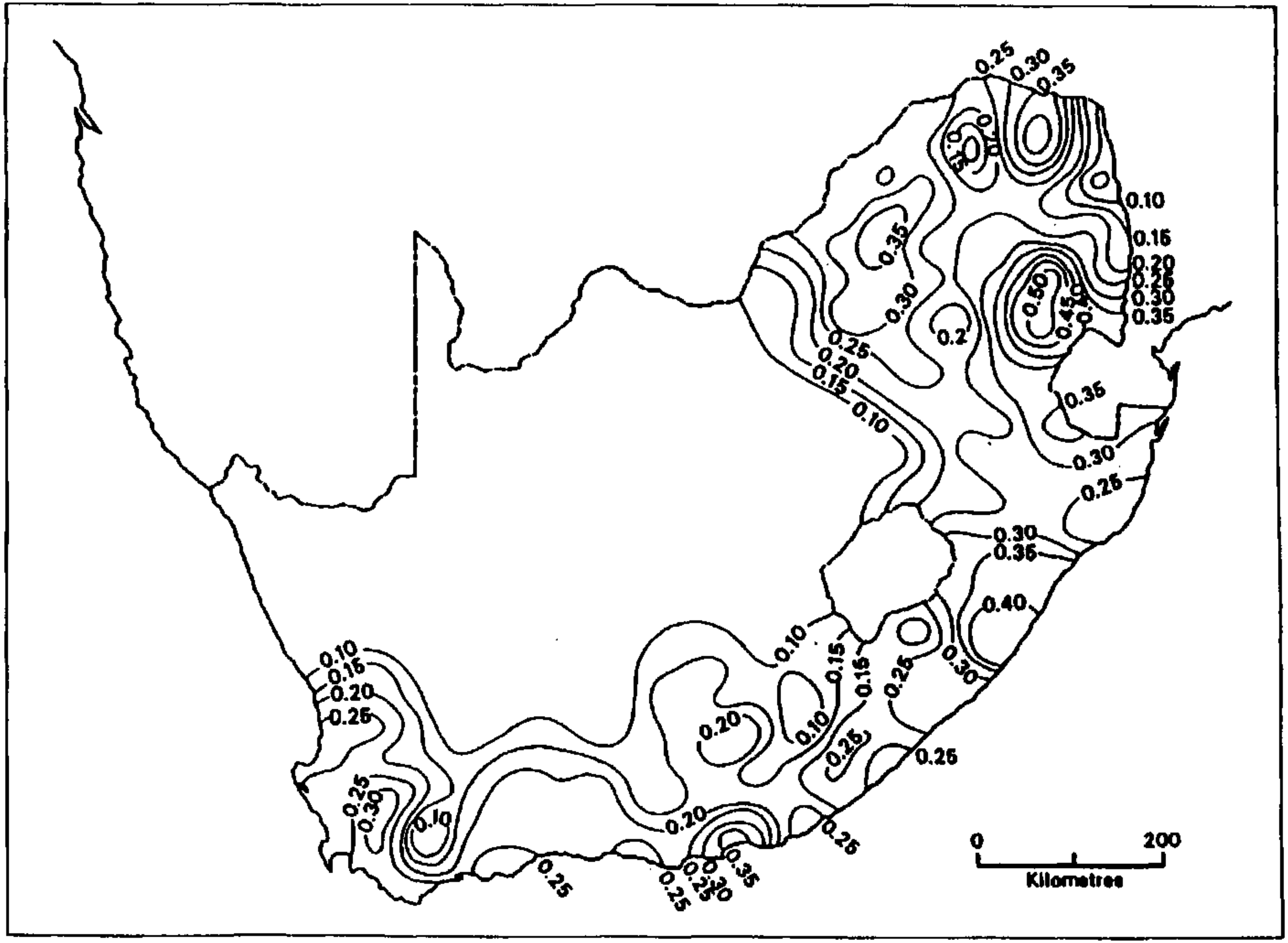


Figure A6.4 Spatial distribution of baseflow index

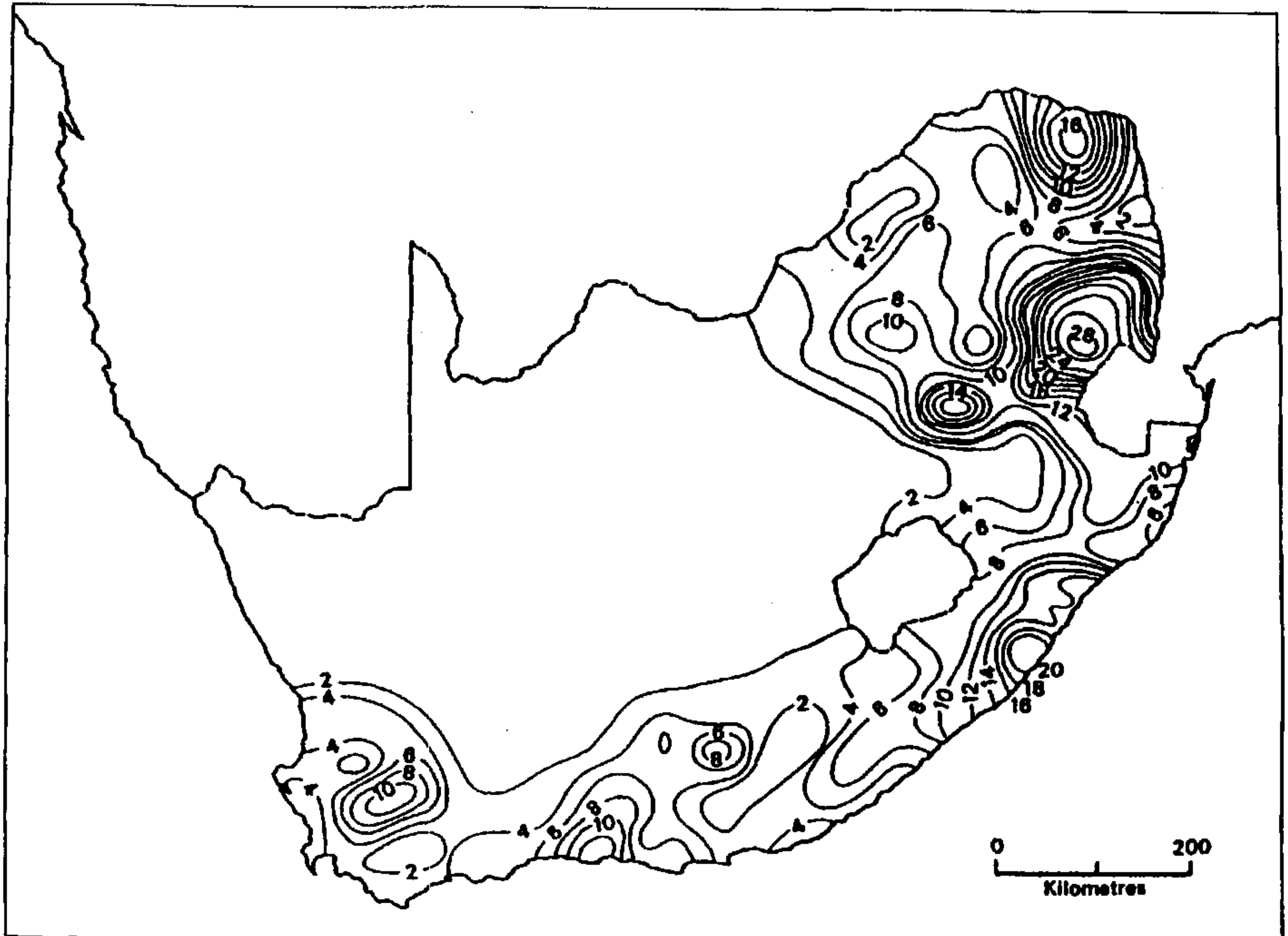


Figure A6.5 Spatial distribution of mean annual 10-day minimum flow (percentage of ADF).

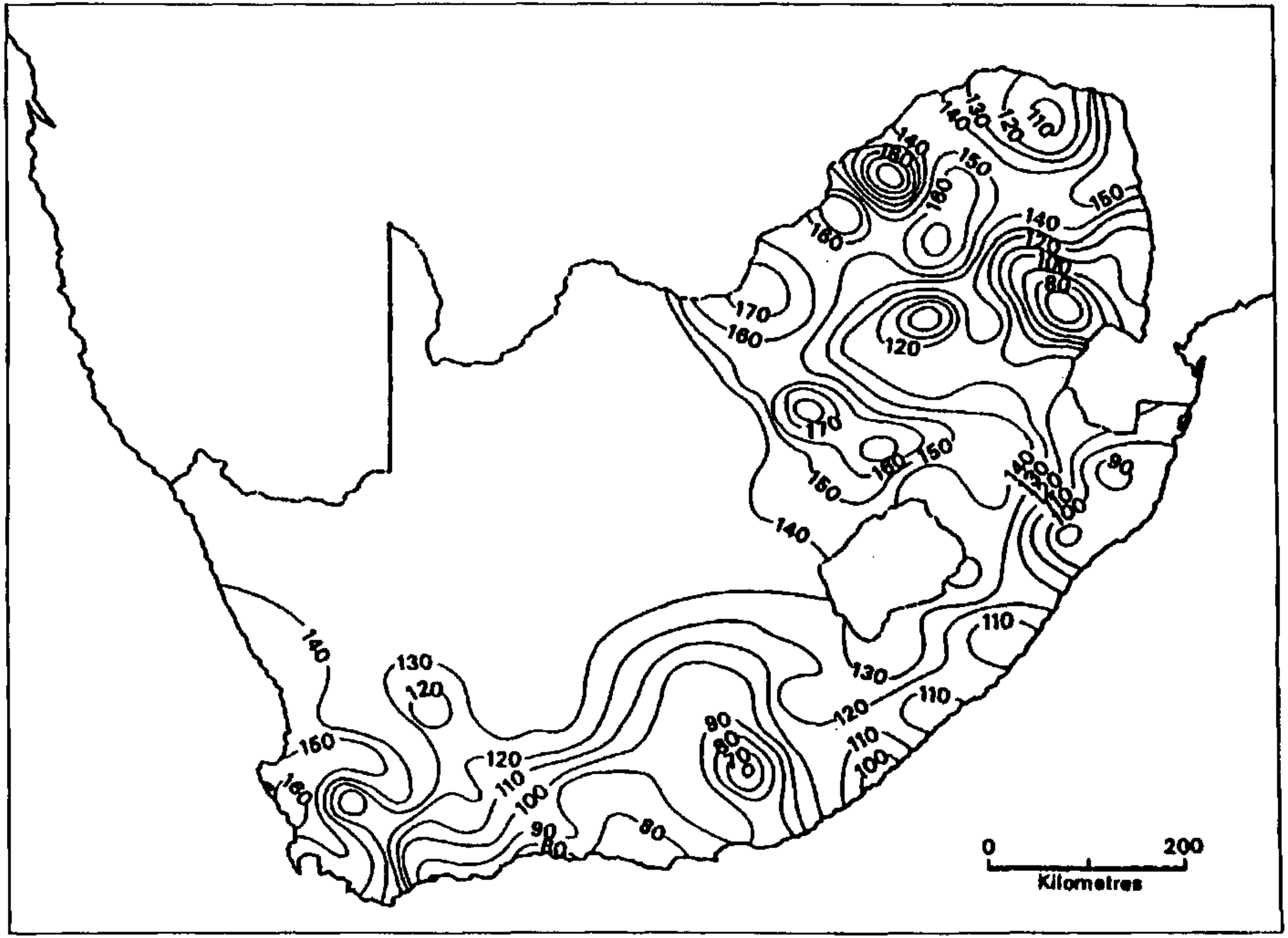


Figure A6.6 Spatial distribution of mean annual maximum duration of low-flow spells below 50% ADF (days).

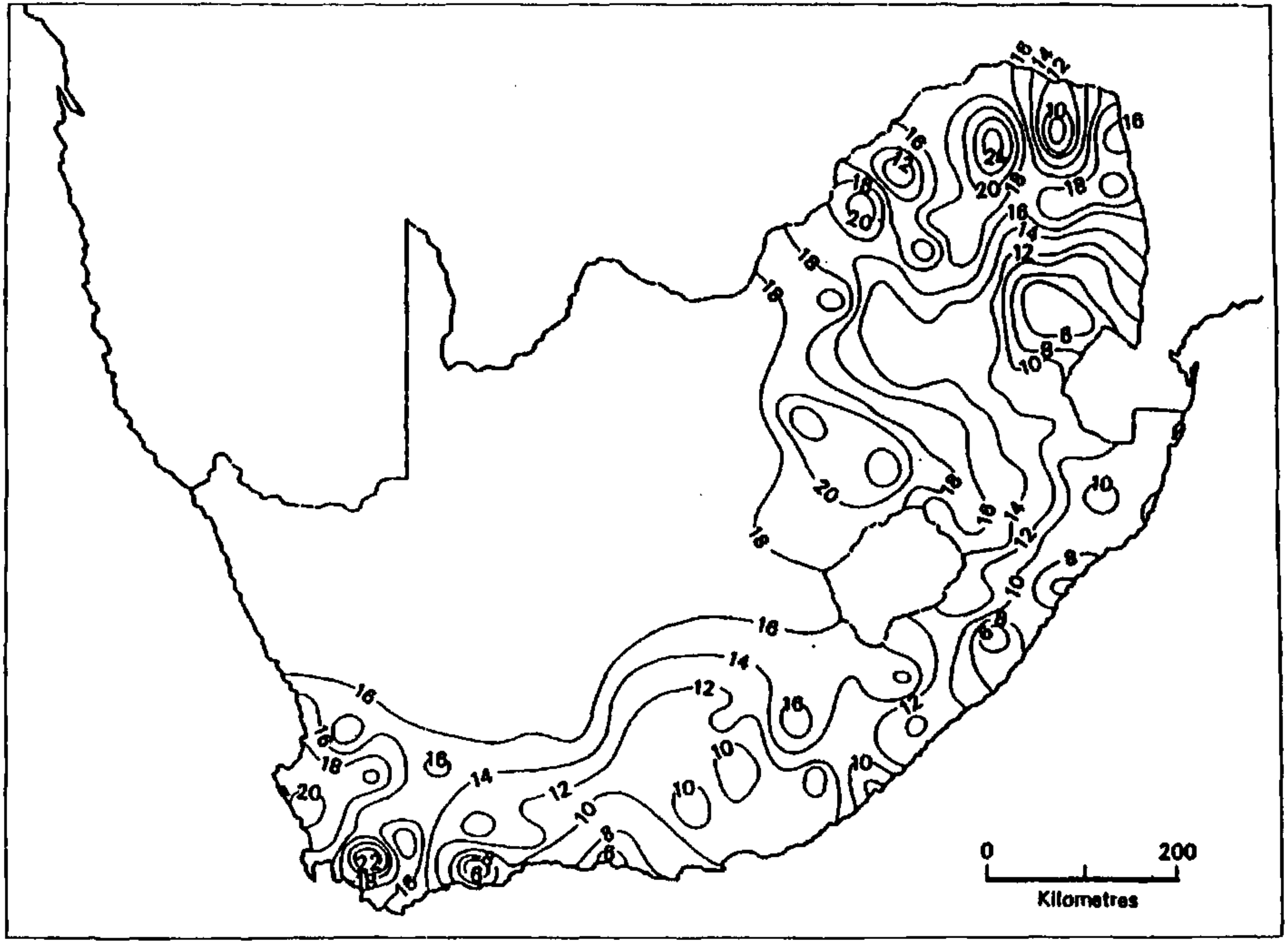


Figure A6.7 Spatial distribution of mean annual maximum deficit volume below 50% ADF (percentage of MAR)

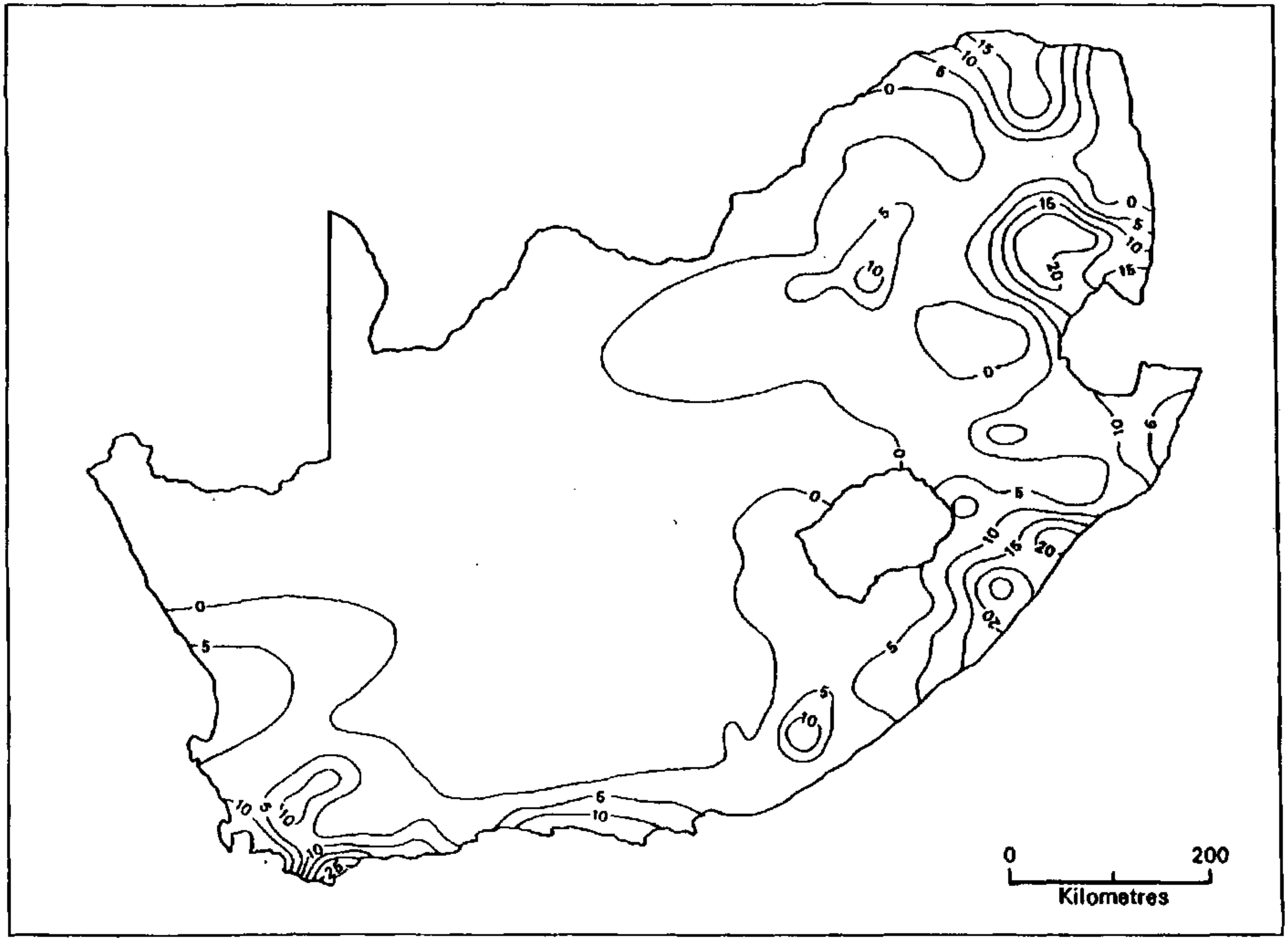


Figure A6.8 Spatial distribution of 1-day 90-percentile flow (percentage of ADF).

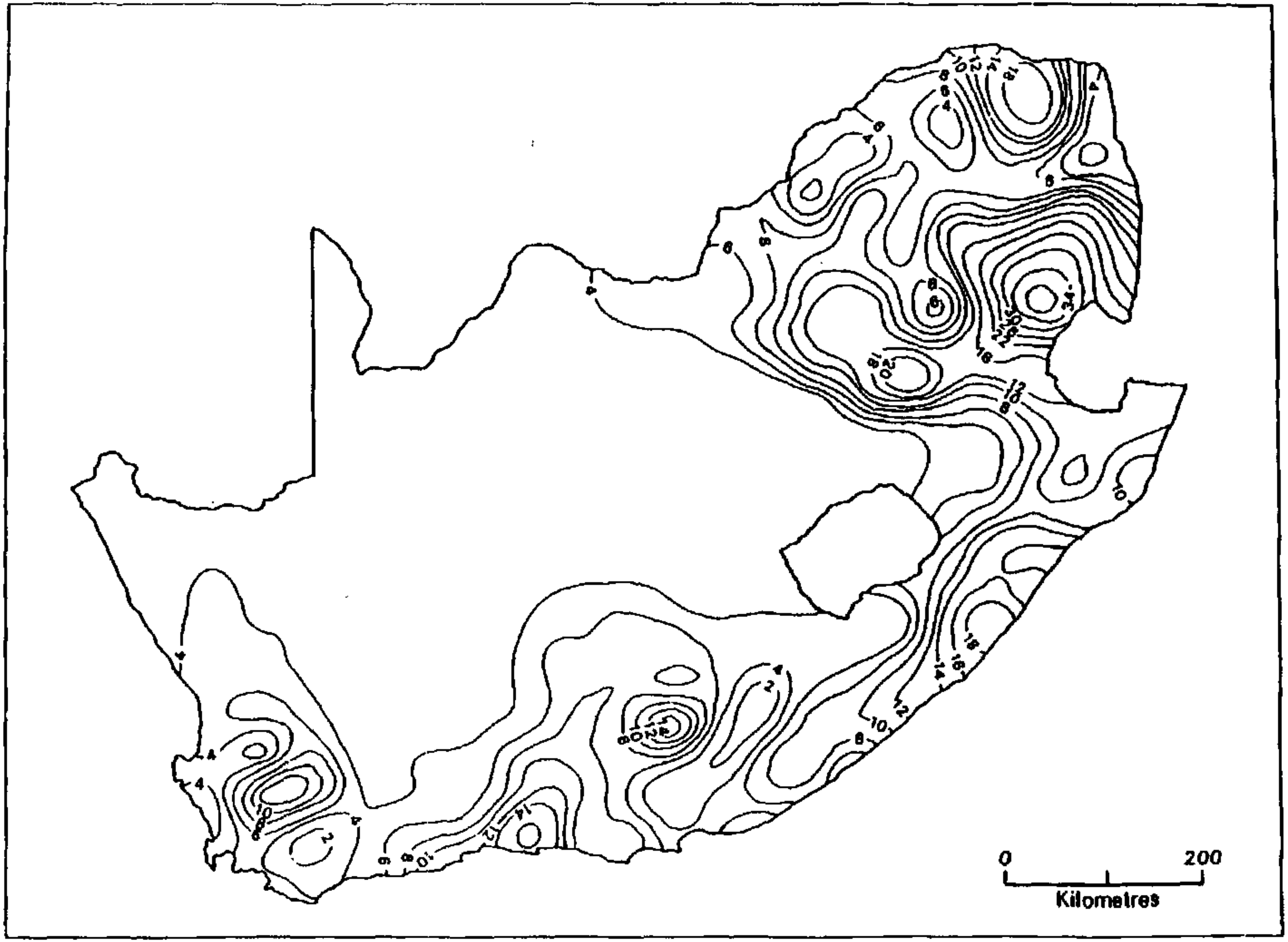


Figure A6.9 Spatial distribution of mean annual 30-day minimum flow (percentage of ADF).

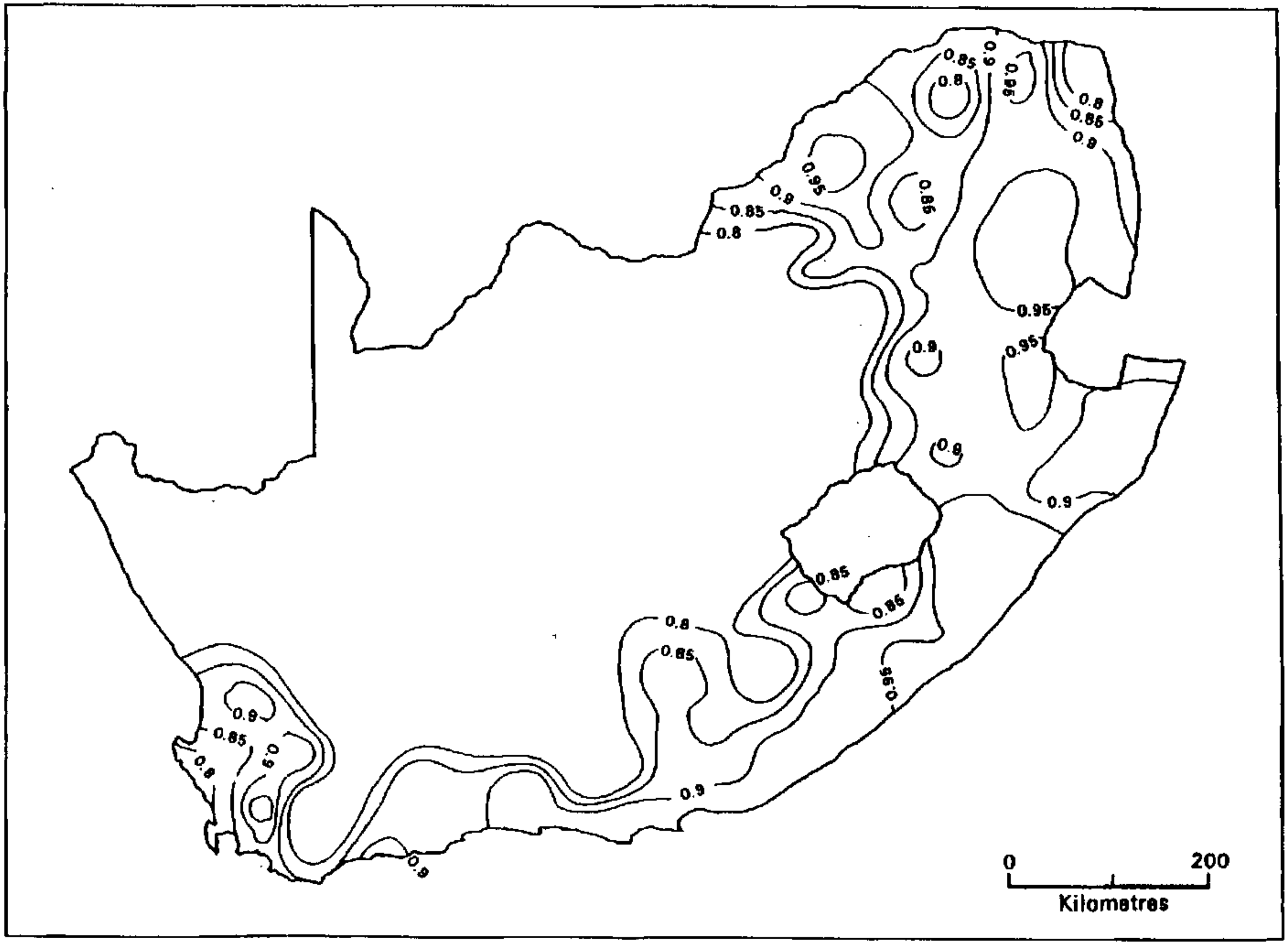


Figure A6.10 *Spatial distribution of 50-percentile recession ratio (REC50)*

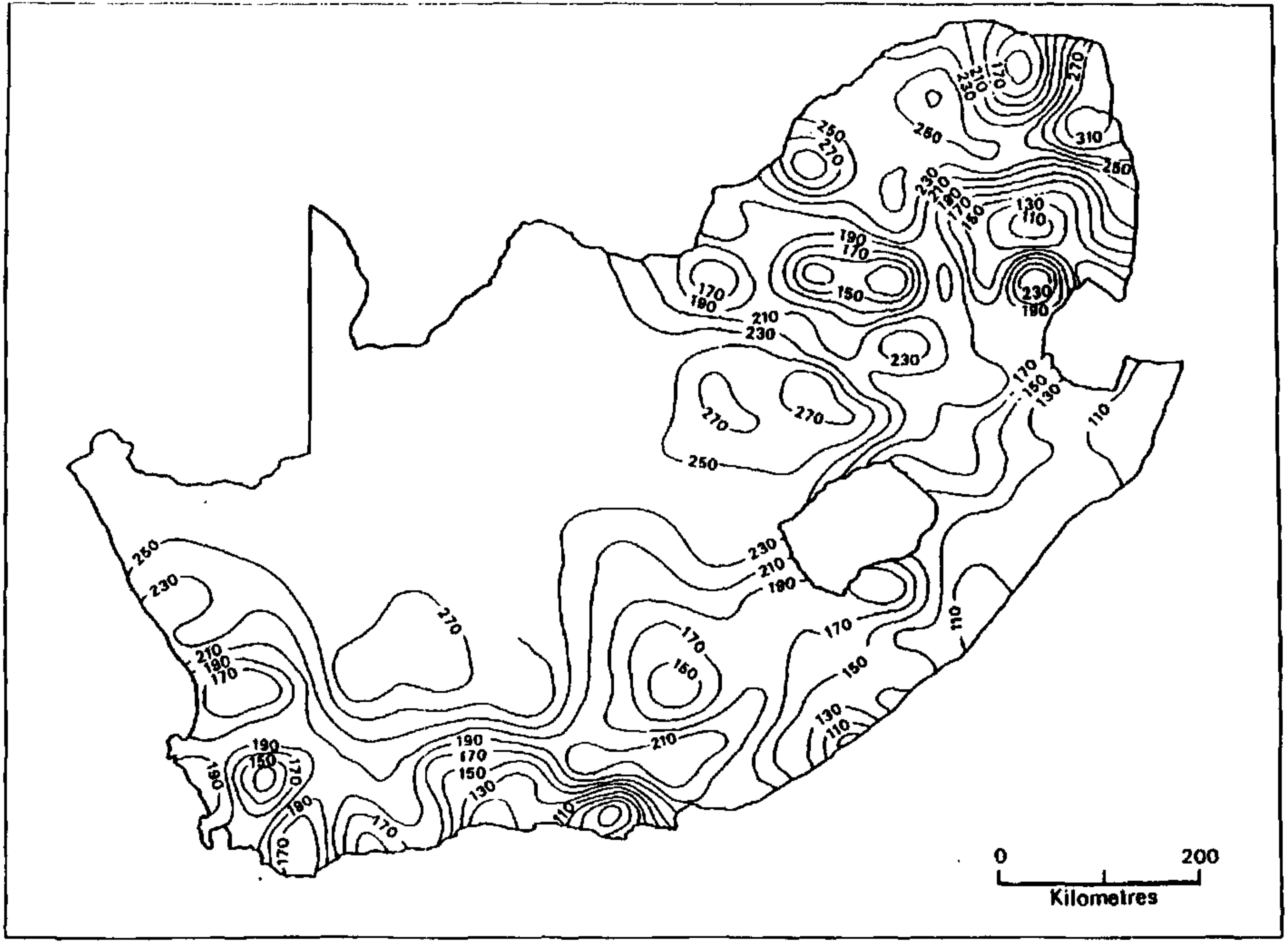


Figure A6.11 *Spatial distribution of 1 in 10-year low-flow spell duration below 20% ADF (days).*

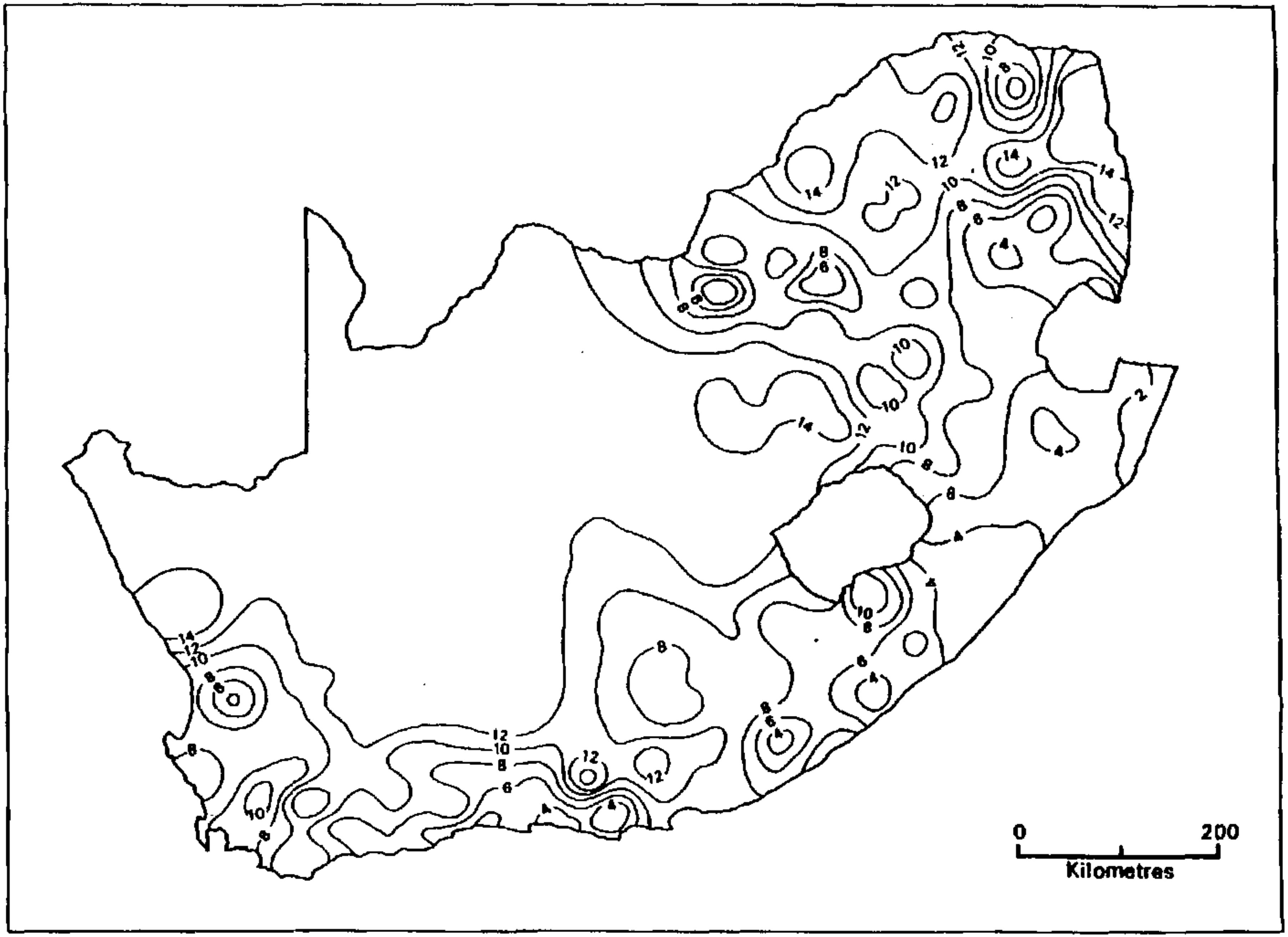


Figure A6.12 *Spatial distribution of 1 in 10-year deficit volume below 20% ADF (percentage of MAR).*

VOLUME II

INTRODUCTION

Volume II summarises the results of low-flow estimation in several catchments in South Africa. The catchments have been drawn from different parts of the country and are characterised by different physiographic conditions, variety of low-flow generation mechanisms, degree of artificial influence and availability and quality of streamflow data.

The following catchments/regions have been considered during the course of the study: the Sabie River (Mpumalanga Province), the Berg River (Western Cape), the Tugela River (KwaZulu-Natal), T drainage region in the Eastern Cape Province including such catchments as Mzimvubu and Mzimkhulu and the Olifants River (Northern Province).

The Volume consists of several Appendices; each catchment/region is represented by two Appendices. The Appendices of the first group (B1, C1, D1, E1, F1) include the description of the study area, the analysis of available observed streamflow data, the analysis of simulation results (where appropriate), the tables with estimated low-flow characteristics for each of the subdivisions at the adopted level of spatial discretization of the catchment and the GIS coverages illustrating the spatial distribution of these low-flow characteristics.

The second group of Appendices (B2, C2, D2, E2, F2) include time series graphs of annual flow totals and several low-flow characteristics for each catchment. These graphs have been constructed on the basis of available observed streamflow data and illustrate the quality of the data used and the temporal changes in low flows.

The description of the estimation techniques used in catchment low-flow studies is included in Volume I of the current Report. However, in some cases (T drainage region, Appendix E1) the technique is described directly in the Appendix.

The results of low-flow estimation for the Sabie River catchment are presented in Appendices B1 and B2, for the Berg River - in C1 and C2, for the Tugela River - in D1 and D2, for the T drainage region - in E1 and E2, for the Olifants River catchment in F1 and F2.

APPENDIX B1

Low-flow estimation in the Sabie catchment

B1.1 INTRODUCTION.

Low flows in the Sabie river catchment have been studied using the deterministic modelling approach. The gauged catchment area is relatively small (5713 km^2) and the catchment has been set up for simulation completely. All available gauged records have been analyzed in terms of several low-flow characteristics to demonstrate the temporal changes in low-flow regimes within the catchment. The Variable Time Interval (VTI) model has been calibrated for several interlinked subdivisions in the catchment against available observed daily data, to establish representative model parameter values. The objective of the simulation approach was to provide satisfactorily long daily flow sequences at a range of locations in the catchment using the calibrated model. After the calibration was completed, 40 years of daily flow time series at present day and virgin conditions in the catchment were simulated. Several low-flow indices were extracted from the simulated series for each subdivision in the catchment. The results allowed a catchment-wide picture of low-flow conditions within the Sabie basin to be constructed. The results are summarised in the tables and also presented by GIS coverages showing the spatial distribution of low-flow characteristics in the catchment.

B1.2 CATCHMENT DESCRIPTION.

The Sabie river catchment is located in the Northern Province and Mpumalanga Province and stretches from the Drakensberg mountains in the west across the Lebombo mountains in the east to its confluence with the Incomati river in Mozambique. The total area of the catchment is 7096km^2; approximately 6440 km^2 lies within South Africa and the border approximately follows the watershed of the Lebombo mountains. The northern and southern watersheds consist of mostly undulating or fairly flat terrain and are not clearly defined by any significant physical features.

The Sabie river originates in the Drakensberg mountains at an altitude of about 2200m. Its main tributary, the Sand river, originates 50km further to the north-east and at an altitude of about 1500m. The Sand has a length of about 125km to its confluence with the Sabie, at an altitude of 235m. The Sabie has a length of 140km to its confluence with the Sand and a total length of about 230km to its confluence with the Incomati, at an altitude of 40m.

The catchment can be categorised into two distinctive topographic regions (Fig. B1.1), the Lowveld and the Middleveld, whose boundary broadly follows the 600m contour. The Middleveld consist of undulating to very steep topography in the west (slopes generally exceed 15%). The Lowveld is flat to gently undulating with slopes generally less than 5%, except in the east in the vicinity of the Lebombo mountains. There are no large floodplains or wetlands in the catchment.

The catchment essentially falls within the Eastern Transvaal Lowveld climatic region, which is warm to hot sub-tropical. Climatic conditions are closely associated with topography and a somewhat cooler climate prevails along the Drakensberg escarpment in the west. In the Lowveld the MAP is about 600mm. In the Middleveld rainfall increases rapidly with altitude due to orographic effects and reaches 2000mm at the edge of the escarpment (Fig. B1.2). The region is characterised by summer rainfall, with 75% of the MAP falling between November to March. Rainfall is predominantly due to the convergence of tropical air masses and thunderstorms, with some heavy showers exceeding 300mm being recorded. The average gross Symon's pan evaporation varies from 1700mm in the east to 1400 in the west. During the summer, evaporation is about 40% higher than during the winter months in the Middleveld and 60% higher in the Lowveld.

The Sabie catchment is underlain by five major lithostratigraphic units (running parallel to the Drakensberg escarpment), which are in turn intruded by a network of diabase and dolerite dykes and sills. The oldest unit, the Archean basement complex underlying the Lowveld, consists of granite, granodiorite, diabase and gabbro. In the Middleveld, it is overlain by three sedimentary groups of the Transvaal Sequence, which all dip gently to the west. The first is the Wolksberg Group (prominent as a cliff line forming the Drakensberg escarpment), which consists predominantly of quartzites and shales with subordinate conglomerate and basaltic lava. The Wolksberg Group is overlain by the Chuniespoort Group of dolomites, limestone and shale. The Pretoria Group of shale and quartzites with subordinate conglomerate and volcanic members form the high mountain ranges in the west. In the east, basalt, sandstone, shale and mudstone of the Karoo Sequence overlay the basement complex and form the Lebombo mountains.

There are major differences in soil properties according to the geological substrate. The Lowveld consists of moderate to deep well drained sandy loams which have formed over the basement complex and moderate to deep clayey soils over the Karoo Sequence. The Middleveld soils are highly variable in terms of depth, texture and structure due to varying geological substrate and slope conditions.

According to the Acocks classification, the Lowveld consists of Lowveld Tropical bush and Savannah, with Arid Lowveld vegetation in the more arid north-east margin of the catchment. The Middleveld consists of the Inland Tropical Forest types known as Lowveld Sour Bushveld with North-Eastern Mountain Sourveld on the steep western margin of the catchment. The Middleveld has been extensively modified by the transition of large tracts to pine plantation forestry.The total area of the exotic afforestation in the catchment is 742km^2 (Sabie-Sand IFR Workshop, 1996). Large scale irrigation development has also occurred upstream of the Kruger National Park, with 116km^2 of irrigated tropical fruit, tobacco and maize and vegetables in the former homeland areas. The irrigation demand has resulted in the construction of several medium sized irrigation dams as well as numerous farm dams in

Figure B1.1 1' X 1' minute altitude data (m) for the Sabie catchment (based on the information obtained from the CCWR).

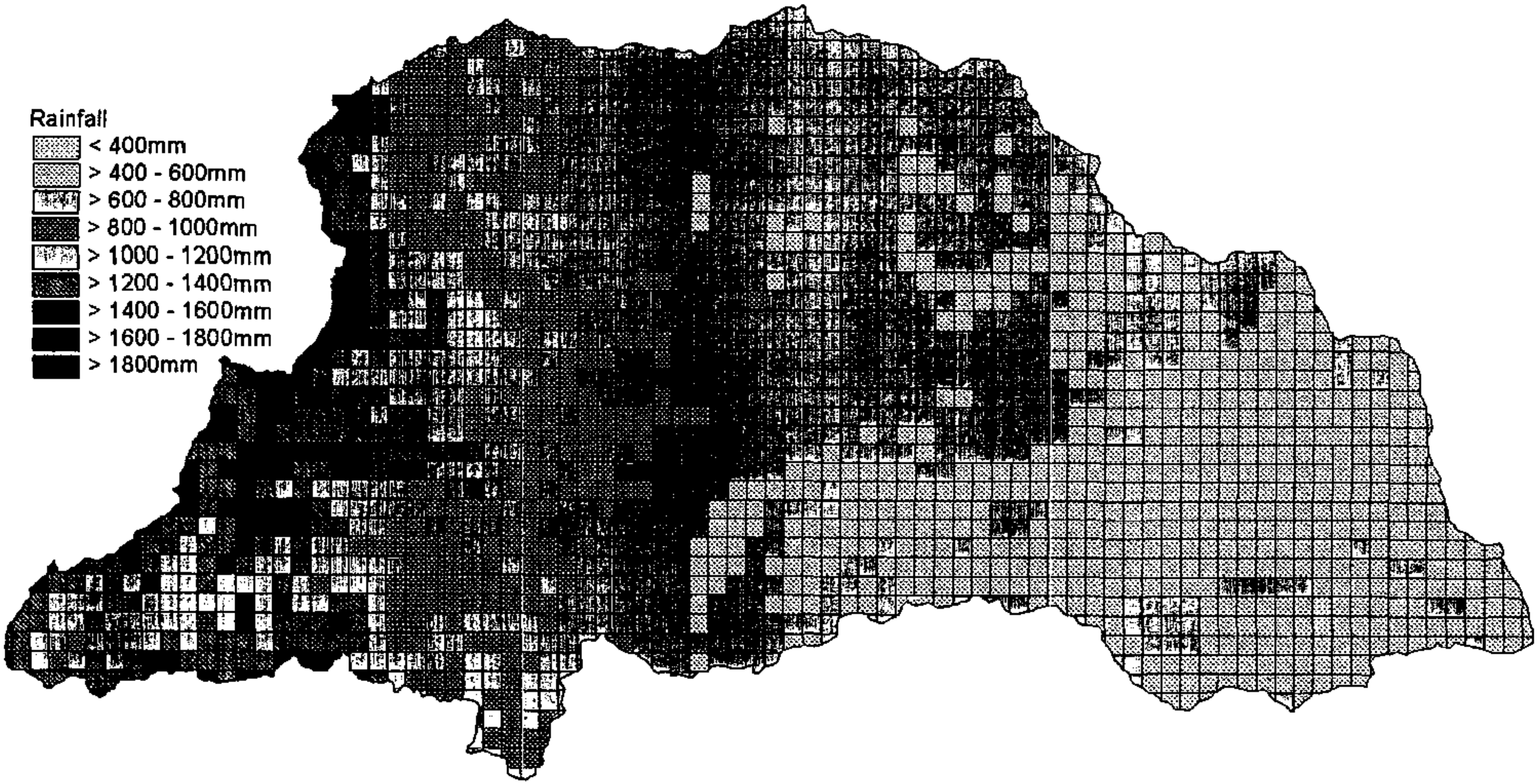


Figure B1.2 1' X 1' minute grid MAP data (mm) for the Sabie catchment (based on the information obtained from CCWR).

some areas. In spite of this, water shortages exist in several tributaries of the Sabie river and especially in the Sand system. Consequently only about 95km² of irrigation land is actually in production at present (Sabie-Sand IFR Workshop, 1996).

B1.3 OBSERVED STREAMFLOW DATA

Table B1.1 provides some details about streamflow gauges in the Sabie catchment while their location is shown in Figures B1.3 and B1.4. It is clear that the detailed catchment-wide analysis of low-flows can hardly be based on observed records only. Most of these gauges are concentrated in the upper reaches while the middle and lower reaches of the Sabie and its main tributaries are not properly gauged.

Table B1.1 Flow gauges in the Sabie river catchment

Code	River	Area, km^2	Available record, start - end	DTL[1], m^3/s
X3H001	Sabie	174	1948 - 1994	
X3H002	L. Sabie	55	1963 - 1994	3.5
X3H003	Mac-Mac	52	1948 - 1994	13.6
X3H004	North Sand	204	1948 - 1994	25.3
X3H006	Sabie	766	1958 - 1993	60.0
X3H007	White Waters	46	1963 - 1991	
X3H008	Sand	1064	1967 - 1993	16.5
X3H011	Mariter	212	1978 - 1993	28.9
X3H015	Sabie	5713	1987 - 1995	
X3H021	Sabie	2407	1990 - 1995	88.5

[1] Discharge Table Limit.

Each observed flow data set (except gauges X3H015 and X3H021 whose records are very short) has been analyzed by plotting the annual flow totals as a time series and extracting several low-flow characteristics from each year of record. These procedures allow the general quality of the data to be assessed and temporal variations in annual total flows and low-flows to be illustrated. The low-flow indices extracted were flows exceeded 75 and 95% of the time (Q75 and Q95), expressed as mm/day over the total area commanded by each gauge. Also the digital filter (Chapter 3) has been passed through each observed daily time series to separate the baseflow from total streamflow, and the total baseflow volume and baseflow index for each year of record, have been estimated.

Plots of annual total streamflow, baseflow and low-flow characteristics are presented in the APPENDIX B2. It is clear from these graphs that many of the available daily flow records are non-stationary. The record at gauge X3H001 is non-stationary in terms of both : annual flow totals and annual low flows (Fig. B2.1). An increasing trend in mean is very clear especially in the earliest part of the record and may probably be explained by mining activities. A decreasing trend in mean is present in the record of gauge X3H003. The values of Q95 at this gauge in recent years droped below the level of 0.5mm/day, which never occurred until the 1980s. A clear decreasing trend in both annual streamflow totals and annual low-flows is detected at gauge X3H004. This is the consequence of progressing irrigation development and associated flow diversions and dam constructions (including a large DaGama Dam upstream, in the White Waters river). The river dried up several times during the last 15 years (Fig. B2.4), which never occurred before (even during pronounced droughts in the mid-1960s). In addition, the decreasing trend in baseflow index illustrates the diminishing portion of baseflow in the annual hydrograph. The record at gauge X3H008 - the only gauge in the Sand River, contains a lot of missing data and is known to be of a generally poor quality (DWA, 1990). The remaining gauges have either relatively short records (X3H011) or appeared to be stationary (X3H002, X3H006).

B1.4 CALIBRATION OF THE VTI MODEL.

For the purpose of basin-wide low-flow estimation in the Sabie catchment, daily flow sequences have been simulated at a number of locations using the VTI model. The catchment was subdivided into several interlinked components (projects). Each project corresponded to one of the gauged catchments X3H001, X3H002, X3H003, X3H004, X3H006, X3H008, X3H011, X3H015, X3H021. The portion of the catchment below X3H015 at Lower Sabie was not modelled. Each project was subdivided into several sub-areas according to tributary structures, variations in geology, landuse and rainfall. Figures B1.3 and B1.4 illustrate the adopted discretisation of the Sabie catchment into projects and subareas and also show the location of rainfall and streamflow gauges used in the simulation exercise.

Calibration of the VTI model was attempted over the period 1979-1984, with subsequent verification of the results for 1984-1989. However, a different period had to be used for projects commanded by gauges X3H021 (the record period available at the time of calibration was from 1990 to 1993 inclusive) and X3H015 (available record period was 1987-1993). All the data on irrigation abstractions, forestry, dam volumes etc. were taken from the Sabie Basin Study Report (DWA, 1990). Due to time dependent changes in the abstraction pattern during 1979-1989, in many cases water demand and dam volume parameters had to be changed during the calibration and verification periods (time sliced). The results of calibration and verification of the model for each of the projects are briefly summarised below.

Project 1 (Sabie1) - gauge X3H001

Sabie1 forms the steep forested headwater region of the Sabie river in the western mountain range west of the Great Escarpment. It is underlain mostly by shales and quartzites with dolomite and alluvium in the lower reaches. Soils are predominantly shallow, stony, well to excessively drained clay loams. Dolomite derived soils are well drained silty clays and are significantly deeper. A line of perennial springs and waterfalls associated with quartzite layers was simulated as springflow in sub-areas underlain by shales and quartzites. In addition, spring baseflow was supplemented by the intersection of the groundwater table with the surface in the alluvial valley bottom and dolomitic sub-areas. Land use and present day water demand is predominantly related to the impact of afforestation.

A visual comparison of observed and simulated flows demonstrates that good fits have been achieved in terms of hydrograph peaks and shape (Fig. B1.5a) as well as in terms of the flow duration curves (Fig. B1.6a). This is also confirmed by the fit statistics (Table B1.2).

Project 2 (Sabie2) - gauge X3H002

Sabie2 consists of the hilly catchment of the Little Sabie down to its confluence with the Sabie. The catchment is underlain by dolomites with outcrops of shales and quartzites in the headwater regions. Compared to Sabie1, significantly less runoff is generated in this catchment due to much lower catchment slopes and much higher recharge rates associated with the dolomites. Baseflow is generated primarily by groundwater from the dolomite aquifer, with a component of spring flow to account for high lying springs coming from the headwater region. Water is predominantly used by forestry, with additional abstractions occurring for mining, sawmills and Sabie town.

The gauging weir is unable to record flows exceeding 3.5 $m^3 s^{-1}$, thus fit statistics, especially the coefficient of efficiency, are relatively poor (Table B1.2). However the comparison log-transformed observed and simulated discharge values (which places a greater emphasis on low flows) and flow duration curves (Fig. B1.6a), suggest a better simulation.

Project 3 (Sabie3) - gauge X3H003

Sabie3 consists of the headwater regions of the Mac-Mac river. Its geology and topography are similar to Sabie2. Therefore, baseflow is generated in a similar fashion to Sabie2, by groundwater from the dolomite aquifer, with a component of spring flow. Water is primarily used by forestry. The gauging weir is unable to record flows exceeding 13.6 $m^3 s^{-1}$, which is exceeded 0.1% of the time. Statistics of the log-transformed discharge values, especially the coefficient of efficiency, therefore exhibit a better fit. These fit statistics, as well as visual comparisons of observed and simulated flow duration curves and hydrographs suggest that an excellent simulation has been achieved (Figs. B1.5a and B1.6a, Table B1.2).

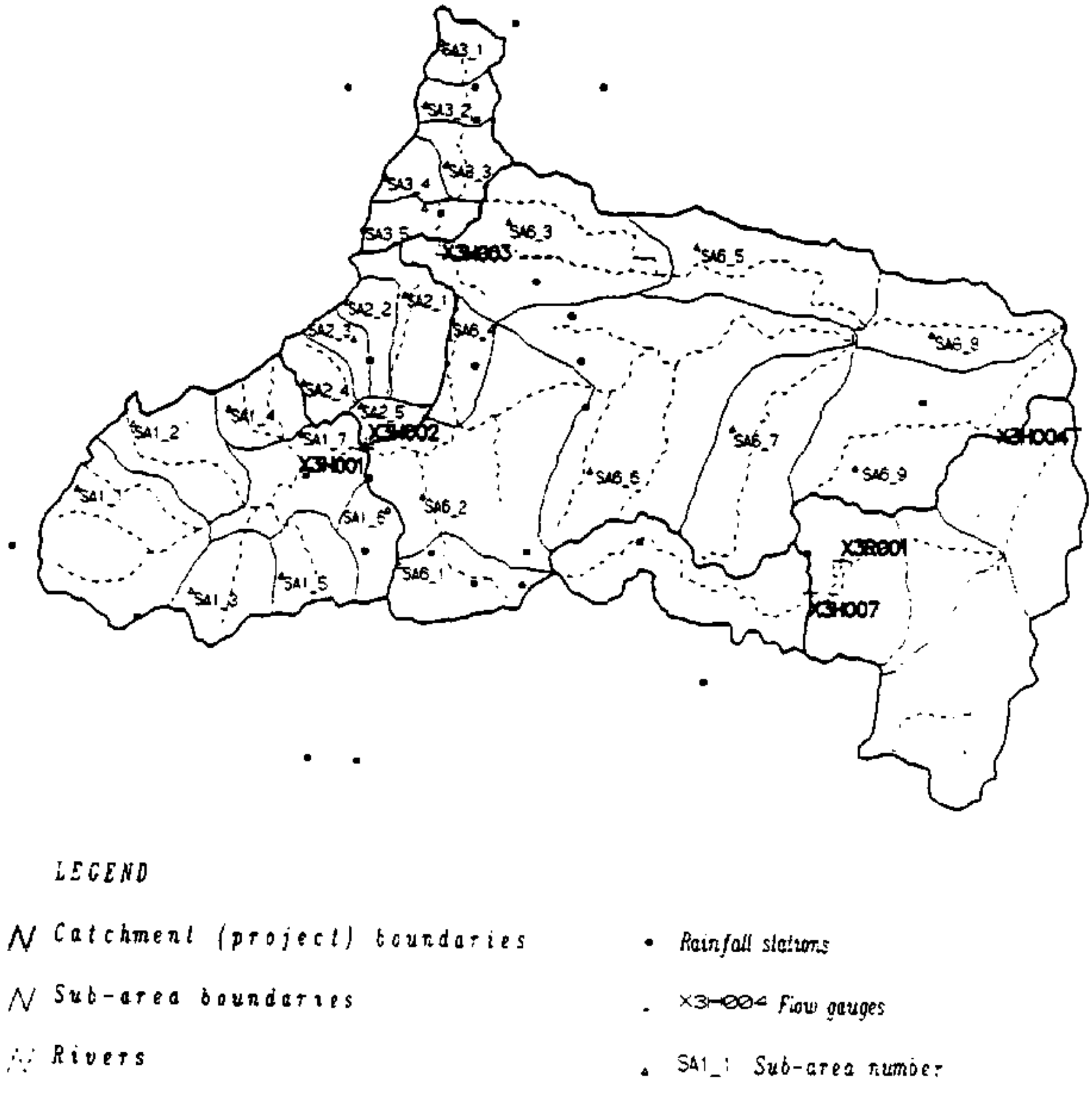


Figure B1.3 Discretisation of the Sabie catchment (projects 1, 2, 3, 4 and 6).

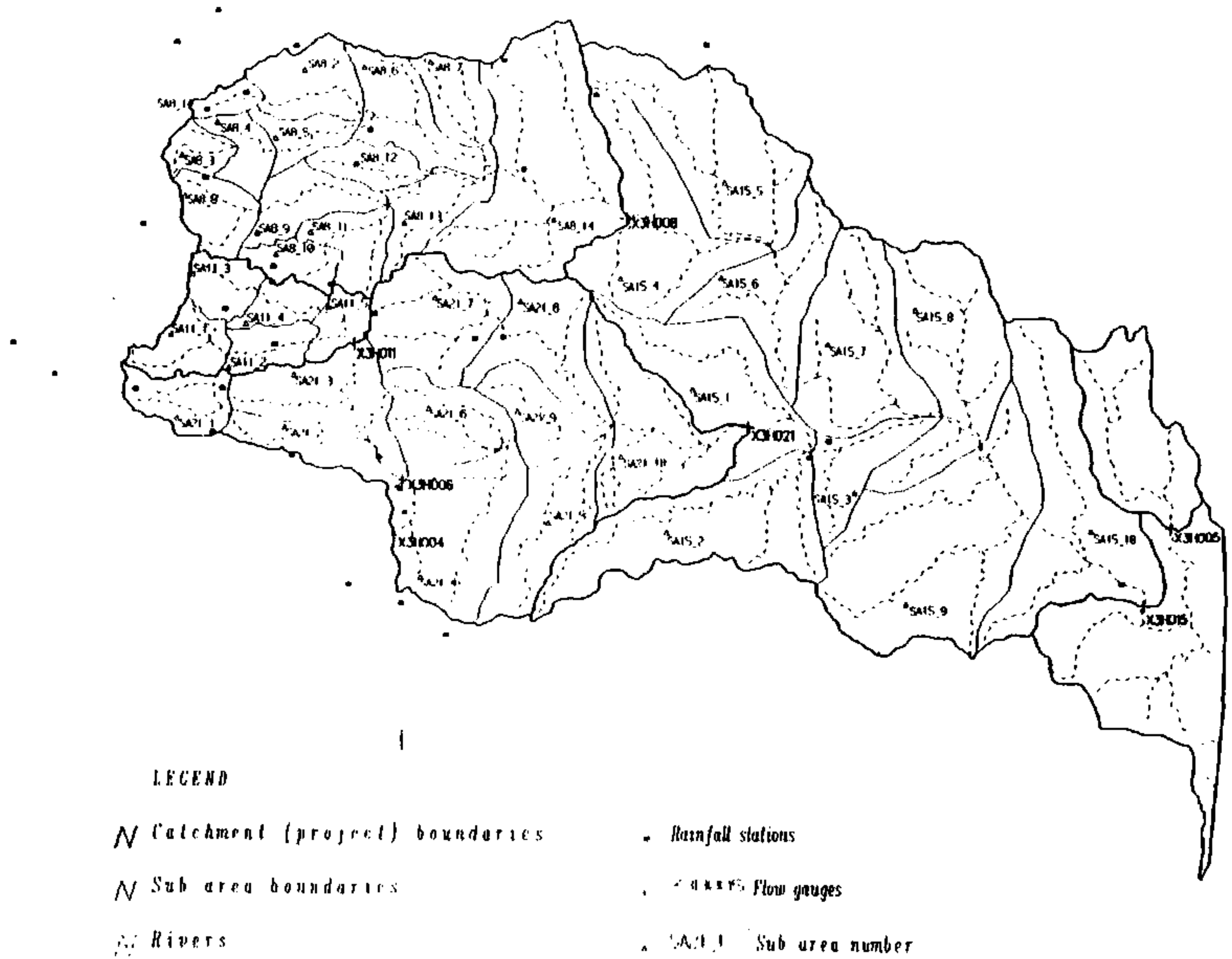


Figure B1.4 Discretisation of the Sabie catchment (projects 8, 11, 21 and 15).

Project 4 (Sabie4) - gauge X3H004

Sabie4 includes the White Waters river catchment and the majority of the North Sand catchment. It is underlain by the Archean basement complex immediately below the Great Escarpment and consists of sharply dissected topography with frequently exposed granite domes in the White Waters catchment. This zone descends steeply to the more gentle topography of the North Sand catchment with slopes of 12-17%. Granite derived soils at the edge of the Escarpment form the deepest soils in the catchment, well to excessively drained sandy clay loams. Near surface soils have a low water retention capacity, however, hydromorphic soils tend to develop in bottomlands. Baseflow from granite terrain is generated by simulation as groundwater re-emergence from localised aquifers forming in valley bottoms. Afforestation is the dominant water demand in the White Waters catchment and the headwaters of the North Sand. The DaGama Dam on the White Waters river controls 22% of the total catchment and supplies water to a large scale irrigation scheme downstream on the White Waters and North Sand. A number of farm dams and direct river abstractions are also present.

Due to the extent of flow modification, continuously expanding irrigation and the role of dam releases on the runoff regime, no detailed calibration was performed. Parameters of the model were transferred from similar topographic regions in Sabie6 and Sabie11 with subsequent minor calibration of groundwater parameters in order to obtain a visual fit with present day low flows. Abstraction data was then time sliced using gradually increasing abstraction and farm dam volumes from 1978 to 1984.

Fit statistics reflect a marginally successful simulation. However since the difference between observed and simulated MAR for a period of 1979-1989 was within 10% (observed - 16.3 MCM, simulated - 17.8 MCM), the results were assumed to be acceptable. Low flows appear to have been oversimulated in the early part of the record (Fig. B1.5a), but according to fit statistics based on log-transformed discharge values, low flows generally appear to be undersimulated (Table B1.2). These discrepancies may be attributed to inaccuracies in the estimated mean monthly irrigation volumes.

Project 6 (Sabie6) - gauge X3H006

Sabie6 incorporates runoff generated in Sabie1, Sabie2 and Sabie3 and extends from the edge of the Great Escarpment to the edge of the Lowveld. It is underlain mostly by granite. The topography varies from steep sharply dissected areas and gorges in the upper reaches to the more gentle topography of the Lowveld at the eastern margin. Hence sub-area catchment slopes vary approximately from 7 to 29%. Land use predominantly consists of forestry throughout most of the catchment. The mining and timber industry account for additional minor abstractions. Irrigation is concentrated along some tributaries, and has been steadily expanding since the 1950's, resulting in increasing water shortages. Water is supplied by two irrigation canals from the Sabie and an extensive network of farm dams.

To achieve a reasonable calibration, water demand and dam volumes were time sliced between 1978-1984. Annual variations in mean daily abstraction were simulated using monthly weighting factors varying between a minimum of 0.86 in February to a maximum of 1.10 in May and August. The gauging weir is unable to record flows exceeding 60 $m^3 s^{-1}$, (nearly 1% of the time series). Consequently, the log-transformed discharge values exhibit a significantly better fit than the untransformed flows (Table B1.2). This coupled with good visual fits between observed and simulated hydrographs and flow duration curves, suggests that a good simulation has been achieved (Figs. B1.5a and B1.6a).

Project 8 (Sabie8) - gauge X3H008

The project includes the Sand river catchment above the Sabie-Sand Game Park. It is underlain by the Archean Basement Complex and extends from the Great Escarpment into the Lowveld. The headwater region at the escarpment consists of steep cliffs. It is followed by a relatively narrow band of steep sharply dissected terrain. The rest of the catchment is of low relief, with baseflow being generated from localised aquifers in valley bottoms where saturated conditions exist. As rainfall decreases from west to east, such conditions exist predominantly in the western portion of the catchment where a large proportion of the baseflow is generated. At the edge of the escarpment, springflow has also been generated where quartzite layers are present. Afforestation is restricted to the western portion of the catchment. Further east, the catchment is densely populated with large scale irrigation being the predominant water user. Several domestic supply schemes also abstract significant amounts of water. Irrigation abstraction is serviced by several medium sized dams as well as by direct abstraction from canals when sufficient flow exists. Variable fractions of the irrigable land are irrigated in any one year. Due to the haphazard pattern of irrigation, abstractions are very variable in time and difficult to quantify.

These difficulties affected the results of the simulation. Existing irrigation demand is distributed between dams and direct abstraction, while the hectarage serviced by direct abstraction is considered to have gradually increased since 1978. Inadequacies in the observed record, such as the inability of the gauge to record flows above 16.5 $m^3 s^{-1}$ which are exceeded 1% of the time, frequent clogging of the gauge and gaps in the record, also made calibration a difficult exercise. The fit statistics for both untransformed and log-transformed flows reflect only a marginally successful calibration (Table B1.2). However, the comparison of hydrographs and especially, flow duration curves, suggest that low flows have been satisfactorily simulated.

Project 11 (Sabie11) - gauge X3H011

The project includes the upstream catchments of the Marite river. It is underlain by Archean Granites and extends from the cliffs of the Great Escarpment to the edge of the Lowveld. Its characteristics are similar to those of Sabie4 and Sabie6. Land use consists predominantly of forestry, however, the eastern edge of the catchment marks the beginning of the irrigation farming region of the Marite river. Irrigation increases since the late 1980's have not been simulated.

The gauging weir is unable to record flows exceeding 28.9 m^3 s^{-1}, which is exceeded about 0.5% of the time. Consequently, the log-transformed discharge values exhibit a significantly better fit than untransformed flows and indicate that a good simulation has been achieved (Table B1.2), although low flows have been slightly undersimulated in several years (Fig. B1.5b).

Project 21 (Sabie21) - gauge X3H021

This is an incremental part of the Sabie catchment between gauges X3H006, X3H011, X3H004 and the gauge X3H021 located just to the east of Paul Kruger Gate. The catchment collects runoff from Sabie4, Sabie6 and Sabie11. It is underlain by the Archean Granites and extends from the Great Escarpment (at the headwater of the Motitsi river) into the Lowveld. The headwater region at the escarpment is capped by quartzite and consists of sharply dissected terrain, which covers approximately 110 km^2 of the catchment. Springflow has been generated from the forested headwater sub-catchment. The remainder of the catchment is categorised as Lowveld with predominantly low relief, and baseflow generated from localised aquifers in valley bottoms where saturated conditions exist. As rainfall decreases from west to east, such conditions exist predominantly in the western portion of the catchment where a large proportion of the baseflow is generated.

Along the Marite and Sabie rivers large scale irrigation by direct abstraction from rivers is the predominant water user. Several domestic supply schemes also abstract significant amounts of water. Once the Sabie enters the Kruger Park transmission losses begin to occur as groundwater recharge is no longer sufficient to sustain baseflow. In addition, the presence of extensive riverine vegetation results in the further depletion of groundwater. Riverine water use has been simulated as groundwater abstraction.

The observed record at the time of calibration was available only for 1990-1993, and therefore, calibration was restricted to this period. In addition the flow gauge is unable to record flows above 88.5 m^3 s^{-1}, which occur nearly 1% of the time. The fit statistics for both untransformed and log-transformed discharge values imply that an excellent fit has been achieved (Table B1.2), although medium to low flows appeared to be somewhat oversimulated (Fig. B1.6b).

Project 15 (Sabie15) - X3H015

This is the incremental catchment between gauges X3H008, X3H021 and X3H015. It contains parts of the Sabie and Sand catchments within the Kruger and Sabie-Sand Parks and collects runoff from Sabie8 and Sabie21. The catchment is underlain by the Archean Granite and is covered by relatively flat Lowveld. Transmission losses occur throughout the catchment as groundwater recharge is insufficient to sustain baseflow. In addition, the presence of extensive riverine vegetation results in the further depletion of groundwater. Riverine water use has been simulated as groundwater abstraction. Transmission losses and riverine vegetation result in a net loss of water compared to runoff derived from upstream sources, hence no incremental discharge is generated within the catchment.

The observed record available only starts in 1986, therefore, calibration was restricted to the period 1986-1993. Little calibration was required due to the lack of runoff generation within the catchment. The fit statistics imply a good fit (at least in the case of log-transformed flows). A reasonable fit has also been obtained in terms of hydrographs and flow duration curves (Figs. B1.5b and B1.6b).

B1.5. SIMULATION OF DAILY FLOW TIME SERIES AND LOW-FLOW ESTIMATION UNDER PRESENT DAY AND VIRGIN CONDITIONS.

Once a calibration was completed, the simulation of flow under present day conditions for the period 1952-1993 was performed in order to obtain representative daily flow time series for subsequent low-flow calculations. The daily time-series of flows in natural (virgin) conditions was simulated for this period by removing abstractions, dam volumes, afforestation areas from the parameter set. In addition, the simulation of virgin flow included a reduction of crop factor parameters from a maximum of 1.5 in afforested sub-areas to 1.0 once afforestation was removed. This accounts for the lower evaporative demand of the natural vegetation, while the replacement of plantation forest by natural bush reduces interception losses and affected the sub-area routing parameters. The index of surface organic litter was also slightly reduced for virgin conditions causing infiltration capacities to be approximately 10% lower.

Two low-flow indices have been estimated for each subarea from simulated 40-year daily flow time series: 7-day average flows exceeded 75 and 95% of the time (Q75(7) and Q95(7)). The use of 7-day average flows instead of original daily flows is based on a premise that the former are less prone to inaccuracies in the data and less sensitive to effects of minor abstractions. For these reasons the moving averaging technique is recommended in some sources for application to the original daily data prior to low-flow estimation (Drayton et al, 1980; Pirt and Simpson, 1983).

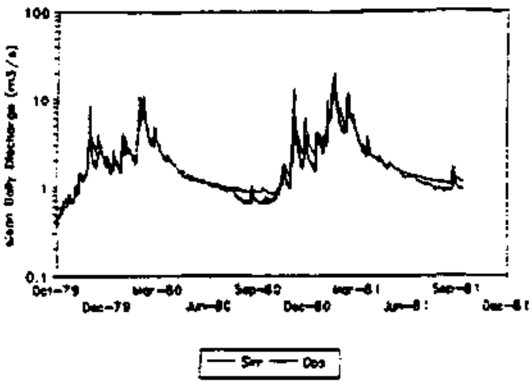
Two different types of flow for each exceedence level have been estimated. The first is the flow generated within each sub-area (total sub-area flow). The first demonstrates how much flow is actually flowing into a stream channel from an incremental sub-area (at the selected level of exceedence) regardless of the upstream inflow to a sub-area. This flow has (at present day conditions) already been influenced by farm dams and forestry, but has not yet been subjected to transmission losses (if any) and direct abstractions from a stream in this sub-area.

Table B1.2 Comparative statistics for the Sabie catchments

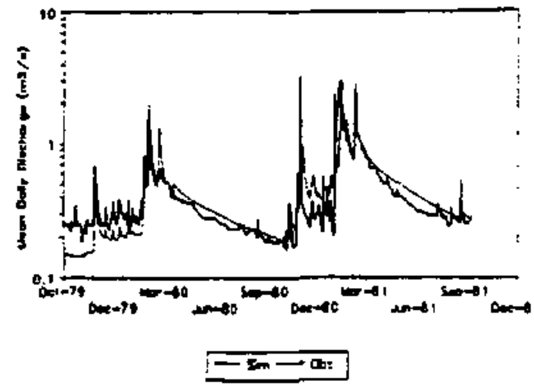
Code	Data	Untransformed						Ln transformed					
		Max m^3/s	Min m^3/s	Mean m^3/s	SD m^3/s	R^2	CE	Max	Min	Mean	SD	R^2	CE
Sab1	Obs	36.0	0.07	1.81	1.95			3.58	-2.63	0.35	0.62		
	Sim	36.5	0.50	1.82	1.86	0.79	0.79	3.60	-0.69	0.38	0.59	0.87	0.87
Sab2	Obs	3.42	0.09	0.31	0.26			1.23	-2.45	-1.34	0.50		
	Sim	27.2	0.10	0.40	0.69	0.47	-3.79	3.30	-2.26	-1.18	0.59	0.70	0.48
Sab3	Obs	13.7	0.24	0.71	0.74			2.61	-1.41	-0.52	0.55		
	Sim	23.3	0.30	0.78	1.03	0.78	0.51	3.15	-1.22	-0.46	0.52	0.86	0.83
Sab4	Obs	25.2	0.00	0.54	1.49			3.23	-6.91	-1.61	1.52		
	Sim	126	0.00	0.61	3.28	0.55	-1.58	4.84	-9.57	-1.86	1.67	0.55	0.40
Sab6	Obs	60.0	0.83	5.14	6.26			4.10	-0.19	1.32	0.70		
	Sim	197	0.65	5.34	10.1	0.76	0.21	5.28	-0.44	1.27	0.75	0.88	0.85
Sab8	Obs	16.6	0.00	1.81	3.06			2.81	-6.96	-0.36	1.49		
	Sim	132	0.00	2.20	7.06	0.17	-3.37	4.88	-6.96	-0.42	1.60	0.59	0.50
Sab11	Obs	28.9	0.17	1.84	2.49			3.36	-1.79	0.23	0.78		
	Sim	98.4	0.34	1.74	3.82	0.71	0.23	4.59	-1.08	0.12	0.75	0.81	0.79
Sab15	Obs	88.5	0.02	9.92	13.5			4.48	-3.73	1.65	1.17		
	Sim	406	0.00	10.9	22.8	0.58	-0.30	6.01	-5.64	1.71	1.19	0.82	0.80
Sab21	Obs	204	0.34	6.61	13.0			5.32	5.10	1.22	1.05		
	Sim	165	0.14	7.07	12.4	0.72	0.71	-1.08	-1.94	1.33	1.08	0.86	0.84

The second 'flow type' is the final routed runoff - the actual discharge at the outlet of each sub-area. This flow takes into account all upstream inflows into a sub-area (if those exist) and has already been subjected to direct abstractions from a stream (at present day conditions). It therefore demonstrates how much water at a particular location is actually available in a stream channel.

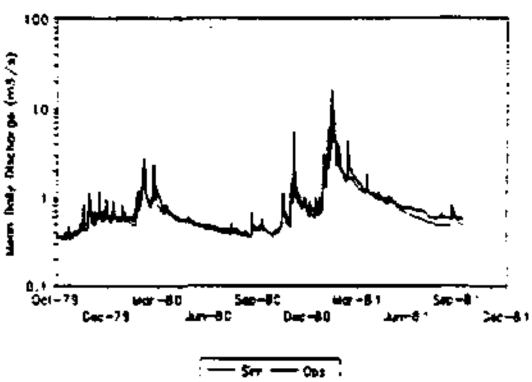
Table B1.3 summarises this information for all sub-areas in the Sabie catchment at present day conditions, while Table B1.4 contains similar information for virgin conditions. Total sub-area flow is expressed in m^3/s and mm per annum (mm/a) from a unit area of each subarea.



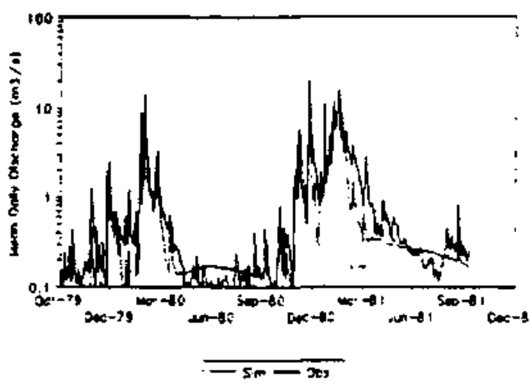
SABIE1



SABIE2



SABIE3



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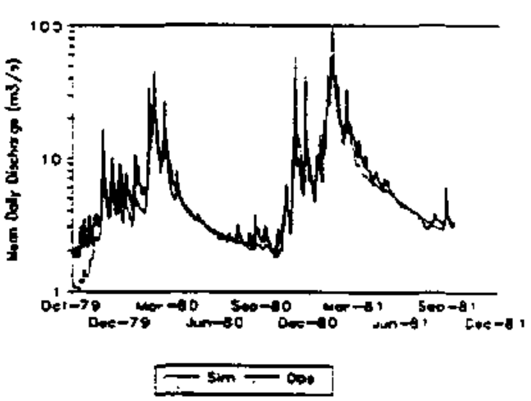
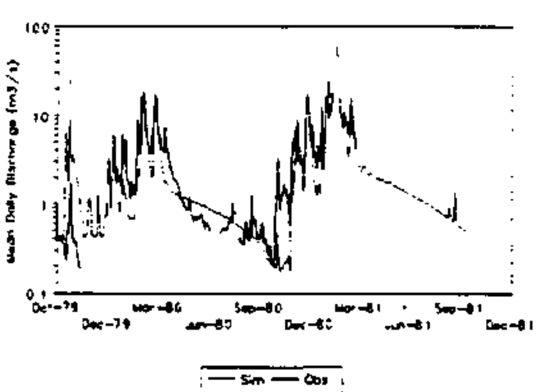
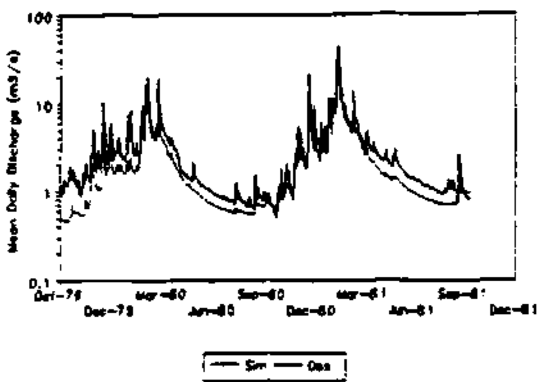


SABIE6



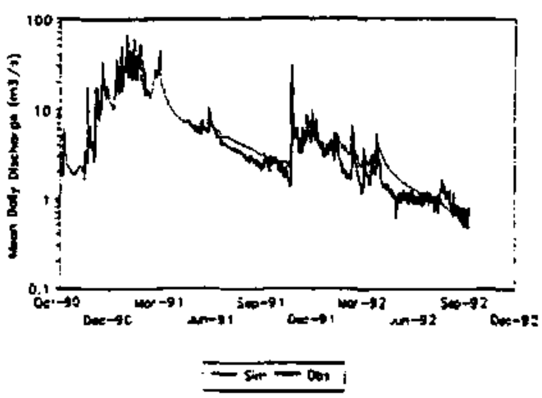
SABIE8

Figure B1.5a Comparison of observed and simulated by the VTI model daily hydrographs.



SABIE11

SABIE15



SABIE21

Figure B1.5b Comparison of observed and simulated by the VTI model daily hydrographs.

Final runoff (actual water in a channel) is expressed in m³/s and MCM. The codes of subareas in Tables B1.3 and B1.4 correspond to those in Figures B1.3 and B1.4. Figures B1.7 and B1.8 illustrate the distribution of Q75(7) and Q95(7) values (total subarea runoff in mm/a) in the Sabie catchment. The degree of changes in flow regime in each project is illustrated by Figure B1.9 which presents 1-day annual flow duration curves constructed on the basis of 40 years of simulated daily streamflow data in present and virgin conditions.

Additional low-flow indices from the flow duration curve or any other low-flow indices can be estimated on request from the simulated flow time series (present day or virgin). The actual simulated daily streamflow time series are also available from IWR.

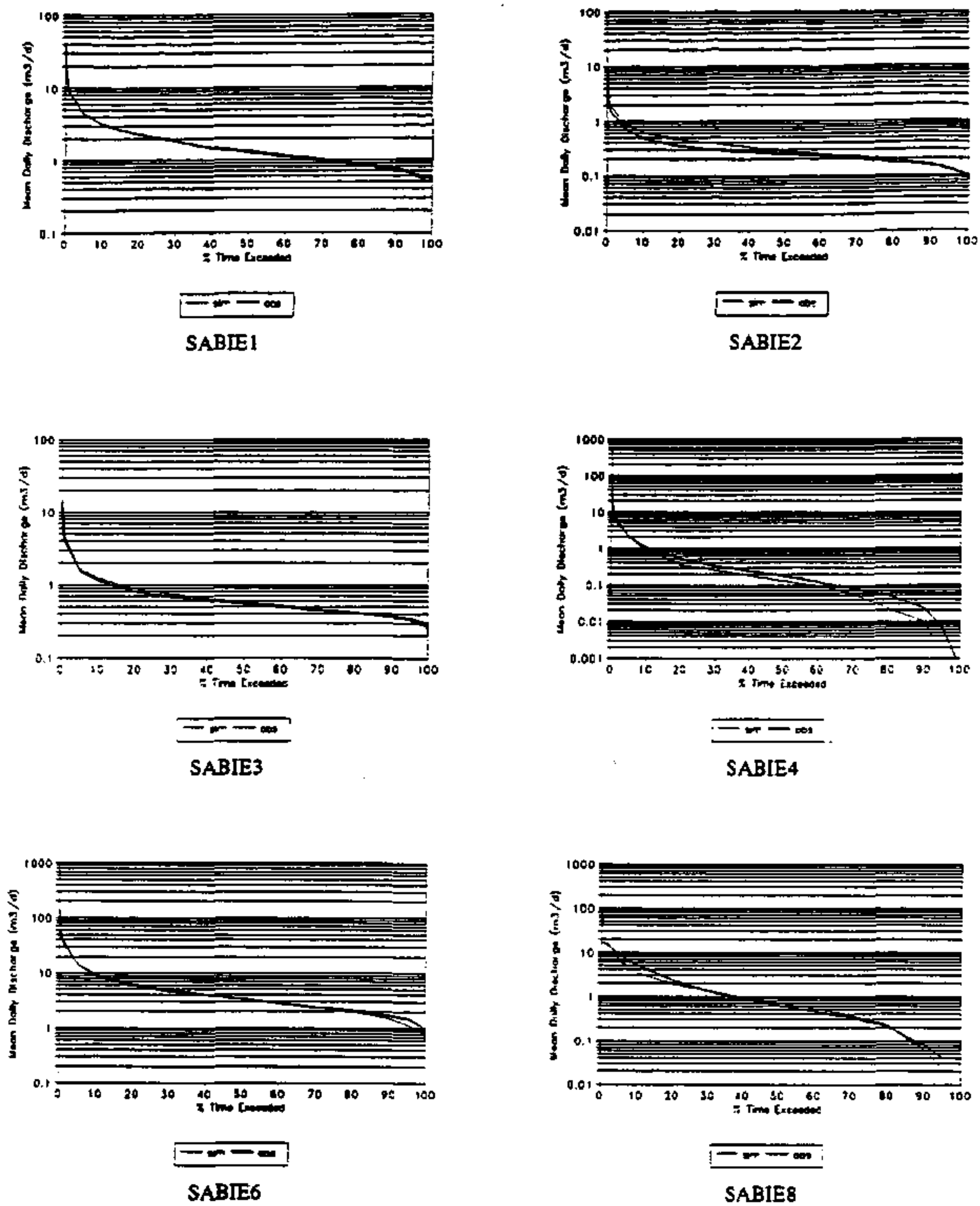
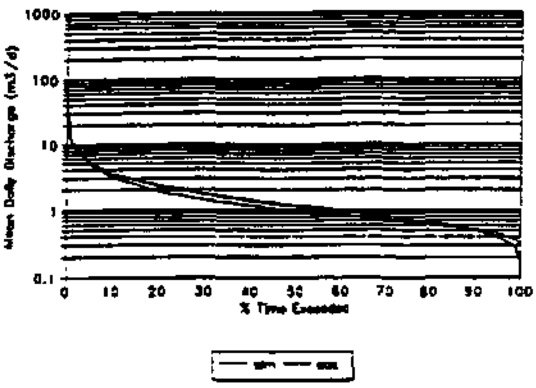
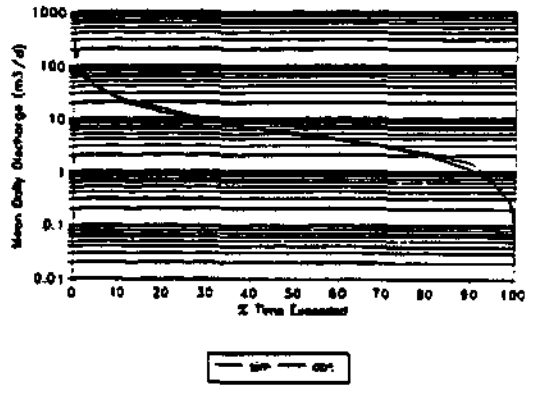


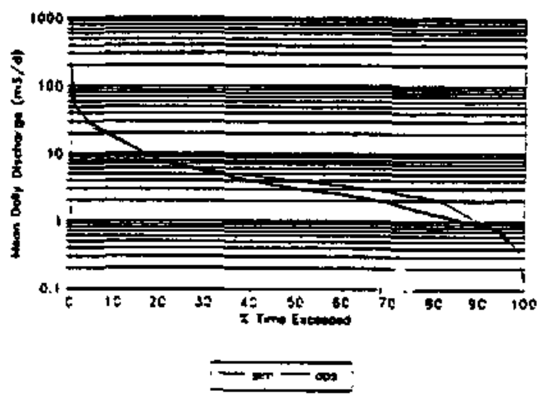
Figure B1.6a Observed and simulated 1-day annual flow duration curves based on data for 1979 - 1989.



SABIE11 (1979-1989)



SABIE15 (1986-1993)



SABIE21 (1990-1993)

Figure B1.6b. *Observed and simulated 1-day annual flow duration curves.*

Table B1.3 Estimated Q75(7) and Q95(7) flow values for subcatchments in the Sabie river basin (present day conditions).

Sub.No.	Subarea km^2	Q75(7), from subarea		Q75(7), routed runoff		Q95(7), from subarea		Q95(7), routed runoff	
		m^3/s	mm/a	m^3/s	MCM	m^3/s	mm/a	m^3/s	MCM
1	2	3	4	5	6	7	8	9	10
1.1	57.3	0.225	124	0.225	7.1	0.164	90	0.164	5.2
1.2	27.4	0.155	178	0.155	4.9	0.107	123	0.107	3.4
1.3	20.0	0.084	132	0.084	2.6	0.060	95	0.060	1.9
1.4	18.1	0.121	211	0.121	3.8	0.079	138	0.079	2.5
1.5	10.9	0.062	179	0.062	2.0	0.040	116	0.040	1.3
1.6	17.5	0.072	130	0.072	2.3	0.042	76	0.042	1.3
1.7 (X3H001)	22.8	0.225	311	1.028	32.4	0.161	223	0.737	23.2
2.1	15.9	0.084	167	0.084	2.6	0.054	107	0.054	1.7
2.2	13.2	0.075	179	0.075	2.3	0.050	119	0.050	1.6
2.3	4.3	0.029	212	0.029	0.9	0.019	139	0.019	0.6
2.4	11.6	0.067	182	0.067	2.1	0.044	120	0.044	1.4
2.5 (X3H002)	9.9	0.069	220	0.271	8.5	0.061	194	0.171	5.4
3.1	7.5	0.054	227	0.054	1.7	0.046	193	0.046	1.5
3.2	7.0	0.061	275	0.114	3.6	0.050	225	0.096	3.0

Table B1.3 (cont.) Estimated Q75(7) and Q95(7) flow values for subcatchments in the Sabie river basin (present day conditions).

Sub.No.	Subarea km^2	Q75(7), from subarea		Q75(7), routed runoff		Q95(7), from subarea		Q95(7), routed runoff	
		m^3/s	mm/a	m^3/s	MCM	m^3/s	mm/a	m^3/s	MCM
1	2	3	4	5	6	7	8	9	10
3.3	14.9	0.169	358	0.291	9.2	0.118	250	0.232	7.3
3.4	10.7	0.086	253	0.086	2.7	0.060	177	0.060	1.9
3.5 (X3H003)	11.7	0.102	275	0.483	15.2	0.077	208	0.383	12.1
X3H007	46.0	0.000	0	0.000	0	0.000	0	0.000	0
4.1	36.0	0.017	15	0.011	0.3	0.000	0	0.000	0
4.2	31.0	0.011	12	0.017	0.5	0.001	1	0.000	0
4.3	43.0	0.081	59	0.060	1.9	0.053	39	0.032	1
4.4 (X3H004)	44.0	0.025	18	0.060	1.9	0.010	7	0.032	1
6.1	34.2	0.183	169	0.183	5.8	0.146	135	0.146	4.6
6.2	68.2	0.410	190	2.055	64.8	0.269	124	1.452	45.8
6.3	60.5	0.315	164	0.815	25.7	0.175	91	0.585	18.4
6.4	9.0	0.078	273	0.078	2.5	0.060	210	0.060	1.9
6.5	36.5	0.106	92	0.938	29.6	0.047	41	0.645	20.3
6.6	99.5	0.351	111	1.799	56.7	0.199	63	1.055	33.3

Table B1.3 (cont.) Estimated Q75(7) and Q95(7) flow values for subcatchments in the Sabie river basin (present day conditions).

Sub.No.	Subarea km^2	Q75(7), from subarea		Q75(7), routed runoff		Q95(7), from subarea		Q95(7), routed runoff	
		m^3/s	mm/a	m^3/s	MCM	m^3/s	mm/a	m^3/s	MCM
1	2	3	4	5	6	7	8	9	10
6.7	82.5	0.146	56	0.041	1.3	0.096	37	0.000	0
6.8 (X3H006)	53.8	0.161	94	2.676	84.4	0.097	57	1.524	48.1
6.9	40.8	0.000	0	0.000	0.0	0.000	0	0.000	0
11.1	56.0	0.210	118	0.210	6.6	0.127	72	0.127	4.0
11.2	35.0	0.114	103	0.346	10.9	0.070	63	0.217	6.8
11.3	46.5	0.162	110	0.162	5.10	0.102	69	0.102	3.2
11.4	34.0	0.139	129	0.319	10.0	0.089	83	0.203	6.4
11.5 (X3H011)	40.5	0.128	100	0.815	25.7	0.073	57	0.507	16.0
8.1	24.8	0.053	67	0.053	1.7	0.034	43	0.034	1.1
8.2	72.7	0.079	34	0.106	3.3	0.027	12	0.031	1.0
8.3	36.9	0.081	69	0.081	2.6	0.059	50	0.059	1.9
8.4	44.0	0.060	43	0.158	5.0	0.025	18	0.091	2.9
8.5	50.2	0.031	19	0.046	1.4	0.010	6	0.000	0
8.6	110.0	0.062	18	0.154	4.9	0.015	4	0.000	0
8.7	60.3	0.000	0	0.000	0.0	0.000	0	0.000	0
8.8	46.5	0.107	73	0.060	1.9	0.077	52	0.031	1

Table B1.3 (cont.) *Estimated Q75(7) and Q95(7) flow values for subcatchments in the Sabie river basin (present day conditions).*

Sub.No.	Subarea km^2	Q75(7), from subarea		Q75(7), routed runoff		Q95(7), from subarea		Q95(7), routed runoff	
		m^3/s	mm/a	m^3/s	MCM	m^3/s	mm/a	m^3/s	MCM
1	2	3	4	5	6	7	8	9	10
8.9	70.7	0.088	39	0.131	4.1	0.020	9	0.029	0.9
8.10	40.6	0.077	60	0.077	2.4	0.024	19	0.024	0.8
8.11	68.5	0.049	23	0.111	3.5	0.000	0	0.018	0.6
8.12	39.6	0.000	0	0.000	0.0	0.000	0	0.000	0
8.13	72.7	0.033	14	0.282	8.9	0.000	0	0.033	1
8.14 (X3H008)	338.0	0.000	0	0.506	16.0	0.000	0	0.048	1.5
21.1	60.0	0.211	111	0.211	6.6	0.103	54.0	0.103	3.2
21.2	57.0	0.089	49	0.314	9.9	0.023	13.0	0.139	4.4
21.3	194.0	0.347	56	1.364	43.0	0.143	23.0	0.692	21.8
21.4	273.0	0.076	9	4.159	131.2	0.004	0.5	2.051	64.7
21.5	108.0	0.012	4	0.012	0.4	0.000	0.0	0.000	0
21.6	80.0	0.065	26	0.065	2.0	0.014	6.0	0.014	0.4
21.7	125.0	0.103	26	0.103	3.2	0.010	3.0	0.010	0.3
21.8	151.0	0.023	5	0.132	4.2	0.000	0.0	0.013	0.4
21.9	74.0	0.000	0	3.853	121.5	0.000	0.0	1.642	51.8
21.10 (X3H021)	102.0	0.000	0	4.056	127.0	0.000	0.0	1.685	53.1

Table B1.3 (cont.) Estimated Q75(7) and Q95(7) flow values for subcatchments in the Sabie river basin (present day conditions).

Sub.No.	Subarea km^2	Q75(7), from subarea		Q75(7), routed runoff		Q95(7), from subarea		Q95(7), routed runoff	
		m^3/s	mm/a	m^3/s	MCM	m^3/s	mm/a	m^3/s	MCM
1	2	3	4	5	6	7	8	9	10
15.1	193.0	0.000	0	4.016	126.6	0.000	0.0	1.586	50
15.2	280.0	0.000	0	0.000	0.0	0.000	0.0	0.000	0
15.3	80.0	0.000	0	3.967	125.1	0.000	0.0	1.544	48.7
15.4	210.0	0.000	0	0.441	13.9	0.000	0.0	0.000	0
15.5	282.0	0.000	0	0.000	0.0	0.000	0.0	0.000	0
15.6	157.0	0.000	0	0.332	10.5	0.000	0.0	0.000	0
15.7	194.0	0.000	0	0.237	7.5	0.000	0.0	0.000	0
15.8	241.0	0.000	0	4.236	133.6	0.000	0.0	1.514	47.7
15.9	355.0	0.000	0	4.052	127.8	0.000	0.0	1.304	41.1
15.10 (X3H015)	299.0	0.000	0	3.986	125.7	0.000	0.0	1.209	38.1

Table B1.4 Estimated Q75(7) and Q95(7) flow values for subcatchments in the Sabie river basin (virgin conditions).

Sub.No.	Subarea km^2	Q75(7), from subarea		Q75(7), routed runoff		Q95(7), from subarea		Q95(7), routed runoff	
		m^3/s	mm/a	m^3/s	MCM	m^3/s	mm/a	m^3/s	MCM
1	2	3	4	5	6	7	8	9	10
1.1	57.3	0.272	150	0.272	8.58	0.208	114	0.208	6.56
1.2	27.4	0.194	223	0.194	6.11	0.128	147	0.128	4.04
1.3	20.0	0.112	177	0.112	3.53	0.078	123	0.078	2.46
1.4	18.1	0.158	275	0.158	4.98	0.103	179	0.103	3.25
1.5	10.9	0.090	260	0.090	2.83	0.062	179	0.062	1.96
1.6	17.5	0.117	211	0.117	3.69	0.079	142	0.079	2.49
1.7 (X3H001)	22.8	0.284	393	1.303	41.10	0.220	304	0.970	30.59
2.1	15.9	0.108	214	0.108	3.40	0.071	141	0.071	2.24
2.2	13.2	0.097	232	0.097	3.06	0.065	155	0.065	2.05
2.3	4.3	0.037	271	0.037	1.17	0.025	183	0.025	0.79
2.4	11.6	0.086	234	0.086	2.71	0.057	155	0.057	1.80
2.5 (X3H062)	9.9	0.097	309	0.437	13.78	0.086	274	0.316	9.97
3.1	7.5	0.066	278	0.066	2.08	0.053	223	0.053	1.67
3.2	7.0	0.069	311	0.129	4.10	0.058	261	0.105	3.31

Table B1.4 (cont.) Estimated Q75(7) and Q95(7) flow values for subcatchments in the Sabie river basin (virgin conditions).

Sub.No.	Subarea km^2	Q75(7), from subarea		Q75(7), routed runoff		Q95(7), from subarea		Q95(7), routed runoff	
		m^3/s	mm/a	m^3/s	MCM	m^3/s	mm/a	m^3/s	MCM
1	2	3	4	5	6	7	8	9	10
3.3	14.9	0.192	406	0.336	10.60	0.152	322	0.269	8.48
3.4	10.7	0.102	301	0.102	3.20	0.072	212	0.072	2.27
3.5 (X3H003)	11.7	0.126	340	0.570	18.00	0.096	259	0.458	14.44
X3H007	46	0.135	93	0.135	4.26	0.057	39	0.057	1.80
4.1	36	0.086	75	0.231	7.28	0.056	49	0.115	3.63
4.2	31	0.068	69	0.307	9.68	0.046	47	0.166	5.23
4.3	43	0.117	86	0.117	3.69	0.079	58	0.079	2.49
4.4 (X3H004)	44	0.068	49	0.509	16.05	0.038	27	0.297	9.37
6.1	34.2	0.258	238	0.258	8.14	0.203	187	0.203	6.40
6.2	68.2	0.552	255	2.749	86.69	0.397	184	2.053	64.70
6.3	60.5	0.438	228	1.023	32.30	0.281	146	0.766	24.10
6.4	9.0	0.101	354	0.101	3.19	0.08	280	0.08	2.52
6.5	36.5	0.167	144	1.182	37.30	0.093	80	0.871	27.46
6.6	99.5	0.531	168	3.322	104.80	0.339	107	2.412	76.10

Table B1.4 (cont.) Estimated Q75(7) and Q95(7) flow values for subcatchments in the Sabie river basin (virgin conditions).

Sub.No.	Subarea km^2	Q75(7), from subarea		Q75(7), routed runoff		Q95(7), from subarea		Q95(7), routed runoff	
		m^3/s	mm/a	m^3/s	MCM	m^3/s	mm/a	m^3/s	MCM
1	2	3	4	5	6	7	8	9	10
6.7	82.5	0.363	139	0.363	11.45	0.232	89	0.232	7.31
6.8 (X3H006)	53.8	0.222	130	5.420	170.49	0.129	76	3.835	120.90
6.9	40.8	0.165	128	0.165	5.20	0.104	80	0.104	3.28
11.1	56.0	0.284	160	0.284	9.00	0.175	99	0.175	5.50
11.2	35.0	0.180	162	0.491	15.50	0.114	103	0.318	10.02
11.3	46.5	0.209	142	0.209	6.60	0.121	86	0.121	3.82
11.4	34.0	0.187	173	0.415	13.10	0.117	109	0.270	8.51
11.5 (X3H011)	40.5	0.166	129	1.108	34.90	0.100	78	0.721	22.74
8.1	24.8	0.067	85	0.067	2.11	0.043	55	0.043	1.36
8.2	72.7	0.092	40	0.175	5.52	0.033	14	0.090	2.84
8.3	36.9	0.113	97	0.113	3.56	0.080	68	0.080	2.52
8.4	44.0	0.078	56	0.220	6.94	0.038	27	0.127	4.00
8.5	50.2	0.052	33	0.295	9.30	0.018	11	0.161	5.08
8.6	110.0	0.062	18	0.571	18.01	0.015	4.3	0.298	9.40
8.7	60.3	0.031	16	0.031	0.98	0.003	1.6	0.003	0.095
8.8	46.5	0.143	97	0.143	4.51	0.105	71	0.105	3.31

Table B1.4 (cont.) Estimated Q75(7) and Q95(7) flow values for subcatchments in the Sabie river basin (virgin conditions).

Sub.No.	Subarea km^2	Q75(7), from subarea		Q75(7), routed runoff		Q95(7), from subarea		Q95(7), routed runoff	
		m^3/s	mm/a	m^3/s	MCM	m^3/s	mm/a	m^3/s	MCM
1	2	3	4	5	6	7	8	9	10
8.9	70.7	0.086	38	0.264	8.32	0.018	8	0.153	4.82
8.10	40.6	0.108	84	0.108	3.40	0.048	37	0.048	1.51
8.11	68.5	0.046	21	0.161	5.08	0.000	0	0.059	1.86
8.12	39.6	0.020	16	0.020	0.63	0.002	1.6	0.0002	0.006
8.13	72.7	0.029	13	0.533	16.81	0.000	0	0.251	7.92
8.14 (X3H008)	338.0	0.000	0	1.182	38.28	0.000	0	0.595	18.76
21.1	60.0	0.331	174	0.331	10.43	0.187	98	0.187	5.9.0
21.2	57.0	0.120	66	0.468	14.76	0.041	23	0.248	7.82
21.3	194.0	0.353	57	2.002	63.14	0.152	25	1.121	35.35
21.4	273.0	0.077	8.9	8.179	257.93	0.005	0.58	5.446	171.7
21.5	108.0	0.015	4.4	0.015	0.47	0.000	0	0.000	0.00
21.6	80.0	0.067	26	0.067	2.11	0.015	5.9	0.015	0.47
21.7	125.0	0.102	25	0.102	3.21	0.013	3.3	0.013	0.41
21.8	151.0	0.022	4.6	0.137	4.32	0.000	0	0.015	0.47
21.9	74.0	0.000	0	8.269	260.8	0.000	0	5.435	171.0
21.10 (X3H021)	102.0	0.000	0	8.475	267.27	0.000	0	5.486	173.0

Table B1.4 (cont.) Estimated Q75(7) and Q95(7) flow values for subcatchments in the Sabie river basin (virgin conditions).

Sub.No.	Subarea km^2	Q75(7), from subarea		Q75(7), routed runoff		Q95(7), from subarea		Q95(7), routed runoff	
		m^3/s	mm/a	m^3/s	MCM	m^3/s	mm/a	m^3/s	MCM
1	2	3	4	5	6	7	8	9	10
15.1	193	0.000	0	8.432	265.90	0.000	0	5.383	169.8
15.2	280	0.000	0	0.000	0.00	0.000	0	0.000	0.000
15.3	80	0.000	0	8.378	264.20	0.000	0	5.349	168.70
15.4	210	0.000	0	1.122	35.38	0.000	0	0.492	15.50
15.5	282	0.000	0	0.000	0.00	0.000	0	0.000	0.000
15.6	157	0.000	0	1.036	32.67	0.000	0	0.380	12.00
15.7	194	0.000	0	0.957	30.18	0.000	0	0.279	8.80
15.8	241	0.000	0	9.33	294.23	0.000	0	5.734	180.80
15.9	355	0.000	0	9.152	288.62	0.000	0	5.573	175.80
15.10 (X3H015)	299	0.000	0	9.079	286.32	0.000	0	5.511	173.80

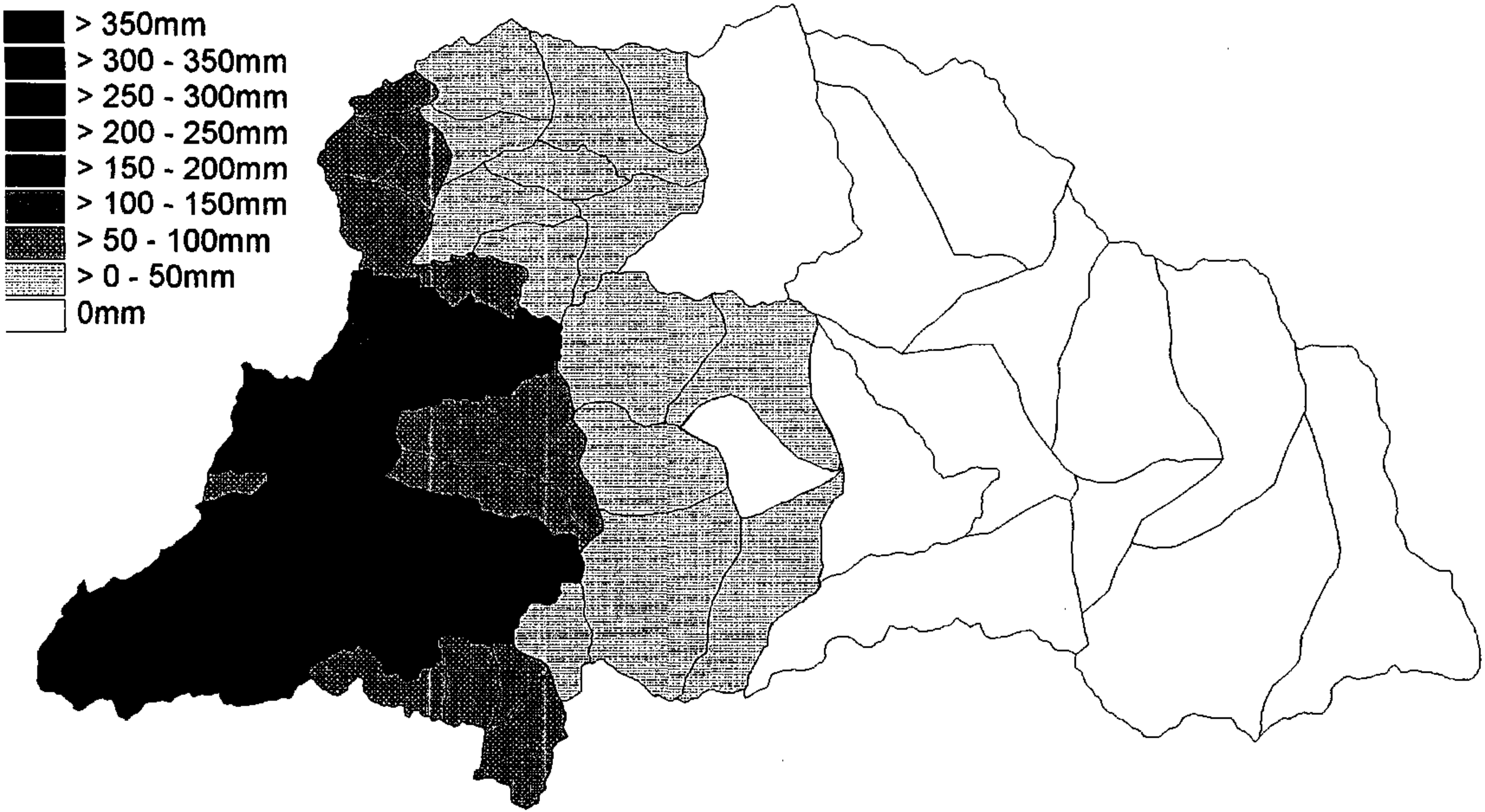


Figure B1.7 Distribution of Q75(7) values (subarea runoff, mm/a) in the Sabie catchment (virgin conditions).

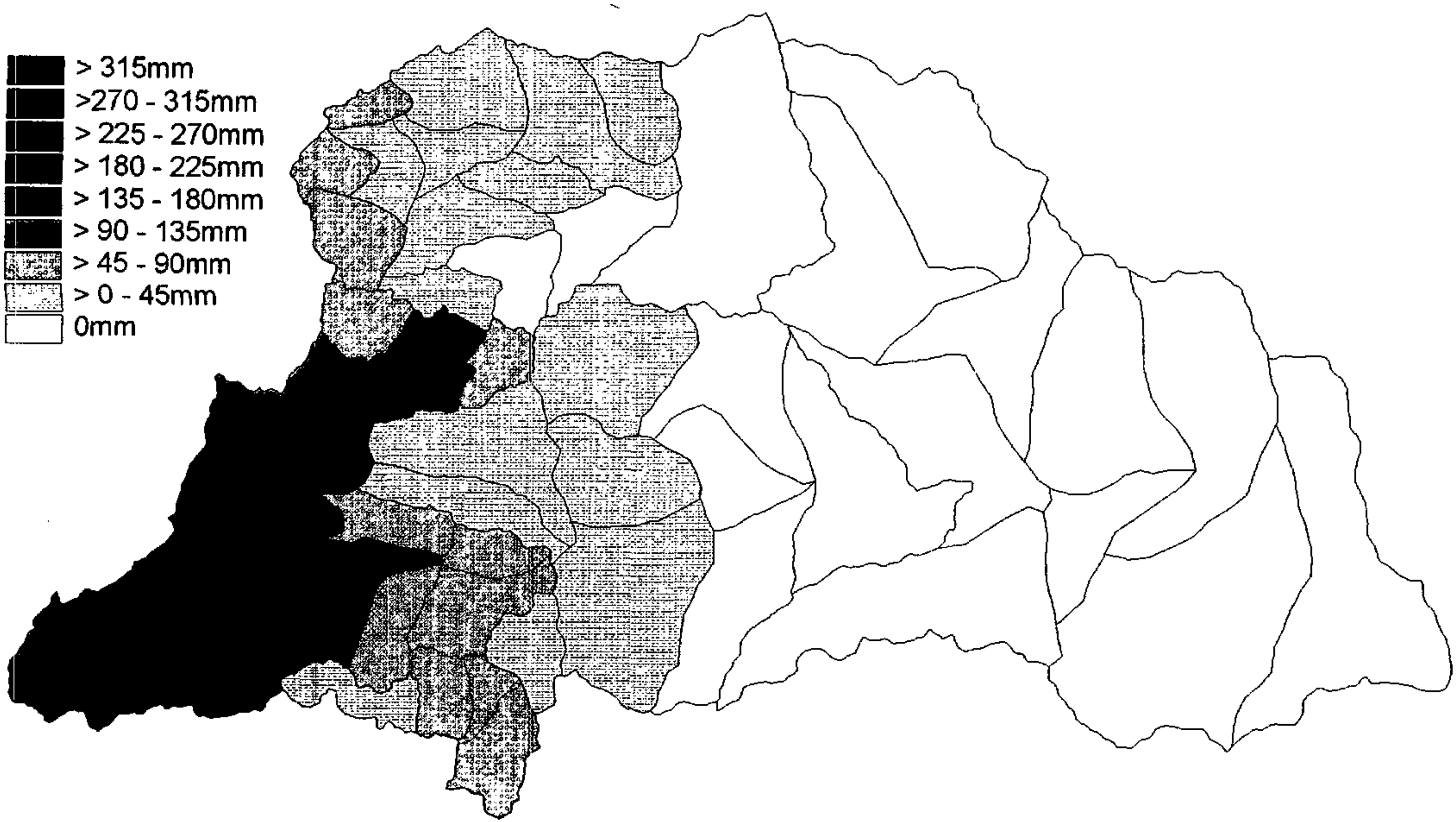
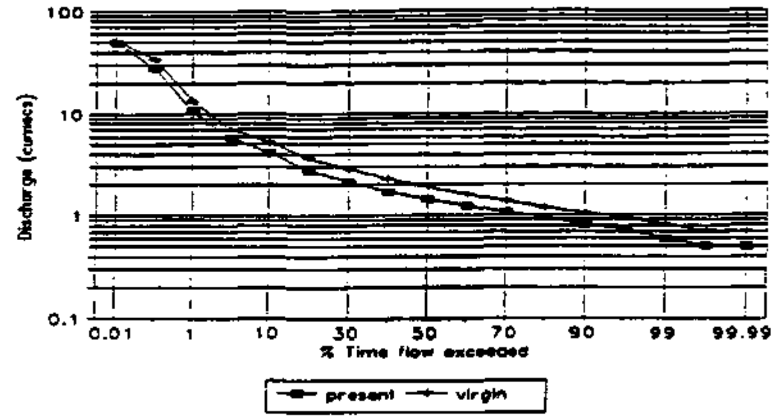


Figure B1.8 Distribution of Q95(7) values (subarea runoff, mm/a) in the Sabie catchment (virgin conditions).

GAUGE X3H001



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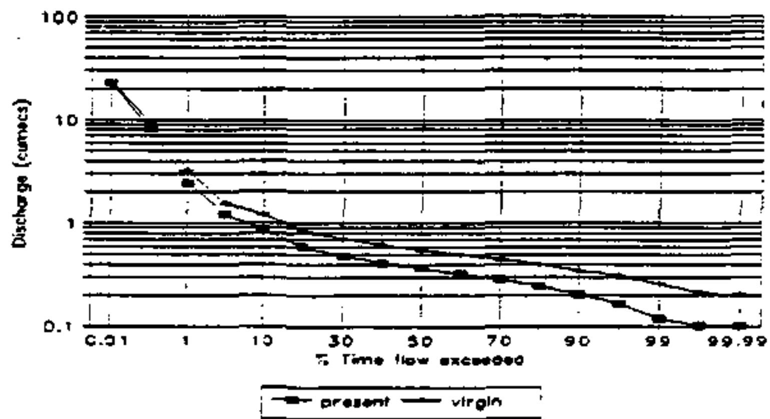

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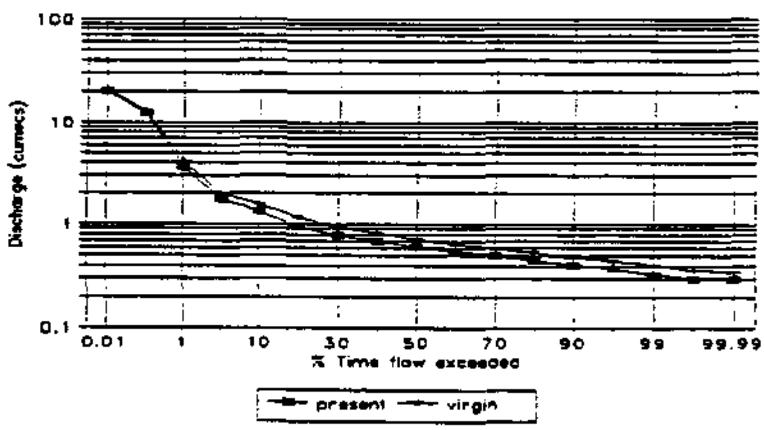
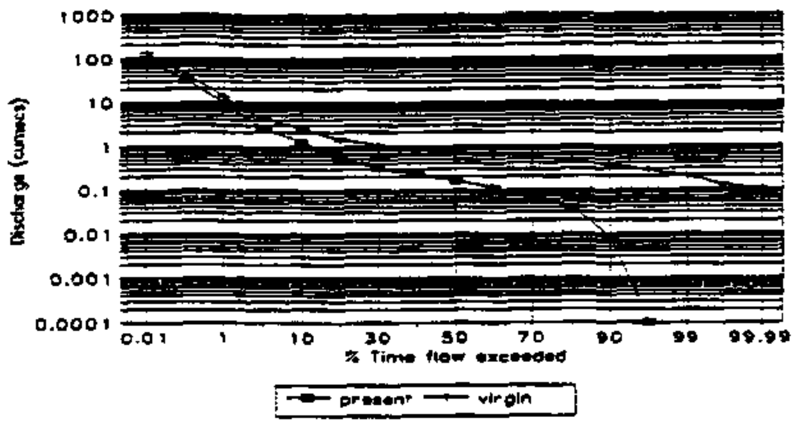
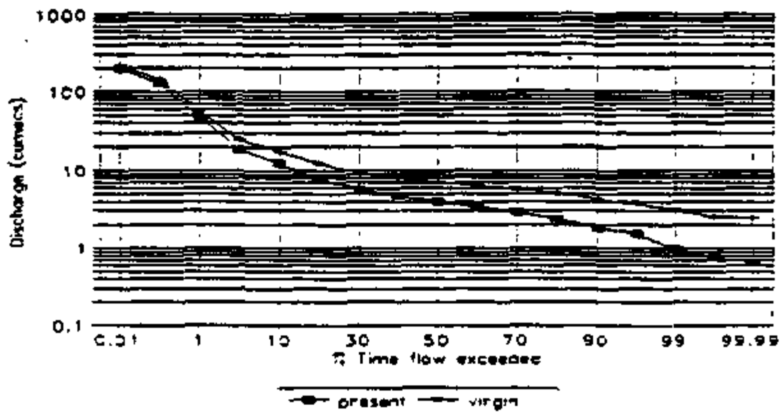


Figure B1.9a Simulated 1-day annual flow duration curves in present and virgin conditions.

GAUGE X3H004



GAUGE X3H006



GAUGE X3H011

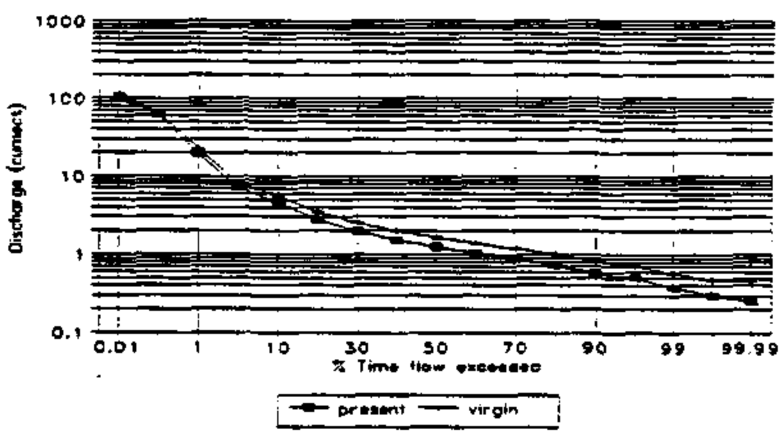
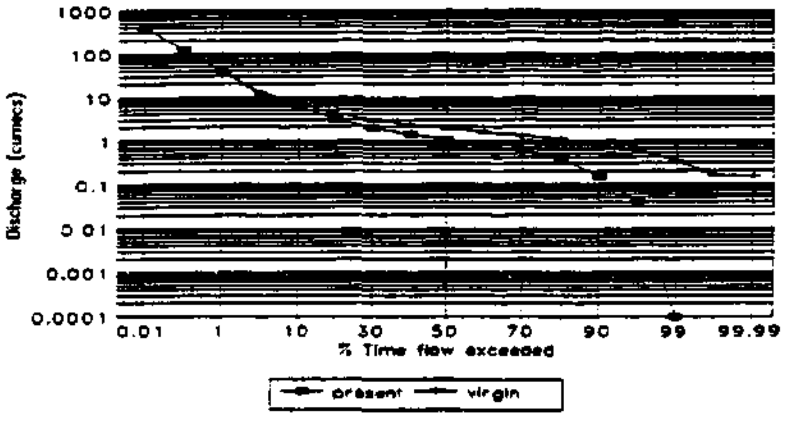
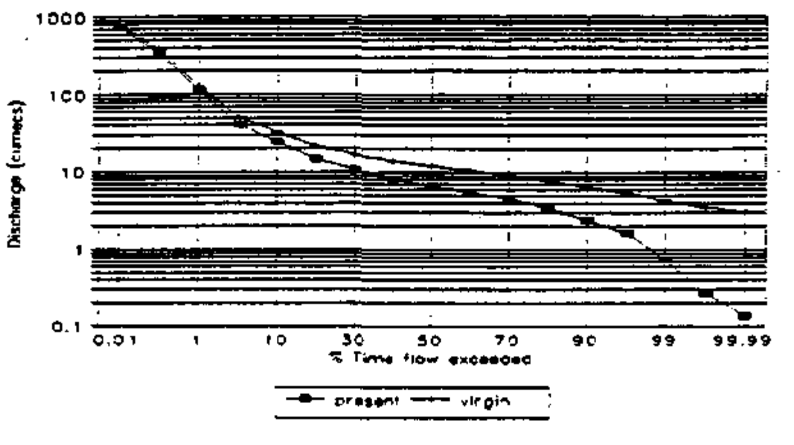


Figure B1.9b Simulated 1-day annual flow duration curves in present and virgin conditions.

GAUGE X3H008



GAUGE X3H021



GAUGE X3H015

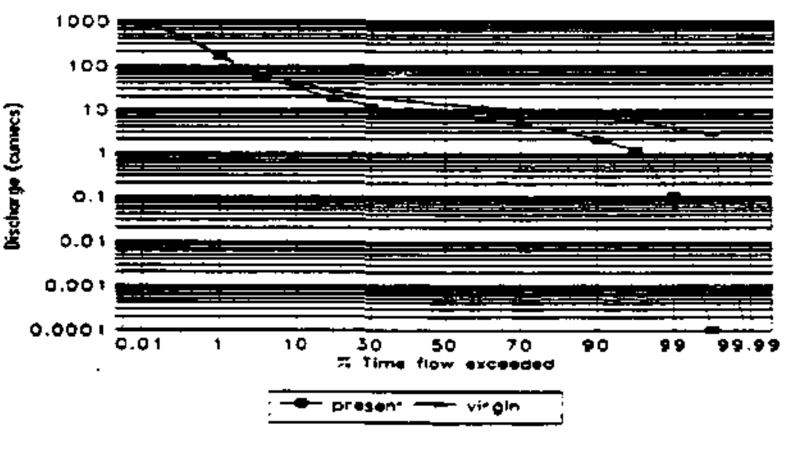
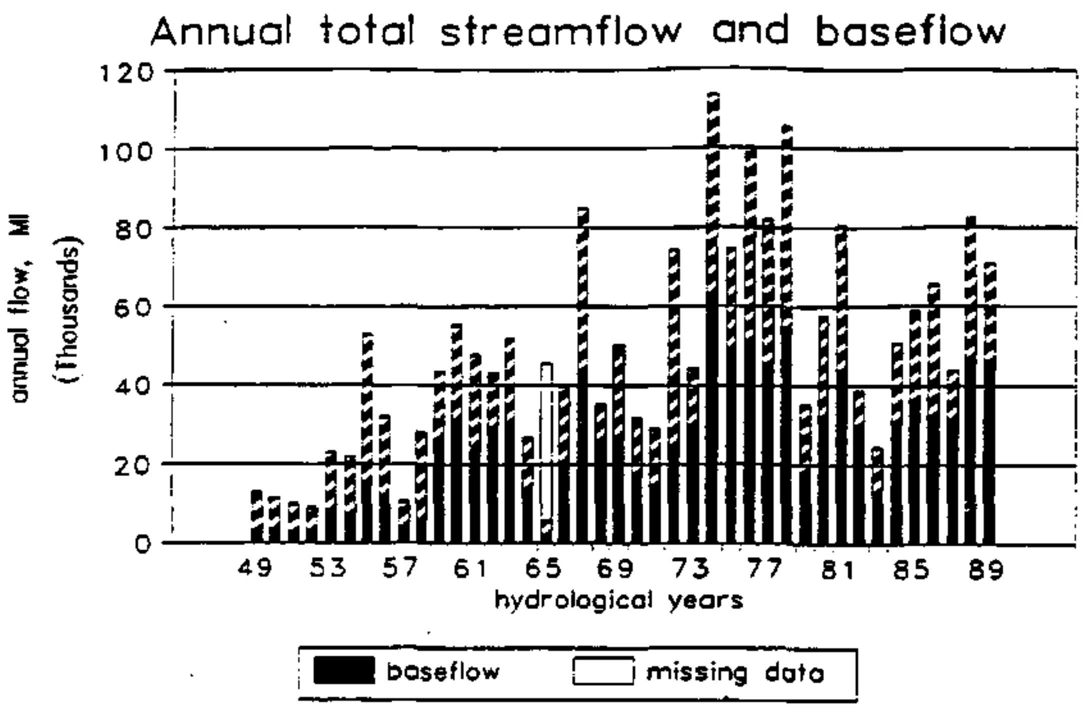


Figure B1.9c Simulated 1-day annual flow duration curves in present and virgin conditions.

APPENDIX B2

Annual flows and low-flow indices in the Sabie catchment

Note : each year on graphs is from October of the previous calendar year to September of the next calender year (the year 1952 is from October 1951 to September 1952).



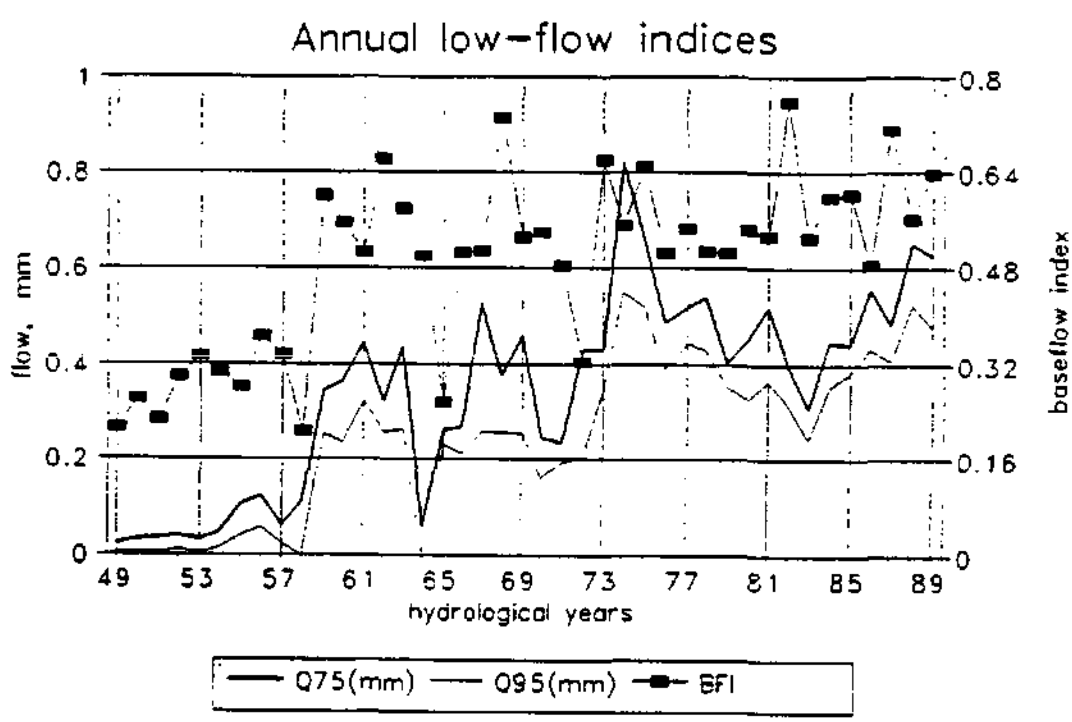
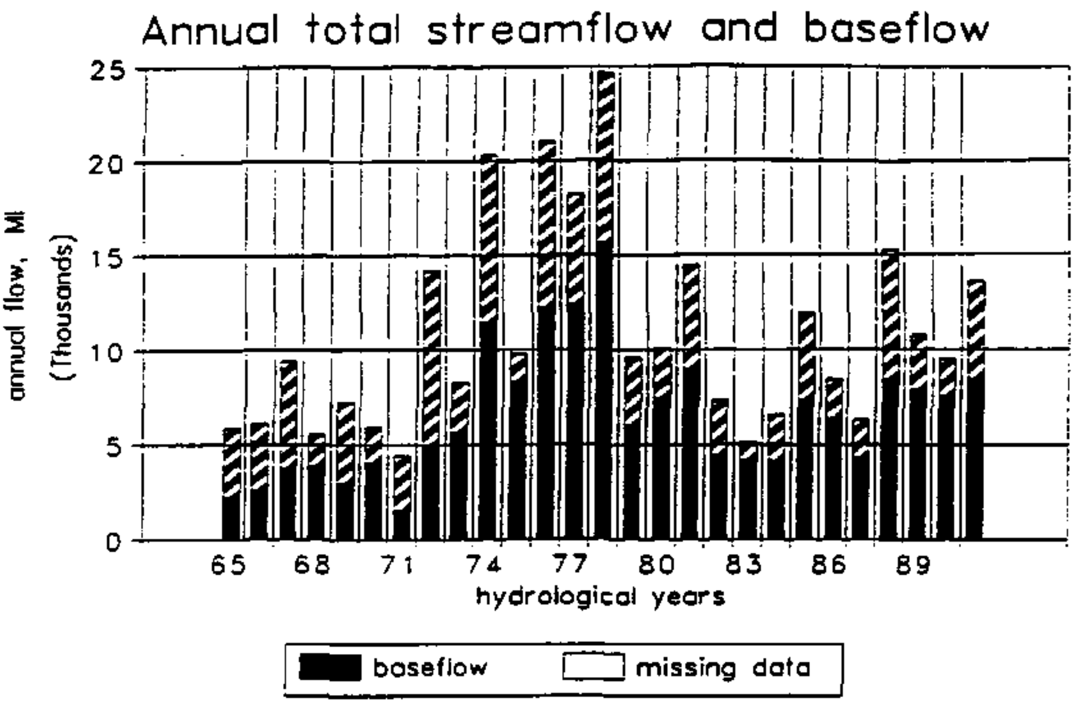


Figure B2.1. Gauge X3H001



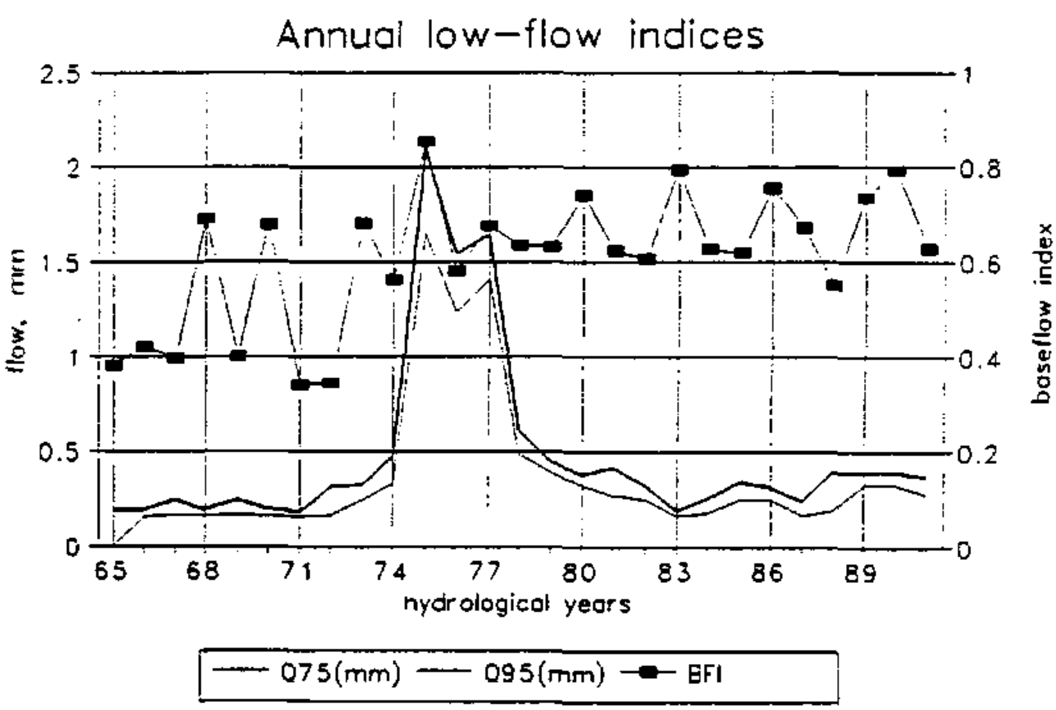
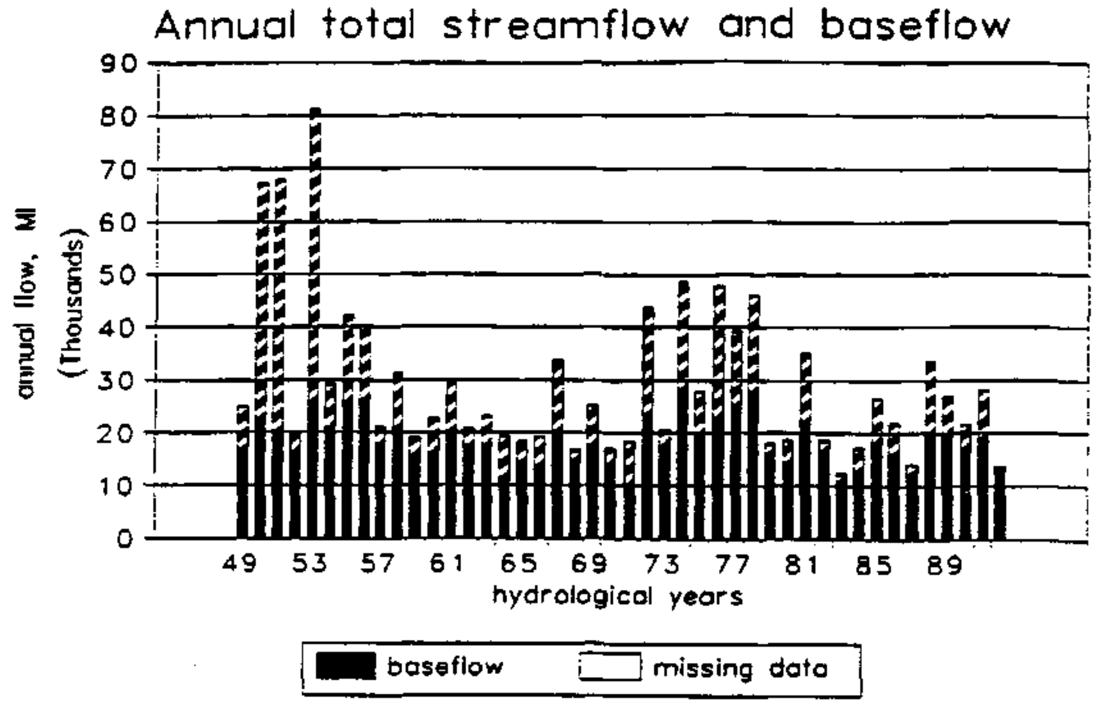


Figure B2.2. Gauge X3H002



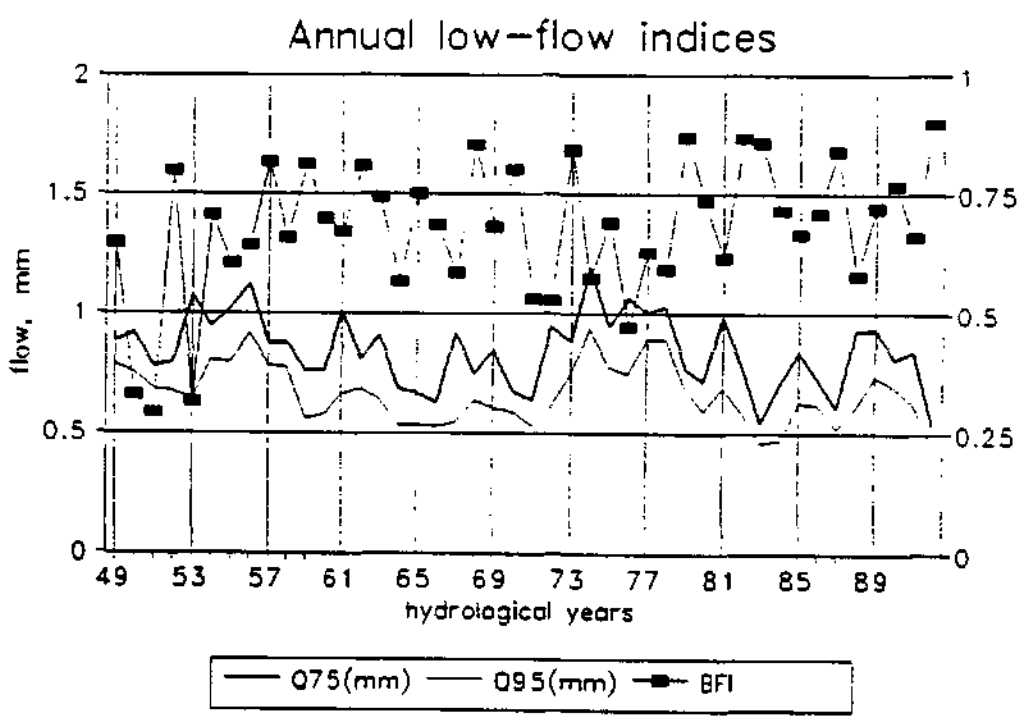
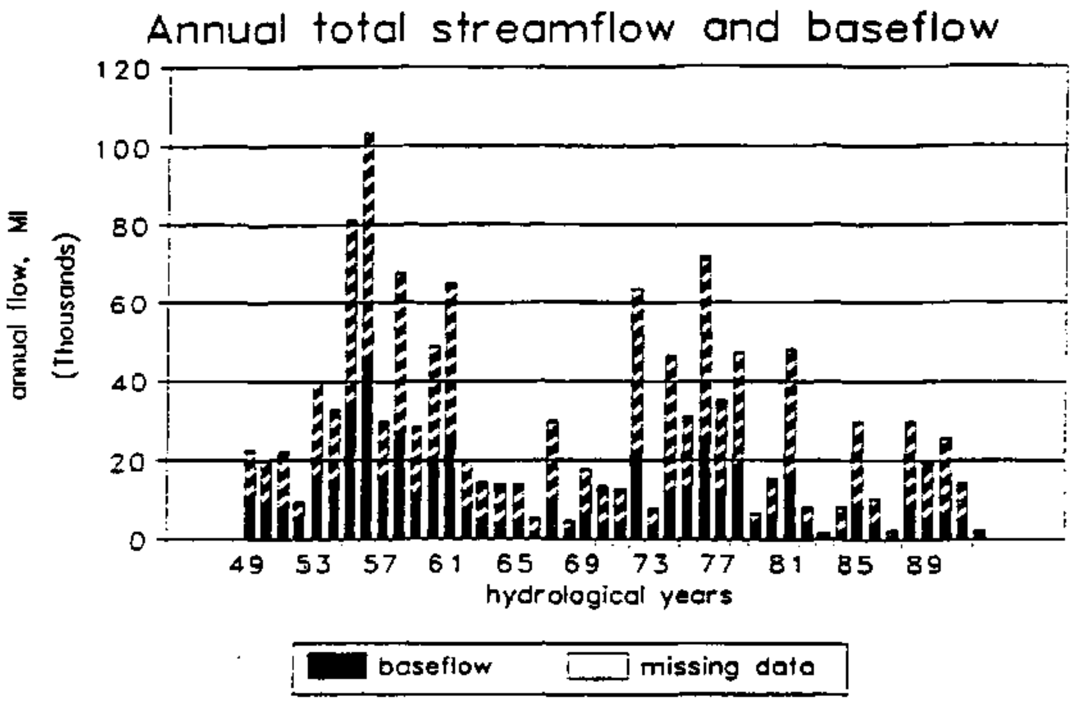


Figure B2.3. Gauge X3H003



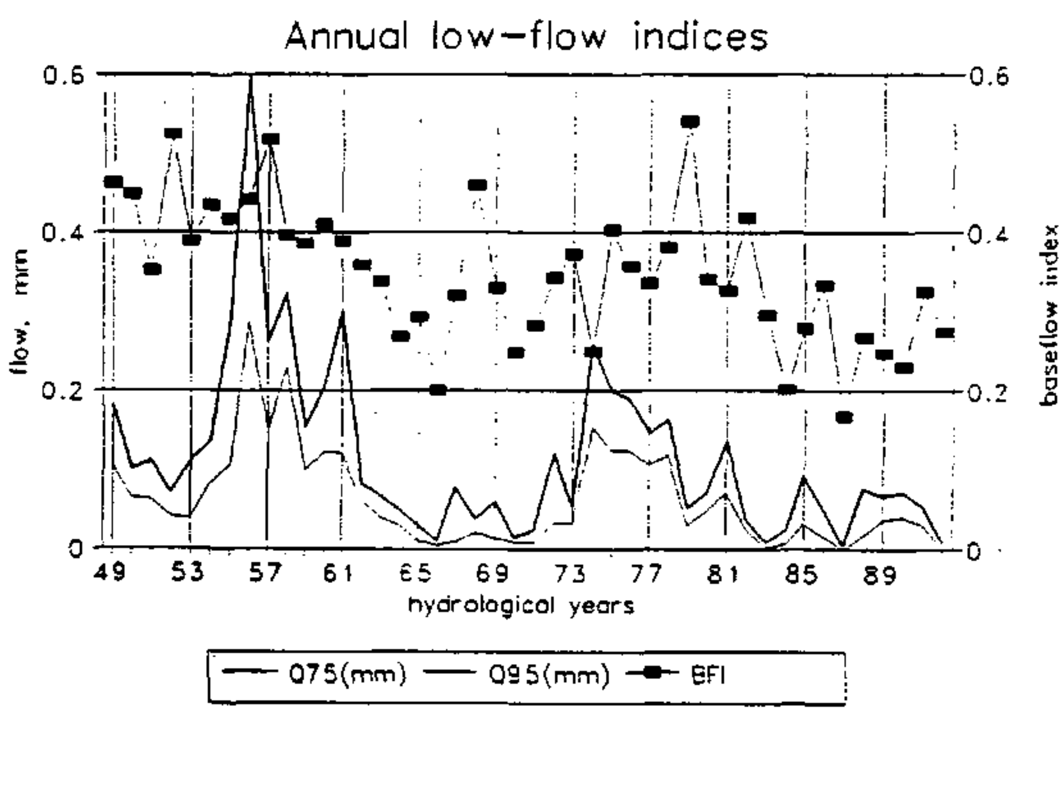
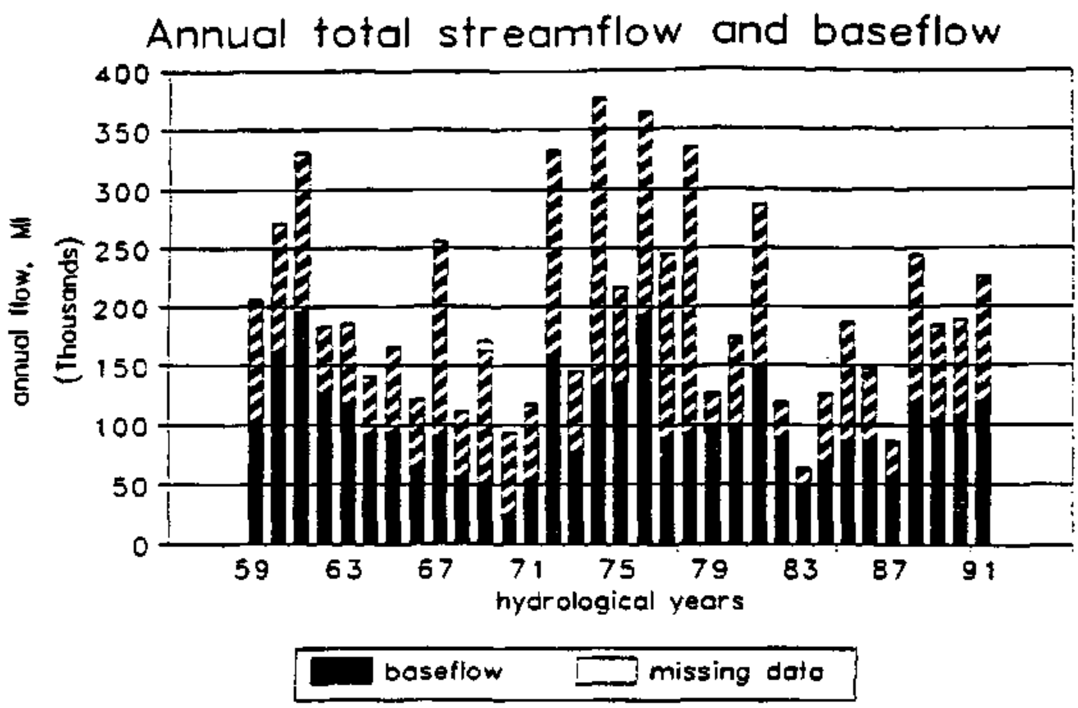


Figure B2.4. Gauge X3H004



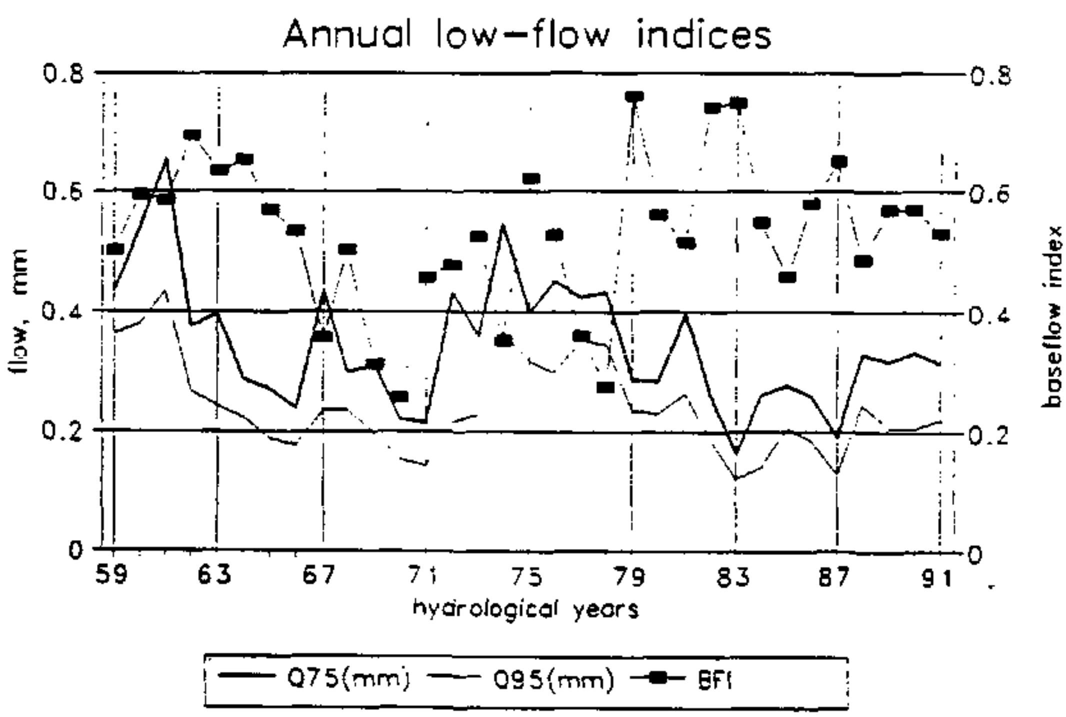
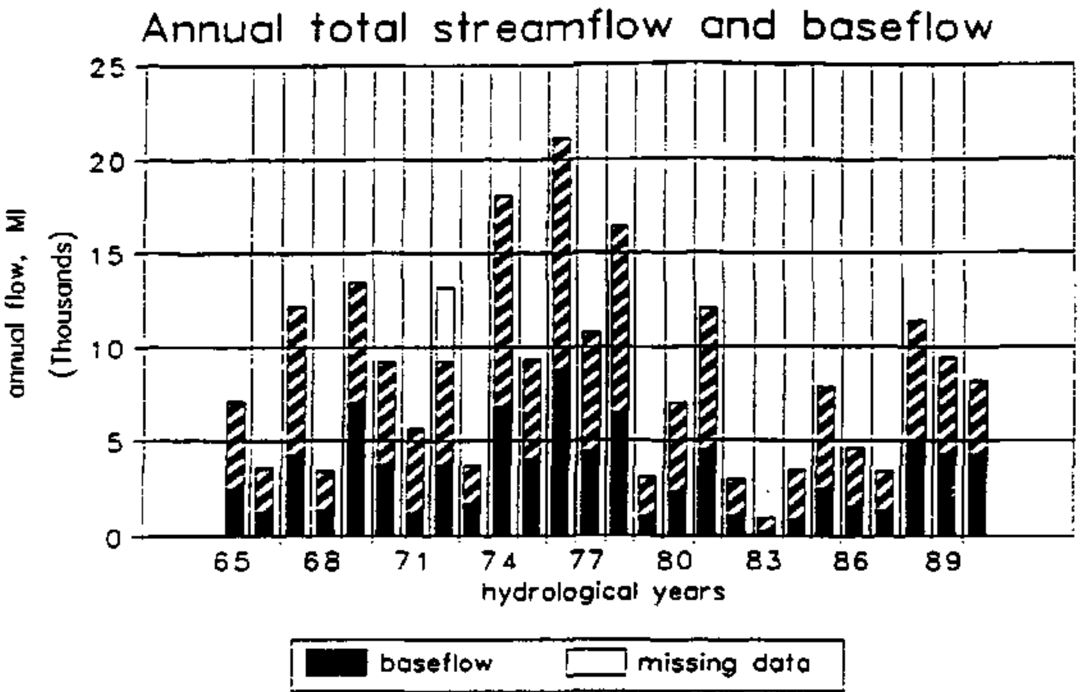


Figure B2.5. Gauge X3H006



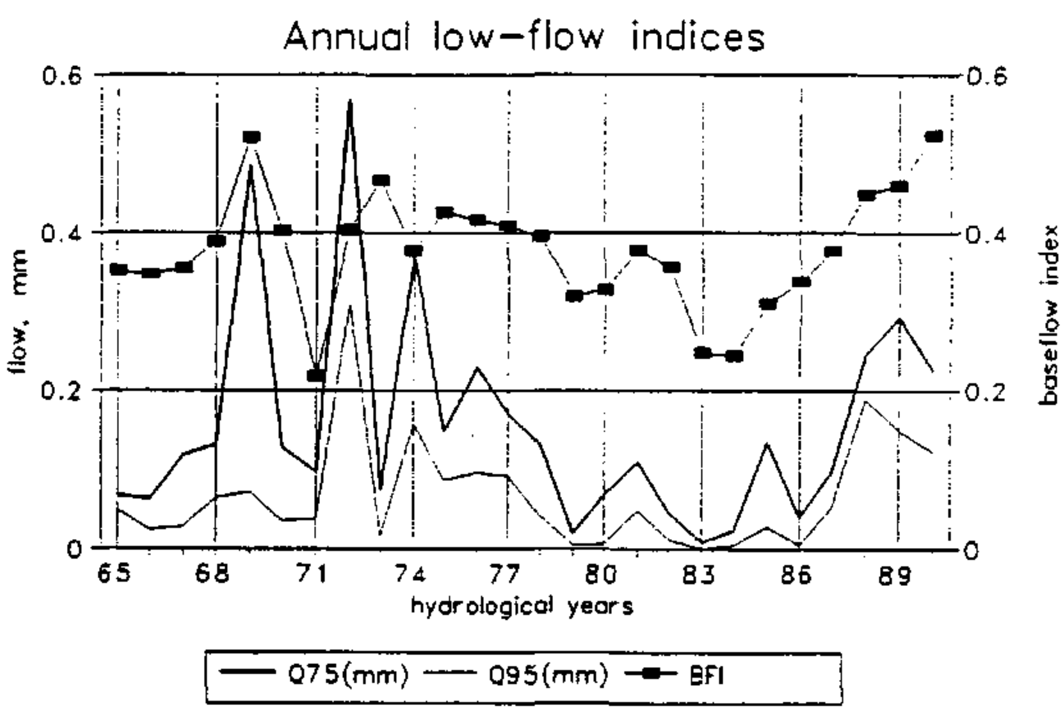
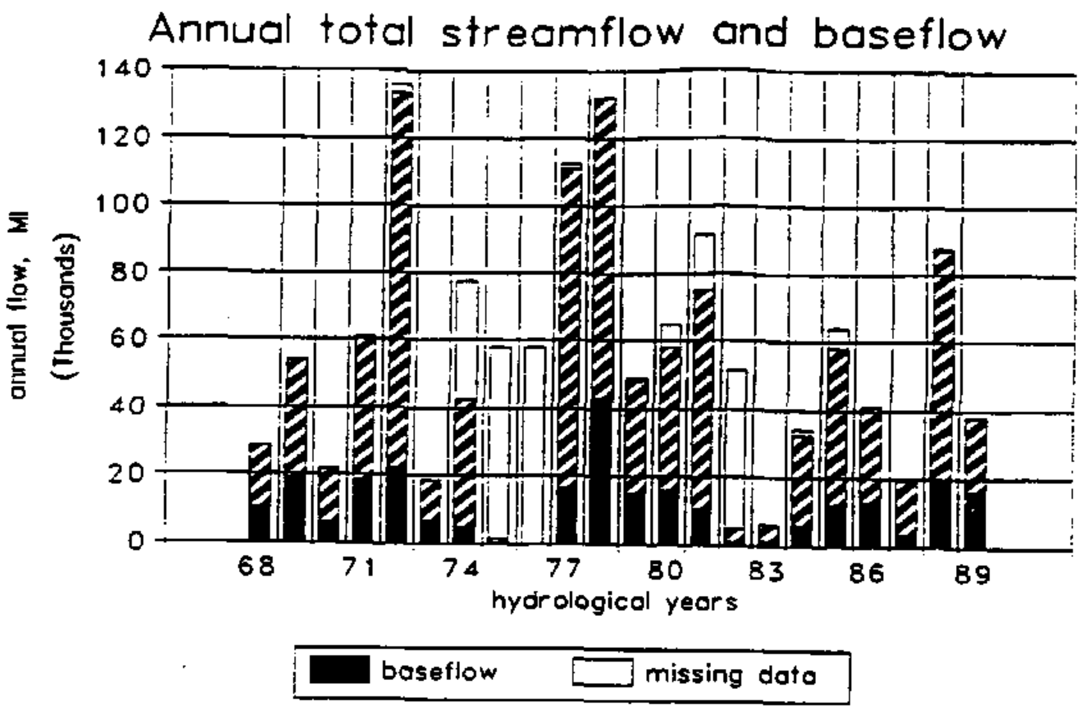


Figure B2.6. Gauge X3H007



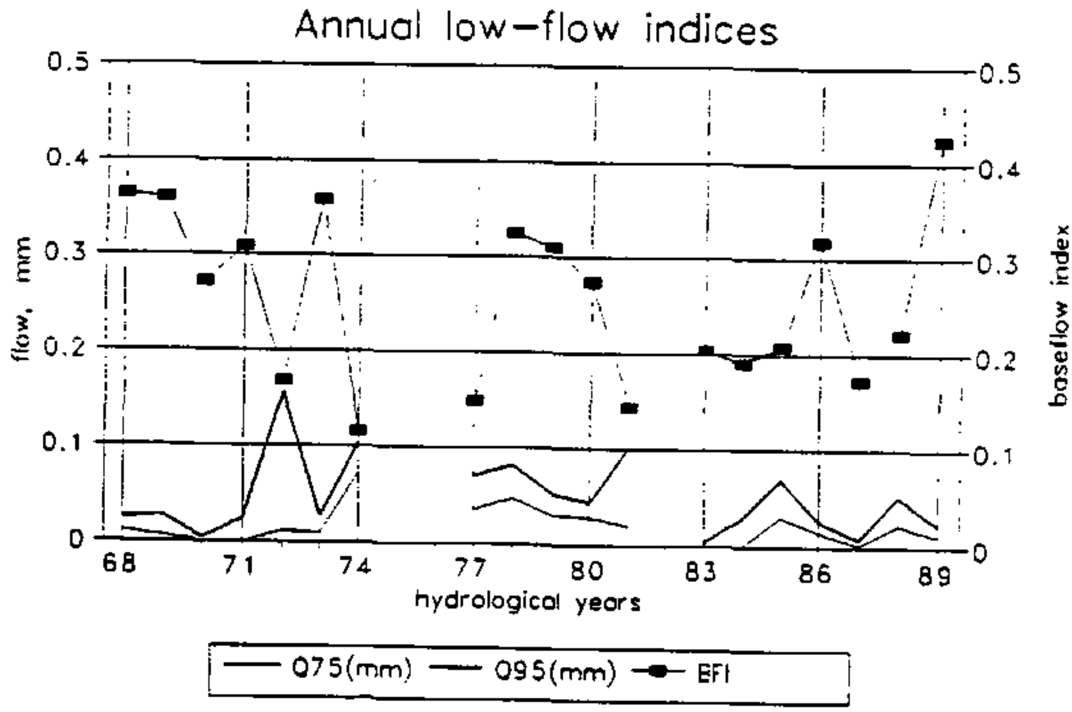
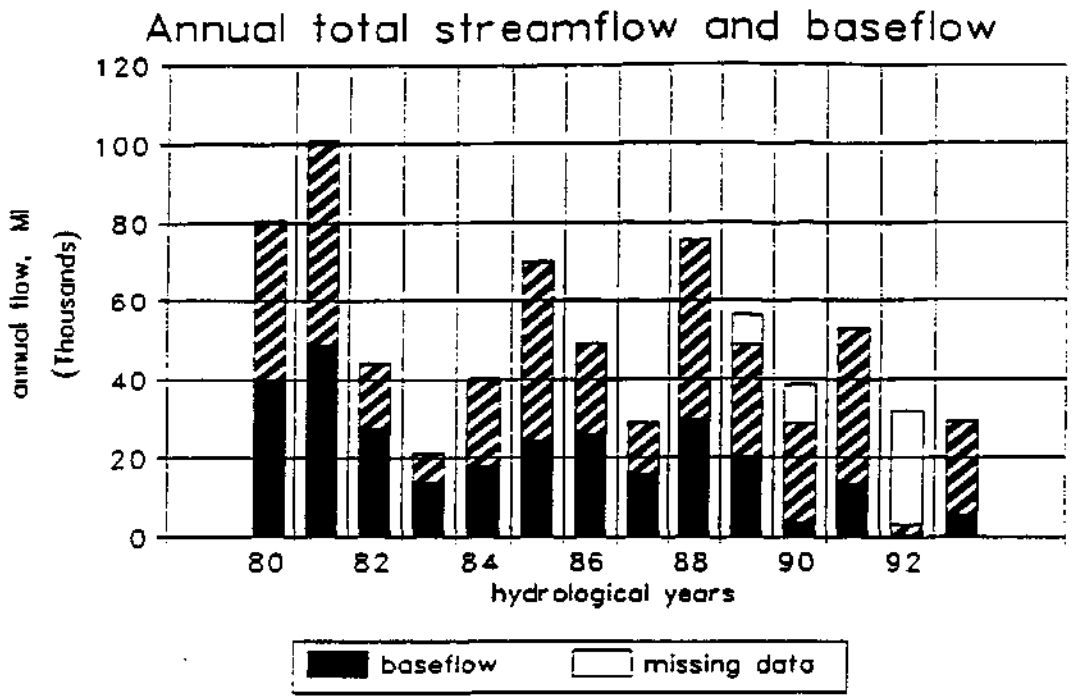


Figure B2.7. Gauge X3H008



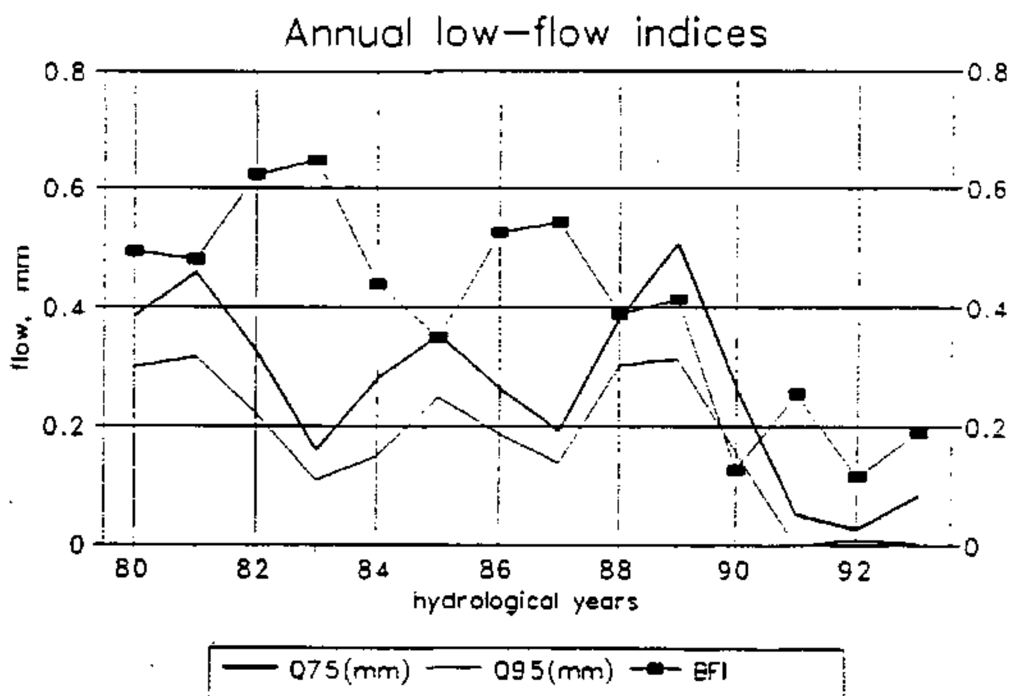


Figure B2.8. Gauge X3H011

APPENDIX C1

Low-flow estimation in the Berg catchment (Western Cape)

C1.1 INTRODUCTION

Low flows in the Berg river catchment have been investigated similarly to the Sabie river (Appendix B1). All available gauged records have been analyzed in terms of several low-flow characteristics. The VTI model has been set up and calibrated for the largest gauged area of the catchment (G1H031, 4012 km^2). The objective of the simulation approach was to provide daily flow sequences at a range of locations in the catchment using the calibrated model. After the calibration was completed, 30 years long daily flow time series at present day and virgin conditions have been simulated. Several low-flow indices have been extracted from the simulated series for each subdivision in the catchment. The results are summarised in the tables and GIS coverages which illustrate the spatial distribution of low-flow characteristics in the catchment.

C1.2 CATCHMENT DESCRIPTION.

The Berg River has its source in the Franschhoek/Drakenstein mountainous area approximately 60 km east of Cape Town. It flows northwards past the town of Paarl and Wellington, arcs northwestwards and reaches the Atlantic Ocean approximately 130 km north of Cape Town. Its total length is about 270 km. The river takes on nine major and seven minor tributaries.

The upstream parts of the catchment are surrounded by mountain ranges (up to 1 500 m above sea level) and for that reason the river basin is narrow between the source and the town of Wellington. Northwards of Wellington, the Limietberg mountains bound the catchment to the east, while in the west the basin flattens out. The general topographic features of the catchment are illustrated by Figure C1.1 which is constructed using the data obtained from the CCWR.

The Berg River basin lies within the winter rainfall region (approximately 80 % of the rainfall falls as short winter downpours). Precipitation originates predominantly from cold fronts approaching the catchment from the northwest. MAP is high - up to 2 600 mm in the high lying areas of the Groot Drakenstein, but drops to 400 - 500 mm up in the middle and lower reaches. The spatial variability of the MAP in the catchment is illustrated by Figure C1.2 constructed on the basis of the information obtained from the CCWR (derived by the Dept. of Agricultural Eng., Univ. of Natal, Pietermaritzburg). The mean annual S-pan evaporation varies from about 1 000 mm in the upstream mountainous parts of the catchment to 2200 - 2400 mm in the middle and lower reaches. Evaporation during the summer months (230 - 250 mm) is approximately 5 times higher than in winter.

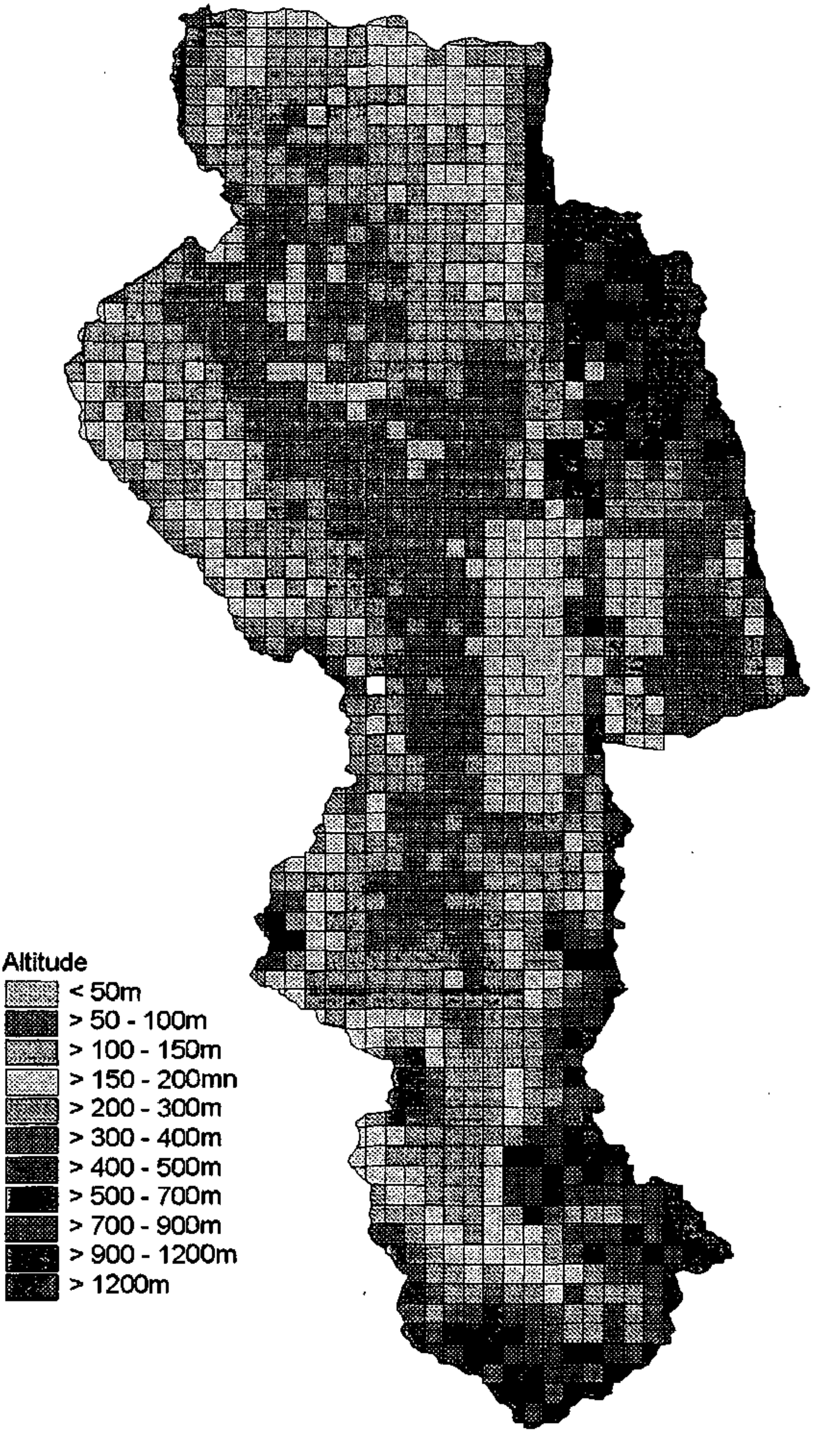


Figure C1.1 1' X 1' grid altitude data (m) for the Berg River catchment.

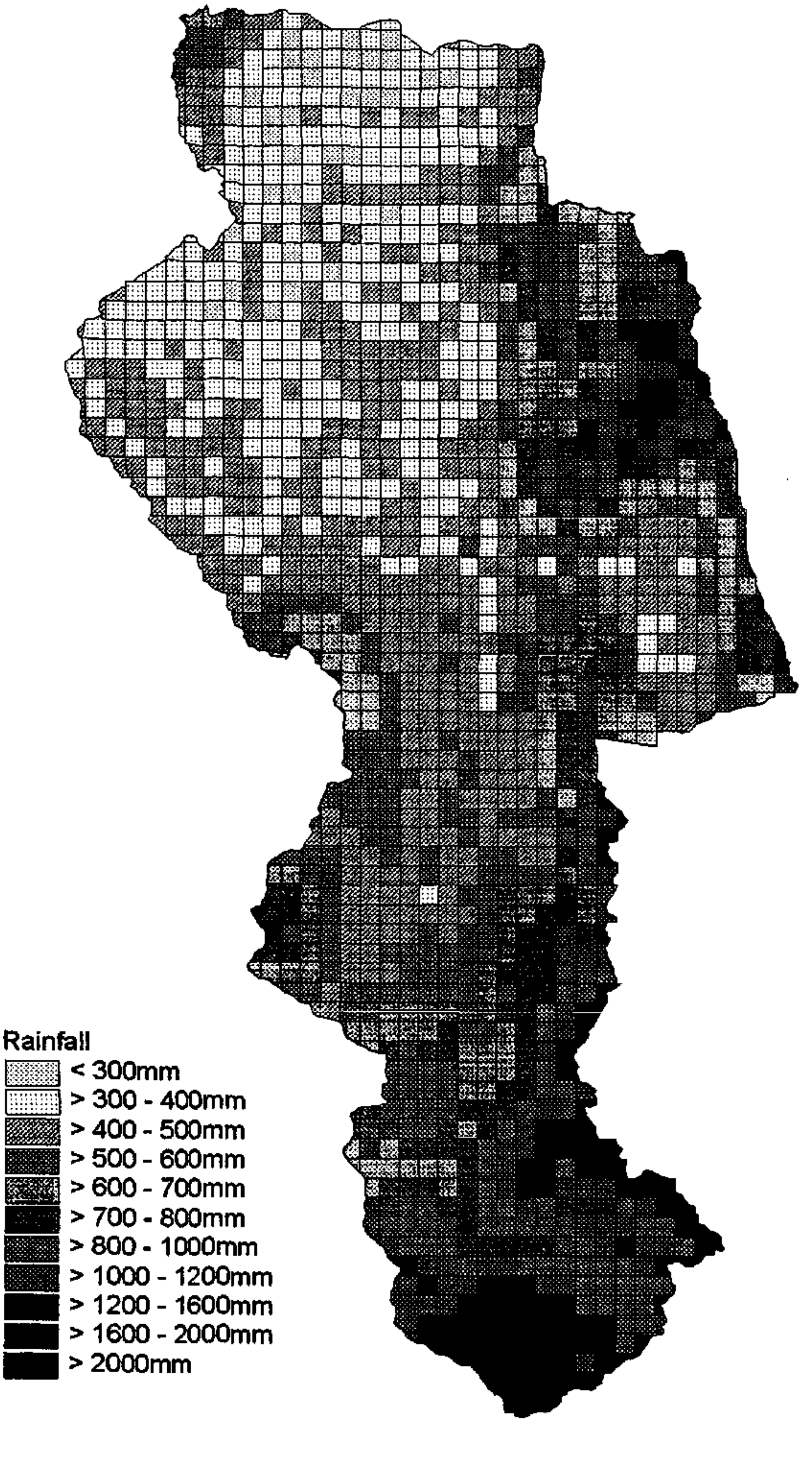


Figure C1.2 1' X 1' grid MAP (mm) for the Berg River catchment.

The peaks and most of the mountainous part of the catchment are composed of quartzitic Table Mountain Sandstone. Lower down the erodible Malmesbury shales become the dominant underlying rock formation. A noticeable characteristic of the lower reach is the meandering nature of the river, a feature which is directly linked to the erodible nature of the Malmesbury shales.

Soils on steep slopes in the mountainous parts of the catchment are shallow (moderate to deep on the slopes of the eastern mountains) and predominantly of sandy loam texture. In the flat parts of the catchment the soils are primarily moderate to deep clayey loams.

Indigenous "fynbos" vegetation is present in most areas but varies from dense concentrations in gulleys to sparse coverings on rocky mountain slopes. The land is primarily used for wine and fruit farming. A portion of the land is irrigated with water either taken from farm dams or abstracted directly from the main river and its tributaries. Vegetables are also grown but in small amounts. Forestry predominates in the high altitudes and rainfall areas (mostly in the southern, upstream parts of the catchment). The river also provides water for trout farming and water supply to the Cape Town area.

C1.3 OBSERVED STREAMFLOW DATA.

Flow in the Berg River catchment is measured at more than 30 gauges. Some of these gauges measure flow in irrigation canals and some from very small catchments (the latter are generally of little relevance to the present study). The details of the streamflow gauges are summarised in Table C1.1, while their location is shown in Figure C1.3, C1.4 and C1.5. Compared to many other similar sized catchments in South Africa the Berg River is relatively well gauged, although the gauges are not evenly distributed spatially. Most of the gauges record flow during the last 20 years and therefore a concurrent period of observations could probably be established and a possibility may exist to analyze low flows from the observed records at present conditions.

Most of the observed data sets (including those from very small catchments but excluding those on canals), have been analyzed by plotting the annual low flow totals and annual low-flow indices as time series. These analyses allow the general quality of the data to be evaluated and temporal variations in annual total flows and low flows to be illustrated. The low-flow indices extracted were flows exceeded 75 and 95 % of the time, baseflow index and baseflow volume. Plots of these characteristics are presented in the APPENDIX C2.

The hydrological regime of the catchment has been significantly modified and this is reflected in many streamflow records. Gauge G1H002 recorded reasonably natural flow until 1970 when the diversion weir G1H028 just upstream of the original station was constructed. Since then the significant amount of runoff (gauged by G1H058) has been diverted into Voelvlei Dam which cut off all low flows (Fig. C2.1, APPENDIX C2). The same is also true for gauge G1H029 (Fig. C2.19).

Gauge G1H007 records a gradual decrease in both annual totals and low flows while a number of gauges in very small catchments (G1H009, G1H014 - G1H018) record stationary flow regimes. Flow regimes in the headwater areas (G1H003, G1H004, G1H019) are affected by various water imports and exports, factory, domestic abstractions and irrigation which may either be reflected in the records (e.g. Fig. C2.3, APPENDIX C2) or masked by a complex nature of combined effects (Fig. C2.2).

In the Berg river itself annual total flows have been gradually increasing during the last 10 - 15 years which is demonstrated by records at gauges (from top to bottom of the catchment) G1H020, G1H036 and G1H013 (Figs C2.17, C2.23 and C2.10 correspondingly) while low flows remained stationary with the exception of gauge G1H020 (Fig. C2.17). The gauges located in the dry downstream parts of the catchment record either no or occasional low flows (Figs. C2.21, C2.22, C2.24 - C2.26).

C1.4 CALIBRATION PROCEDURE.

For the purpose of basin-wide low-flow estimation in the Berg River catchment daily flow sequences have been simulated at a number of locations using the VTI model. For model calibration and subsequent generation of long daily time series the catchment was subdivided into several interlinked components (projects). Each project corresponded to one of the gauged catchments: G1H020, G1H036, G1H008, G1H013 and G1H031. The portion of the Berg River catchment below gauge G1H031 was not simulated. Each project was further subdivided into several sub-areas according to tributary structures, available 'internal' flow gauges, variations in altitude, landuse and rainfall. Figure C1.3 illustrates the adopted discretisation of the whole catchment into projects and subareas, while Figures C1.4 and C1.5 show this discretisation on a larger scale for the upper and lower parts of the catchment correspondingly. These Figures also show the approximate location of the rainfall and most of the existing streamflow gauges with available data.

Calibration of the VTI model was attempted over the period 1978 - 1982, with subsequent verification of the results for 1983 - 1988. All the data on water usage in each project have been taken from the report on Hydrology of the Berg River Basin (1993). The results of the calibration and verification of the model for each of the projects are briefly summarised below.

Project 20 (Berg20) - gauge G1h020.

Berg20 includes the steep headwater region of the Berg river and its several tributaries (Franschoek, Wemmers, Banhoek) which levels out further downstream where the river runs through the town of Paarl. The project was subdivided into 8 subareas. Calibration of the VTI model was attempted at sub-areas 1 (gauge G1H004), 2 (gauge G1h019), 5 (gauge

Table C1.1 Details of flow gauges in the Berg River catchment.

Gauge	River	Area, km^2	Available record
G1H004	Berg	70	1949 - 1994
G1H019	Bandhoek	25	1968 - 1994
G1H003	Franschoek	46	1949 - 1992
G1H020	Berg	609	1996 - 1994
G1H037	Krom	69	1978 - 1992
G1H041	Kompanjies	121	1979 - 1995
G1H039	Doring	43	1979 - 1994
G1H036	Berg	1 312	1978 - 1994
G1H012	Waterfall	36	1964 - 1992
G1H010	Knolvlespruit	10	1964 - 1992
G1H009	Brakkloospruit	5.7	1964 - 1992
G1H021	Klein-Berg	19	1968 - 1992
G1H008	Klein-Berg	395	1954 - 1992
G1H043	Sandspruit	152	1980 - 1994
G1H013	Berg	2 934	1964 - 1994
G1H035	Matjies	676	1975 - 1994
G1H034	Moorresburg spruit	134	1976 - 1994
G1H031	Berg	4 102	1975 - 1994
G1H002	Vier en twintig	187	1963 - 1970
G1H028	Vier en twintig	183	1972 - 1992
G1H007	Berg	713	1951 - 1976
G1H011	Waterwalsrivier	27	1964 - 1992
G1H014	Zachariashoekspruit	2.8	1964 - 1992
G1H015	Kasteelkloofspruit	1.9	1964 - 1988
G1H016	Kasteelkloofspruit	3.3	1964 - 1992
G1H017	Zachariashoekspruit	1.7	1964 - 1988
G1H018	Zachariashoekspruit	3.4	1964 - 1992
G1H029	Leeurivier	36	1972 - 1994
G1H038	Wolwekloofrivier	17	1989 - 1994

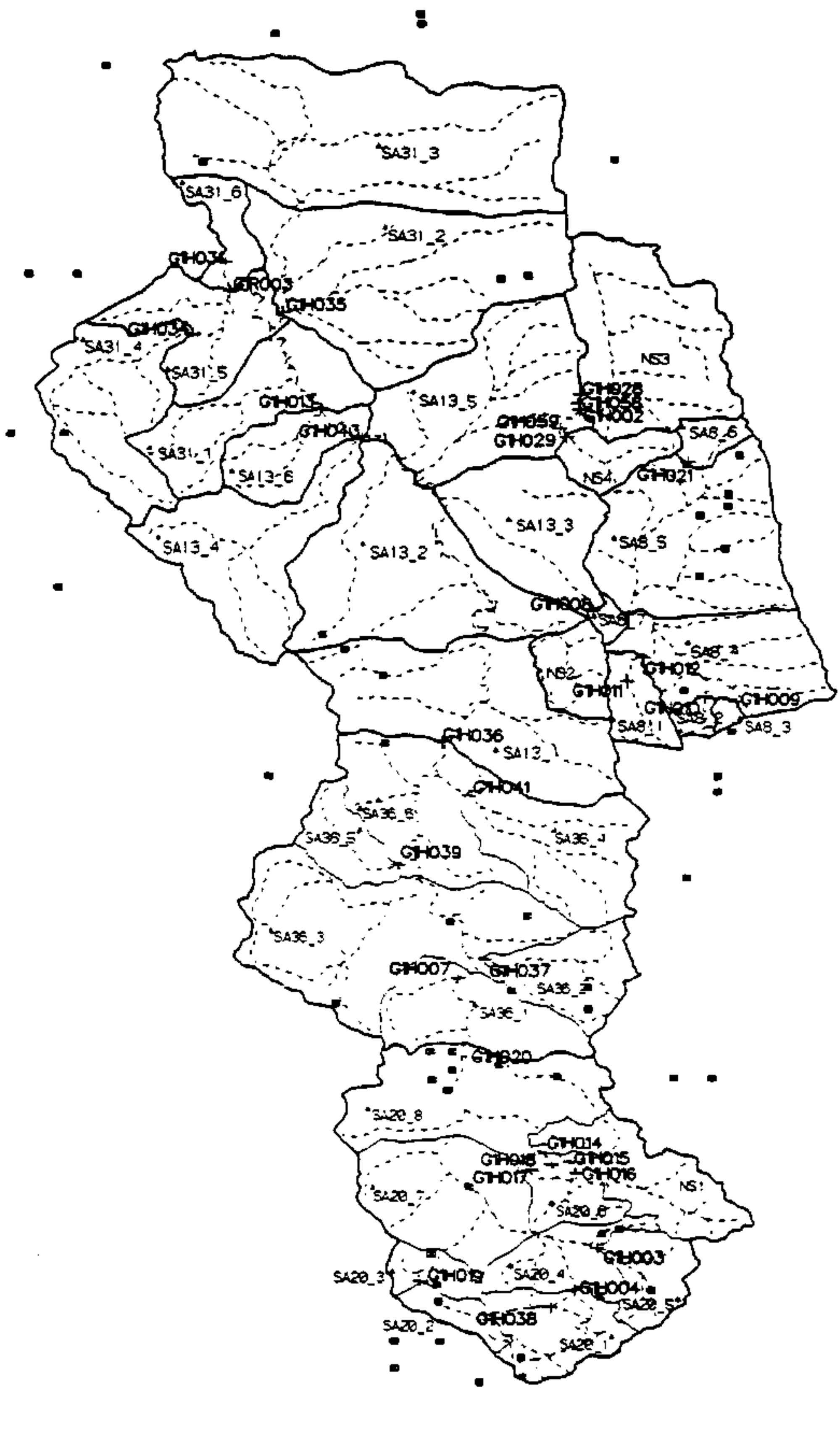


Figure C1.3 Discretisation of the Berg River catchment (see legend in Figs C1.4 and C1.5).

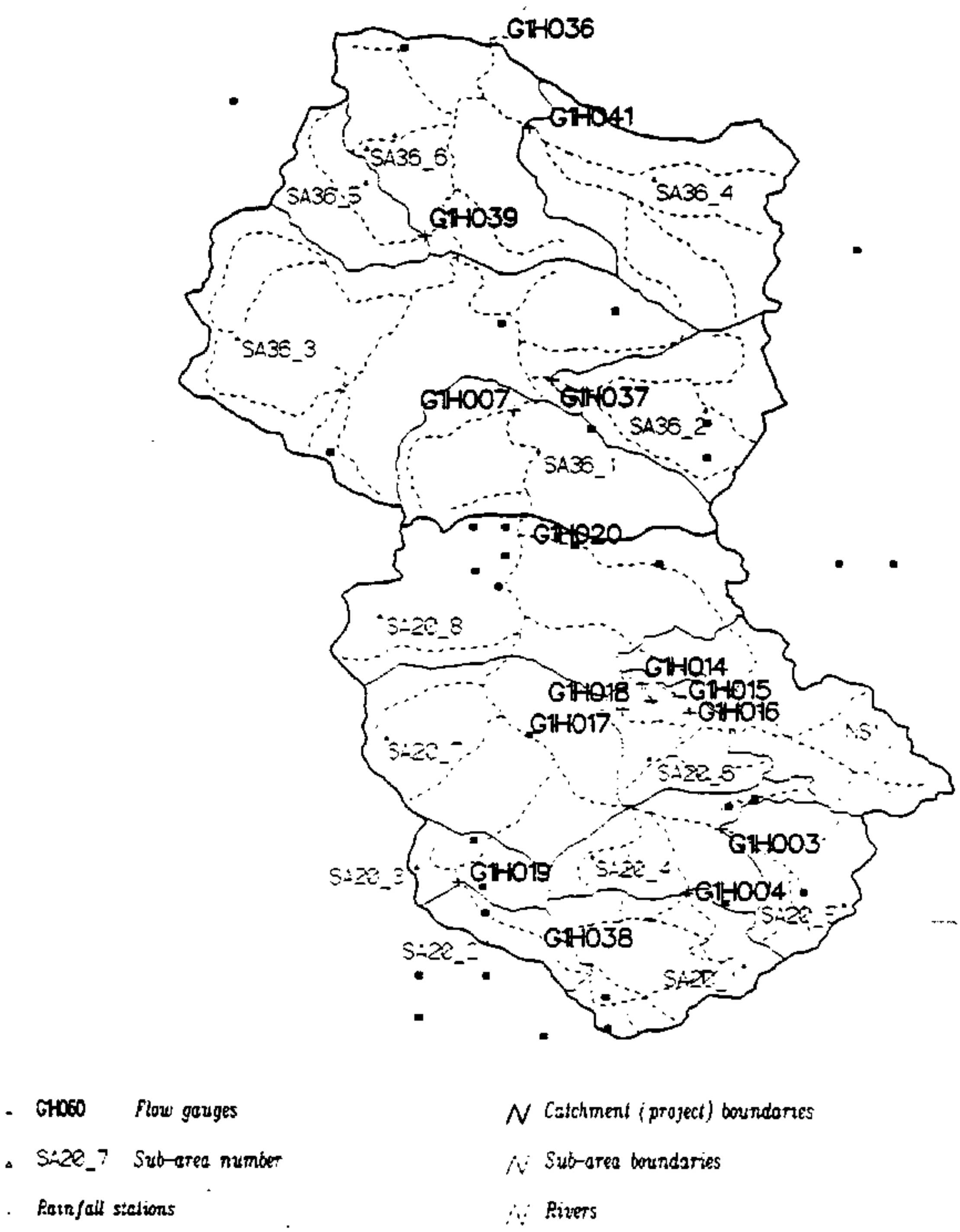


Figure C1.4 Discretisation of the Berg River catchment (projects 20 and 36).

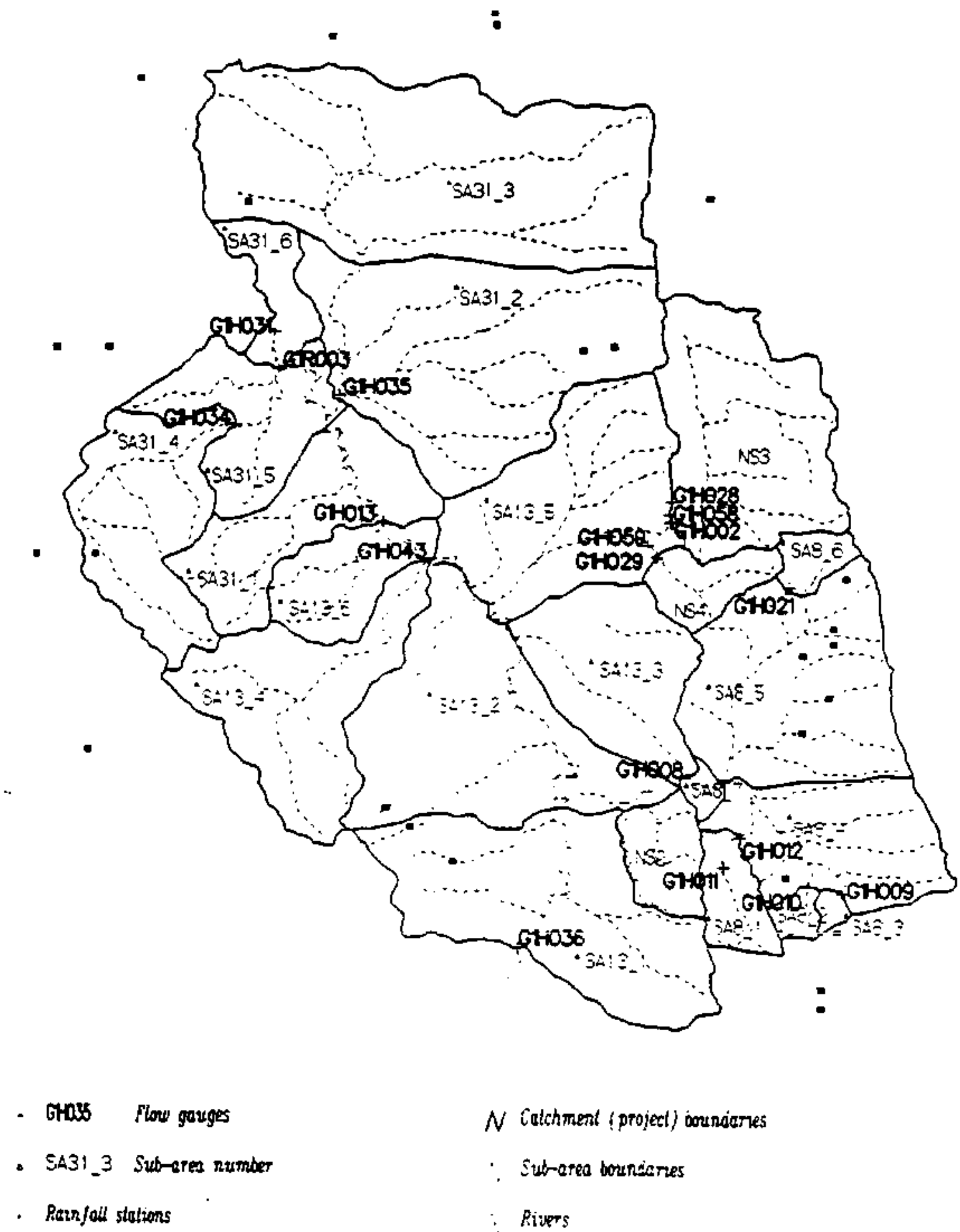


Figure C1.5 Discretisation of the Berg River catchment (projects 8, 13 and 31).

G1H003) and at the outlet of the project (sub-area 7 - gauge G1H020). Since no data were available for the releases from the Wemmershoek Dam, the portion of the project above the dam was simulated and the assumption of zero inflows from that portion of the catchment had to be made (the area is marked on Figures C1.3 and C1.4 as NS1 - "Not Simulated area 1"). In the headwater subareas the model was set up to simulate springflow, while in the flatter downstream subareas baseflow was simulated as the intersection of the groundwater table with the surface.

The impacts in this project include forestry, trout farming, agriculture (mostly vineyards), Robertsvlei and Paarl municipal abstractions and interbasin transfer from Theewaterskloof Dam (in Riviersonderend catchment) to the Upper Berg in summer. Only monthly data for a short period (1983 - 1988) are available on releases from the Theewaterskloof tunnel. Therefore, it is virtually impossible to describe this effect properly in the model. However, these releases are large (Hydrology of the Berg River, 1993) and have significantly modified the flow regime (especially in the subarea 1). An attempt was made to create an input time series of releases by distributing monthly flows evenly between the days of the month for all available period of record. This approach however was not entirely successful: the visual inspection of observed hydrographs at gauge G1H004 revealed large 'peaks of releases' during summer low-flow season which could not be simulated. The other effect of the tunnel is that in winter the surplus water is diverted into it from the Banhoek river (subarea 2, gauged by G1H019). No data for these transfer were available.

Difficulties have also been experienced with specifying a representative rainfall input to the model. The rainfall in the headwater areas is extremely spatially variable. As usual, the median monthly rainfall data available at a resolution 1' X 1' from the CCWR have been used to weight station rainfall data by the ratio of the average of the medians for all grids within a subarea over the median monthly rainfall at the gauge site. These weighting factors vary on a monthly basis and should ensure that the input rainfall depths are more accurately represented, even when individual daily rainfalls are less accurate. However, this approach may have a reverse effect by excessively scaling up (or down) the individual gauged rainfall depths in areas of strong orographic effect, which is typical for the headwater subareas of the project.

In general the calibration for the internal headwater subareas resulted in varying success. The effect of Theewaterkloof Tunnel releases to a large degree deteriorated the resultant fit statistics which remained relatively low for both untransformed and log-transformed flows (R^2 just less than 0,5 CE less than 0.3). The visual comparison of observed and simulated hydrographs revealed oversimulation of high flows in the latter period and slight oversimulation of low-flows. However, the general pattern of recessions was satisfactorily simulated.

Maximum flows in sub-area 2 of the project also appeared to be oversimulated. This resulted in relatively poor fit statistics for this sub-area for untransformed flow (R^2 = 0.47, CE = -1.28). However, the visual comparison of observed and simulated hydrographs suggested that low-flows were satisfactorily simulated, which is also supported by much better fit statistics for log-transformed flows (R^2 = 0.75, CE = 0.54). The same applies to sub-area 5 (untransformed flows: R^2 =0.09, CE = -1.09; log-transformed: R^2 = 0.75, CE = 0.70).

A visual comparison of observed and simulated flows (Fig. C1.7) at the outlet of the whole project (sub-area 8, gauge G1H020) demonstrated that a reasonable fit had been achieved in terms of hydrograph peaks and shape. This is also confirmed by reasonable fit statistics (Table C1.2). However, low-flows appeared to be oversimulated which is demonstrated by the comparison of observed and simulated flow duration curves (Fig. C1.6).

Table C1.2 Comparative statistics for the Berg catchments.

Code	Data	Untransformed						Ln transformed					
		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
Berg20	Obs	291	0.05	9.88	20.8			5.68	-2.98	1.31	1.35		
	Sim	390	0.89	9.50	20.1	0.55	0.50	5.97	-0.12	1.57	1.02	0.74	0.69
Berg36	Obs	310	0.0	12.7	26.2			5.74	-6.21	1.24	1.83		
	Sim	365	0.1	11.6	22.6	0.55	0.53	5.90	-2.15	1.57	1.31	0.62	0.58
Berg8	Obs	41.5	0.00	1.91	4.00			3.71	-6.91	-0.51	1.57		
	Sim	103	0.06	2.23	6.50	0.44	-0.55	4.64	-2.86	-0.63	1.62	0.79	0.77
Berg13	Obs	498	0.00	18.0	41.5			6.21	-6.91	1.68	1.53		
	Sim	363	0.19	15.7	29.1	0.85	0.80	5.90	-1.67	1.81	1.38	0.79	0.78

Project 36 (Berg36) - gauge G1H036

Berg36 includes the gradually sloping area between the town of Paarl (gauge G1H020) and gauge G1H036 (Fig. C1.4). To the east it is bounded by a mountain range with maximum altitudes of 1500 - 1800 m above the sea level. Water is used for irrigation and the demand is satisfied from the farm dams as well as from the river. There are also municipal abstractions to the towns of Wellington and Malmesbury.

The project has been broken down into 6 subareas (Fig. C1.4) and calibration was attempted in subareas 2 (G1H037), 4 (G1H041) and 6 (G1H036, the outlet of the whole project). No calibration was possible at gauge G1H007 since the flow record at the gauge was only available until 1976. Gauge G1H039 was not considered separately for calibration since very little runoff and no low flows are generated in this catchment (Fig. C2.25, APPENDIX C2).

The scarcity of good quality rainfall gauges and the difficulties in the adequate quantification of abstraction patterns in the area have affected the quality of calibration. According to fit statistics, a marginally successful calibration was achieved for subarea 2 (R^2 just above 0.6, CE varies from 0.33 (log-transformed flows) to 0.43 (untransformed flows)). However, flows appeared to be undersimulated through most of the flow range in the physiographically similar subarea 4, which resulted in relatively poor fit statistics for both transformed and log-transformed flows (all criteria are just above 0.30). This is most probably a consequence of using a set of rainfall gauges completely different from that in subarea 2.

Satisfactory calibration was achieved in the outlet of the whole project (Table C1.2, Fig C1.9), however, low flows remained oversimulated as in the case of the previous project (Fig. C1.8).

Project 8 (Berg8) - gauges G1H008.

The project includes the upstream and middle reaches of the Little Berg River and is bound by the Witzenberg Mountains in the east and the Voelvlei Mountains in the west. The area is characterised by highly spatially variable rainfall (Fig. C1.3) and extensive irrigation development in its central parts, characterised by numerous small farm dams with a total storage exceeding 9 MCM (more than 10 % of the catchment MAR). The project was split into 7 subareas (Fig. C1.5). The calibration was attempted in subareas 1, 6 (located in a high rainfall area) and 7 (in the outlet of the whole project) gauged correspondingly by G1H012, G1H021 and G1H008.

Comparison of observed and simulated flow duration curves and hydrographs in upstream subareas demonstrated that a good fit had been achieved in both cases. Some mismatch between observed and simulated hydrographs in subarea 6 in the earlier part of the record was attributed to the poor quality of measurements at G1H021. Hydrology Report (1993) assumes only part of the record at this gauge from 1984 to 1988 as being reliable and suitable for calibration. Therefore, subarea 6 was actually calibrated only during this period.

Fit statistics for log-transformed flows for subarea 1 ($R^2 = 0.76$, CE = 0.75) were superior than those for untransformed flows ($R^2 = 0.56$, CE = 0.35) which places more confidence in low-flow simulations. Fit statistics for subarea 6 for a period from 1984 to 1988 suggest that a good calibration was achieved (for untransformed flows: $R^2 = 0.75$, CE = 0.60; for log transformed flows $R^2 = 0.88$, CE = 0.85).

Comparison of observed and simulated flow duration curves for the outlet of the project (subarea 7) illustrated a good calibration for most of the flow range (Fig. C1.10) except the most extreme high and low-flows (1 % of the time series at both ends). Oversimulation of the peak flows, illustrated by Figure C1.11 affected the resultant fit statistics for untransformed flows while the statistics for log-transformed flows are much superior.

Project 13 - Berg13 (gauge G1H013).

This is the incremental area between the downstream gauge G1H013 and upstream gauges G1H036, G1H008, G1H029 and G1H028. The project therefore collects water from Berg36, Berg8 and from catchments commanded by G1H028 and G1H029 and is characterised by a very complex 'boundary conditions'. A proper calibration in this project requires a *priori* preparation of inflow time series. Not all of them are available for daily simulations which would obviously affect the results of calibration. Details describing water redistribution at the boundaries of the projects may be found in Berg River Hydrology Report (1993). A brief summary of how these transfers were treated in the model is given below.

Voelvlei Dam, constructed in the early 1950s by enlarging a natural lake basin and later by supplementing the inflow with canals tapping the Little Berg, 24 River (Vier-en-Twintig) and Leeu tributaries, maintains a minimum flow in the downstream parts of the Berg River (projects Berg13 and Berg31). The flow from the area surrounding the dam was not simulated (the area is marked in Figs C1.3 and C1.5 as NS2 -"Not Simulated area 2"). The data on releases from the dam into the Berg River were not available and therefore the input to the system from the dam had to be ignored.

A diversion structure is located on the Little Berg River shortly downstream of gauge G1H008. This transfer is measured and the inflow time series to Berg13 from Berg8 was corrected by subtracting measured daily diverted flows (G1H066) from the simulated flows at gauge G1H008.

The areas commanded by gauges G1H028 and G1H029 have not been simulated and are marked on Figure C1.3 and C1.5 as NS3 and NS4. Since the diversion structures G1H058 and G1H059 are located upstream of gauges G1H028 and G1H029 correspondingly, the latter two already measure "correct" inflows to Berg 13 at least during the calibration period.

The project was subdivided into 6 subareas, however no calibration was performed since generally very little runoff and no low flows are generated in the area (e.g. Fig. C2.26, APPENDIX C2) and the water balance of the project is determined by the boundary inflows. Figures C1.12 and C1.13 however, illustrate that a good coincidence between observed and simulated flows had been achieved. This is also supported by good fit statistics (Table C1.2).

Project 31 - Berg31 (gauge G1H031).

The project includes the most downstream part of the gauged catchment area and collects water from Berg13. The runoff from this catchment however is not properly measured. Gauge G1R003 records the outflow from the Misverstand Dam while the inflows to the dam are represented only by calculated monthly flow volumes. Very little runoff and no low flows are generated within the project (e.g. Figs. C2.21 and C2.22, APPENDIX C2). The Dam was approximated as a big farm dam. No calibration was attempted.

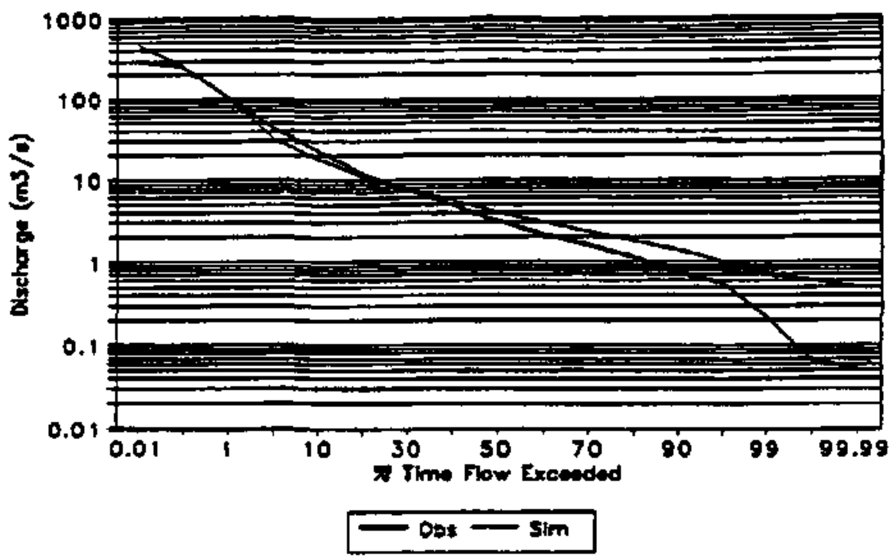


Figure C1.6 Observed and simulated 1-day annual flow duration curves for Berg20 for a period of 1978 - 1988.

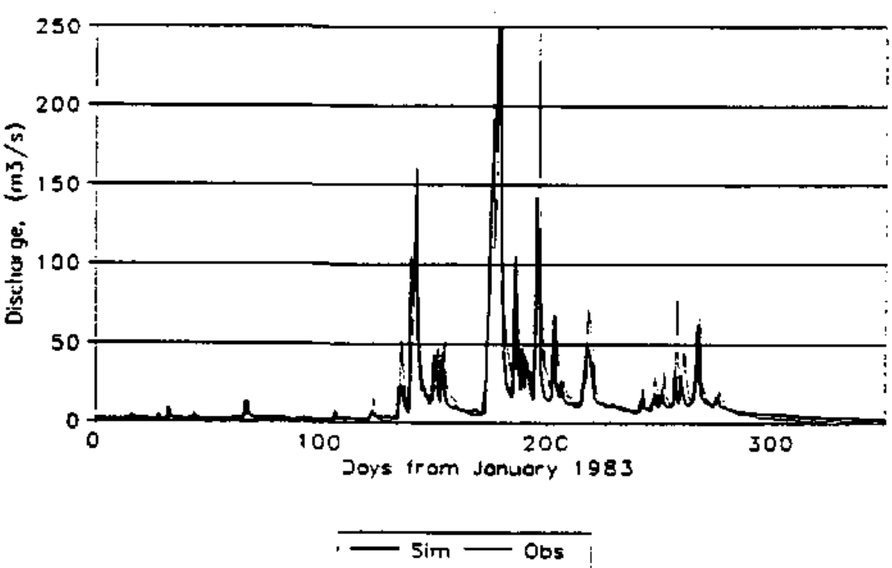


Figure C1.7 Observed and simulated daily hydrographs for Berg 20.

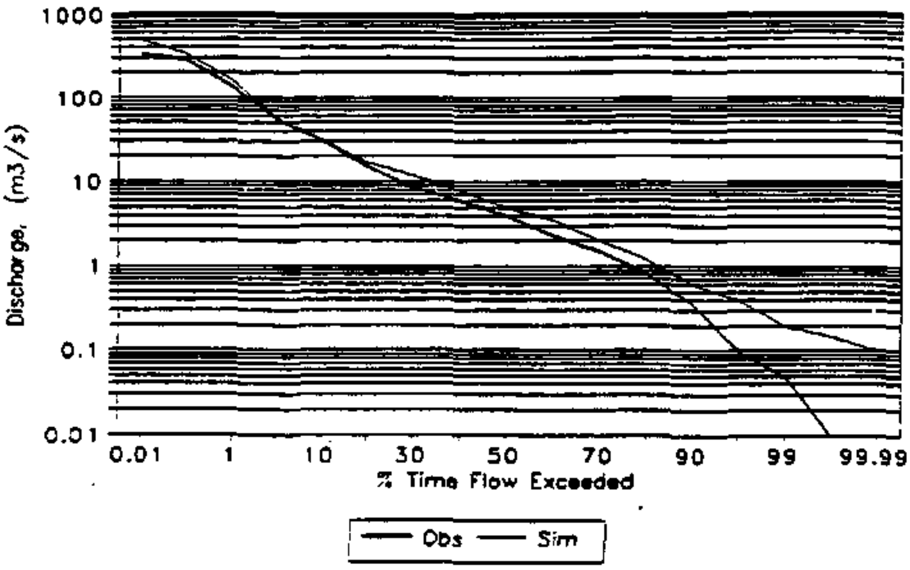


Figure C1.8 Observed and simulated 1-day annual flow duration curves for Berg36 for a period of 1978 - 1988.

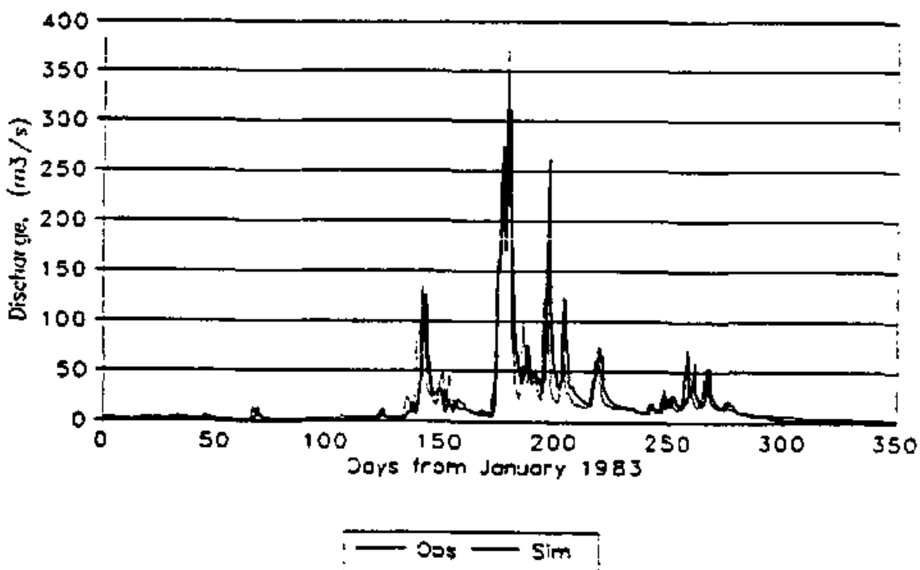


Figure C1.9 Observed and simulated daily hydrographs for Berg36.

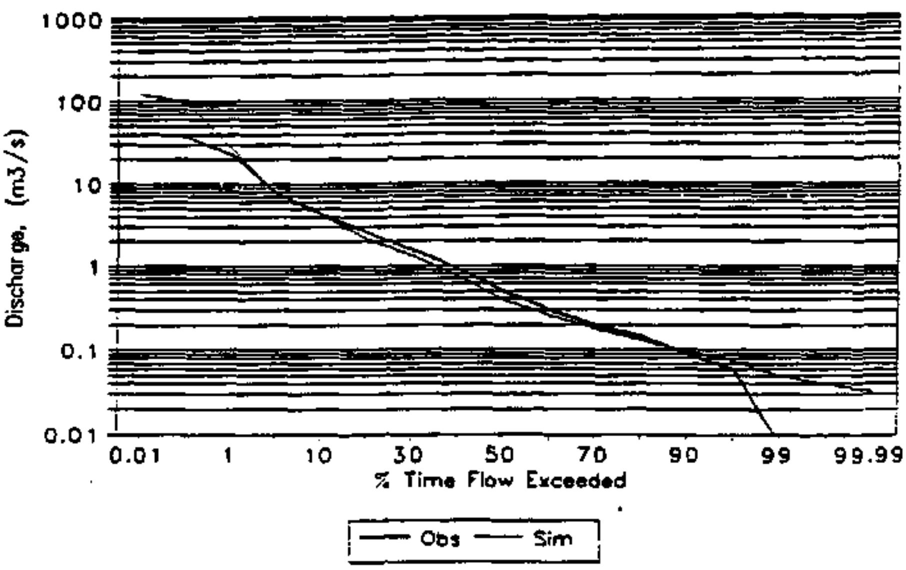


Figure C1.10 Observed and simulated 1-day annual flow duration curves for Berg8 for a period of 1978 - 1988.

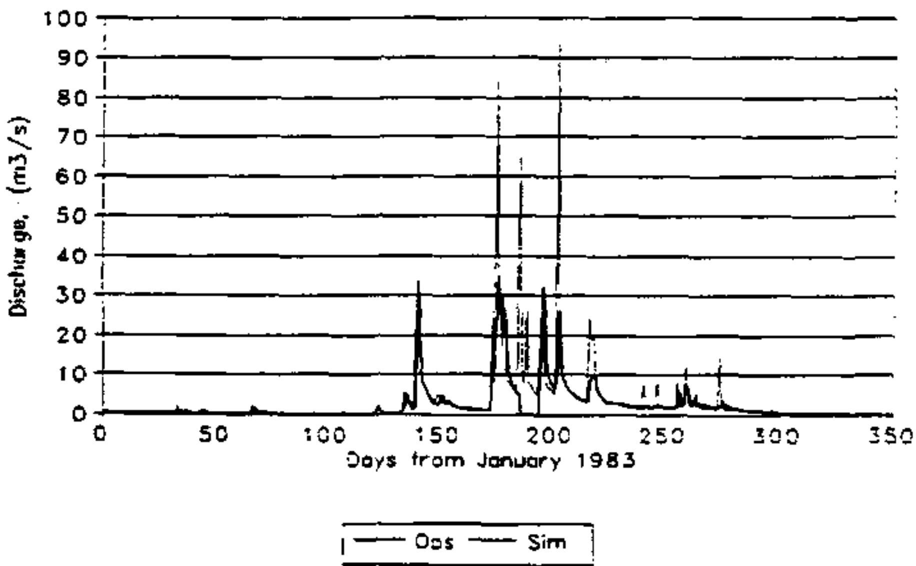


Figure C1.11 Observed and simulated hydrographs for Berg8.

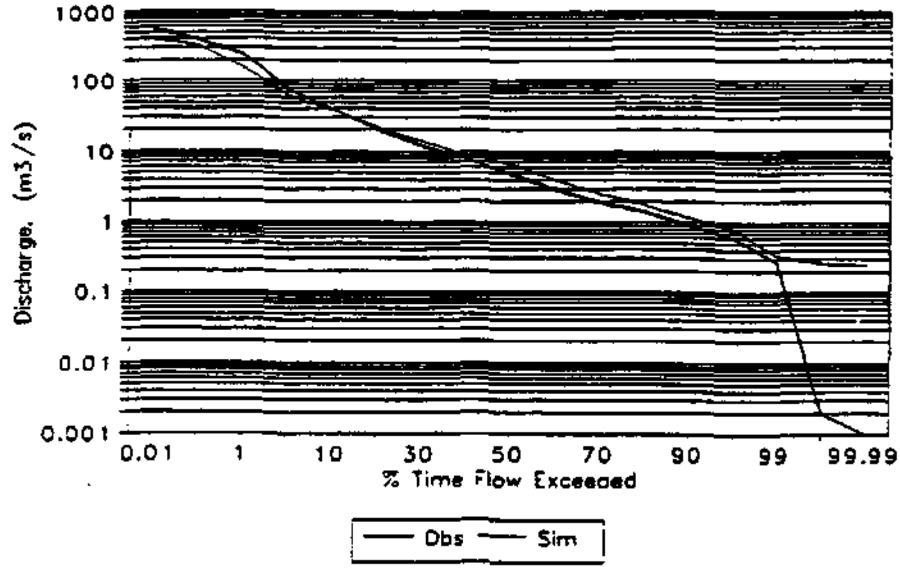


Figure C1.12 Observed and simulated 1-day annual flow duration curves for Berg 13 for a period of 1978 - 1988.

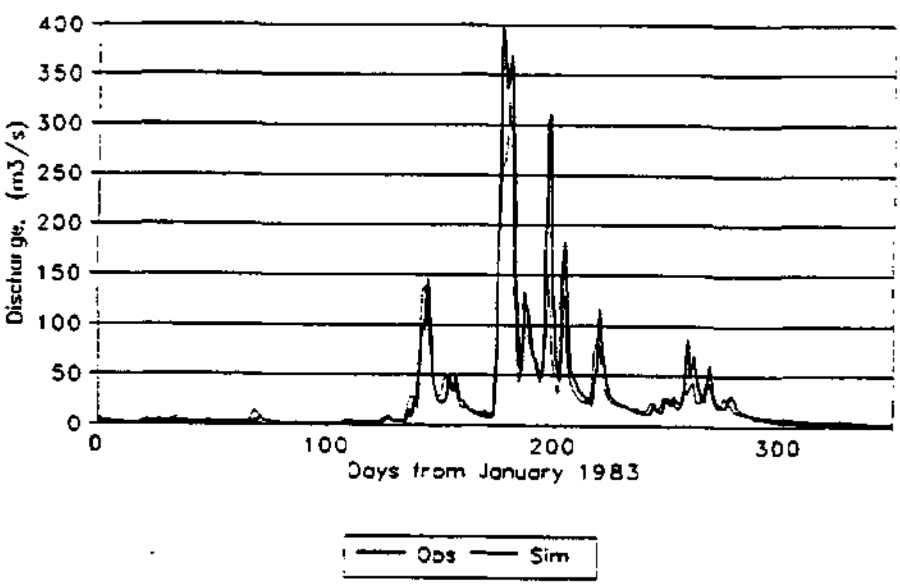


Figure C1.13 Observed and simulated daily hydrographs for Berg13.

Overall, the calibration of the VTI model in different parts of the Berg River catchment resulted in varying success. The problems experienced were mostly a consequence of both insufficient rainfall data and a very complex pattern of water usage in the catchment often coupled with the lack of insufficient quality of corresponding flow data. Also not enough attention has been paid at this stage to the problem of transmission losses in the downstream parts of the catchment.

C1.5 SIMULATION OF DAILY FLOW TIME SERIES AND LOW-FLOW ESTIMATION UNDER PRESENT DAY AND VIRGIN CONDITIONS.

Once a calibration was completed, the simulation of flow under present day conditions for the period 1963 - 1993 was performed in order to obtain representative daily flow time series for subsequent low-flow calculations. The daily time-series of flows in natural (virgin) conditions was also simulated for this period. The following changes have been made to the parameter values and input streamflow time series to simulate natural flow conditions.

- All dam storages and demands have been removed from a parameter set throughout the whole catchment.

- Afforestation areas in some headwater subareas (Berg20) have been removed from the parameter set. A crop factor was reduced from a maximum of 1.3 in afforested subareas to 1.0 once afforestation was removed. This was expected to account for the lower evaporative demand of the natural vegetation.

- The catchment area of subarea 6 in Berg20 was increased by the area above the Wemmershoek Dam to account for free water flow from this part of the catchment in natural conditions. Subarea and channel slope have also been adjusted correspondingly.

- Simulated flow from Berg8 was used as a direct input to Berg13 without any corrections for diversion to Voelvlei Dam.

- Observed daily flow time series at G1H029 and G1H059 were summated to provide an increased inflow to Berg13. (Flows at G1H029 are mostly negligible and alternatively record at G1H059 could be used directly).

- Observed daily flow time series at G1H028 and G1H058 were summated to provide a "natural" inflow to Berg13. In the earlier part of the simulation period (1963 - 1970) the record at gauge G1H002 was used instead. This record was appended to the combined record of G1H028 and G1H058.

- The Misverstand Dam in Berg 31 was "removed". Since the record at gauge G1H031 downstream of the dam is available for the last 18 years and is stationary (Fig. C2.20, APPENDIX C2) it was possible to use it as a time series which represents the present day flow conditions at the gauge and compare it with the simulation by the VTI model time series representing the "natural" flow regime (to illustrate the degree of changes in the flow regime of the catchment).

As in the case of the Sabie River catchment, two low-flow indices have been estimated for each subarea from simulated 30-year daily flow time series: 7-day average flows exceeded 75 and 95 % of the time (Q75(7) and Q95(7)).

Two different types of flow for each exceedence level have been estimated. The first is the flow generated within each sub-area (total sub-area flow). This demonstrates how much flow is actually flowing into a stream channel from an incremental sub-area (at the selected level of exceedence) regardless of the upstream inflow to a sub-area. This flow has (at present day conditions) already been influenced by farm dams, but has not yet been subjected to direct abstractions from a stream in this sub-area.

The second 'flow type' is the final routed runoff - the actual discharge at the outlet of each sub-area. This flow takes into account all upstream inflows into a sub-area (if those exist) and has already been subjected to direct abstractions from a stream (at present day conditions). It therefore demonstrates how much water at a particular location is actually available in a stream channel.

Table C1.3 summarises this information for all sub-areas in the Berg catchment at present day conditions, while Table C1.4 contains similar information for virgin conditions. Total sub-area flow is expressed in m^3/s and mm per annum (mm/a) from a unit area of each subarea.

Final runoff (actual water in a channel) is expressed in m^3/s and MCM. The codes of subareas in Table C1.3 and C1.4 correspond to those in Figure C1.14. Figures C1.15 and C1.16 illustrate the distribution of natural Q75(7) and Q95(7) values (total subarea runoff in mm/a) in the catchment. These Figures (especially Figure C1.16) do not seem to demonstrate an expected gradual but clear decrease in low flows as one moves from the top to the bottom of the catchment (from high flow areas to more drier areas). One explanation is the approximate partition of the existing water development effects between subareas. For example, dam storages and water abstractions from the river are given in Hydrology of the Berg River (1993) for the incremental catchments between existing streamflow gauges. If such an incremental catchment is split into several subareas for the application of the VTI model, these dams and abstractions in the absence of more detailed information have to be arbitrarily (and often evenly) distributed between subareas. This could result in the simulation of zero low flows during the 10-year calibration and 30-year simulation period at present day conditions. However, when all effects are removed, low flows may appear to be non-zero. The possible examples of such effect are subareas 36.6 and 13.1 which generate zero Q75 and Q95 at present day conditions (Table C1.3) but corresponding non-zero flows in natural conditions (Table C1.4).

The degree of changes in the flow regime in each project is illustrated by Figure C1.17 which presents 1-day annual flow duration curves constructed on the basis of 30 years of simulated daily streamflow data in present and virgin conditions (as mentioned above, flow duration curve for gauge G1H031 for present day conditions is constructed on the basis of available observed flow records).

Additional low-flow indices from the flow duration curve or any other low-flow indices can be estimated on request from the simulated flow time series (present day or virgin). It should be noted that due to the high degree of catchment alterations and water resource developments the Berg River catchment appeared to be one of the most complex catchments used in the course of the Project for daily simulation and low-flow estimation.

Table C1.3 Estimated Q75 and Q95 flow values for subcatchments in the Berg river basin (present conditions).

Sub. No.	Subarea km^2	Q75(7), from subarea		Q75(7), routed runoff		Q95(7), from subarea		Q95(7), routed runoff	
		m^3/s	mm/a	m^3/s	MCM	m^3/s	mm/a	m^3/s	MCM
1	2	3	4	5	6	7	8	9	10
20.1	70	0.705	317.6	0.563	17.80	0.417	188.0	0.328	10.30
20.2	25	0.107	135.0	0.104	3.28	0.038	47.9	0.035	1.10
20.3	30	0.149	156.6	0.264	8.32	0.054	56.8	0.059	1.86
20.4	70	0.650	292.9	1.226	38.70	0.426	191.9	0.701	22.10
20.5	46	0.139	95.3	0.083	2.62	0.064	43.9	0.031	0.98
20.6	40	0.179	141.1	0.179	5.64	0.105	82.8	0.105	3.31
20.7	110	0.367	105.2	1.881	59.32	0.229	65.7	0.976	30.80
20.8 (G1H020)	160	0.022	4.33	1.704	53.74	0.000	0.00	0.683	21.50
36.1	120	0.051	13.40	1.974	62.20	0.024	6.31	0.930	29.30
36.2	80	0.024	9.46	0.004	0.126	0.000	0.00	0.000	0.00
36.3	227	0.018	2.50	1.870	59.00	0.000	0.0	0.749	23.60
36.4	121	0.013	3.39	0.000	0.00	0.000	0.0	0.000	0.00
36.5	50	0.000	0.00	0.000	0.00	0.000	0.0	0.000	0.00
36.6 (G1H036)	105	0.000	0.00	1.533	48.30	0.000	0.0	0.305	9.62
8.1	36	0.025	21.90	0.025	0.79	0.000	0.00	0.000	0.00
8.2	10	0.000	0.00	0.00	0.00	0.000	0.0	0.000	0.00

Table C1.3 (cont.) Estimated Q75 and Q95 flow values for subcatchments in the Berg river basin (present conditions).

Sub. No.	Subarea km^2	Q75(7), from subarea		Q75(7), routed runoff		Q95(7), from subarea		Q95(7), routed runoff	
		m^3/s	mm/a	m^3/s	MCM	m^3/s	mm/a	m^3/s	MCM
1	2	3	4	5	6	7	8	9	10
8.3	5.7	0.000	0.00	0.000	0.00	0.000	0.0	0.000	0.00
8.4	150	0.000	0.00	0.026	0.82	0.000	0.0	0.000	0.00
8.5	168	0.000	0.00	0.100	3.15	0.000	0.0	0.076	2.40
8.6	19	0.099	164.30	0.099	3.12	0.076	126.0	0.076	2.40
8.7 (G1H008)	6	0.000	0.00	0.146	4.60	0.000	0.0	0.086	2.71
NS3	187	0.000	0.00	0.000	0.00	0.000	0.0	0.000	0.00
NS4	40	0.000	0.00	0.000	0.00	0.000	0.0	0000	0.0
13.1	190	0.000	000	1.216	38.30	0.000	0.0	0.100	3.15
13.2	261	0.000	0.00	1.183	37.30	0.000	0.0	0.074	2.33
13.3	110	0.000	0.00	0.090	2.84	0.000	0.0	0.023	0.72
13.4	160	0.000	0.00	0.000	0.00	0.000	0.0	0.000	0.00
13.5	152	0.000	0.00	0.205	6.46	0.000	0.0	0.089	2.81
13.6 (G1H013)	90	0.000	0.00	1.481	46.70	0.000	0.0	0.272	8.58
31.1	133	0.000	0.00	1.473	46.60	0.000	0.0	0.266	8.39
31.2	276	0.000	0.00	0.000	0.00	0.000	0.0	0.000	0.00
31.3	400	0.000	0.00	0.000	0.00	0.000	0.0	0.000	0.00

Table C1.3 (cont.) Estimated Q75 and Q96 flow values for subcatchments in the Berg river basin (present conditions).

Sub. No.	Subarea km²	*Q75(7), from subarea*		*Q75(7), routed runoff*		Q95(7), from subarea		Q95(7), routed runoff	
		m³/s	mm/a	m³/s	MCM	m³/s	mm/a	m³/s	MCM
1	2	3	4	5	6	7	8	9	10
31.4	134	0.000	0.00	0.000	0.00	0.000	0.0	0.000	0.00
31.5	90	0.000	0.00	1.487	46.9	0.000	0.0	0.267	8.42
31.6 (G1H031)	45	0.000	0.00	1.489	47.0	0.000	0.00	0.269	8.48

Table C1.4 Estimated Q75 and Q95 flow values for subcatchments in the Berg river basin (virgin conditions).

Sub. No.	Subarea km²	Q75(7), from subarea		Q75(7), routed runoff		Q95(7), from subarea		Q95(7), routed runoff	
		m³/s	mm/a	m³/s	MCM	m³/s	mm/a	m³/s	MCM
1	2	3	4	5	6	7	8	9	10
20.1	70	0.705	318	0.705	22.2	0.417	188	0.417	13.2
20.2	25	0.119	150	0.119	3.75	0.042	53	0.042	1.32
20.3	30	0.149	157	0.297	9.37	0.054	56.8	0.106	3.34
20.4	70	0.703	317	1.649	52.0	0.466	210	1.012	31.9
20.5	46	0.186	128	0.186	5.86	0.087	59.6	0.087	2.74
20.6	128	1.080	266	1.080	34.1	0.757	186	0.757	23.9
20.7	110	0.430	123	3.587	113	0.272	78	2.227	70.2
20.8 (G1H020)	160	0.046	9.07	3.689	116	0.000	0.0	2.287	72.1
36.1	120	0.051	13.4	3.749	118	0.024	6.31	2.347	74.1
36.2	80	0.030	11.8	0.030	0.946	0.000	0.0	0.000	0.0
36.3	227	0.025	3.47	4.865	122	0.000	0.0	2.394	75.5
36.4	121	0.000	0.00	0.000	0.0	0.000	0.0	0.000	0.0
36.5	50	0.000	0.00	0.000	0.0	0.000	0.0	0.000	0.0
36.6 (G1H036)	105	0.087	26.1	3.979	125	0.039	11.7	2.513	79.2
8.1	35	0.039	34.2	0.039	1.23	0.000	0.0	0.000	0.0
8.2	10	0.000	0.00	0.000	0.0	0.000	0.0	0.000	0.0

Table C1.4 (cont.) Estimated Q75 and Q95 flow values for the subcatchments in the Berg river basin (virgin conditions).

Sub. No.	Subarea km²	Q75(7), from subarea		Q75(7), routed runoff		Q95(7), from subarea		Q95(7), routed runoff	
		m³/s	mm/a	m³/s	MCM	m³/s	mm/a	m³/s	MCM
1	2	3	4	5	6	7	8	9	10
8.3	5.7	0.000	0.00	0.000	0.0	0.000	0.0	0.000	0.0
8.4	150	0.000	0.00	0.040	1.26	0.000	0.0	0.000	0.0
8.5	168	0.000	0.00	0.109	3.44	0.000	0.0	0.081	2.55
8.6	19	0.107	178	0.107	3.37	0.081	134	0.081	2.55
8.7 (G1H008)	6	0.000	0.00	0.150	4.88	0.000	0.0	0.108	3.40
NS3	187	0.826	139	0.826	26	0.000	0.0	0.000	0.0
NS4	40	0.000	0.00	0.000	0.0	0.000	0.0	0.000	0.0
13.1	190	0.061	10.1	4.004	126	0.043	7.14	2.579	81.3
13.2	261	0.000	0.00	4.015	127	0.000	0.0	2.591	81.7
13.3	110	0.016	4.59	0.208	6.56	0.000	0.0	0.113	3.56
13.4	160	0.000	0.00	0.000	0.0	0.000	0.0	0.000	0.0
13.5	152	0.000	0.00	0.863	27.2	0.000	0.0	0.000	0.0
13.6 (G1H013)	90	0.000	0.00	5.405	170	0.000	0.0	3.270	103
31.1	133	0.000	0.00	5.420	171	0.000	0.0	3.270	103
31.2	276	0.000	0.00	0.000	0.0	0.000	0.0	0.000	0.0
31.3	400	0.000	0.00	0.000	0.0	0.000	0.0	0.000	0.0

Table C1.4 (cont.) Estimated Q75 and Q95 flow values for subcatchments in the Berg river basin (virgin conditions).

Sub. No.	Subarea km^2	Q75(7), from subarea		Q75(7), routed runoff		Q95(7), from subarea		Q95(7), routed runoff	
		m^3/s	mm/a	m^3/s	MCM	m^3/s	mm/a	m^3/s	MCM
1	2	3	4	5	6	7	8	9	10
31.4	134	0.000	0.00	0.000	0.0	0.000	0.0	0.000	0.0
31.5	90	0.000	0.00	5.440	172	0.000	0.0	3.280	103
31.6 (G1H031)	45	0.000	0.00	5.440	172	0.000	0.0	3.280	105

Figure C1.14 Subarea codes in the Berg River catchment.

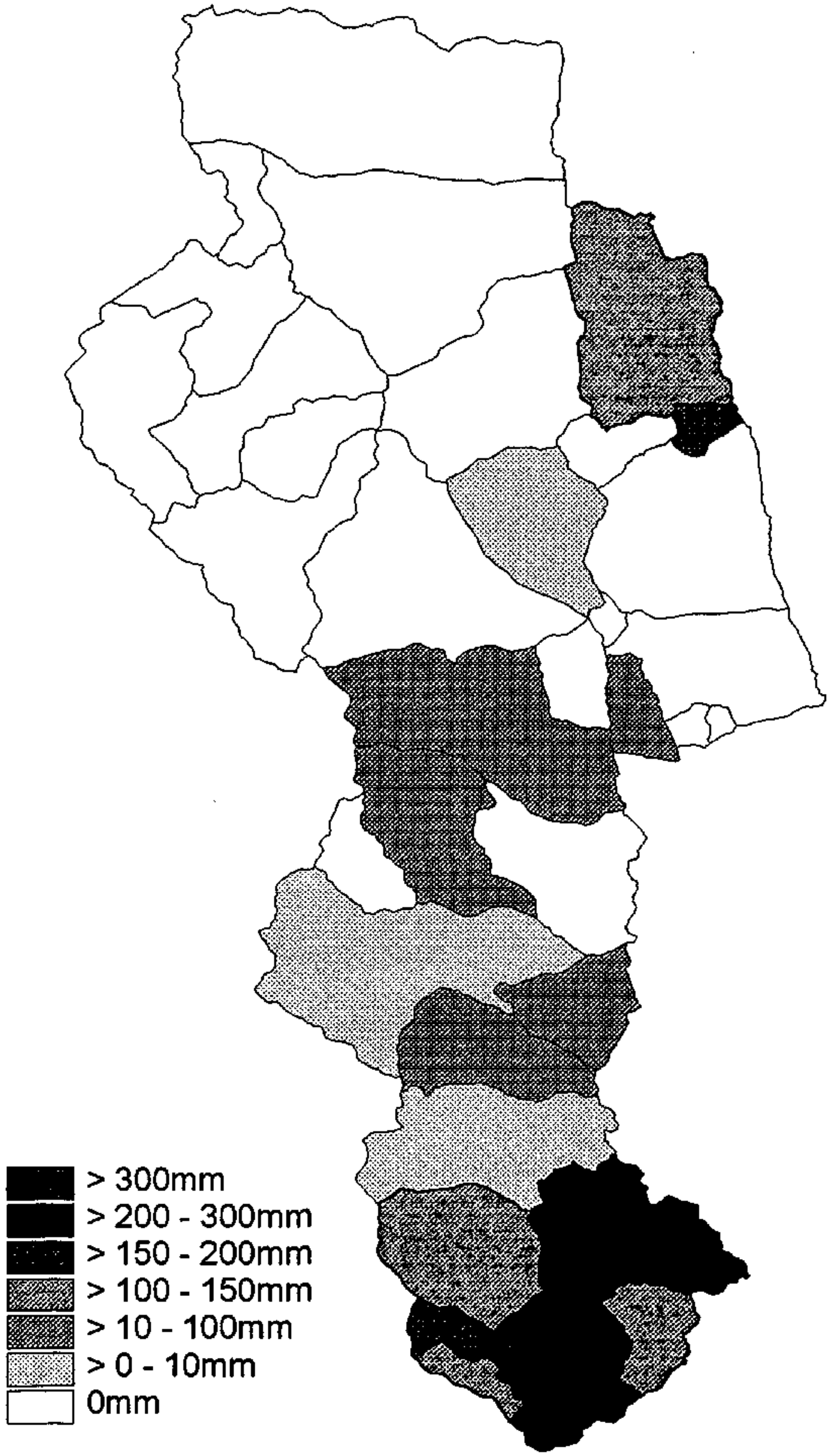


Figure C1.15 Distribution of Q75(7) values (subarea runoff, mm/a) in the Berg catchment (virgin conditions).

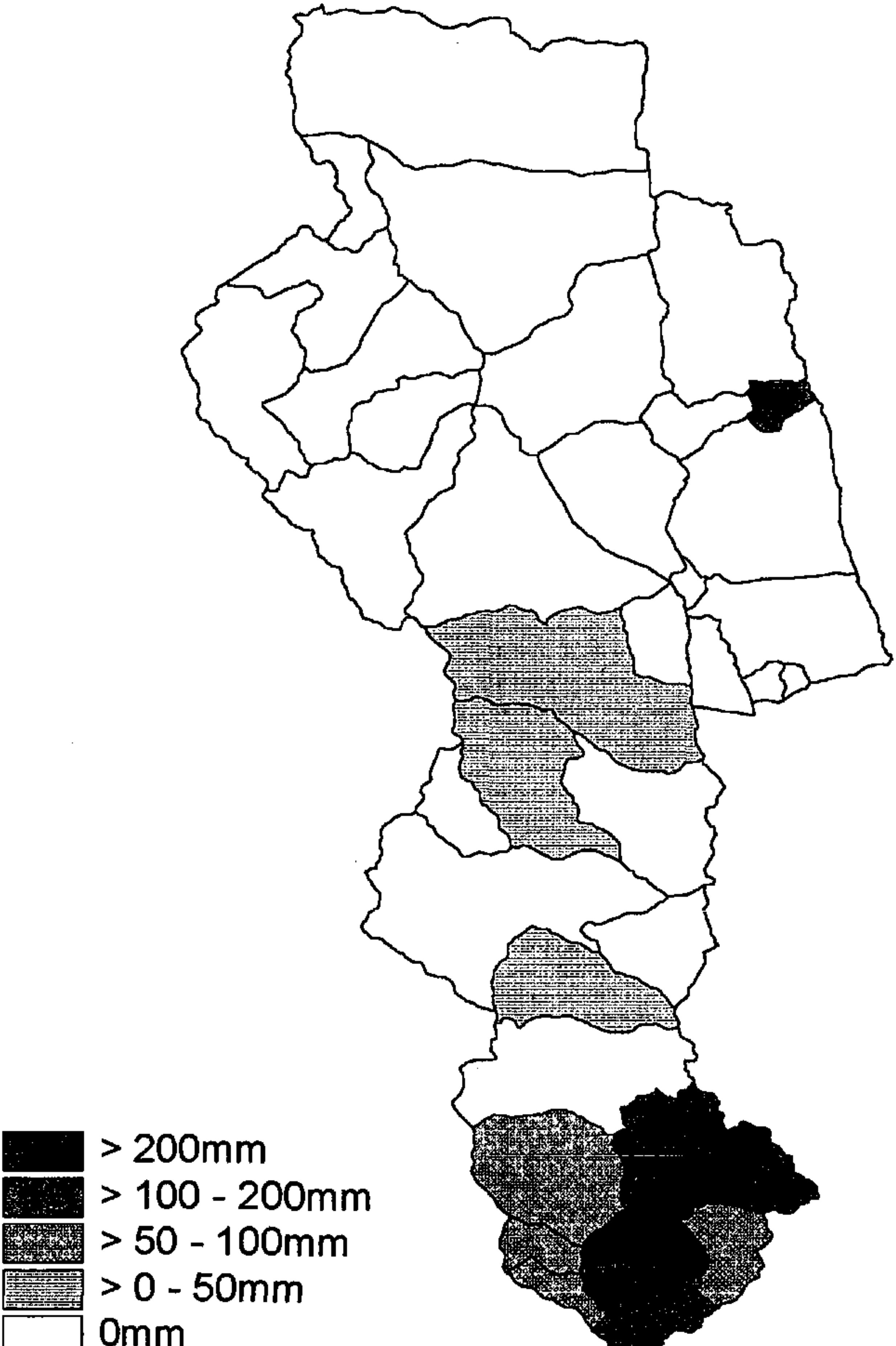
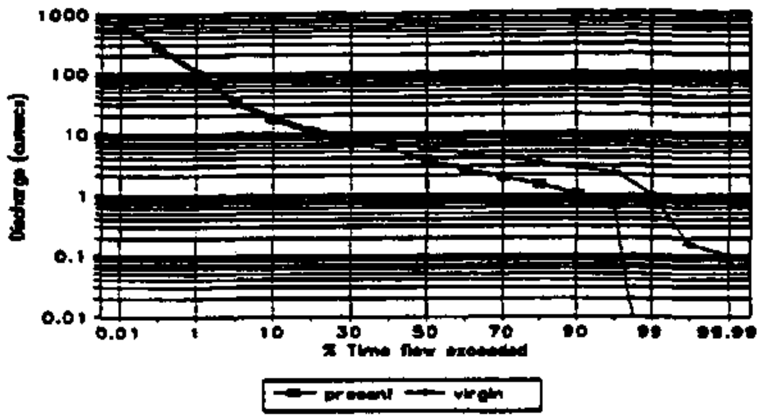
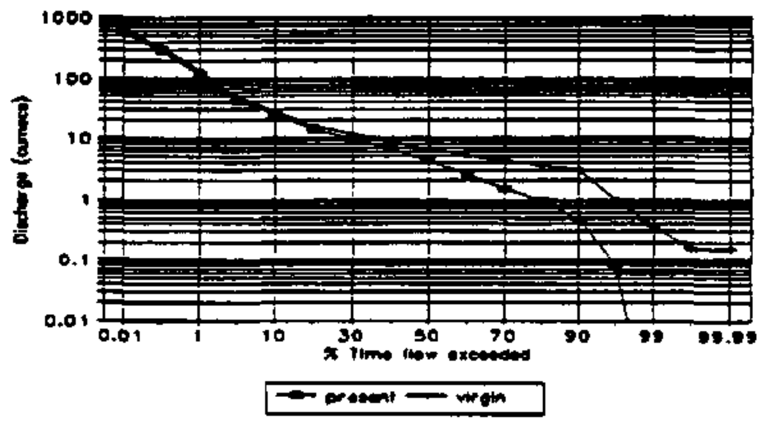


Figure C1.16 Distribution of Q95(7) values (subarea runoff, mm/a) in the Berg catchment (virgin conditions).

GAUGE G1H020



GAUGE G1H036



GAUGE G1H008

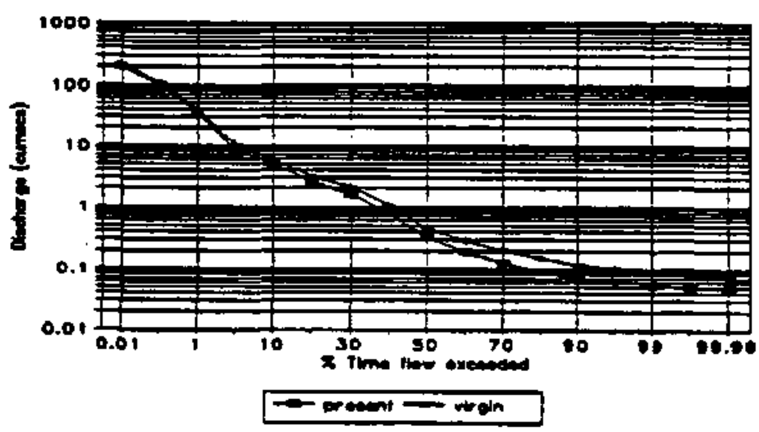
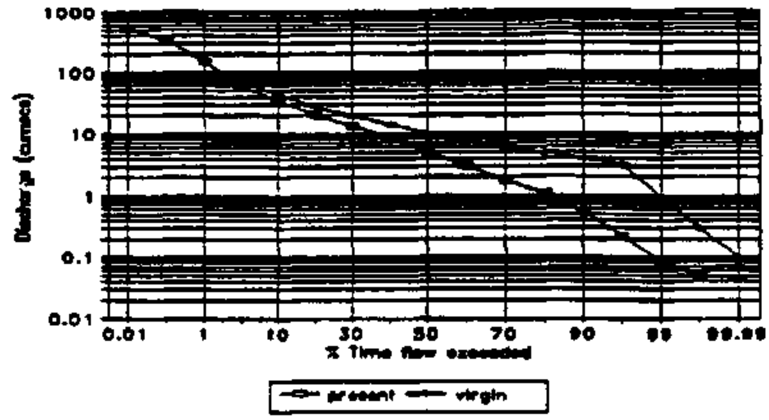


Figure C1.17a Simulated 1-day annual flow duration curves in present and virgin conditions.

GAUGE G1H013



GAUGE G1H031

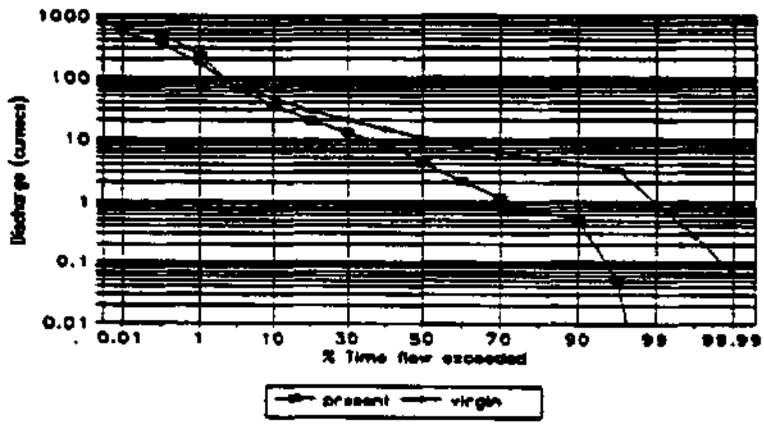
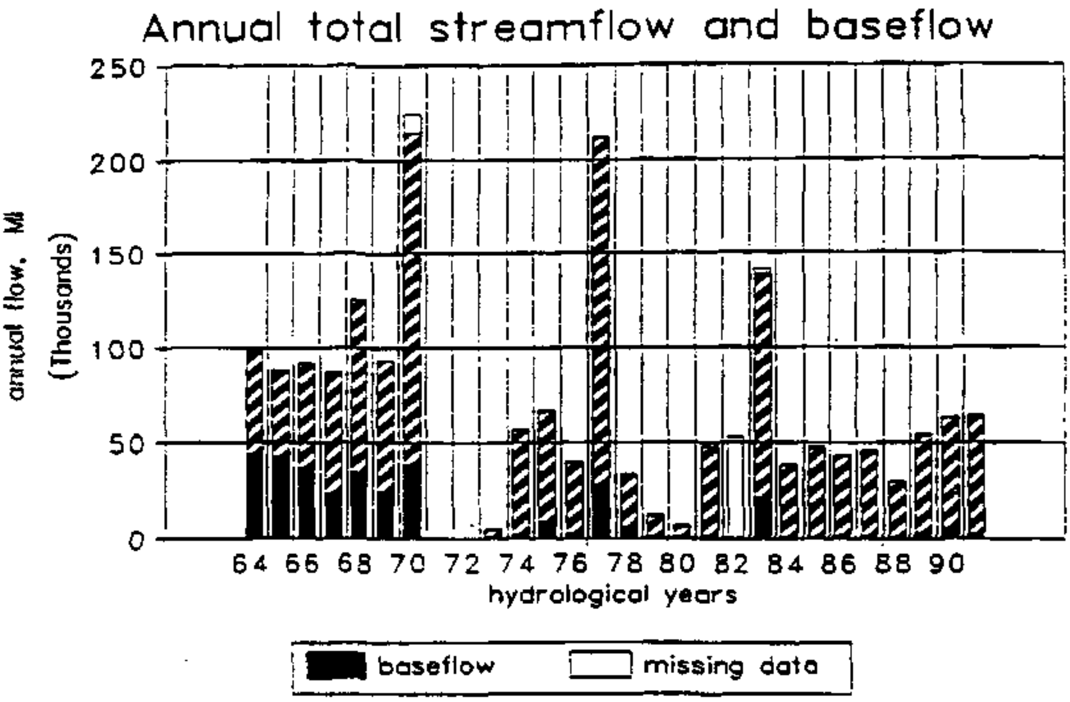


Figure C1.17b *Simulated 1-day annual flow duration curves in present and virgin conditions.*

APPENDIX C2

Annual flows and low-flow indices in the Berg catchment

Note : each year on graphs is from October of the previous calendar year to September of the next calendar year (the year 1952 is from October 1951 to September 1952).



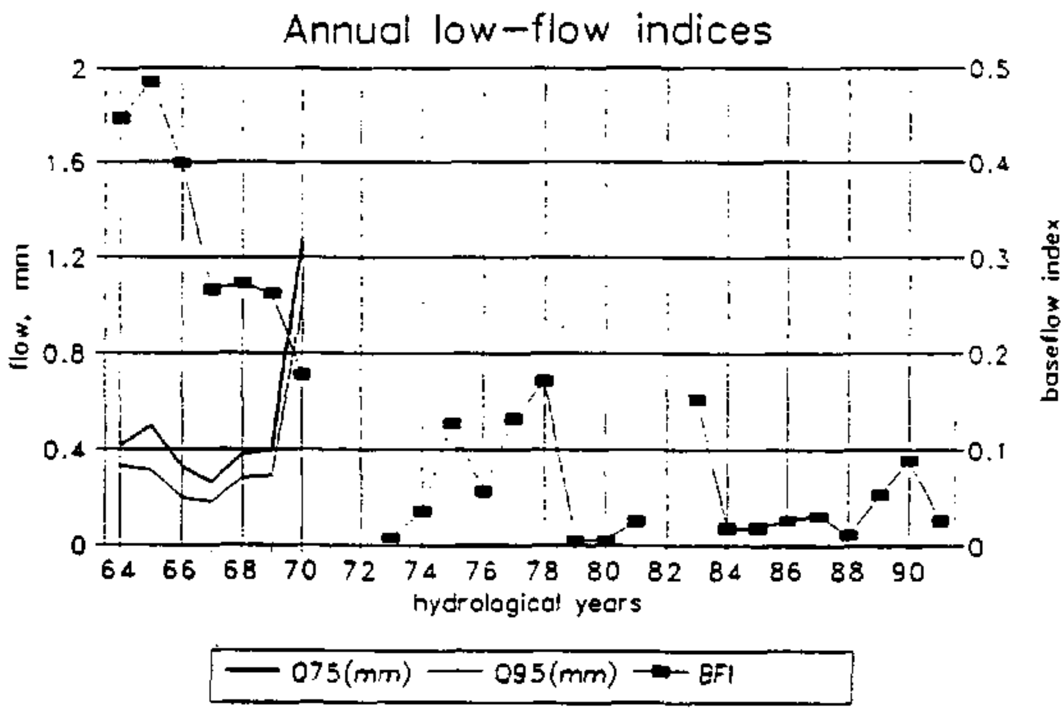
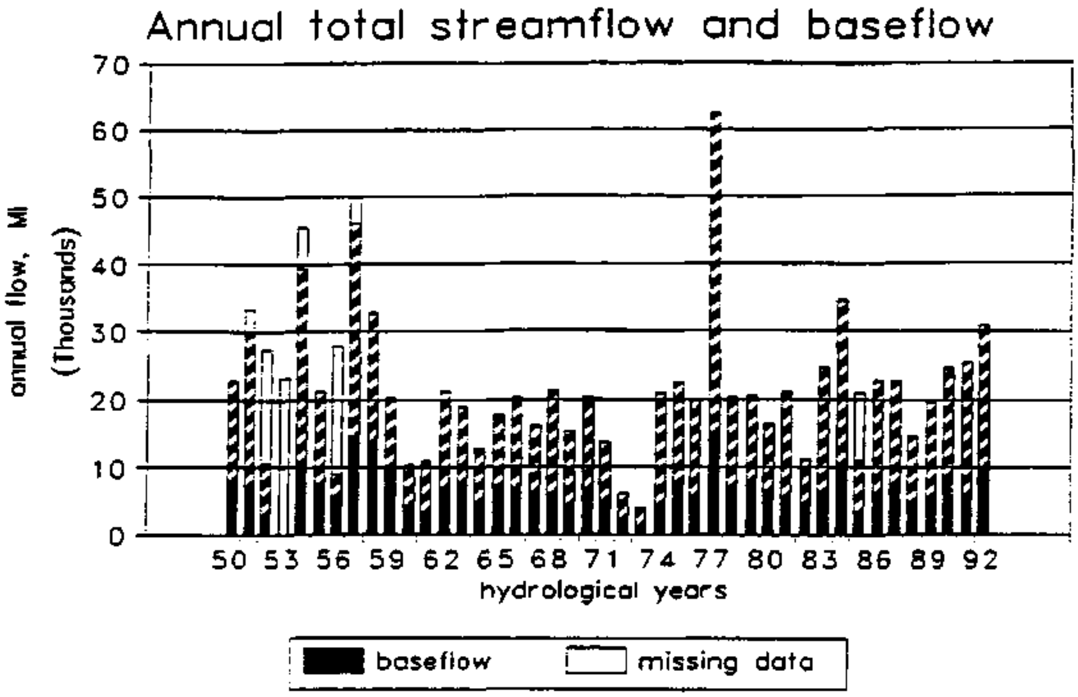


Figure C2.1. Gauges G1H002 (1963-70) and G1H028 (1972-92).



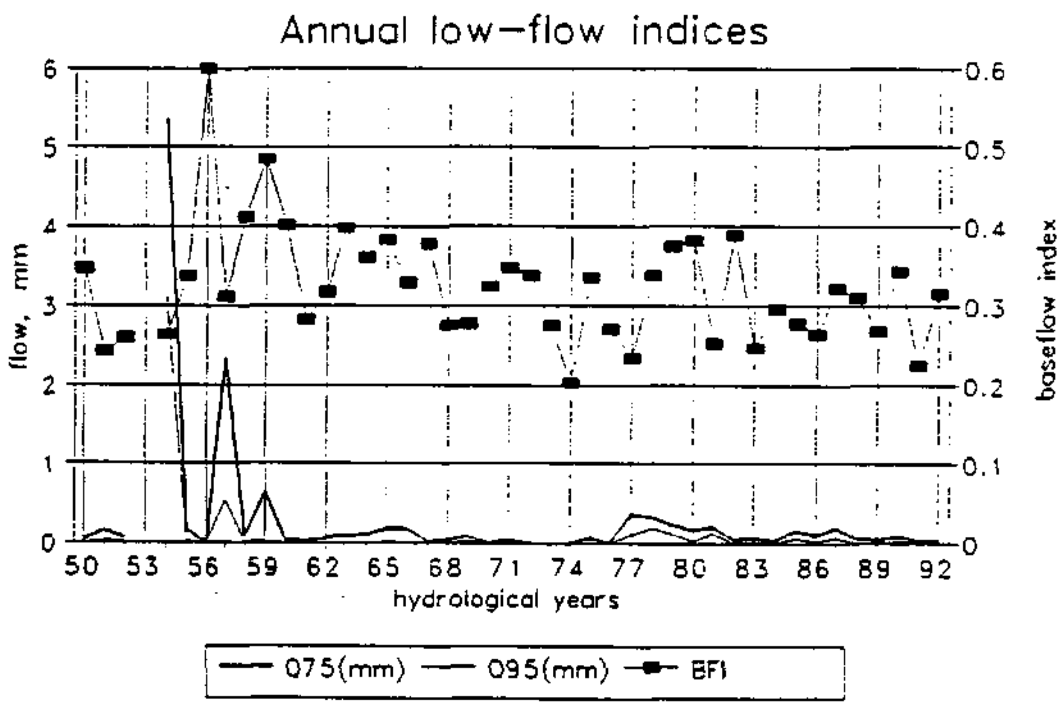
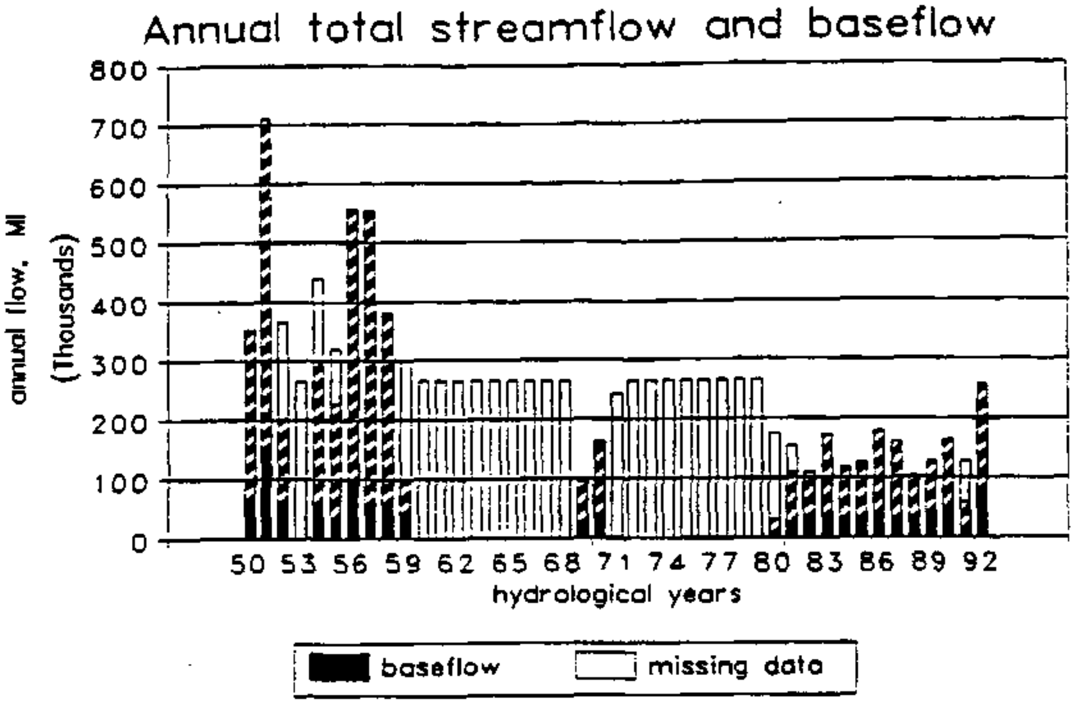


Figure C2.2. Gauge G1H003.



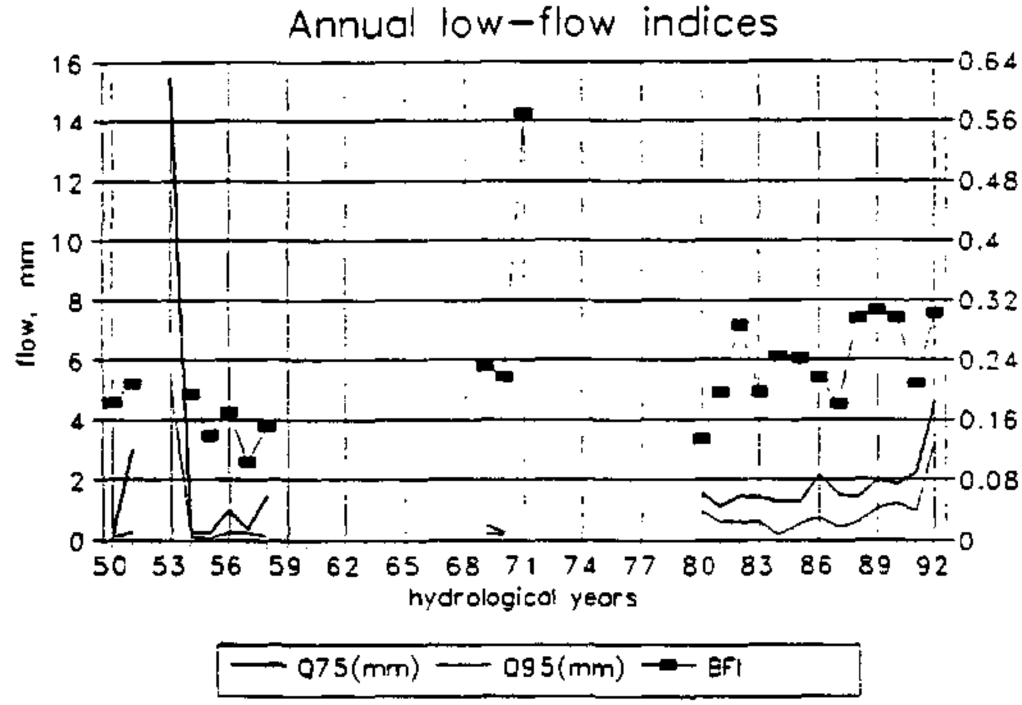
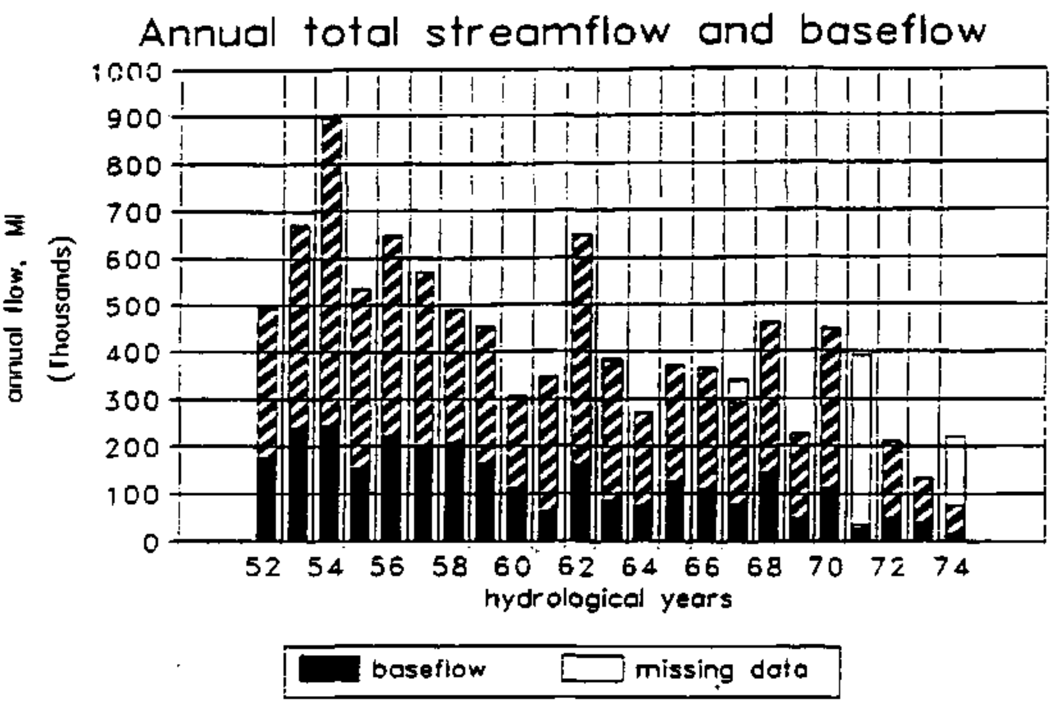


Figure C2.3. Gauge G1H004.



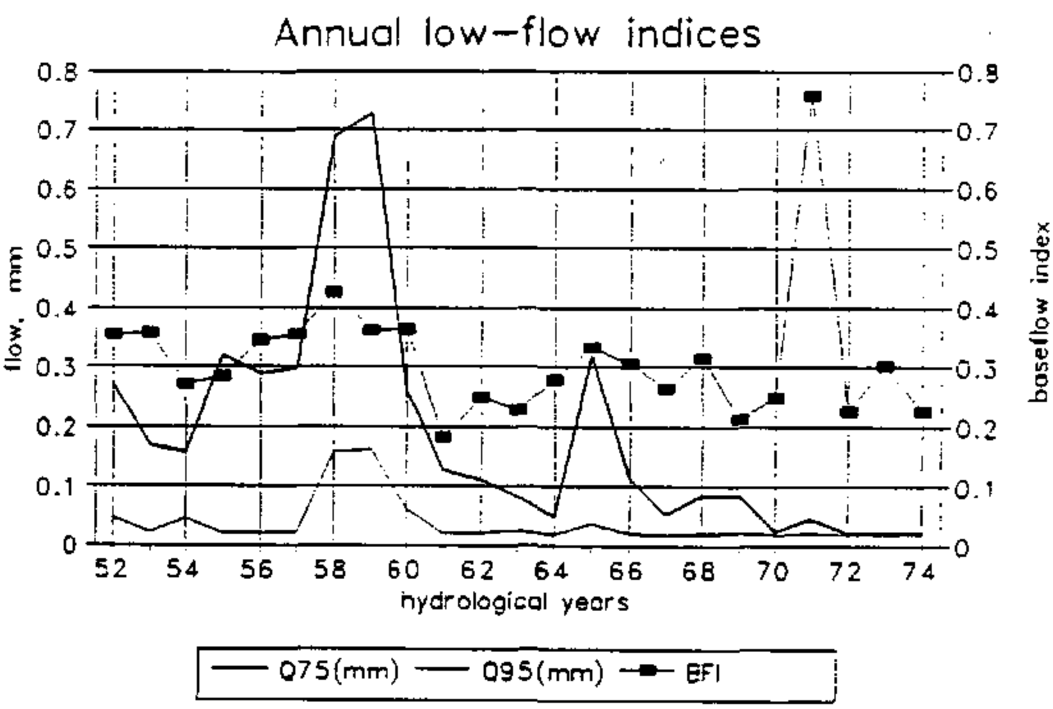
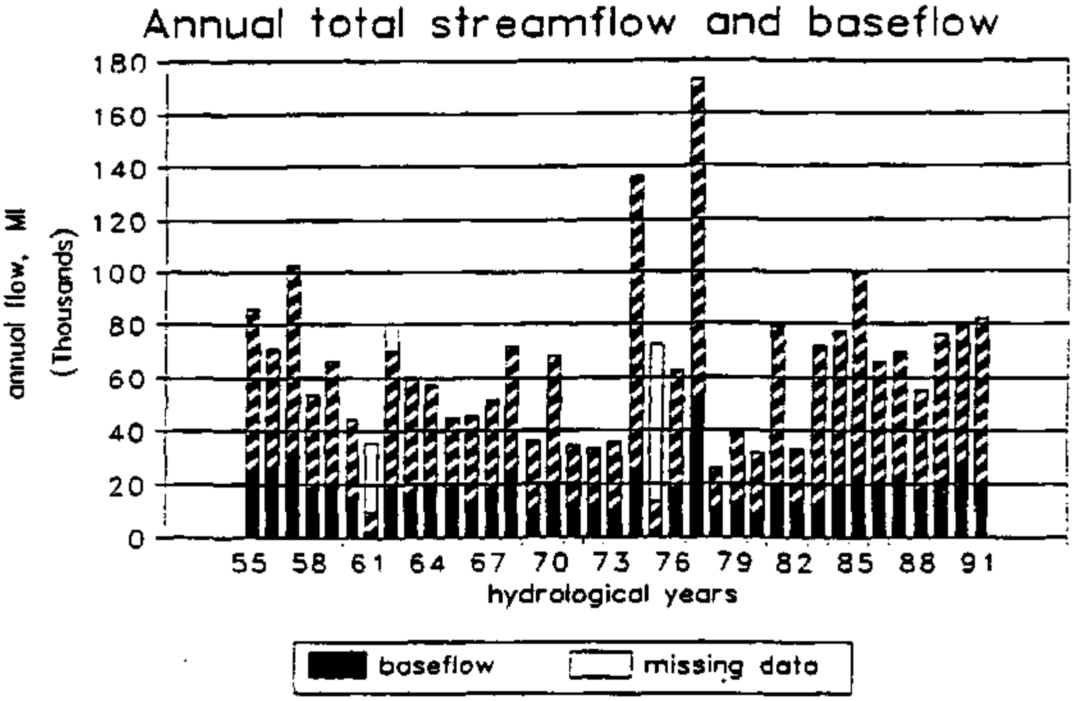


Figure C2.4. Gauge G1H007.



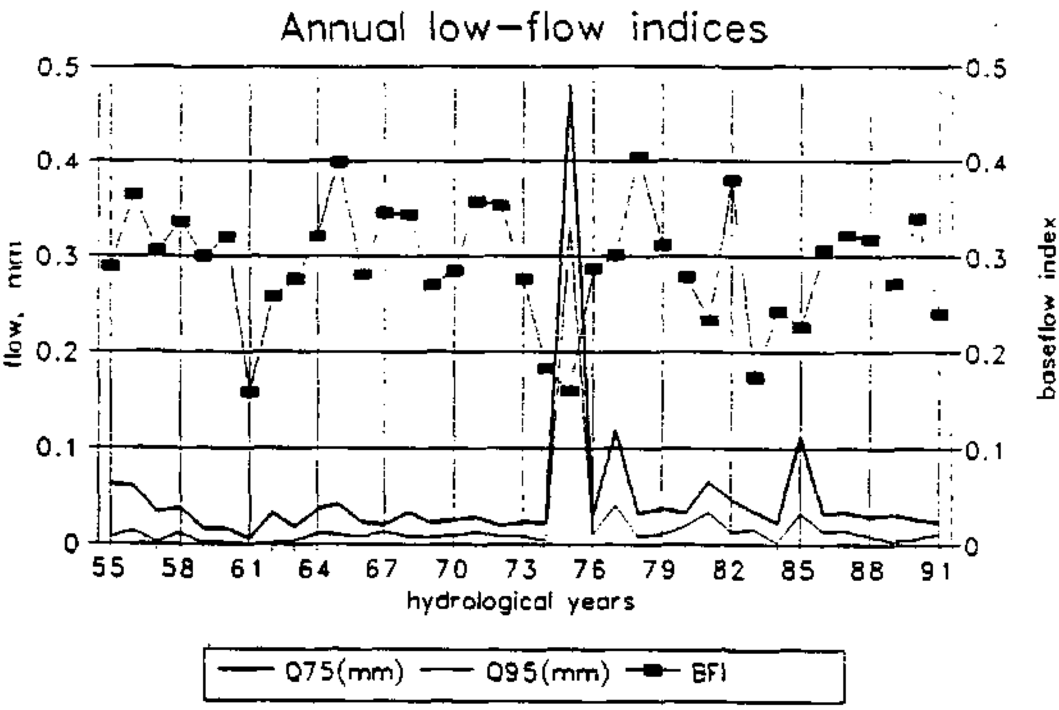
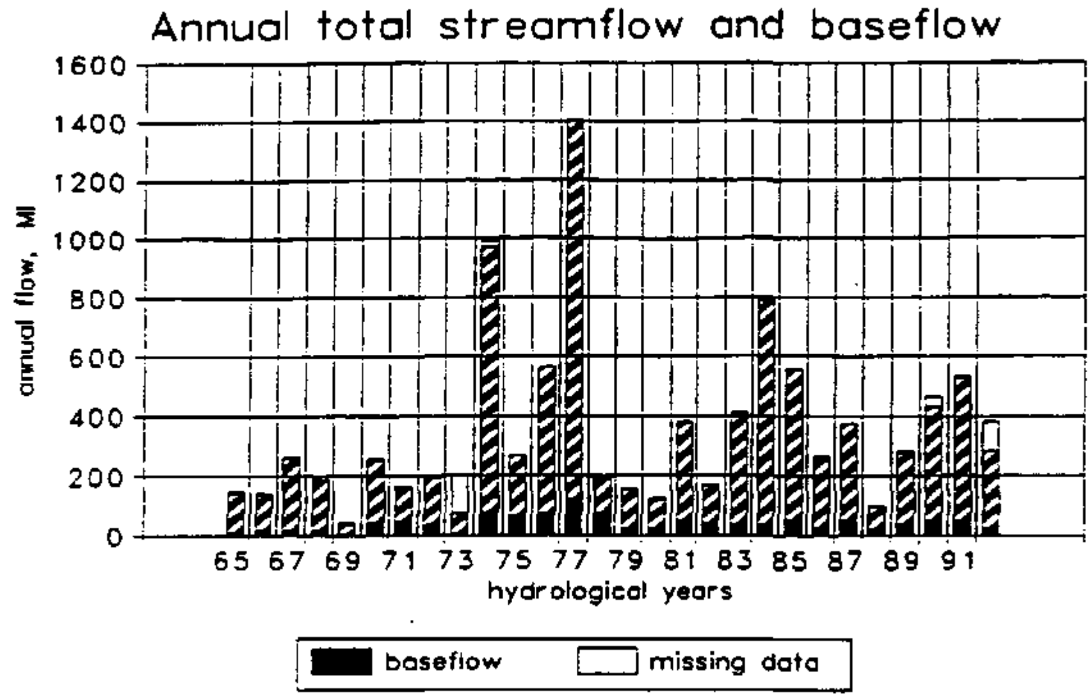


Figure C2.5. Gauge G1H008.



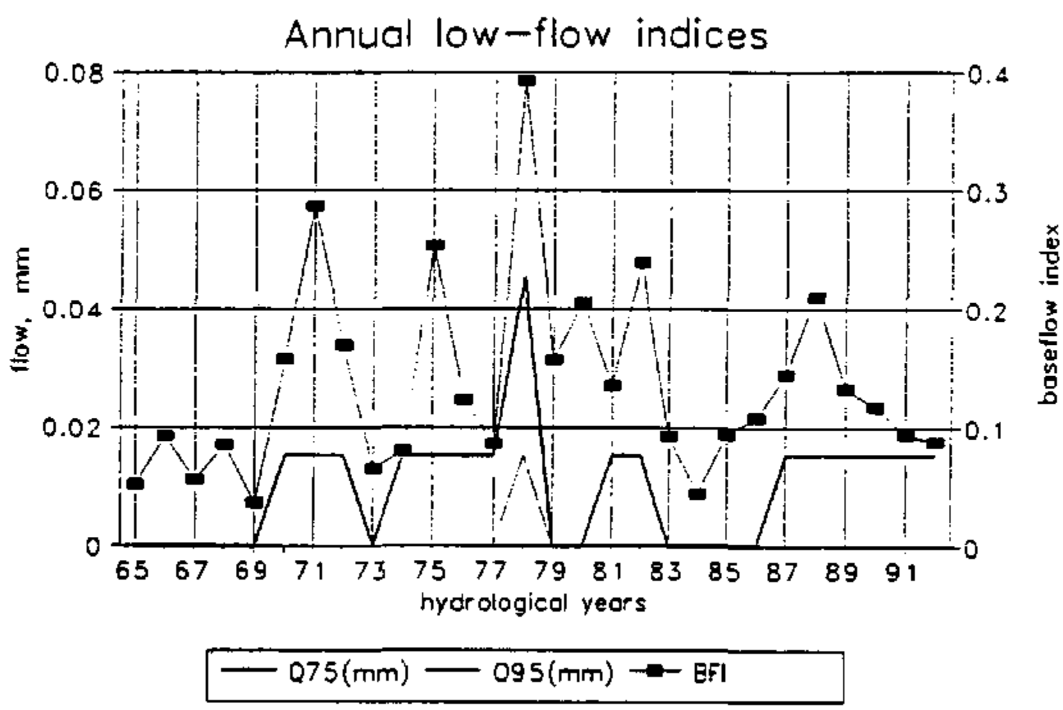
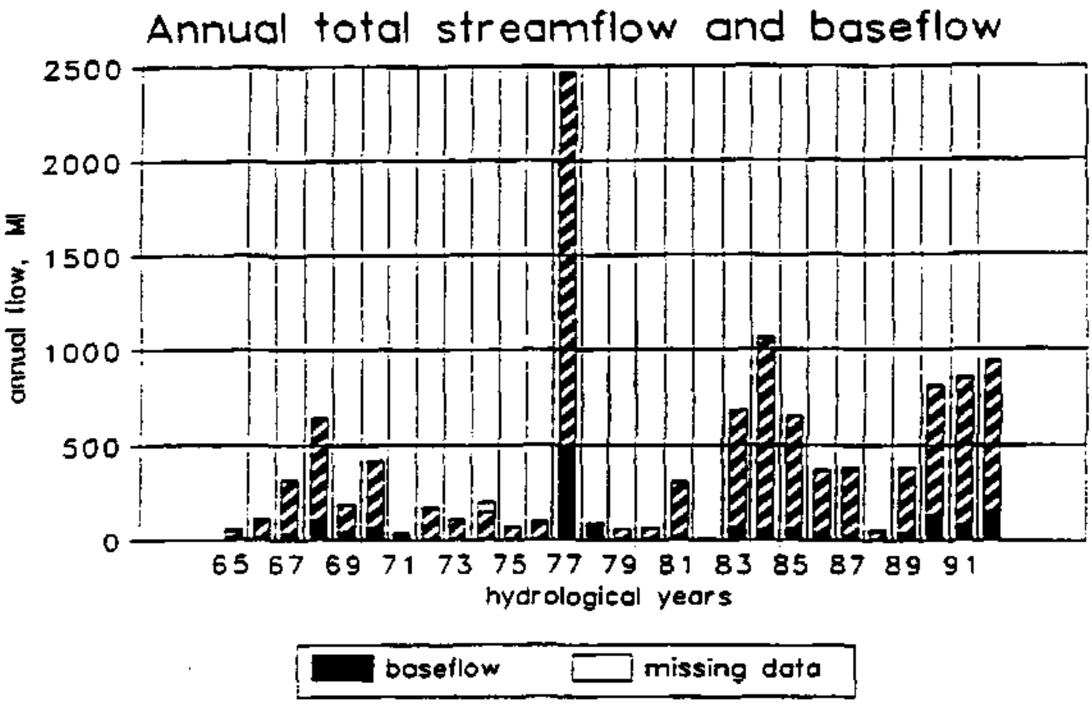
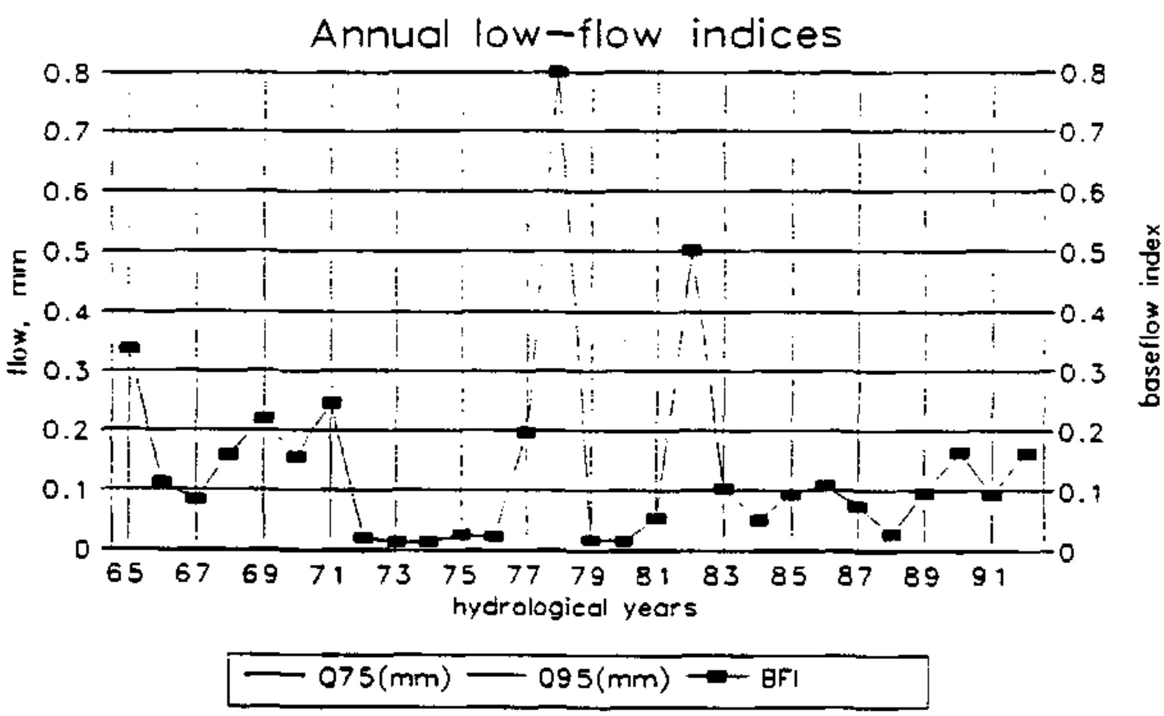


Figure C2.6. Gauge G1H009.





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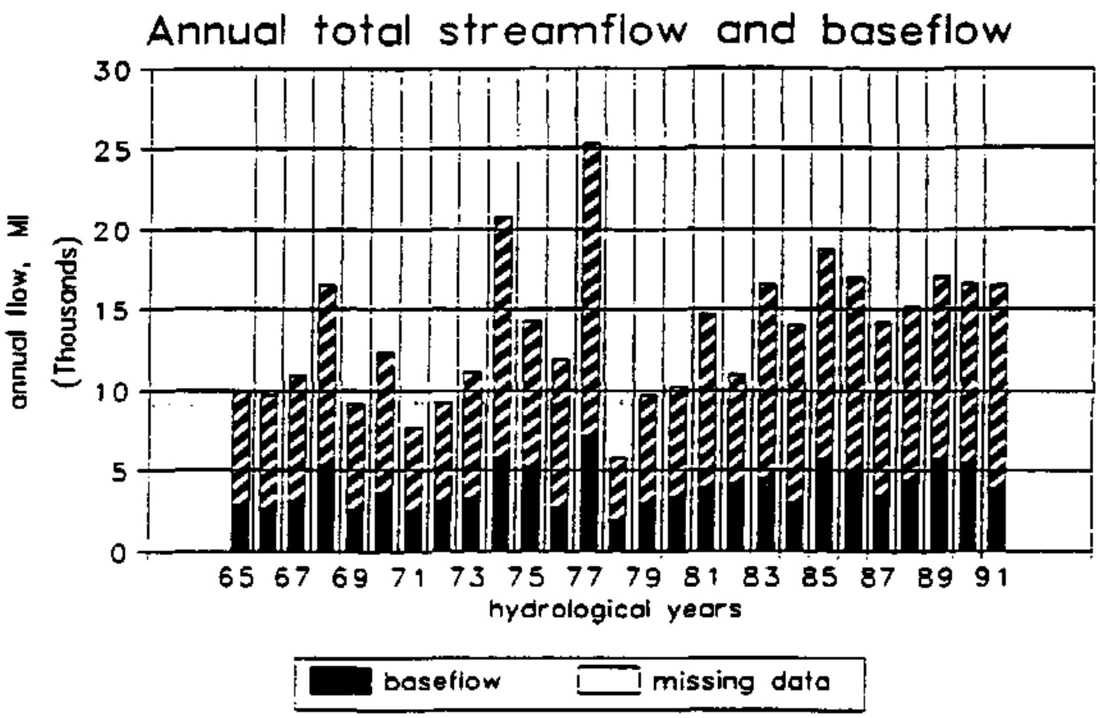

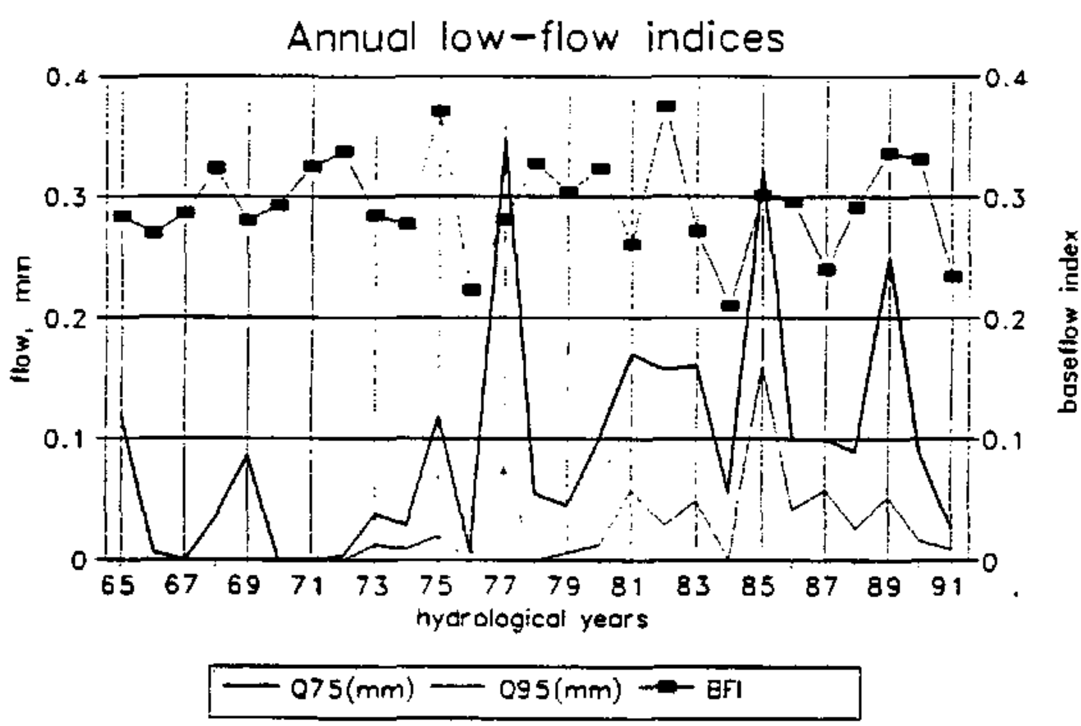

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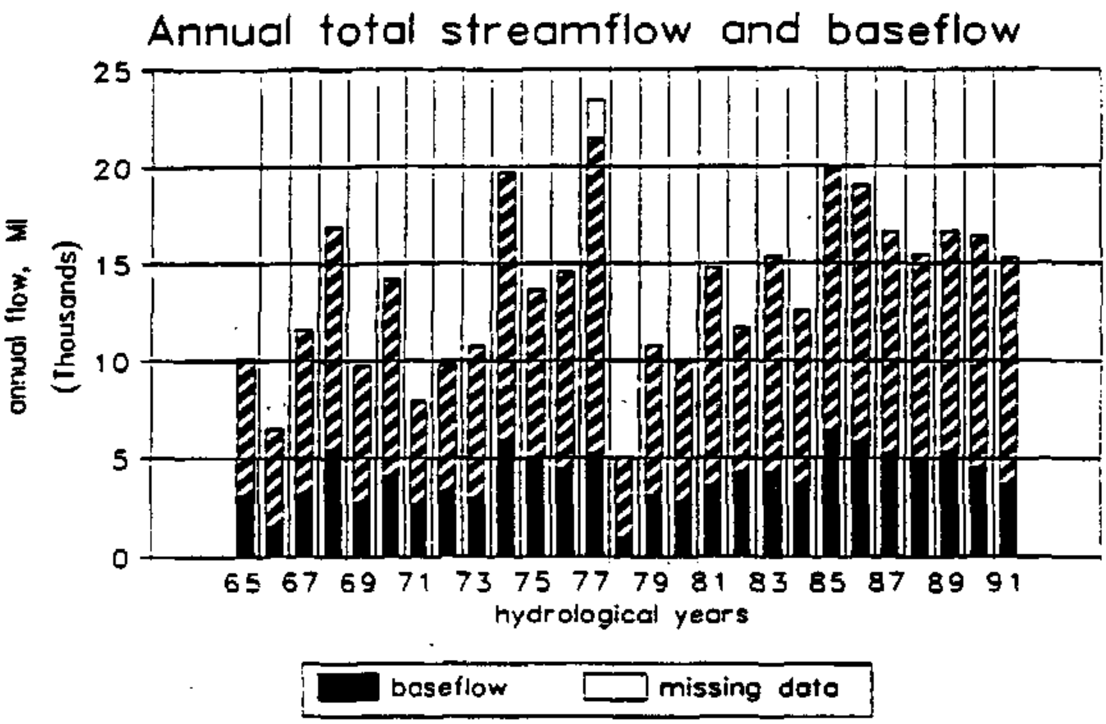

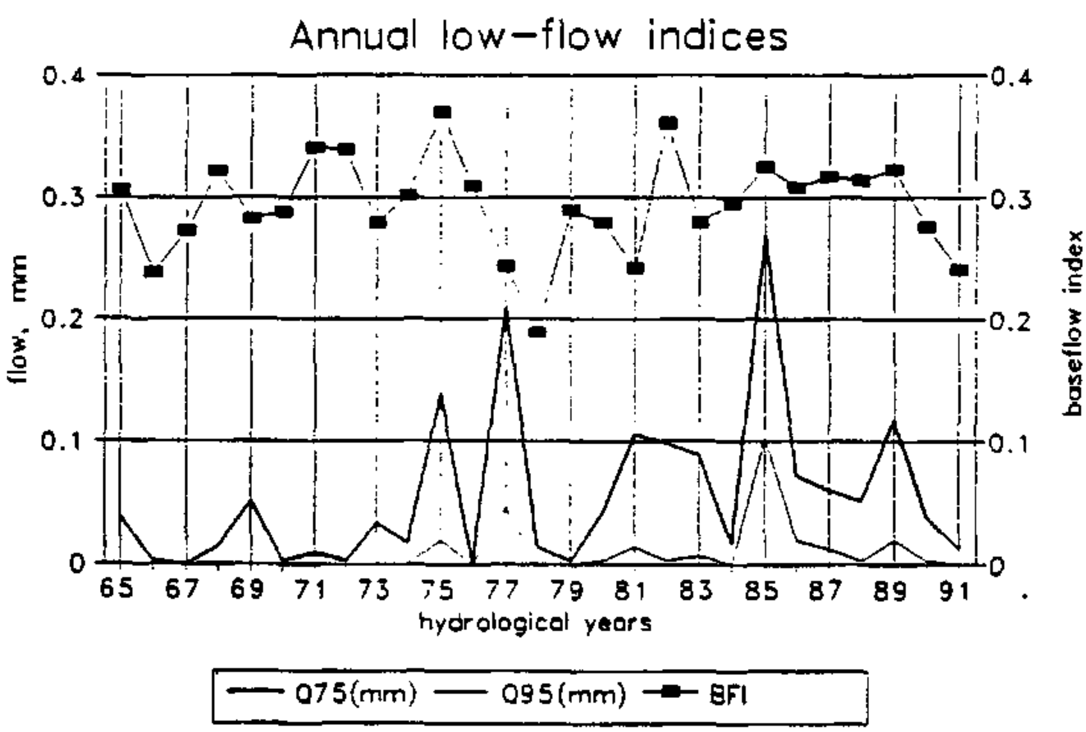

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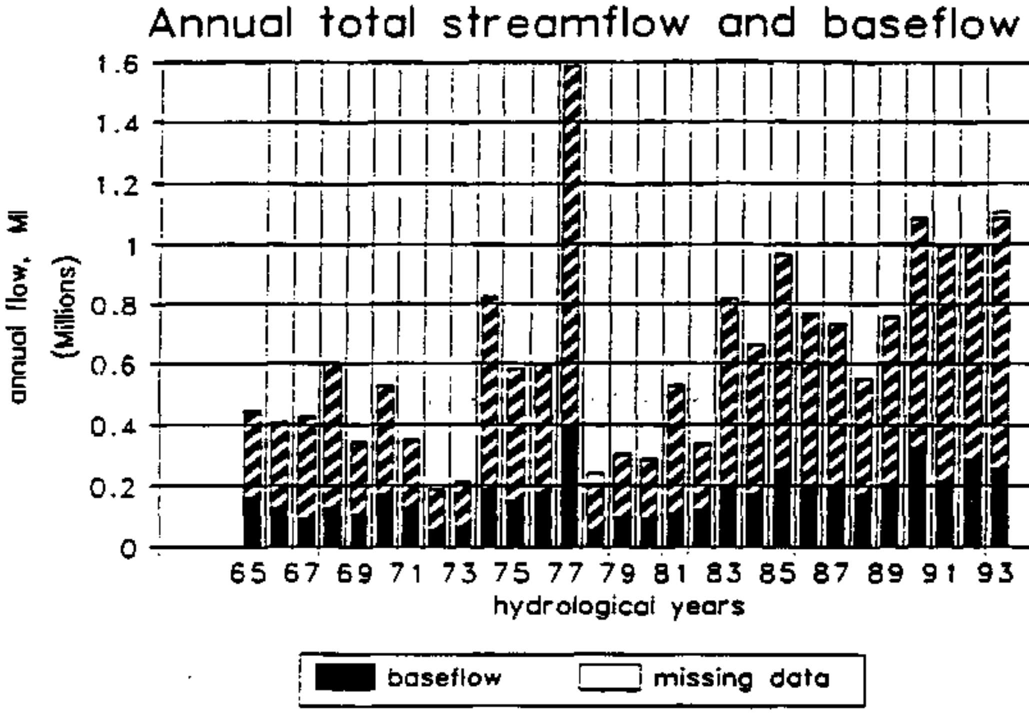

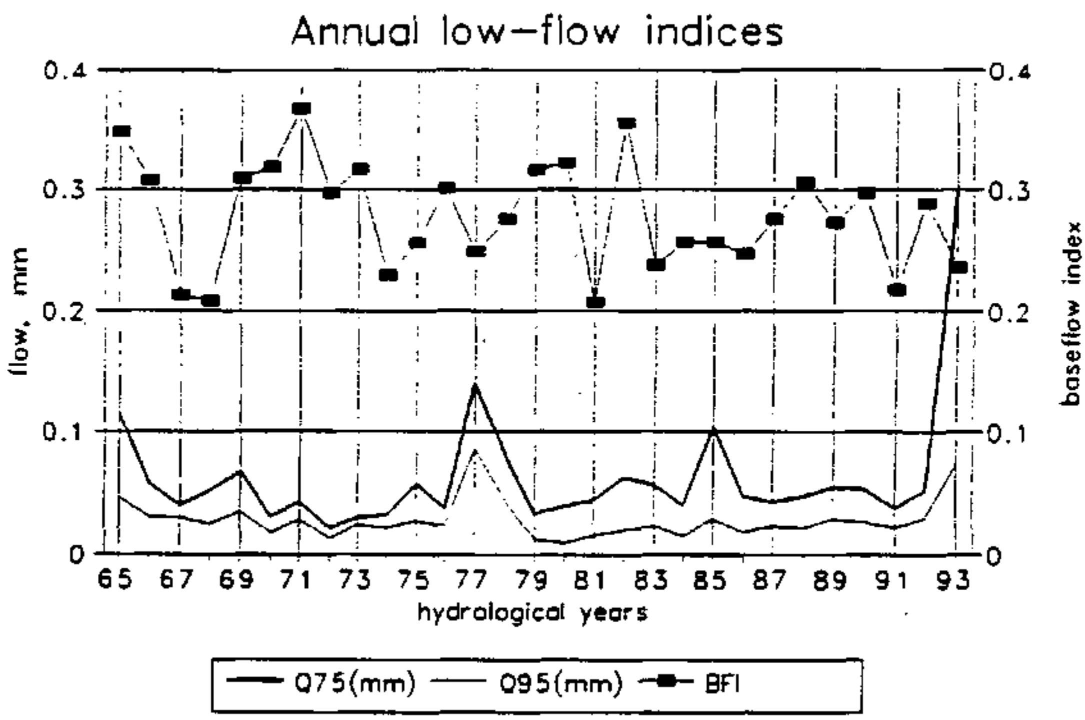

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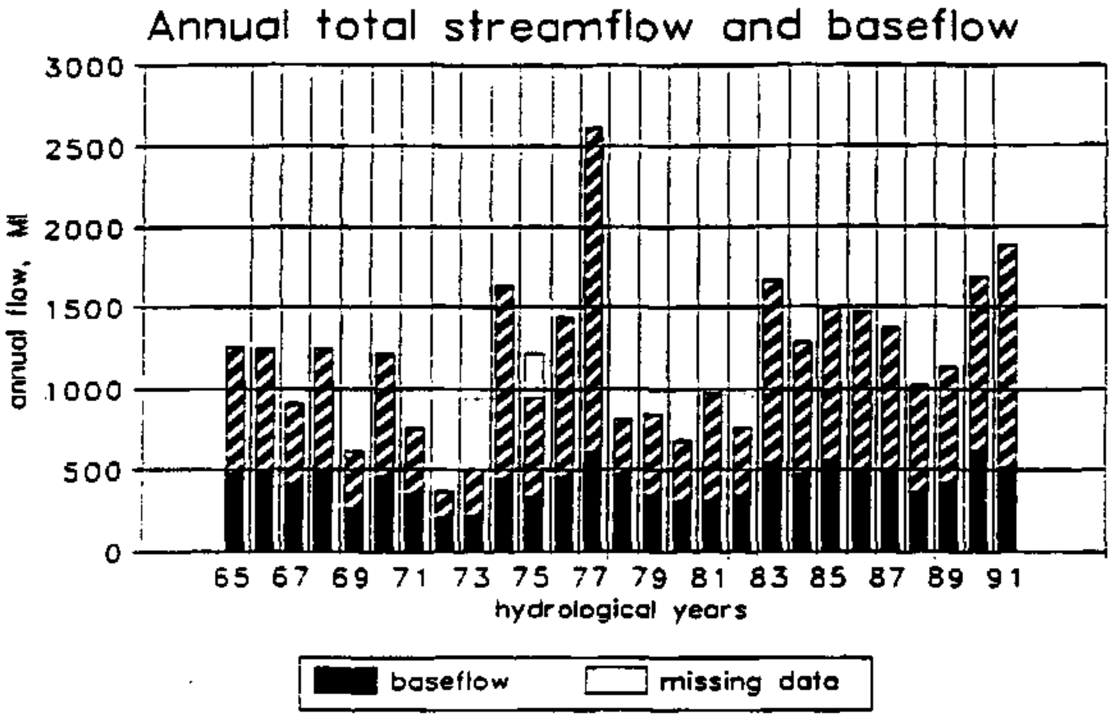


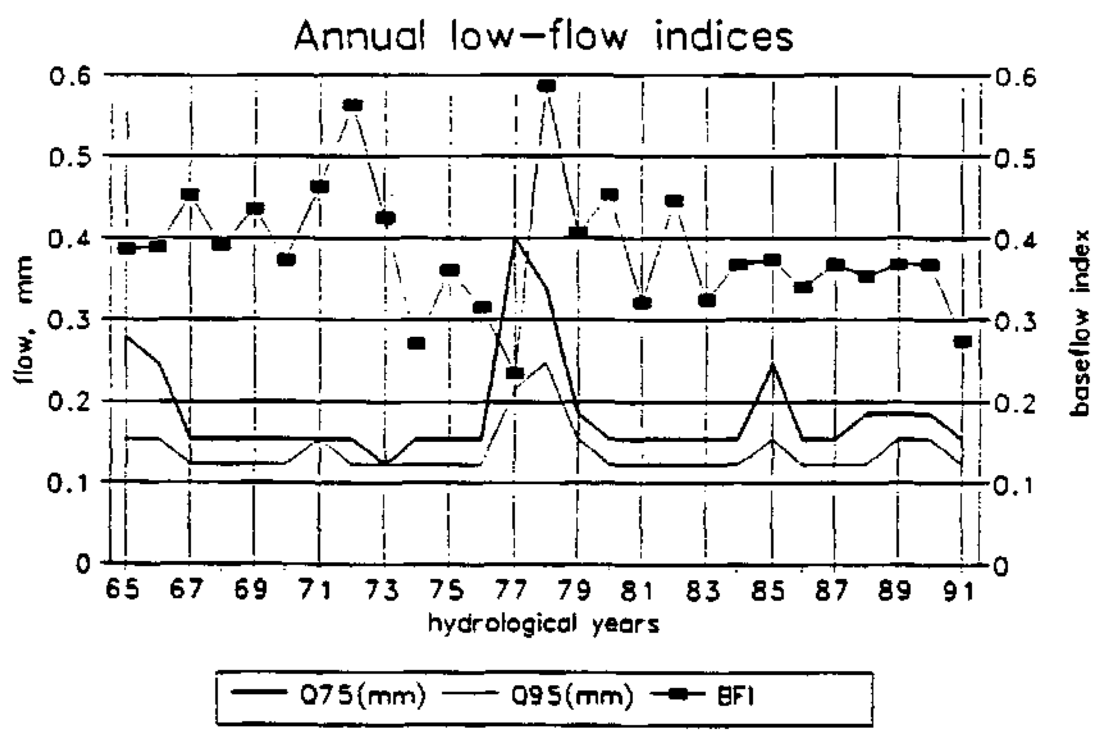
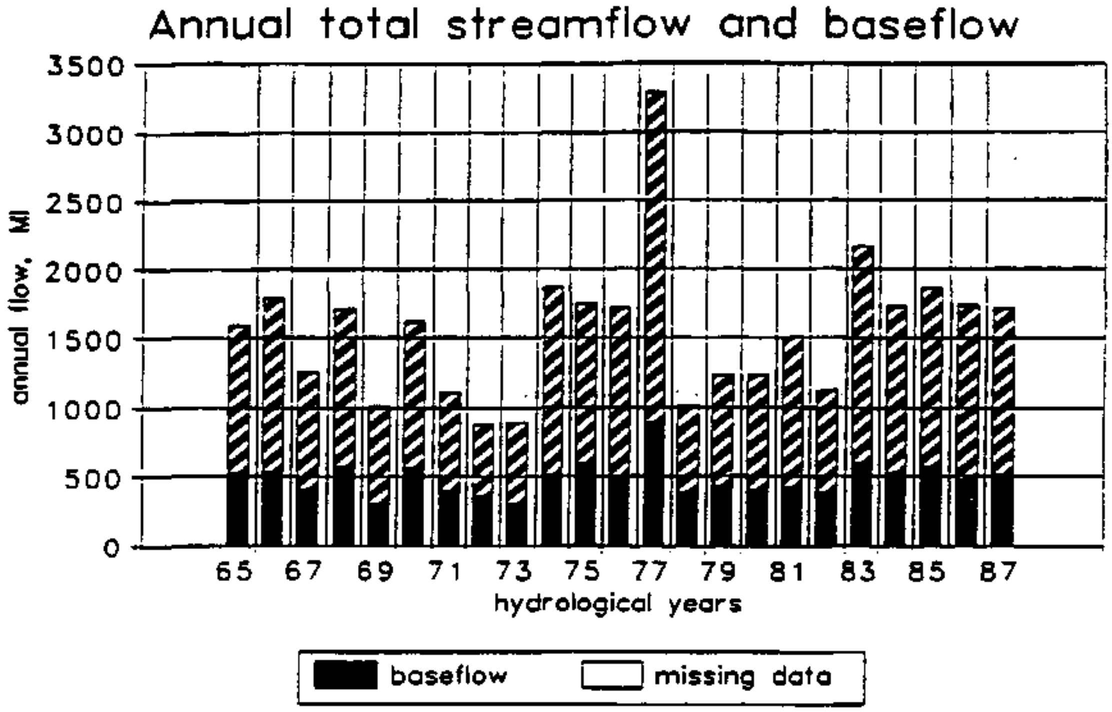
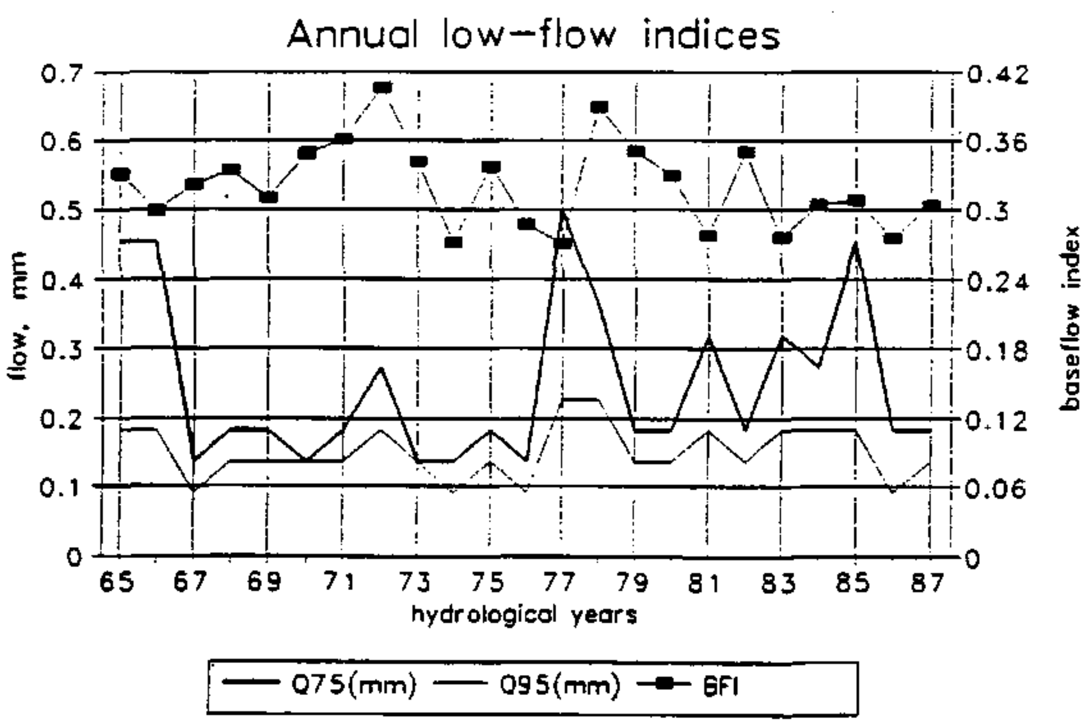


Figure C2.11. Gauge G1H014.





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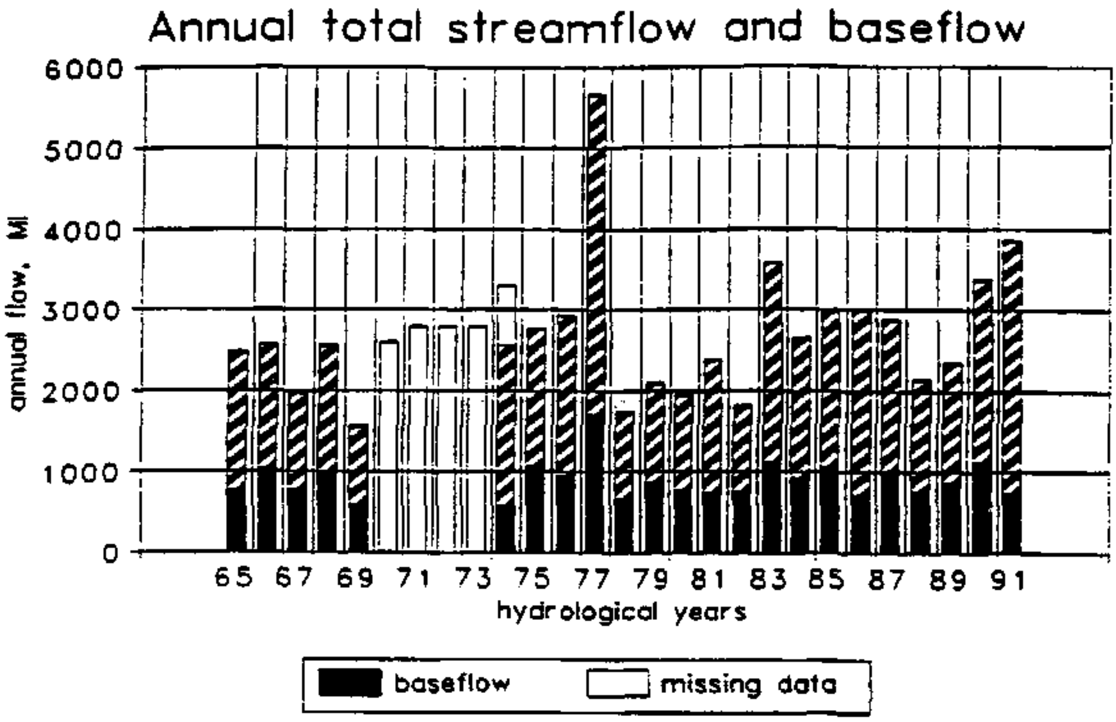


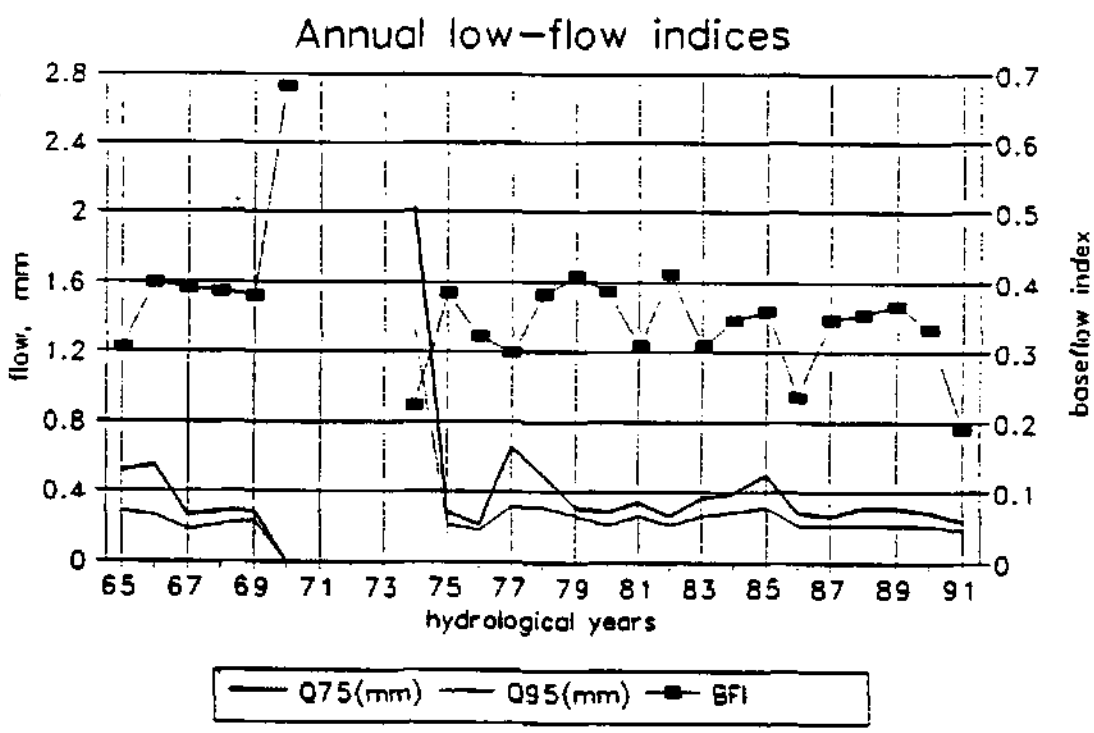
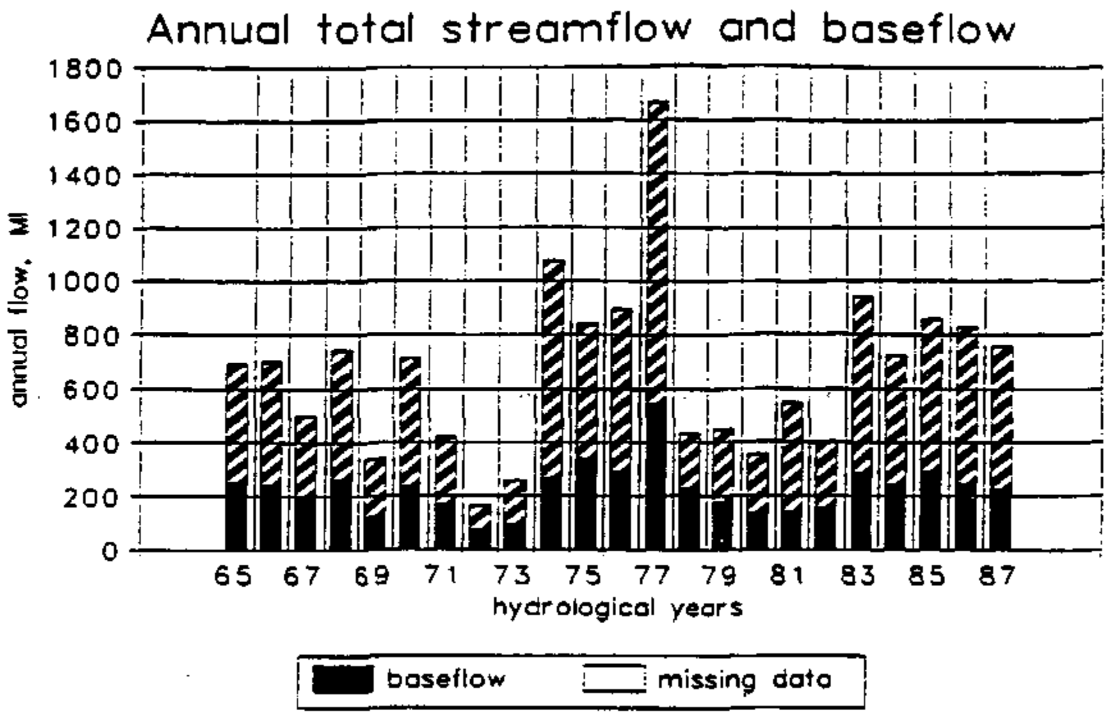
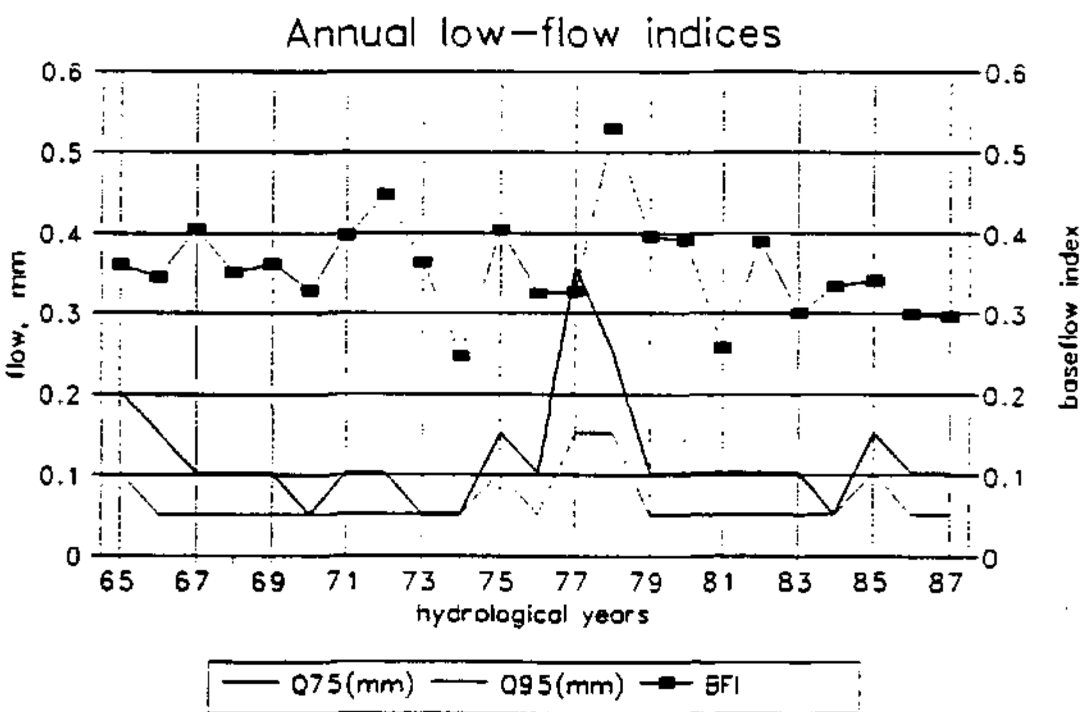


Figure C2.13. Gauge G1H016.





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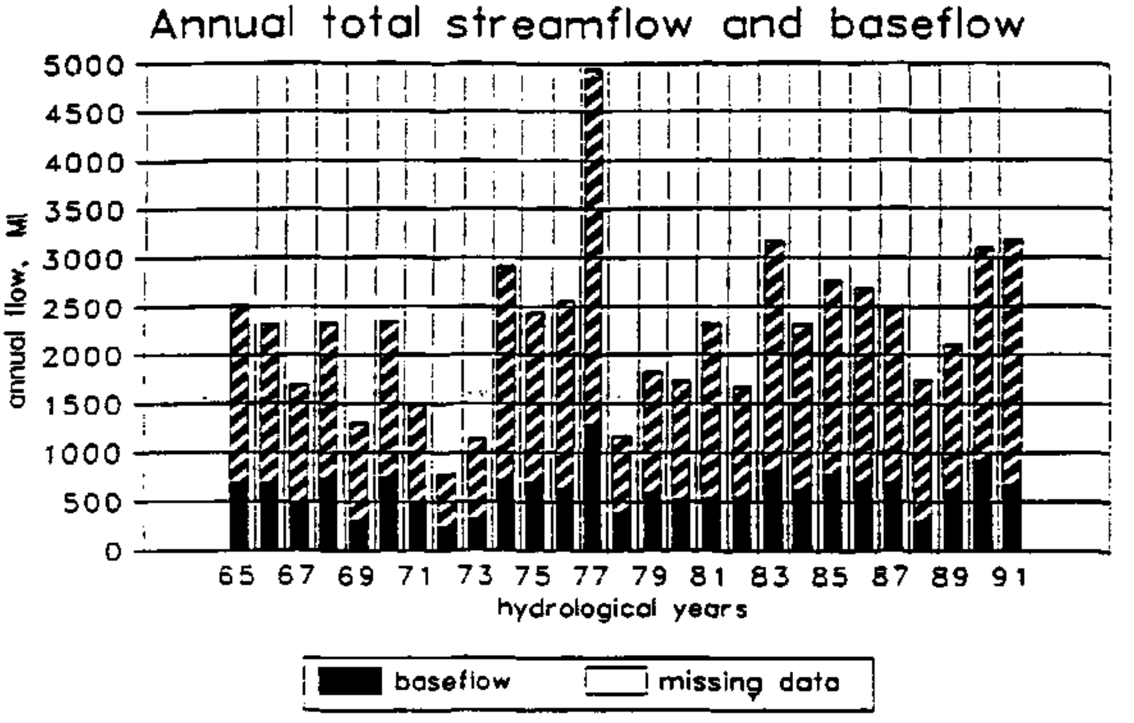

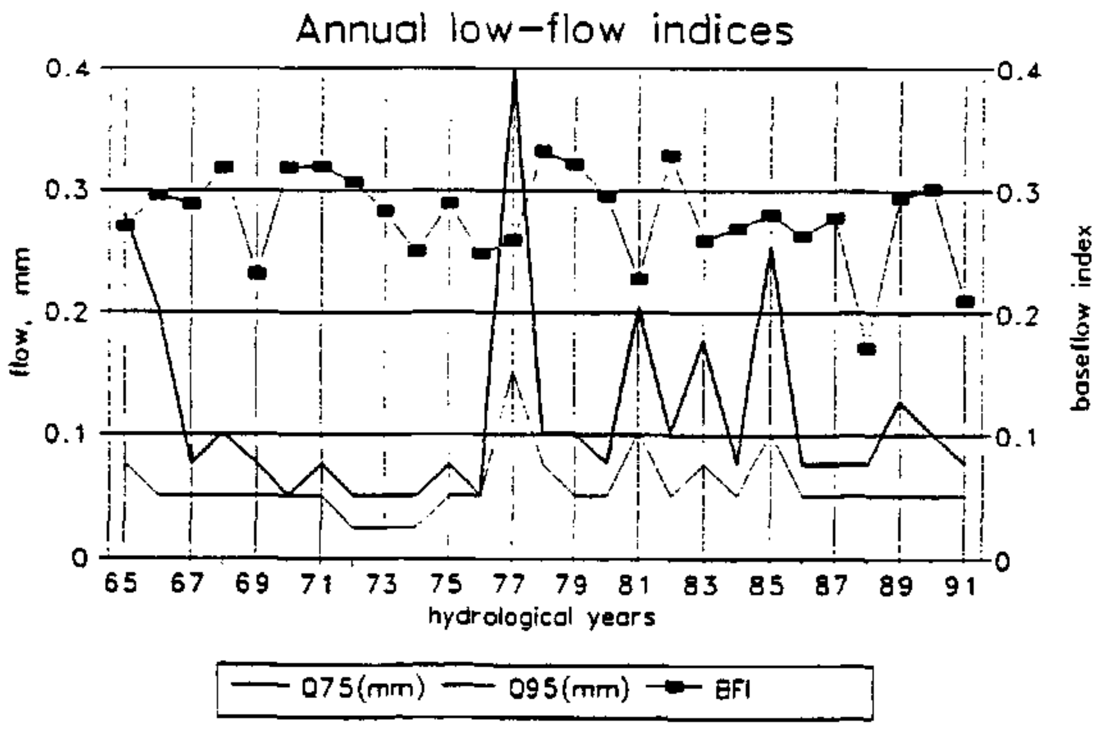

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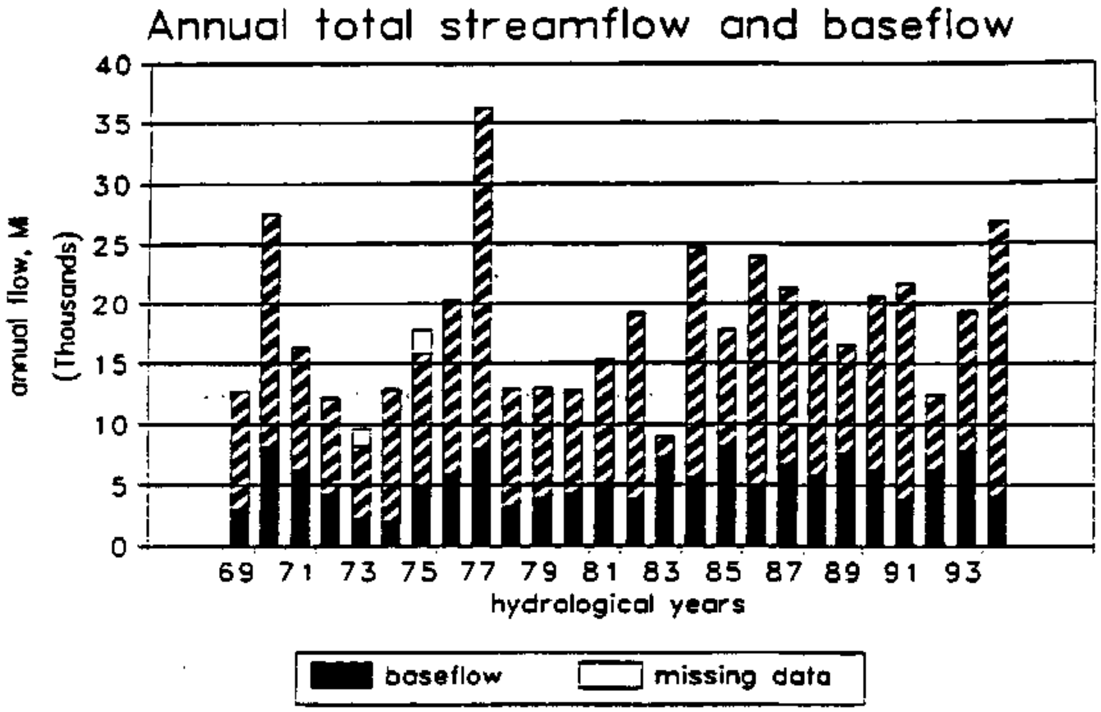

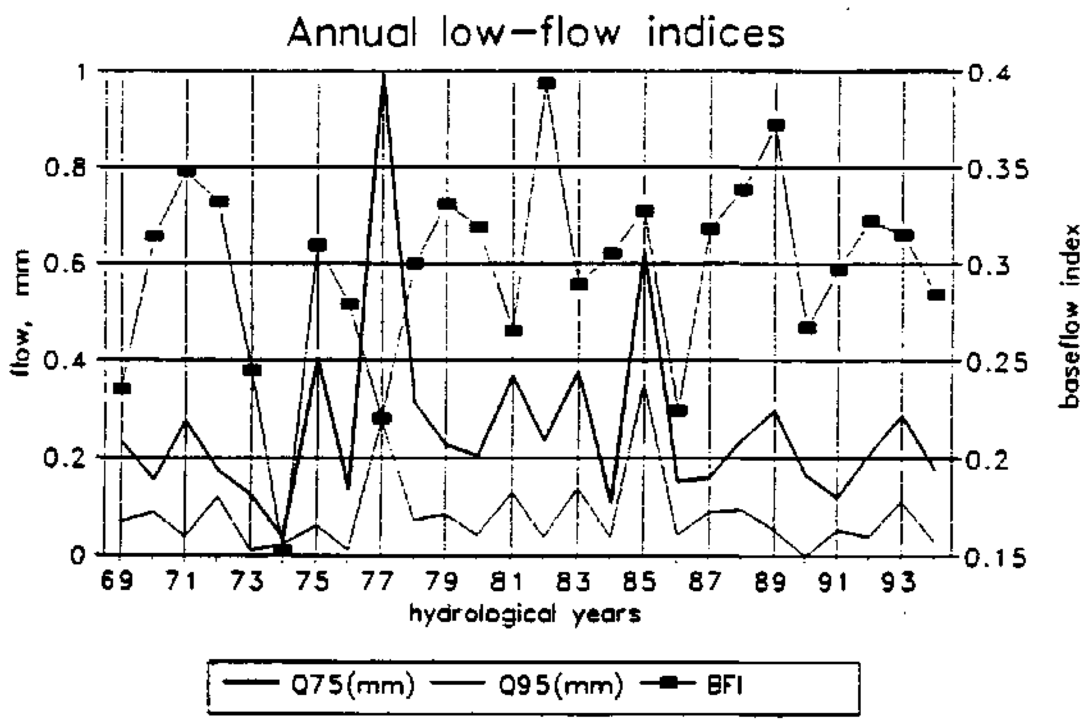

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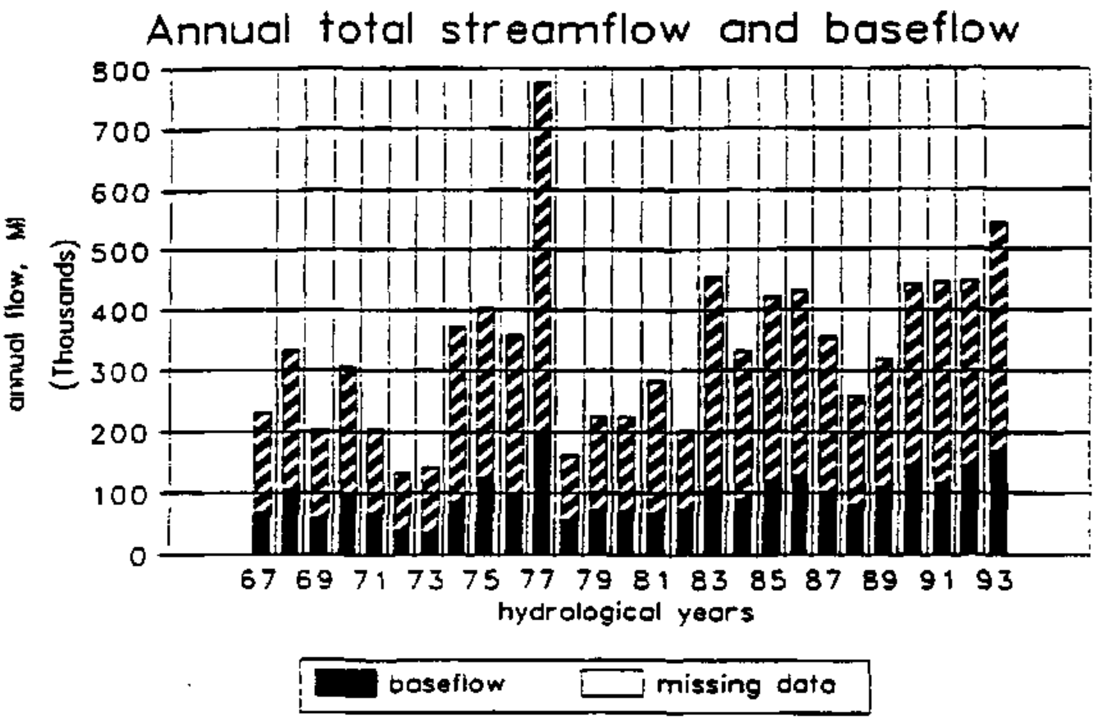

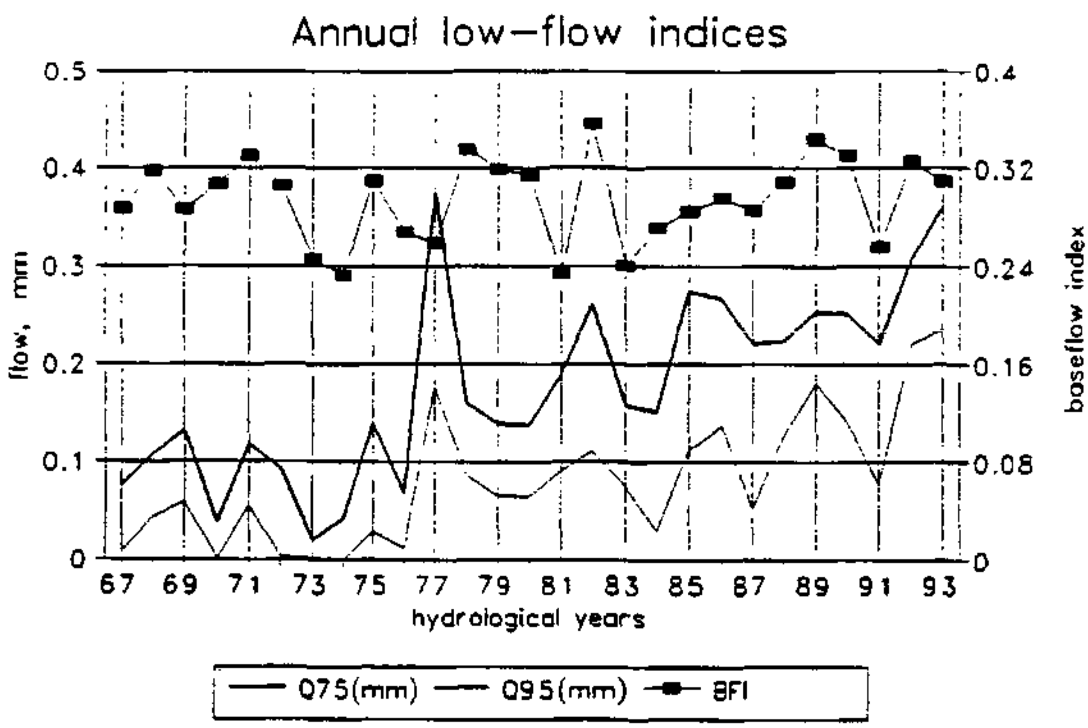

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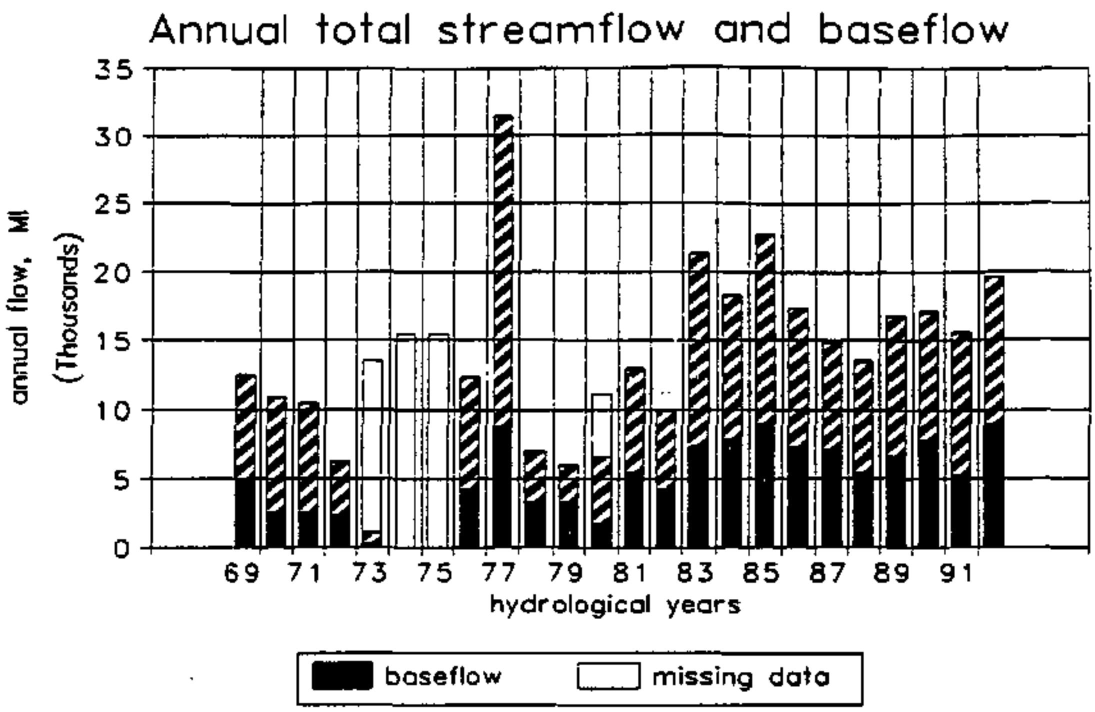


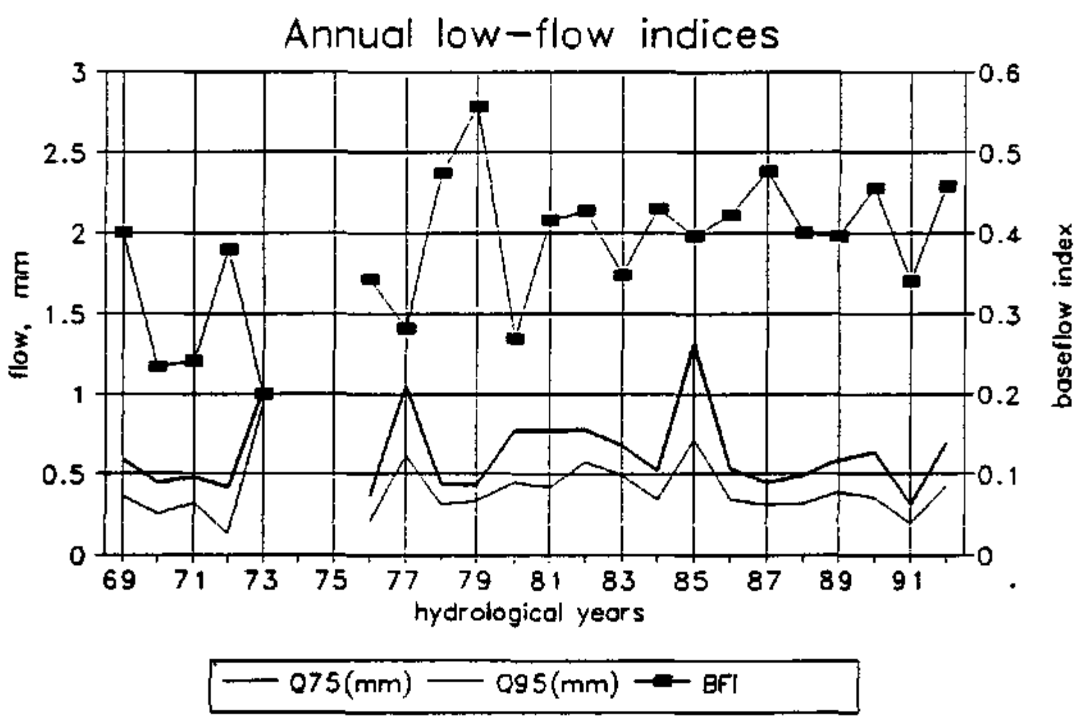
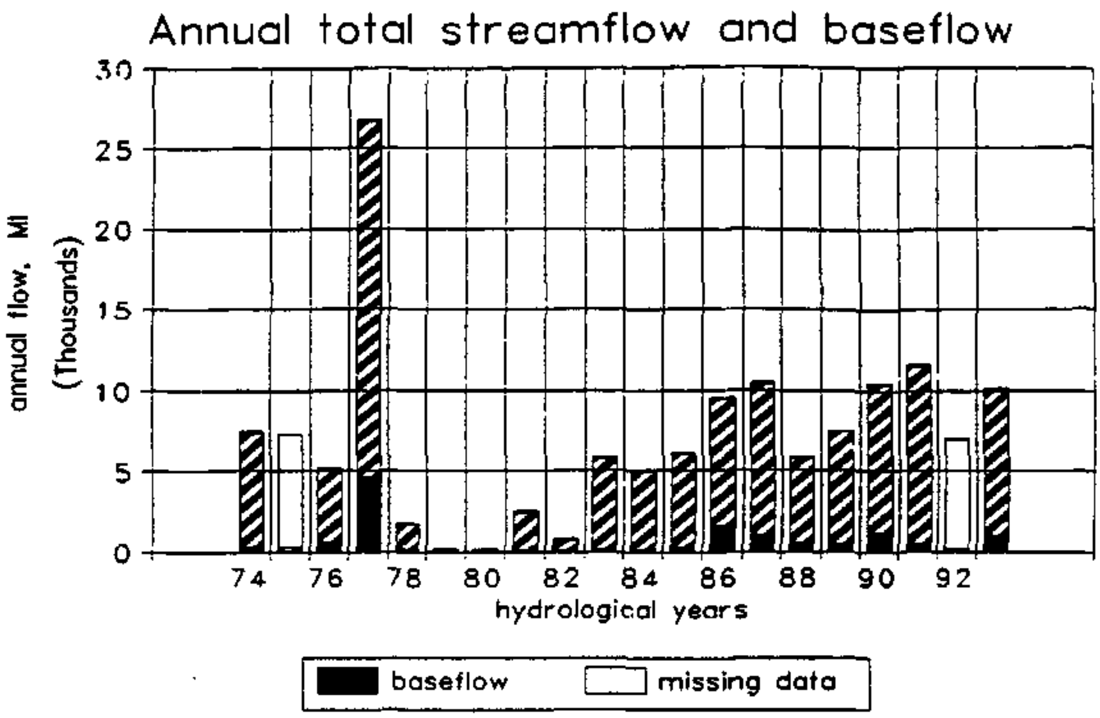


Figure C2.18. Gauge G1H021.



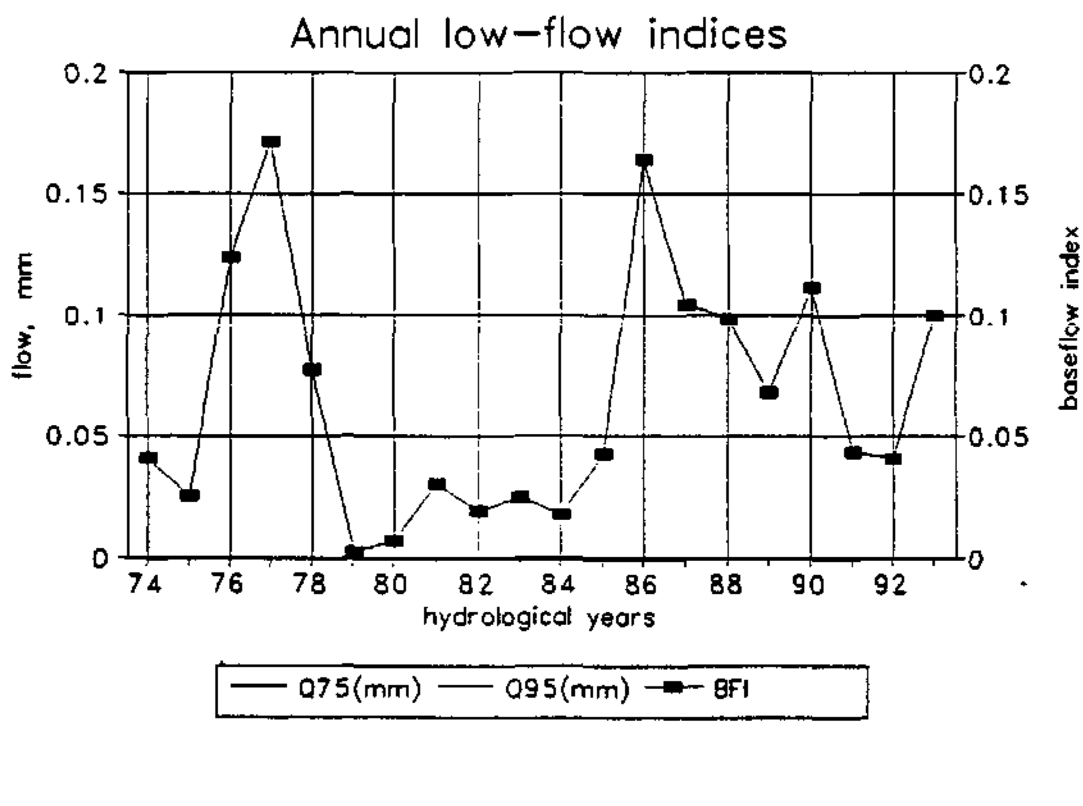
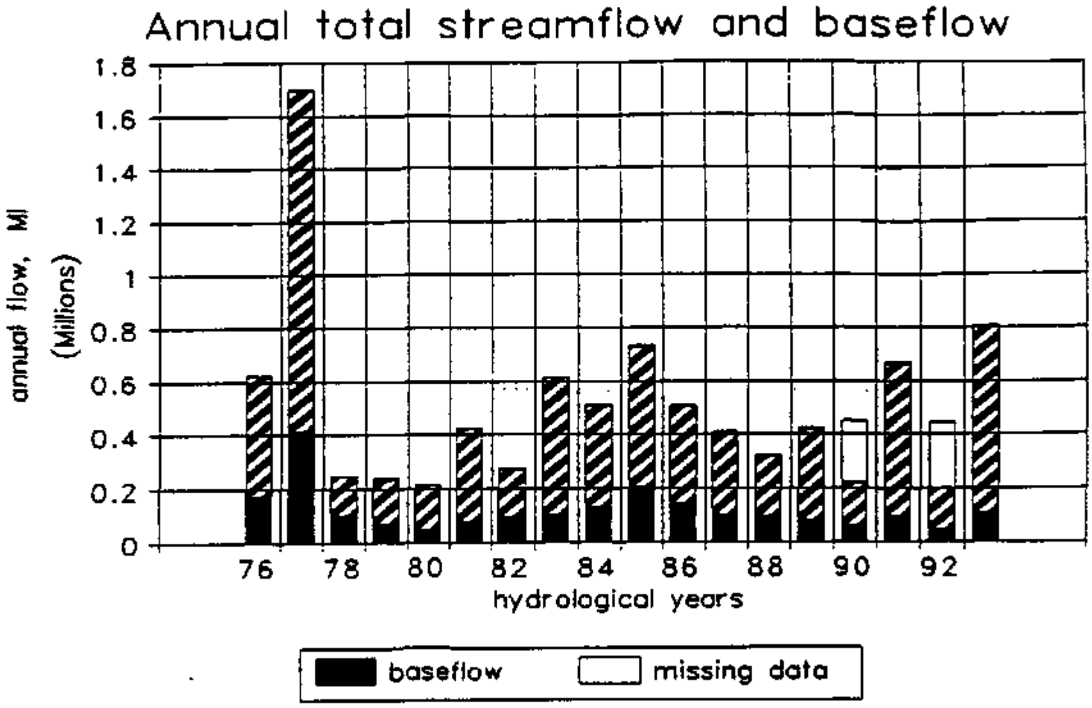


Figure C2.19. Gauge G1H029.



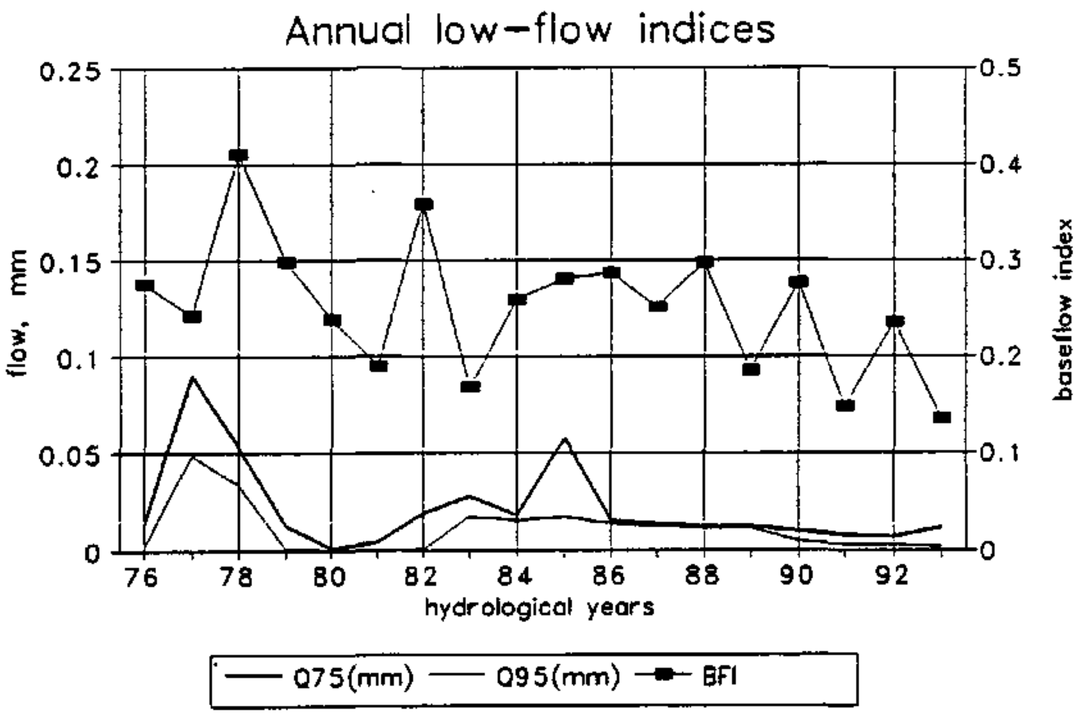
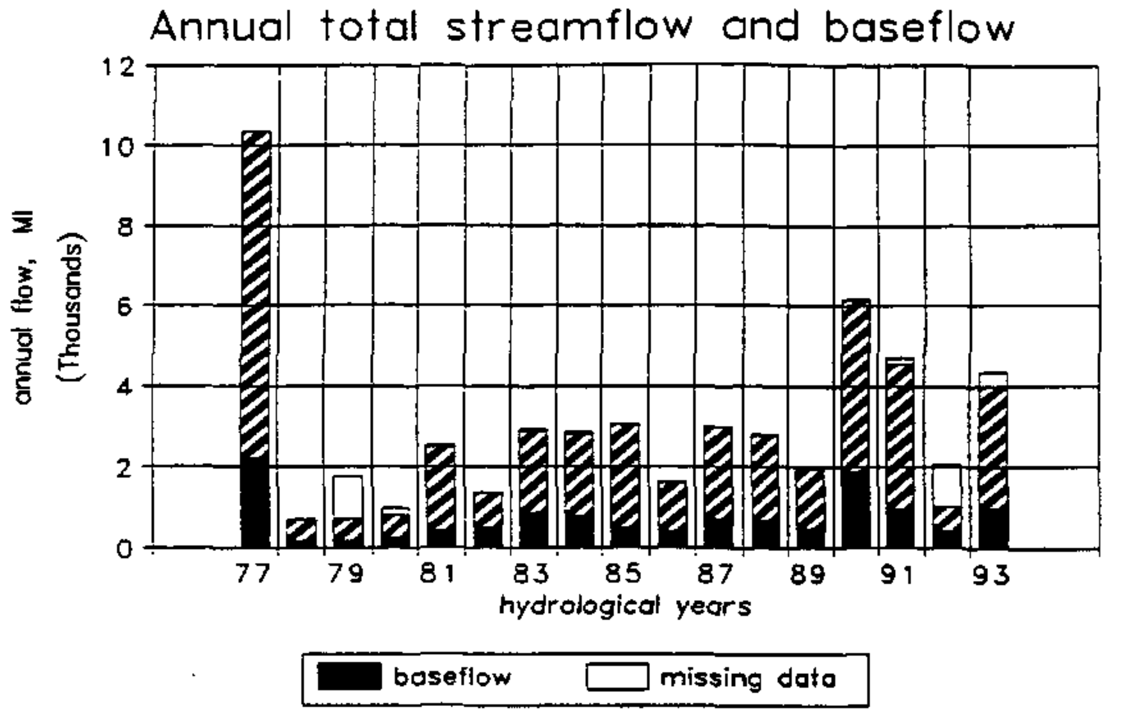
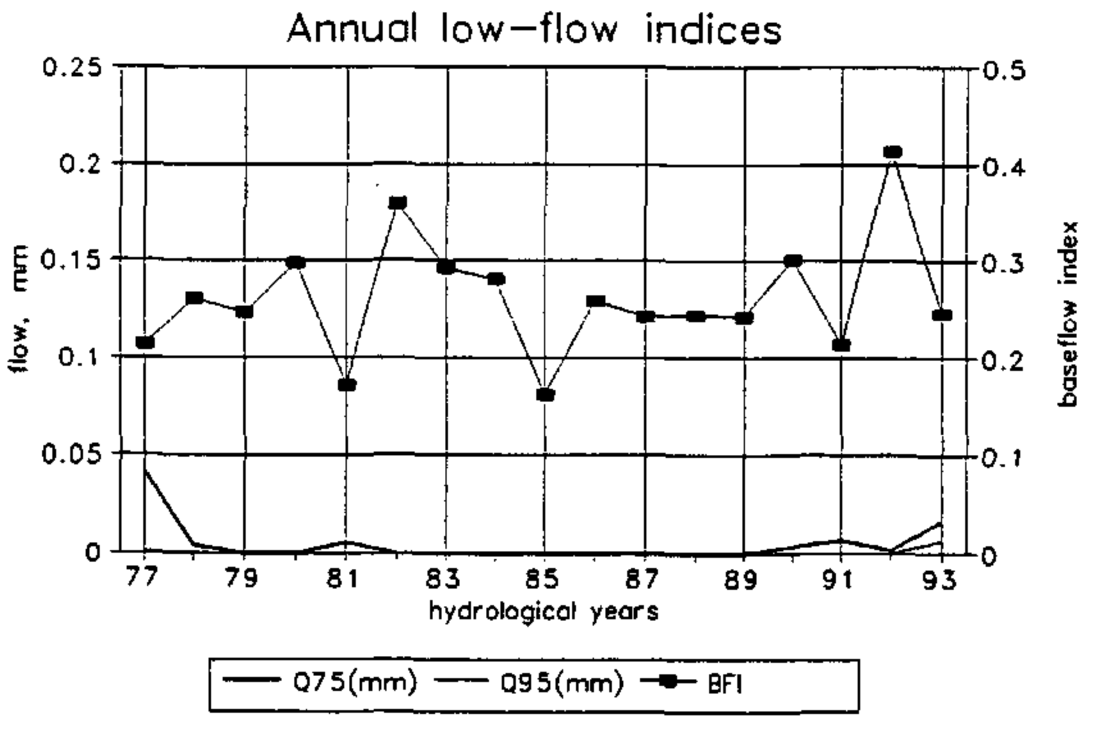


Figure C2.20. Gauge G1H031.





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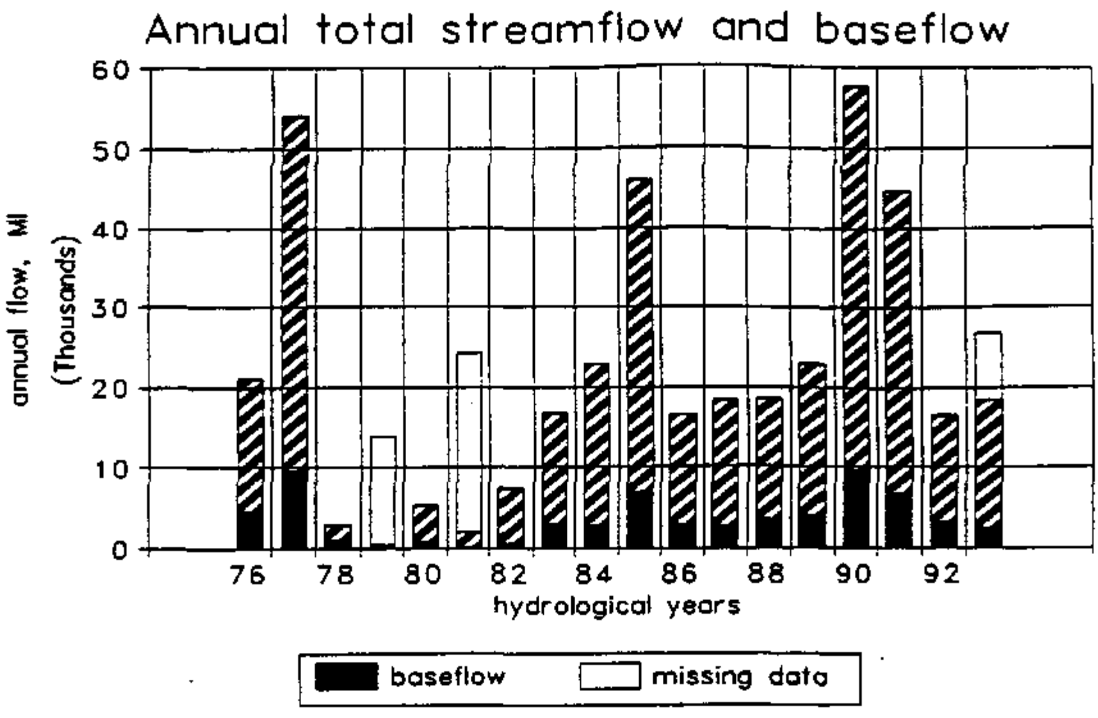


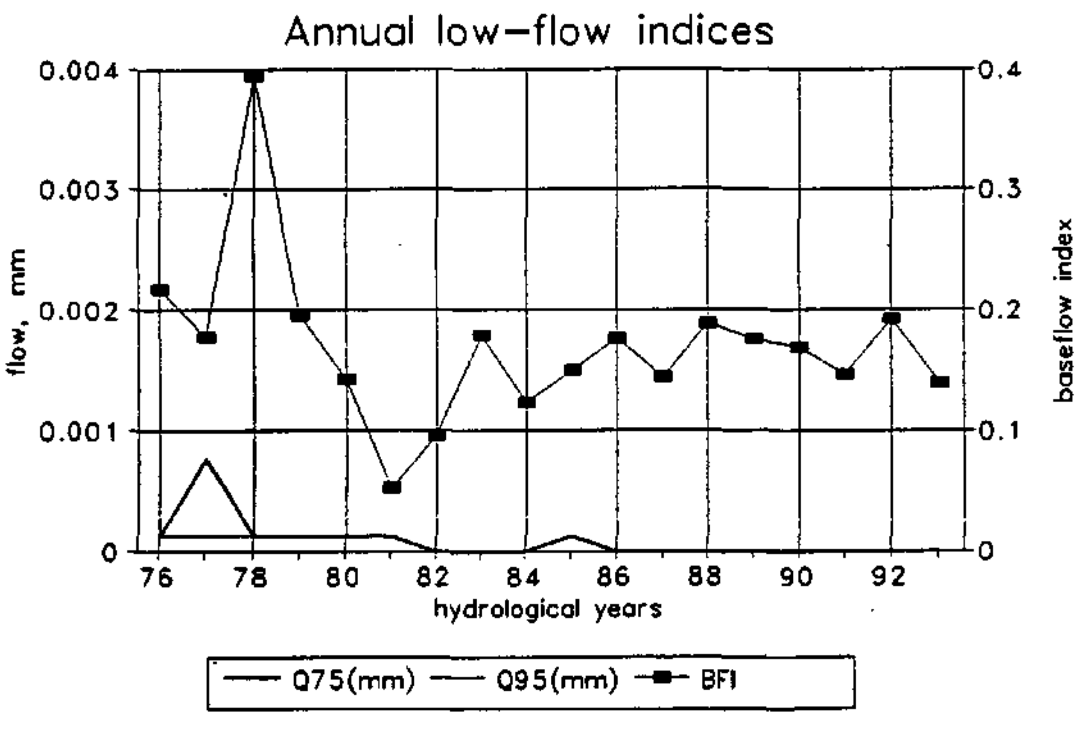
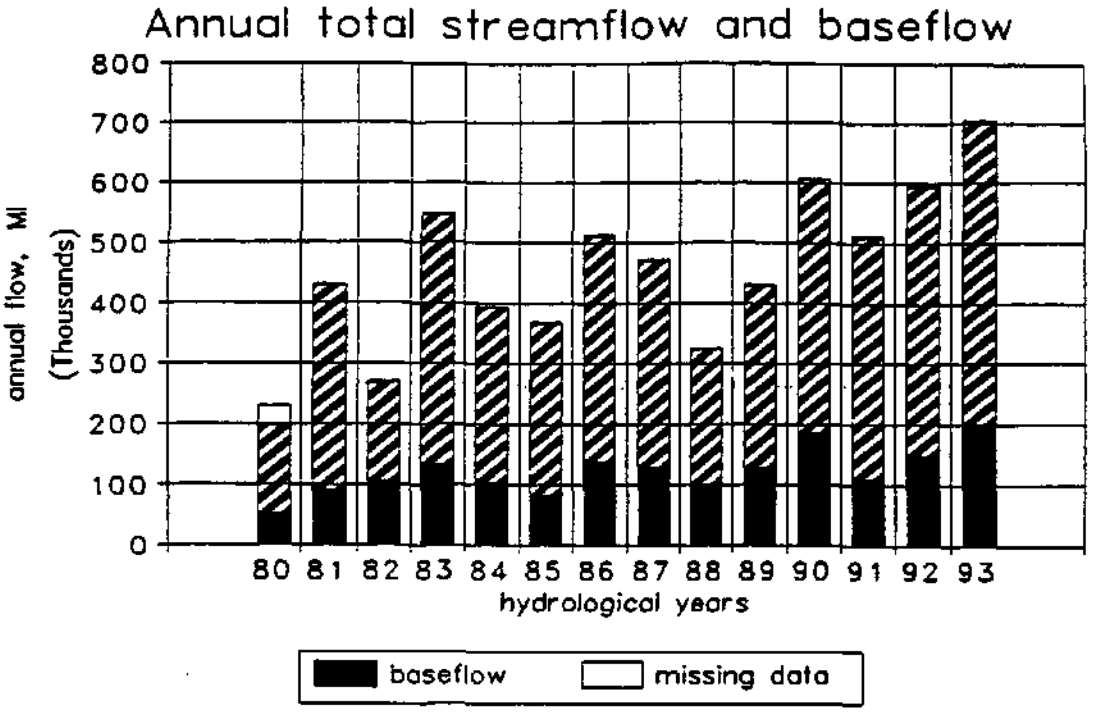


Figure C2.22. Gauge G1H035.



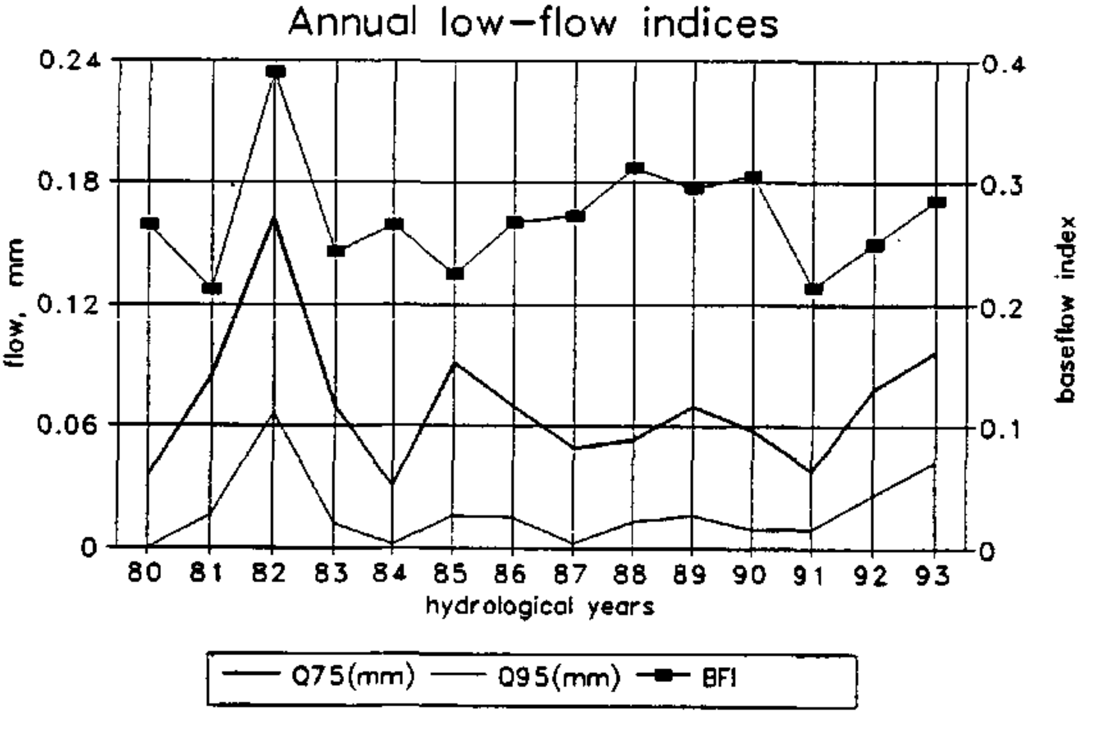
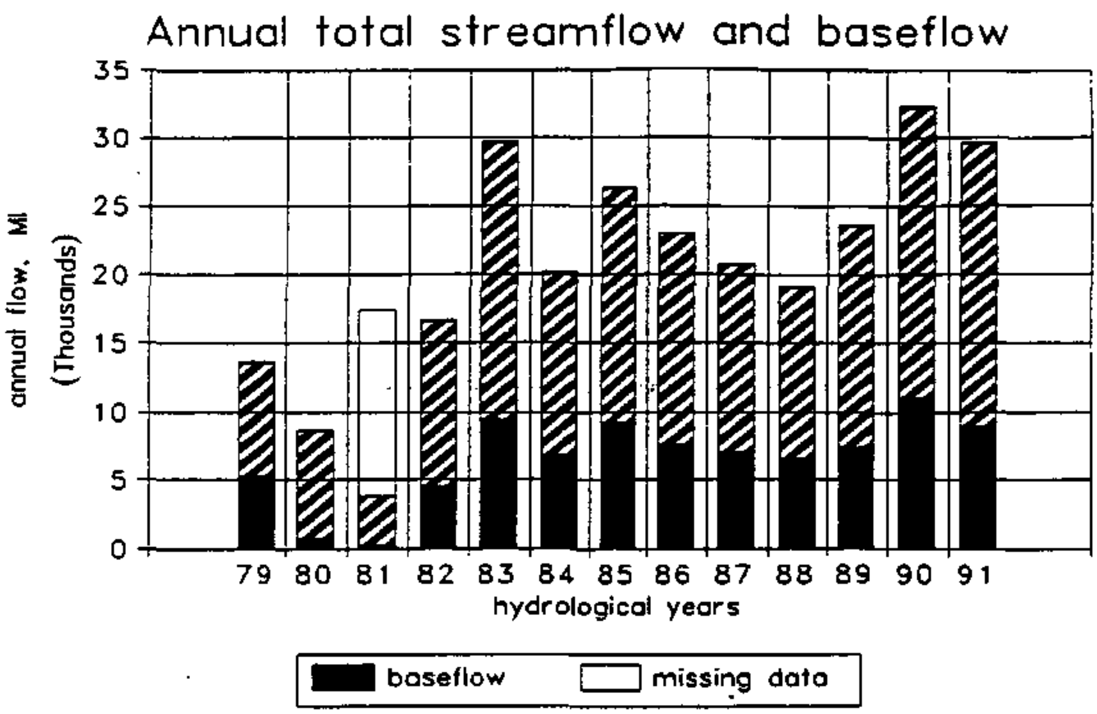


Figure C2.23. Gauge G1H036.



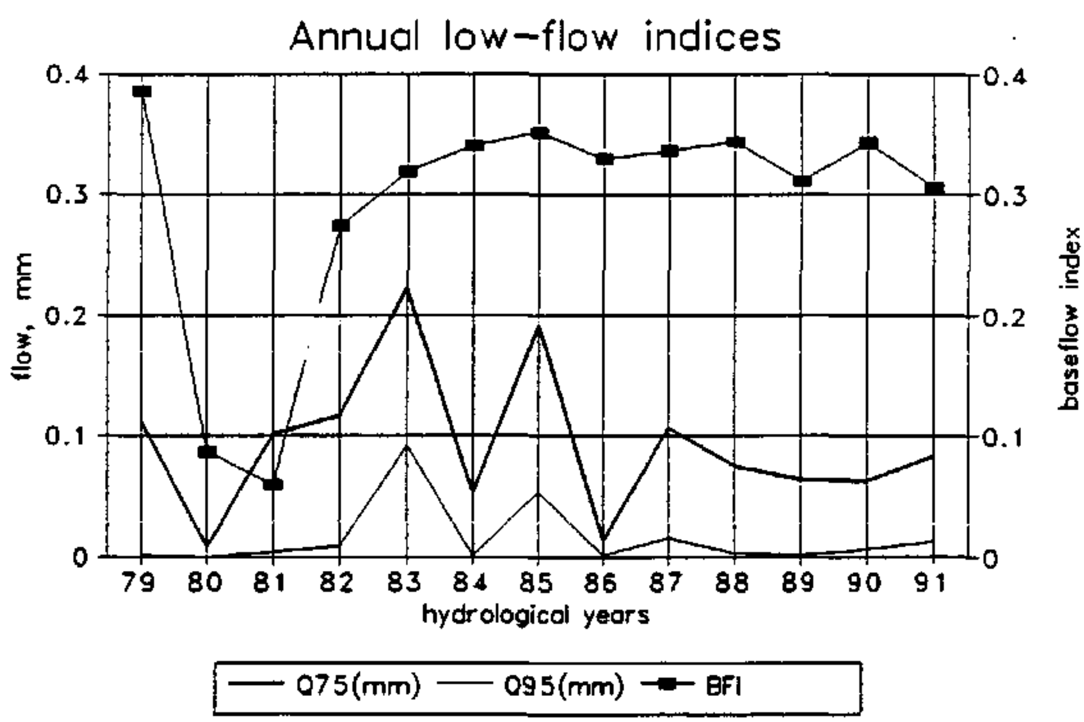


Figure C2.24. Gauge G1H037.

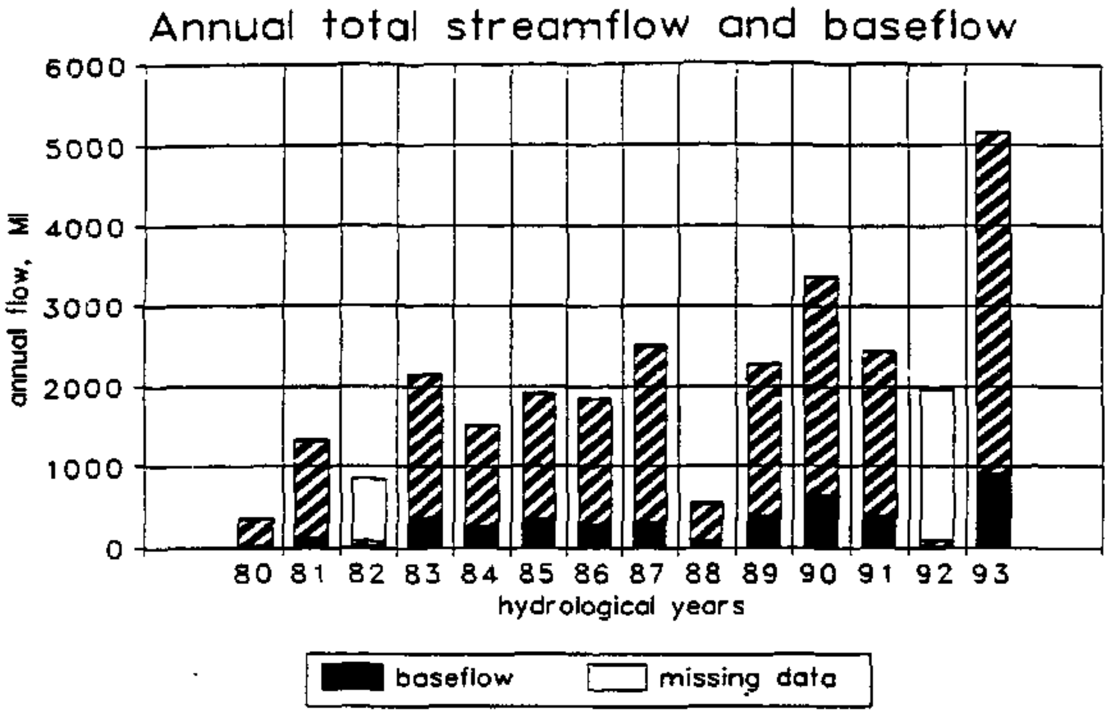


Figure C2.25. Gauge G1H039.

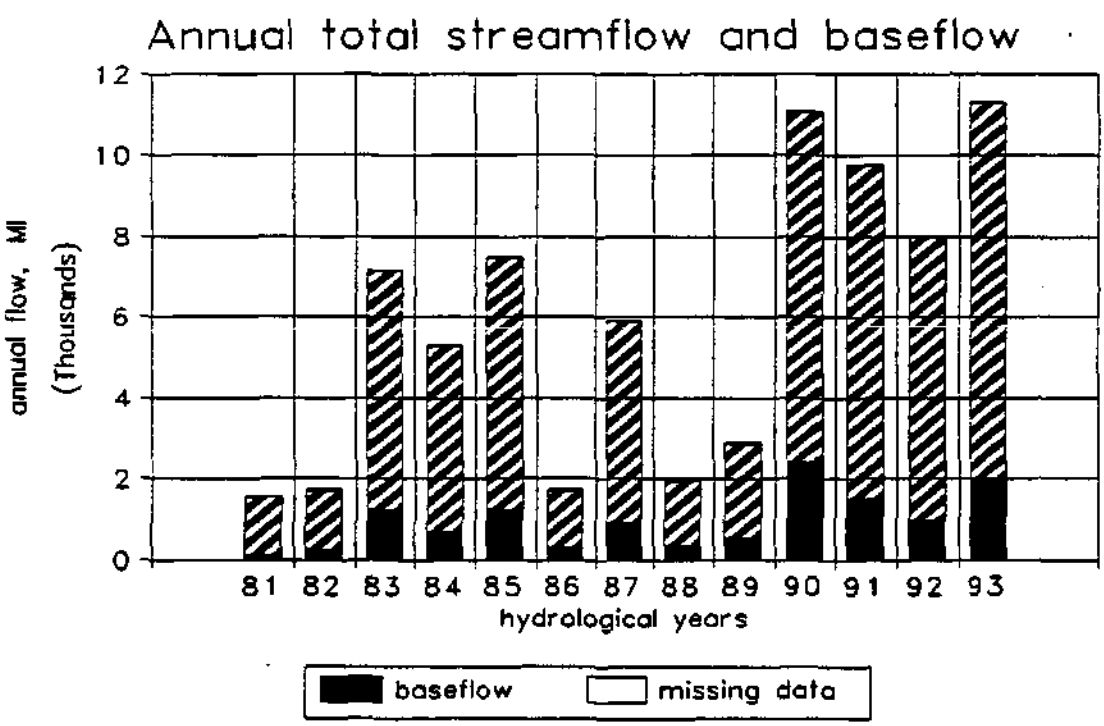


Figure C2.26. Gauge G1H043.

(These two gauges do not have low flows)

APPENDIX D1

Low-flow estimation in the Tugela catchment

D1.1 INTRODUCTION.

For the characterisation of low-flows the Tugela catchment (total area over 29 000 km²) was initially subdivided into several major subcatchments. Each subcatchment included one of the main Tugela tributaries or parts of the main river catchment area (Mooi, Sundays, central Tugela, Buffalo, etc.). It was decided to address the problem of low flows in each subcatchment separately and envisaged that the basin-wide picture of the low-flow regime would eventually emerge from this approach. It was taken into account that the availability of streamflow information required for detailed spatial low-flow estimation in many parts of Tugela basin was limited. Therefore, the spatial resolution of catchment discretisation varied. The estimation techniques may vary similarly. The data used for estimation may be of different origins - observed, simulated by the deterministic daily model (or other simplified method), or mixed. In several major tributaries of the Tugela (Mooi, Sundays) the flow time series were simulated using the VTI model and/or the spatial interpolation algorithm. In the rest of the catchment, wherever it was possible, use was made of available observed flow records. The applicability of the regional regression approach was also tested and the possibility of estimating daily low-flow characteristics from synthetic monthly flow sequences, available at the quaternary subcatchment scale was investigated.

D1.2 CATCHMENT DESCRIPTION.

The Tugela catchment is the largest river system in KwaZulu-Natal. It has its source in the Drakensberg Mountains, where peaks rise to over 3 000 m, and flows approximately eastward to the Indian Ocean north of Durban. On its way to the ocean it is joined by several major tributaries - the Little Tugela, Klip, Bushmans, Sundays, Mooi and Buffalo (the largest tributary).

The general topographical pattern of the entire catchment is illustrated by Figure D1.1 which presents a 1' x 1' grid altitude data and is constructed based on the information obtained from the CCWR. About 90 % of the catchment is underlain by the rocks of the Karoo System with the domination of the Ecca and Beaufort series. The Ecca series is present in the Klip, Buffalo, lower Mooi and central Tugela catchments and consists mostly of coarse-grained sandstones which alternate with softer layers of sandy shales. The Beaufort series occupies about one quarter of the Tugela catchment, covering a wide section in the southwestern part of the catchment (surrounding the Drakensberg mountains). It consists mostly of mudstones and shales.

The Tugela basin lies in the high-rainfall region of South Africa. Different sources give the estimate of the mean areal catchment precipitation in the range of 840 - 870 mm. These figures are much higher than the average MAP for the whole country (about 485 mm). The MAP varies in the catchment from more than 1 500 mm in the Drakensberg mountains to as low as 600 mm (in places along the lower reaches). The general spatial pattern of

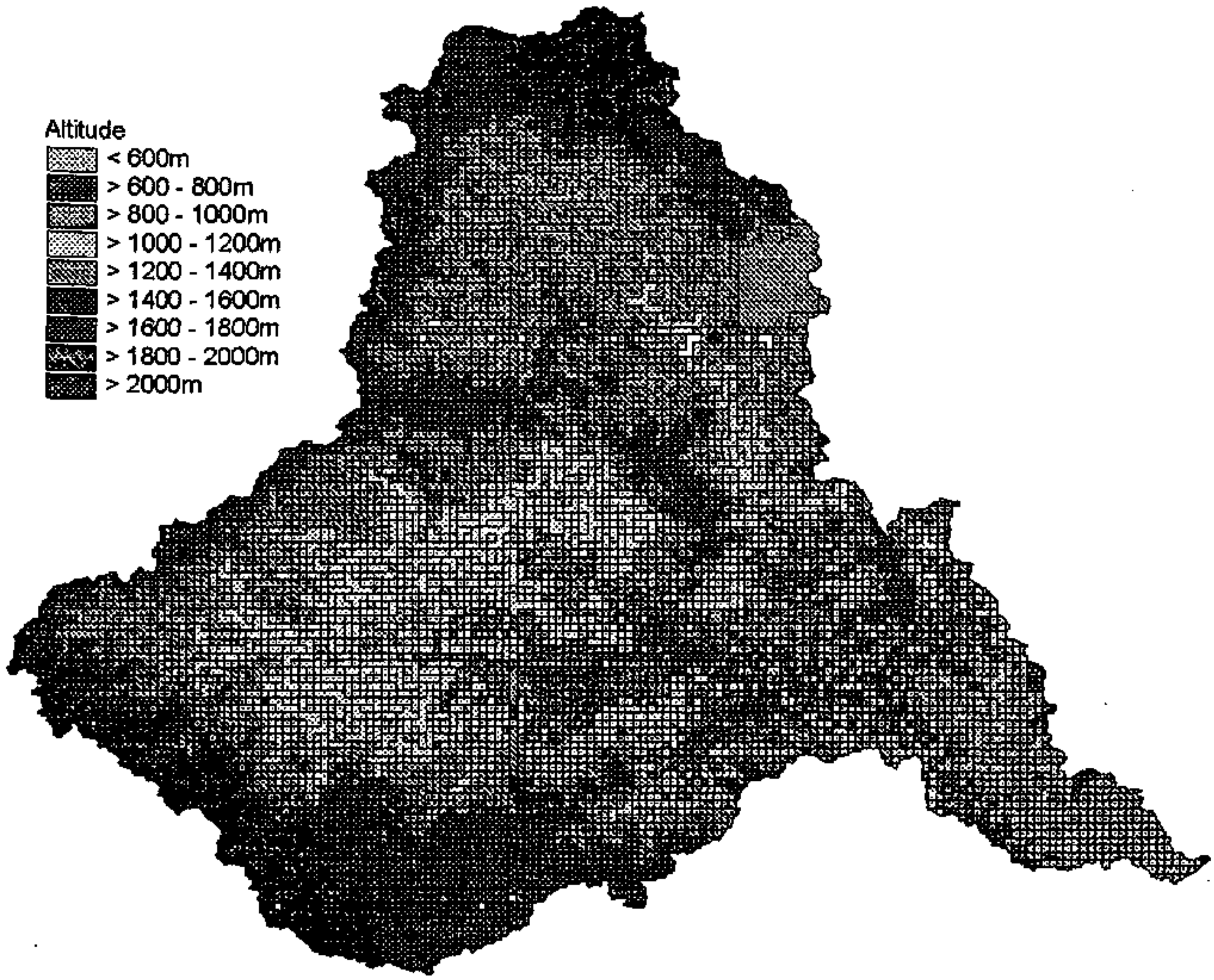


Figure D1.1   1' X 1' grid altitude data (m) for the Tugela catchment.

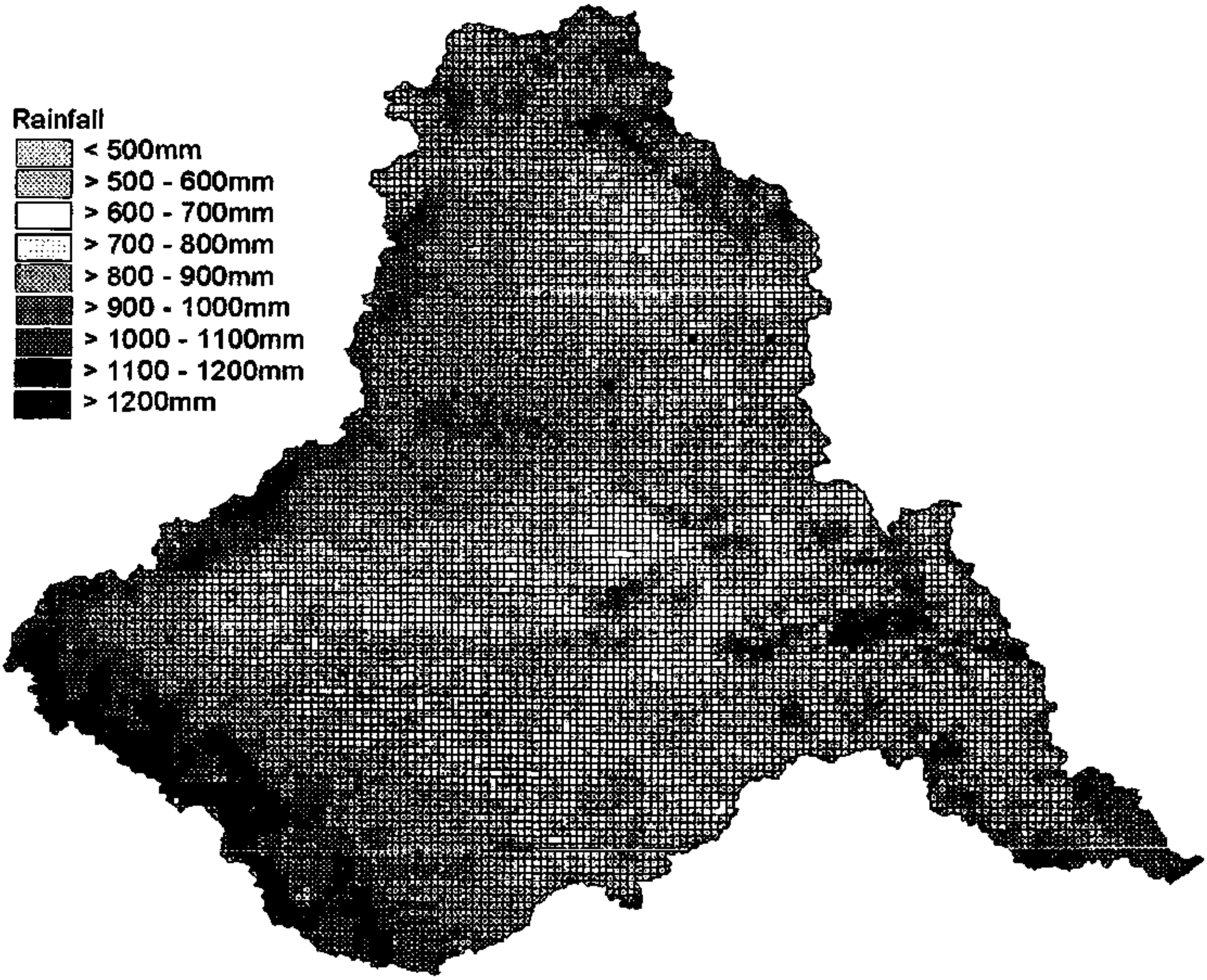


Figure D1.2 1' X 1' grid MAP data (mm) for the Tugela catchment.

precipitation is illustrated by the Figure D1.2 which presents a 1' x 1' grid MAP data and is based on the information obtained from the CCWR. On average over the entire catchment more than 80% of the MAP falls between October and March. The 3 summer months receive about 50 % and the 3 winter months only 5 % of the annual rainfall.

Water usage within the Tugela catchment remains at a relatively low level. Water demand comes mostly from three different sources: irrigation, forestry, and domestic and industrial use. In total the water consumption in the catchment amounts to less than 10 % of the MAR of the Tugela river which is approximated by different hydrological studies to be at the level of 4 000 MCM.

D1.3 OBSERVED STREAMFLOW DATA.

According to the Flow Data Catalogue regularly published by the DWAF, streamflow in the Tugela catchment is (or was) measured at about 130 gauging stations. However, many of these measure flow in very small experimental catchments and are of little relevance to catchment-wide low-flows analysis. The others (some river and reservoir stations, gauges on canals and pipelines) have no or very short (less than 2 years) records or inadequate information to construct a reliable stage-discharge relationship. For these reasons the data for less than 40 streamflow gauges were used (or at least initially considered) in this study. Details of most of these gauges are given in Table D1.1 and their locations are shown in Figure D1.3.

The quality of streamflow records with respect to possible sources of error were not specifically examined in this project, since for most of the stations, this analysis had been previously carried out in the Streamflow Hydrology Report of the Vaal Augmentation Planning Study, 1994 (further referred to as VAPS, 1994). This report provides the necessary details about the measuring structures, measuring problems experienced at each gauging station, and often the quality of both high and low flows. The report rated the quality of flow data at each gauge as "unreliable", "good" or "very good". The intermediate ratings are indicated in Table D1.1 in some cases as "+" or "-". Several stations used in this study were not considered and rated in VAPS.

It is evident, from Figure D1.3, that most of the streamflow gauges are concentrated in the upper reaches of the streams, where most of the runoff is generated. However, the lower reaches of the Tugela and its main tributaries are not properly gauged. In fact no representative observed daily flow records exist in most of the downstream parts of the catchment which makes low-flow estimation as well as any other hydrological analysis in these areas a difficult exercise.

In order to assess the quality of available observed streamflow records for direct low-flow estimation and model calibration, each observed flow data set (except gauges with short flow records and gauges on existing structures) has been analyzed by plotting the annual flow

Table D1.1 Details of streamflow gauges in the Tugela basin.

Code	River	Location	LAT. ddmmss	LONG. ddmmss	Catchment area, km^2	Available record	VAPS rating
V1H001	Tugela	Colenso	284408	294914	4 176	1951 - 1992	reasonable
V1H002	Tugela	Bergville	284415	292109	1 689	1931 - 1970	not rated
V1H004	Mlambonja	The Delta	284745	291811	441	1962 - 1975	reasonable
V1H009	Bloukrans	Frere	285329	294614	196	1954 - 1992	reasonable
V1H010	L. Tugela	Winterton	284905	293242	782	1964 - 1992	reasonable
V1H026	Tugela	Kl. Waterval	284315	292133	1 894	1967 - 1992	good
V1H029	Gelugsburgspruit	Schoonspruit	283028	292054	21	1968 - 1992	not rated
V1H031	Sandspruit	Bergville	284321	292105	162	1972 - 1992	not rated
V1H034	Khombe	Groot Geluk	284023	290509	51	1974 - 1992	not rated
V1H038	Klip	Ladysmith	283342	294509	1 644	1971 - 1994	reasonable +
V1H041	Mlambonja	Kleine-River	294842	291843	434	1976 - 1992	reasonable
V1H039	L. Tugela	Drakensberg	290329	293144	233	1977 - 1993	not rated
V1H058 (V1R002)	Tugela	Driel Barrage	284544	291733	1 656	1985 - 1993	good
V2H001	Mooi	Scheepersdaal	290158	302137	1976	1932-1976	not rated
V2H002	Mooi	Mooi River	291310	295937	937	1950 - 1994	good
V2H004	Mooi	Doornkloof	290415	301445	1 546	1960 - 1993	reasonable +
V2H005	Mooi	The Bend-Avon	292134	295252	260	1972 - 1992	good +
V2H006	Little Mooi	Dartington	291529	296209	188	1972 - 1992	not rated
V2H007	Hlatikulu	Broadmoor	291409	294718	109	1972 - 1992	good
V2R001	Mnyamvubu	Craigie Burn	290947	301717	152	1983 - 1994	not rated

Table D1.1(cont.) Details of streamflow gauges in the Tugela basin.

Code	River	Location	LAT. ddmmss	LONG. ddmmss	Catchment area, km^2	Available record	VAPS rating
V3H002	Buffels	Schurverpoort	273608	295634	1 518	1933 - 1992	reasonable
V3H003	Ngagane	Ballengeich	275519	295705	850	1929 - 1961	not rated
V3H005	Slang	Vlankdrift	272608	295834	676	1947 - 1992	unreliable
V3H007	Ncandu	Rust	275058	295027	129	1948 - 1992	not rated
V3H009	Horn	Ballengeich	275345	295705	148	1962 - 1992	not rated
V3H010	Buffels	Tayside	280332	302225	5 887	1960 - 1993	reasonable
V3H011	Bloed	Rietvlei	275352	303453	543	1960 - 1985	not rated
V3R001 (V3H027)	Ngagane	Chelmsford Dam	275711	195653	830	1961 - 1993	good
V3R003 (V3H028)	Slang	Zaaihoek Dam	272615	300340	604	1988 - 1994	not rated
V5H002	Tugela	Mandini	290826	312331	28 920	1959 - 1993	unreliable
V6H002	Tugela	Tugela Ferry	284500	302634	12 862	1927 - 1994	reasonable
V6H003	Wasbank	Kuikvlei	281834	300853	312	1954 - 1992	reasonable
V6H004	Sundays	Kleinfontein	282416	300047	658	1954 - 1992	good
V6H007	Tugela	Impafana	284445	302244	12 498	1982 - 1987	not rated
V7H012	L. Bushmans	Estcourt	290008	295254	196	1962 - 1994	reasonable -
V7H017	Bushmans	Drakensberg	291115	293813	276	1972 - 1993	reasonable
V7H018	L. Bushmans	Loch Sloy Craig	290405	294451	119	1972 - 1992	not rated
V7R001 (V7H020)	Bushmans	Wagendrift Dam	290232	295105	744	1963 - 1993	not rated

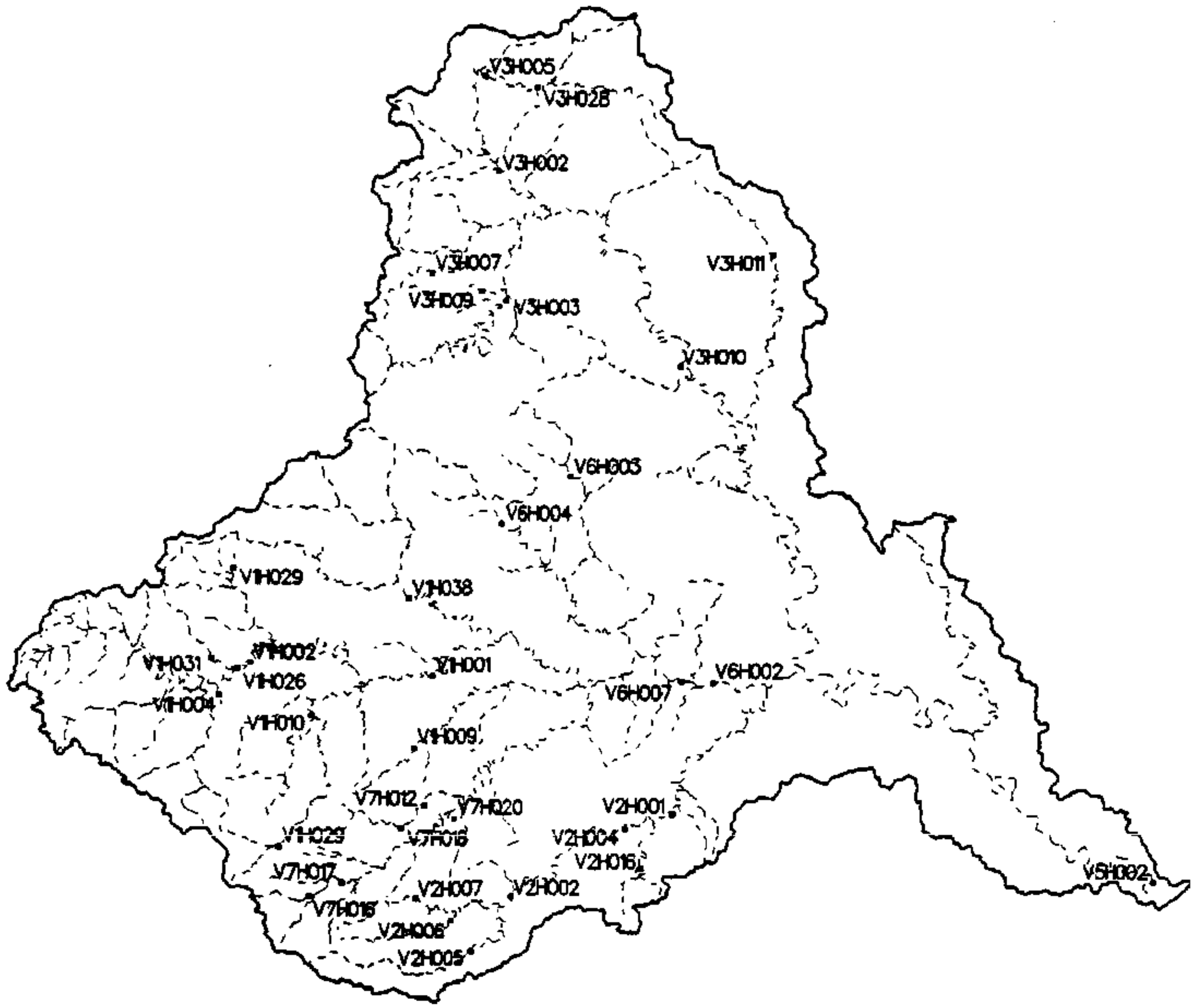


Figure D1.3 Streamflow gauges in the Tugela River catchment.

totals as a time series and extracting several low-flow characteristics from each year of record. These procedures allow the general quality of the data to be assessed and temporal variations in annual total flows and low-flows to be illustrated. The low-flow indices extracted where flows exceeded 75 and 95 % of the time expressed in mm/day over the upstream area commanded by each gauge. Baseflow has been separated from the original streamflow hydrograph by the digital filter and then the baseflow volume and baseflow index for each year of record have been estimated. Plots of annual total streamflow, baseflow and low-flow characteristics are presented in APPENDIX D2. Brief comments on most of these gauges are given below.

Drainage region V1. Many gauges in this region are characterized by a high degree of non-stationarity which becomes evident from the plots presented in the APPENDIX D2. Gauge V1H001 on the Tugela is the most downstream one in this region. Its record clearly reveals the decreasing trend in annual flow totals (Figure D2.1), the result of an intensive water resource development upstream (large dams - Spioenkop, Driel, Woodstock etc., export of water, irrigation). The last 9 - 10 years of record may probably be considered suitable for estimation of low flows in the river at present day conditions.

Gauge V1H002 was located just upstream of the major water schemes and was in operation until 1970 thus recording reasonably natural or at least unregulated flow. However, the discharge table limit is extremely low, especially in the earliest part of the record, which is clearly demonstrated by the plot of annual totals (Figure D2.2). The record on its own does not seem to reveal pronounced trends in low flows, but an obvious decrease in BFI is present. Another nearby gauge V1H026 is located between Driel Barrage and Spioenkop Dam on the Tugela and may be viewed as recording both outflows from Driel Barrage (after 1982) and inflows to the Spioenkop Dam. The record demonstrates an abrupt decrease in both annual totals and low flows after the construction of the Driel Barrage. Taken together, the two ungauged records (V1H002 and V1H026) reveal a dramatic change in low flows in the last 35 years (Figs. D1.4 and D1.5).

Gauges V1H004 and V1H041 may be considered together because they measure flow from the same catchment at approximately the same point. Gauge V1H004 has 13 years of data and was closed when Driel Barrage inundated the weir and gauge V1H041 was constructed upstream. The individual records on each gauge are too short to reveal any trends. The DTL at gauge V1H041 is low but the combined record of two gauges is suitable for low-flow estimation.

Gauge V1H009 provides the streamflow information on the relatively dry catchment. This is revealed by the plots of annual low-flow indices which often fall to zero, and a small baseflow contribution (Fig. D2.4). The record is long and stationary and is suitable for low-flow estimation.

The record at gauge V1H010 reveals an abrupt decrease in all flow characteristics since the beginning of 1980s. This may probably be attributed to the extensive irrigation and the construction of a large dam on one of the Little Tugela tributaries upstream. The record is

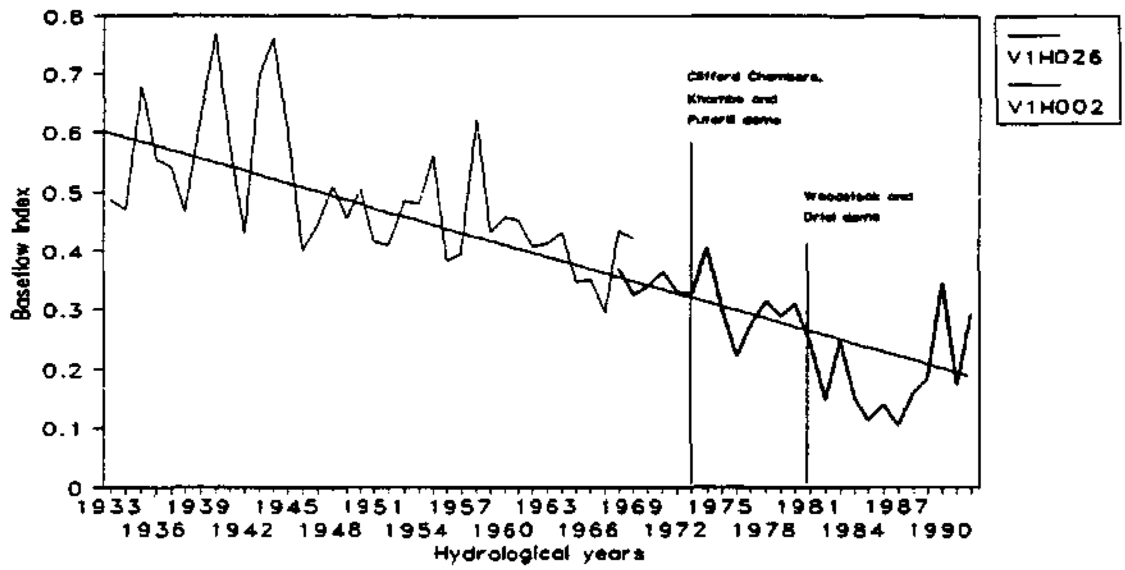


Figure D1.4 A decreasing trend in baseflow index at gauges V1H002 (first part of the record) and V1H026 (second part).

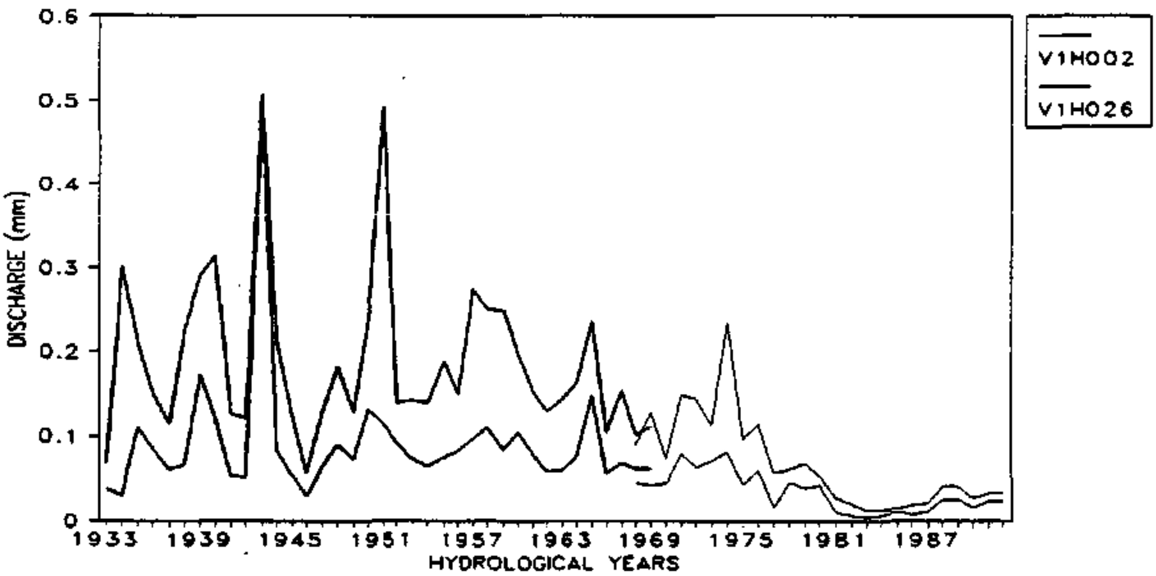


Figure D1.5 Temporal changes in Q75 (upper line) and Q95 (lower line) annual flow values at gauges V1H002 (first part of the record) and V1H026 (second part).

considered to be unreliable due to siltation problems and unmetered abstractions from theweir. However, the part of the record from 1980 onwards is stationary and may represent present day conditions in the catchment (Fig. D2.5).

Gauge V1H031 records flow from a relatively small catchment with some irrigation which explains frequently occurring zero-flow conditions (Fig. D2.8). Gauge V1H038 is the only one on the large left tributary of the Tugela - the Klip river. The record seems to be stationary for practical purposes, although low flows are slightly decreasing during the last 20 years which may be explained by municipal abstractions and irrigation development. Gauge V1H039 records flow from a natural catchment in the Drakensberg mountains.

Overall, the quality and amount of gauged daily streamflow data is insufficient for detailed analysis. This part of the Tugela catchment is the most affected by water resource development which imposes additional problems. The quantification of low flows from observed records can not be done at a detailed level of spatial resolution and only rough estimates may be obtained at and between the gauged locations.

Drainage region V2. Gauges in this subregion measure flow from the Mooi River catchment - the largest right tributary of the Tugela. Gauges V2H007, V2H006 and V2H005 (Figs. D2.16. D2.17, D2.18) measure flow from three headwater catchments which originate in the Drakensberg mountains. All three gauges have concurrent records and good quality data for low-flow estimation. However, low flows have been slightly decreasing at gauges V2H005 and V2H006, most probably as a result of increasing total farm dam capacity in these catchments.

Gauge V2H002 is located in upstream Mooi below the confluence of its three main tributaries and has a long representative flow record (Fig. D2.14). Low flows demonstrate a slight decrease in the last 30 years.

Gauges in the middle reaches of the Mooi river are of a much poorer quality. The usable period of record at gauge V2H004 is only up till 1976; after that the record mostly contains missing data (Fig. D2.15). Therefore, no clear trends in low flows can be detected. The record at gauge V2H001 is generally unreliable. In addition it does not cover the latest historical period. Gauge V2H016 records inflows to the Mooi river from its right tributary - Mnyamvubu, impounded by the Craigie Burn Dam (Fig. D2.19). Low-flow contribution from this catchment is negligible. Overall, it can be concluded that only the upstream reaches of the Mooi are properly gauged.

Drainage region V3. Gauge V3H002 in the upper reaches of the Buffalo River has a long record (Fig. D2.20) but only part of it from 1949 to 1983 is recommended for use by VAPS due to unmetered abstractions from the weir in latter years. The record reveals no clear trends although a slight decrease in annual totals which results from irrigation development may be suspected.

Gauge V3H003 recorded the flow just below the Chelmsford Dam prior to the construction of the latter in 1961 and therefore, reflects the unregulated flow conditions in the Ngagane River. Annual flow totals prior to mid 1940s are affected by the low DTL (Fig. D2.21). The record at gauge V3H005 is highly non-stationary with a clear decreasing trend in both annual totals and low flows (Fig. D2.22). VAPS stated that low-flow measurements at this gauge are particularly of poor quality. The record at gauge V3H007 reveals a slight decreasing trend in low flows (Fig. D2.23). The record at gauge V3H010 could be of strategic importance since it is the most downstream gauge on the Buffalo River. However, it contains a lot of missing data and only a period prior to 1982 is usable (Fig. D2.25).

Overall, the quality and amount of daily streamflow records in the Buffalo catchment leaves a lot to be desired. Only very rough estimates of low-flow conditions could be obtained. The records require extensive patching/extension for low-flow analysis, but this exercise is also hampered by the absence of source gauges with long and reliable records.

Drainage regions V6 and V5. Gauges V6H002 and V6H007 are located very close to each other on the main river and may be of strategic importance. However, gauge V6H002 has an unreliable non-stationary record with frequent missing data periods (Fig. D2.28). Low flows were found to be overestimated (VAPS, 1994) since the gauge records higher flows during the dry months (April - August) than at downstream gauge V5H002 and much higher flows than at V6H007. Gauge V6H007, on the other hand, has a very short record (5 years) which covers mostly dry years and is therefore, not representative. The measurement of low flows at this gauge, however, are more realistic than at the downstream gauge V6H002.

Gauges V6H003 and V6H004 record flow from two catchments in the Sundays River basin. The records appear to be stationary and representative (Figs. D2.29 and D2.30), however, low-flow measurements on V6H003 are considered to be inaccurate (VAPS, 1994). The data on gauge V6H006 located upstream of V6H004 was not available from DWAF at the time of analysis. Overall, the streamflow gauging in the region is insufficient. No reliable data exist in the middle reach of the Tugela River.

The most downstream gauge in the whole catchment is V5H002. It has a long period of observations but the record was rated as unreliable due to siltation problems and underestimation of flows since 1978 which is reflected as a minor non-stationarity on the plot of annual flows (Fig. D2.27).

Drainage region V7. The records at gauges V7H012, V7H016, V7H017 and V7H018 are reasonably long and generally of satisfactory quality. The shape of the daily hydrograph at V7H018 throughout the period of record is almost identical to that at the gauge V7H012 below with just smaller discharge values. Flows are also measured at the Wagendrift Dam (gauge V7H020) constructed in 1963. There is, however, no point in calculating annual low-flows from a totally regulated streamflow record since they are often maintained at a reasonably constant level (Fig. D1.6). The data for the downstream flow gauge (V7H001) which recorded flow prior to dam construction was not available. Overall, the Bushmans river catchment is relatively well gauged in its upstream reaches and low-flow estimation is possible from the observed flow records.

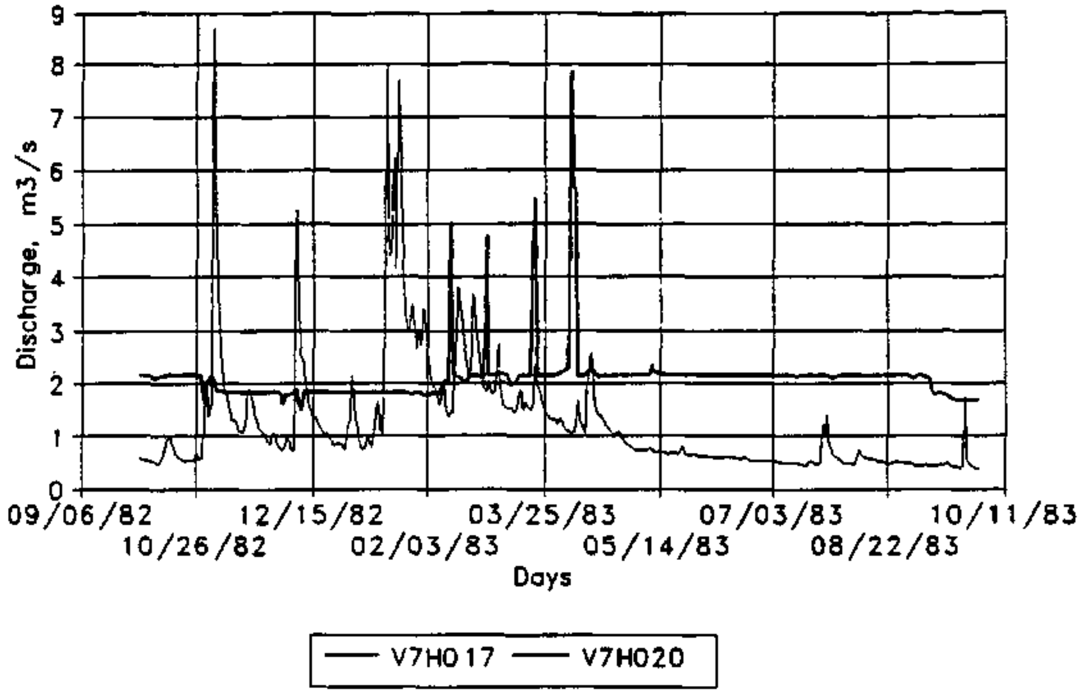


Figure D1.6 Observed daily hydrographs above (gauge V7H017) and below (gauge V7H020) Wagendrift Dam, illustrating the degree of changes in low-flow regime after dam construction.

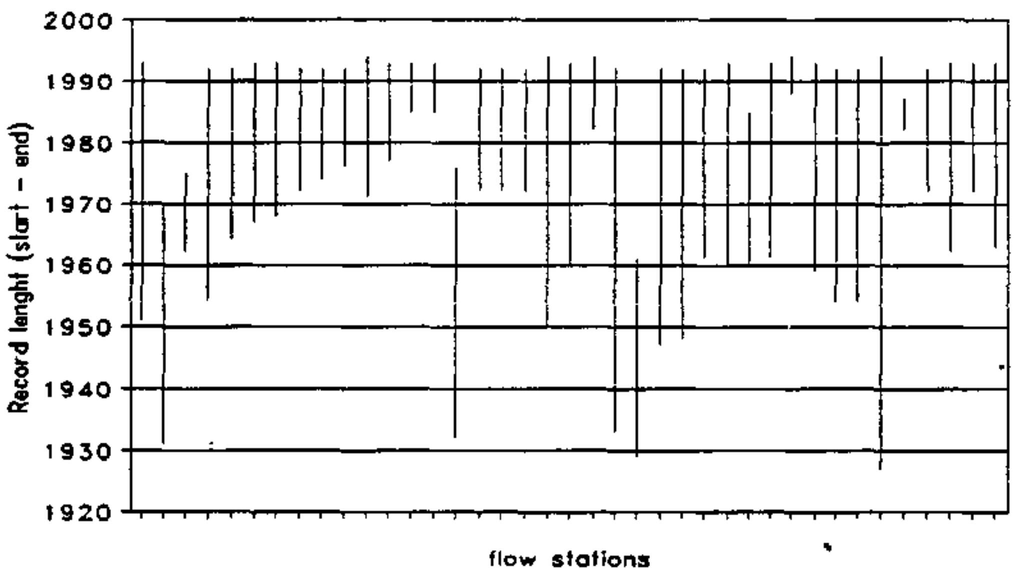


Figure D1.7 Flow record lengths in Tugela catchment.

If low-flow regimes in the catchment are to be analyzed on the basis of observed flow records, it would be important to ensure that all site estimates of any low-flow index are based on records with the same start and end year (concurrent or standard period) and a reasonable length of observation, such as 30 years. For the Tugela catchment this standard period cannot be set up without losing either several gauges with records, part of the record for some gauges or both (Fig. D1.7). The problem is exacerbated by a number of missing data periods in some records which make them considerably shorter. Therefore, the existing records should be extended/patched where possible if they are to be used for direct estimation of low-flow characteristics. Alternatively, a deterministic modelling approach should be used to generate additional time series.

With a view on low-flow estimation from observed flow records, the Tugela catchment has been broken down into a number of smaller subcatchments and this subdivision has initially been based on the location of flow gauges. The ARCINFO coverages of gauged catchment boundaries for the whole of the country have been obtained from the DWAF. The coverage of gauged catchments in the Tugela basin has been extracted from the original DWAF coverages and edited using the list of streamflow gauges, the records for which were actually available. The ungauged parts of the catchment have been subdivided according to quaternary catchment boundaries or their combinations (the quaternary subcatchments used were from the older version of Surface Water Resources of SA, 1981). Additional subcatchments have been used in parts of the catchment where the VTI model was applied (see below). These correspond either to particular subareas or their combinations. Combining quaternary subcatchments and/or subareas for the purpose of catchment-wide low-flow estimation was a rather arbitrary process. Additional difficulties arose when the new version of Surface Water Resources of SA (Midgley et al, 1994) was published, since 'new' quaternary subcatchments in many cases had different boundaries.

The discretisation of the Tugela catchment is illustrated by Figure D1.8. It also shows the areas where the VTI model was applied to general daily streamflow time series:

- The major part of the Mooi River catchment;
- The entire Sundays River catchment;
- The central part of the Tugela catchment where it accepts most of the major tributaries (Klip, Little Tugela, Bloukrans, Bushmans, Sundays).

The calibrated model was then used to simulate long representative streamflow time series in present day and natural conditions. The details of model calibration and subsequent low-flow estimation from simulated series in the three catchments are summarised in the following sections.

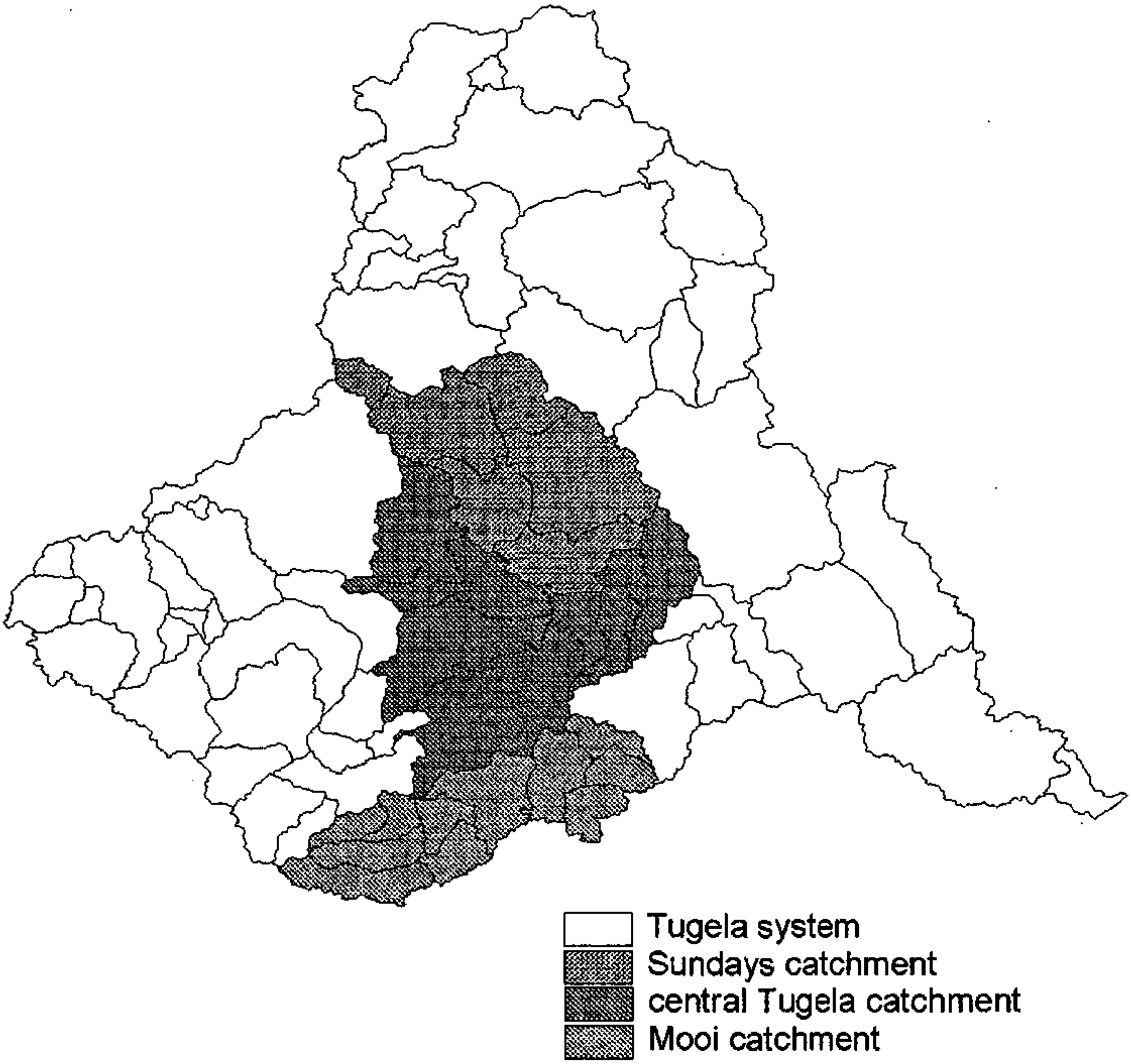


Figure D1. 8 Discretisation of the Tugela catchment showing the areas where the VTI model was applied.

D1.4 MOOI CATCHMENT: THE VTI MODEL CALIBRATION.

The Mooi river originates in the Drakensberg escarpment, flows north-eastward and joins the Tugela in its middle reaches. It is the second largest tributary of the Tugela after the Buffalo. In the headwater areas the catchment is underlain by basalt and sediments of the Stormberg series; further downstream the predominant geological substrate is sandstones and mudstones of the Beaufort and Ecca series. These rocks are generally of low permeability which restricts the percolation of groundwater and results in frequent surface saturation, reflected as vleis and wetlands in topographic lows (especially typical of the upstreams of the catchment where 3 main tributaries: Mooi, Little Mooi and Hlatikulu join together). Soils are moderate to deep and of clayey texture in the headwater areas; further downstream the soils are deep and of clay loam to clay texture but with high infiltration rates and permeabilities (Soils of the Tugela Basin, 1969). Most of the catchment is covered by highland sourveld with small patches of yellow wood forest. The MAP varies from 800 to 1 300 mm across the catchment. Precipitation occurs predominantly in the summer months, with a large proportion of long duration low intensity events.

The gauged area of the catchment is 1 976 km^2 (V2H001). The flow in the catchment is measured at 7 gauges (gauges in the secondary drainage region V2). Reliable observed flow records are available at the four upstream flow gauges: V2H007, V2H006, V2H005, V2H002 and gauge V2H004 (VAPS, 1994), although the latter contains large gaps due to missing data. The catchment was broken down into 4 interlinked projects. Each project corresponded to one of the gauged catchments (V2H002, V2H004, V2H016 and V2H001) and in its turn, was broken down into several sub-areas according to tributary structures, variation in topography, landuse and rainfall. Figure D1.9 illustrates the adopted discretisation of the Mooi catchment. It also shows the location of rainfall and streamflow gauges used for simulation.

Project 1 (Mooi2) - gauge V2H002.

Mooi2 includes the headwater region of the Mooi river and consists of 3 main subcatchments: the Hlatikulu (gauge V2H007), the Little Mooi (gauge V2H006) and the Mooi itself (gauges V2H005 and V2H002). The catchment is split into 9 subareas (Fig. D1.9). Sub-areas 1 and 4 together form the quaternary subcatchment V20C (WR90, 1994), sub-areas 2 and 5 - quaternary subcatchment V20B, sub-areas 3 and 6 - V20A, sub-areas 7 and 8 - V20D.

The baseflow was assumed to be generated as an intersection of groundwater in a thin aquifer with the surface. Groundwater outflow is supplemented by soil baseflow in valley bottoms where saturation conditions exist. Initial soil and vegetation parameters for this catchment (as well as for other projects in the Tugela catchment) have been approximated on the basis of information given in Soils of Tugela Basin (1969) and 1:100 000 soil maps supplied on request by the Natal Town and Regional Planning Commission.

Water in the catchment is predominantly used for irrigation. Most of the irrigation demand is satisfied from a large number of farm dams. The information on total farm dam storage and irrigated areas in each quaternary subcatchment has been taken from VAPS (1994). The volume of average annual irrigation demand has been estimated by multiplying the area under irrigation in each quaternary subcatchment by the demand per unit area (listed for tertiary catchments in WR90). Annual variations in mean daily abstractions were simulated using a set of monthly weighting factors. The apportionment of farm dam storage and demand between sub-areas in each quaternary catchment was performed arbitrarily by studying the 1:100000 topographical maps. The proportion of each sub-area commanded by farm dams had also been approximated using mapped information. The parameters describing irrigation development in the catchment were assumed to be constant for the period of simulation. Calibration of the VTI model was attempted over the period 1972 - 1982.

Fit statistics for untransformed flows for sub-area 1 (Hlatikulu catchment, gauge V2H007) appeared to be rather low (Table D1.2) mostly due to inadequate rainfall input (some observed flow events cannot be simulated since rainfall input appeared to be negligible during the days of event and vice versa). This inadequacy may result from high spatial variation in rainfall which may not be fully accounted for in the model, given the existing set of rainfall gauges. For example, in the case of sub-area 1, the nearest rainfall gauges which are used to generate rainfall input, are located outside the Hlatikulu catchment in sub-area 2

Table D1.2 Comparative statistics for the Mooi catchments.

Code	Data	Untransformed						Ln transformed					
		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
Mooi2, sub.1	Obs	21.3	0.07	1.01	1.72			3.06	-2.67	-0.77	1.16		
	Sim	32.2	0.21	0.81	1.61	0.28	0.11	3.47	-1.57	-0.71	0.79	0.64	0.63
Mooi2, sub.5	Obs	18.1	0.03	1.92	3.31			2.90	-3.41	-0.27	1.31		
	Sim	53.3	0.06	2.71	4.92	0.40	-0.39	3.98	-2.73	0.14	1.26	0.68	0.56
Mooi2, sub.6	Obs	74.9	0.24	3.65	5.97			4.32	-1.44	-0.60	1.10		
	Sim	85.5	0.24	3.44	5.82	0.60	0.55	4.45	-1.43	-0.61	1.03	0.80	0.80
Mooi2, sub.9	Obs	307	0.29	9.46	18.7			5.73	-1.24	1.44	1.19		
	Sim	184	0.88	10.1	14.5	0.68	0.67	5.21	-0.13	1.72	1.04	0.85	0.79
Mooi4	Obs	243	0.01	11.2	21.2			5.49	-4.27	1.53	1.32		
	Sim	197	0.89	13.4	19.3	0.80	0.79	5.28	-0.11	1.91	1.17	0.82	0.73

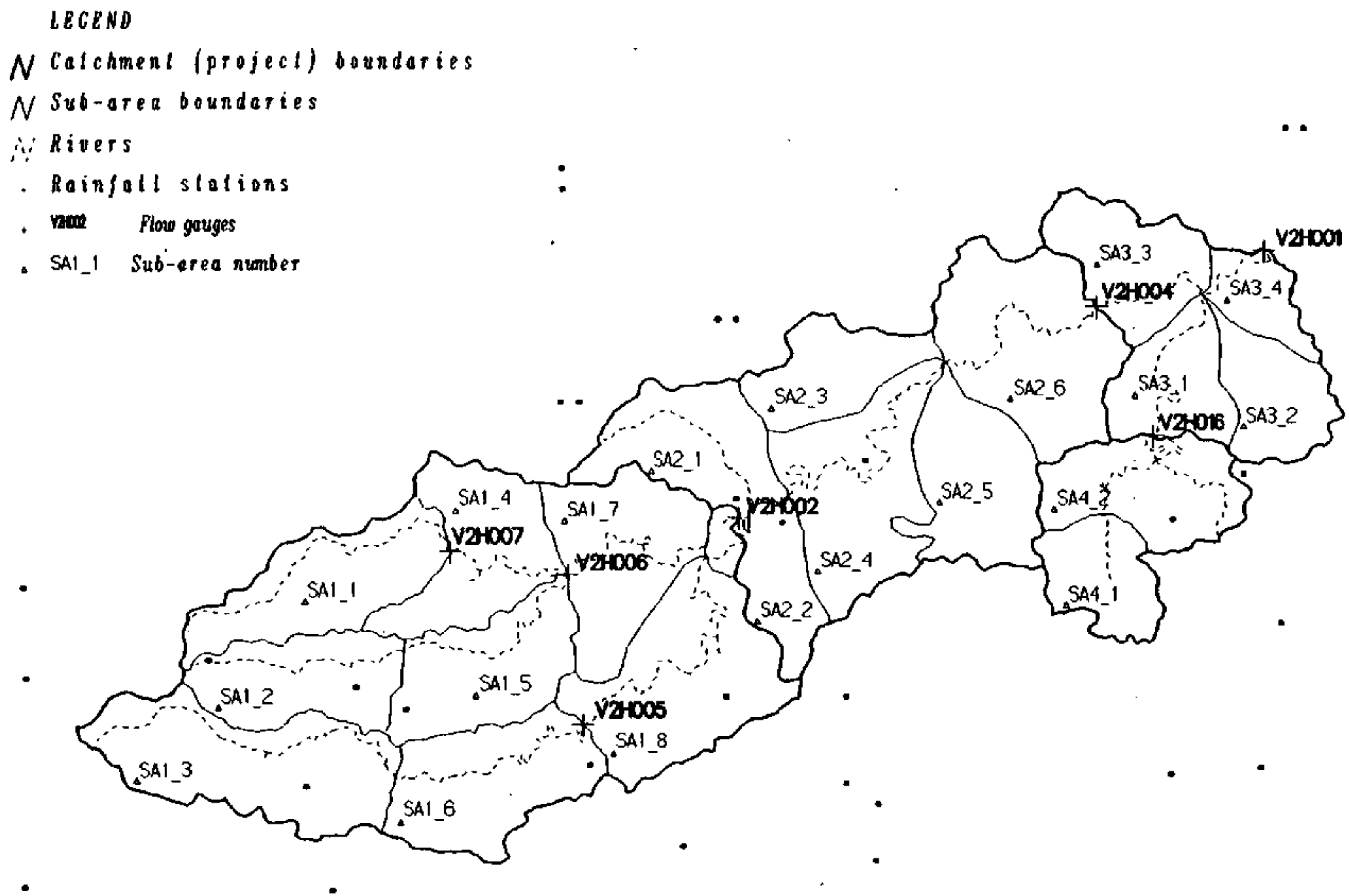


Figure D1.9 Discretisation of the Mooi river catchment showing subarea boundaries and gauge locations.

(Fig. D1.9) and may have a different rainfall pattern. The fit statistics for log-transformed flows in sub-area 1 suggest a much better simulation, which places more confidence in simulated low-flows. However, visual inspection of observed and simulated hydrographs indicates that simulated low flows are too sustained.

The calibration for sub-area 5 (little Mooi catchment, gauge V2H006) in terms of fit statistics ended with approximately the same results as for sub-area 1 (Table D1.2). In this case the gauging weir is unable to record flows exceeding 18.1 m^3/s (nearly 1 % of the time series) and therefore many events have been oversimulated. Consequently, the log-transformed discharges exhibit a significantly better fit than untransformed flows. However, overall the simulated hydrograph appeared to be more "peaky" than simulated, and low flows have been slightly oversimulated.

Satisfactory calibration was achieved for sub-area 6 (gauge V2H005; Table D1.2). Log-transformed flows exhibit a better fit than untransformed discharges. The visual inspection of simulated and observed hydrographs indicated that the model simulated a slightly faster recession immediately after the peaks, which results in the occasional underestimation of medium flows.

The fit statistic for both untransformed and log-transformed flow suggest that a successful calibration has been achieved for sub-area 9 (gauge V2H002) - the outlet of the whole project (Table D1.2). This is supported by a good visual fit between observed and simulated hydrographs (Fig. D1.10). Comparison of observed and simulated 1-day annual flow duration curves (Fig. D1.11) also suggests a good fit, although low flows have been slightly oversimulated which may partly be attributed to oversimulation of low flows in the headwater sub-areas 1, 2 and 5 referred to above.

Project 2 (Mooi4) - gauge V2H004.

The project includes the incremental catchment area between gauges V2H002 and V2H004 and collects runoff from the upstream project Mooi2. The whole area represents one quaternary subcatchment - V20E (WR90, 1994) and is broken down into 6 sub-areas (Fig. D1.9). Baseflow is simulated as the groundwater intersection with the surface as well as the outflow from localised aquifers in valley bottoms where saturated conditions exist. Water is predominantly used for irrigation and most of the demand is satisfied from farm dams. The parameters which determine the irrigation development in the area have been estimated using the information from VAPS (1994) in the same way as for project 1 (Mooi2).

Calibration of the VTI model was attempted over the period 1972-1982. Calibration was only possible at the outlet of the whole project (gauge V2H004). Low flows in some years have been oversimulated which is reflected by the comparison of simulated and observed flow duration curves (Fig. D1.13). However, favourable fit statistics for both untransformed and log-transformed flows (Table D1.2) coupled with a good visual fit between observed and simulated hydrographs (Fig. D1.12) suggest that overall, a successful calibration was achieved.

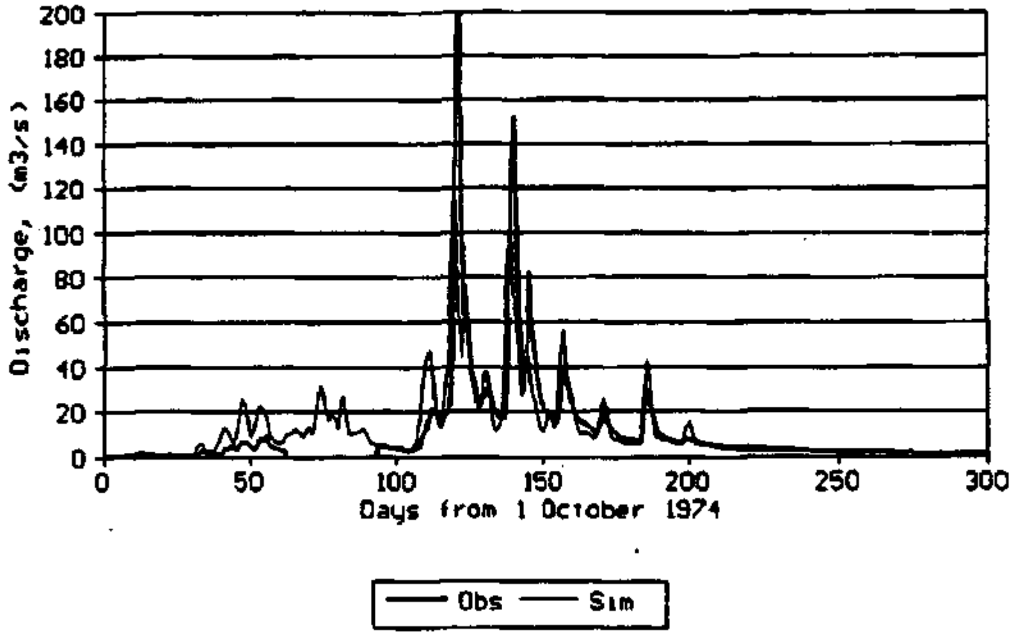


Figure D1.10 Observed and simulated daily hydrographs for Mooi2 (V2H002).

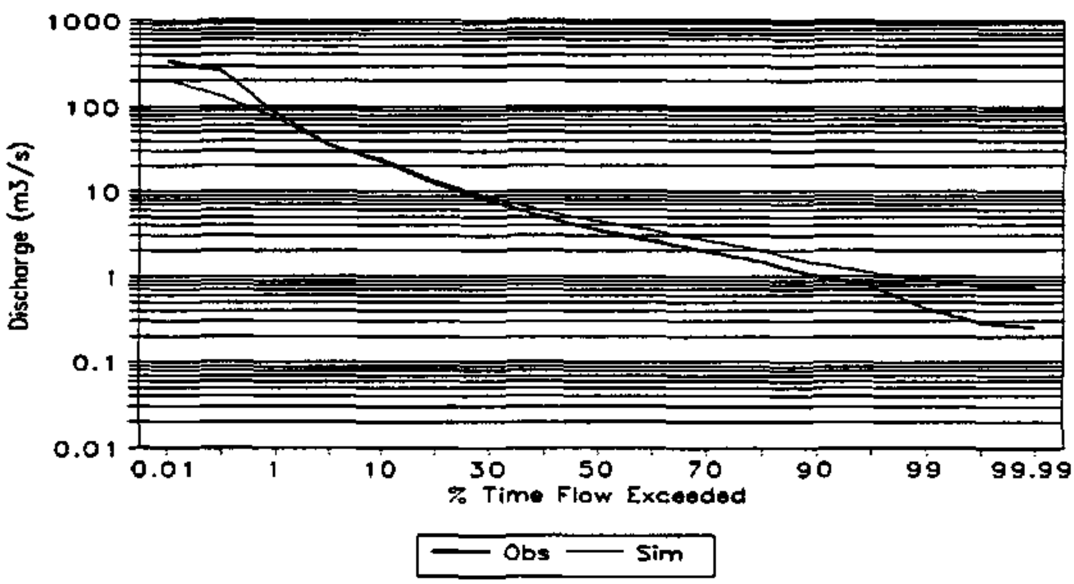


Figure D1.11 Observed and simulated 1-day annual flow duration curves for Mooi2 for a period of 1972 - 1982.

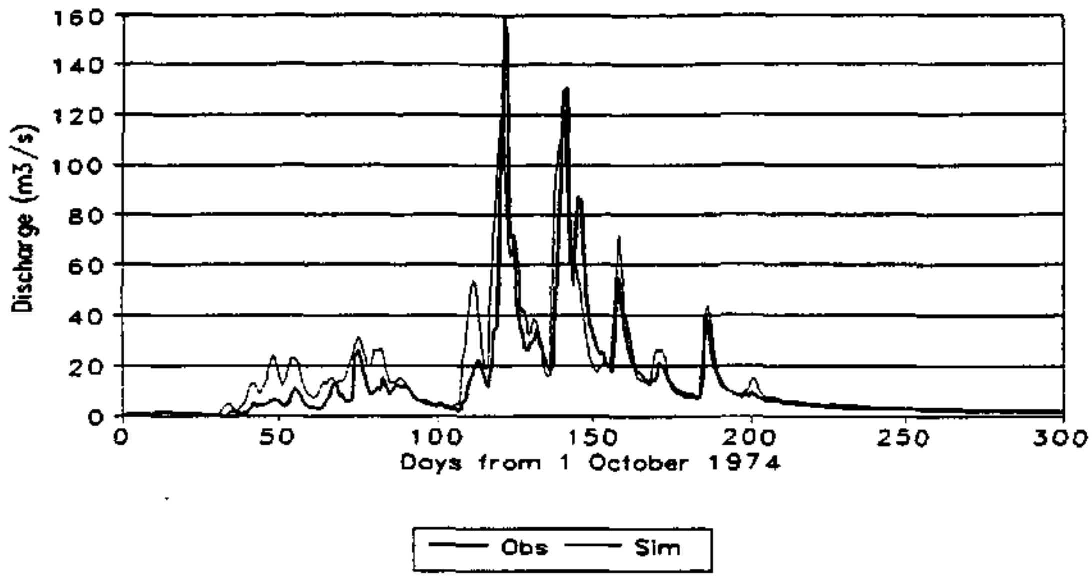


Figure D1.12 Observed and simulated hydrographs for Mooi4 (V2H004).

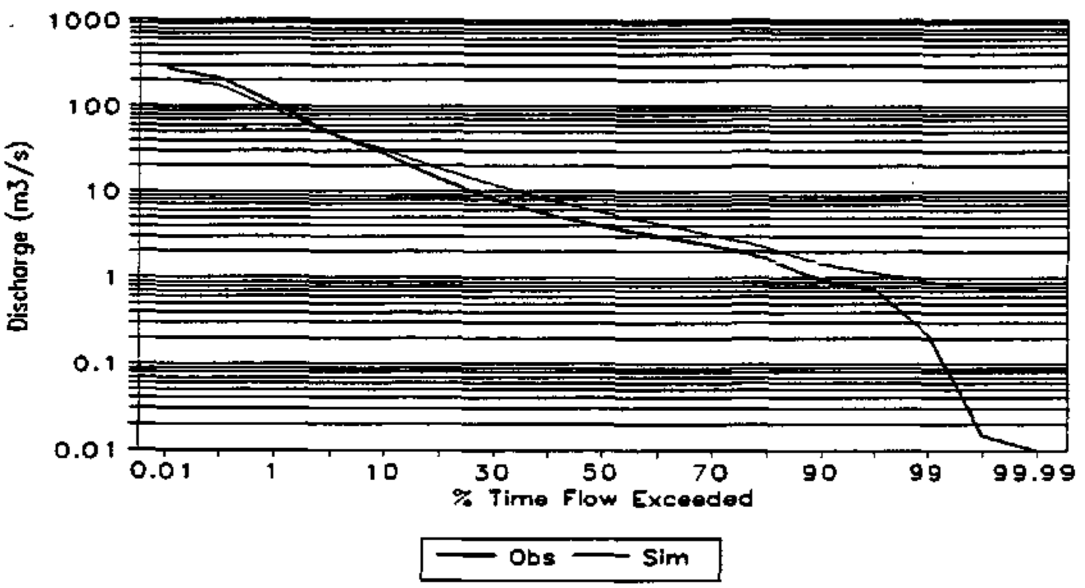


Figure D1.13 Observed and simulated 1-day annual flow duration curves for Mooi4 (V2H004) for a period for 1972 - 1982.

Project 4 (Mooi16) - gauge V2H016.

This is a small catchment (144 km^2) above the Craigie Burn Dam on the Mnyamvubu river. It represents one quaternary subcatchment - V20F (WR90, 1994) and is split into 2 subareas. Approximately one third of sub-area 1 (26 km^2 out of 70 km^2) is afforested (WR90, 1994) while irrigation concentrates mostly in sub-area 2. About 20 % of irrigation demand is satisfied from farm dams while the rest is supplied by run-of-river schemes.

The flow from this catchment is not properly measured. Craige Burn Dam, constructed in 1963 with a capacity of 23 MCM collects runoff from the whole of the catchment and supplies irrigation schemes downstream. The attempt was made to calibrate the VTI model over the period 1982 - 1992, for which data was available at gauge V2H016, downstream of the dam. The sequence of steps followed initially was: simulation of daily inflows to the dam from the catchment upstream using the VTI model; use of daily reservoir simulation model (RESSIMD) to simulate outflows from the dam and, therefore, calibrate both models against the observed data at V2H016.

This exercise resulted in limited success because of inaccurate rainfall input and difficulties in the quantification of the RESSIMD model parameter values. In addition the quality of streamflow records at gauge V2H016 is rather poor since it severely overestimates flows (VAPS, 1994) and for that reason even "good" calibrations would be of questionable use. Therefore, the VTI model for the catchment was not calibrated. Pine plantations in sub-area 1 have been accounted for by changing relevant vegetation parameters in this sub-area and increasing winter and summer crop factors.

The outflow from the dam and hence the inflow to the downstream project Mooi1 was assumed to be zero. This pragmatic assumption was based largely on the fact that according to VAPS (1994), the mean annual release volume from Craigie Burn Dam is about 24.5 MCM, which constitutes less than 10 % of observed MAR at gauge V2H004 (270 MCM).

Project 3 (Mooi1) - gauge V2H001.

This is the most downstream part of the simulated Mooi river catchment. It includes an incremental subcatchment between gauges V2H004, V2H016 and V2H001 (Fig. D1.9). The project corresponds to one quaternary subcatchment V20G and is broken down into 4 sub-areas. The primary water use is for irrigation and according to VAPS(1994), more than 90% of it is abstracted directly from the river.

No calibration of the VTI model was possible during the concurrent calibration period at two upper projects (Mooi2 and Mooi4) since the gauge V2H001 stopped recording flow in 1973. The earlier part of the record is also of questionable quality.

D1.5 MOOI CATCHMENT: TIME SERIES GENERATION AND LOW-FLOW ESTIMATION

A representative 32-year long daily streamflow time-series at present day conditions has been simulated using the calibrated model for a period from 1960 to 1992. Longer time series are impossible to simulated due to the lack of suitable rainfall records prior to the 1960s. The daily flow time-series in natural conditions was simulated from this period by removing all abstractions and dam volumes from the parameter set. Since these constitute the only major influence in the simulated catchment, no other changes to the model parameters have been made. In the project Mooi16 the Craigie Burn Dam was "removed" and the outflow from this project constituted the inflow to sub-area 1 of project Mooi1. In addition, in sub-area 1 of Mooi16, the afforestation area was removed from the parameter set and crop factors were reduced.

Two low-flow indices have been estimated for each subarea from simulated 32-year daily flow time series: 7-day average flows exceeded 75 and 95 % of the time (Q75(7) and Q95(7)). Two different types of flow for each exceedence level have been estimated. The first is the flow generated within each sub-area (total sub-area flow). It demonstrates how much flow is actually flowing into a stream channel from an incremental sub-area (at the selected level of exceedence), regardless of the upstream inflow to a sub-area. This flow has (at present day conditions) already been influenced by farm dams, but has not yet been subjected to direct abstractions from a stream in this sub-area.

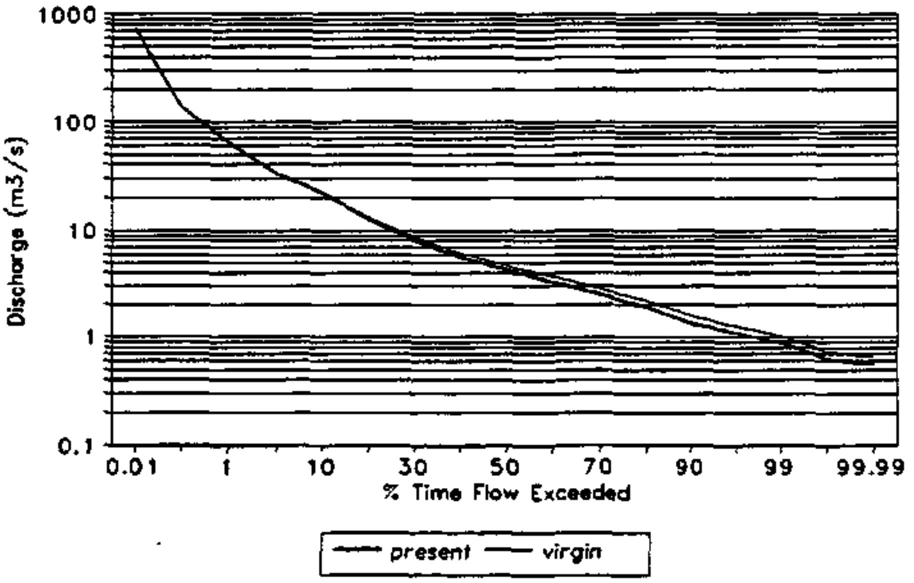


Figure D1.14 Simulated 1-day annual flow duration curves for Mooi2 (V2H002) in present and natural conditions.

The second 'flow type' is the final routed runoff - the actual discharge at the outlet of each sub-area. This flow takes into account all upstream inflows into a sub-area (if those exist) and has already been subjected to direct abstractions from a stream (at present day conditions). It therefore demonstrates how much water at a particular location is actually available in a stream channel.

Table D1.3 summarises this information for all sub-areas in the Mooi catchment at present day conditions, while Table D1.4 contains similar information for virgin conditions. Total sub-area flow is expressed in m^3/s and mm per annum (mm/a) from a unit area.

Final runoff (actual water in a channel) is expressed as m^3/s and MCM. The codes of subareas in Tables D1.3 and D1.4 correspond to those on Figure D1.9. Figures D1.15 and D1.16 illustrate the distribution of Q75(7) and Q95(7) values (total sub-area runoff in mm/a, natural conditions) in the catchment. The degree of changes in flow regime is illustrated by Figure D1.14 which presents 1-day annual flow duration curves constructed on the basis of 32 years of simulated daily streamflow data in present and natural conditions for one of the projects (Mooi2 - gauge V2H002). According to the model results, these changes are relatively low. The results for other projects in the Mooi catchment are broadly similar.

It should be noted that low flows appeared to be oversimulated in some headwater subareas and that despite the good fit statistics, affected the estimates of final routed runoff. On the other hand, reliable observed flow records exist in the headwater areas of the catchment and use should be made of the patching model to extend these records and to make them coincident in time for subsequent low-flow estimation.

D1.6 MOOI CATCHMENT: APPLICATION OF THE 'PATCHING MODEL' FOR LOW-FLOW ESTIMATION.

As an alternative to the VTI model, the patching model (spatial interpolation algorithm described in Chapter 6, Vol 1) has also been applied in the Mooi river basin for the purpose of generating a continuous long daily streamflow time series at the available streamflow gauges. The gauge with the longest and the most reliable record (V2H002) has been used as the 'base' source gauge and its record length (1950 - 1992) determined the length of the output time series for all other gauges. Consequently, the records at gauges V2H007, V2H006, V2H005 have been extended backwards from 1972 (the start year of observations at all three gauges, Table D1.1) to 1950. The record at gauge V2H004 has been extended backwards from 1960 to 1950 and patched in the latter period (Fig. D2.15, APPENDIX D2). The record at gauge V2H001 has been extended onwards from 1974 (the end year of observations at this gauge) to 1992. The records at three upstream gauges have been extended using solely the record at V2H002, the record at gauge V2H004 has been extended and patched using gauges V2H002 and V2H001 with weights 0.8 and 0.2 correspondingly. The records from gauges V2H002 and V2H004 have been used to extend the record at V2H001 (weights 0.8 and 0.2). The record at the 'base' gauge V2H002 itself has been patched using the combination of gauges V2H005 and V2H006 with equal weights.

Table D1.3 Estimated Q75(7) and Q95 (7) flow values in the Mooi river basin (present day conditions).

Sub. No.	Subarea km²	Q75(7), from subarea		Q75(7), routed runoff		Q95(7), from subarea		Q95(7), routed runoff	
		m^3/s	mm/a	m^3/s	MCM	m^3/s	mm/a	m^3/s	MCM
1	2	3	4	5	6	7	8	9	10
1.1	109	0.296	85.70	0.280	8.83	0.168	48.60	0.155	4.89
1.2	90	0.302	106.00	0.303	9.55	0.105	36.80	0.105	3.31
1.3	155	0.521	106.00	0.521	16.40	0.216	43.90	0.216	6.81
1.4	105	0.344	103.00	0.629	19.80	0.189	56.80	0.406	12.80
1.5	98	0.184	59.30	0.504	15.90	0.035	11.20	0.147	4.63
1.6	105	0.279	83.90	0.812	25.60	0.115	34.50	0.344	10.80
1.7	110	0.045	12.90	1.228	38.70	0.007	2.00	0.623	19.60
1.8	150	0.199	41.90	1.402	44.20	0.118	24.80	0.496	15.60
1.9 (V2H002)	15	0.010	21.00	2.321	73.20	0.002	4.20	1.121	35.30
2.1	90	0.011	3.85	0.011	0.35	0.000	0.00	0.000	0.00
2.2	70	0.014	6.31	0.014	0.44	0.000	0.00	0.000	0.00
2.3	85	0.000	0.00	0.000	0.00	0.000	0.00	0.000	0.00
2.4	130	0.023	5.58	2.402	75.70	0.000	0.00	1.126	35.50
2.5	90	0.035	12.30	0.035	1.10	0.000	0.00	0.000	0.00
2.6 (V2H004)	144	0.031	6.79	2.562	80.70	0.000	0.00	1.135	35.80

Table D1.3 (cont.) Estimated Q75(7) and Q95(7) flow values for in the Mooi river basin (present day conditions)

Sub. No.	Subarea km^2	Q75(7), from subarea		Q75(7), routed runoff		Q95(7), from subarea		Q95(7), routed runoff	
		m^3/s	mm/a	m^3/s	MCM	m^3/s	mm/a	m^3/s	MCM
1	2	3	4	5	6	7	8	9	10
4.1	70	0.019	8.75	0.019	0.60	0.000	0.00	0.000	0.00
4.2 (V2H016)	72	0.017	7.45	0.040	1.26	0.000	0.00	0.000	0.00
3.1	71	0.000	0.00	0.000	0.00	0.000	0.00	0.000	0.00
3.2	77	0.000	0.00	0.000	0.00	0.000	0.00	0.000	0.00
3.3	80	0.000	0.00	2.596	81.90	0.000	0.00	1.139	35.90
3.4	50	0.000	0.00	2.597	81.90	0.000	0.00	1.086	34.20

Table D1.4 Estimated Q75(7) and Q95(7) flow values in the Mooi River basin (virgin conditions).

Sub. No.	Subarea km^2	Q75(7), from subarea		Q75(7), routed runoff		Q95(7), from subarea		Q95(7), routed runoff	
		m^3/s	mm/a	m^3/s	MCM	m^3/s	mm/a	m^3/s	MCM
1	2	3	4	5	6	7	8	9	10
1.1	109	0.318	92.00	0.318	10.00	0.193	55.80	0.193	6.09
1.2	90	0.314	110.00	0.314	9.90	0.114	39.90	0.114	3.60
1.3	155	0.523	106.00	0.523	16.50	0.220	44.80	0.220	6.94
1.4	105	0.367	110.00	0.685	21.60	0.211	63.40	0.404	12.70
1.5	98	0.276	88.80	0.605	19.10	0.113	36.40	0.153	4.82
1.6	105	0.331	99.40	0.865	27.30	0.139	41.70	0.372	11.73
1.7	110	0.081	23.20	1.426	45.00	0.012	3.44	0.782	24.70
1.8	150	0.253	53.20	1.147	36.20	0.124	26.10	0.526	16.60
1.9 (V2H002)	15	0.010	21.00	2.641	83.30	0.002	4.20	1.306	41.20
2.1	90	0.012	4.2	0.012	0.38	0.000	0.00	0.000	0.00
2.2	70	0.050	22.5	0.050	1.58	0.000	0.00	0.000	0.00
2.3	85	0.009	3.34	0.009	0.28	0.000	0.00	0.000	0.00
2.4	130	0.033	8.00	2.825	89.10	0.000	0.00	1.327	41.80
2.5	90	0.043	15.1	0.043	1.36	0.000	0.00	0.000	0.00
2.6 (V2H004)	144	0.033	7.23	3.017	95.10	0.000	0.00	1.339	42.20

Table D1.4 (cont.) Estimated Q75 and Q95 flow values in the Mooi river basin (virgin conditions).

Sub. No.	Subarea km²	Q75(7), from subarea		Q75(7), routed runoff		Q95(7), from subarea		Q95(7), routed runoff	
		m^3/s	mm/a	m^3/s	MCM	m^3/s	mm/a	m^3/s	MCM
1	2	3	4	5	6	7	8	9	10
4.1	70	0.059	26.60	0.059	1.86	0.000	0.00	0.000	0.00
4.2 (V2H016)	72	0.028	12.30	0.094	2.96	0.000	0.00	0.007	0.22
3.1	71	0.000	0.00	0.113	3.56	0.000	0.00	0.008	0.25
3.2	77	0.000	0.00	0.000	0.00	0.000	0.00	0.000	0.00
3.3	80	0.000	0.00	3.066	96.70	0.000	0.00	1.343	42.40
3.4	50	0.000	0.00	3.285	104.00	0.000	0.00	1.379	43.50

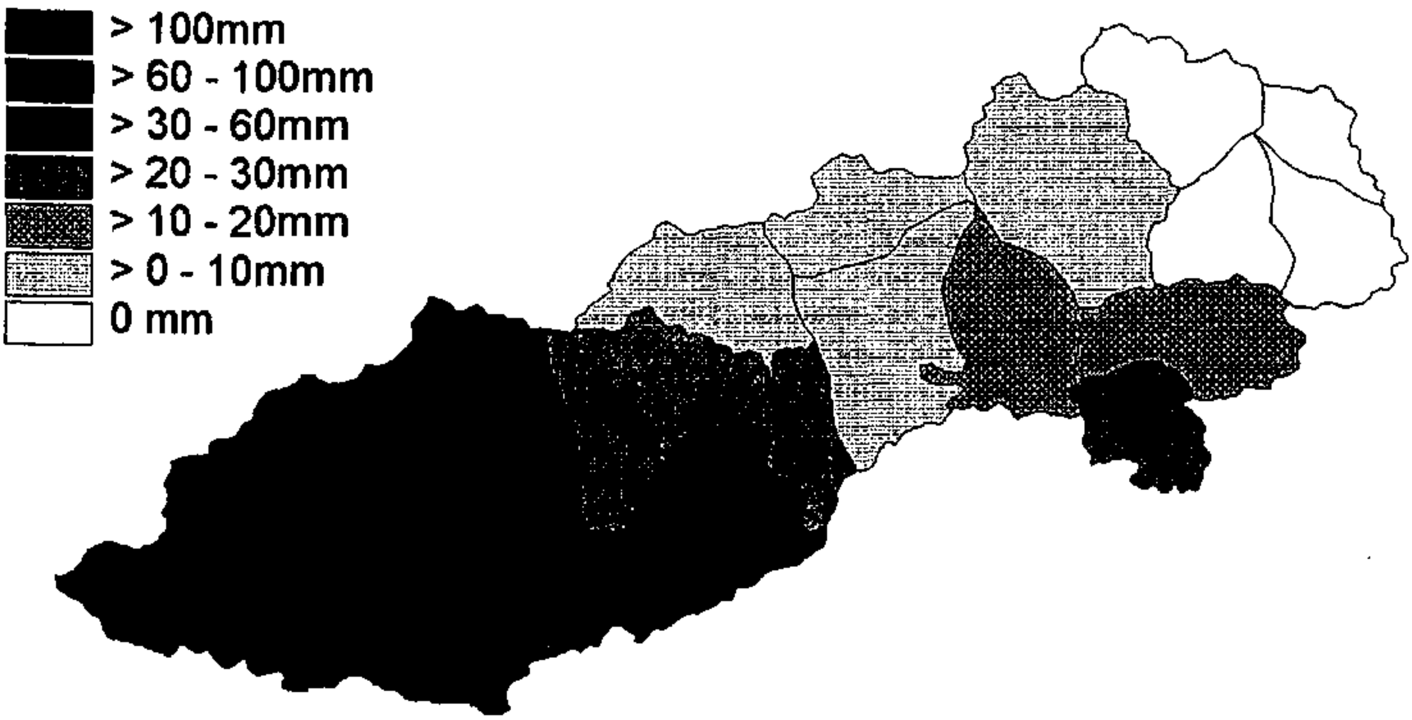


Figure D1.15 Spatial distribution of Q75(7) values in the Mooi catchment (virgin conditions).

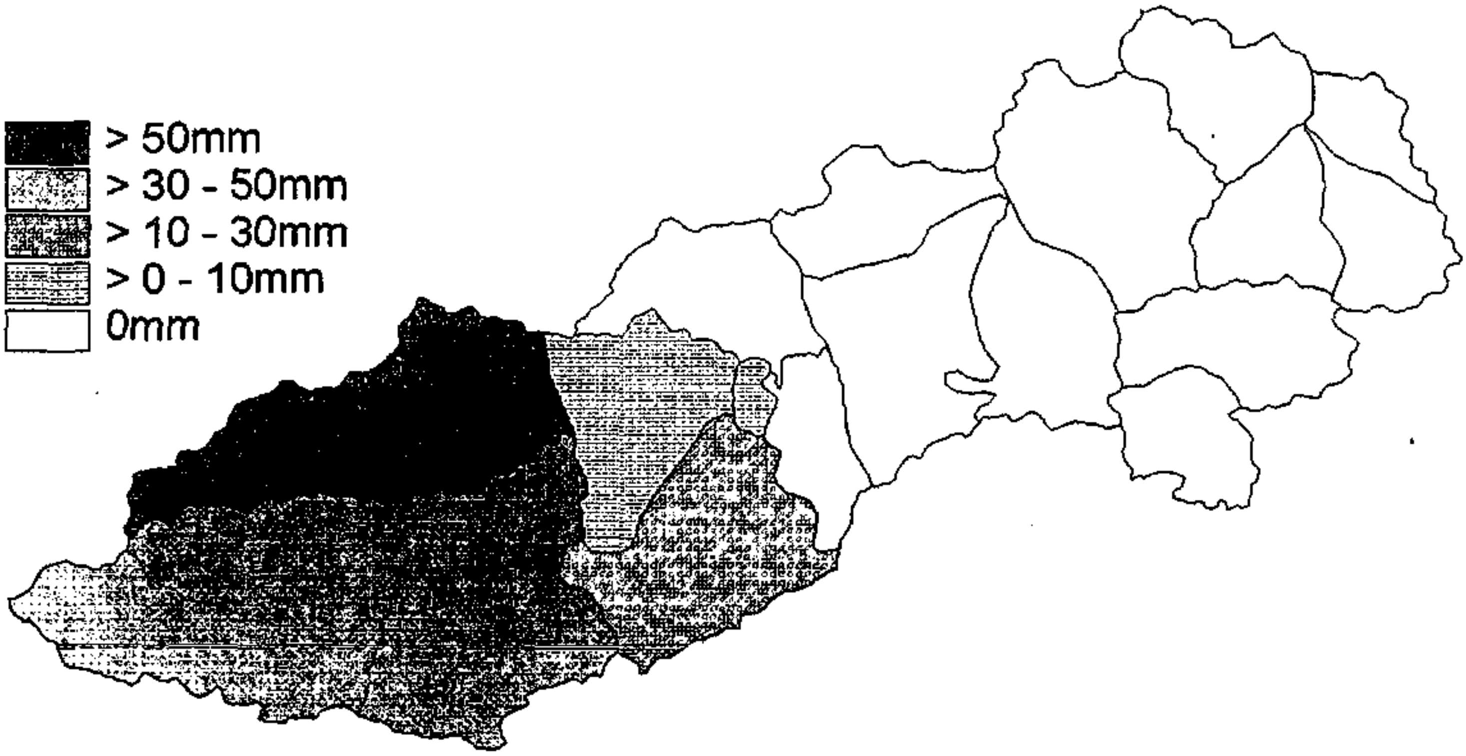


Figure D1.16 Spatial distribution of Q95(7) values in the Mooi catchment (virgin conditions).

The model, in all cases, performed exceptionally well. The differences between observed and simulated hydrographs and flow duration curves appeared to be almost indistinguishable (Figs. D1.17 and D1.18). Table D1.5 summarises the results of the model application in terms of conventional fit statistics. Statistics for log-transformed flow demonstrate that low flows have been especially well predicted. The patching model therefore gave much better results than the VTI model (although the latter also performed satisfactorily).

The same low-flow indices (Q75(7) and Q95(7)) have been extracted from the extended/ patched 42-year long time series generated by the patching algorithm. The patching model at this stage does not give the level of spatial resolution achievable using the VTI model. Therefore, low-flow indices have been estimated at gauged locations and for incremental areas between gauges. Also, it was only possible to assess present day conditions. Low flows for the incremental area (where it is different from the total) were estimated by subtracting flow value(s) at upstream gauge(s) from the flow value at the downstream gauge. These flow values were similar to the runoff from the sub-area and can be compared with the corresponding flow values generated by the VTI model. The results of the calculations are summarized in Table D1.6 and Figure D1.19.

Table D1.5 The results of the patching model application for the Mooi catchments.

Gauge (period)	Data	Untransformed						Ln transformed					
		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
V2H007 (1972-92)	Obs	21.3	0.02	0.97	1.67			3.06	-3.91	-0.87	1.24		
	Sim	24.4	0.02	1.01	1.83	0.80	0.76	3.19	-4.18	-0.94	1.32	0.91	0.89
V2H006 (1972-92)	Obs	18.1	0.01	1.89	3.37			2.90	-4.83	-0.42	1.47		
	Sim	18.1	0.01	1.96	3.54	0.87	0.86	2.90	-4.77	-0.53	1.61	0.94	0.92
V2H005 (1972-92)	Obs	77.4	0.07	3.54	5.82			4.35	-2.70	-0.52	1.18		
	Sim	86.8	0.07	3.72	6.62	0.81	0.76	4.46	-2.73	-0.45	1.27	0.95	0.93
V2H002 (1972-92)	Obs	307	0.01	8.61	17.3			5.73	-4.20	1.24	1.33		
	Sim	300	0.00	9.87	25.6	0.72	0.31	5.70	-7.90	1.36	1.26	0.94	0.93
V2H004 (1960-92)	Obs	243	0.00	7.95	14.5			5.49	-5.81	1.11	1.51		
	Sim	249	0.00	7.49	14.1	0.92	0.91	5.51	-9.21	0.98	1.63	0.90	0.88
V2H001 (1960-74)	Obs	239	0.01	8.18	17.2			5.48	-4.83	1.06	1.45		
	Sim	243	0.03	8.67	16.6	0.72	0.70	5.50	-3.59	1.24	1.35	0.84	0.83

Table D1.6 Low flow indices calculated from patched/extended flow records (1950-1992).

Gauge	VTI sub.no.	Area, km^2 (total/increm.)	Q75(7)		Q95(7)	
			at gauge, m^3/s	incremental, (m^3/s (mm/a))	at gauge, m^3/s	incremental, (m^3/s(mm/a))
V2H007	1.1	109	0.174	0.174 (50.3)	0.098	0.098 (28.3)
V2H006	1.5	188	0.233	0.233 (39.1)	0.098	0.098 (16.4)
V2H005	1.6	260	0.702	0.702 (85.1)	0.379	0.379 (46.0)
V2H002	1.9	937 (380)	1.536	0.437 (35.4)	0.645	0.07 (5.8)
V2H004	2.6	1 548 (611)	1.653	0.117 (6.0)	0.451	0.0 (0.0)
V2H001	3.4	1 976 (428)	1.358	0.0 (0.0)	0.416	0.0 (0.0)

Since the performance of the 'patching model' is better than that of the VTI, more confidence can be placed on the results of the former. Comparison of data presented in Tables D1.3 and D1.6 shows that the VTI model generally overestimates low-flows in present day conditions, especially in some upstream sub-areas. Similarly, low-flows in the main stream appear to be overestimated by the VTI model at the outlet of the whole catchment. This may be partly attributed to the inaccuracies in the water abstraction information used by the VTI model. For example, the model does not take into account the interbasin transfer of water from the Mooi to the Mgeni since no data on that was available. However, the problem most probably relates to the difficulties with the calibration of the VTI model for the headwater sub-areas. This case represents one of the most successful applications of the patching algorithm on a catchment-wide basis.

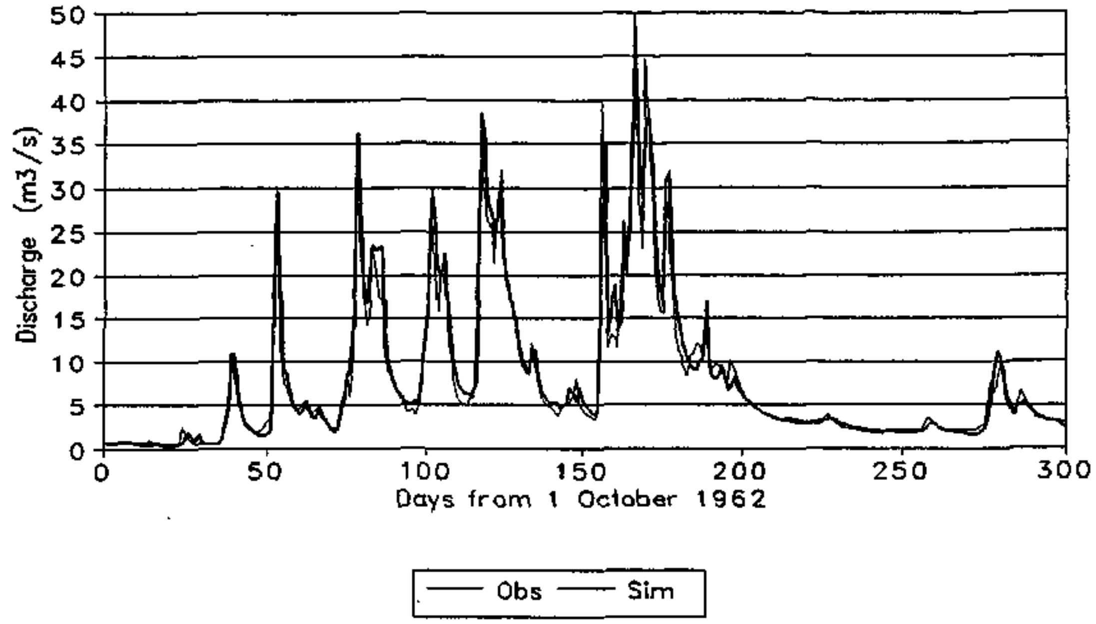


Figure D1.17 Observed and simulated by patching model daily hydrographs at gauge V2H004.

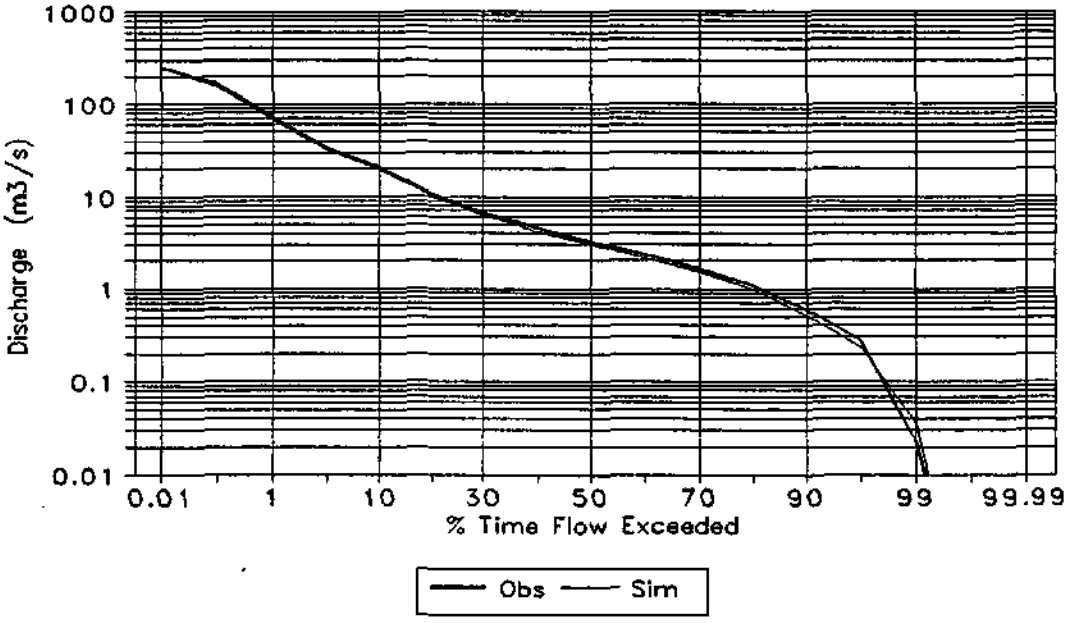


Figure D1.18 1-day annual flow duration curves at gauge V2H004 based on observed and simulated by patching model flow time series for a period 1950-1992.

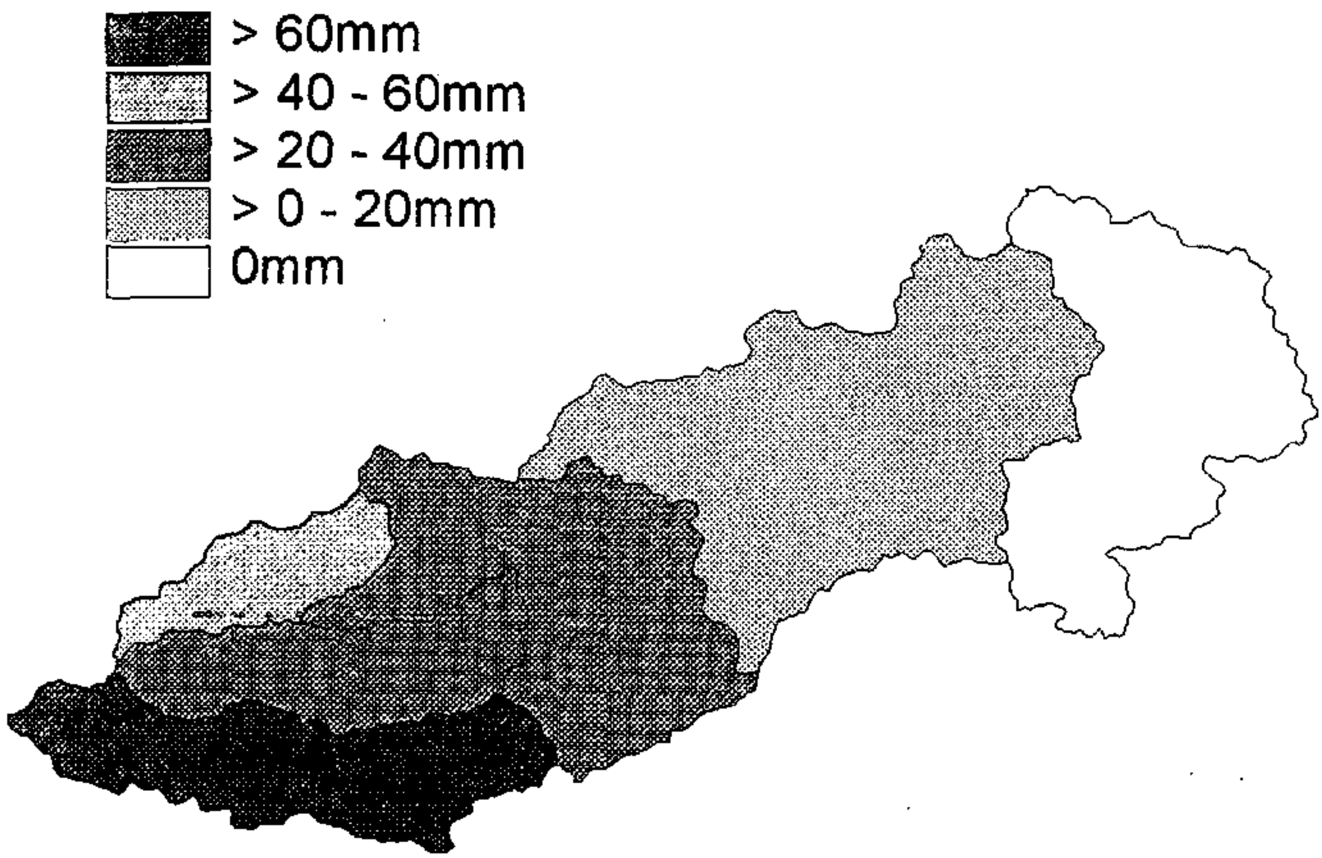


Figure D1.19 Spatial distribution of Q75(7) values in the Mooi catchment from patched/extended observed flow records

D1.7 SUNDAYS CATCHMENT: MODEL CALIBRATION AND LOW-FLOW ESTIMATION.

The Sundays River is the second largest left-hand tributary of the Tugela after the Buffalo. It's total catchment area is about 2425 km² (8.3% of the Tugela catchment). The river originates in the Low Drakensberg Mountains (1600 - 1800 m above sea level) and flows through the undulating country lying, in general, at 1000 - 1200 m above sea level broken in some places by groups and rows of hills. It is underlain predominantly by the Ecca series sandstones and covered by stony shallow soils changing to moderate clayey and loamy soils and gley soils along the major river valleys. The climate becomes gradually drier from upstream of the Sundays and Wasbank rivers (the major left-hand tributary of Sundays) where the MAP exceeds 900 mm to the catchment outlet where the MAP is in the range of 600 - 700 mm. More than 70% of the annual rain falls in the October to March period. Precipitation often occurs in the form of heavy localised thunderstorms.

Flow data are available for 2 gauges (V6H004 and V6H003) which record flow from 38 % of the catchment area. The rest of the catchment is ungauged (the data for gauge V6H006 located upstream of V6H004 was not available during the time of model calibration). The whole catchment has been split up into 3 projects, the first two with outlets at gauges V6H004 and V6H003 correspondingly, the third one- the incremental catchment between two upstream gauges and the confluence with the Tugela (Fig. D1.20). Each project in its turn has been broken down into several subareas. The discretisation was based primarily on the tributary structure and topography of the subcatchment. Since general physiographic conditions in the upper (gauged) and lower (ungauged) parts of the catchment are similar (Soils of the Tugela Basin, 1969; Surface Water Resources of SA, 1981), it was expected that most of the model parameters estimated for the upstream parts of the catchment may be transferred to the downstream parts.

Calibration was attempted during the period of 1954 - 1964. This early period was initially selected in order to ignore water resource development influences. Also many more rainfall gauges were available in the region in the earlier years (before mid 1960s). The model calibration for the most upstream part of the Sundays catchment (project 1, gauge V6H004) appeared to be satisfactory. The general pattern of observed daily hydrograph was satisfactorily reproduced by the model (Fig. D1.22). Fit statistics for untransformed flows (R^2 = 0.57, CE = 0.48) have been affected by the oversimulation of peaks. Log-transformed flows demonstrated a better fit (R^2 = 0.70, CE = 0.65) with slightly oversimulated low flows (Fig. D1.21) mostly in drier years.

The calibration of the model for the Wasbank catchment (project 2, gauges V6H003) resulted in limited success (fit statistics for untransformed flows were: R^2 = 0.22, CE = 0.19; for log-transformed flows: R^2 = 0.34, CE = 0.12). The analysis of observed and simulated hydrographs has demonstrated that this may be explained by the inadequate rainfall input data (a number of observed streamflow peaks have not been supported by corresponding rainfall). Peaks appeared to be undersimulated in the earlier years while low flows - oversimulated in some latter years (Fig. D1.24). The comparison of observed and simulated flow duration curves illustrates that poor calibration resulted mostly from the undersimulation of peak flows while low flows appeared to be adequately simulated (Fig. D1.23). It should however be noted that according to VAPS (1994), low flows are not adequately measured at the gauge V6H003.

The flow from the downstream, ungauged parts of the catchment has been simulated using the observed patched daily records for V6H004 and V6H003 as the upstream inflow. This was done to ensure that the inaccuracies in the simulations of the two upstream projects (and especially project 2 - Wasbank river) would not have any effect further downstream. Since flow downstream of gauges V6H004 and V6H003 is not measured, no calibration was possible. However, the output from the model was converted to monthly flow volumes and compared with the monthly flow volume time series simulated by the Pitman monthly model for tertiary catchment V04 (Surface Water Resources of SA, 1981). The results demonstrated that although flows in some "medium" months were often oversimulated by the VTI model, as compared to the Pitman model, the flows during the dry months simulated by both models match well (Fig. 10.25). Although simulated monthly flows represent the response of the catchment under natural conditions it still seems legitimate to compare these results since the water consumption and other development impacts in the catchment remained relatively small (VAPS, 1994).

A 32-year long daily streamflow time series for the period 1960 - 1992 has been simulated for the whole Sundays catchment, after the completion of the calibration exercise. Although the current water resource effects (farm dams and direct abstractions from the river) have been incorporated into a parameter set, they were considered to be relatively small and therefore no attempt was made to simulate natural flow conditions separately.

Since the calibration in at least one upstream project (project 2 - Wasbank river) was not entirely successful, the 32-year long flow time series in the downstream part of the catchment has been simulated using the observed daily flow records at gauges V6H004 and V6H003, as inflows to project 3. These records required minor patching to ensure that all negative (missing) data were suppressed. This patching was performed using the "patching" model. The records at both gauges were patched from one another. The patching model did not perform much better than the VTI model in this case. However, since the initial records did not contain much missing data, the patched records were accepted as a better alternative for the VTI simulations.

The standard set of low-flow indices has been estimated from a 32-year long simulated streamflow time series. The results of calculations are summarised in Table D1.7. Figures D1.26 and D1.27 illustrate the spatial distribution of Q75(7) and Q95(7) (subarea runoff, mm/a) correspondingly, in the Sundays River catchment at present conditions. No attempt was made to simulate the streamflow time series and estimate the low-flow characteristics in the Sundays catchment under natural conditions.

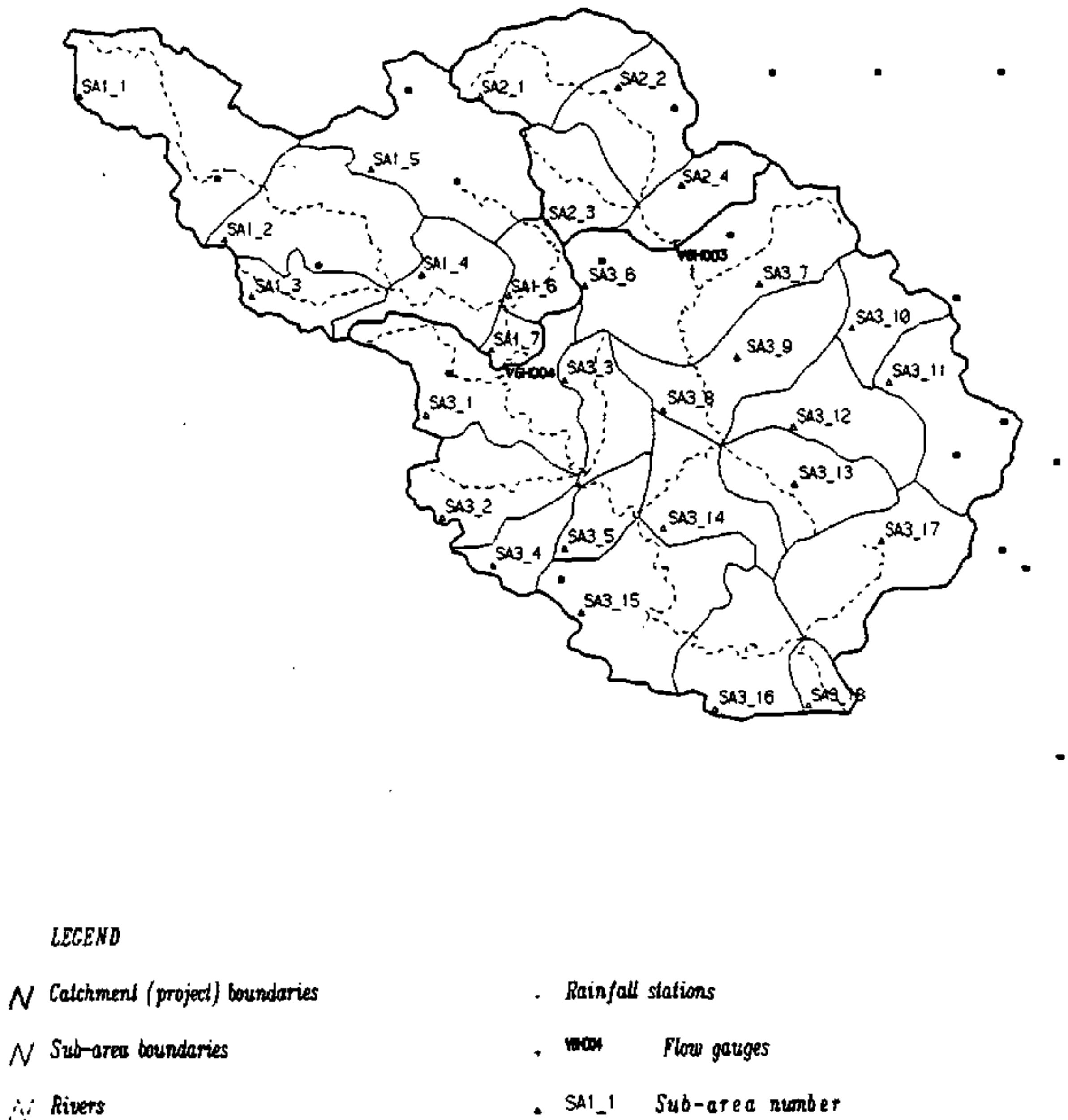


Figure D1.20. *Discretization of the Sundays River catchment showing streamflow and rainfall gauges.*

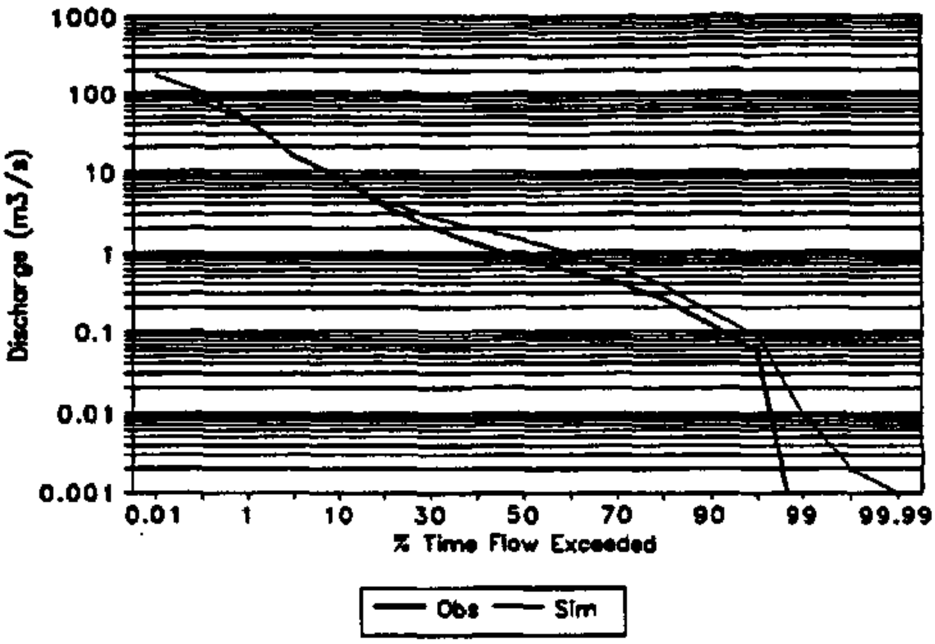


Figure D1.21 Observed and simulated 1-day annual flow duration curves for Sundays1 (V6H004) for a period of 1954 - 1964.

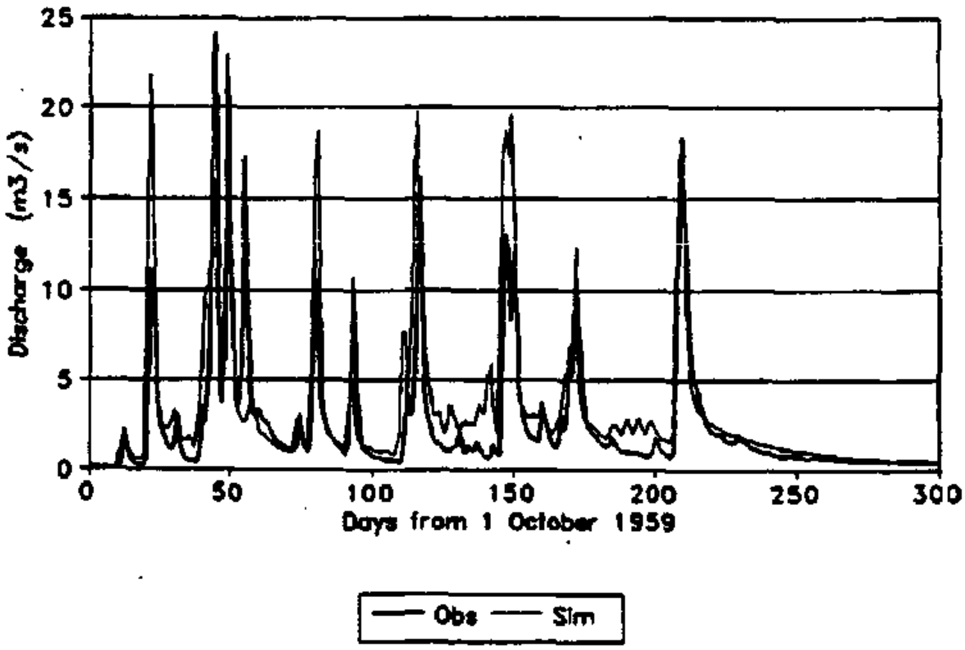


Figure D1.22 Observed and simulated daily hydrographs in Sundays1 (V6H004).

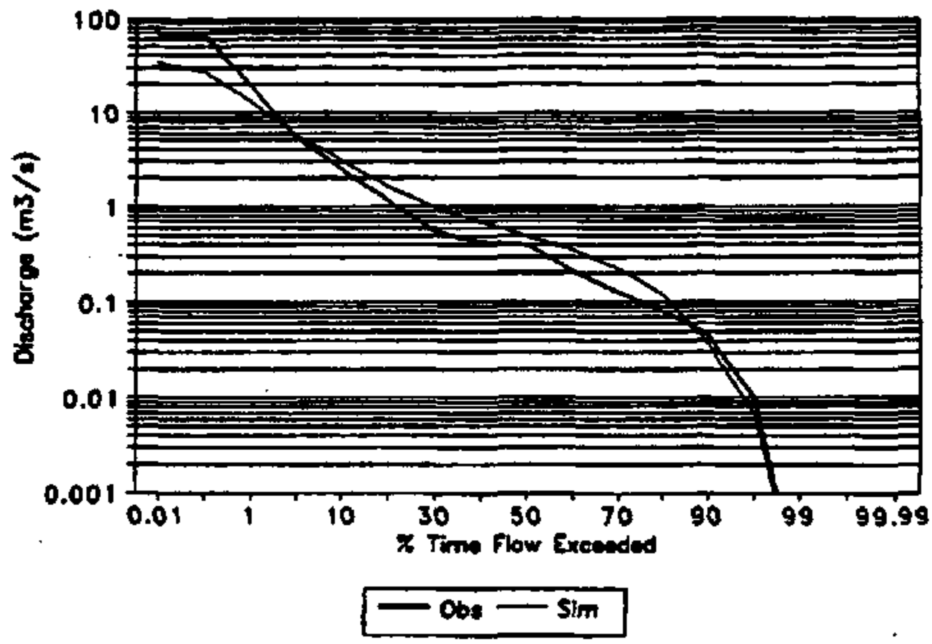


Figure D1.23 Observed and simulated 1-day annual flow duration curves for Wasbank (V6H003) for a period of 1954 - 1964.

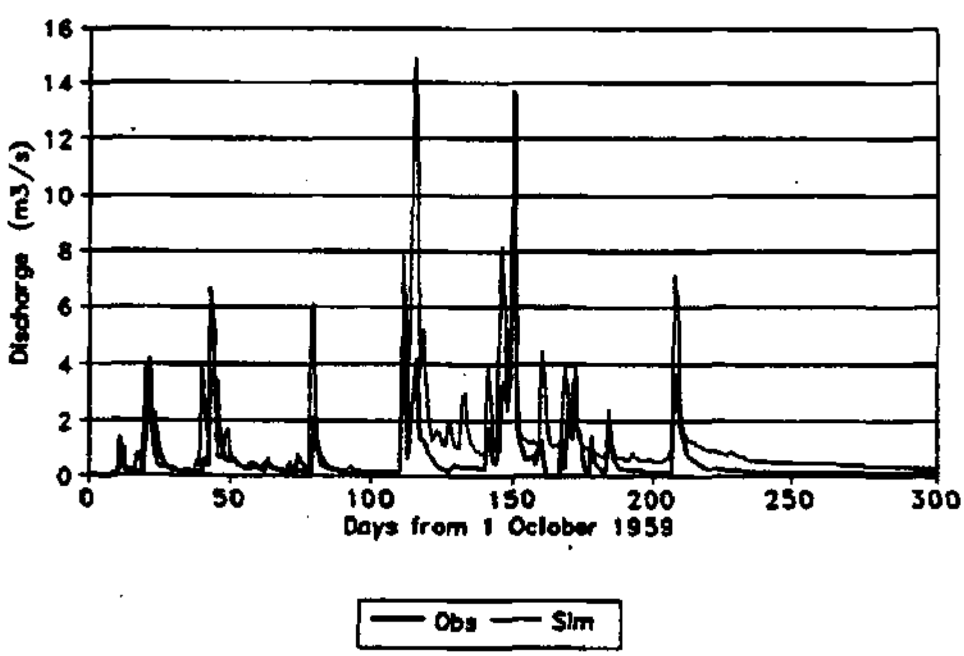


Figure D1.24 Observed and simulated daily hydrographs in Wasbank (V6H003).

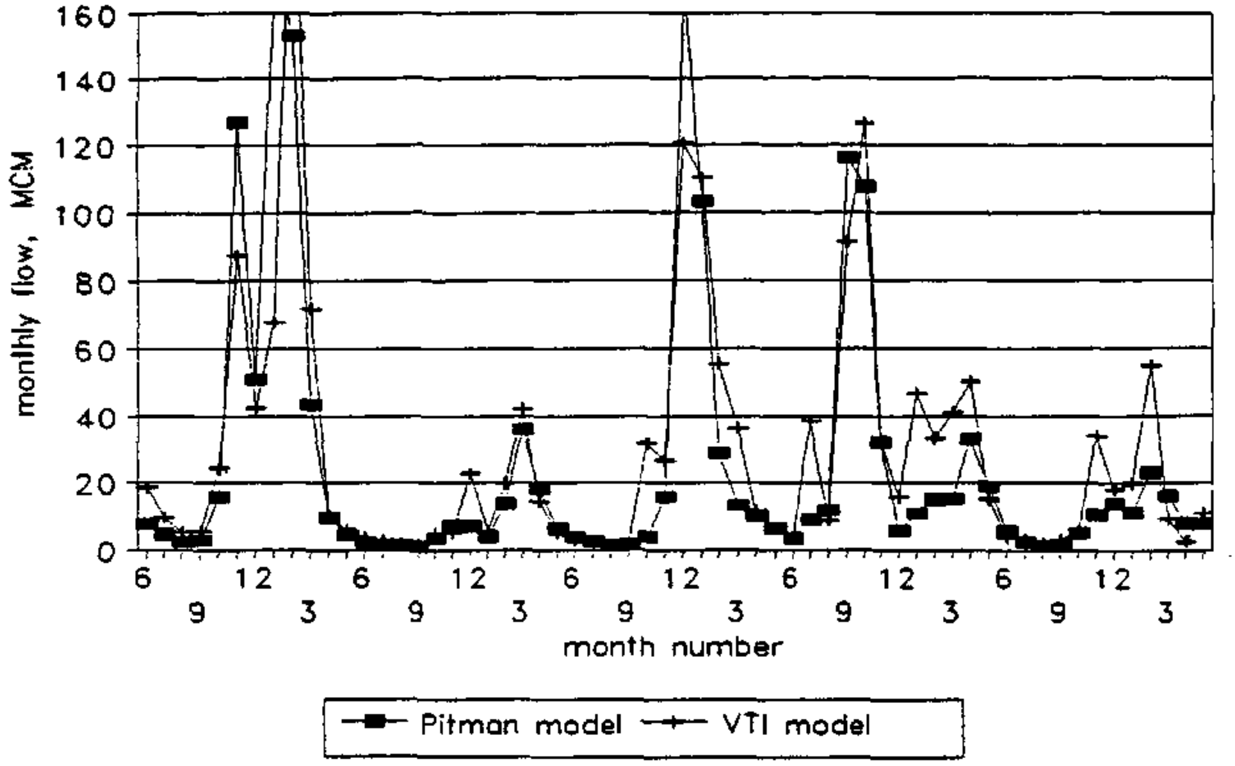


Figure D1.25 Simulated hydrographs at Sundays River outlet for a period 6.1954 - 5.1959.

Table D1.7 Estimated Q75(7) and Q95(7) flow values in the Sundays river basin (present day conditions).

Sub. No.	Area km^2	Q75(7), from subarea		Q75(7), routed runoff		Q95(7), from subarea		Q95(7), routed runoff	
		m^3/s	mm/a	m^3/s	MCM	m^3/s	mm/a	m^3/s	MCM
1	2	3	4	5	6	7	8	9	10
1.1	182	0.115	19.90	0.115	3.63	0.000	0.00	0.000	0.00
1.2	112	0.045	12.70	0.110	3.47	0.008	2.25	0.000	0.00
1.3	60	0.057	29.90	0.057	1.80	0.017	8.94	0.017	0.54
1.4	69	0.026	11.90	0.166	5.23	0.000	0.00	0.000	0.00
1.5	154	0.102	20.90	0.085	2.68	0.008	1.64	0.000	0.00
1.6	54	0.039	22.80	0.131	4.13	0.005	2.92	0.007	0.22
1.7 (V6h004)	27	0.014	16.40	0.332	10.50	0.000	0.00	0.011	0.35
2.1	117	0.061	16.40	0.047	1.48	0.109	5.12	0.002	0.06
2.2	81	0.077	30.00	0.109	3.44	0.007	2.73	0.000	0.00
2.3	57	0.005	2.77	0.005	0.16	0.000	0.00	0.000	0.00
2.4 (V6H003)	57	0.007	3.87	0.192	60.5	0.000	0.00	0.027	0.85
3.1	114	0.025	6.92	0.202	6.37	0.000	0.00	0.000	0.00
3.2	65	0.010	4.85	0.010	0.31	0.000	0.00	0.000	0.00
3.3	56	0.021	11.80	0.010	0.32	0.000	0.00	0.000	0.00
3.4	66	0.000	0.00	0.000	0.00	0.000	0.00	0.000	0.00
3.5	40	0.029	22.90	0.275	8.67	0.020	15.80	0.025	0.79

Table D1.7 (cont.) Estimated Q75 and Q95 flow values for subcatchments in the Sundays river basin (present day conditions).

Sub. No.	Area km^2	Q75(7), from subarea		Q75(7), routed runoff		Q95(7), from subarea		Q95(7), routed runoff	
		m^3/s	mm/a	m^3/s	MCM	m^3/s	mm/a	m^3/s	MCM
1	2	3	4	5	6	7	8	9	10
3.6	75	0.025	10.50	0.025	0.79	0.012	5.04	0.012	0.38
3.7	112	0.082	23.10	0.082	2.59	0.050	14.10	0.050	1.58
3.8	33.6	0.018	16.90	0.006	0.19	0.010	9.38	0.000	0.00
3.9	57	0.024	13.30	0.012	0.38	0.011	6.09	0.000	0.00
3.10	90	0.000	0.00	0.000	0.00	0.000	0.00	0.000	0.00
3.11	117	0.000	0.00	0.000	0.00	0.000	0.00	0.000	0.00
3.12	85.5	0.047	17.30	0.069	2.18	0.028	10.30	0.015	0.47
3.13	74	0.000	0.00	0.000	0.00	0.000	0.00	0.000	0.00
3.14	92	0.050	17.10	0.452	14.30	0.023	7.88	0.202	6.37
3.15	129	0.065	15.90	0.082	27.20	0.030	7.33	0.303	9.56
3.16	84	0.067	25.10	0.949	29.90	0.026	0.76	0.353	11.10
3.17	132	0.031	7.40	0.030	0.95	0.000	0.00	0.000	0.00
3.18	33	0.000	0.00	1.047	33.00	0.000	0.00	0.379	11.90

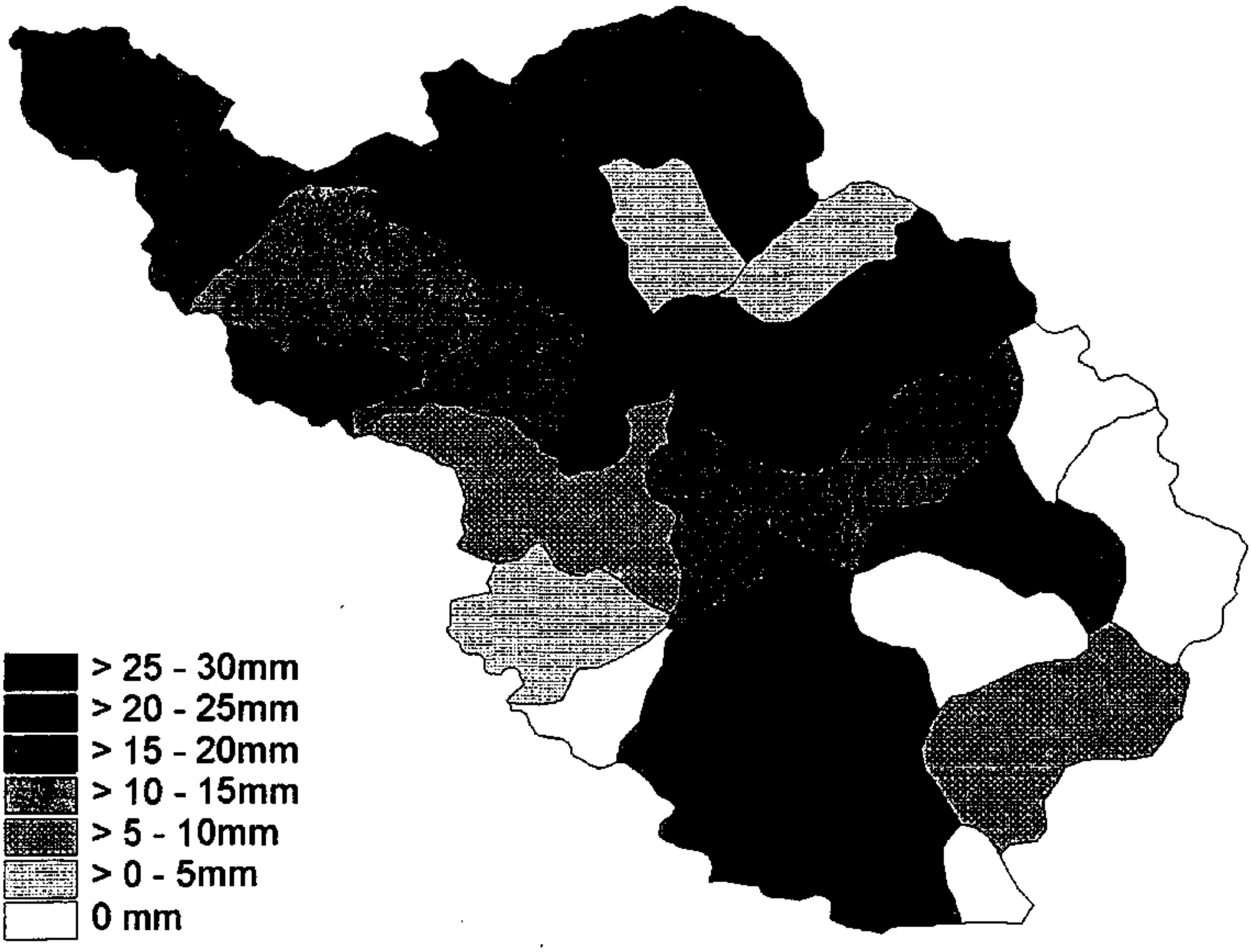


Figure D1.26 Spatial distribution of Q75(7) flow values in the Sundays catchment (present conditions).

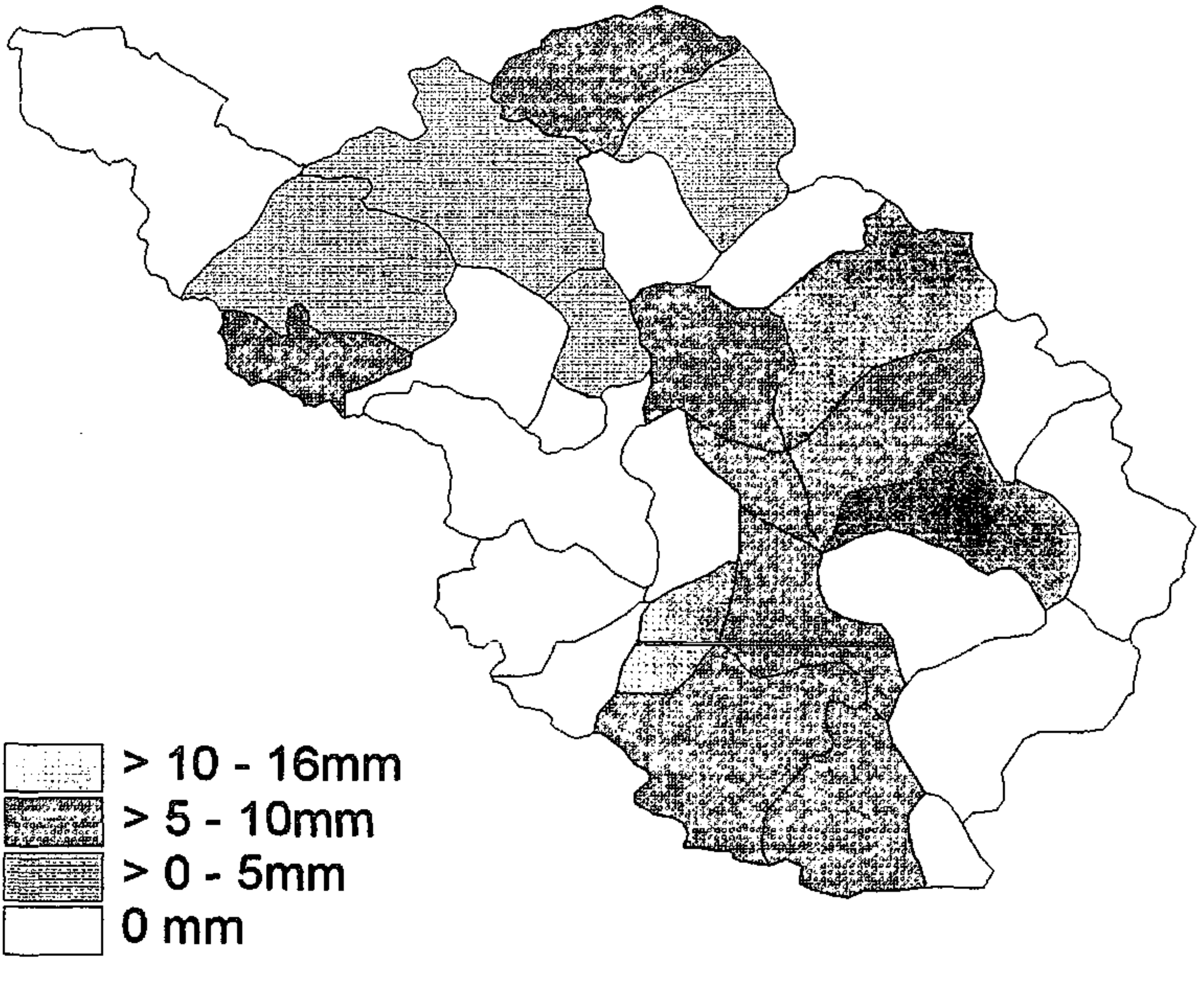


Figure D1.27 Spatial distribution of Q95(7) flow values in the Sundays catchment (present conditions).

D1.8 CENTRAL TUGELA CATCHMENT: MODEL CALIBRATION AND LOW-FLOW ESTIMATION.

The Central Tugela is an arbitrary name used in this Report as a reference to the incremental catchment between gauges V1H038, V1H001, V1H009, V7H012, V7H020, the Sundays river outlet and the downstream gauge V6H002. In this part of the catchment the Tugela accepts all the major tributaries (except Mooi and Buffalo). The physiographic conditions are generally similar to those in the lower Sundays catchment.

The catchment has been considered as one big project and split into 11 relatively large subareas (Fig. D1.28, see also Figure D1.3 and Figure 6.10 in Chapter 6, Vol 1). The calibration is possible at the two downstream gauges - V6H007, and V6H002. The first one has only 5 years of record but more reliable data than the second (although the latter has the longest flow record in the whole Tugela catchment (VAPS, 1994)). The observed flow records at all upstream gauges (V1H038, V1H001, V1H009, V7H012, V7H020) as well as simulated daily flows at the Sundays catchment outlet have been used as upstream inflows to the project.

The calibration was attempted during the period from 1978 to 1988. The model was initially calibrated against the observed record at gauge V6H002 located at the outlet of the whole project. The resultant fit statistics for V6H002 suggested that a good calibration was achieved (for untransformed flows: R^2 = 0.74, CE = 0.74; for log-transformed flows: R^2 = 0.81, CE = 0.81). This can, to a large extent, be attributed to the dominating effect of the upstream inflows (more details about fit statistics may be found in Table 6.4 in Chapter 6, Vol. 1). However, the comparison of observed and simulated flow duration curves at the upstream gauge V6H007 has demonstrated that low flows have been significantly oversimulated (Fig. 6.11, Chapter 6, Vol. 1). This is also reflected in a relatively low CE at this gauge for log-transformed flows (Table 6.4, Chapter 6, Vol. 1). This is a clear consequence of a poor quality of measurements at the gauge V6H002 which overestimates low flow and therefore directly affects the results of the calibration.

The alternative approach is to calibrate the model against the shorter record at gauge V2H007 which records more accurate low flows (VAPS, 1994). The calibration in such a case is only possible for the period from 1982 to 1986 (for which the observed record was available at gauge V6H007). This calibration, as in the previous case, resulted in good fit statistics. The general pattern of daily hydrographs was also well reproduced at both gauges (Fig. D1.29). However, a better fit was obtained for log-transformed flows at V6H007 (R^2 = 0.93, CE = 0.84). Although low-flows at gauge V6H007 remained slightly overestimated, this overestimation was less than in the first calibration exercise. This may be illustrated by comparing Figures D1.30 and 6.11 (Chapter 6, Vol. 1). Since simulated low flows exhibit a better fit with observed at gauge V6H007, it is inevitable and expected that simulated low flows at V6H002 downstream appeared to be underestimated by the model (Fig. D1.30).

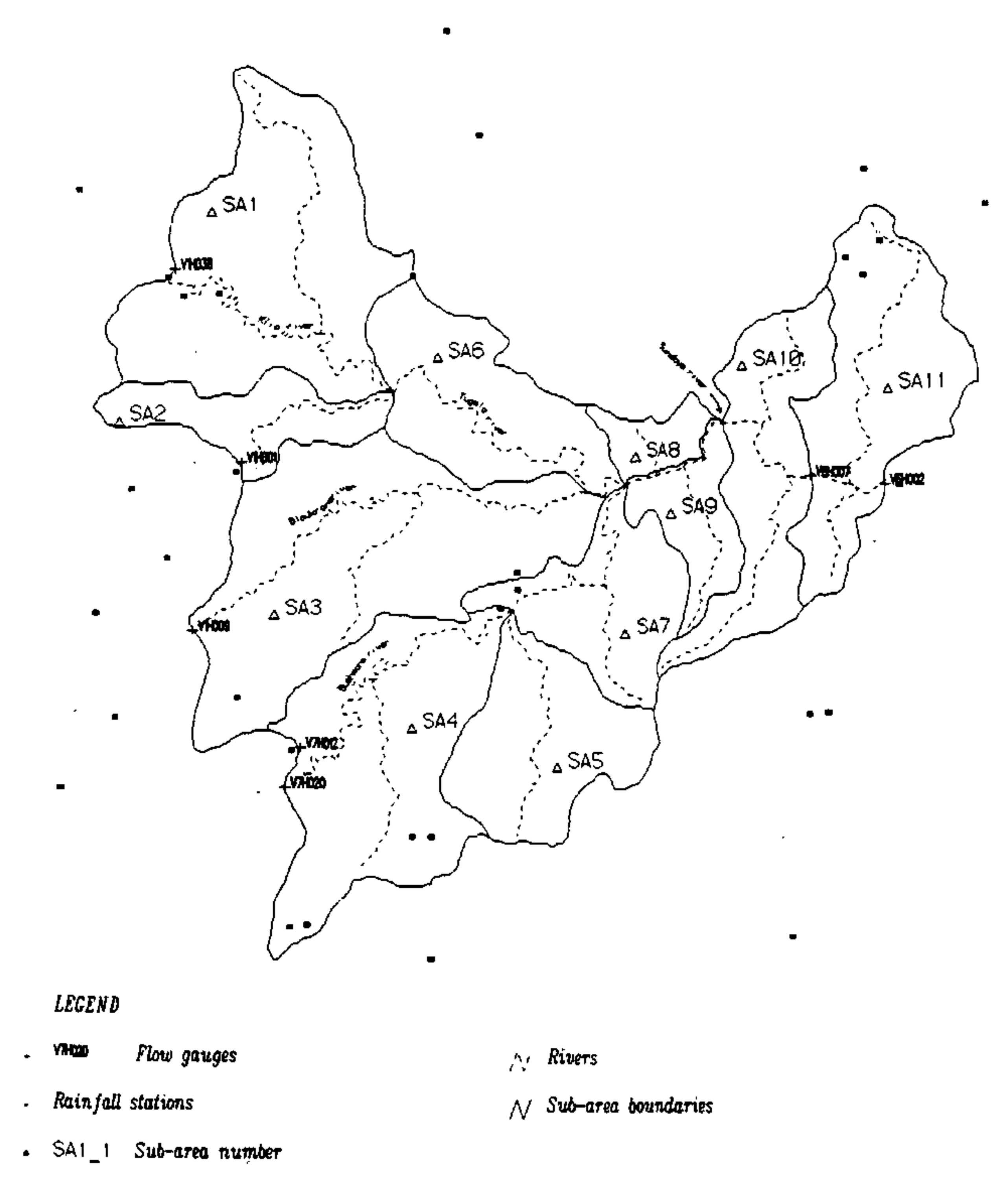


Figure D1.28 Discretization of the Central Tugela catchment showing streamflow and rainfall gauges.

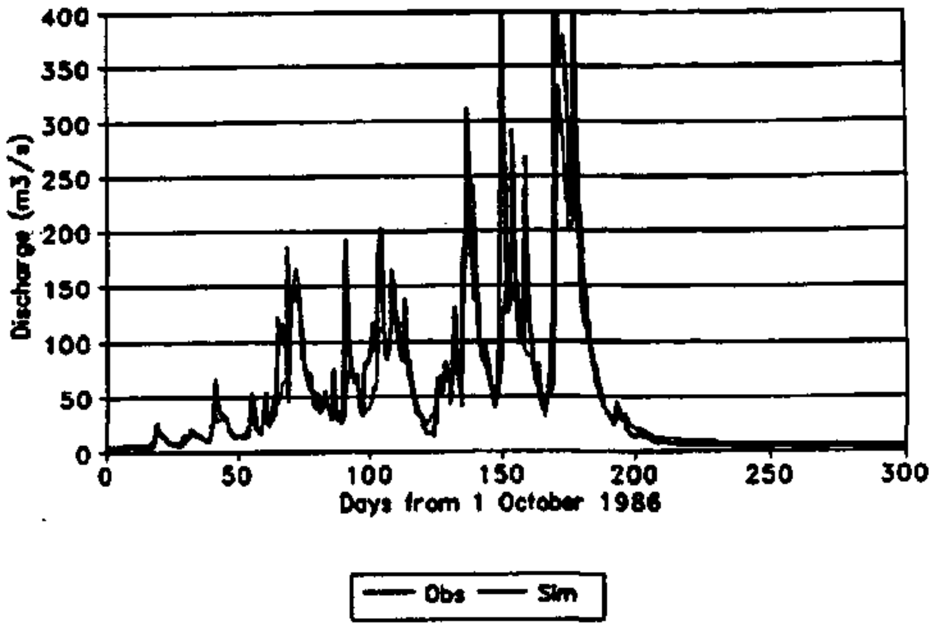
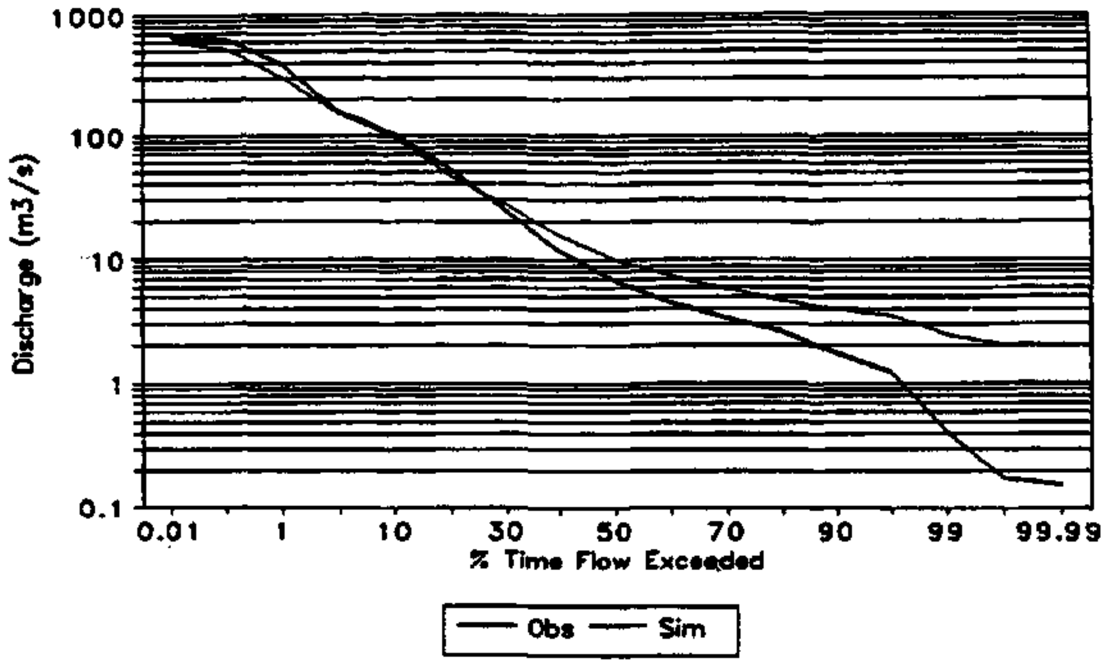


Figure D1.29 Observed and simulated daily hydrographs for gauge V6H007.

The results of calibration and simulation in the central Tugela are obviously significantly affected by the "boundary conditions" - inflows from the upstream gauges. Since these inflows represent the actual historical records, no streamflow simulation in natural conditions was attempted in the central Tugela catchment. The 32-year long simulated time series of daily flows may be assumed to represent present day conditions.

A standard set of low-flow characteristics has been estimated from the simulated time series. The results of the calculations are summarised in Table D1.8 and illustrated by Figures D1.31 and D1.32



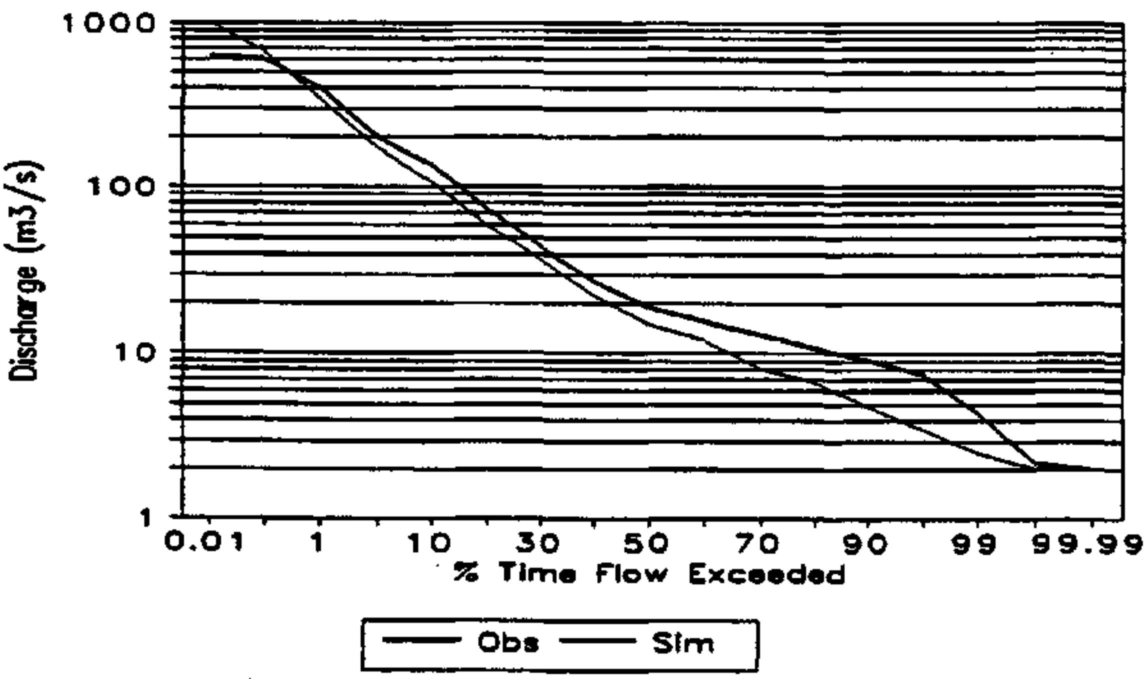


Figure D1.30 Observed and simulated 1-day flow duration curves for gauges V6H007 (top) and V6H002 (bottom) for a period of 1982-1986.

Table D1.8 Estimated Q75(7) and Q95(7) flow values for subcatchments in the central Tugela catchment (present day conditions).

Sub. No.	Area km^2	Q75(7), from subarea		Q75(7), routed runoff		Q95(7), from subarea		Q95(7), routed runoff	
		m^3/s	mm/a	m^3/s	MCM	m^3/s	mm/a	m^3/s	MCM
1	2	3	4	5	6	7	8	9	10
1	530	0.075	4.46	0.512	16.10	0.000	0.00	0.098	3.09
2	170	0.035	6.49	4.373	138.00	0.011	2.04	1.353	42.70
3	650	0.042	2.04	0.032	1.00	0.000	0.00	0.000	0.00
4	400	0.099	7.81	1.869	58.90	0.051	4.02	1.281	40.40
5	310	0.027	2.75	0.000	0.00	0.000	0.00	0.000	0.00
6	293	0.164	17.60	5.159	163.00	0.109	11.70	1.742	54.90
7	300	0.112	11.80	1.981	62.50	0.080	8.41	1.317	41.50
8	70	0.041	18.50	0.041	1.29	0.023	10.40	0.023	0.72
9	104	0.059	17.90	0.059	1.86	0.031	9.40	0.031	0.98
10	283	0.118	13.10	8.833	278.00	0.012	1.34	4.566	144.00
11	365	0.059	5.10	8.993	284.00	0.000	0.00	4.610	145.00

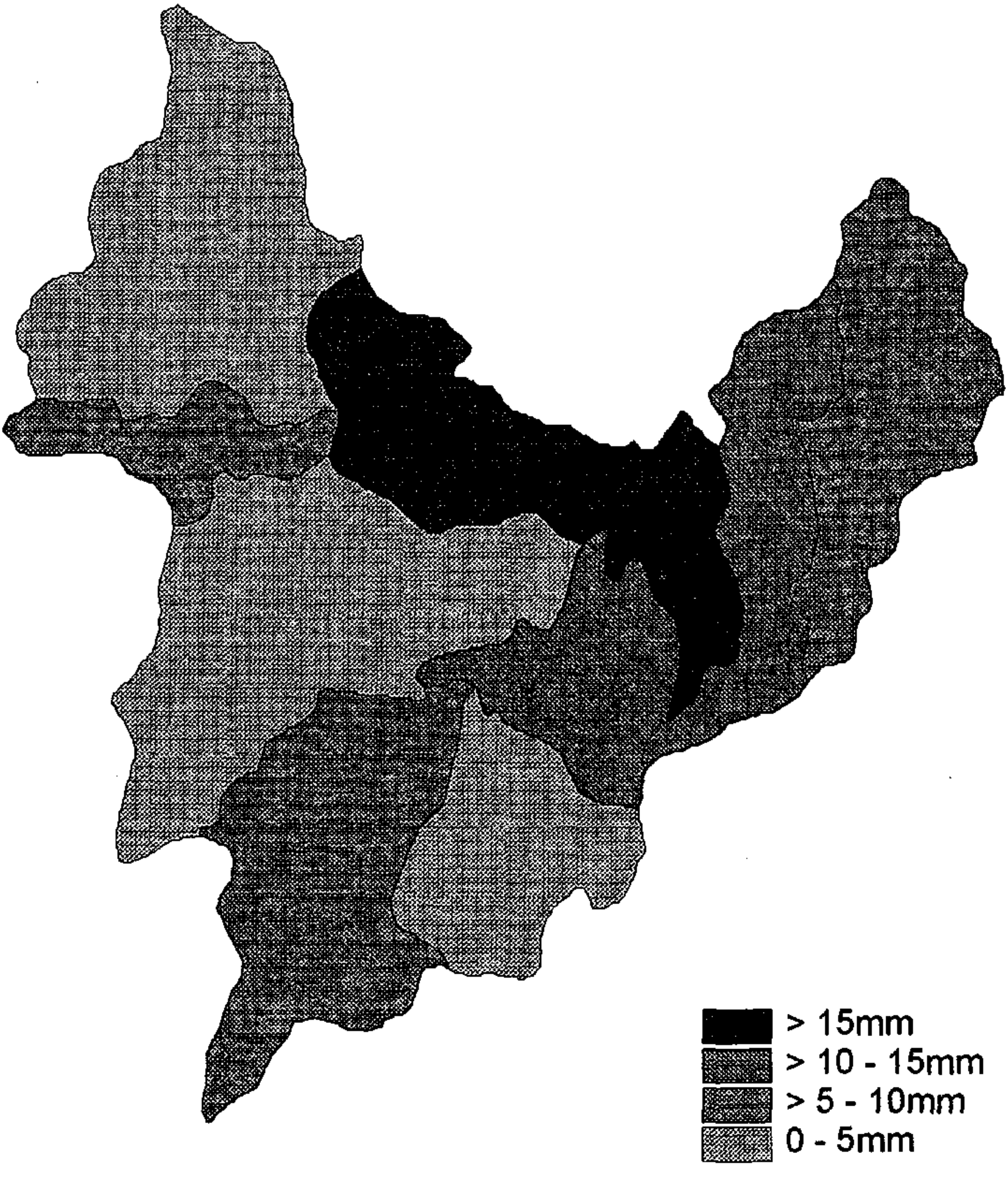


Figure D1.31 Spatial distribution of Q75(7) flow values in the central Tugela catchment (present conditions).

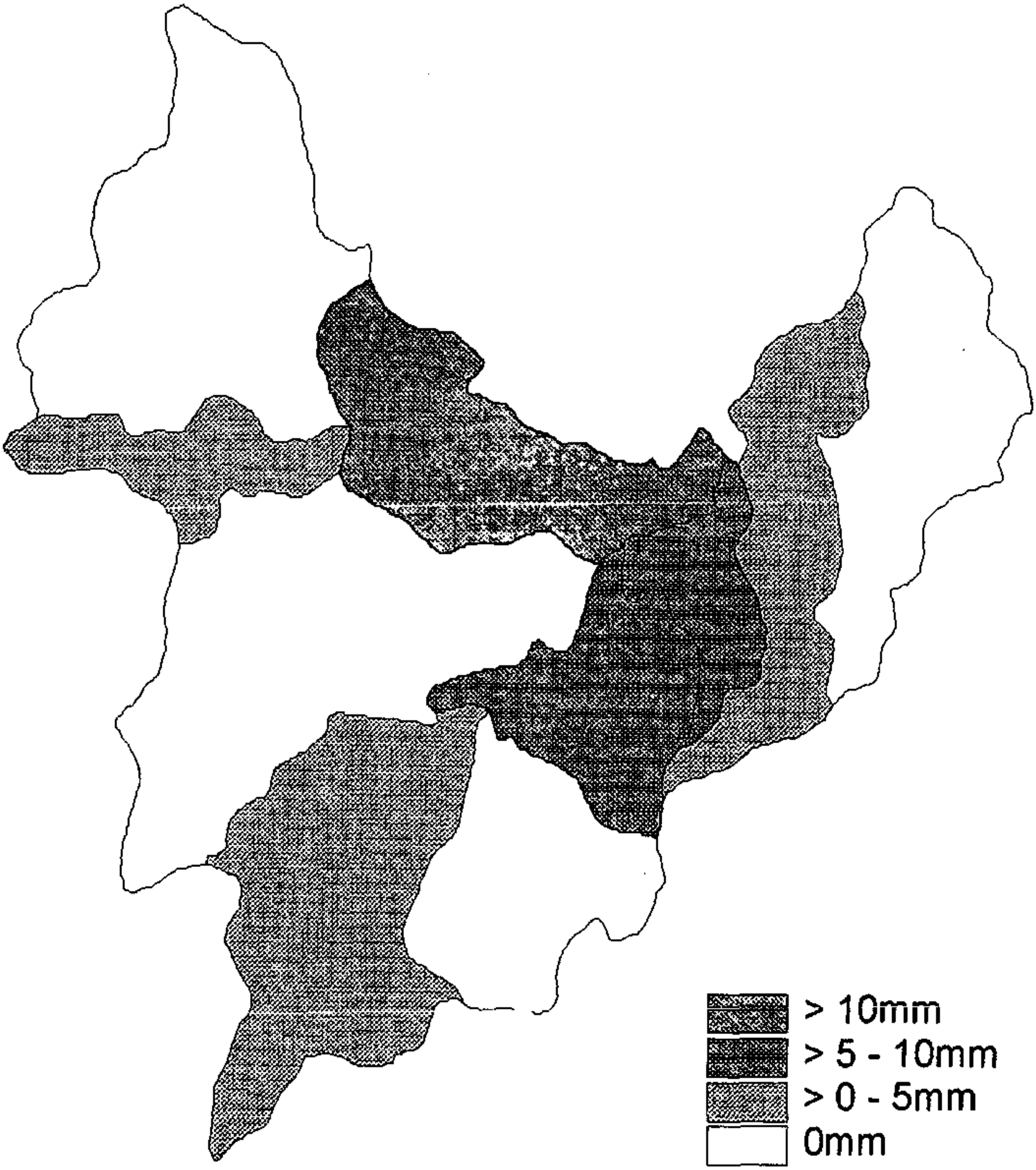


Figure D1.32 Spatial distribution of Q95(7) flow values in the central Tugela catchment (present conditions).

D1.9 REGIONAL ESTIMATION METHODS.

Estimating low-flow characteristics from the daily streamflow time series simulated by the VTI model is obviously a very labour intensive approach. It may or may not be successful depending on the quality of the input data. Alternative approaches to daily time series generation and the estimation of low-flow indices are advocated in Chapters 6, 7 (Vol 1) and Appendix E1. Eventually, they are all aimed at the use of synthetic monthly flow time series (available for the whole of the country at the scale of quaternary catchments) for the derivations of daily low-flow characteristics.

The approach to low-flow estimation which is briefly discussed in this section also has the same objective and is based on multiple regression analysis techniques. Regression analysis is widely used in low-flow studies (Chapter 2, Vol 1). A low-flow characteristic is normally predicted by means of a multiple regression model which relates the former with several catchment and physiographic parameters. The "true" physical relationships may or may not be fully uncovered by such a regression model. On the other hand, it is more likely that a strong relationship exists between, for example, daily and monthly low flows. If monthly low flows (e.g. simulated) are already available at a site of interest, daily low flow characteristics may also be estimated. The simplest estimation method of that kind would be a division of a monthly flow volume into a number of days or a number of seconds in a month to obtain an average daily flow volume or average daily discharge within this month. Even if a required exceedence level can be assigned to a monthly flow, this approach will still remain very simplistic, since it does not take into account the variability of daily flows within a month.

The more realistic approach would be to establish a regression relationship between monthly and daily low flows using observed streamflow records. If this relationship proves to be strong, daily low-flow indices at an ungauged location in a catchment may be estimated from already available synthetic monthly streamflow data.

In the case of the Tugela catchment, the attempt was made to relate Q75(7) flow value with the mean monthly flow during the driest month of a year and the coefficient of variation of these 'driest' monthly flows. The data from 22 streamflow gauging stations have been selected for this analysis. Generally, only gauges that measure flow in unregulated streams and from relatively natural catchments have been used. With only few exceptions, the record periods on selected gauges overlap (entirely or partially). Several gauges with non-overlapping record periods have still been used if the period was long and representative.

The mean driest month's flow and it's CV at each selected gauge have been estimated using HYMAS 'seasonal distribution' procedure, which is a convenient facility to calculate,display and print seasonal flow characteristics (Chapter 3, Vol 1). The example graphs to gauge V7H012 shown in Figure D1.33 illustrate that the driest month at the gauge is July, its mean flow is about 500 ML and its CV is approximately 0.7 (to obtain the exact values they should be printed out)

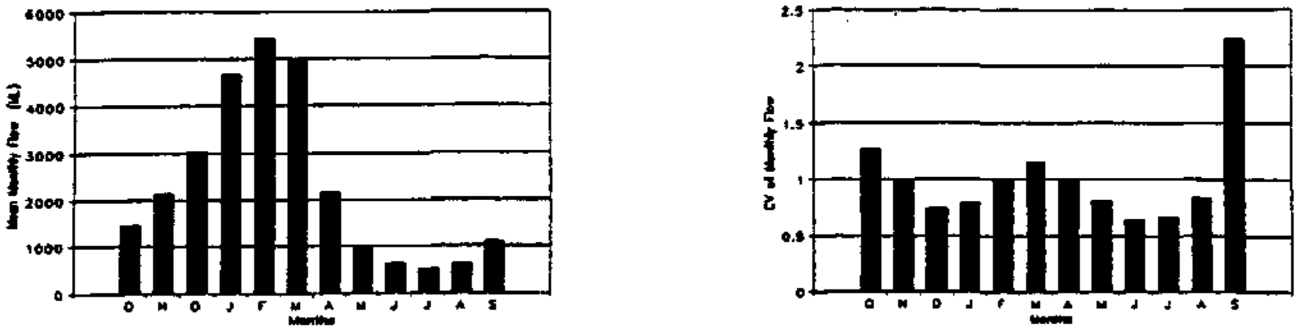


Figure D1.33 Monthly flow means (left) and CV's (right) for gauge V7H012.

Several types of regression models have been tried. The best results have been obtained using the following logarithmic model:

$$\ln (Q75_7) = -1.685 + 1.131^* \ln (DMF) - 0.901^* \ln (CV_{DMF})$$
$$(R^2 = 0.97; SE = 0.31)$$

where DMF is mean Dry Month Flow (expressed in thousands Ml) and CV_{DMF} - coefficient of variation of the dry month flows. The data used for the analysis and the best results are summarised in Table D1.9. Figure D1.34 illustrates the correlation between observed Q75(7) flow values and flow values calculated using the established regression model. The use of CV_{DMF} as an additional independent variable may be excessive since it is obviously related to the mean DMF. The log-regression model which relates Q75(7) with mean DMF alone already explains 92 % of Q75(7) variability ($R^2 = 0.92$; SE = 0.47).

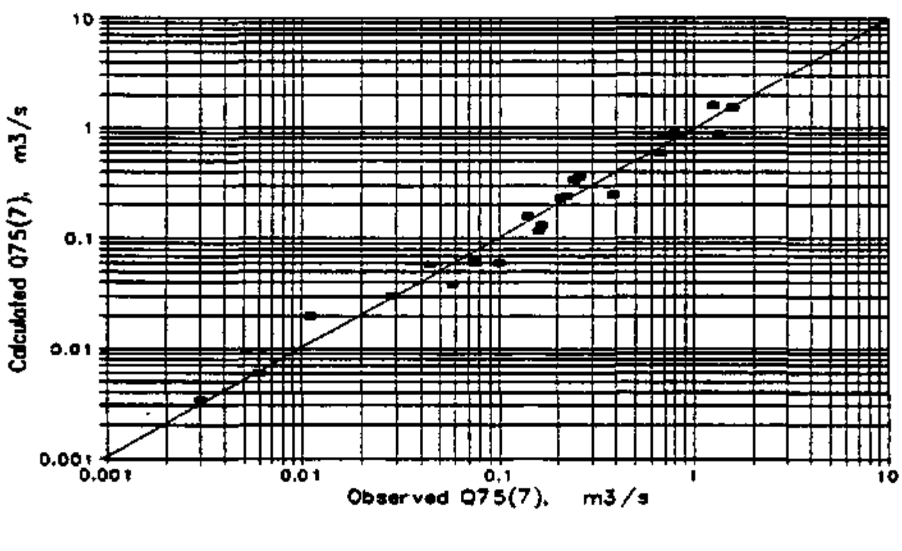


Figure D1.34 Correlation between observed and calculated by regression model Q75(7) flow values.

Table D1.9 Calculation of Q75(7) flow using the regression model.

Gauge	Area, km^2	Period used	Q75(7), m^3/s	DMF, Ml/1000	CV_{DMF}	Log DMF	Log CV_{DMF}	Log Q75(7), obs	Log Q75(7), calc	Q75(7), m^3/s, calc
V1H004	441	1962-75	1.334	3.0	0.72	1.10	-0.33	0.29	-0.14	0.867
V1H041	434	1976-92	1.239	3.0	0.36	1.10	-1.02	0.21	0.48	1.619
V1H009	196	1954-92	0.011	0.18	1.4	-1.71	0.34	-4.51	-3.92	0.020
V1H029	21	1968-93	0.003	0.035	1.25	-3.35	0.22	-5.81	-5.67	0.003
V1H031	162	1972-92	0.006	0.066	1.49	-2.72	0.40	-5.12	-5.11	0.006
V1H034	51	1984-92	0.058	0.26	1.05	-1.35	0.05	-2.85	-3.25	0.039
V1H038	1644	1971-94	0.257	2.05	1.15	0.72	0.14	-1.36	-0.99	0.370
V6H003	312	1954-92	0.14	0.65	0.7	-0.43	-0.36	-1.97	-1.85	0.158
V6H004	658	1954-92	0.243	1.7	1.0	0.53	0.00	-1.41	-1.08	0.339
V2H005	260	1972-92	0.68	2.41	0.55	0.88	-0.60	-0.39	-0.15	0.863
V2H006	188	1972-92	0.221	1.0	0.75	0.00	-0.29	-1.51	-1.42	0.241
V2H007	109	1972-92	0.166	0.55	0.70	-0.60	-0.36	-1.80	-2.03	0.131
V2H002	937	1950-92	1.555	4.5	0.64	1.50	-0.45	0.44	0.42	1.526
V7H018	119	1972-92	0.076	0.38	1.01	-0.97	0.01	-2.58	-2.78	0.062
V7H012	196	1962-93	0.16	0.51	0.72	-0.67	-0.33	-1.83	-2.14	0.117
V7H017	276	1972-93	0.782	2.5	0.55	0.92	-0.60	-0.25	-0.10	0.900
V3H002	1518	1949-83	0.665	3.0	1.1	1.10	0.10	-0.41	-0.52	0.592
V3H003	850	1945-61	0.384	2.0	1.73	0.69	0.55	-0.96	-1.39	0.249
V3H005	676	1961-87	0.208	2.0	1.89	0.69	0.64	-1.57	-1.47	0.230
V3H007	129	1948-92	0.099	0.4	1.1	-0.92	0.10	-2.31	-2.80	0.061
V3H009	148	1961-92	0.028	0.24	1.25	-1.43	0.22	-3.58	-3.49	0.030
V3H011	543	1960-85	0.044	0.6	1.9	-0.51	0.64	-3.12	-2.83	0.059

Using this model and assuming that selected observed data sets represent reasonably natural flow regimes, it is possible to estimated Q75(7) flow for each quaternary subcatchment in the Tugela basin. Since synthetic monthly flow time series are available for all these subcatchments, their mean driest month's flows and the CV's of these flows may be calculated using HYMAS 'seasonal distribution' procedure, and used as input to the established regression model to obtain the required estimate. The regression model was established using data from catchments with areas ranging from 21 to 1 644 km^2. This indicates that the method is likely to be applicable at subquaternary scale as well, provided that monthly flow characteristics at this scale are made available. Further research is necessary to investigate the reliability of regression relationships of this type for other daily low-flow characteristics.

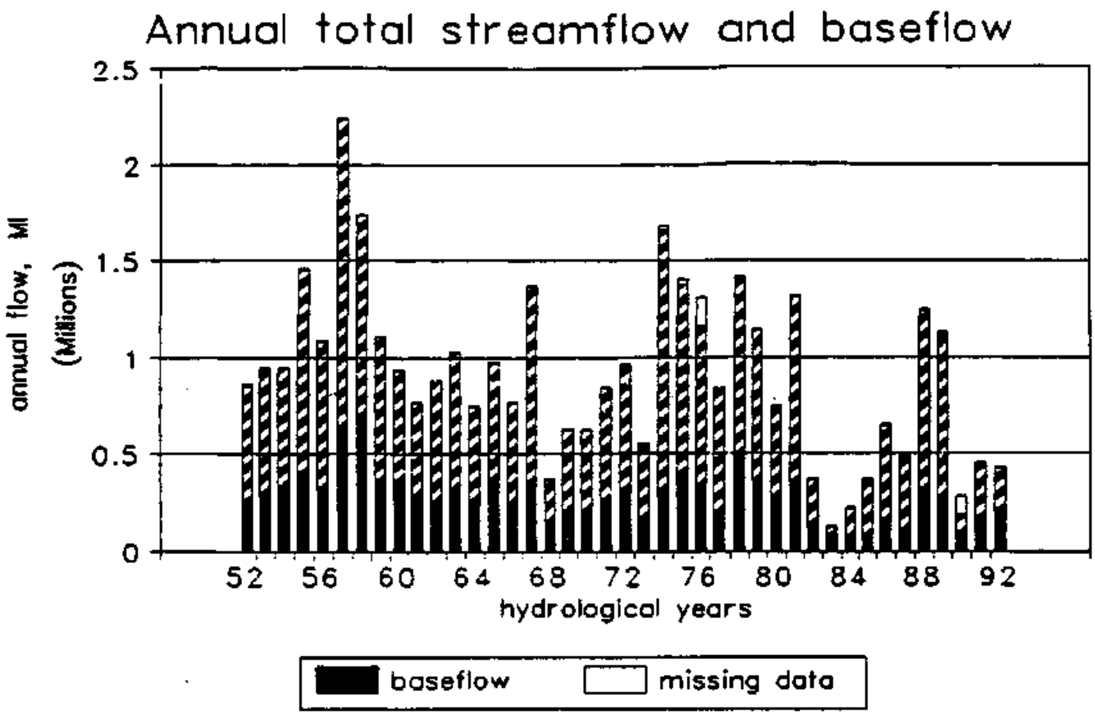
The approach described above illustrates the applicability of the regression technique for the estimation of daily low-flow characteristics from monthly data. The other possible way of utilizing monthly data for daily flow estimation has been described in Chapter 7 (Vol.1). This approach is aimed at the derivation of 'regional ration curves' which should then be used to convert a 1-month flow duration curve into a 1-day flow duration curve (either for a year, a season or calendar month). Chapter 7 describes the results of testing the method in the Sabie catchment.

Similar research has started in the Tugela catchment, 1-month and 1-day flow duration curves have been constructed for most of the gauges listed in Table D1.9. The curves have been constructed for the whole year, each season and each calendar month. The preliminary analysis has shown that in some parts of the Tugela catchment, daily low-flow indices can be approximated as a fixed ratio of corresponding monthly flow characteristics. For example, 1-day Q70 flow is equal to about 75 - 80 % of 1-month Q70 flow in most parts of the Tugela catchment, except the left-hand tributaries of the upper Tugela. For 1-day Q90 flow, this ratio is even more stable throughout the catchment: about 75-85 % of 1-month Q90 flow except for the Sundays river (where this ratio drops to 30-50%). The analysis of corresponding pairs of curves and "ratio curves" is only at the initial stage at present and it is premature to draw any conclusions about the validity of this approach in the Tugela catchment. The estimated ratios for particular levels of exceedence and/or entire "ratio curves" should be subject to grouping, or regression analysis. Their relation with the hydrological zones delineated in WR90 should also be investigated.

APPENDIX D2

Annual flows and low-flow indices in the Tugela catchment

Note : each year on graphs is from October of the previous calendar year to September of the next calendar year (the year 1952 is from October 1951 to September 1952).



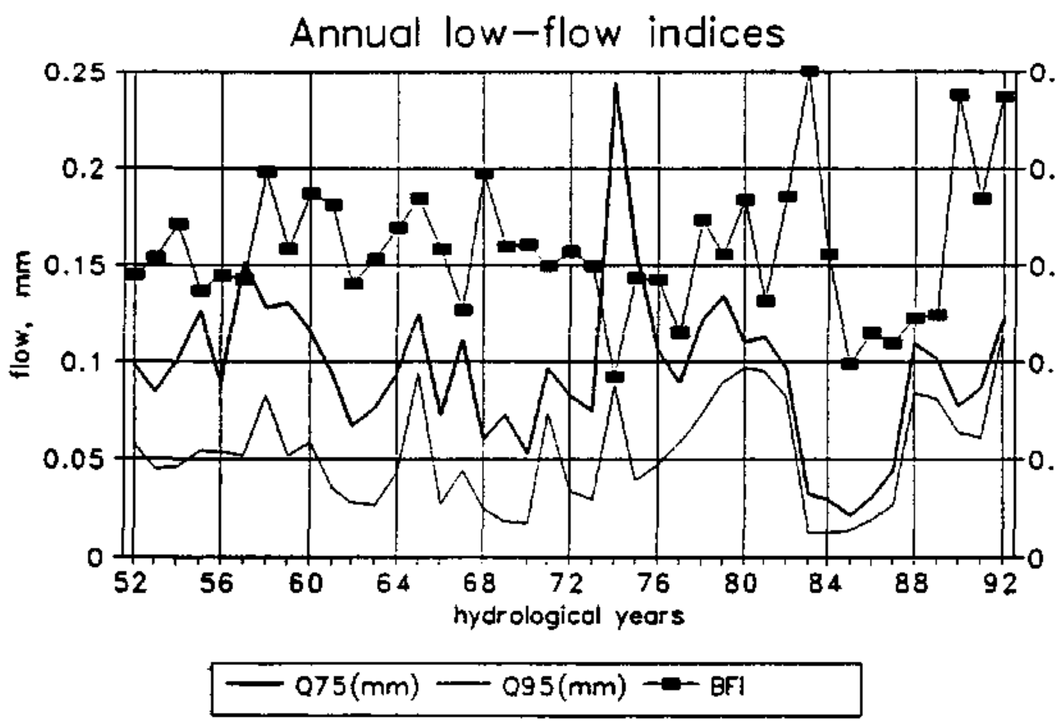
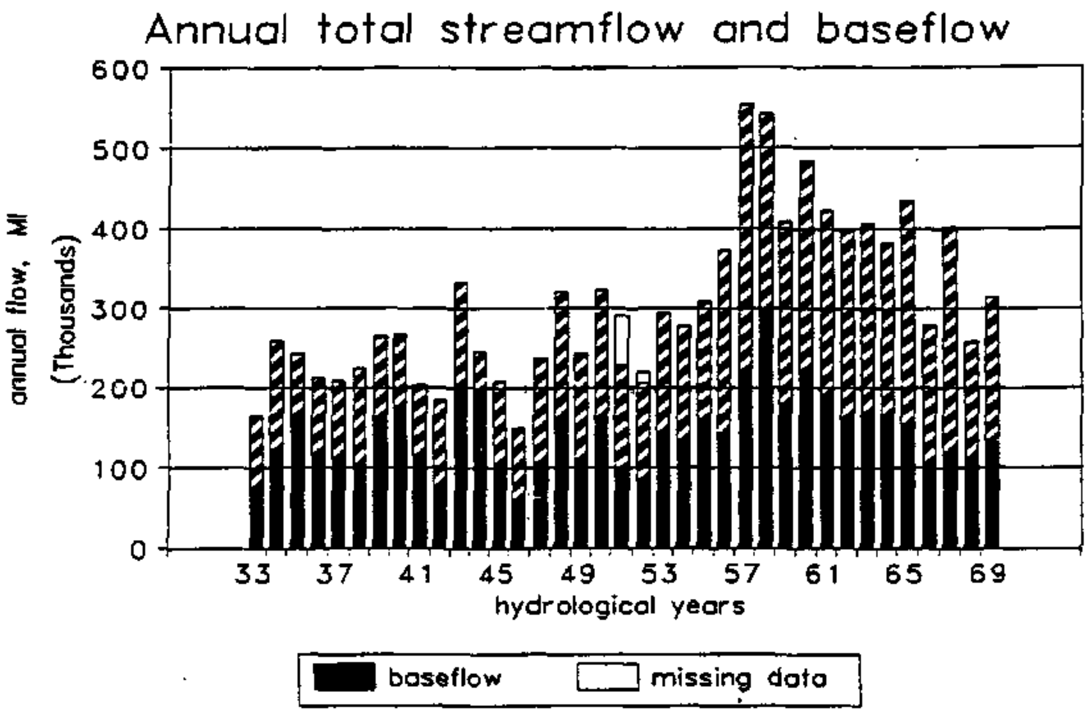


Figure D2.1. Gauge V1H001.



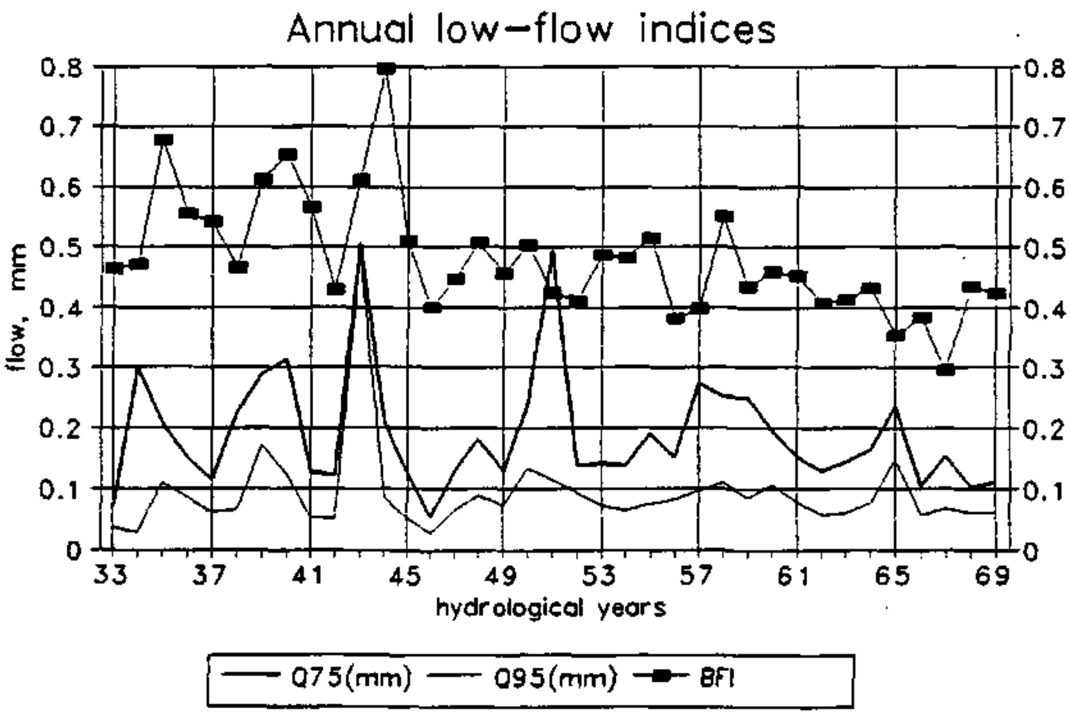
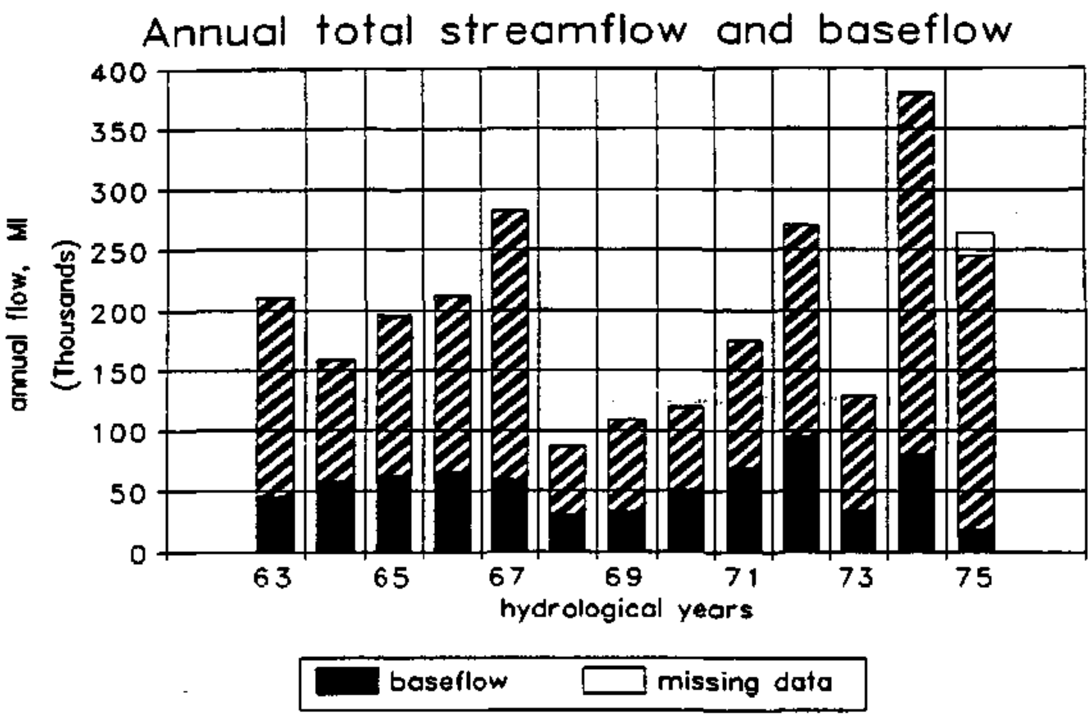


Figure D2.2. Gauge V1H002.



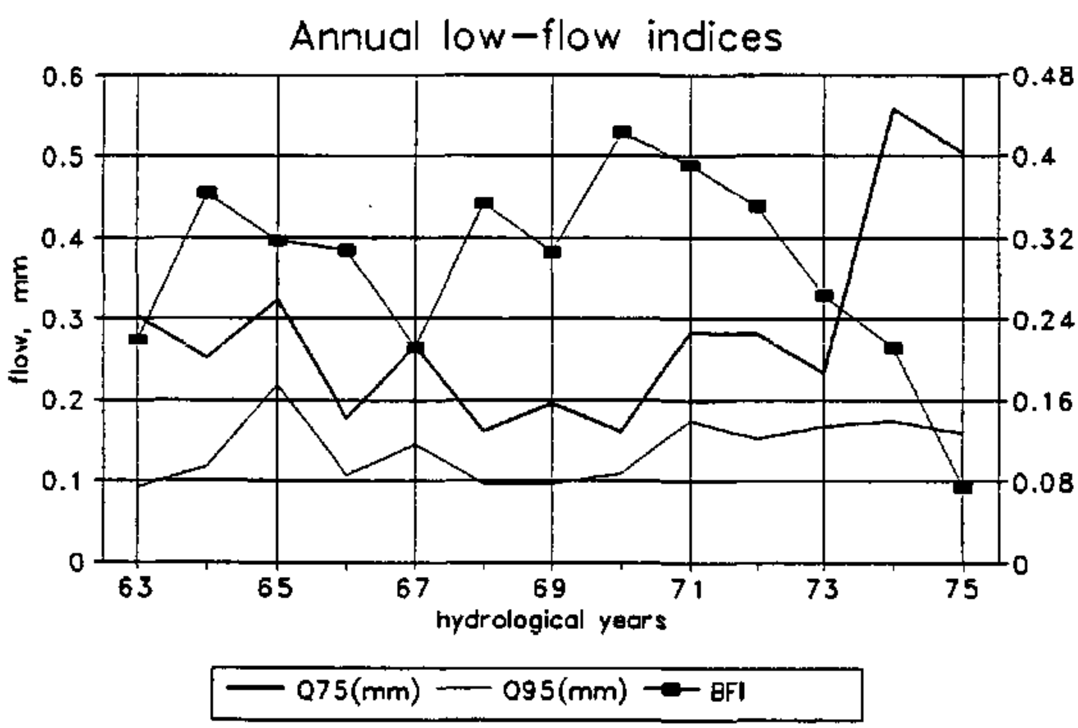
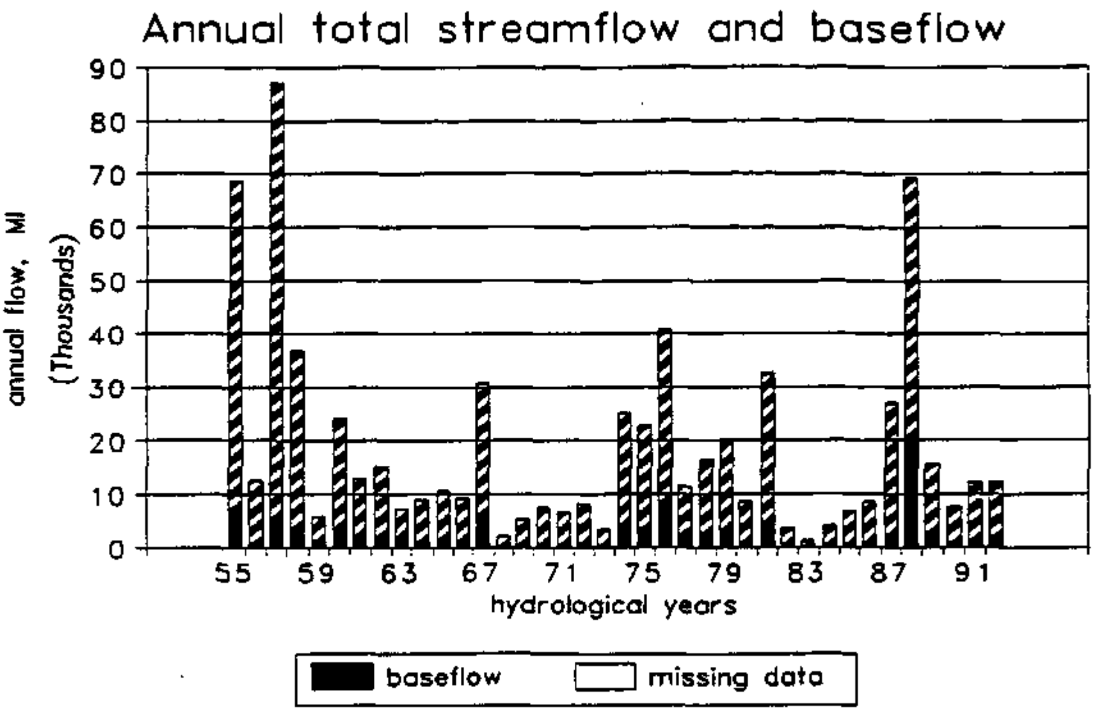


Figure D2.3. Gauge V1H004.



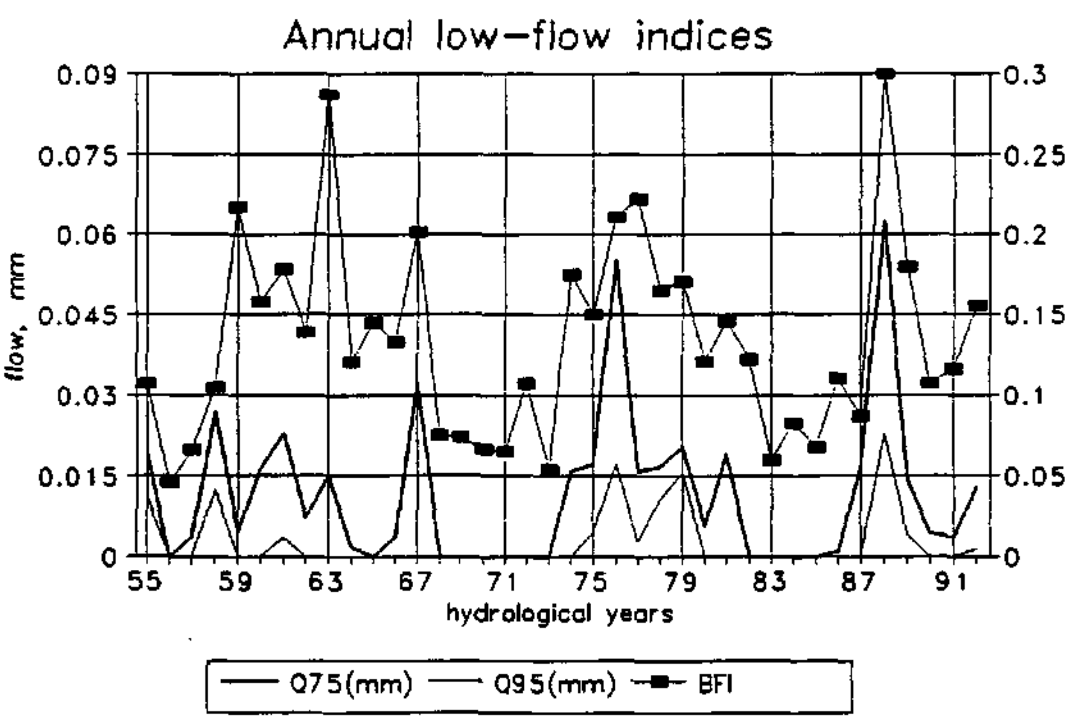
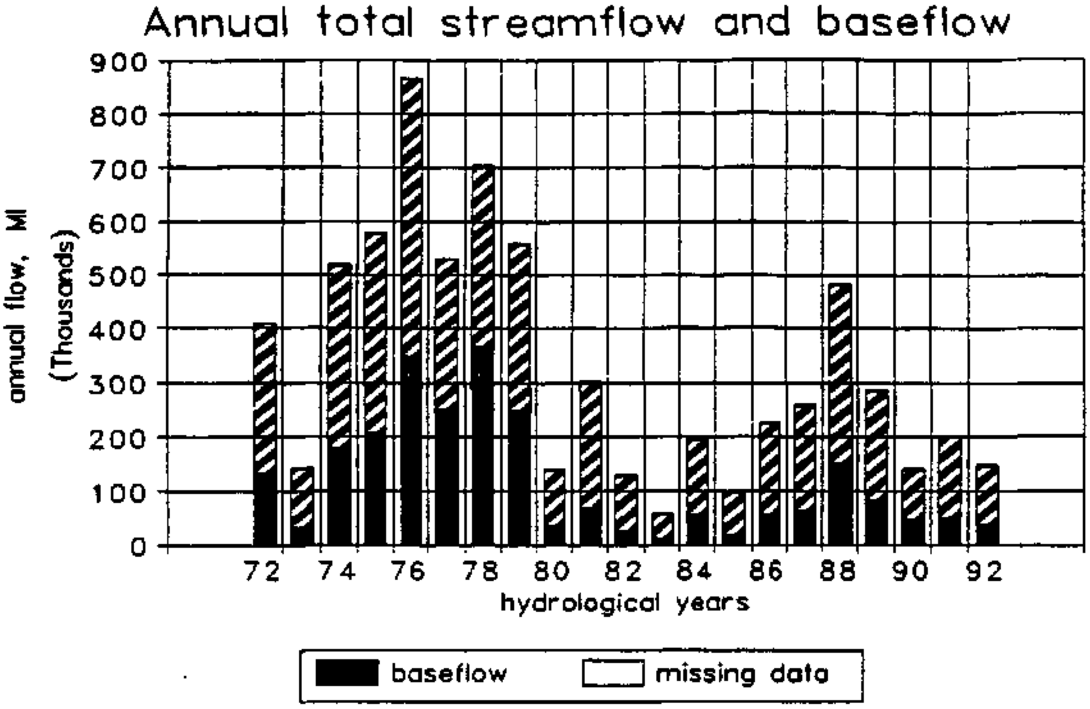


Figure D2.4. Gauge V1H009.



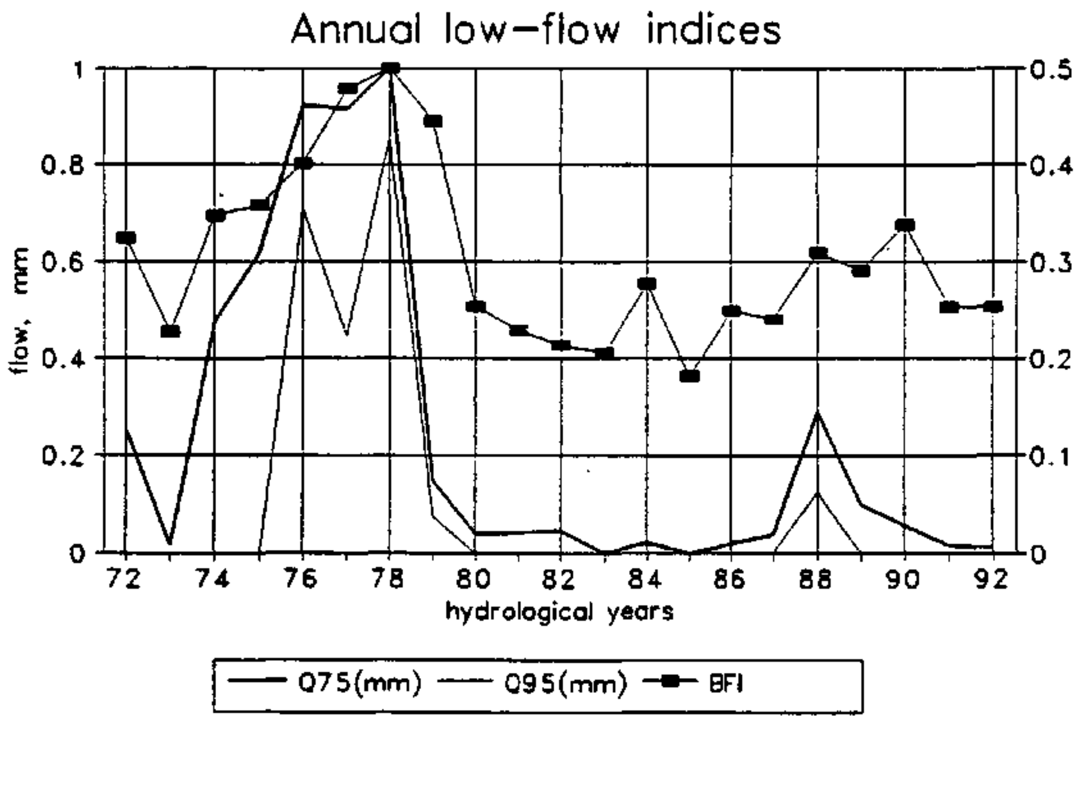
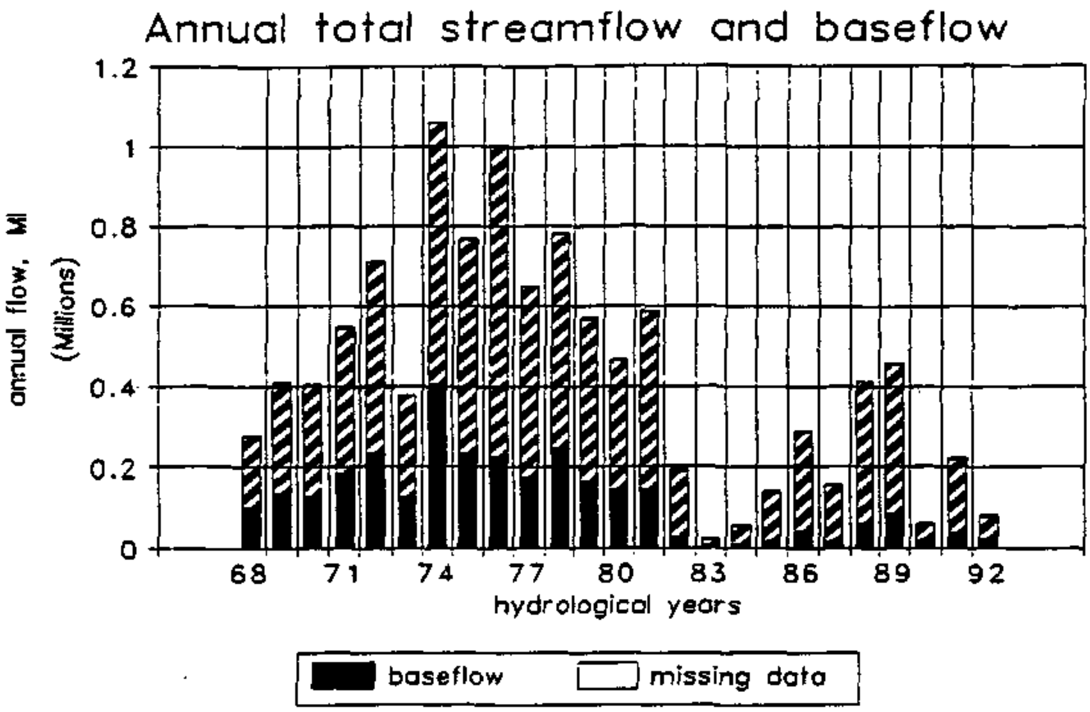


Figure D2.5. Gauge V1H010.



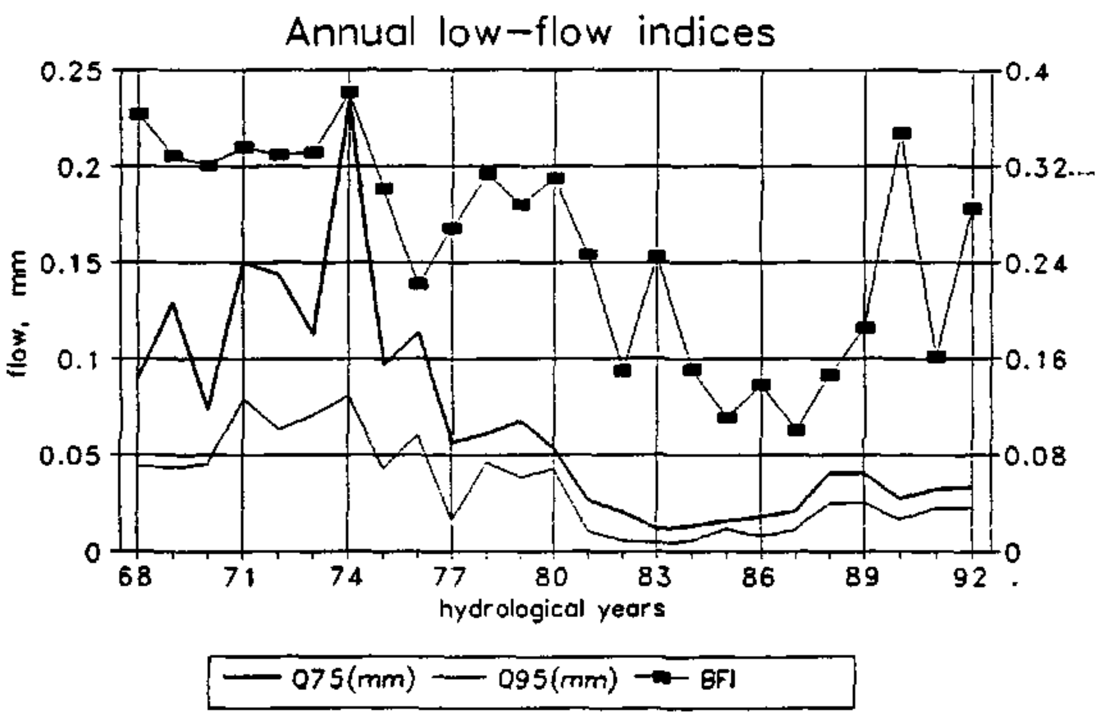
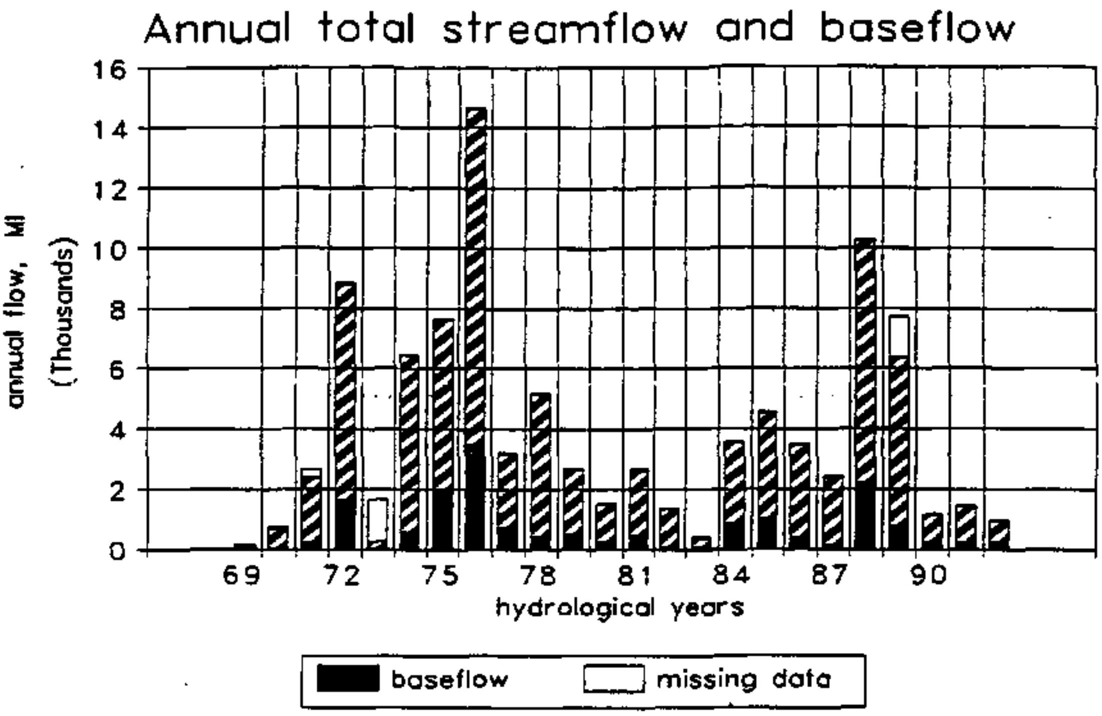


Figure D2.6. Gauge V1H026.



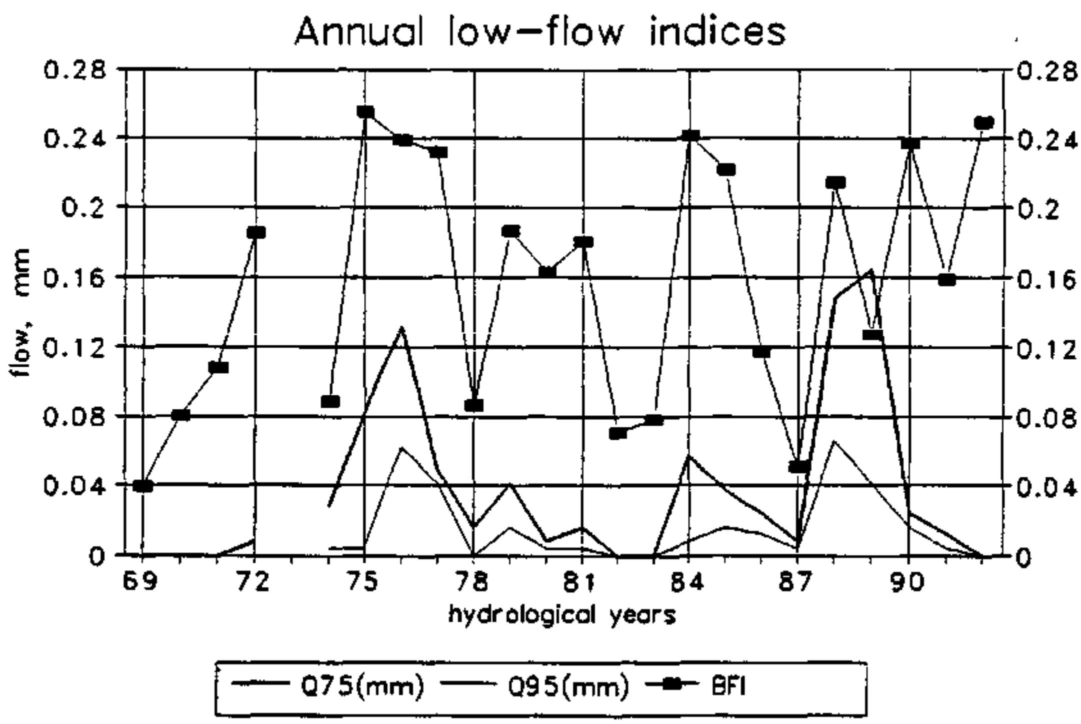
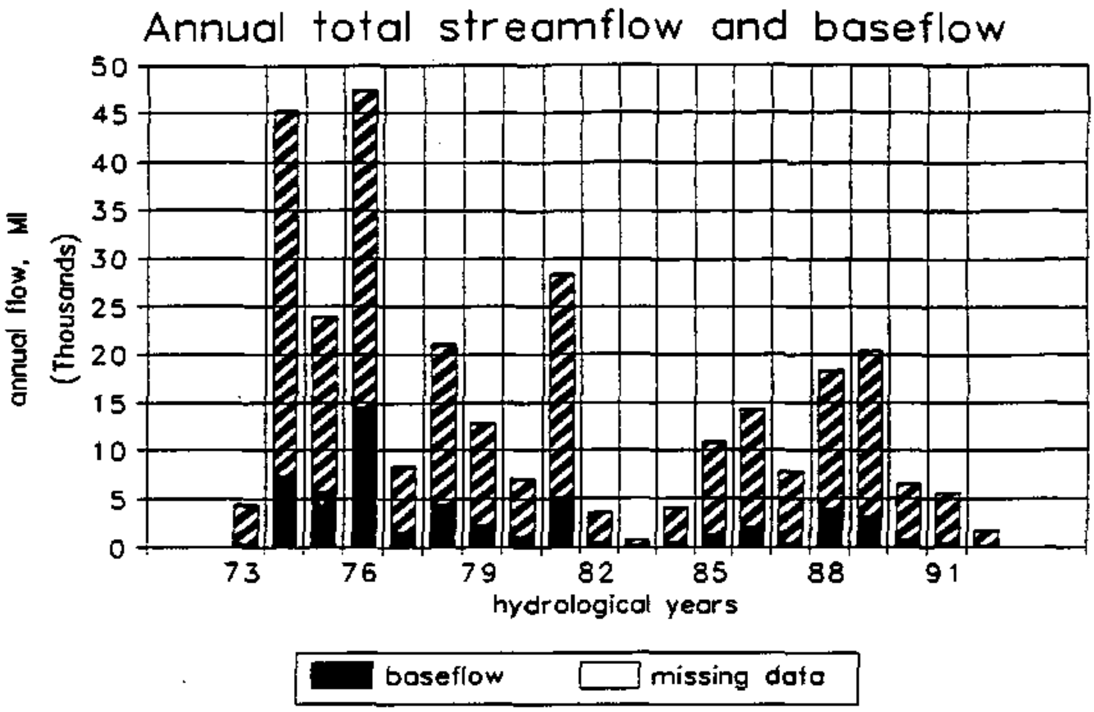


Figure D2.7. Gauge V1H029.



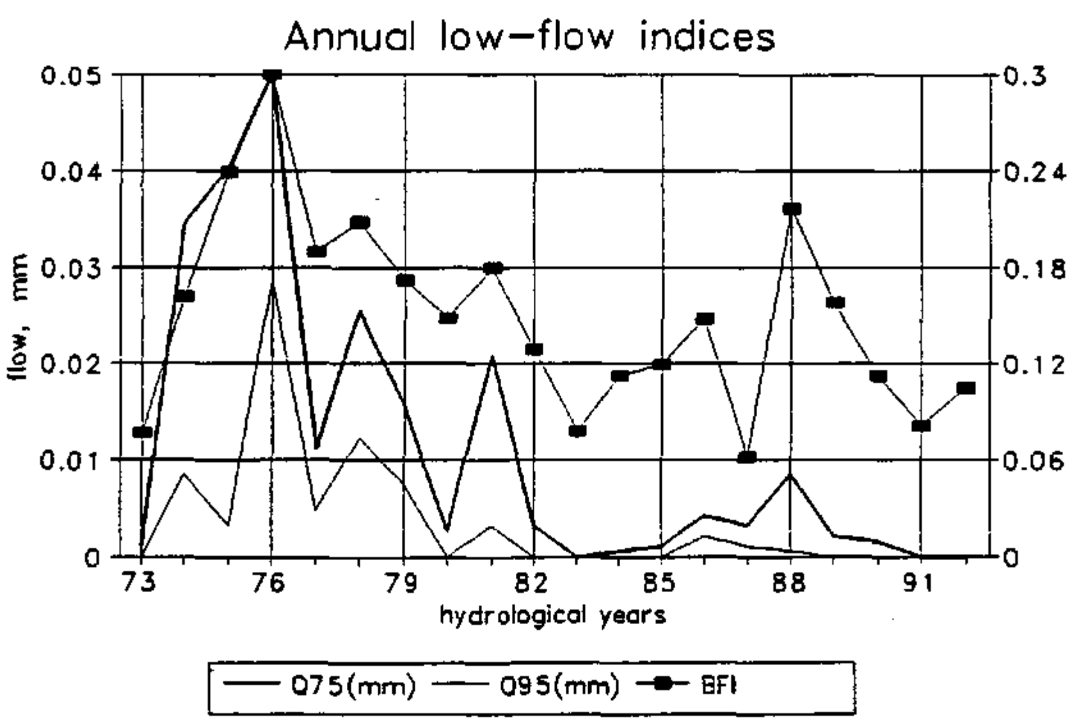
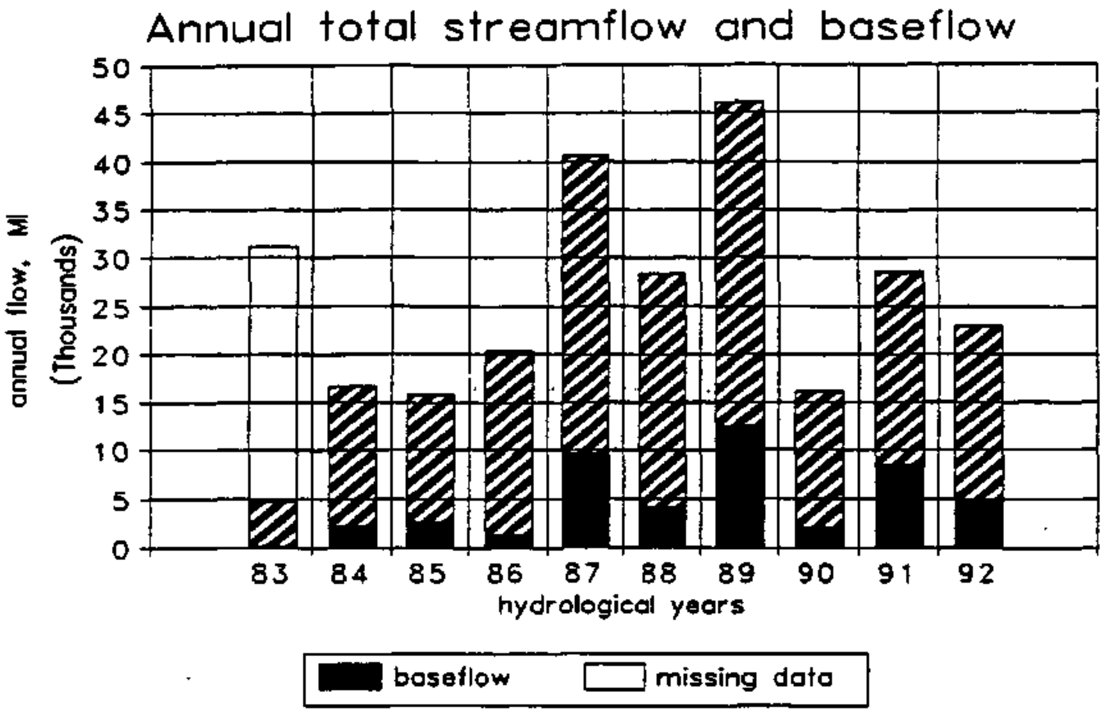


Figure D2.8. Gauge V1H031.



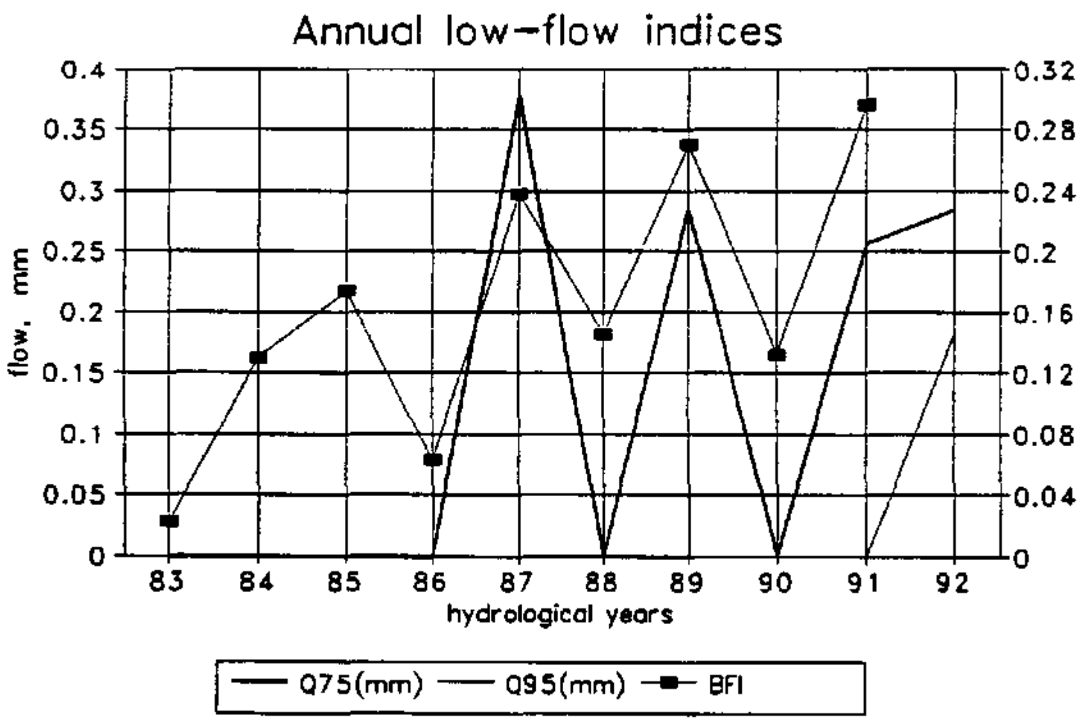
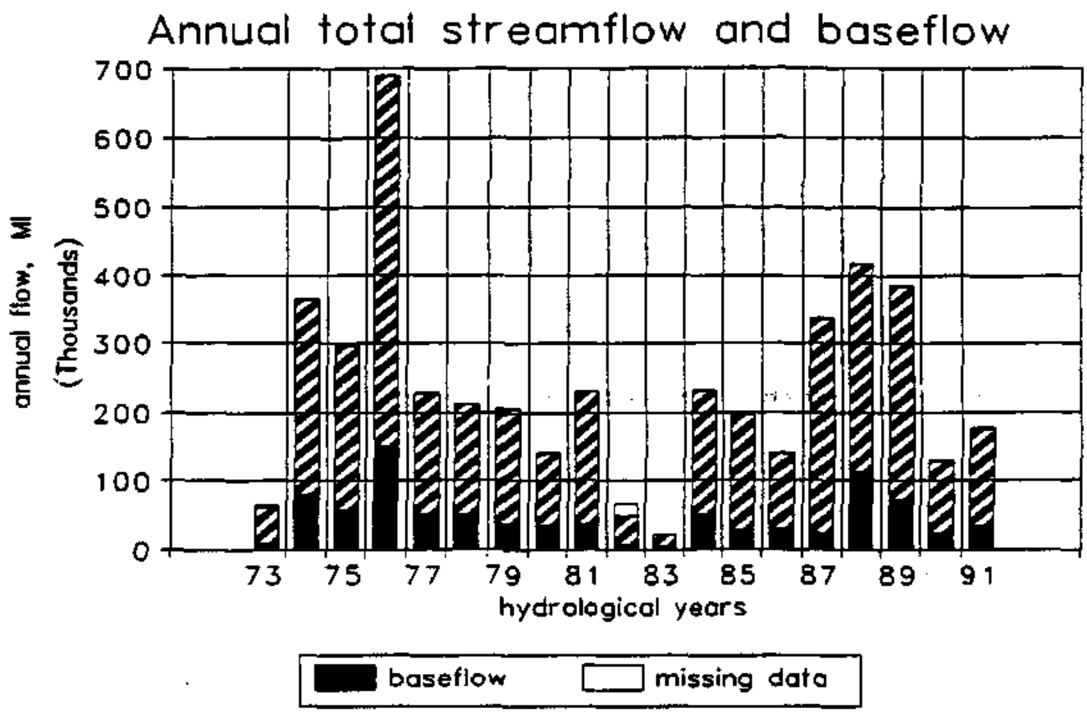


Figure D2.9. Gauge V1H034.



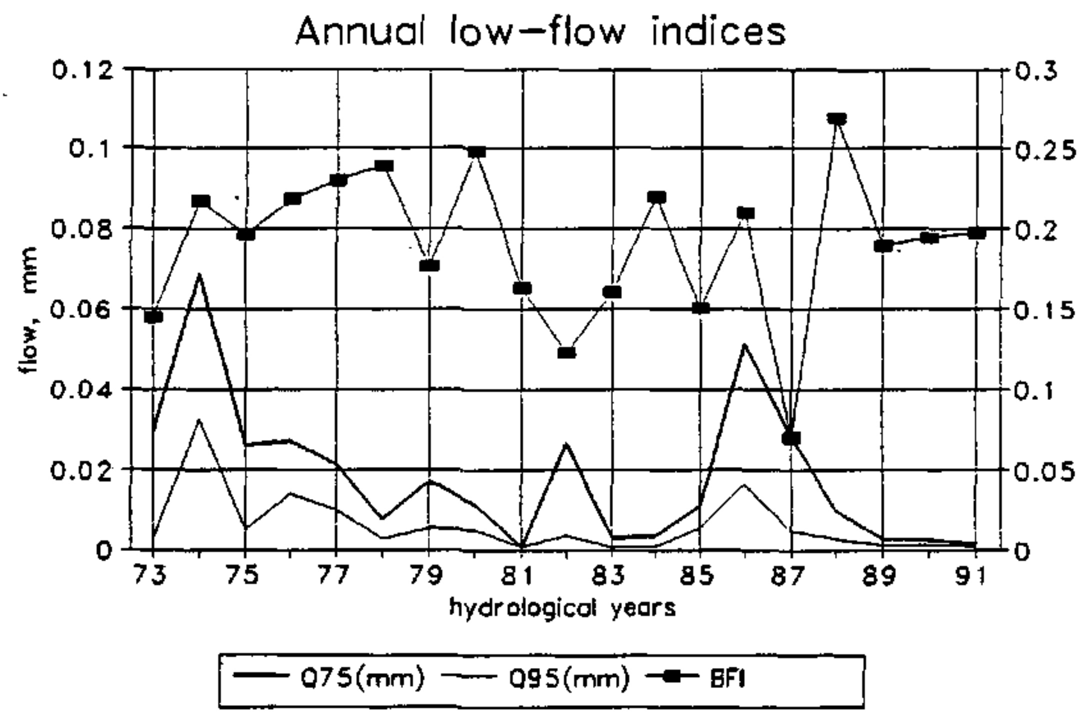
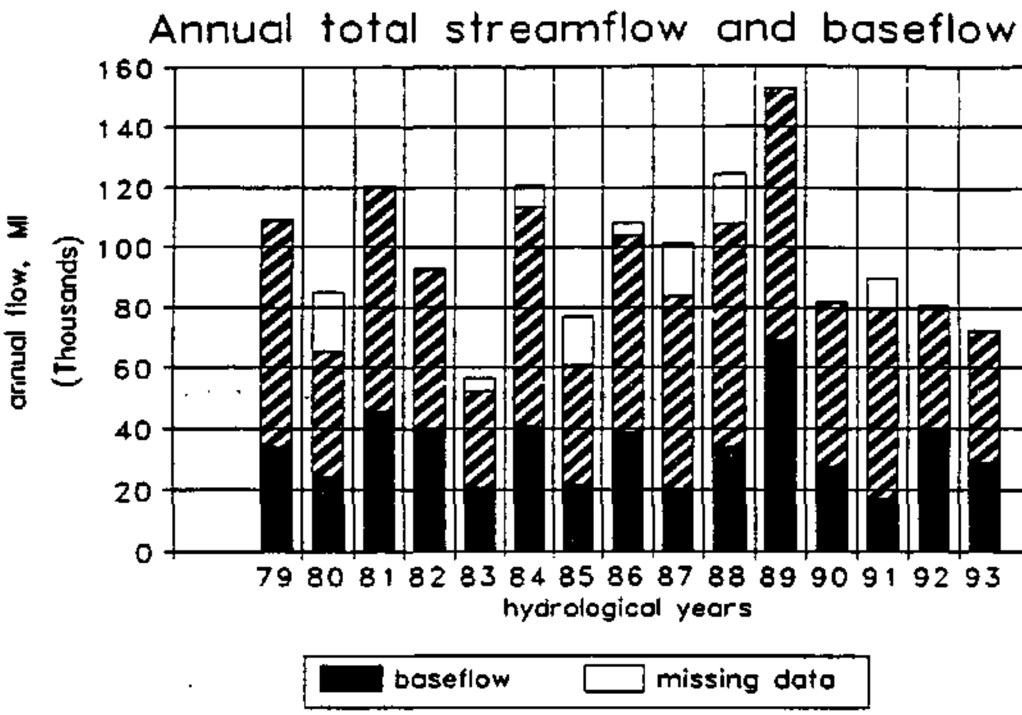


Figure D2.10. Gauge V1H038.



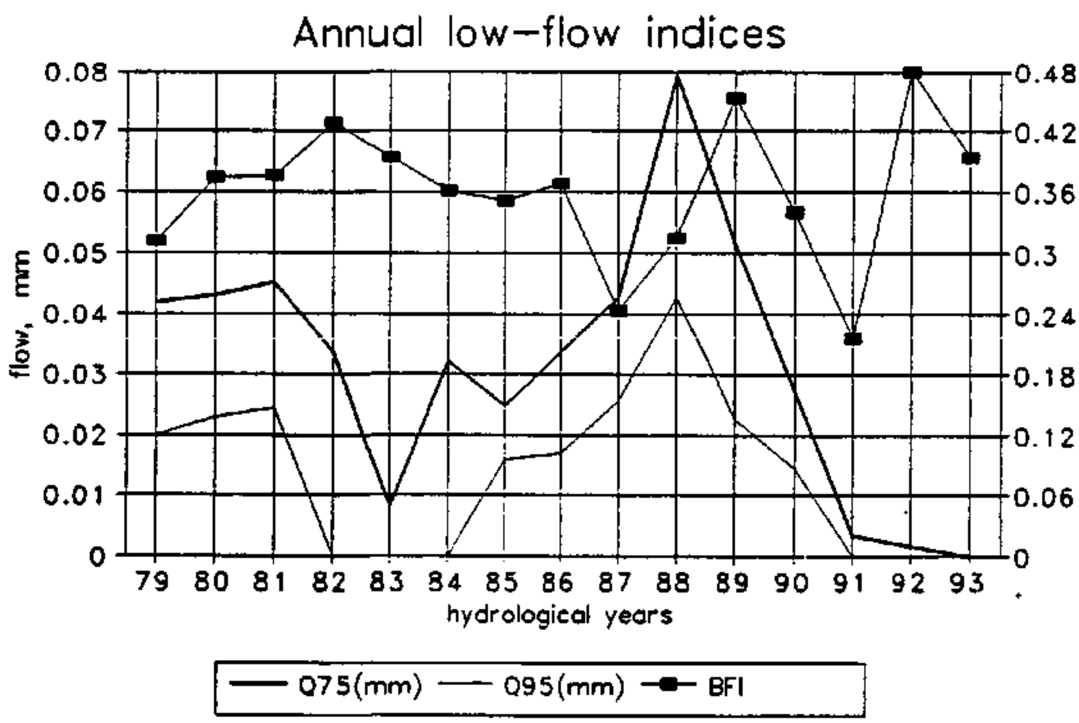
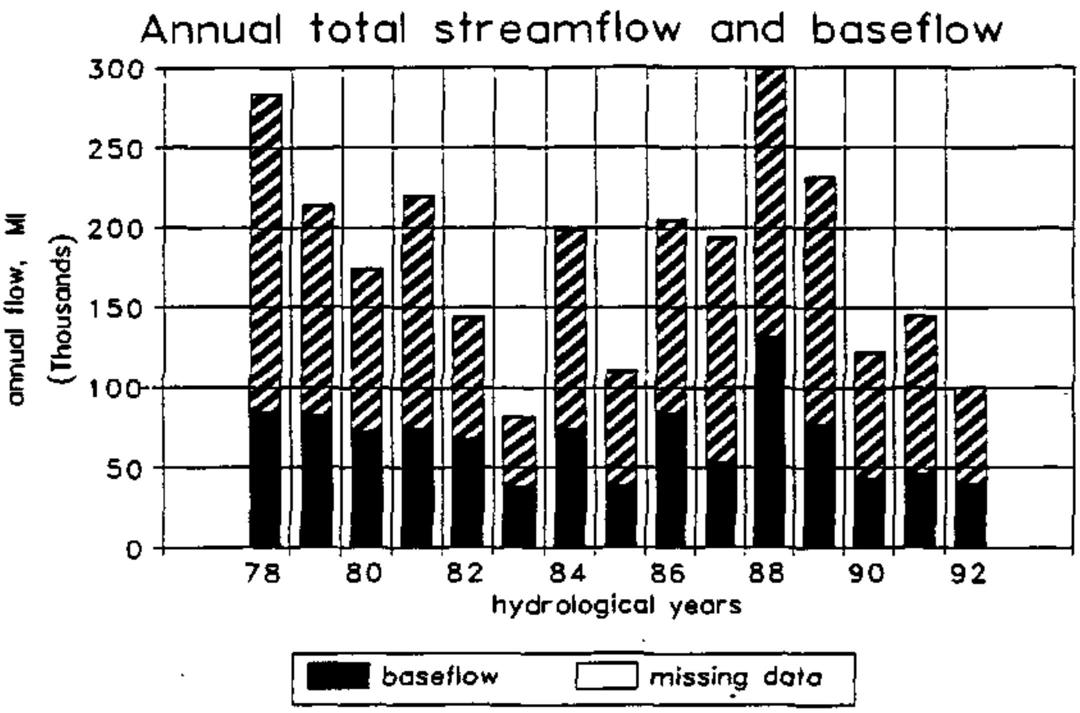


Figure D2.11. Gauge V1H039.



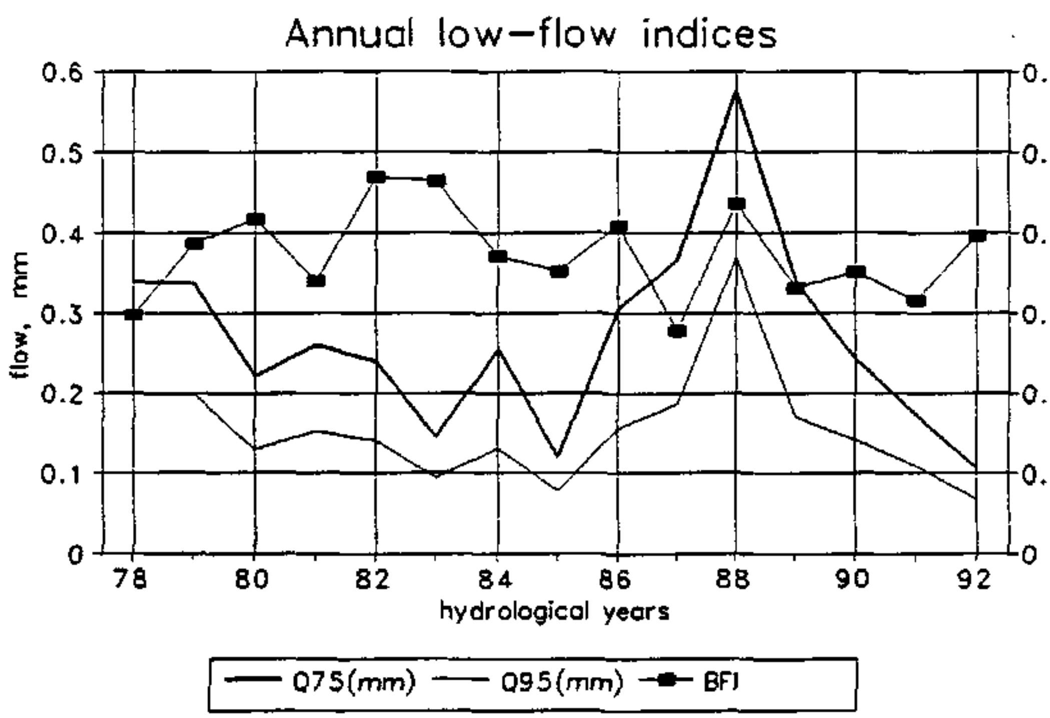
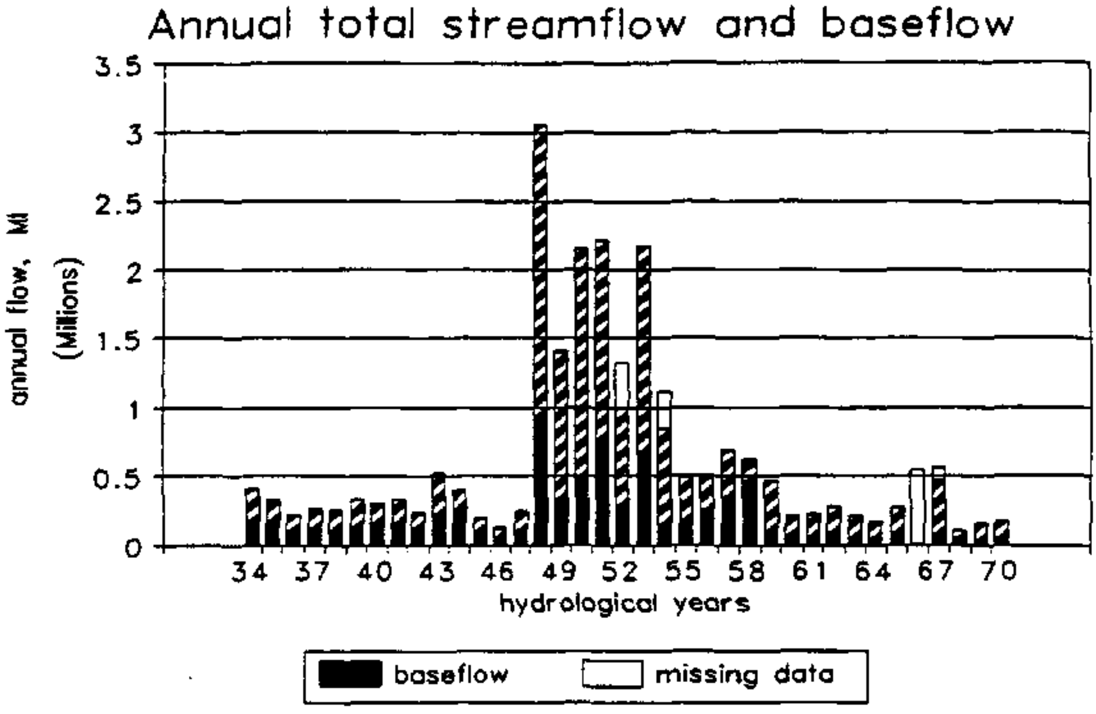
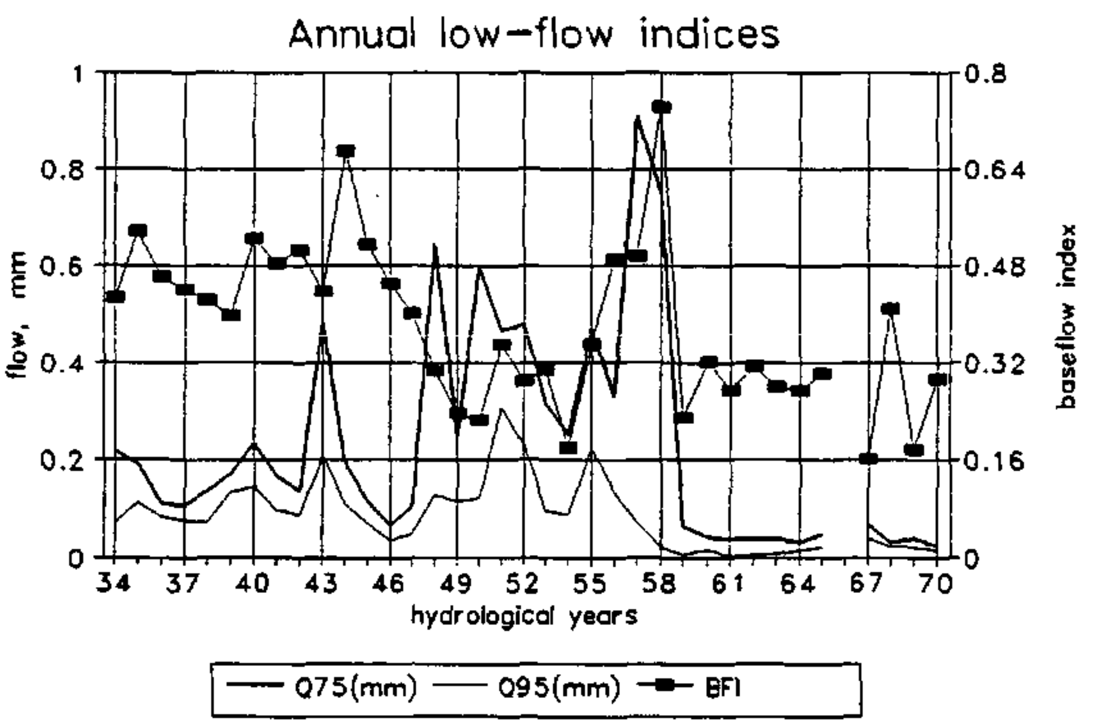


Figure D2.12. Gauge V1H041.





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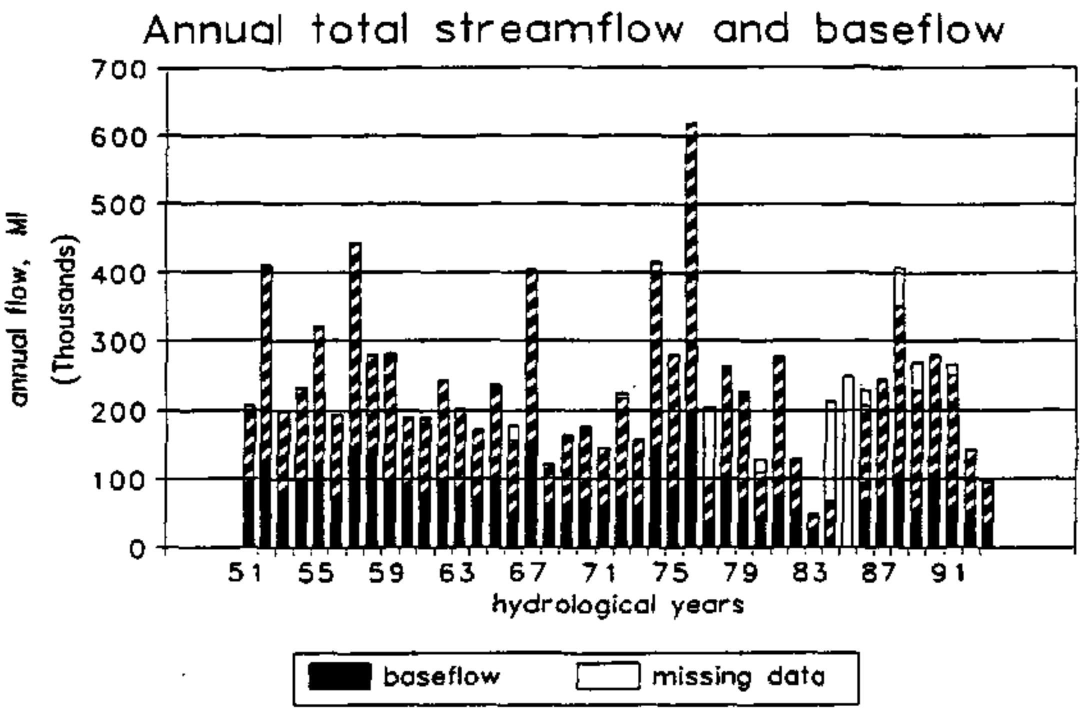

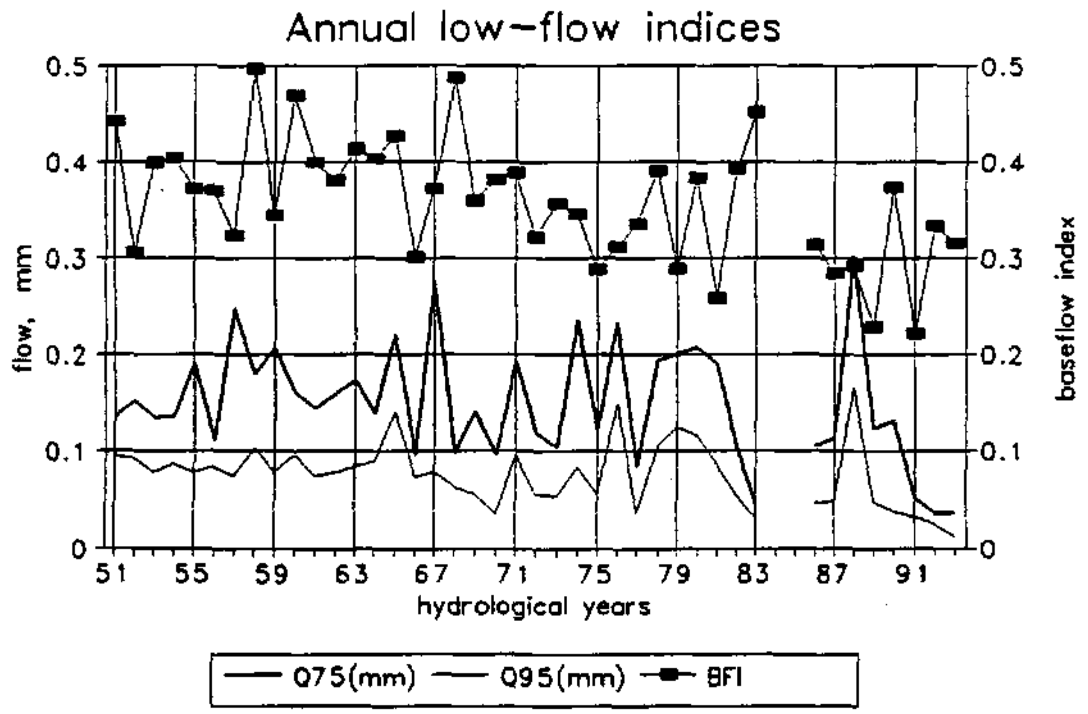

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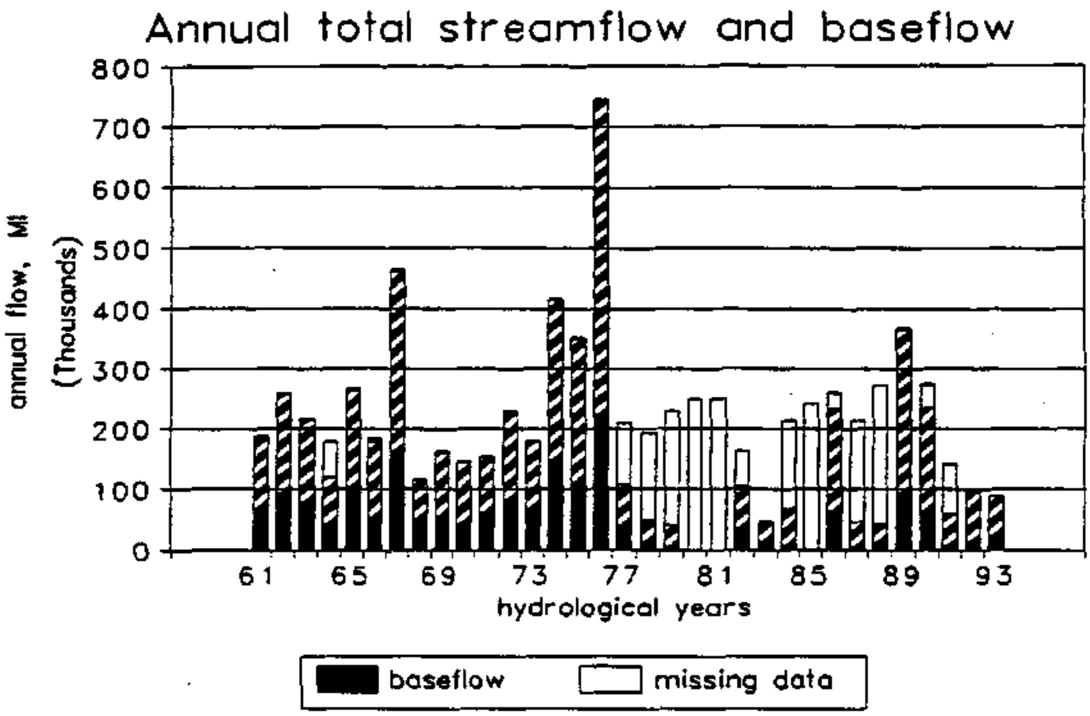

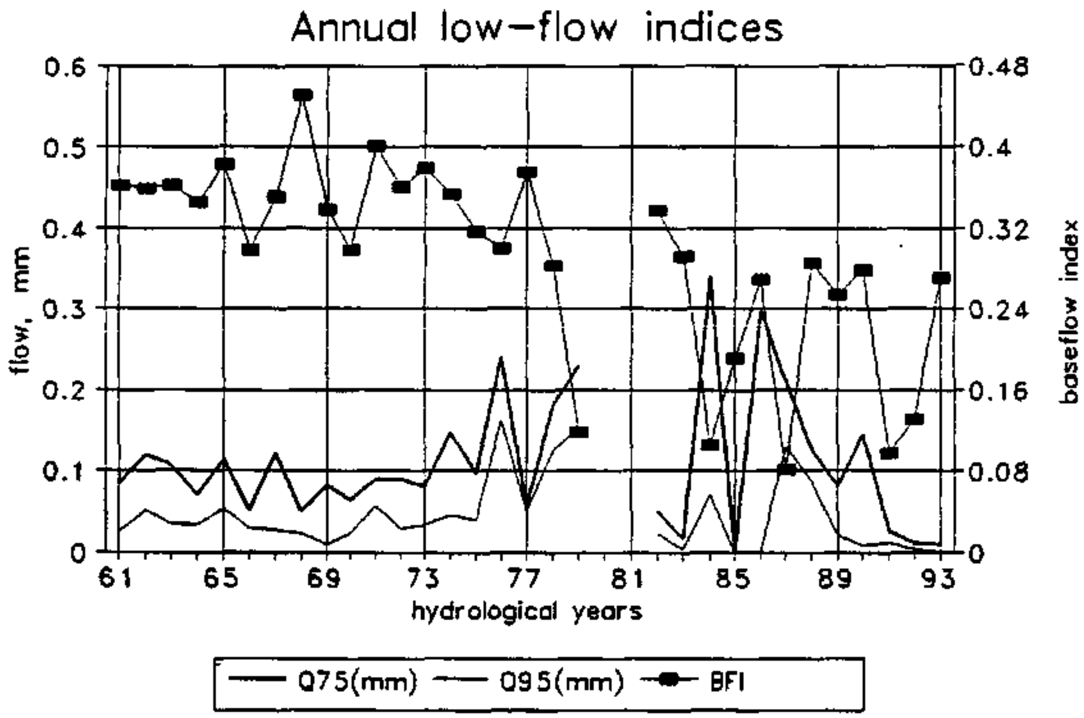

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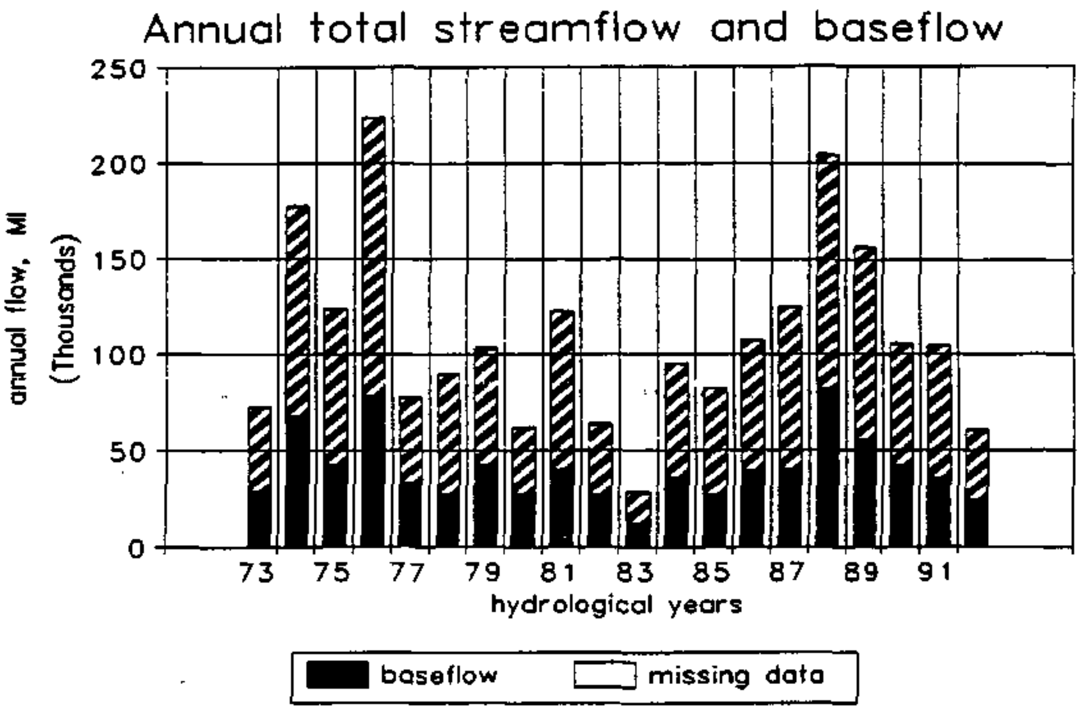

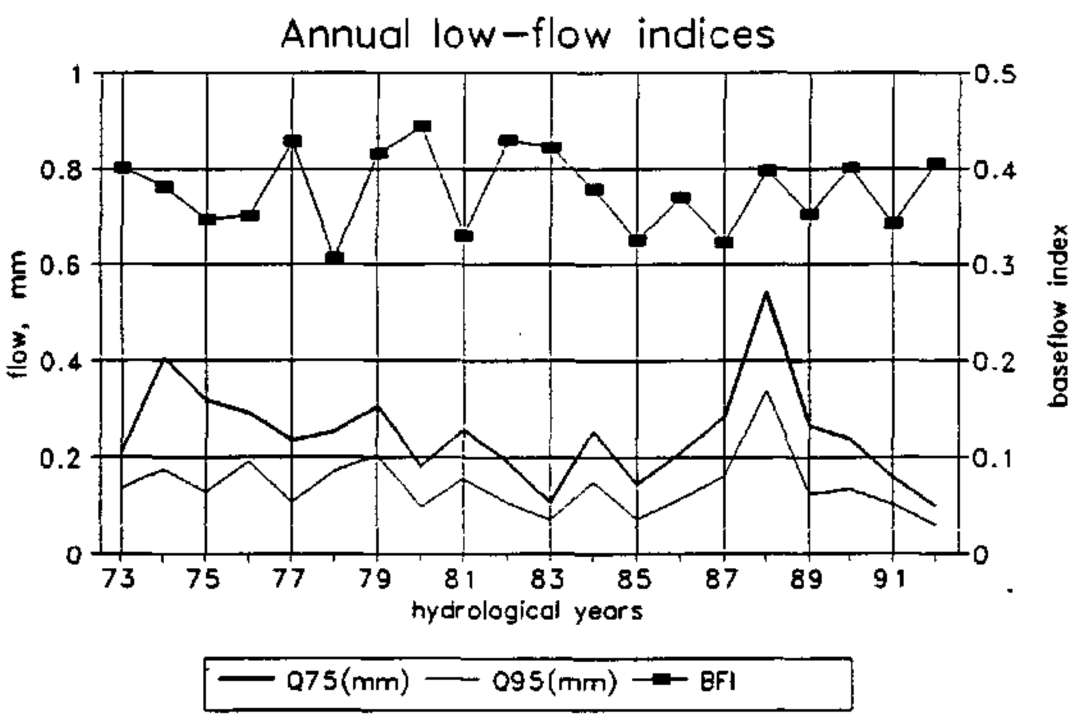

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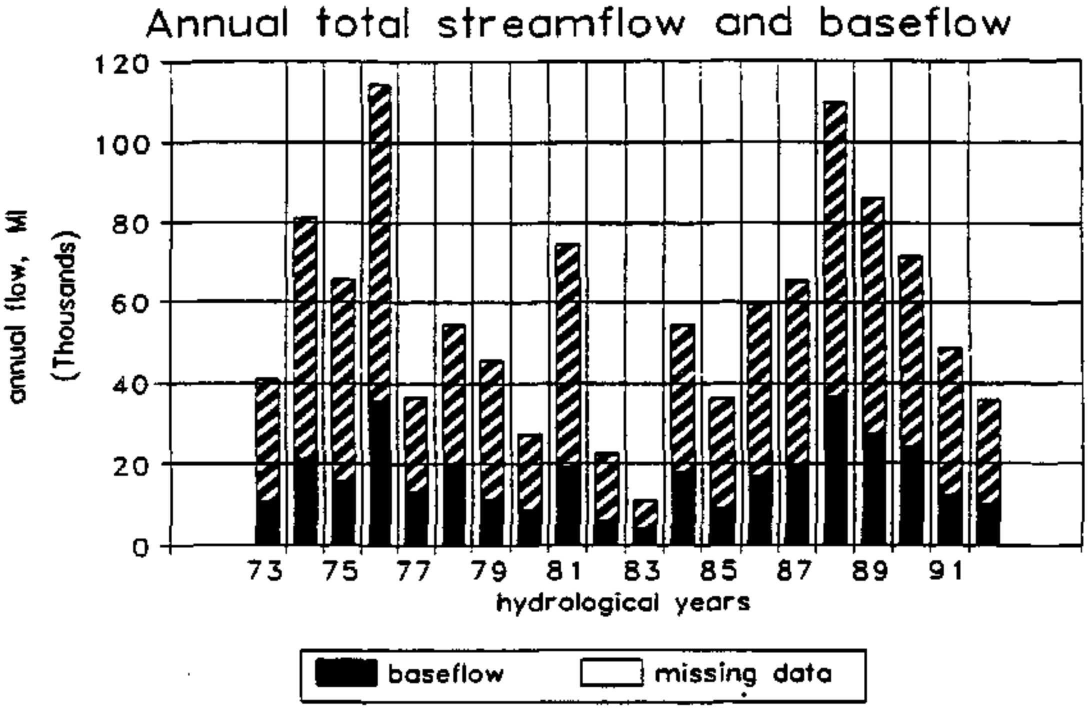

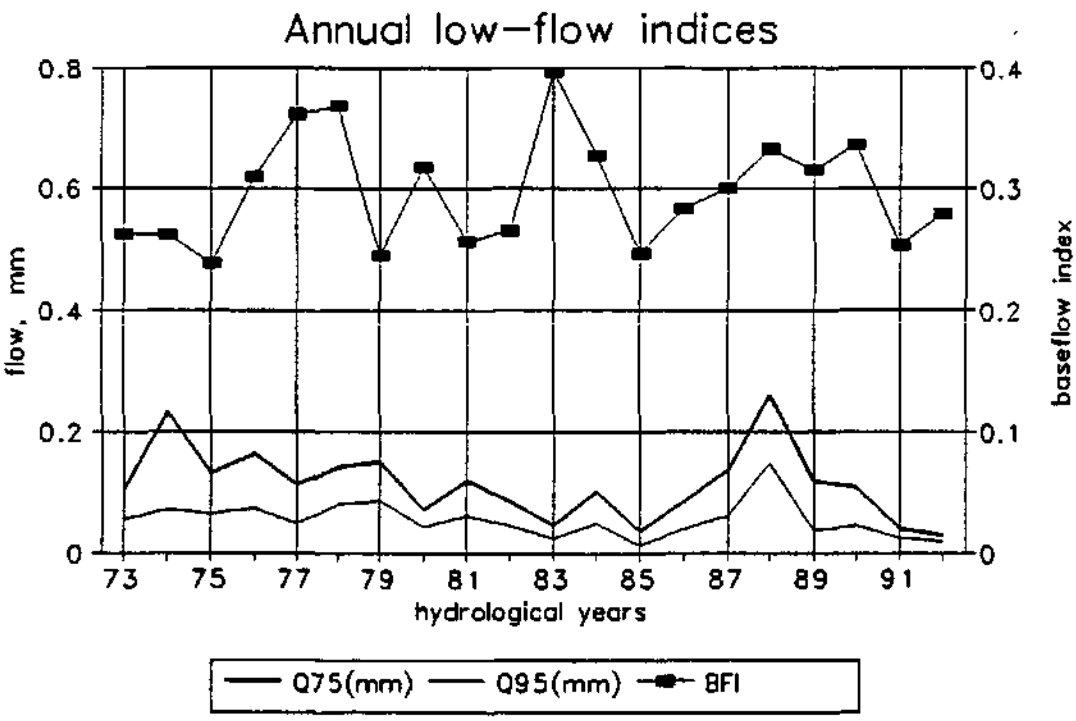

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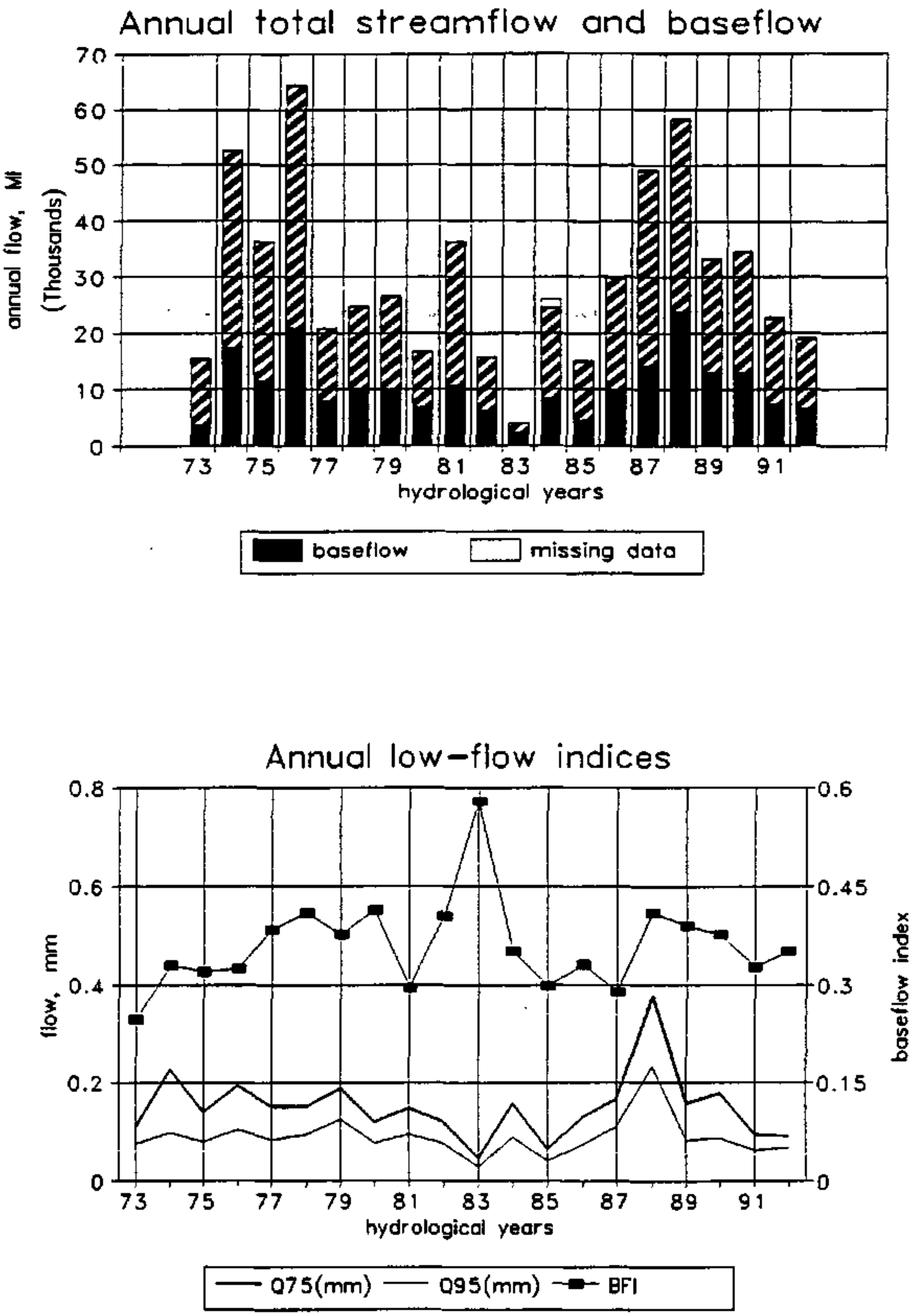

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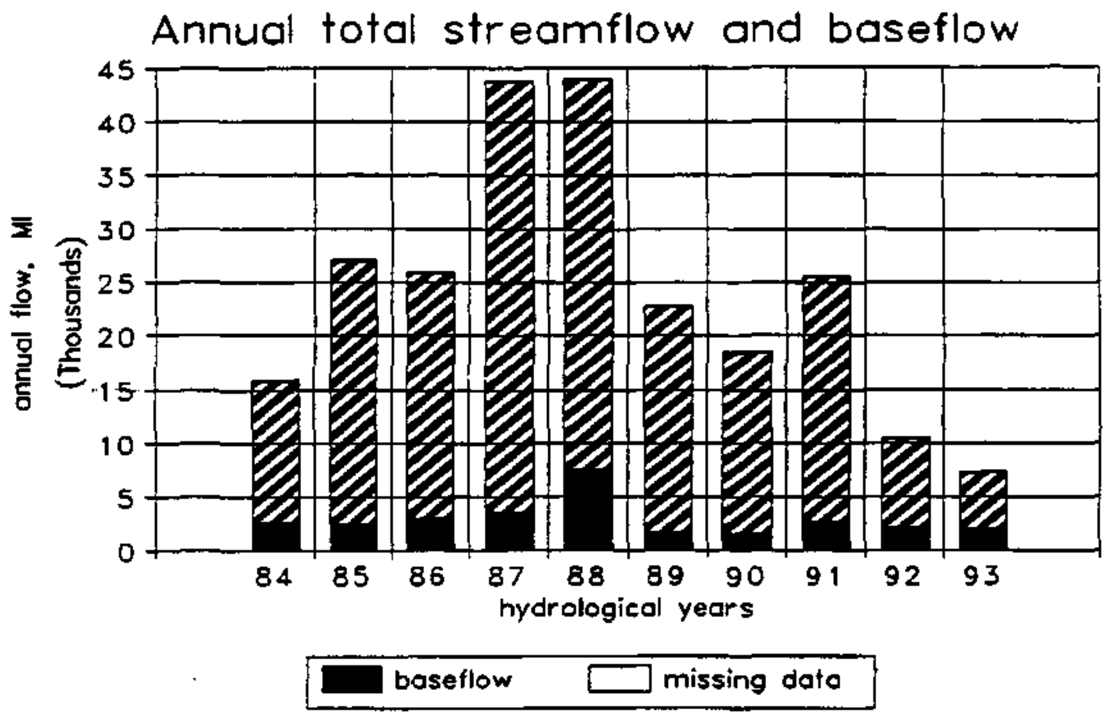

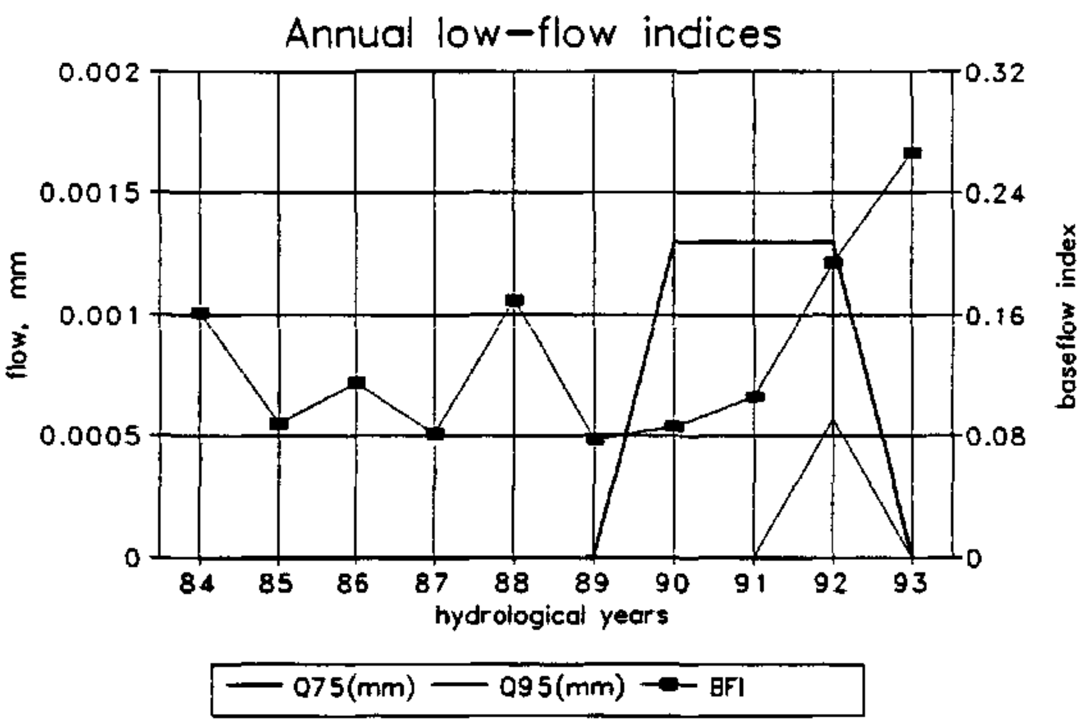

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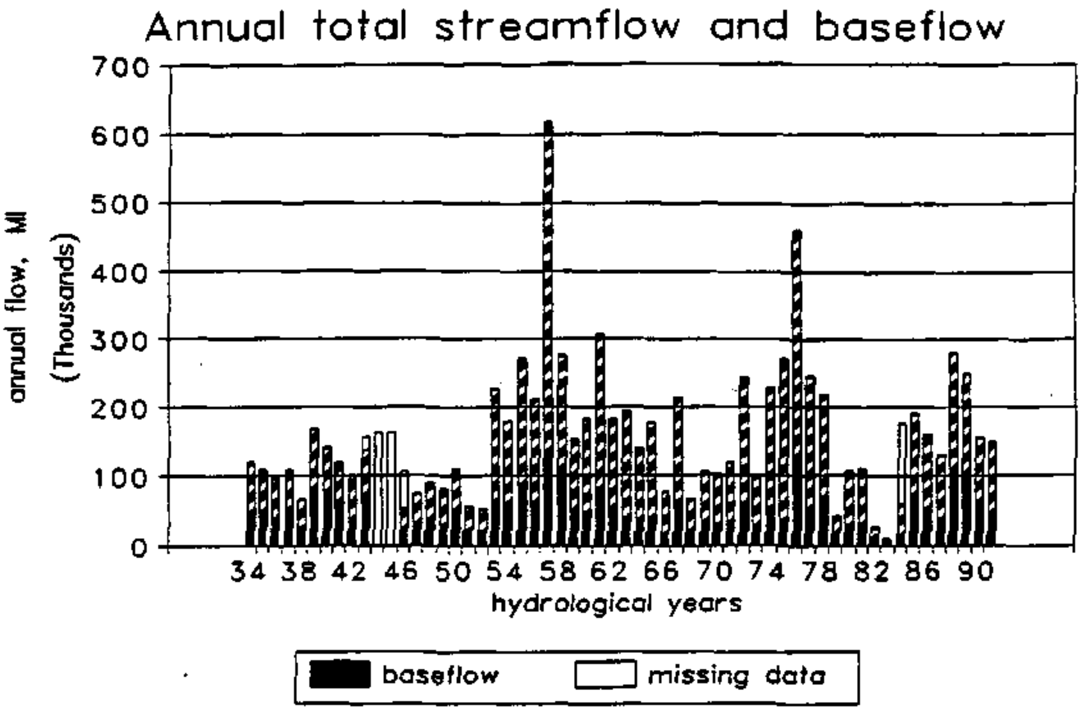

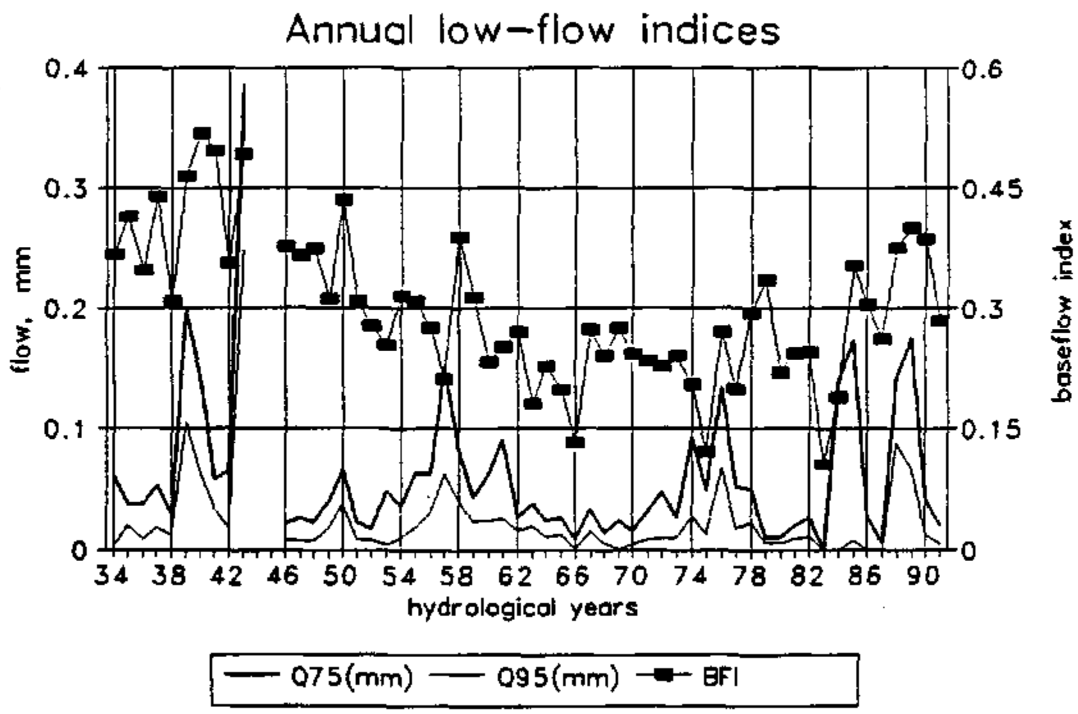

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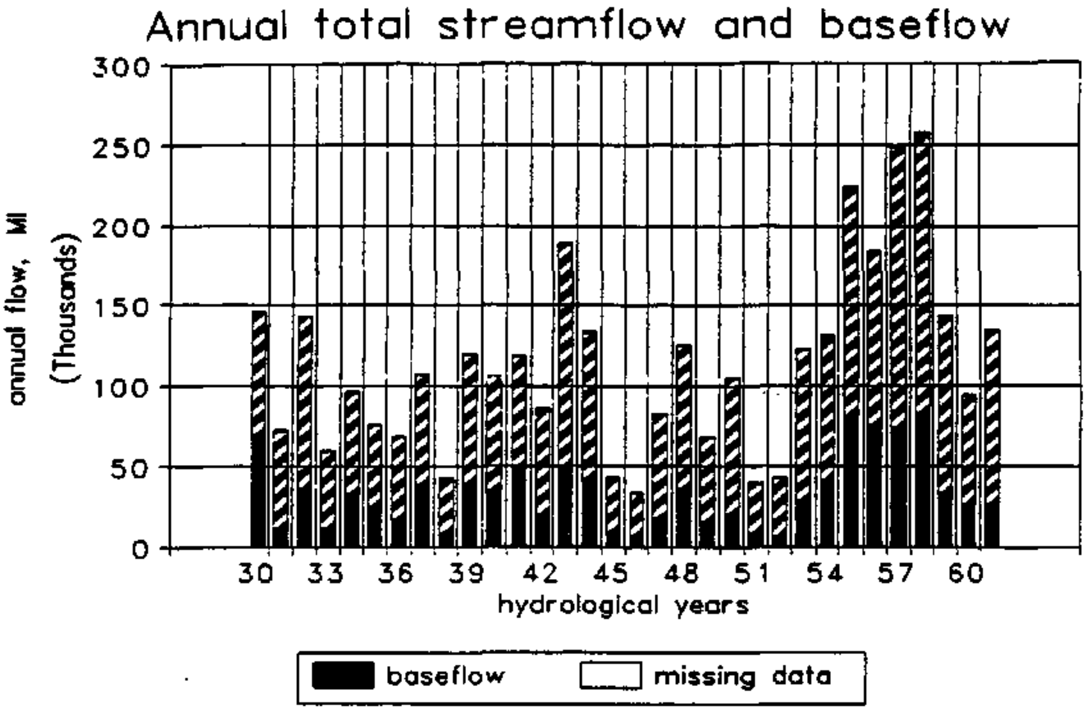

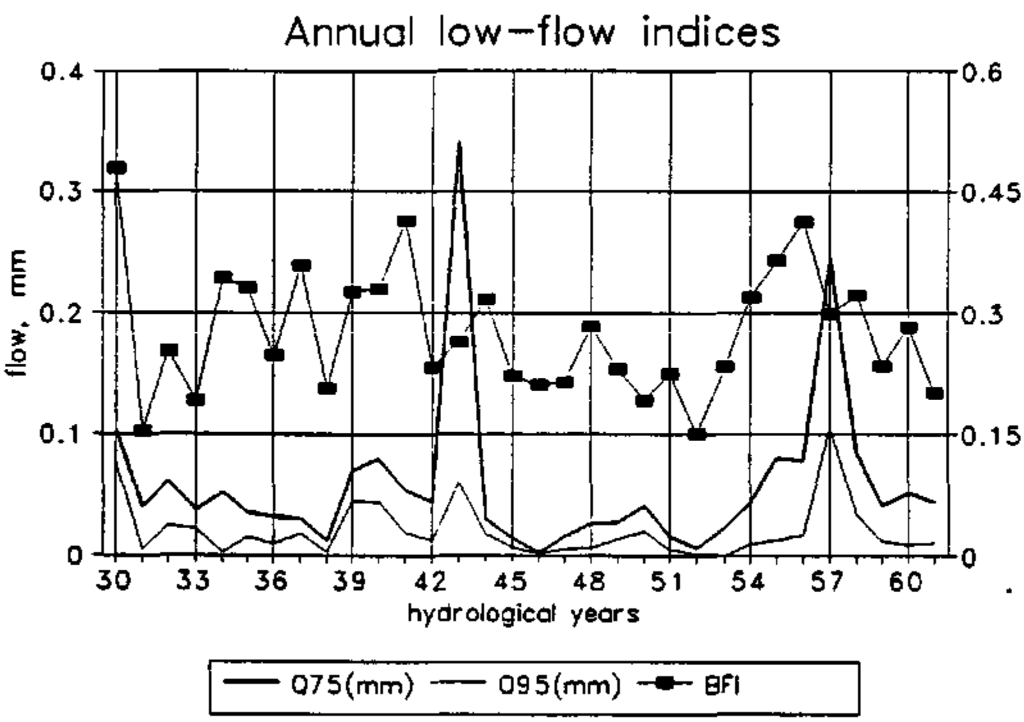

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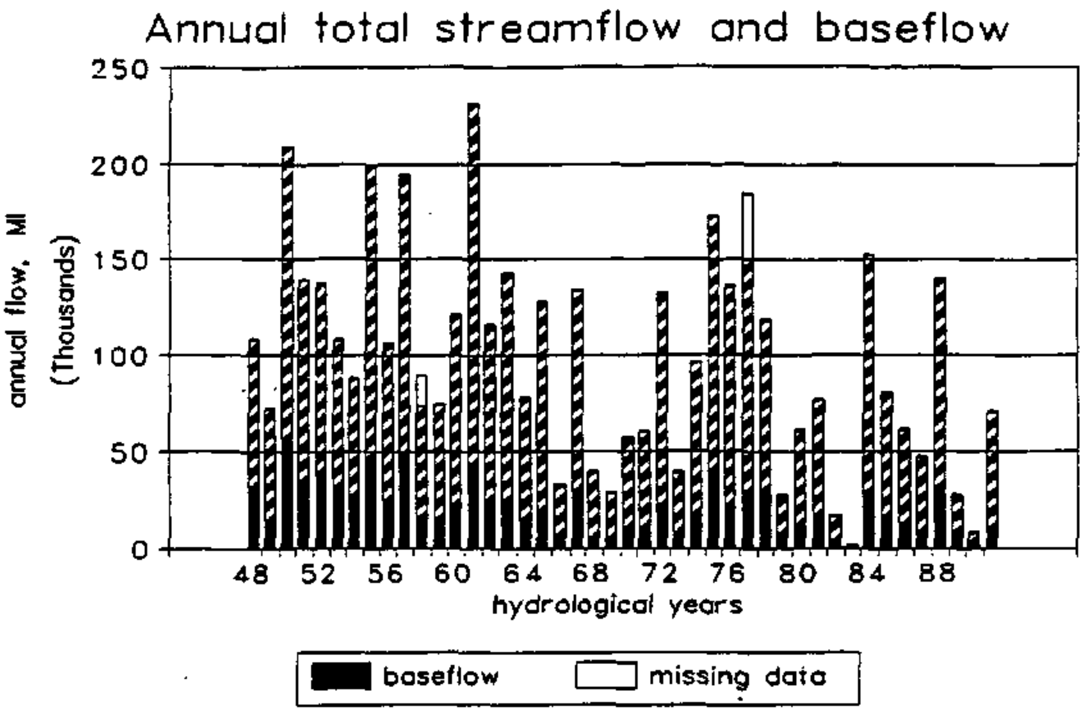

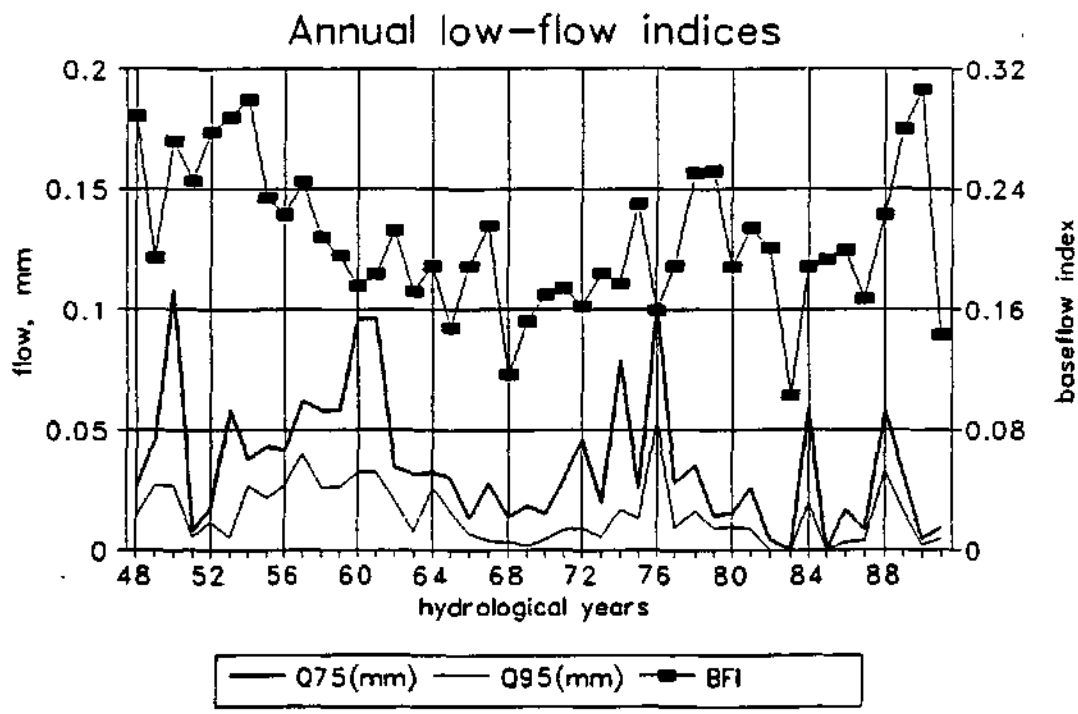

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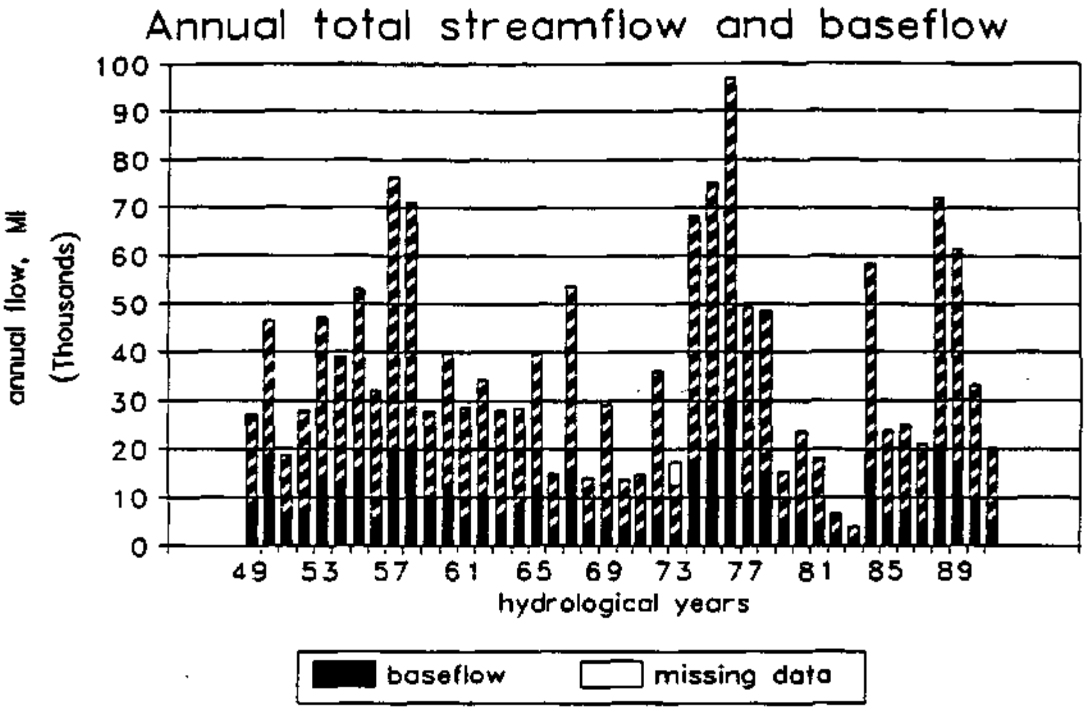

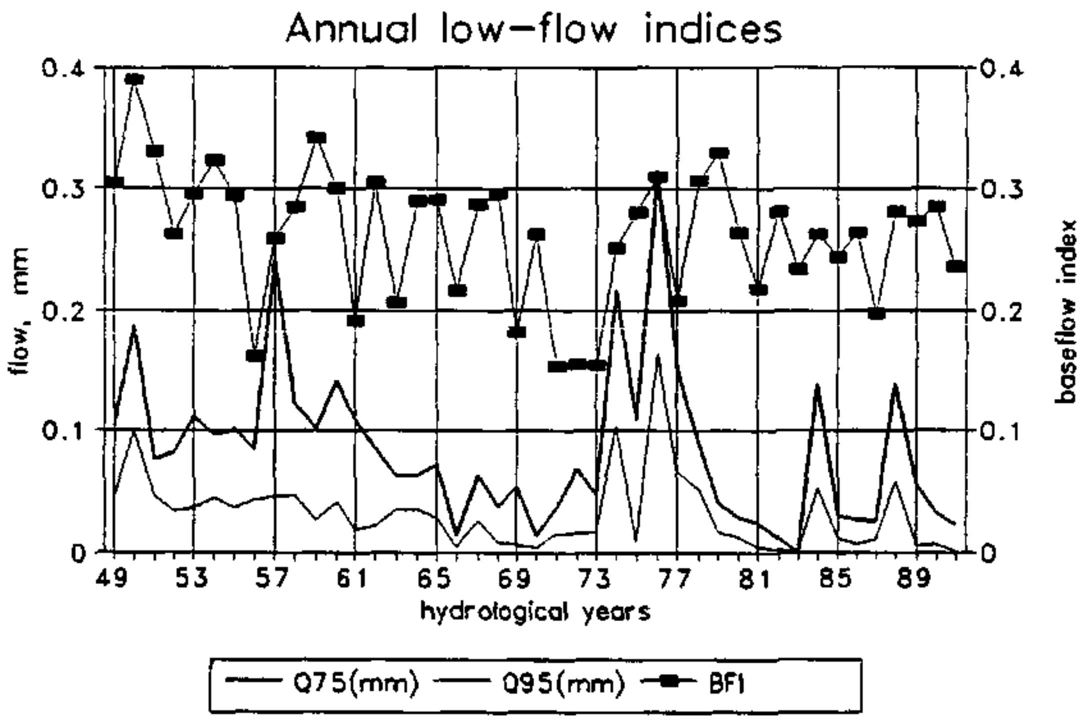

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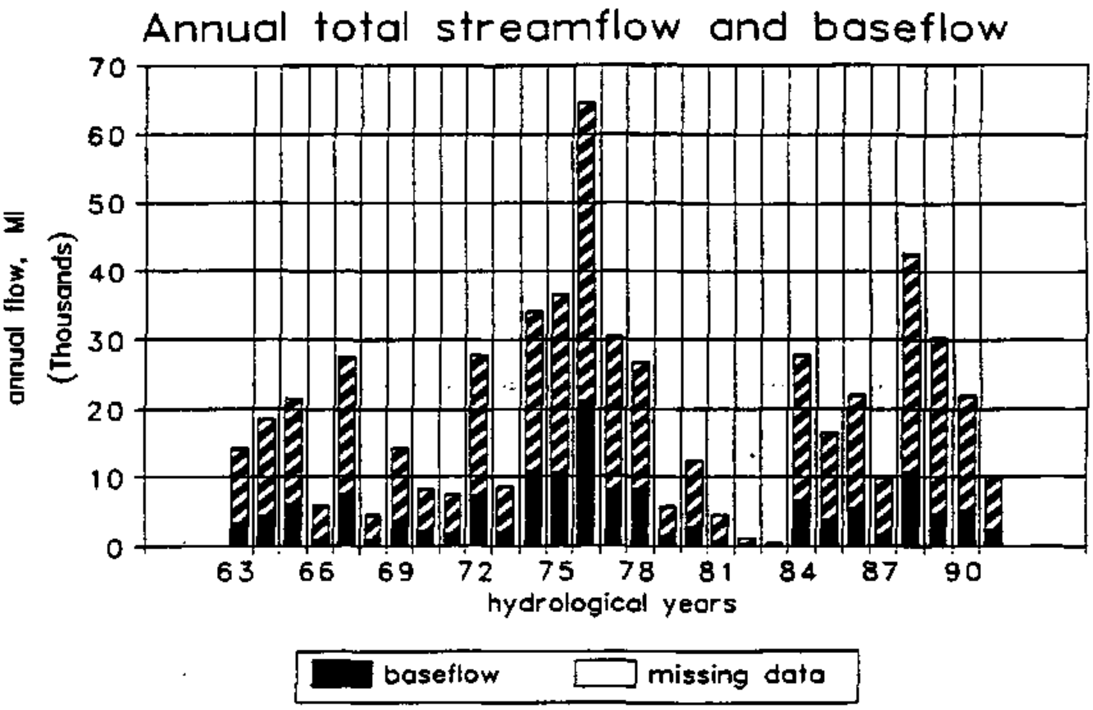

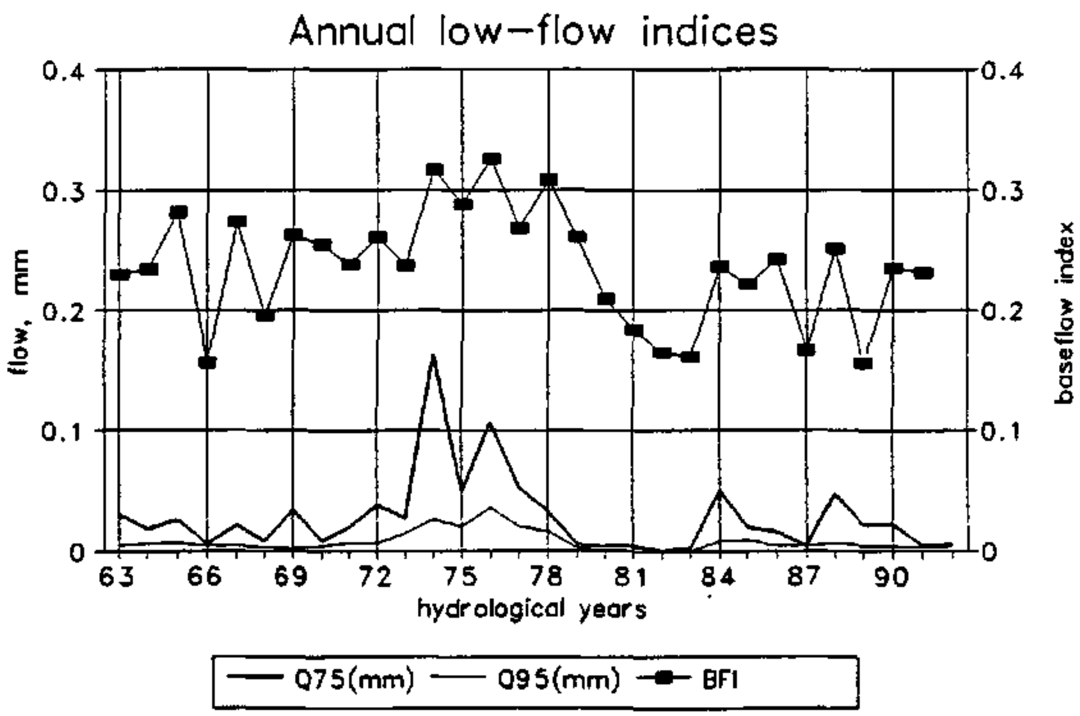

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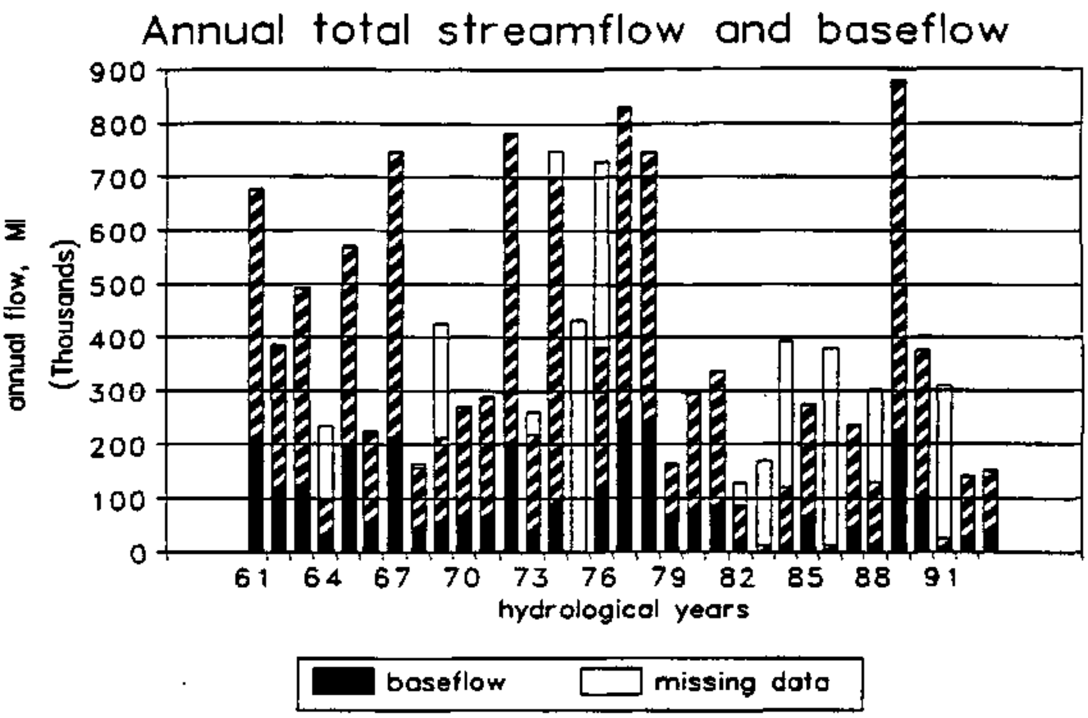

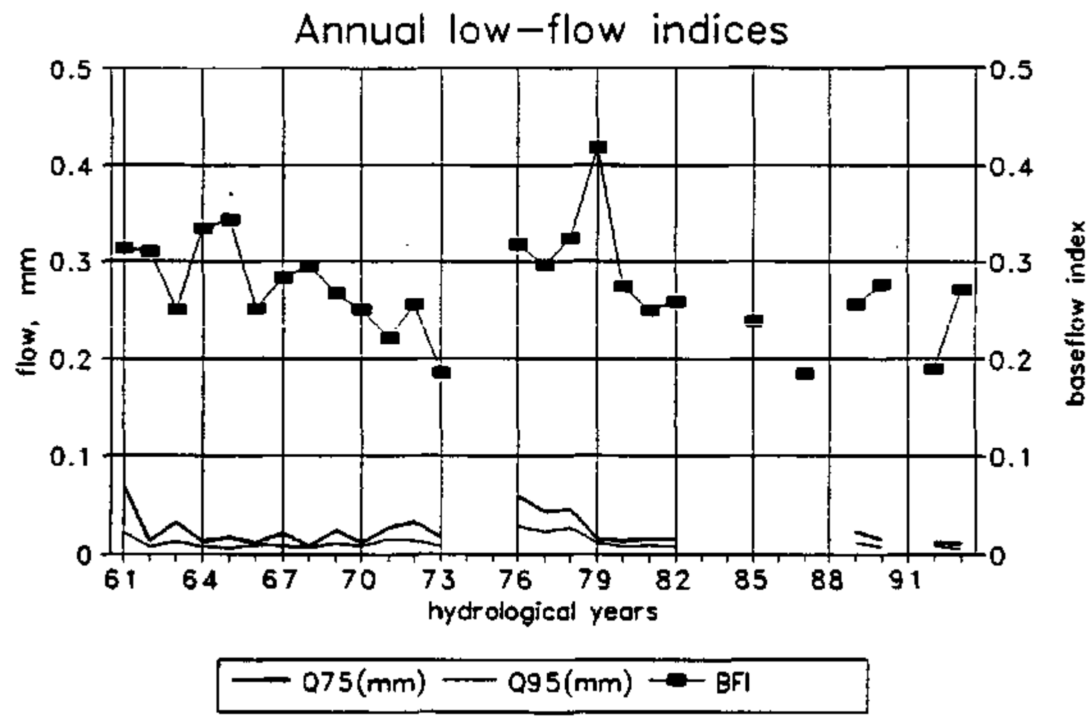

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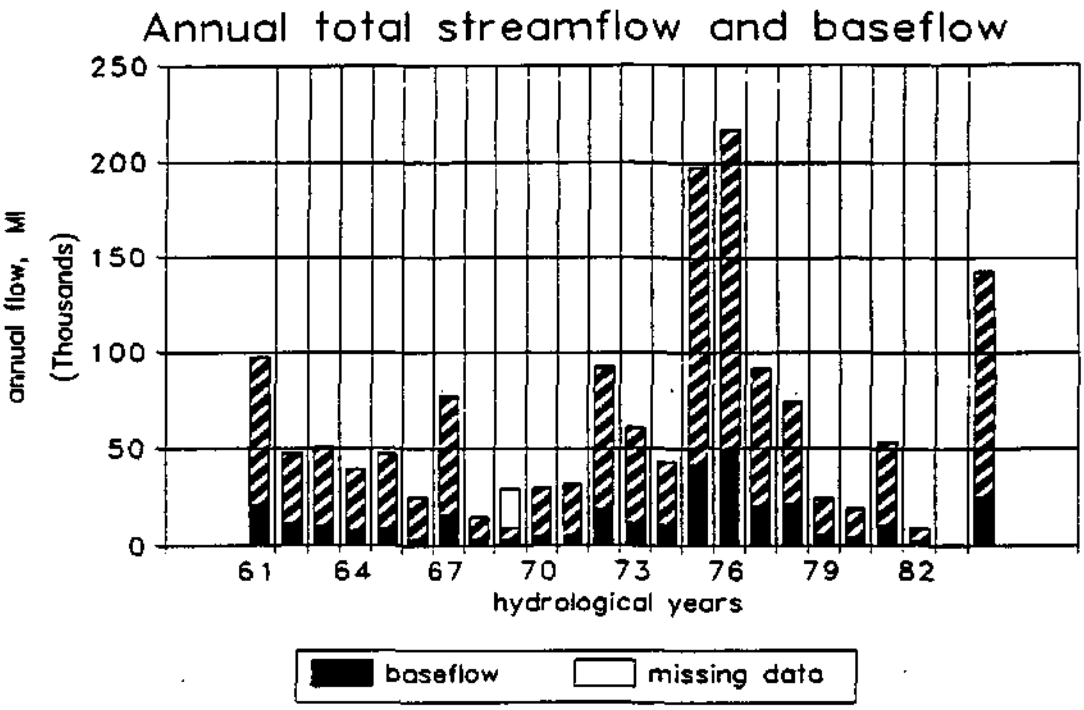

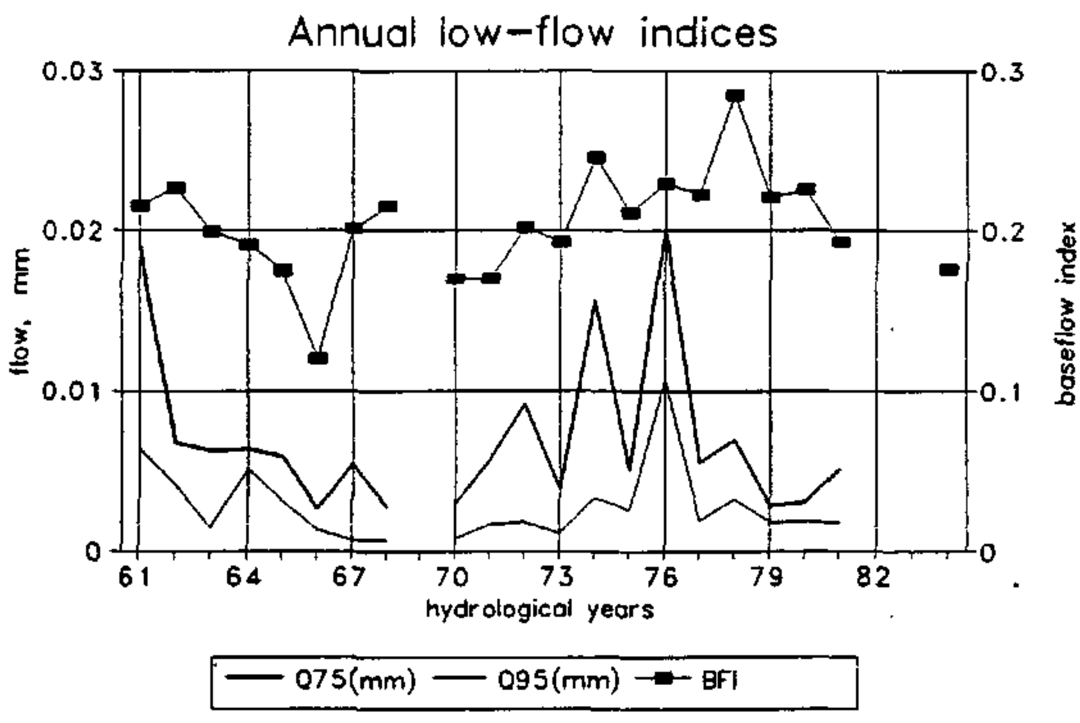

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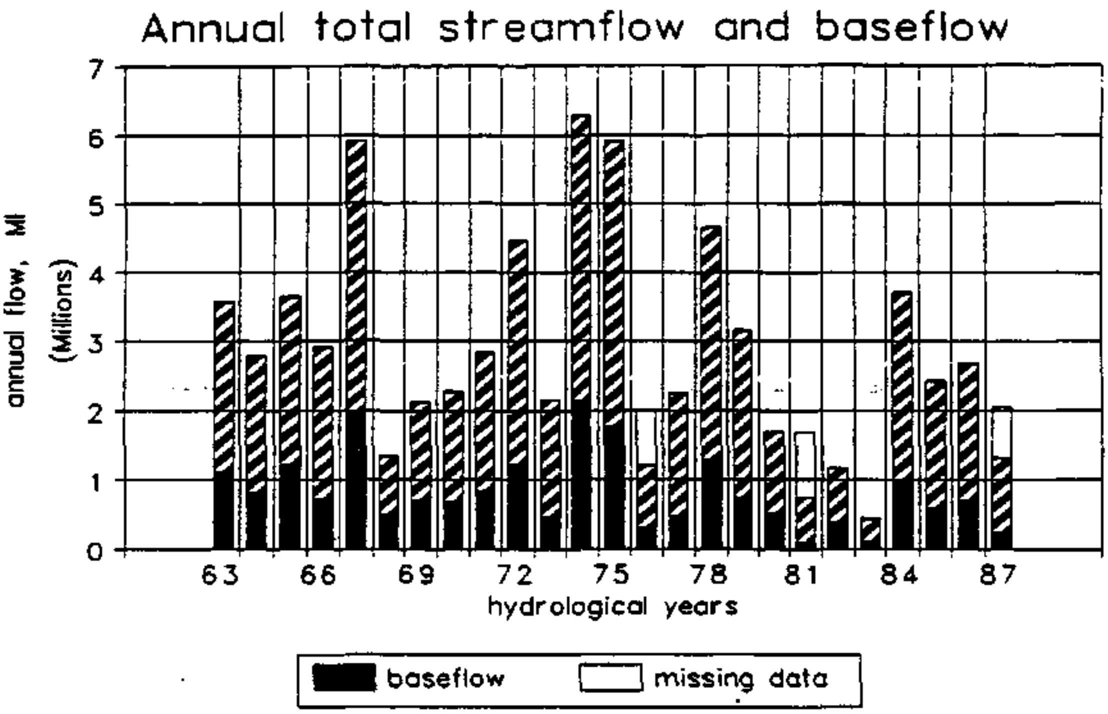

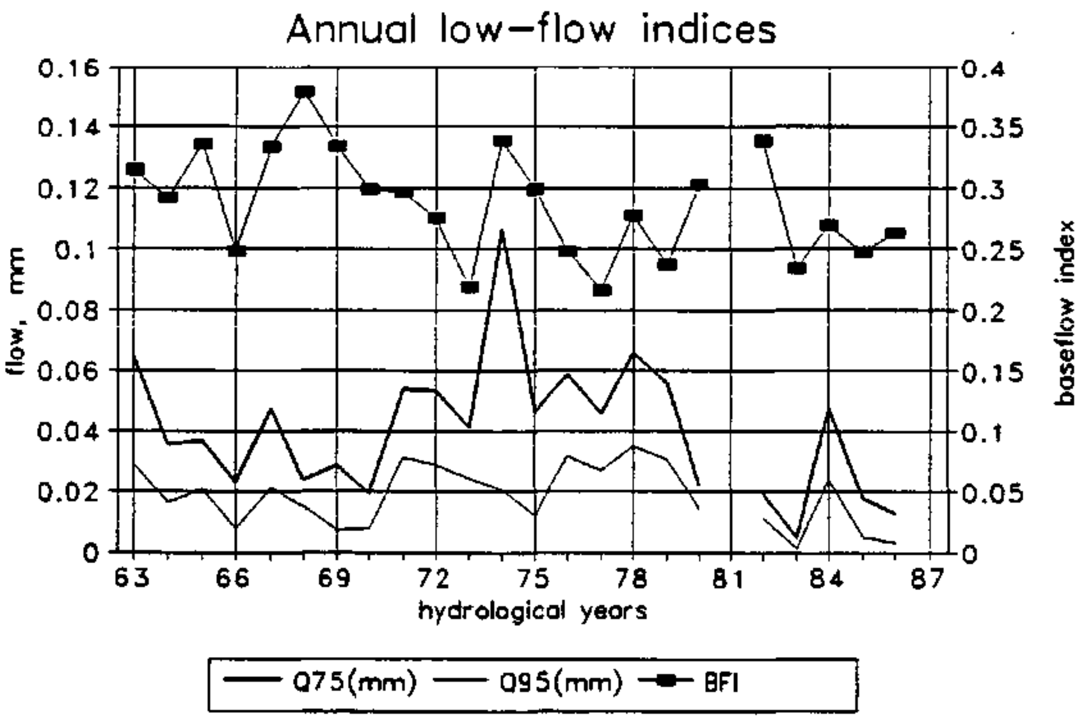

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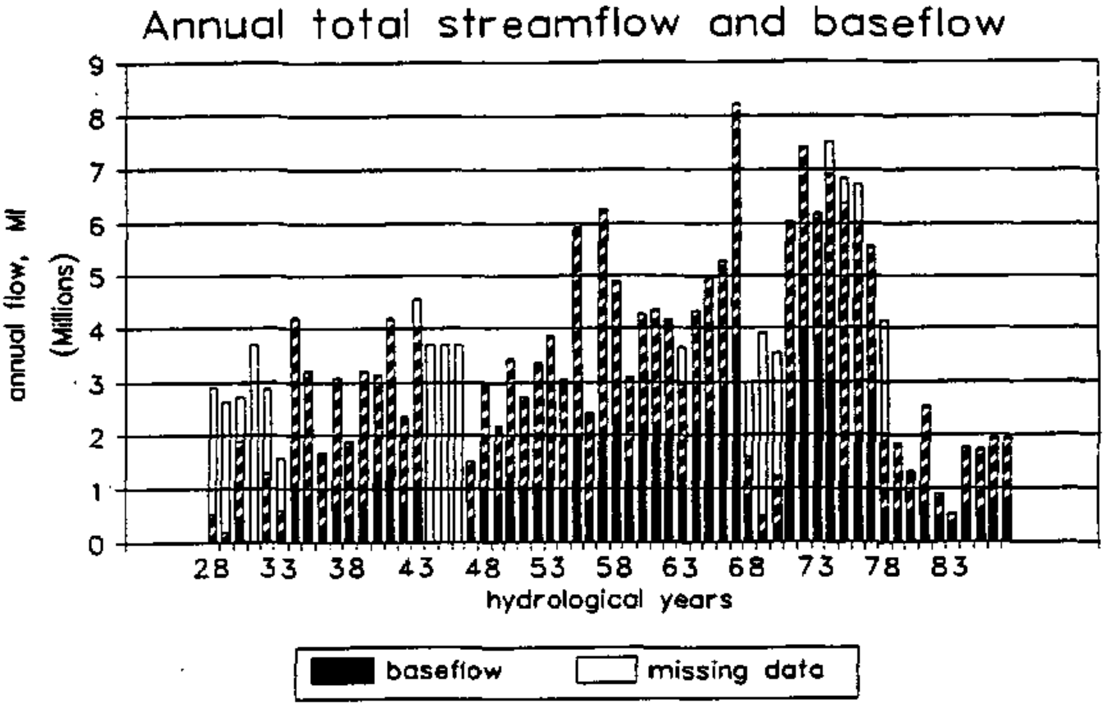

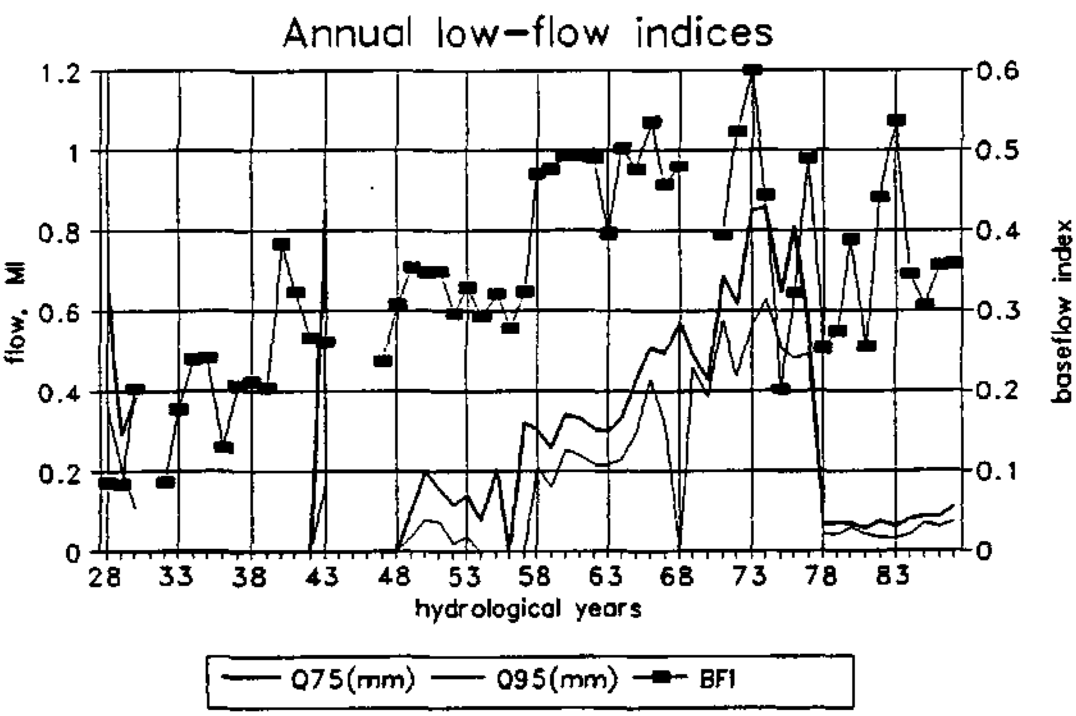

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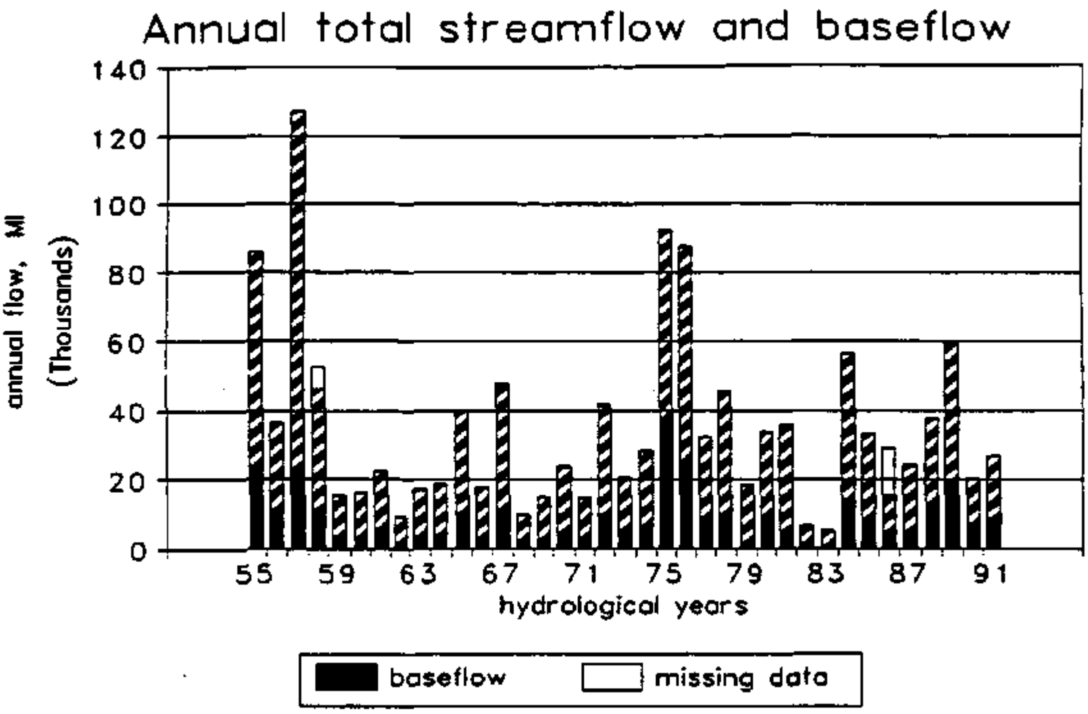

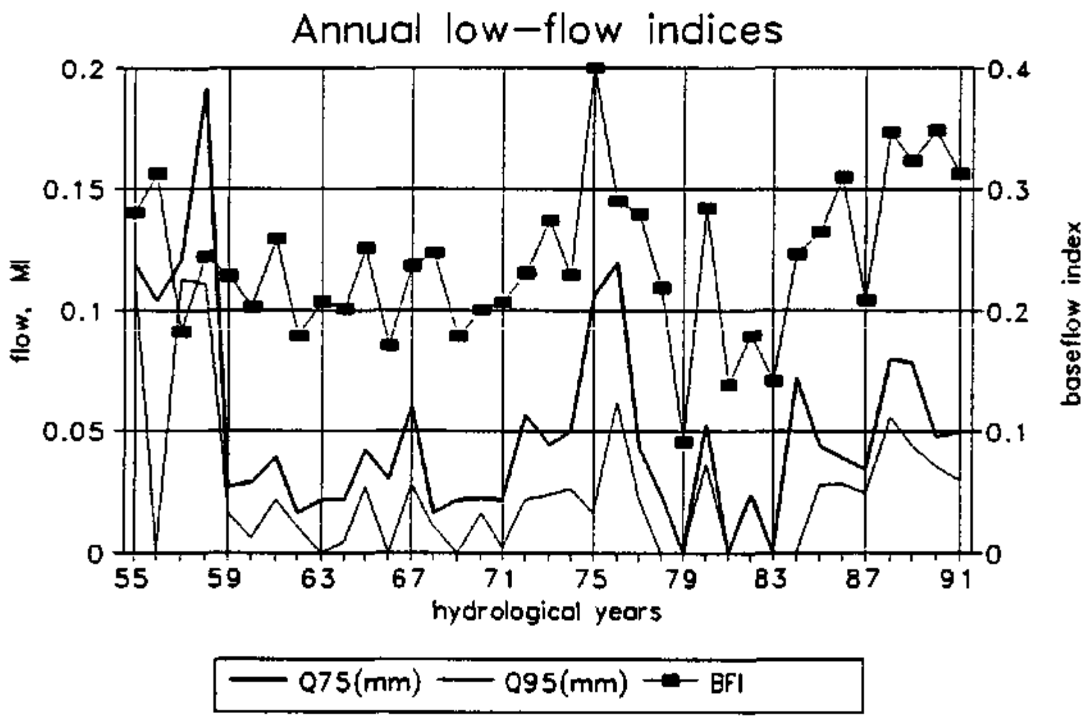

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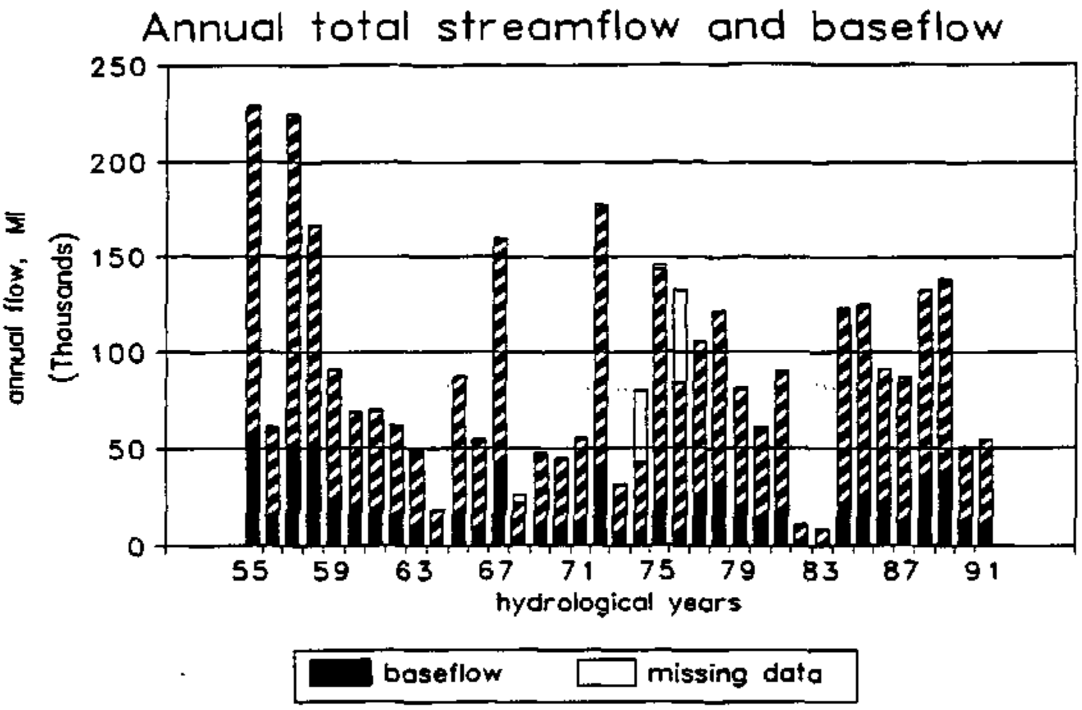

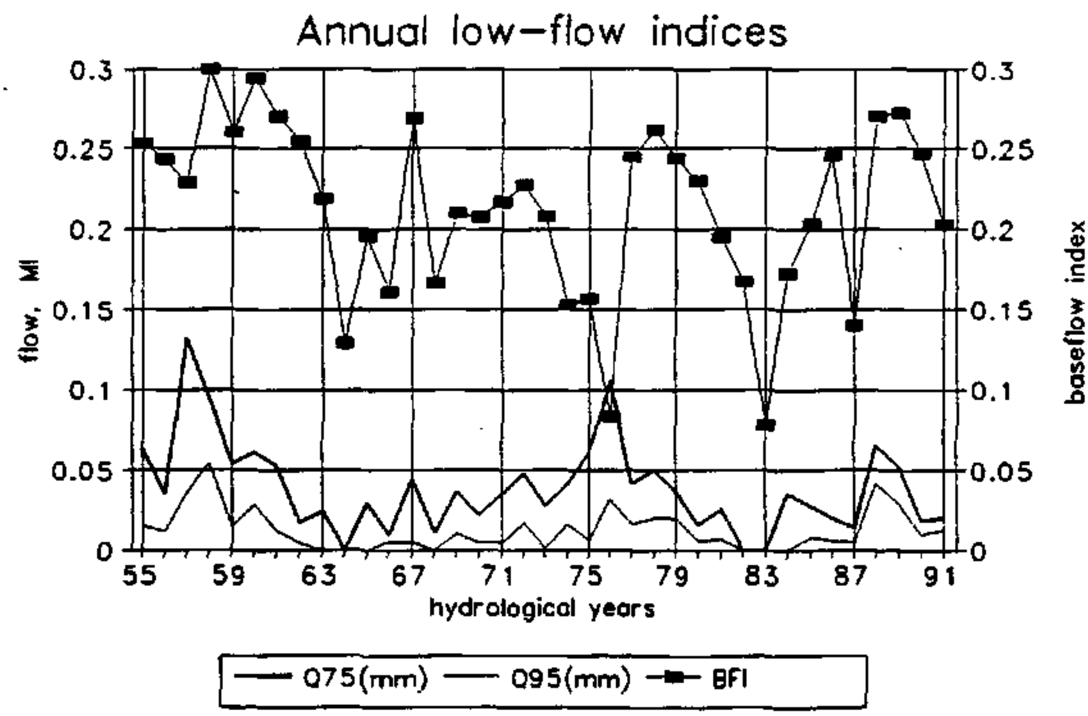

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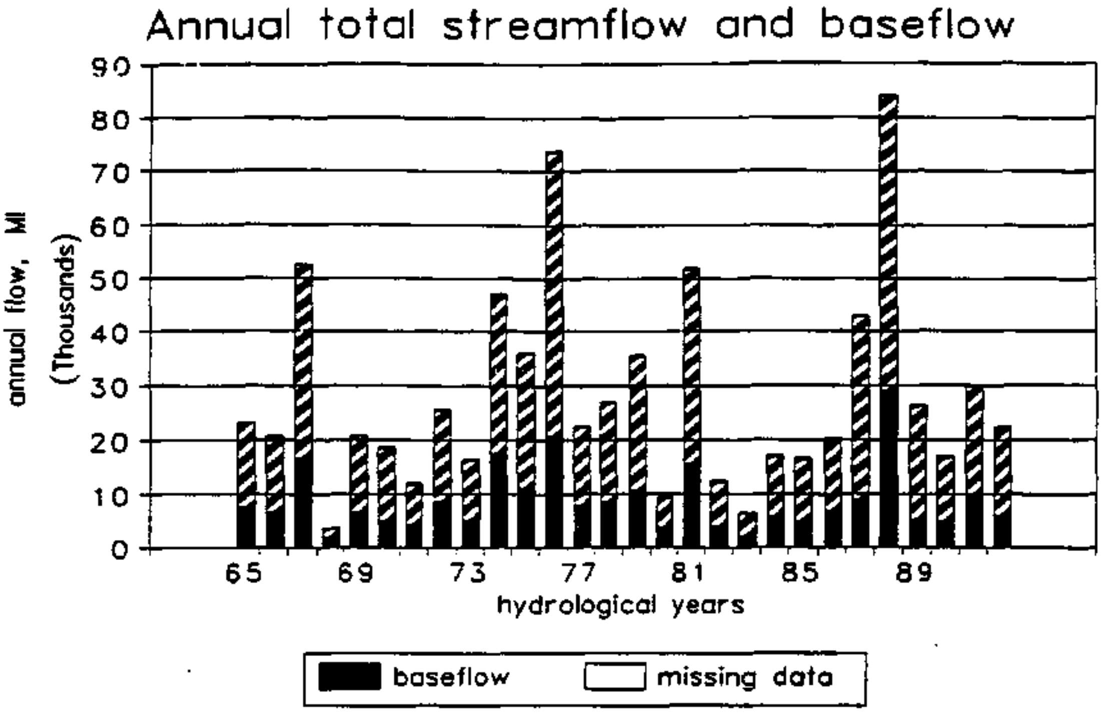

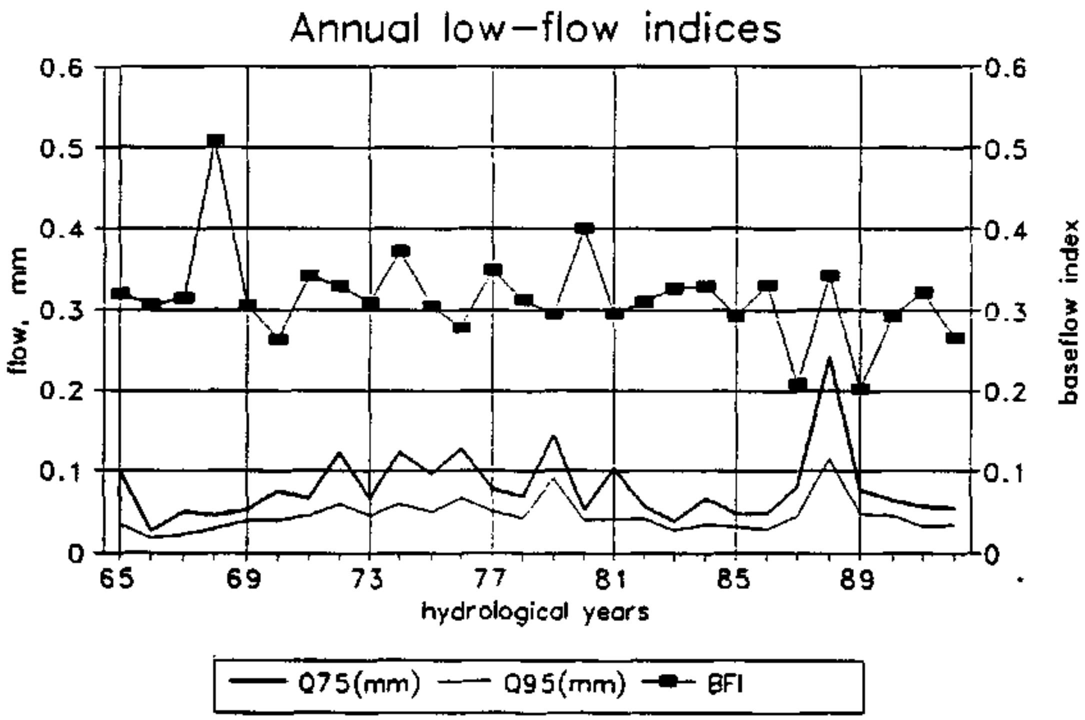

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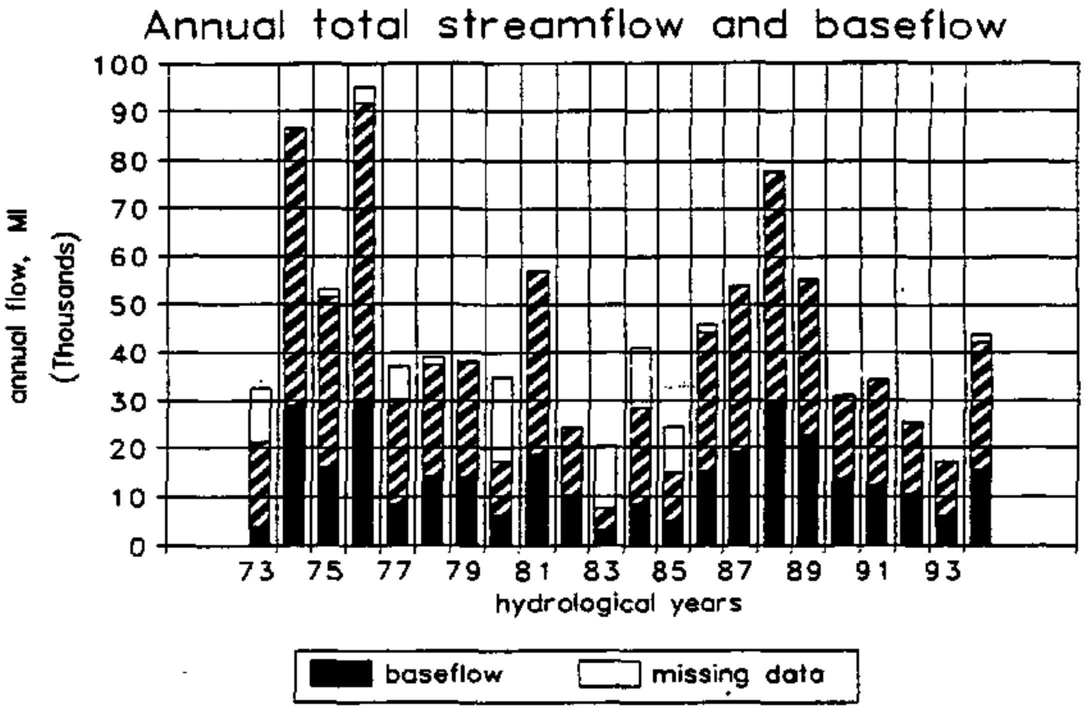

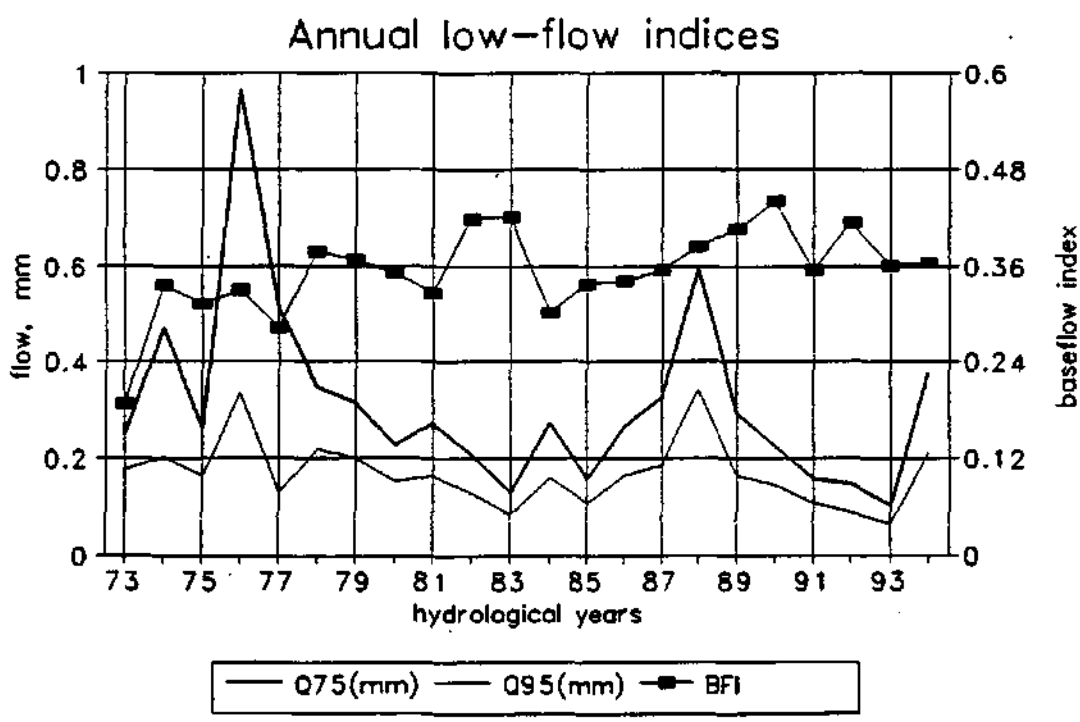

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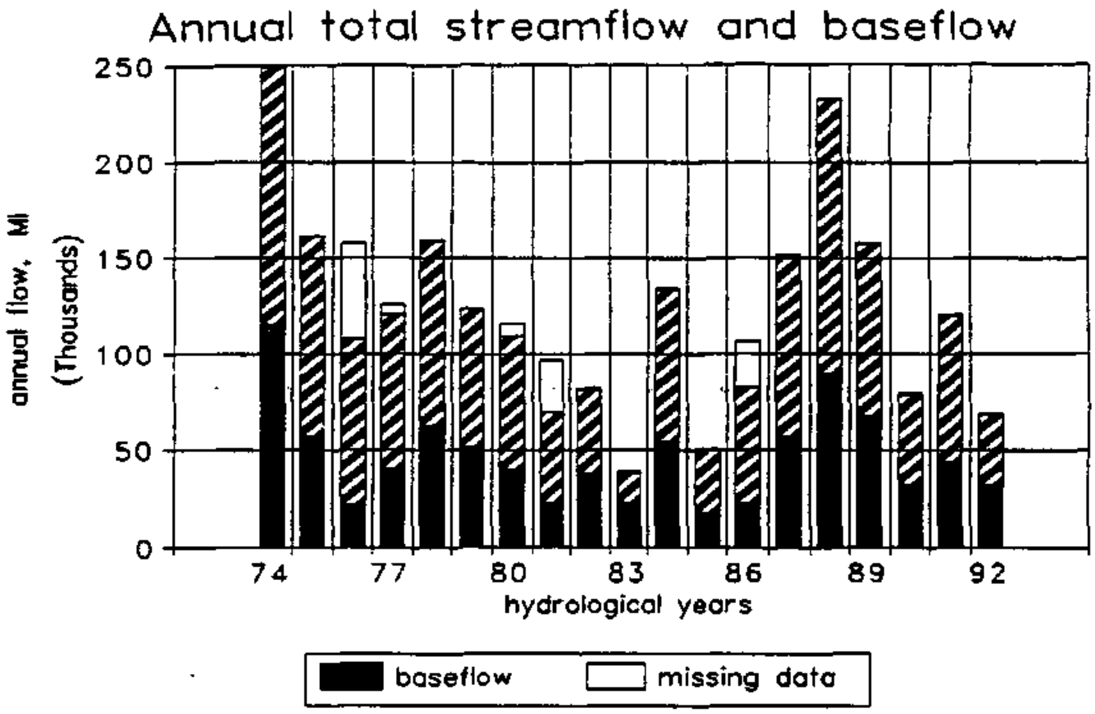

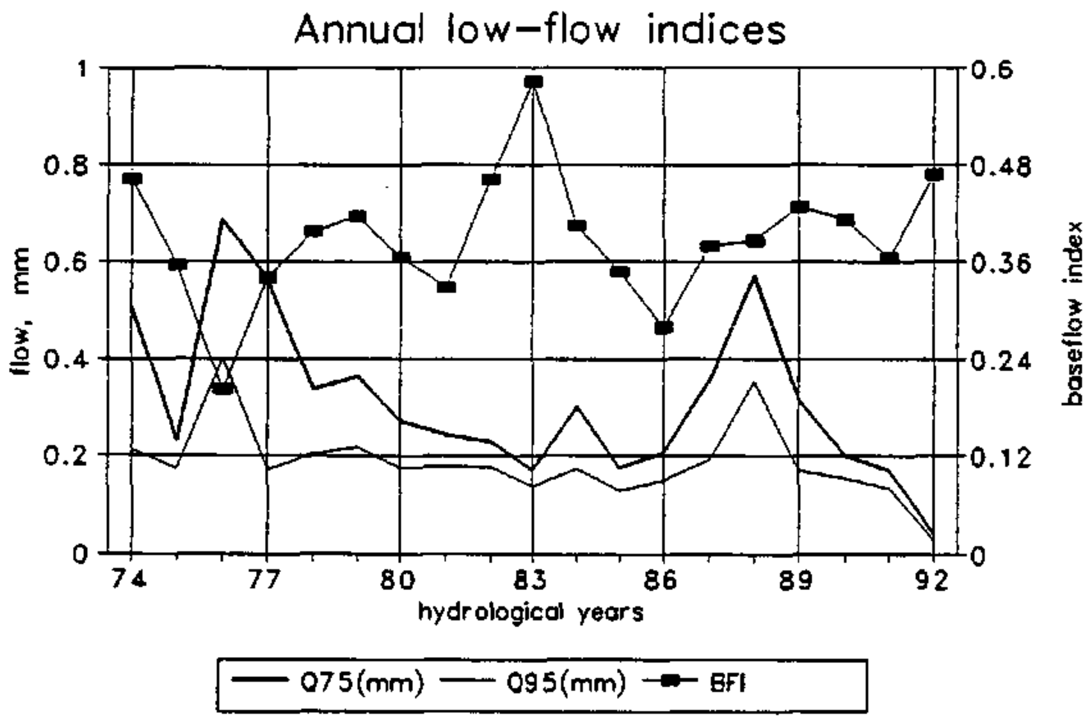

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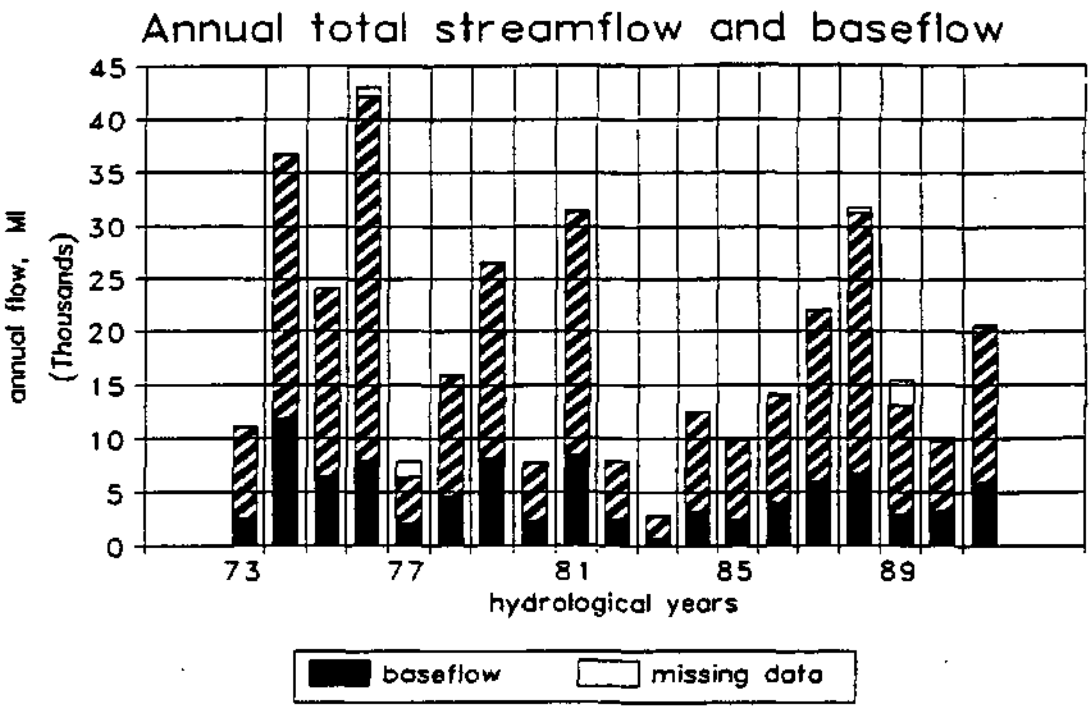


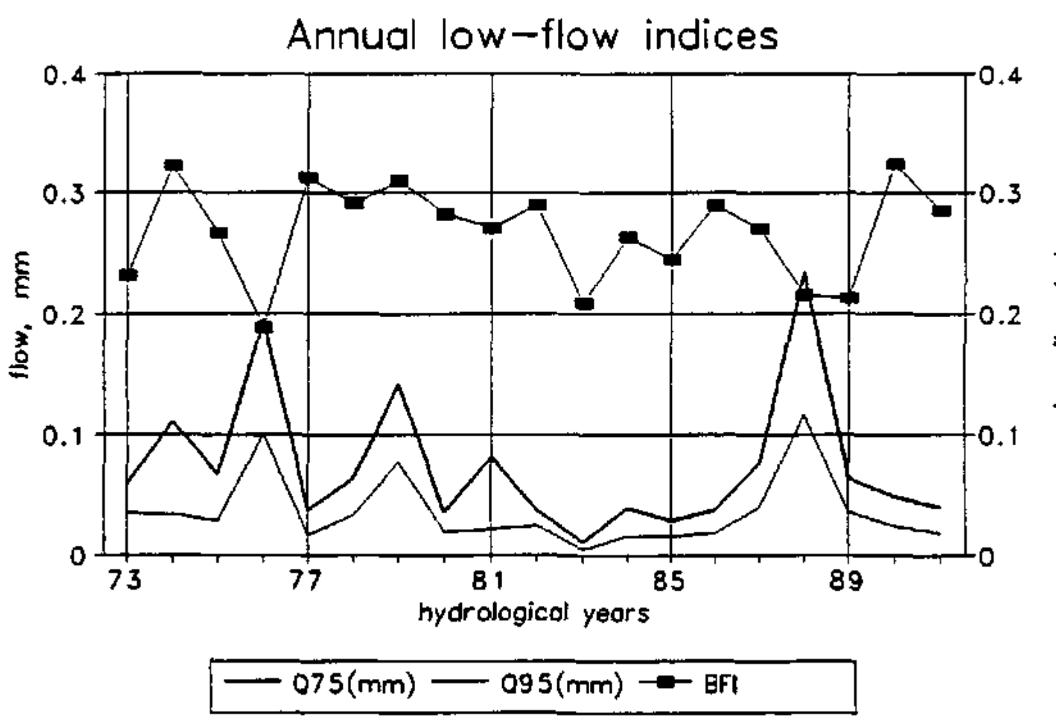


Figure D2.34. Gauge V7H018.

APPENDIX E1

Low-flow estimation in the T drainage region

E1.1 INTRODUCTION.

In all previous cases the approach for basin-wide low-flow estimation has been based primarily on the application of the deterministic modelling technique. It has been demonstrated how a satisfactorily long daily flow time sequence may be simulated for ungauged sites in the catchment and how any required low-flow characteristic may be calculated from simulated series. It has also been shown that the simulation approach may result in varying success since this success depends on the adequate quantification of model parameter values and the availability of reliable rainfall input data. The former is often hampered by a lack of knowledge on the physiographic characteristics of the drainage basins and data on water resource developments, while the latter are not always available in southern African conditions. The problem is exacerbated in underdeveloped and/or remote parts of the country, where the quality of both daily streamflow and daily rainfall data is poor. Daily flow simulation is also a rather time consuming and labour intensive exercise. The cost and timing of small-scale water projects (for example, rural water supply schemes) does not always justify the use of such sophisticated methods and simpler estimation techniques may be preferable.

Daily flow information for an ungauged site may be obtained by means of regionalization techniques which are based on available observed flow records. Regionalisation concentrates either on the estimation of a particular flow characteristic (e.g. flood or low flow with a certain return period, mean annual flow, etc) or some composite flow characteristic describing the range of flows (flow duration curve, low-flow frequency curve, etc). Therefore regionalisation techniques do not normally have the objective of generating a complete flow time series. Methods for regional estimation of floods, low-flow indices, flow duration curves, low-flow frequency curves are described in a number of sources with examples from all over the world (e.g. FREND, 1989; Regionalization in Hydrology, 1990). In southern Africa regional methods of flood estimation are described by Alexander (1990), while regional Deficient Flow - Duration - Frequency and Storage - Draft - Frequency curves are available from the study on Surface Water Resources of South Africa 1990 - WR90 (Midgley et al, 1994). The latter study is based on synthetic monthly flow time series data widely used in South African engineering practice. No attempt has been previously made to regionalise daily flow characteristics in the country. However, if this approach is successfully applied in South African conditions, it may provide a pragmatic alternative to deterministic daily flow simulations and a possibility to simplify the estimation of low-flow characteristics.

In this Appendix the available observed daily streamflow data are first examined by HYMAS data analysis routines and the existing low-flow conditions in the region are illustrated in terms of several standard low-flow indices. The approach which has been used to calculate low-flow characteristics in the region is then described. This approach belongs to a family of classical regionalisation techniques and is aimed at the regionalisation of 1-day flow duration curves. Since a flow duration curve gives only a "summary" of a flow regime at a site, and in many cases a complete time series of daily flows is required to perform other types of hydrological analysis, the Appendix also describes an approach by which an established regional FDC can be used to generate synthetic hydrographs at ungauged sites. Finally the results of the regionalization approach are used to calculate several low-flow indices for each quaternary subcatchment in two major river basins in the region.

E1.2 THE DESCRIPTION OF THE STUDY AREA.

The T drainage region includes the north-eastern parts of the Eastern Cape Province (Fig. E1.1) to the south of the Great Escarpment (Figure E1.1 has been constructed based on the ARCINFO coverage of "blue lines" available from the DWAF). The topography of the region is characterised primarily by steep slopes and deep river gorges. Most of the rivers are bedrock-controlled in their upper reaches and partially bedrock-controlled in the middle and lower reaches. The area is underlain predominantly by fine sedimentary rocks (tillites, sandstones). Soils are moderate to deep and of a sandy loam to clayey loam texture. The vegetation types gradually change in a south-easterly direction from pure grassveld and temperate forests and scrubs to tropical forest and veld in the coastal regions. False grassveld type is present along the major river valleys in the central parts of the region. Over most of the region mean annual precipitation varies between 700 and 1000 mm with a peak rainfall in the summer months. Part of the precipitation especially at the beginning of the summer season, is orographic in origin. Later in the season precipitation may result from convectional instability. Coastal areas receive more rain (900 -1500 mm) falling throughout the year.

T drainage region has about 14.5% of the overall surface water resources of South Africa (Pitman, 1995). The largest river in the region, the Mzimvubu, with a catchment area of about 20000 km^2 and mean annual runoff over 2.8 billion m^3 (the fourth highest in the country) is currently considered as a possible source of water which could increase the yield of the Vaal river system. The total MAR of the two other major rivers (Mzimkhulu and Mbashe) is 2.2 billion m^3 (Pitman, 1995). Most of the rivers are perennial with a clear wet season during December to March followed by a long recession period with minimum flows in July to September. Until now the region has not experienced any major water resource development. Limited areas in the north-eastern parts of the region are used for forestry plantations. The population is concentrated mostly in a rural sector with predominant utilization of local water resources through small-scale irrigation and water supply schemes. The latter sector of water utilisation is likely to be developing very fast in the region to meet the requirement of the Government Rural Water Supply and Sanitation Programme (Water Supply and Sanitation Policy, 1994).

E1.3 OBSERVED STREAMFLOW DATA.

Although streamflow in the T region is (or was) measured at more than 40 gauges, the data for only 18 gauging stations are actually available from the DWAF. Two of these gauges are almost at the same position in the same stream and that effectively reduces the number of gauges to 17. Since these daily flow records are the only observed source of hydrological

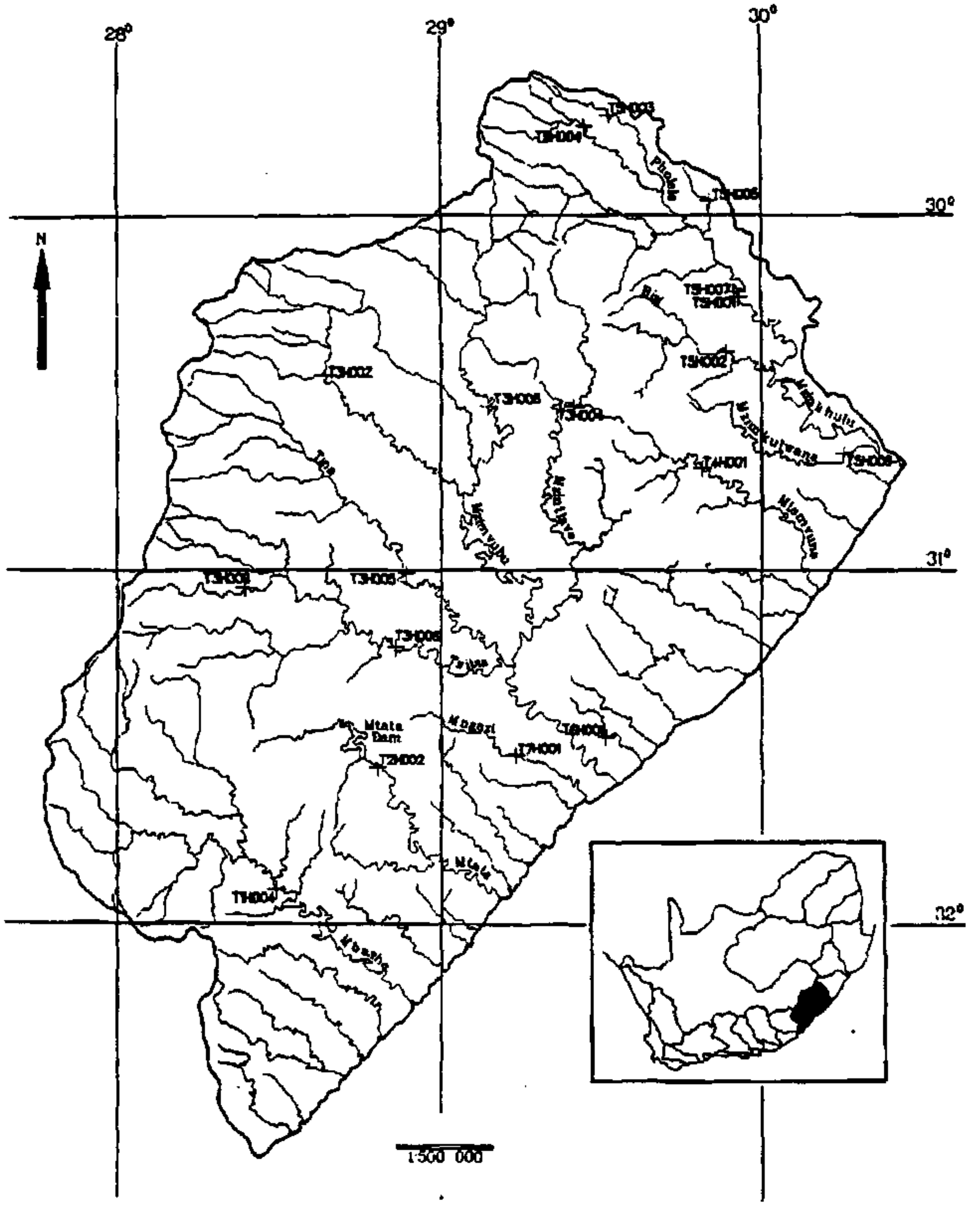


Figure E1.1. The map of the study area showing streamflow gauge locations.

information for the entire region, all of them have to be considered. Some details of these gauges are summarised in Table E1.1, while their location is shown on Figure E1.1.

All data sets have been examined by means of the HYMAS data analysis routine which allows annual flow volumes for each gauge to be calculated from the original daily data and plotted as a time series. This provides an easy way of looking at the quality of the data since

Table E1.1. *Flow gauges in the T drainage region.*

N	Code	River	Area, km^2	Record period	Comments
1	T1H004	Mbashe	4924	1956-1973	
2	T2H002	Mtata	1199	1959-1983	Period used 1959-1976,(dam in 1977)
3	T3H002	Kinira	2101	1949-1980	DTL = 120 m^3/s, patched, (R^2=0.77, CE=0.76)
4	T3H004	Mzintlava	1029	1947-1991	DTL = 18.4 m^3/s
5	T3H005	Tina	2597	1951-1975	patched and extended (R^2=0.75, CE=0.75)
6	T3H006	Tsitsa	4268	1951-1994	
7	T3H008	Mzimvubu	2471	1962-1993	DTL = 98.6 m^3/s
8	T3H009	Mooi	307	1964-1993	
9	T4H001	Mtamvuna	715	1951-1992	
10	T5H001	Mzimkhulu	3643	1931-1979	
11	T5H002	Bisi	867	1934-1959	DTL = 17 m^3/s
12	T5H003	Phoela	140	1949-1993	DTL = 5 m^3/s until 1957. Period used 1958-1993.
13	T5H004	Mzimkhulu	545	1949-1993	
14	T5H005	Nkonzo	100	1949-1992	
15	T5H006	Mzimkhulwana	534	1950-1959	DTL = 2.85 m^3/s. Patched & extended (R^2=0.72, CE =0.72)
16	T6H001	Mntafufu	108	1969-1979	DTL = 25 m^3/s. Cannot be patched
17	T7H001	Mngazi	315	1970-1981	Cannot be patched

*DTL - Discharge Table Limit

the procedure identifies and graphically displays "bad years" with the potential amount of "missing flow" . This allows the usable period of record for each gauge to be selected and the necessity and possibility of patching the records to be determined.

Temporal changes in low flows have been investigated by extracting similar low-flow indices for each year of record and plotting them as a time series. This provides a possibility to detect obvious trends or other non-stationarities in low-flow regimes themselves as opposed to annual flows. Low-flow indices selected were the same as in the previous Chapters: 1-day Q75 and Q95 flows extracted from the annual flow duration curve for each gauge, annual baseflow volumes and baseflow index values (BFI). The graphs of annual flows and annual low flow indices for each gauge in the region are presented in APPENDIX E2.

This analysis revealed some non-stationarities in several records. For example, the record at gauge T2H002 on the Mtata River demonstrates a stable decrease in annual low-flow during the period from 1959 to 1976, when the dam was constructed upstream of the gauge. However annual totals during the pre-impoundment period seem to remain stationary (Fig. E2.2, APPENDIX E2).

Gauge T3H002 had a low DTL in the earlier part of the record which resulted in the underestimation of the annual flow totals prior to the 1970s (Fig. E2.3). However, low flows remained stationary. Other gauges in drainage region T3 do not demonstrate obvious trends in either annual totals or low flows.

Some gauges in the upstream reaches of drainage region T5 seem to demonstrate a slight decrease in annual low-flows (T5H003, T5H004, T5H005), however, annual flow totals remain stationary. No low-flow estimation on an annual basis has been done for gauges T6H001 and T7H001 since their records are short and contain a number of gaps due to missing data.

Plots of annual total flows have also demonstrated that in some data sets missing data periods make flow records considerably shorter and therefore less representative (e.g. gauge T3H005, Fig. E2.5). In these cases patching of records has been performed using the spatial interpolation algorithm described in Chapter 6 (Vol 1). Table E1.1 lists the stations where the patching was performed. The table also illustrates the degree of success of each application in terms of the coefficient of determination (R^2) and efficiency (CE) - conventional criteria used to assess the quality of simulation by any model. The time series compared were the original observed daily flows and the daily flows generated by the spatial interpolation algorithm. The latter were substituted in the observed time series to fill missing data periods. If the fit statistics were satisfactory (e.g. CE $>$ 0.6) the flow record at the destination site (where patching was performed) was also extended beyond the observation period, provided the source site observation period was longer. Wherever patching/extension was not possible (or not entirely successful) only the available observed data were used.

For the regional hydrological analysis, described later in this Appendix, it is necessary that all site estimates of the flow characteristic being investigated, are based on records with a concurrent period. In the case of the T region, as in most other parts of South Africa, this standard period cannot be established without loosing part of the record at several gauges or some data sets entirely (Fig.E1.2). Therefore, in this situation any available observation period is forced into use.

The last column in Table E1.1. also demonstrates that many gauges in the region are too small to measure high flow events. This problem cannot be resolved within the limits of the current project and the implications of that are discussed later in the Appendix.

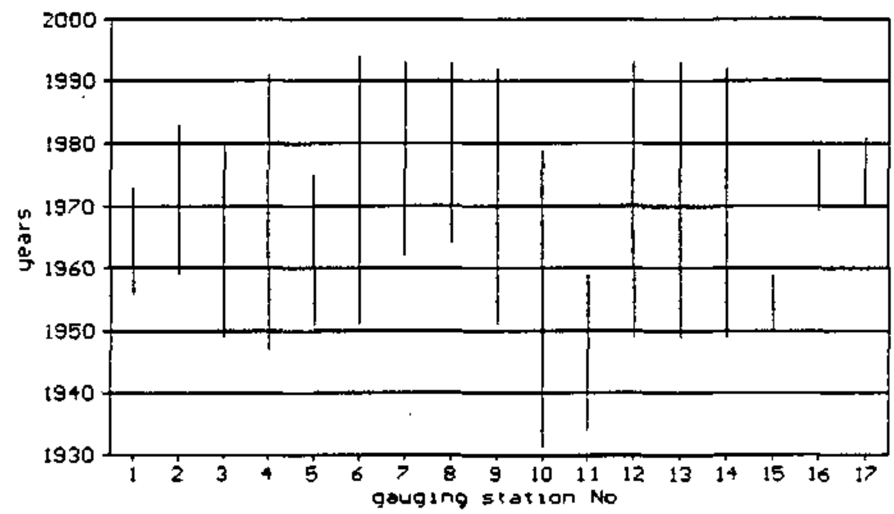


Figure E1.2. The lengths of observation periods at flow gauges in the T region.

E1.4. REGIONALIZATION OF FLOW DURATION CURVES.

Different approaches for the regionalization of FDCs have been described. Nathan and McMahon (1992) used the assumption of the linearity of a 1-day annual FDC in log-normal space and derived regional regression equations for two points on a curve: flows exceeded 10% and 90% of the time (for intermittent rivers the latter point is replaced by a percent of the time with zero flows). In FREND (1989) study, non-dimensional 1-day annual FDCs were averaged for each of several pre-defined catchment groups. The shape of the whole curve in each group appeared to be dependent on only one point: the flow exceeded 95% of the time. Fennessey and Vogel (1990) developed regional regression equations for parameters of the log-normal distribution which fits the lower half of a FDC. Regionalization of FDCs has also been discussed by Mimikou and Kaemaki (1985) and Quimpo et al (1983).

The method adopted to establish regional FDC in this study includes two major steps:

i) construction of non-dimensional FDCs for each flow gauge by dividing discharges from a curve by the mean daily flow and

ii) superposition of all individual FDCs in the region on one plot and the construction of a composite regional non-dimensional FDC.

Each individual FDC has been constructed using the relevant HYMAS program module (Chapter 3, Vol. 1). This module allows a FDC to be constructed from daily and monthly streamflow data for the whole period of record or any part thereof. The curves may be calculated for any of the 12 months of a year, any season or the whole year. Flows for the curve may be expressed in volumetric or discharge units or as a percentage of mean flow which is automatically calculated from the data set in use. Several fixed percentage points on the curve with corresponding flow rates can be printed or written to a file to allow several FDCs to be further displayed simultaneously using other software. These latter two options facilitate the direct comparison of FDCs between different catchments and are very useful tools for regional analysis.

Steps i) and ii) above have been performed for the whole year, wettest months, driest months and intermediate months of the year which have been identified by the analysis of seasonal flow distribution at all gauged sites in the region. This analysis has demonstrated that for the purpose of the present study the whole year may be split into three major periods: 4 wet (December - March), 4 dry (June - September) and 4 intermediate months (April, May, October, November). Plots of individual normalised FDCs are shown on Figure E1.3. The annual curves lie rather close to each other through most of the time scale. The picture is similar for the wettest and intermediate months while the differences between the individual curves appear to be somewhat larger during the driest period of a year.

The biggest differences in all four 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. The differences in the lowest part of the curves may partly be attributed to the inaccuracies of low-flow measurements, but they are mostly due to the fact that some observed records cover the period of the most severe recorded drought in the 1982 hydrological year while the others do not. During this extraordinary dry year some rivers in the region (normally perennial) ceased to flow for a short period and that has obviously affected the shape of some FDCs in the area of extreme low flows.

Since some of the gauges are rather small to measure high flows, the mean daily flow calculated from the observed records is underestimated, even if the gauge has a relatively long observation period. This results in the overestimation of the non-dimensional ordinates of a corresponding FDCs and therefore pushes up the upper boundary of the domain of the curves. Gauge T5H006 was found to be the most severely limited and was excluded from the final calculations. The FDCs from other limited gauges have been used since the examination of the data has demonstrated that their discharge table limit is exceeded less frequently. Nevertheless their highest (truncated) ordinates have not been used in the derivation of regional curves.

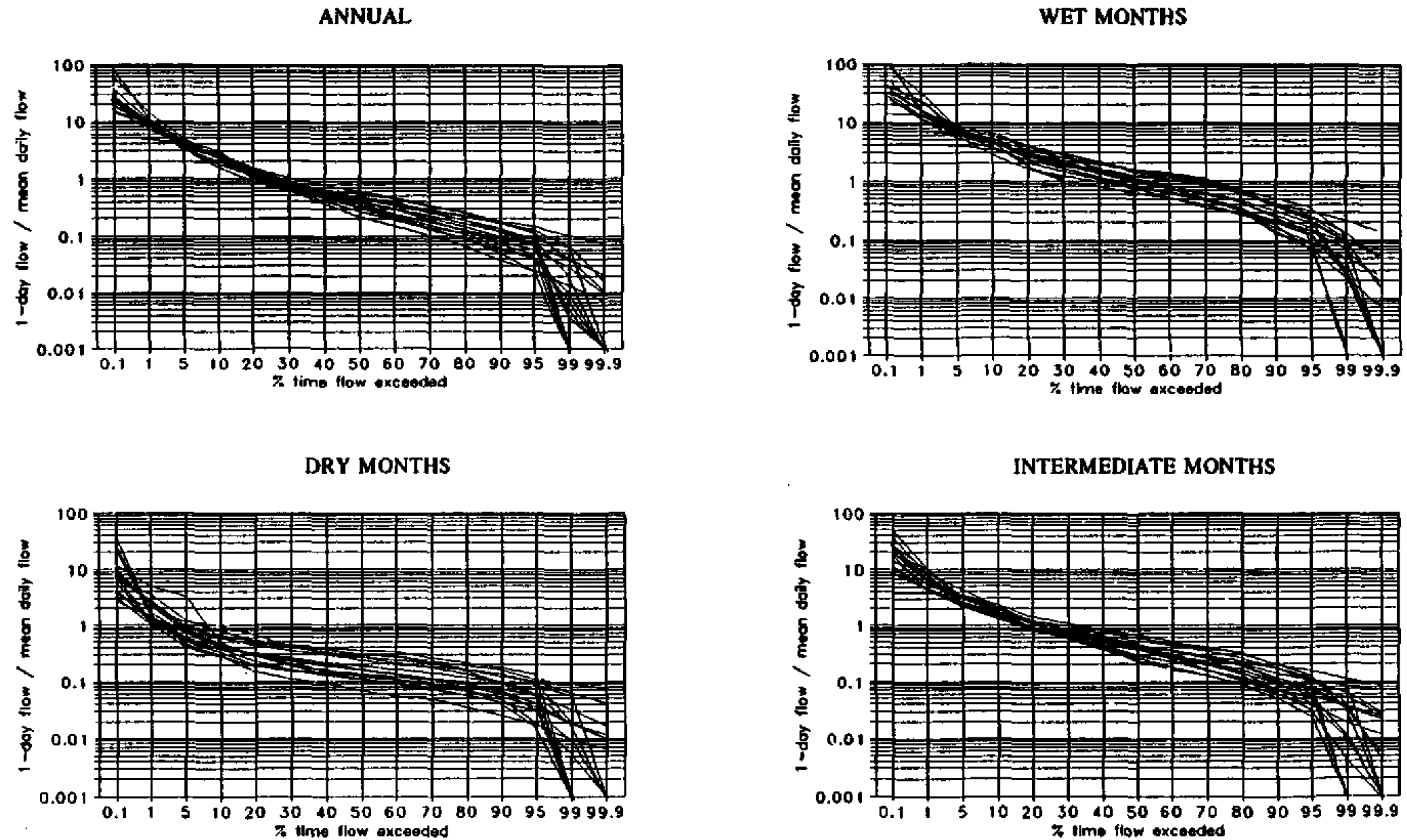


Figure E1.3. Superimposed 1-day flow duration curves

Since some of the observation periods are short, the estimates of mean daily discharge may differ from their "true" values calculated from longer records, if these were available. This can affect the position of an individual FDC based on a short record since all the ordinates (ratios of flow divided by mean flow) will be over- or under-estimated. In an effort to create as large a regional sample of curves as possible, it has been assumed that the observation period is representative to give a reasonable estimate of mean flow (and consequently - standardised FDC), if it includes at least one wet and one dry annual flow sequence.

Alternatively, the necessary minimum length of record (N) to estimate mean flow with the desired level of accuracy can be derived from the expression for standard error of the mean (e.g. Chow, 1964). Rearranging this expression will give

$$N = (CV / SE_{mean})^2 \qquad (E1.1)$$

where CV - coefficient of variation of annual flow and SE_{mean} is a standard error (accuracy of the estimate) as a ratio of mean annual flow. The CVs of annual streamflows in the region vary in the range of 0.4 - 0.5. If the accuracy of 10% is assumed sufficient for mean annual flow calculation, then the necessary length of observation period will range from 16 to 25 years (approximately 20 years on average). Most of the record periods in the region are rather close to this requirement (Fig. E1.2). This is not, however, the case with observations from gauges T6H001 and T7H001 which have only 10 years of record with a number of gaps due to missing data (Figs. E2.17, E2.18; APPENDIX E2). The curves for these two gauges have been constructed but have not been used in the final calculations. The simple averaging procedure was applied to calculate a set of normalised regional annual and seasonal FDCs from the remaining individual curves. The calculated regional FDCs are shown in Figure E1.4, and their ordinates for 17 fixed percentage points are given in Table E1.2.

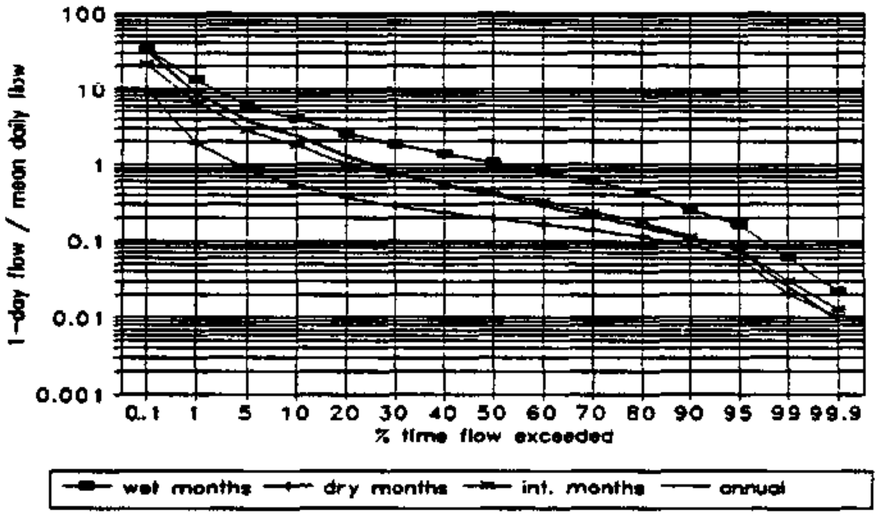


Figure E1.4. Normalised regional 1-day flow duration curves.

Table E1.2. Ordinates of the normalised 1-day flow duration curves.

% Time exceeded	Annual	Wet	Dry	Interm.
0.01	73.9	69.8	32.3	59.6
0.1	32.3	41.0	9.72	21.4
1	8.79	14.8	1.93	6.65
5	3.78	5.99	0.857	2.86
10	2.37	4.07	0.529	1.80
20	1.29	2.57	0.365	1.00
30	0.808	1.86	0.286	0.730
40	0.558	1.39	0.234	0.547
50	0.397	1.06	0.196	0.426
60	0.287	0.815	0.166	0.326
70	0.211	0.618	0.139	0.241
80	0.156	0.437	0.113	0.178
90	0.107	0.259	0.086	0.115
95	0.077	0.166	0.061	0.078
99	0.025	0.062	0.020	0.030
99.9	0.009	0.022	0.010	0.013
99.99	0.006	0.017	0.008	0.011

Once the set of regional normalized FDCs (annual and seasonal) is established, the actual required FDC for any ungauged site in the region may be calculated by multiplying back the non-dimensional ordinates of a corresponding regional FDC by the estimate of the mean daily flow. This estimate may be obtained by means of a regional regression model which would relate mean daily flow with the physiographic and climatic characteristics of the drainage basins. A regional regression model has been developed using most of the daily data sets listed in Table E1.1. Catchment area (A) and mean annual precipitation (MAP) have been used as independent variables. Both are readily available from the national existing database. The following prediction equation has been obtained from the regression:

$$\ln Q_{mean} = -33.86 + 1.125^{*} \ln A + 4.08^{*} \ln MAP \qquad \text{(E1.2)}$$
$$(R^2 = 0.93; \;\; s.e. = 0.36)$$

Mean daily discharge has also been calculated from the estimates of MAR presented in WR90. The MAR values for quaternary subcatchments listed in this source have been calculated for virgin flow conditions. Although the upstream parts of most of the rivers in the region are still in a relatively natural state, some water abstractions are taking place in the central parts of the region. Therefore, MAR estimates for virgin flow conditions should be adjusted wherever any water resource development is present. In the T drainage region, water is abstracted predominantly by small-scale irrigation schemes and by forestry. WR90 contains information on afforested and irrigated areas in each quaternary subcatchment, as well as values for average annual irrigation demand. From these data, the estimates of mean annual abstractions for irrigation can easily be made, while water consumption by forestry may be calculated using Van der Zyl curves which relate virgin MAR and MAR for an entirely afforested catchment.

The results of present day MAR and mean daily flow calculations for gauged catchments in the region using the information from WR90 are presented in Table E1.3. The table also compares these estimates with those calculated from available observed streamflow data and using the regional regression model. The approach based on WR90 performs generally better than the regression model mostly due to the high standard error of estimate of the latter (eq. E1.2). Gauge T5H006 (for which the highest error is produced by both approaches) has already been noted as having a very low discharge table limit, and for that reason its mean daily flow calculated from observed records is under-estimated. Another big discrepancy between observed and estimated mean daily flow occurs at gauge T5H005 which commands only the upstream third of the total quaternary catchment area. The estimate of MAR at this gauge has been made as a simple proportion of the total quaternary catchment MAR. However, this small catchment could receive more rainfall and consequently produce a larger proportion of the total quaternary catchment runoff. Caution should be exercised when the estimates of surface water yields are attempted at sub-quaternary scale using the information from WR90 (largely compiled for the purposes of solving design problems at larger scales). Practical guidelines on how the available information can be modified to be applicable at the smaller scale are currently under development in the Institute for Water Research.

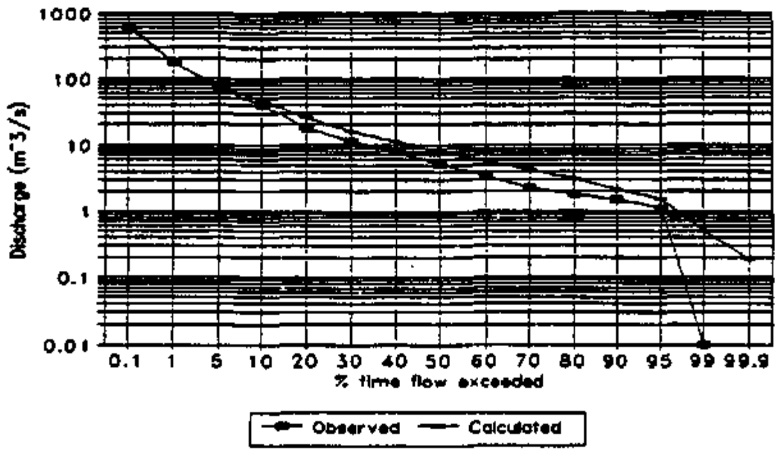
It should also be noted that the estimates of mean daily flow, derived from information presented in WR90, are based on 70 years of synthetic monthly flow time series while the observed records are on average approximately only 20 years long. Therefore (for quaternary and larger catchments) these estimates are likely to be more representative than those obtained from observed records. The estimation of mean daily flow from the quaternary catchment data may also be preferable since it links the two studies and adds value to the extensive research work that has already been done at the national scale.

Figure E1.5 illustrates some typical examples of fit between annual FDCs based on observed data and those obtained using the regionalisation approach. Since the technique is rather sensitive to the estimate of mean daily flow, there are likely to be cases when the calculated ordinates of the curves are either under- or over-estimated (e.g. gauge T1H004). However, overall, the calculated curves appear to be in satisfactory agreement with the observed FDCs throughout most of the time scale.

Table E1.3. Estimation of mean daily flow.

Code	Area,km²	virgin MAR, MCM	% area afforested	Abstraction by forest,MCM	Irrigated area km²	Abstract. by irrig., MCM	Present MAR, MCM	Q mean, m³/s	Q mean (reg) m³/s	Q mean, (obs) m³/s
T1H004	4924	653.8	1.2	4.92	67.7	16.9	632.0	20.0	17.8	16.7
T2H002	1199	261.8	19.2	26.0	0	0	235.8	7.4	5.02	8.50
T3H002	2101	214.7	0	0	14.8	4.44	210.3	6.6	6.47	8.18
T3H004	1029	99.1	0	0	7.1	2.13	97.0	3.0	3.42	2.65
T3H005	2597	486.6	2.3	6.5	2.1	0.42	479.7	15.2	13.4	14.9
T3H006	4268	898.1	1.3	6.1	25.6	5.12	886.9	28.1	23.0	25.7
T3H008	2471	260.4	0	0	30.0	9.0	251.4	7.9	8.23	6.95
T3H009	307	88.6	0	0	2.6	0.52	88.1	2.7	2.26	3.66
T4H001	715	160.7	26.0	19.5	2.2	0.55	140.7	4.4	4.35	5.03
T5H001	3643	957.5	6.3	30.6	42.7	10.7	916.2	29.0	34.5	33.5
T5H002	867	173.7	31	29.6	1.2	0.3	143.8	4.5	4.72	5.0
T5H003	140	62.0	1.4	0.3	1.5	0.37	61.3	1.9	2.17	1.87
T5H004	545	233.1	0	0	5.5	1.37	231.7	7.3	9.57	7.47
T5H005	100	20.0	80.0	8.8	0	0	11.2	0.3	0.41	0.681
T5H006	534	63.4	15.0	5.87	4.0	1.0	56.6	1.7	1.82	0.858
T6H001	108	27.0	0	0	0	0	27.0	0.8	0.91	0.875
T7H001	315	35.9	2.2	0.47	0	0	35.4	1.1	1.22	0.782

GAUGE T1H004



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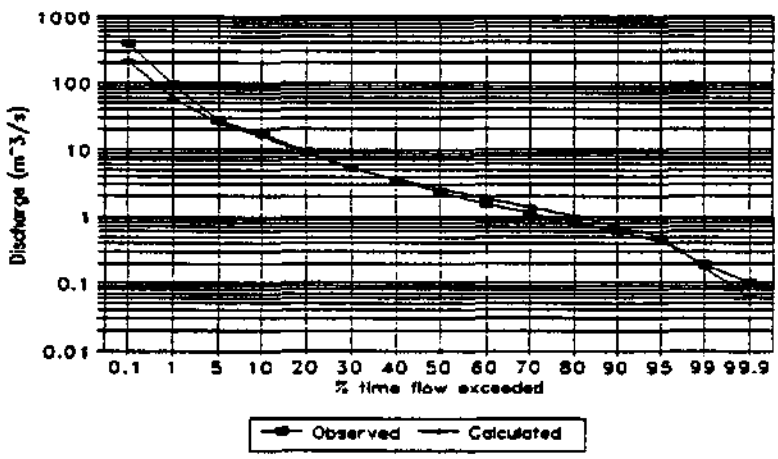


GAUGE T5H001

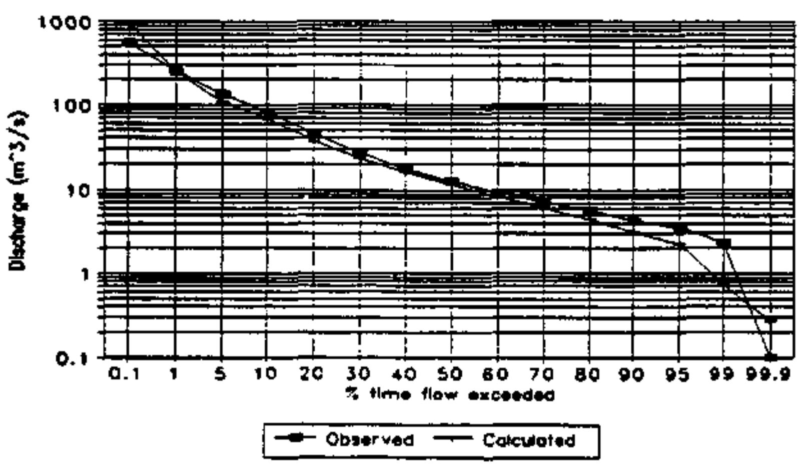
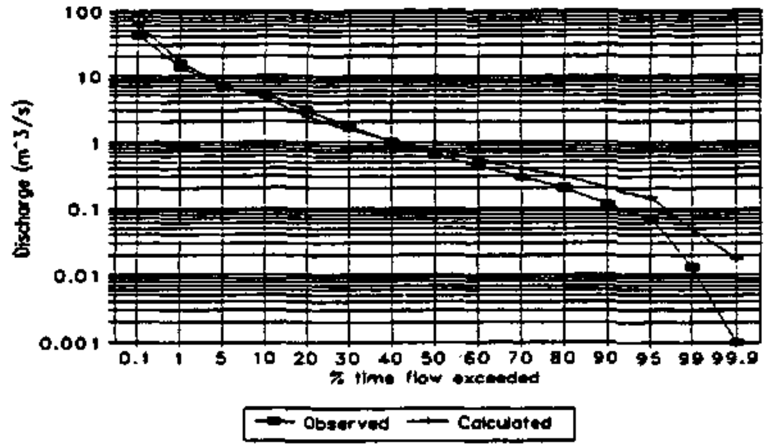


Figure E1.5a. *Observed and calculated 1-day annual flow duration curves.*

GAUGE T5H003



GAUGE T3H006

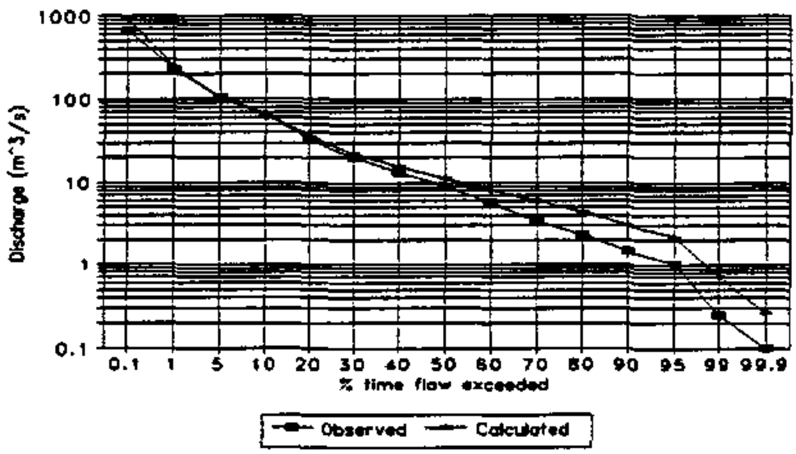


Figure E1.5b Observed and calculated 1-day annual flow duration curves.

E1.5. GENERATION OF DAILY FLOW TIME SERIES USING REGIONAL FLOW DURATION CURVES.

The established set of regional FDCs and the estimates of mean daily discharge obtained from WR90 have been used to generate daily streamflow sequences at several randomly selected flow gauges in the region by means of the spatial interpolation algorithm.

The results of simulations are illustrated for the selected gauges in Table E1.4 using standard criteria of fit between observed and simulated daily streamflow series. The comparison has been made for untransformed and log-transformed flows. The fit statistics used for untransformed flows are the maximum and mean flow value, standard deviation of daily flows and coefficients of determination (R^2) and efficiency (CE). Comparison of log-transformed daily flow values is based on coefficients of determination and efficiency and a minimum flow. The purpose of comparison of untransformed flows was to assess the general quality of simulations, while fit statistics for log-transformed flows provide a better indication of the correspondence for low flows.

When the spatial interpolation algorithm is used to patch/extend the existing flow record at a gauged location, the selection of suitable source sites and quantification of weights could be based on a spatial correlation analysis or, alternatively, observed flow series can be visually compared by means of the HYMAS graphical display facilities. The algorithm is quick and simple to run and therefore the best weighting factors to use can be determined through trial-and-error type calibration. These options are, however, not applicable when the generation of a completely new daily flow time series at an ungauged site is attempted. The pragmatic approach which would most likely be followed is to use just one or two adjacent source flow gauges with equal weights. The disadvantage of using only one source gauge is that all missing data periods in the source record will be automatically transferred to the generated daily flow record at an ungauged site. From this point of view the use of more than one source gauge (if possible) is preferable. In addition the time series at an ungauged site may result from several influences, which may not be reflected in a single source site time series.

The means and standard deviations of the generated flow time series, in most cases, correspond well with those of observed time series (Table E1.4). The general pattern of the observed flows may therefore be satisfactorily reproduced by the method. This is also shown by Figure E1.6 which illustrates the correspondence between observed and simulated hydrographs at several flow gauges. A good (or bad) fit between annual FDCs (calculated using observed data and derived through the regionalization) does not necessarily guarantee the same good (or bad) coincidence between observed and generated daily streamflow discharges. This is mostly due to the fact that the generated time series is produced using the set of seasonal (not annual) FDCs.

The main criticism of the results is that the method does not seem to be capable of satisfactorily reproducing high flow events which are normally either under- or over-simulated. This results in relatively poor fit statistics (R^2 and CE) for untransformed flows for most of the gauges, with the coefficient of efficiency (a measure of one-to-one correspondence between observed and simulated flows) being particularly low. This is a consequence of the averaging of the ordinates of the individual FDCs in the high flow area.

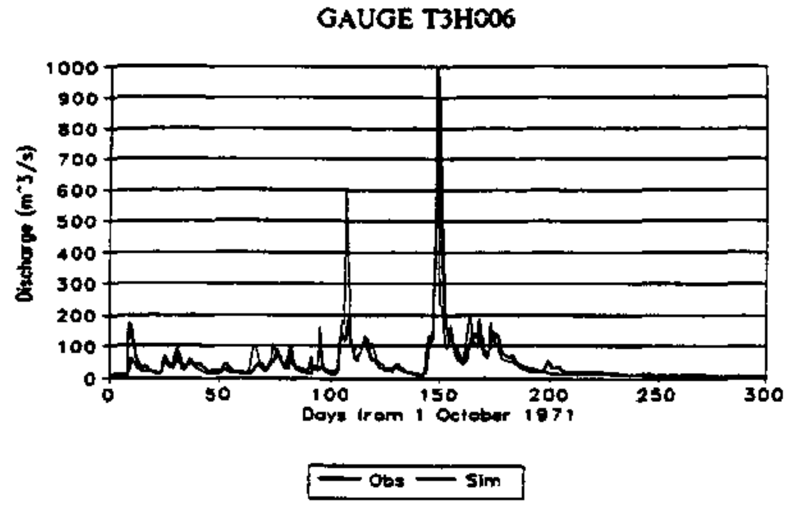
It should also be taken into account that the choice of suitable source flow gauge(s) in the region that can be used to demonstrate the performance of the method is rather limited. The gauges are located far from each other and hence any selected source site may represent a flow regime which is quite different from that at the destination site. This also affects the resultant fit statistics. For example, the flow time series at gauge T1H004, isolated in the southern part of the region (Fig. E1.1), has been simulated using flow data from gauges T3H006 and T2H002 in the absence of better candidates. Flows at gauge T3H009 have been generated using the data from gauge T3H006 downstream (and vice versa) etc.

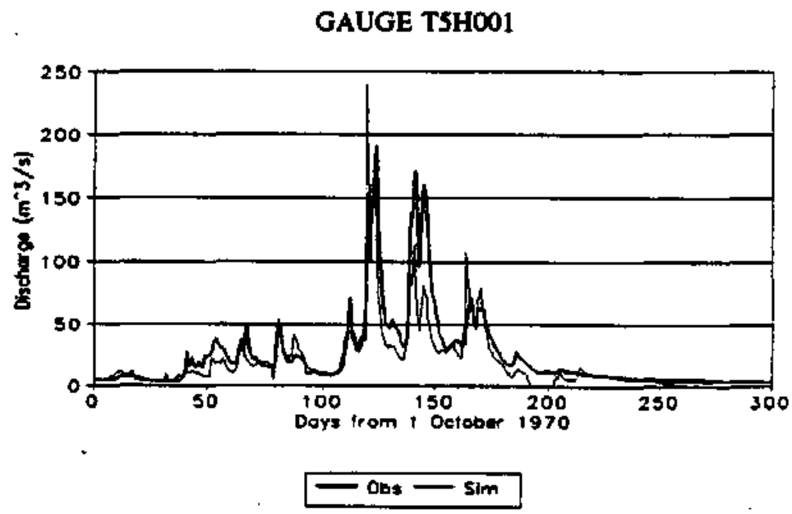
When the generation of flow time series at a "true" ungauged site in the region is attempted the choice of source gauged data sets will be quite obvious. For example, gauge T3H009 and/or T3H006 would be selected as a source site for generating daily hydrographs in any ungauged location in the Tsitsa catchment (Fig. E1.1), gauge T3H002 and/or T3H008 - in the Mzimvubu catchment, gauge T1H004 - in the Mbashe catchment, etc.

Fit statistics based on log-transformed flows are much superior to those for untransformed flows. This implies that moderate to low flows are well simulated by the proposed method. This is a very encouraging conclusion given the attention which is currently being paid to low-flow studies in the country. Since regional FDCs have been estimated by simple averaging of individual FDCs, short-term zero flow conditions that are part of some observed records will not be reproduced by the proposed method and therefore extreme low-flows (< 1% of the time series) are likely to be overestimated in most of the cases. This is, however, not considered to be an important issue in the context of the present study since most of the low-flow indices used in hydrological practice in South Africa are related to flows in the range of 70 to 95% time of exceedence where the uncertainty created by averaging of the individual FDCs is much less.

Table E1.4. Comparative statistics for selected flow gauges in the T region

Gauge	Time series	Untransformed					Log transformed		
		Max m^3/s	Mean m^3/s	SD m^3/s	R^2	CE	Min	R^2	CE
T1H004	Obs.	1160	16.7	42.2			-5.81		
	Sim.	800	20.3	39.8	0.42	0.32	-1.61	0.63	0.47
T3H002	Obs.	385	8.2	26.5			-3.10		
	Sim.	218	5.8	10.8	0.66	0.48	-2.72	0.70	0.69
T3H005	Obs.	451	14.9	28.2			-1.45		
	Sim.	395	15.2	22.1	0.70	0.70	-1.88	0.78	0.75
T3H006	Obs.	913	25.7	58.3			-2.32		
	Sim.	995	27.9	53.2	0.60	0.57	-1.17	0.79	0.71
T3H009	Obs.	528	3.66	15.9			-3.77		
	Sim.	114	2.65	6.0	0.41	0.33	-3.61	0.70	0.68
T5H001	Obs.	2851	33.5	61.3			-1.69		
	Sim.	1416	31.0	55.0	0.51	0.47	-0.98	0.76	0.76
T5H003	Obs.	79.5	1.87	3.56			-6.91		
	Sim.	60.0	1.77	3.15	0.69	0.68	-3.96	0.67	0.65





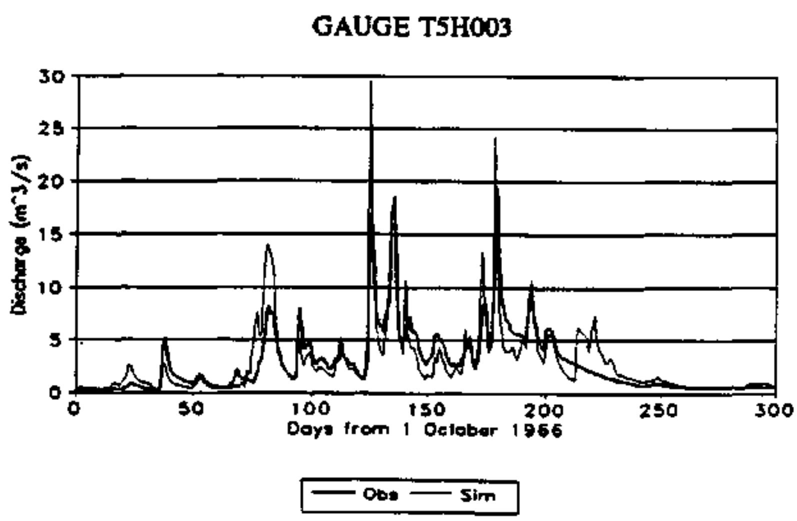
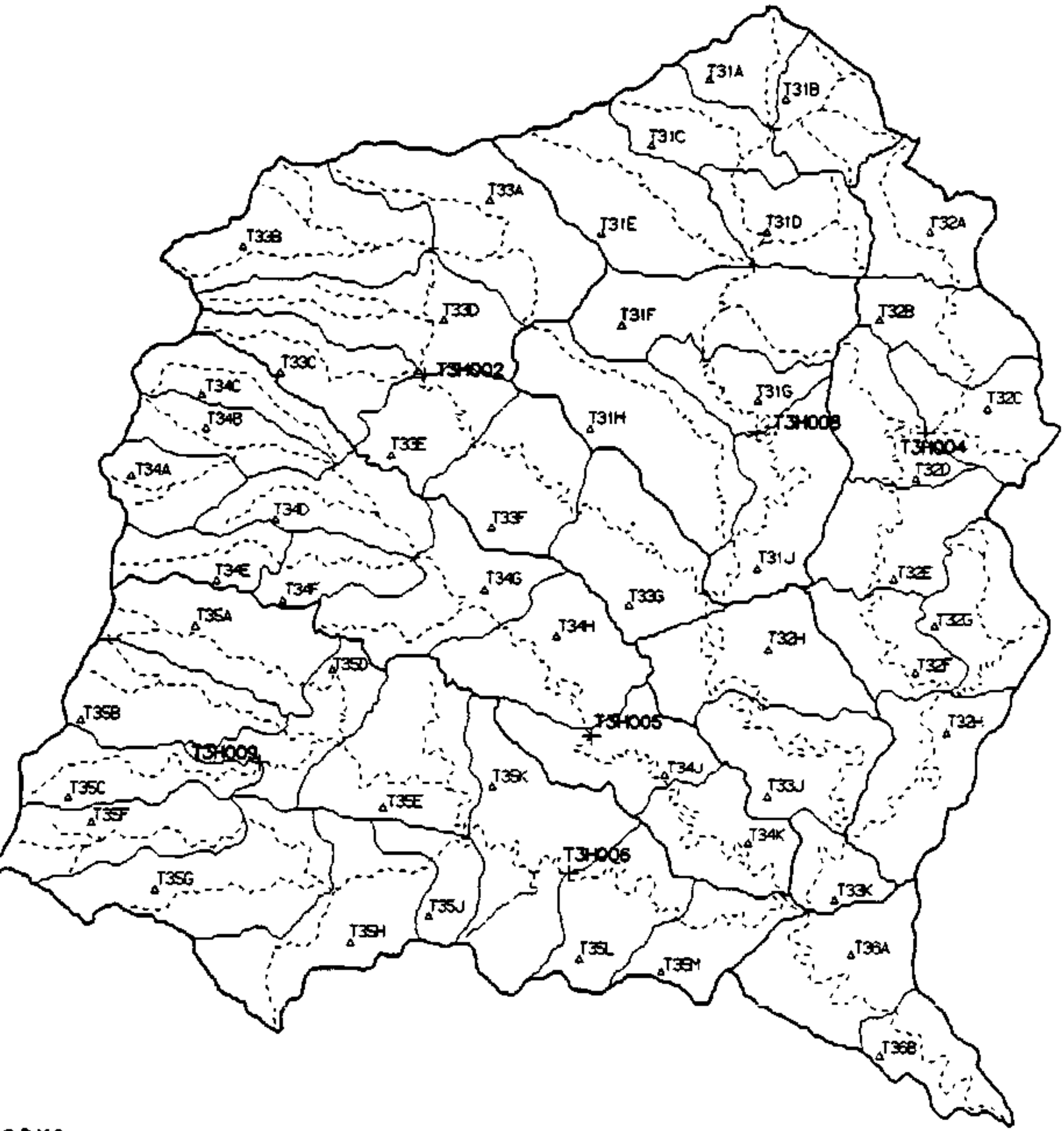


Figure E1.6. Observed and simulated daily hydrographs.

E1.6 LOW FLOW ESTIMATION IN THE MZIMVUBU AND MZIMKHULU CATCHMENTS.

Using the established regional annual Flow Duration Curves the required annual low-flow indices can now be estimated for quaternary catchments in the region by multiplying the corresponding coordinates of a regional FDC by the estimate of mean daily flow. The latter may be derived from quaternary MAR estimates included in the Surface Water Resources of South Africa. If the estimates at quaternary scale are required for present day conditions in a catchment, the MAR should be corrected as explained above. Alternatively, if virgin flow conditions are sought the assumption has to be made that the shape of regional non-dimensional annual FDC estimated on the basis of observed flow data would apply for virgin flow conditions as well. In other words, this means that all ordinates of the curve are equally affected when the change is made from virgin to present day conditions. This is obviously a simplification of the real conditions.

These calculations have been performed for two major catchments in the T region: Mzimvubu and Mzimkhulu. Two low-flow indices have been estimated: 1-day Q75 and Q95 flows. The use of 1-day flows as opposed to 7-day average flows used in the previous catchment low-flow studies is dictated by the resolution of data used to construct regional FDCs. The results are present in Figures E1.7 - E1.2 for natural flow conditions and also summarised in Tables E1.5-E1.8 (for both natural and present day conditions). The coverage for present day conditions have not been constructed since the estimated low flows at least in the case of Mzimvubu catchment, do not demonstrate a significant change. Other flow duration curve indices may be estimated in the same way using the available estimates of MAR (either listed in Tables E1.5 - E1.8 or supplied for other quaternary subcatchments in the T region by WR90) and coordinates of regional curves presented in Table E1.2.



LEGEND

T3H004 *Flow gauges*

Rivers

T33G *Quaternary sub-catchment codes*

Mzimvubu catchment and tertiary sub-catchment boundaries

Figure E1.7 ***The map of the Mzimvubu catchment showing streamflow gauge locations and quaternary subcatchment boundaries***

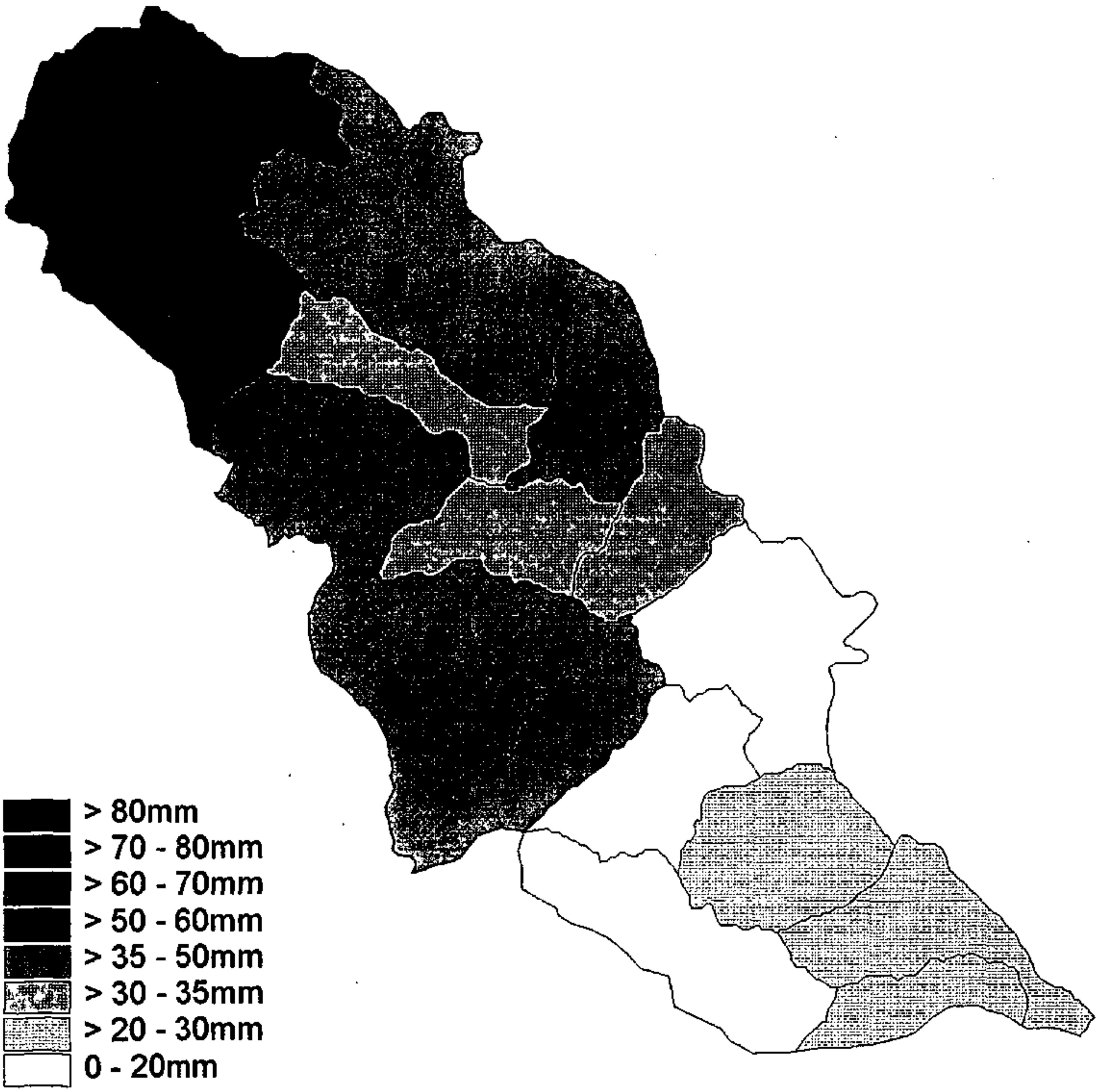


Figure E1.11 *Distribution of Q75 values (mm/a) in the Mzimkhulu catchment (virgin conditions).*

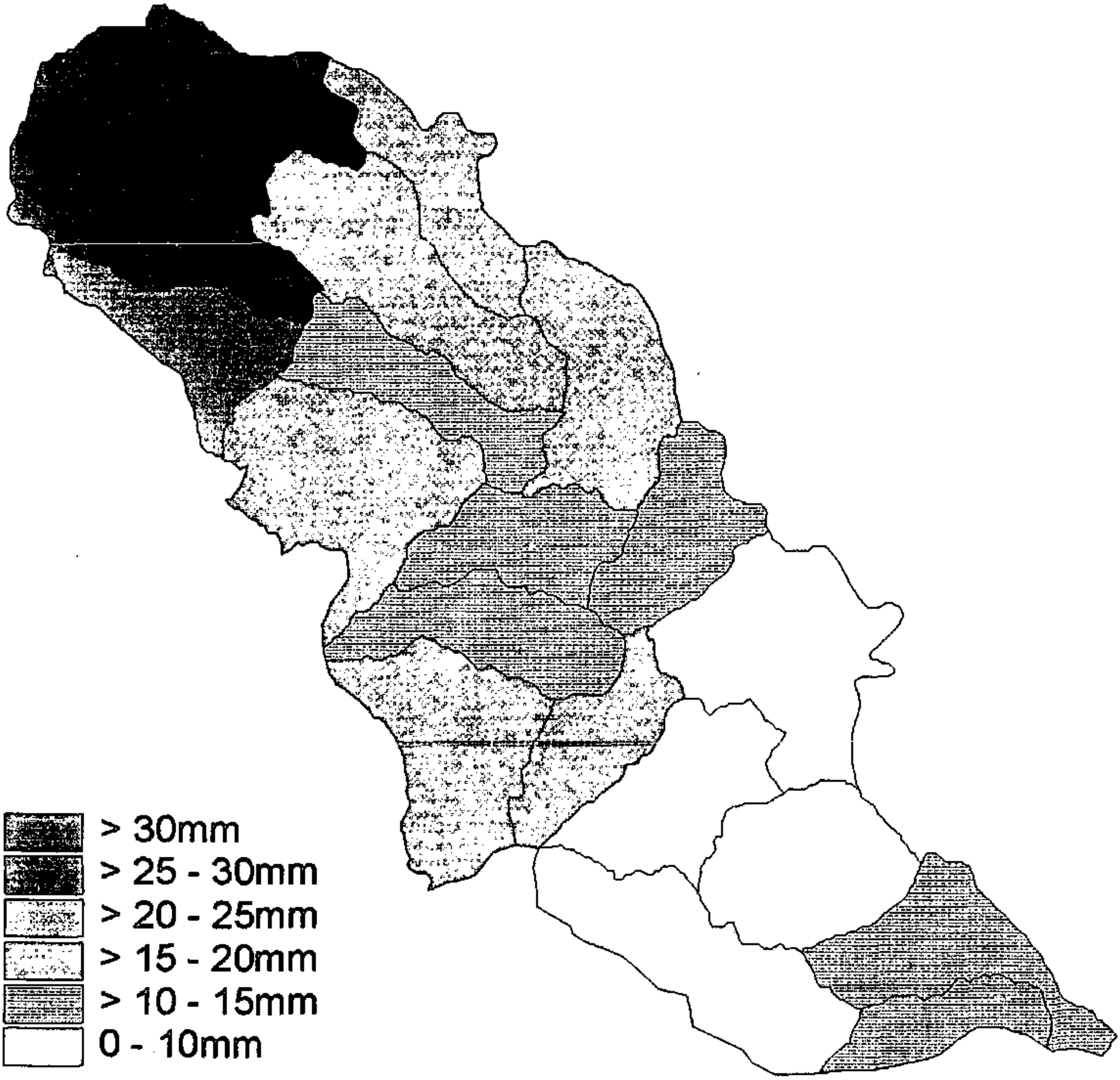
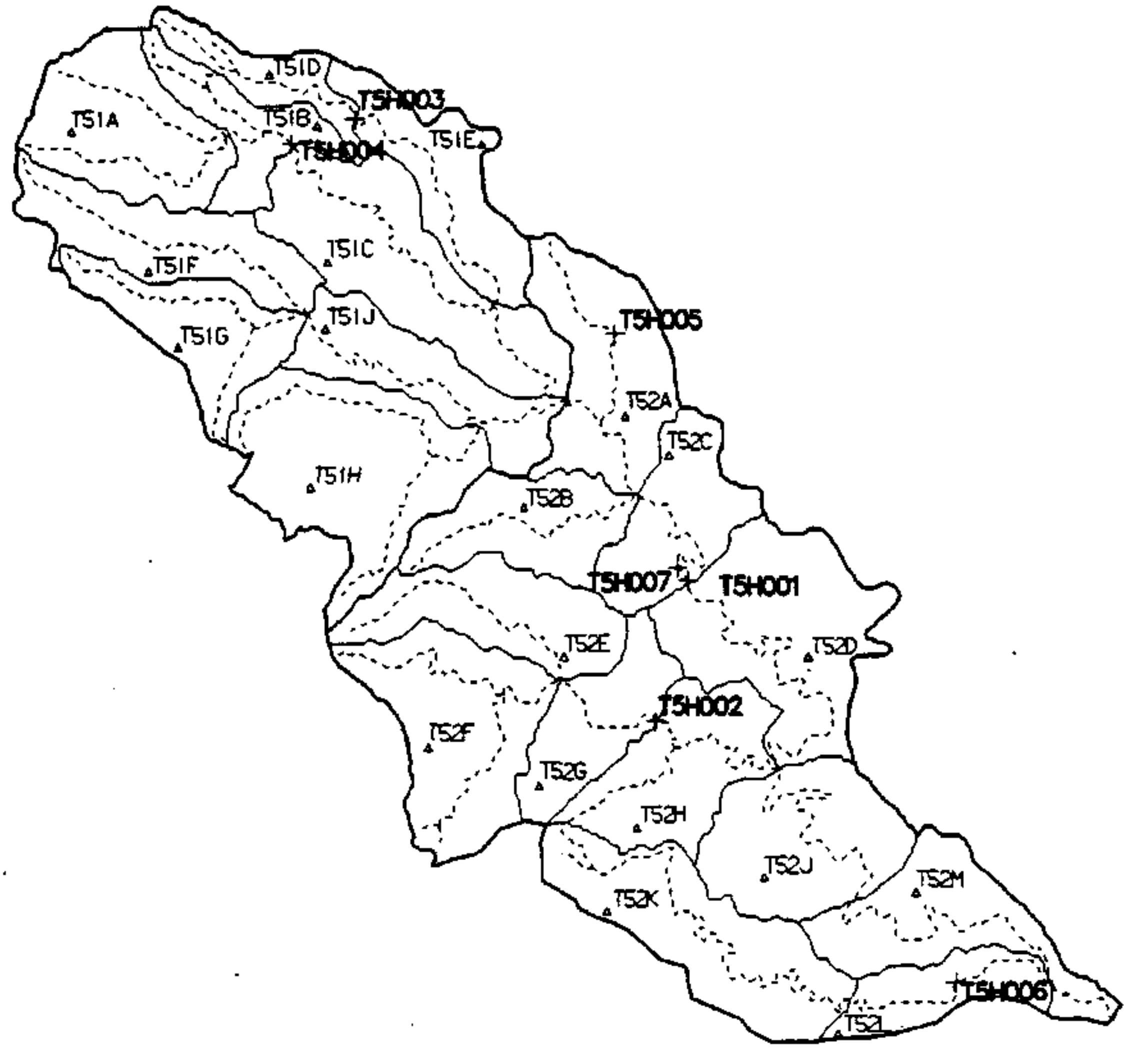


Figure E1.12 *Distribution of Q95 values (mm/a) in the Mzimkhulu catchment (virgin conditions).*



LEGEND

Flow gauges

Rivers

T52B Qualernary sub-catchment codes

Mzimkulu catchment and tertiary sub-catchment boundaries

Figure E1.10 The map of Mzimkhulu catchment showing streamflow gauge locations and quaternary subcatchment boundaries.

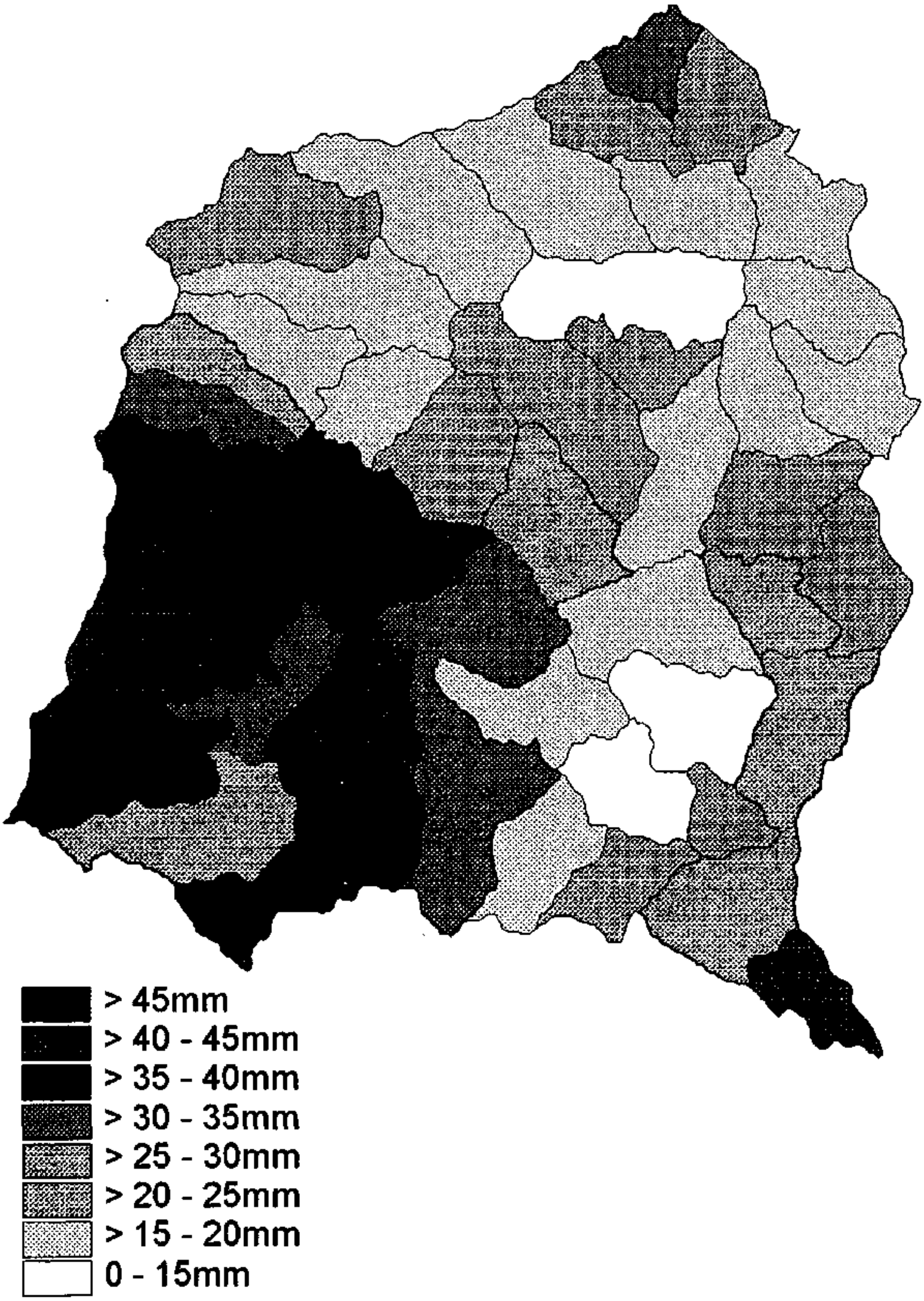


Figure E1.8 *Distribution of Q75 values (mm/a) in the Mzimvubu catchment (virgin conditions).*

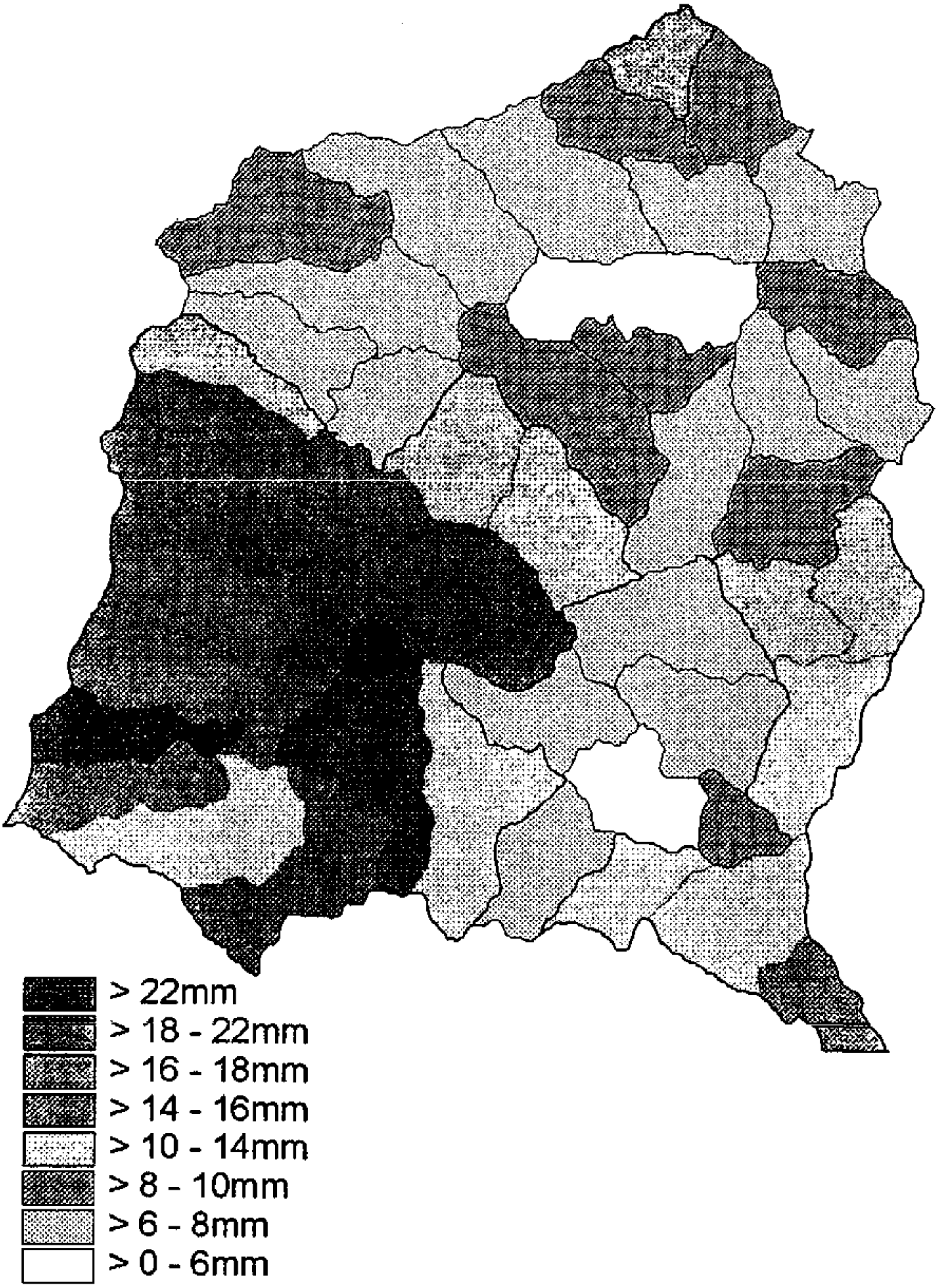


Figure E1.9 *Distribution of Q95 values (mm/a) in the Mzimvubu catchment (virgin conditions).*

Table E1.5 Estimated Q75 and Q95 flow values for quaternary and tertiary subcatchments in the Mzimvubu river basin (virgin conditions).

Code	Area, km^2	MAR, MCM	Qmean, m^3/s	Q75, m^3/s	Q75, mm/a	Q95, m^3/s	Q95, mm/a
T31A	222	37.8	1.20	0.22	31.25	0.09	12.78
T31B	284	36.9	1.17	0.21	23.32	0.09	9.99
T31C	291	37.3	1.18	0.22	23.84	0.09	9.75
T31D	353	30.3	0.96	0.18	16.08	0.07	6.25
T31E	509	47.8	1.52	0.28	17.35	0.12	7.43
T31F	605	45.4	1.44	0.26	13.55	0.11	5.73
T31G	209	24.9	0.79	0.15	22.63	0.06	9.05
T31H	617	75.7	2.40	0.44	22.49	0.18	9.2
T31J	507	49.4	1.57	0.29	18.04	0.12	7.46
T31	3597	385.5	12.22	2.25	19.73	0.94	8.24
T32A	348	31.4	1.00	0.18	16.31	0.08	7.25
T32B	307	31.6	1.00	0.18	18.49	0.08	8.22
T32C	373	36.3	1.15	0.21	17.75	0.09	7.61
T32D	351	32.4	1.03	0.19	17.07	0.08	7.19
T32E	383	45.9	1.46	0.27	22.23	0.11	9.06
T32F	297	47.8	1.52	0.28	29.73	0.12	12.74
T32G	438	56.3	1.79	0.33	23.76	0.14	10.08
T32H	453	65.1	2.06	0.38	26.45	0.16	11.14
T32	2950	346.9	11.00	2.02	21.59	0.85	9.09
T33A	672	67.7	2.15	0.39	18.3	0.16	7.51
T33B	602	68.3	2.17	0.4	20.95	0.17	8.91
T33C	367	36.2	1.15	0.21	18.05	0.09	7.73
T33D	461	42.2	1.34	0.25	17.1	0.1	6.84
T33E	267	24.4	0.77	0.14	16.54	0.06	7.09
T33F	437	55.7	1.77	0.32	23.09	0.14	10.1
T33G	503	70.2	2.23	0.41	25.71	0.17	10.66
T33H	517	45.7	1.45	0.27	16.47	0.11	6.71
T33J	457	35	1.11	0.2	13.8	0.09	6.21

Table E1.5(cont.) Estimated Q75 and Q95 flow values for quaternary and tertiary subcatchments in the Mzimvubu river basin (virgin conditions).

Code	Area, km^2	MAR, MCM	Qmean, m^3/s	Q75, m^3/s	Q75, mm/a	Q95, m^3/s	Q95, m^3/s
T33K	469	22.3	0.71	0.13	24.26	0.05	9.33
T33	4452	467.6	14.83	2.72	19.27	1.14	8.08
T34A	242	50.6	1.60	0.29	37.79	0.12	15.64
T34B	246	45.3	1.44	0.26	33.33	0.11	14.1
T34C	282	44.2	1.40	0.26	29.08	0.11	12.3
T34D	342	64.4	2.04	0.38	35.04	0.16	14.75
T34E	268	55.4	1.76	0.32	37.65	0.13	15.3
T34F	238	48.1	1.53	0.28	37.1	0.12	15.9
T34G	358	68.8	2.18	0.4	35.24	0.17	14.98
T34H	591	109.8	3.48	0.64	34.15	0.27	14.41
T34J	297	26.4	0.84	0.15	15.93	0.06	6.37
T34K	333	24.7	0.78	0.14	13.26	0.06	5.68
T34	3197	537.7	17.05	3.13	30.88	1.31	12.92
T35A	475	109.8	3.48	0.64	42.49	0.27	17.93
T35B	396	92.3	2.93	0.54	43	0.22	17.52
T35C	306	88.6	2.81	0.52	53.59	0.22	22.67
T35D	348	65.2	2.07	0.38	34.44	0.16	14.5
T35E	492	120.4	3.82	0.7	44.87	0.29	18.59
T35F	359	72	2.28	0.42	36.89	0.18	15.81
T35G	575	85.6	2.71	0.5	27.42	0.21	11.52
T35H	520	104.6	3.32	0.61	36.99	0.25	15.16
T35J	188	48.5	1.54	0.28	46.97	0.12	20.13
T35K	625	111.1	3.52	0.65	32.8	0.27	13.62
T35L	340	28.8	0.91	0.17	15.77	0.07	6.49
T35M	305	42	1.33	0.24	24.82	0.1	10.34
T35	4929	969	30.73	5.64	36.09	2.36	15.1
T36A	462	68.4	2.17	0.4	27.3	0.17	11.6
T36B	265	57.8	1.83	0.34	40.46	0.14	16.66
T36	727	126.1	4.00	0.73	31.67	0.31	13.45

Table E1.6 Estimated Q75 and Q95 flow values for quaternary and tertiary subcatchments in the Mzimkhulu river basin (virgin conditions).

Code	Area, km^2	MAR, MCM	Qmean, m^3/s	Q75, m^3/s	Q75, mm/a	Q95, m^3/s	Q95, mm/a
T51A	328	149.6	4.74	0.87	83.65	0.36	34.61
T51B	210	83.5	2.65	0.49	73.58	0.2	30.03
T51C	462	96.1	3.05	0.56	38.23	0.23	15.7
T51D	142	62	1.97	0.36	79.95	0.15	33.31
T51E	256	54	1.71	0.31	38.19	0.13	16.01
T51F	307	109	3.46	0.63	64.72	0.27	27.74
T51G	256	81.4	2.58	0.47	57.9	0.2	24.64
T51H	520	106.7	3.38	0.62	37.6	0.26	15.77
T51J	265	49.4	1.57	0.29	34.51	0.12	14.28
T51	2746	791.6	25.10	4.61	52.94	1.93	22.16
T52A	382	76.2	2.42	0.44	36.32	0.19	15.69
T52B	256	47.5	1.51	0.28	34.49	0.12	14.78
T52C	261	42.1	1.33	0.25	30.21	0.1	12.08
T52D	531	51.3	1.63	0.3	17.82	0.12	7.13
T52E	233	46.1	1.46	0.27	36.54	0.11	14.89
T52F	418	83.9	2.66	0.49	36.97	0.2	15.09
T52G	221	43.7	1.39	0.25	35.67	0.11	15.7
T52H	344	31.5	1.00	0.18	16.5	0.08	7.33
T52J	368	44.3	1.40	0.26	22.28	0.11	9.43
T52K	426	46.9	1.49	0.27	19.99	0.11	8.14
T52L	179	27.4	0.87	0.16	28.19	0.07	12.33
T52M	313	49.2	1.56	0.29	29.22	0.12	12.09
T52	3932	590.2	18.72	3.44	27.59	1.44	11.55

Table E1.7 Estimated Q75 and Q95 flow values for quaternary and tertiary subcatchments in the Mzimvubu basin (present day conditions).

Code	Forest, % area	MAR, mm	Forest abs.,MCM	Irr.area, km^2	Irr.abs., MCM	Prs.MAR, MCM	Qmean, MCM	Q75, m^3/s	Q75, mm/a	Q95, m^3/s	Q95, mm/a
T31A	0	170	0	2.70	0.81	36.99	1.17	0.21	29.83	0.09	12.78
T31B	0	130	0	3.50	1.05	35.85	1.14	0.21	23.32	0.09	9.99
T31C	0	128	0	3.50	1.05	36.25	1.15	0.21	22.76	0.09	9.75
T31D	0	86	0	4.30	1.29	29.01	0.92	0.17	15.19	0.07	6.25
T31E	0.20	94	0.06	6.20	1.86	45.88	1.45	0.27	16.73	0.11	6.82
T31F	0	75	0	7.30	2.19	43.21	1.37	0.25	13.03	0.11	5.73
T31G	0	119	0	2.50	0.75	24.15	0.77	0.14	21.12	0.06	9.05
T31H	0.49	123	0.22	7.50	2.25	73.23	2.32	0.42	21.47	0.18	9.20
T31J	0	97	0	6.20	1.86	47.54	1.51	0.28	17.42	0.12	7.46
T31	0.11	107	0.27	43.70	13.11	372.12	11.80	2.16	18.94	0.91	7.98
T32A	0	90	0	2.40	0.72	30.68	0.97	0.18	16.31	0.07	6.34
T32B	0	103	0	2.10	0.63	30.97	0.98	0.18	18.49	0.08	8.22
T32C	0.80	97	0.18	2.60	0.78	35.34	1.12	0.21	17.75	0.09	7.61
T32D	0	92	0	1.80	0.54	31.86	1.01	0.18	16.17	0.08	7.19
T32E	1.31	120	0.36	2.00	0.60	44.94	1.42	0.26	21.41	0.11	9.06

Table E1.7(cont.) Estimated Q75 and Q95 flow values for quaternary and tertiary subcatchments in the Mzimvubu basin (present day conditions).

Code	Forest, % area	MAR, mm	Forest abs., MCM	Irr.area, km²	Irr.abs., MCM	Prs.MAR, MCM	Qmean, MCM	Q75, m³/s	Q75, mm/a	Q95, m³/s	Q95, mm/a
T32F	1.35	161	0.37	1.60	0.48	46.95	1.49	0.27	28.67	0.11	11.68
T32G	4.57	129	1.54	2.30	0.69	54.07	1.71	0.31	22.32	0.13	9.36
T32H	1.99	144	0.76	2.40	0.72	63.62	2.02	0.37	25.76	0.15	10.44
T32	1.39	118	2.95	17.20	5.16	338.79	10.74	1.97	21.06	0.83	8.87
T33A	0.15	101	0.06	4.70	1.41	66.23	2.10	0.38	17.83	0.16	7.51
T33B	0	113	0	4.20	1.26	67.04	2.13	0.39	20.43	0.16	8.38
T33C	0	99	0	2.60	0.78	35.42	1.12	0.21	18.05	0.09	7.73
T33D	0	92	0	3.30	0.99	41.21	1.31	0.24	16.42	0.10	6.84
T33E	0	91	0	1.80	0.54	23.86	0.76	0.14	16.54	0.06	7.09
T33F	0.69	127	0.23	3.00	0.90	54.57	1.73	0.32	23.09	0.13	9.38
T33G	0.60	139	0.25	3.50	1.05	68.90	2.18	0.40	25.08	0.17	10.66
T33H	0.77	88	0.23	0.20	0.06	45.41	1.44	0.26	15.86	0.11	6.71
T33J	0.44	77	0.10	0.20	0.06	34.84	1.10	0.20	13.80	0.08	5.52
T33K	0	132	0	0.10	0.03	22.27	0.71	0.13	24.26	0.05	9.33
T33	0.29	105	0.850	23.60	7.08	459.67	14.58	2.67	18.91	1.12	7.93

Table E1.7(cont) Estimated Q75 and Q95 flow values for quaternary and tertiary subcatchments in the Mzimvubu basin (present day conditions).

Code	Forest, % area	MAR, mm	Forest abs.,MCM	Irr.area, km^2	Irr.abs., MCM	Prs.MAR, MCM	Qmean, MCM	Q75, m^3/s	Q75, mm/a	Q95, m^3/s	Q95, mm/a
T34A	0	209	0	0.20	0.04	50.56	1.60	0.29	37.79	0.12	15.64
T34B	0.41	184	0.10	0.20	0.04	45.16	1.43	0.26	33.35	0.11	14.10
T34C	0	157	0	0.30	0.06	44.14	1.40	0.26	29.08	0.11	12.30
T34D	0.58	188	0.21	0.30	0.06	64.13	2.03	0.37	34.12	0.16	14.75
T34E	0	207	0	0.20	0.04	55.36	1.76	0.32	37.65	0.13	15.30
T34F	0	202	0	0.20	0.04	48.06	1.52	0.28	37.10	0.12	15.90
T34G	1.96	192	0.73	0.30	0.06	68.01	2.16	0.39	34.35	0.17	14.98
T34H	8.29	186	5.02	0.40	0.08	104.70	3.32	0.61	32.55	0.26	13.87
T34J	0.67	89	0.11	0.10	0.02	26.27	0.83	0.15	15.93	0.06	6.37
T34K	0	74	0	0.20	0.04	24.66	0.78	0.14	13.26	0.06	5.68
T34	1.91	168	5.78	2.40	0.48	531.44	16.85	3.08	30.38	1.29	12.72
T35A	0	231	0	2.60	0.52	109.28	3.47	0.63	41.83	0.27	17.93
T35B	0	233	0	2.20	0.44	91.86	2.91	0.53	42.21	0.22	17.52
T35C	0	289	0	2.60	0.52	88.08	2.79	0.51	52.56	0.21	21.64
T35D	0.57	187	0.21	1.90	0.38	64.61	2.05	0.37	33.53	0.16	14.50

Table E1.7(cont) Estimated Q75 and Q95 flow values for quaternary and tertiary subcatchments in the Mzimvubu basin (present day conditions).

Code	Forest, % area	MAR, mm	Forest abs.,MCM	Irr.area, km^2	Irr.abs., MCM	Prs.MAR, MCM	Qmean, MCM	Q75, m^3/s	Q75, mm/a	Q95, m^3/s	Q95, mm/a
T35E	1.02	245	0.62	2.70	0.54	119.24	3.78	0.69	44.23	0.29	18.59
T35F	0	200	0	2.00	0.40	71.60	2.27	0.42	36.89	0.17	14.93
T35G	0	149	0	3.30	0.66	84.94	2.69	0.49	26.87	0.21	11.52
T35H	0	201	0	2.90	0.58	104.02	3.30	0.60	36.39	0.25	15.16
T35J	9.57	258	2.33	1.10	0.22	45.95	1.46	0.27	45.29	0.11	18.45
T35K	5.12	178	3.17	4.30	0.86	107.07	3.40	0.62	31.28	0.26	13.12
T35L	0.29	85	0.06	0.10	0.02	28.72	0.91	0.17	15.77	0.07	6.49
T35M	0	138	0	0.10	0.02	41.98	1.33	0.24	24.82	0.10	10.34
T35	1.18	197	6.20	25.80	5.16	957.64	30.37	5.56	35.57	2.33	14.91
T36A	0.22	148	0.09	0.10	0.02	68.29	2.17	0.40	27.30	0.17	11.60
T36B	0	218	0	0.00	0.00	57.80	1.83	0.34	40.46	0.14	16.66
T36	0.14	174	0.10	0.10	0.02	125.98	3.99	0.73	31.67	0.31	13.45

Table E1.8 Estimated Q75 and Q95 flow values for quaternary and tertiary subcatchments in the Mzimkhulu river basin (present day conditions).

Code	Forest, % area	MAR, mm	Forest abs.,MCM	Irr.area, km^2	Irr.abs., MCM	Prs.MAR, MCM	Qmean, MCM	Q75, m^3/s	Q75, mm/a	Q95, m^3/s	Q95, mm/a
T51A	0	456	0	3.40	0.85	148.75	4.72	0.86	82.69	0.36	34.61
T51B	0	398	0	2.10	0.53	82.98	2.63	0.48	72.08	0.20	30.03
T51C	6.06	208	3.11	4.40	1.10	91.89	2.91	0.53	36.18	0.22	15.02
T51D	1.41	437	0.36	1.50	0.38	61.26	1.94	0.36	79.95	0.15	33.31
T51E	1.56	211	0.45	2.40	0.60	52.95	1.68	0.31	38.19	0.13	16.01
T51F	0	355	0	2.30	0.58	108.43	3.44	0.63	64.72	0.26	26.71
T51G	0	318	0	1.90	0.48	80.93	2.57	0.47	57.90	0.20	24.64
T51H	7.12	205	4.07	4.90	1.23	101.41	3.22	0.59	35.78	0.25	15.16
T51J	3.77	186	1.02	2.50	0.63	47.75	1.51	0.28	33.32	0.12	14.28
T51	2.95	288	11.31	25.40	6.35	773.94	24.54	4.49	51.56	1.89	21.71
T52A	20.94	200	8.64	7.40	1.85	65.71	2.08	0.38	31.37	0.16	13.21
T52B	8.20	186	2.15	4.90	1.23	44.13	1.40	0.26	32.03	0.11	13.55
T52C	18.77	161	4.50	5.00	1.25	36.35	1.15	0.21	25.37	0.09	10.87
T52D	13.75	97	4.48	12.40	3.10	43.72	1.39	0.25	14.85	0.11	6.53
T52E	34.76	198	8.68	0.30	0.08	37.34	1.18	0.22	29.78	0.09	12.18

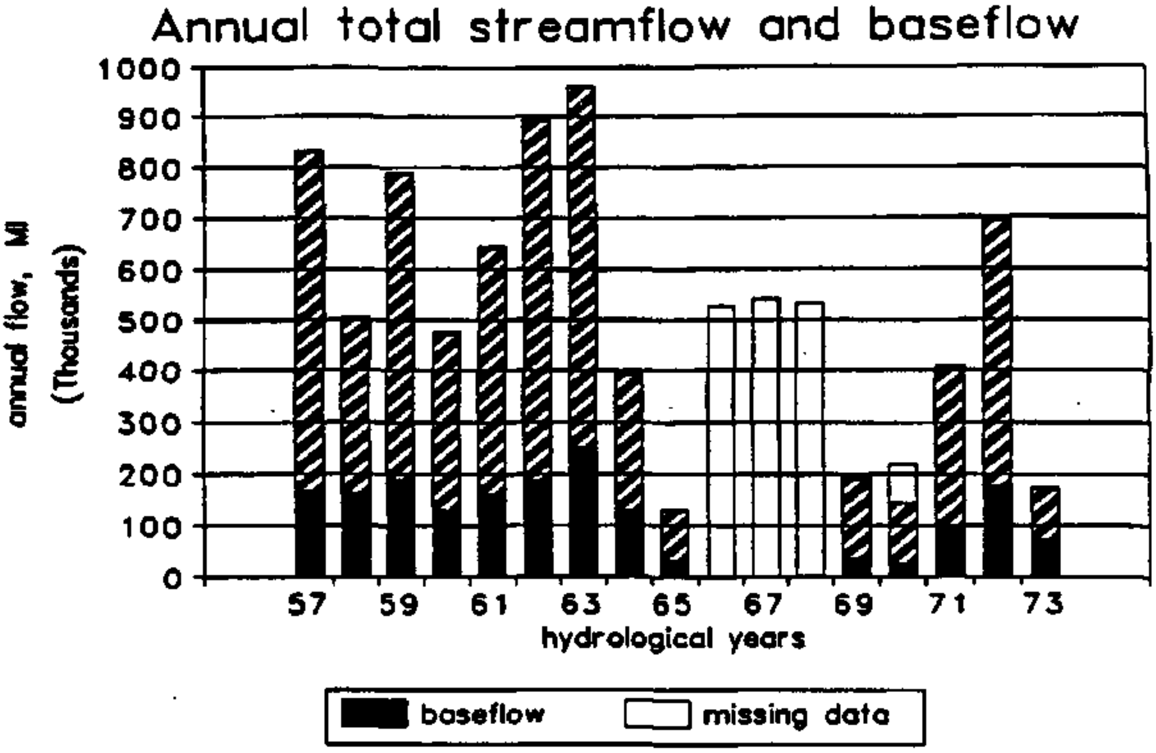
Table E1.8(cont) Estimated Q75 and Q95 flow values for quaternary and tertiary subcatchments in the Mzimkhulu river basin (present day conditions).

Code	Forest, % area	MAR, mm	Forest abs., MCM	Irr.area, km^2	Irr.abs., MCM	Prs.MAR, MCM	Qmean, MCM	Q75, m^3/s	Q75, mm/a	Q95, m^3/s	Q95, mm/a
T52F	35.17	201	15.94	0.60	0.15	67.81	2.15	0.39	29.42	0.17	12.83
T52G	20.36	198	4.82	0.30	0.08	38.80	1.23	0.23	32.82	0.09	12.84
T52H	2.03	92	0.41	0.60	0.15	30.94	0.98	0.18	16.50	0.08	7.33
T52J	2.17	120	0.58	3.00	0.75	42.97	1.36	0.25	21.42	0.10	8.57
T52K	18.31	110	5.30	3.50	0.88	40.72	1.29	0.24	17.77	0.10	7.40
T52L	12.29	153	1.94	1.50	0.38	25.08	0.80	0.15	26.43	0.06	10.57
T52M	2.88	157	0.81	2.50	0.63	47.76	1.51	0.28	28.21	0.12	12.09
T52	15.77	152	53.87	42.00	10.50	525.83	16.67	3.05	24.46	1.28	10.27

APPENDIX E2

Annual flows and low-flow indices in the T drainage region

Note : each year on graphs is from October of the previous calendar year to September of the next calendar year (the year 1952 is from October 1951 to September 1952).



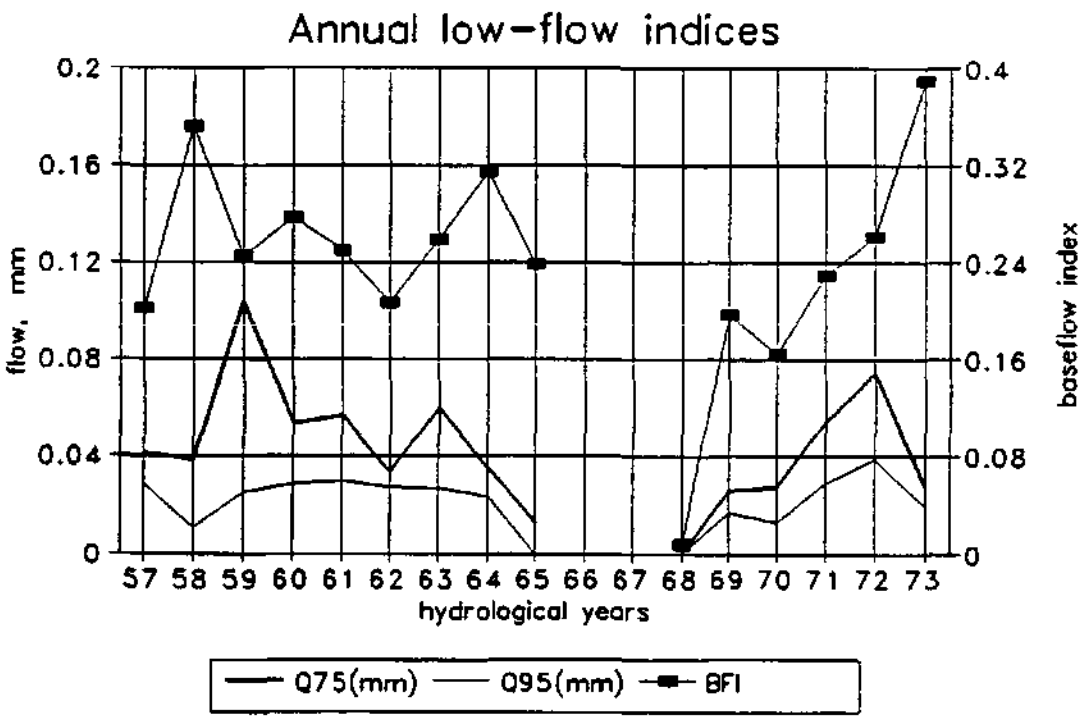
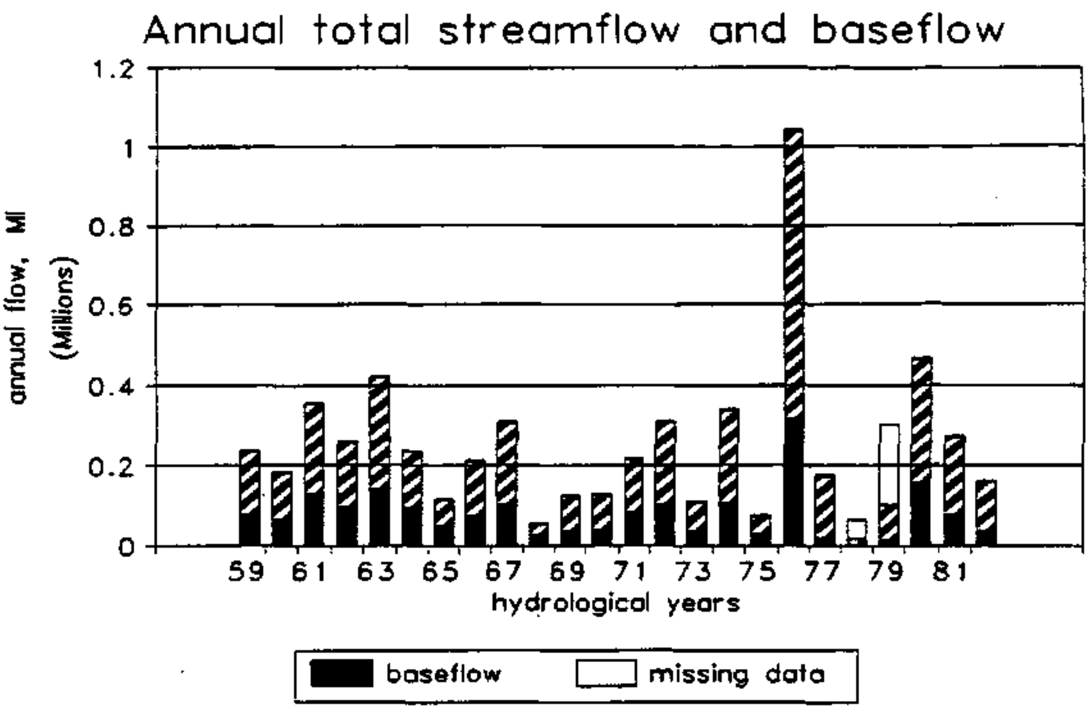


Figure E2.1. Gauge T1H004



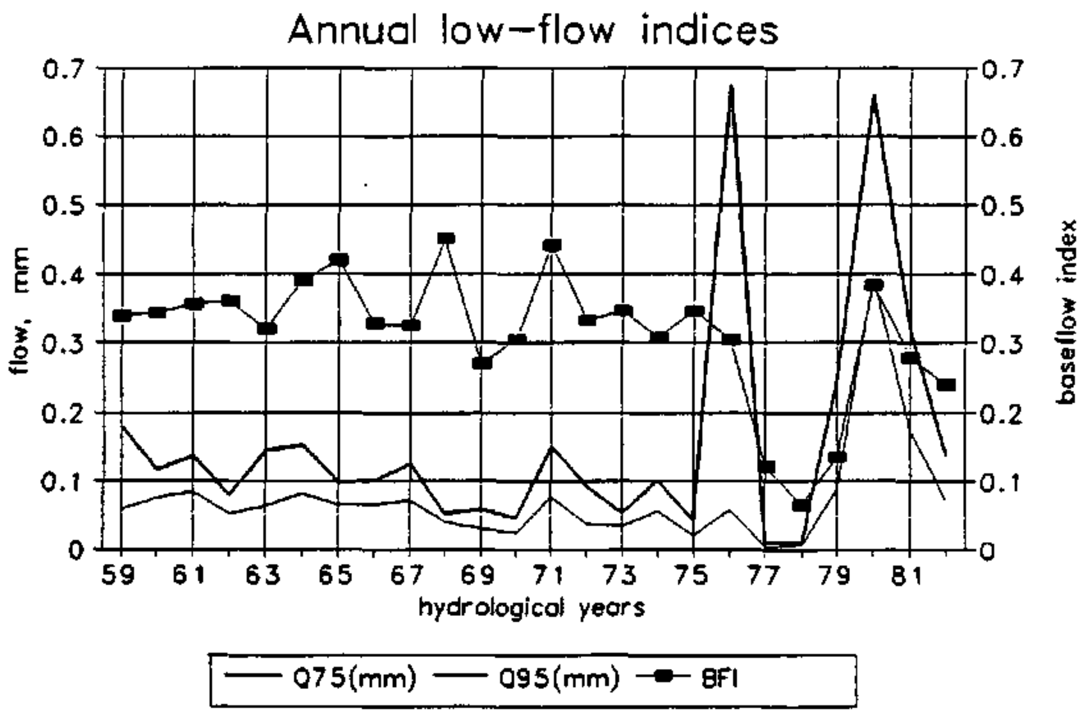
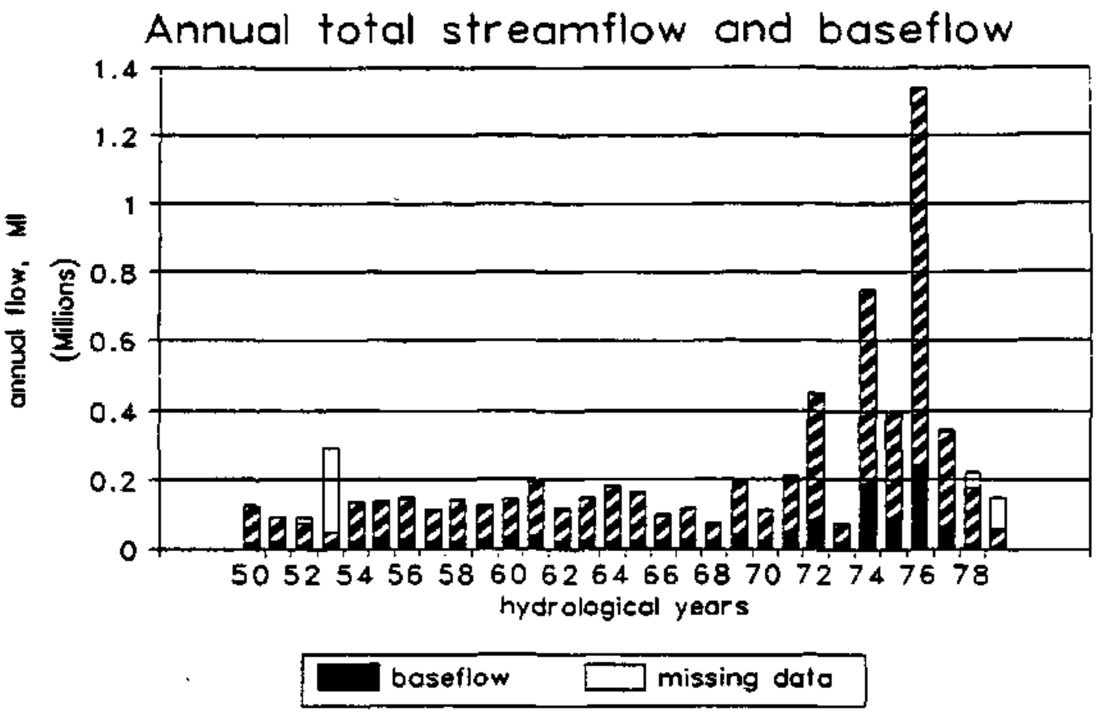


Figure E2.2. Gauge T2H002



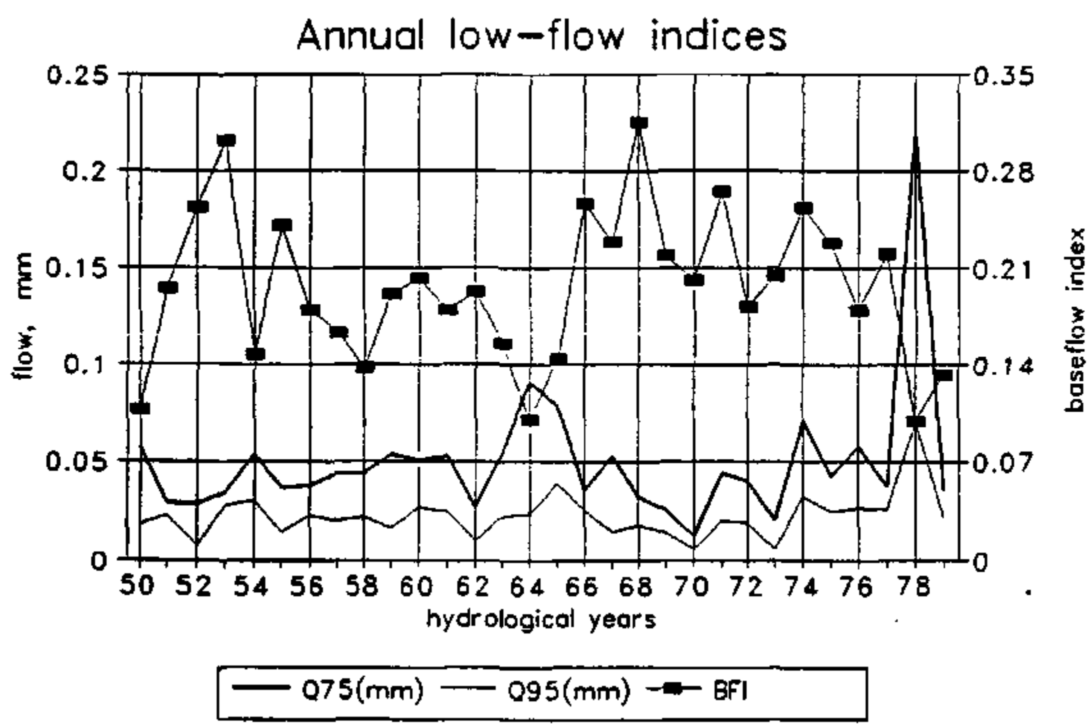
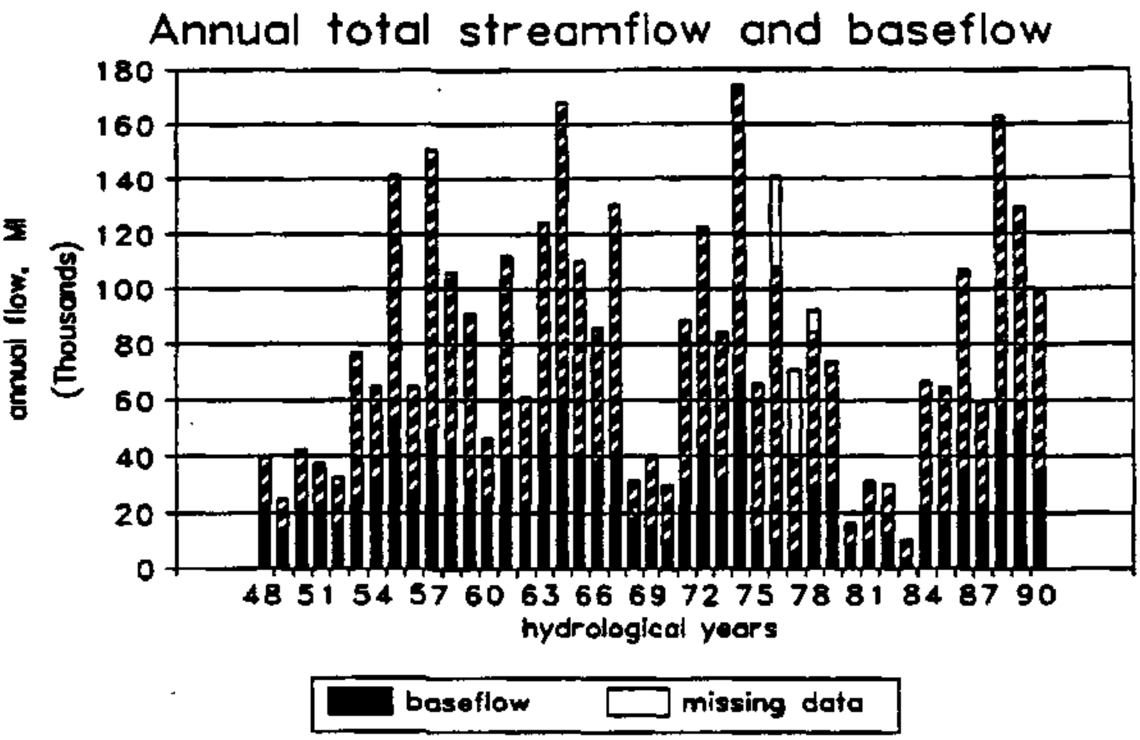


Figure E2.3. Gauge T3H002



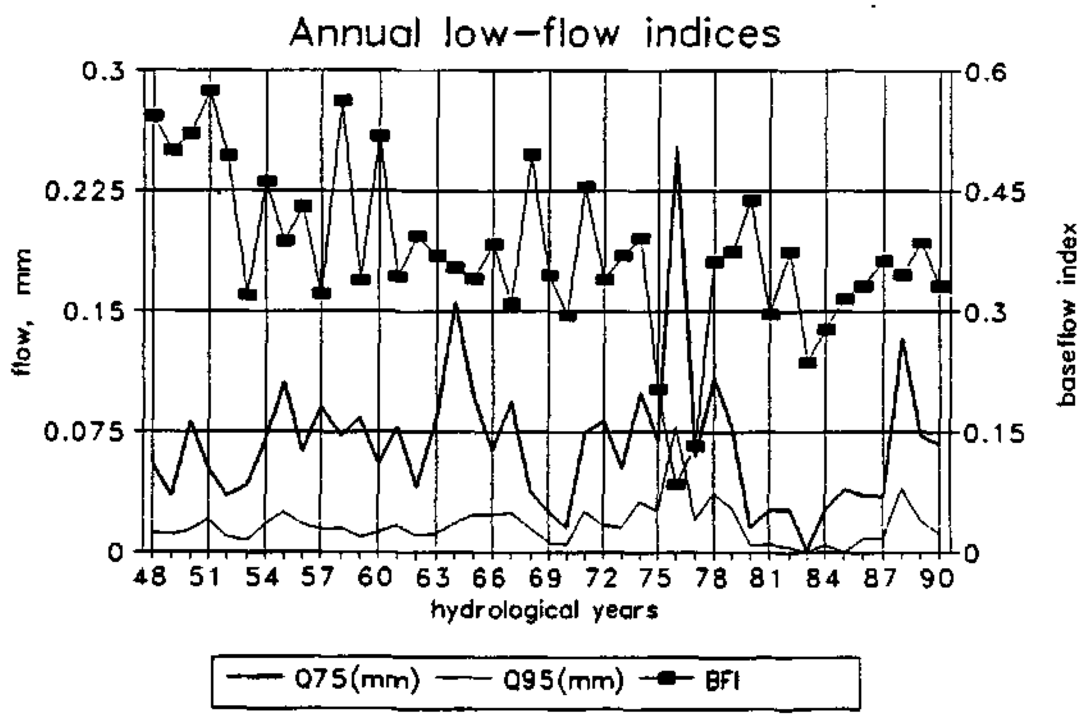
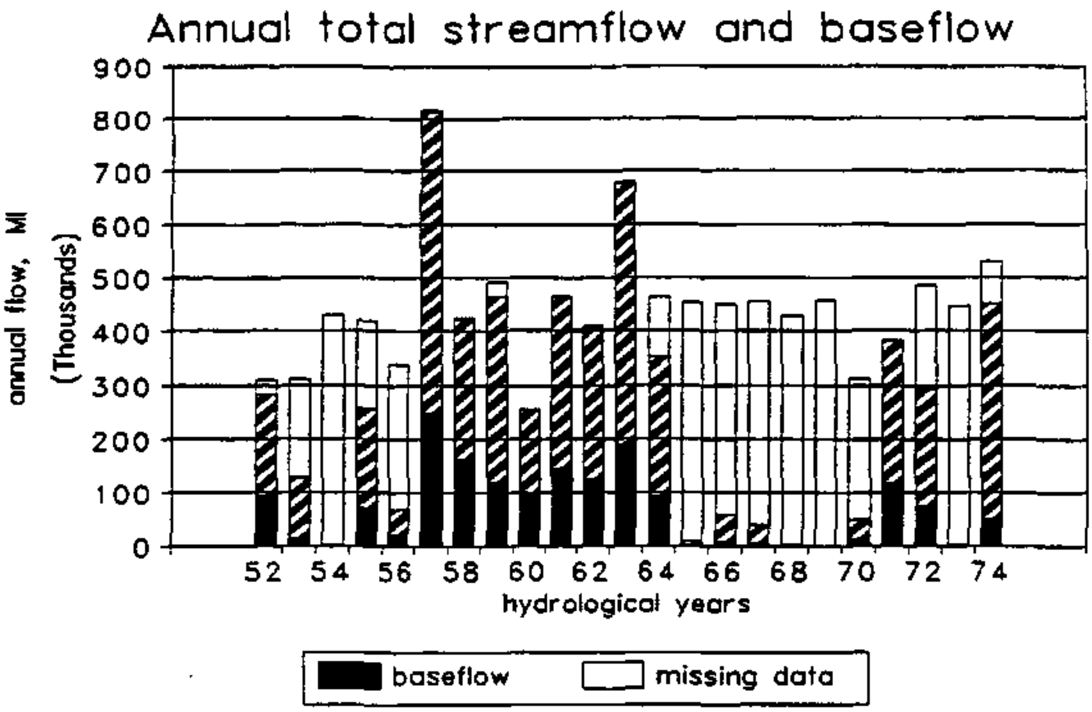


Figure E2.4. Gauge T3H004



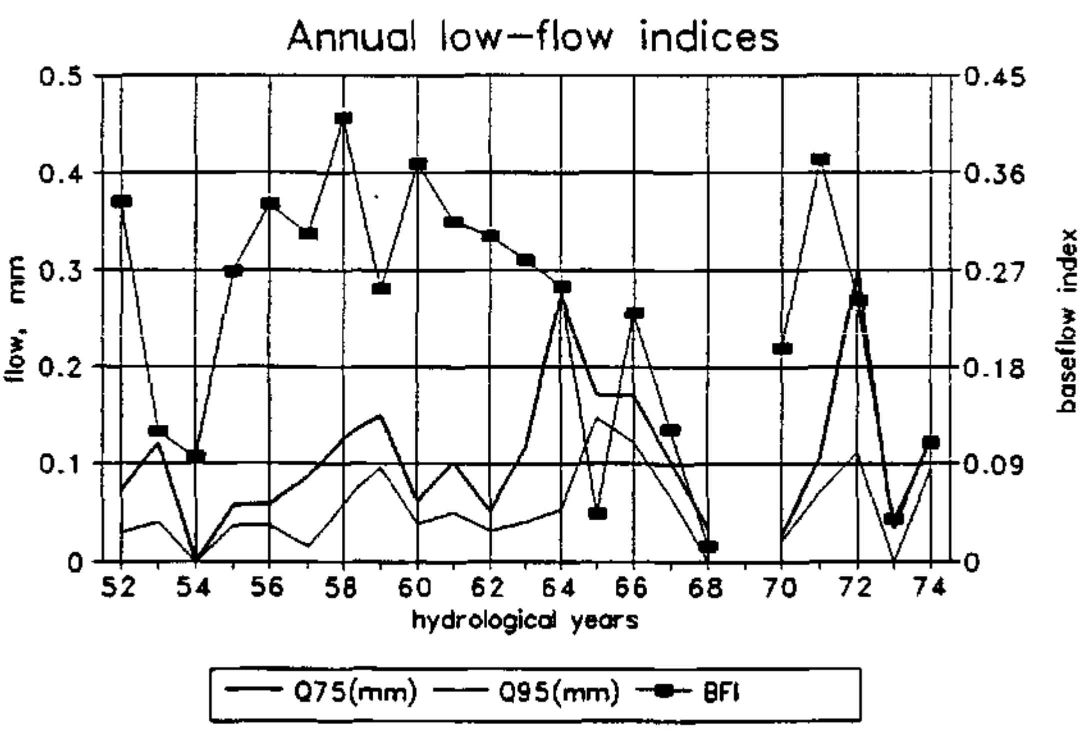
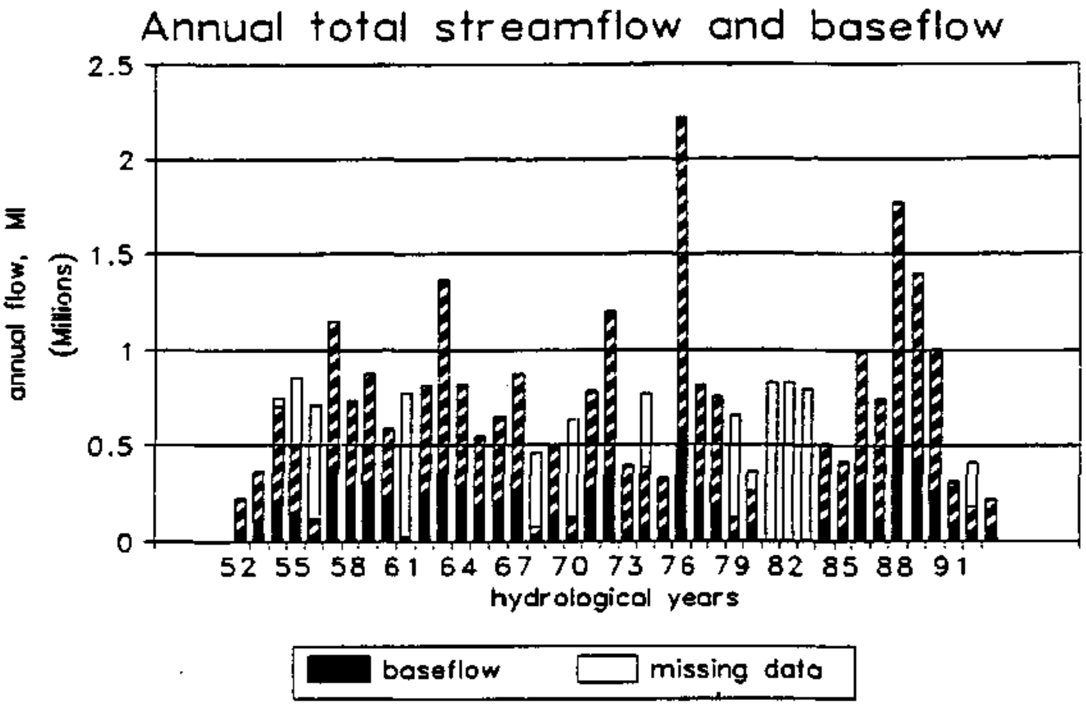


Figure E2.5. Gauge T3H005



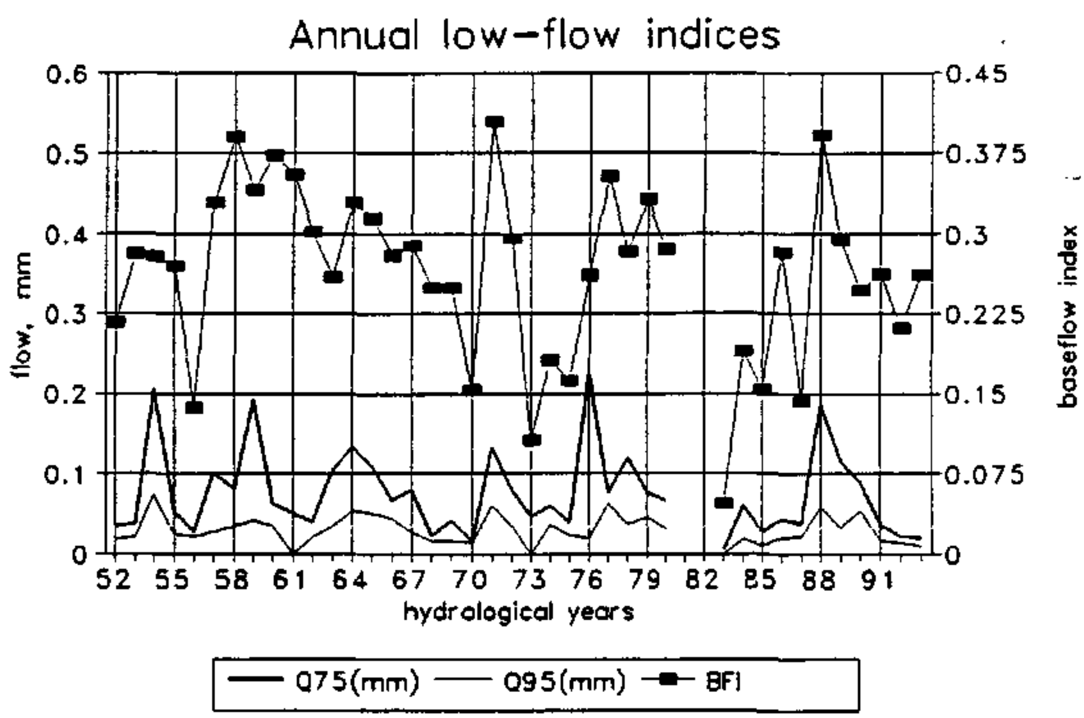
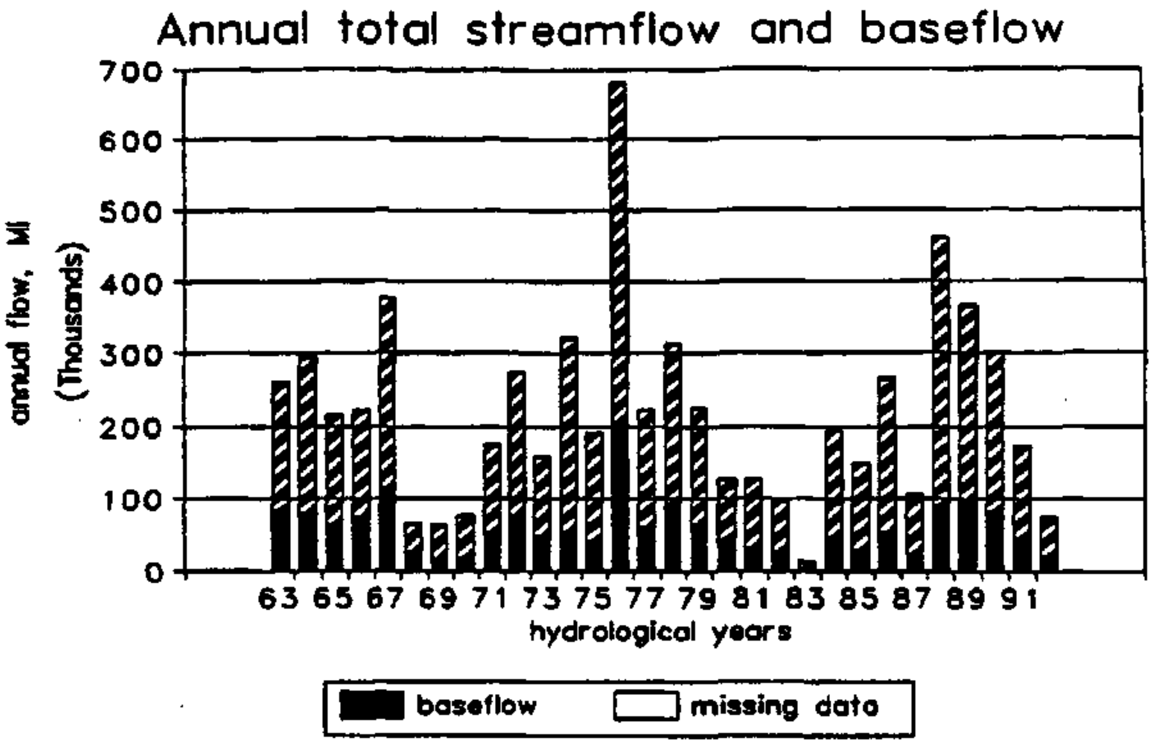


Figure E2.6. Gauge T3H006



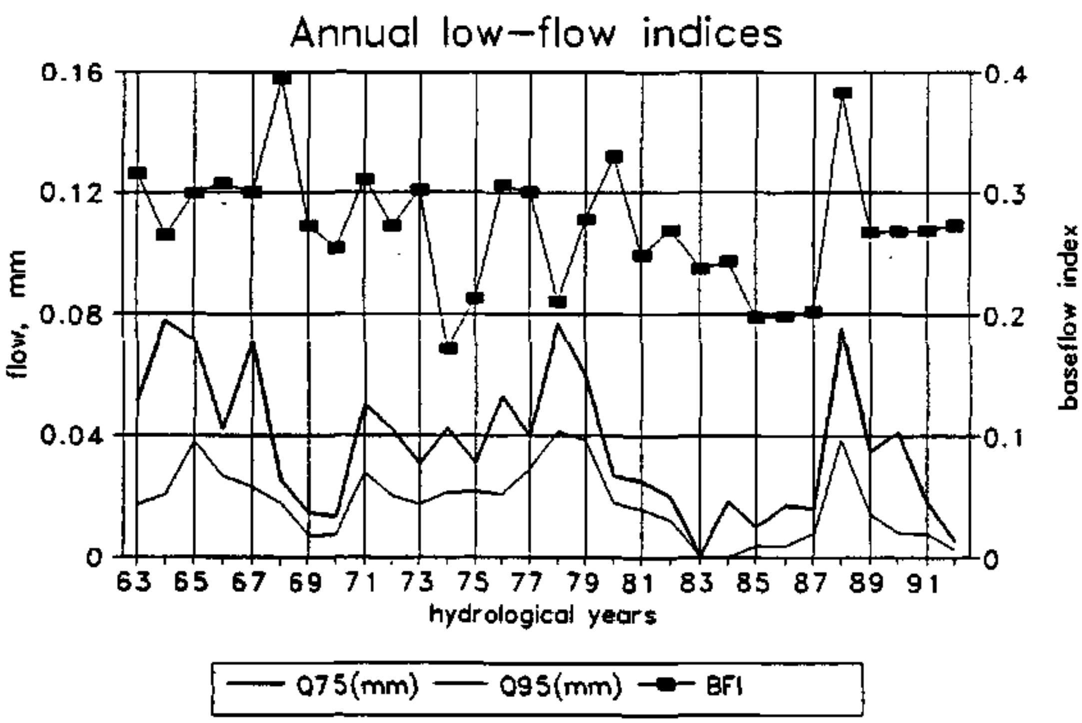
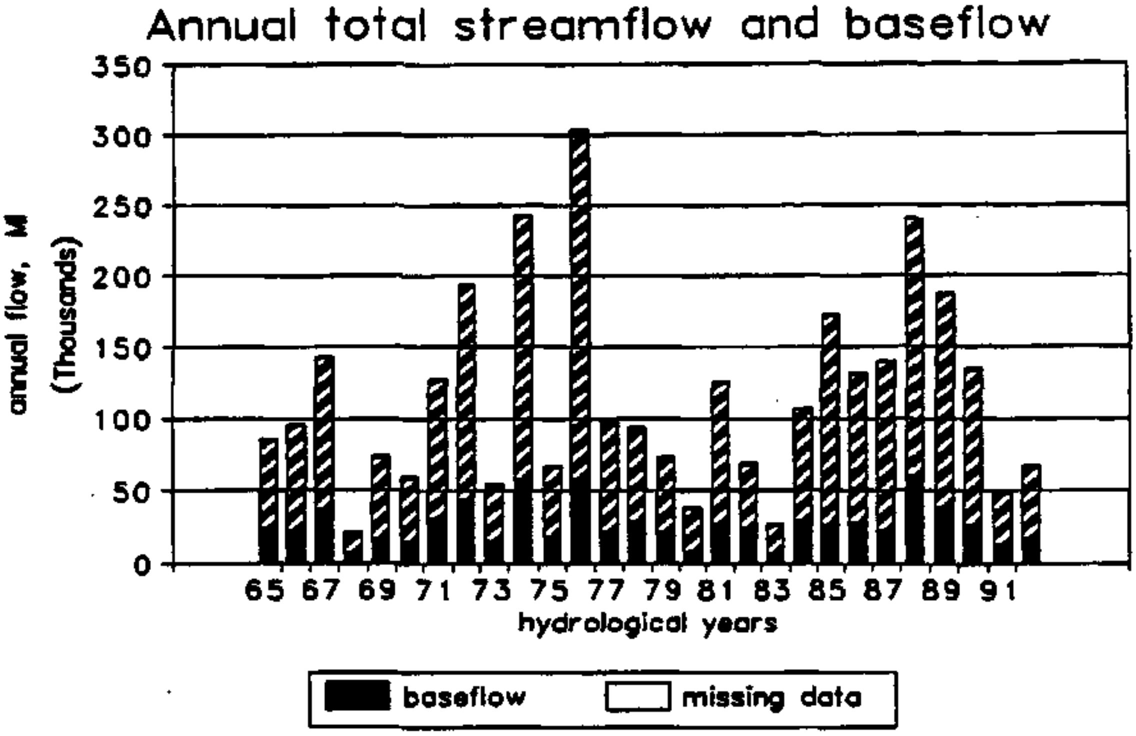


Figure E2.7. Gauge T3H008



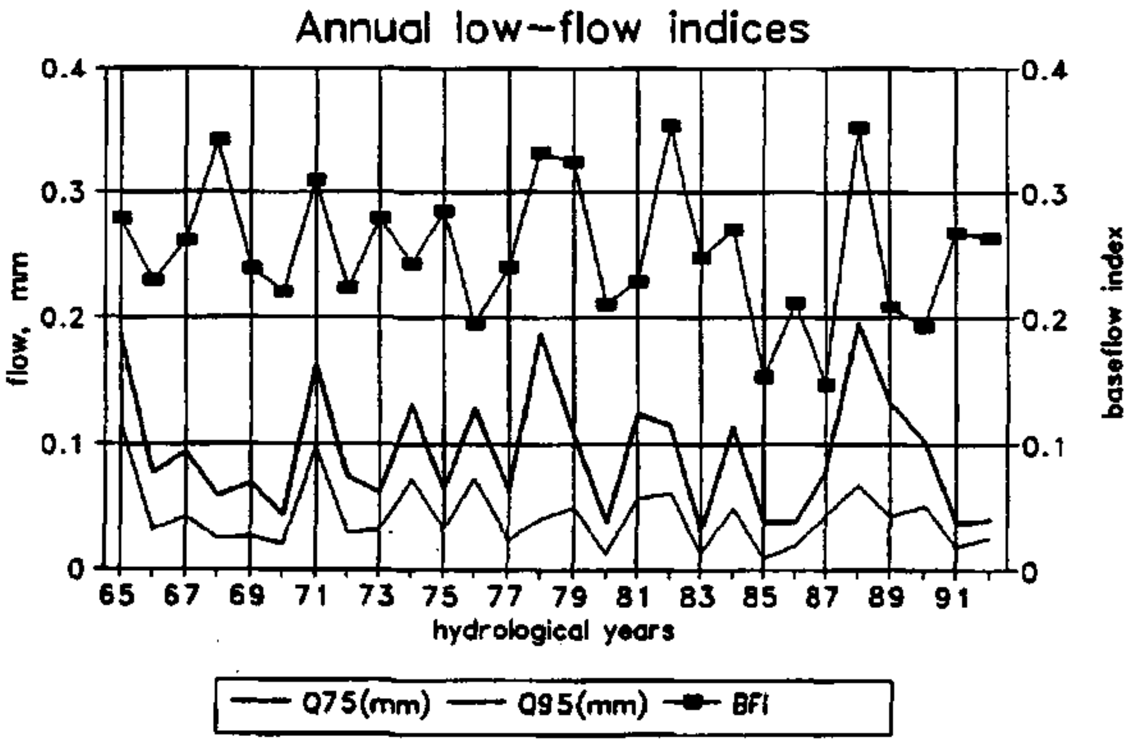
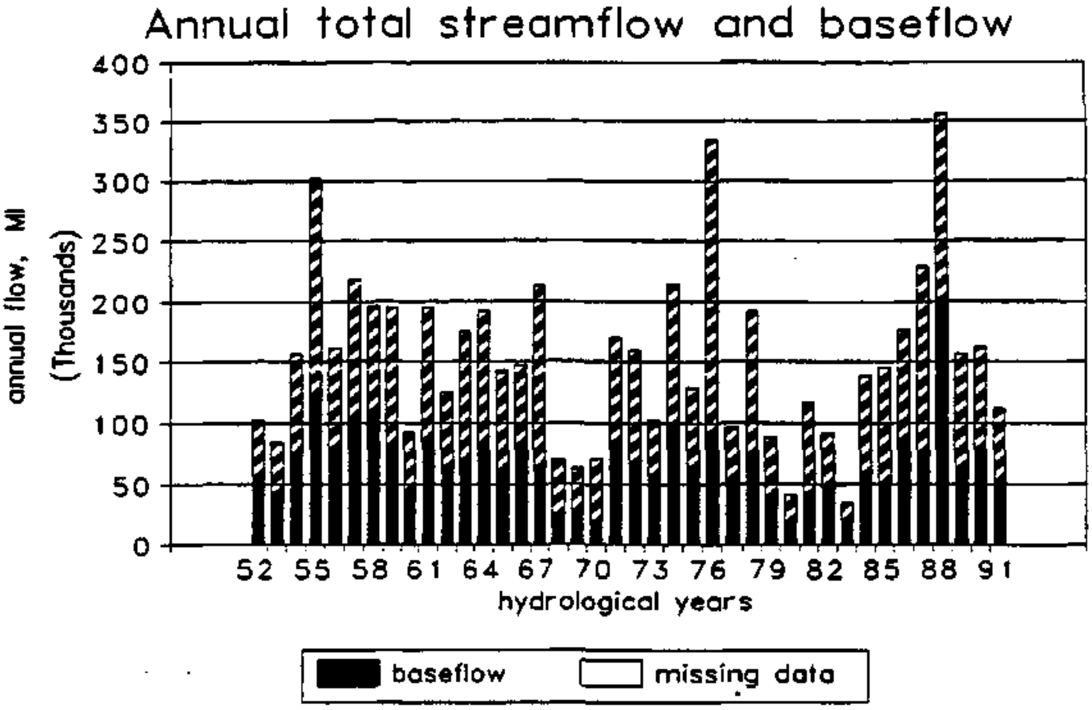


Figure E2.8. Gauge T3H009



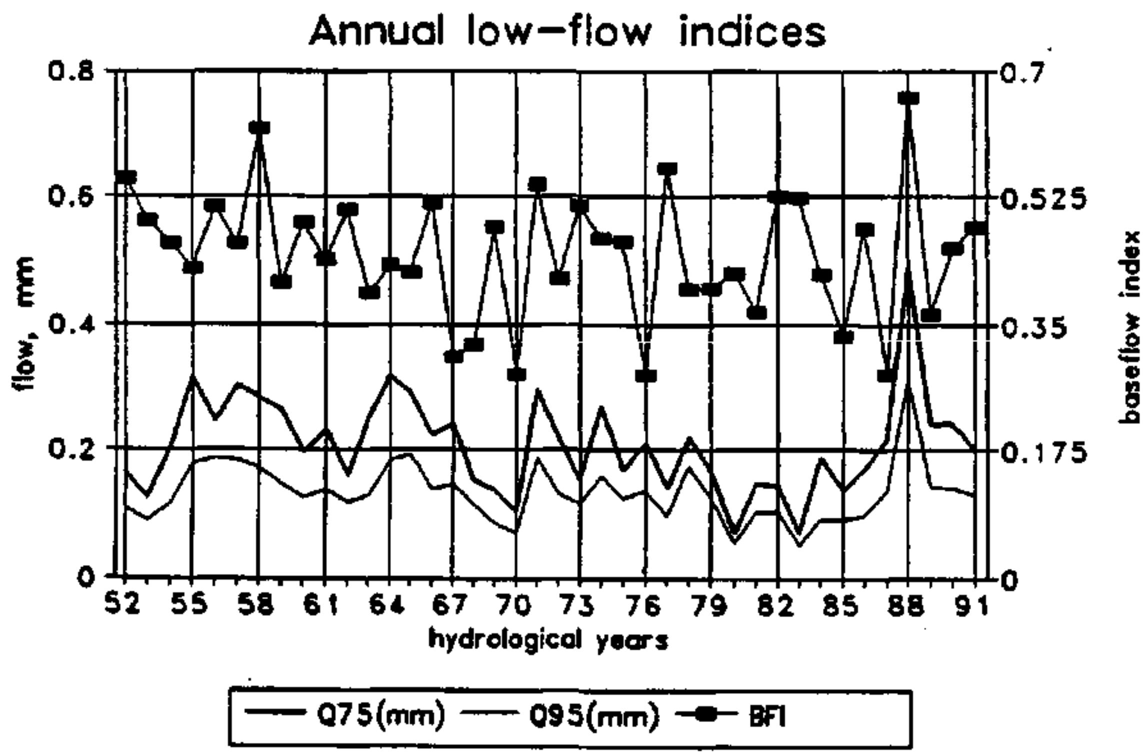
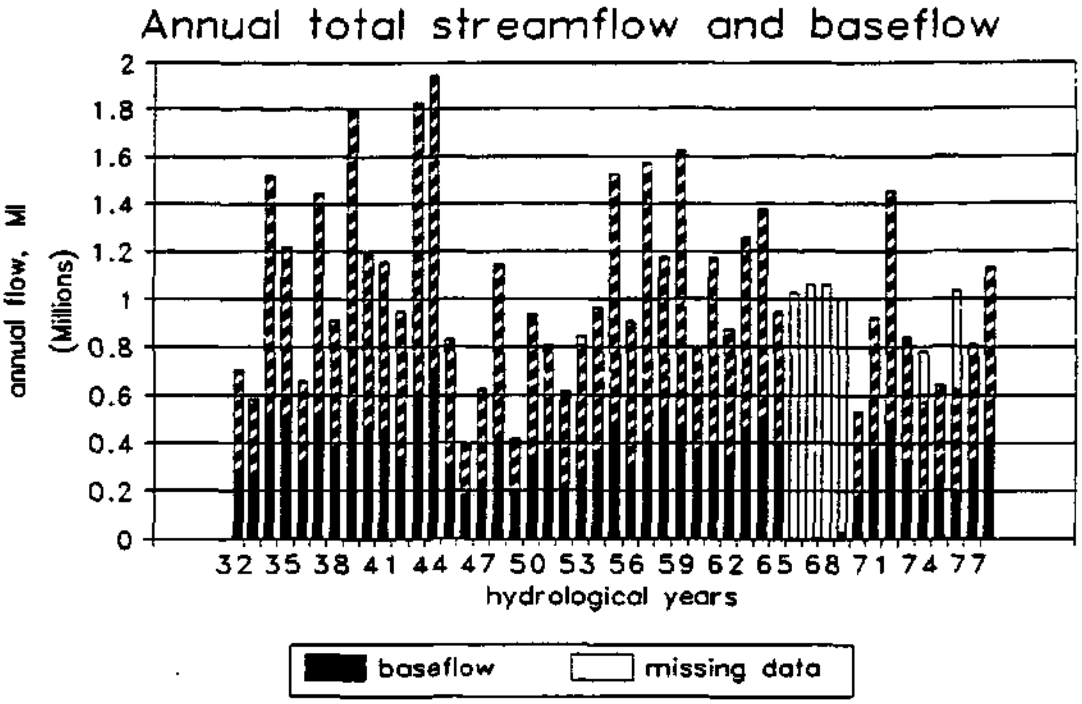


Figure E2.9. Gauge T4H001



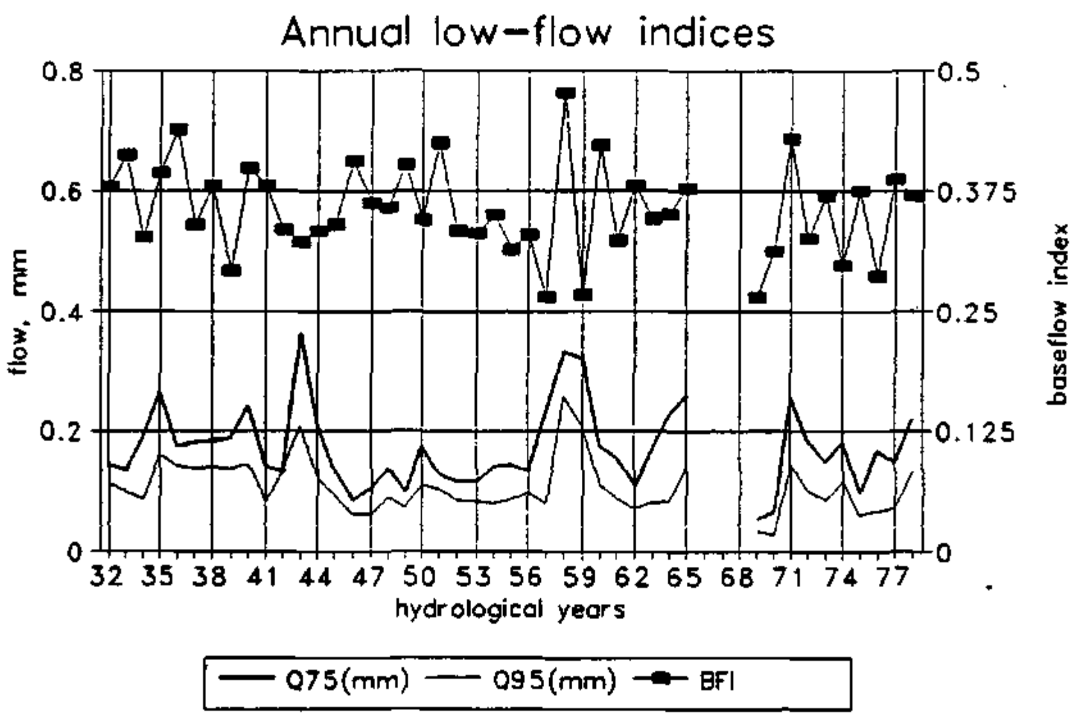
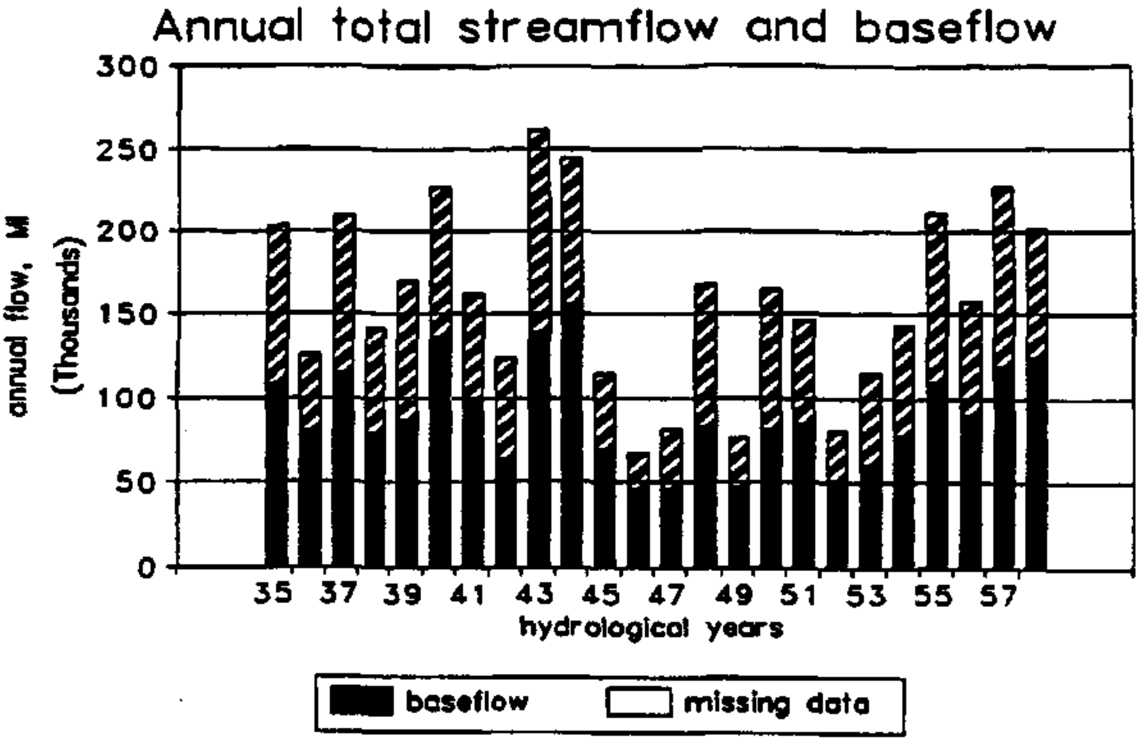


Figure E2.10. Gauge T5H001



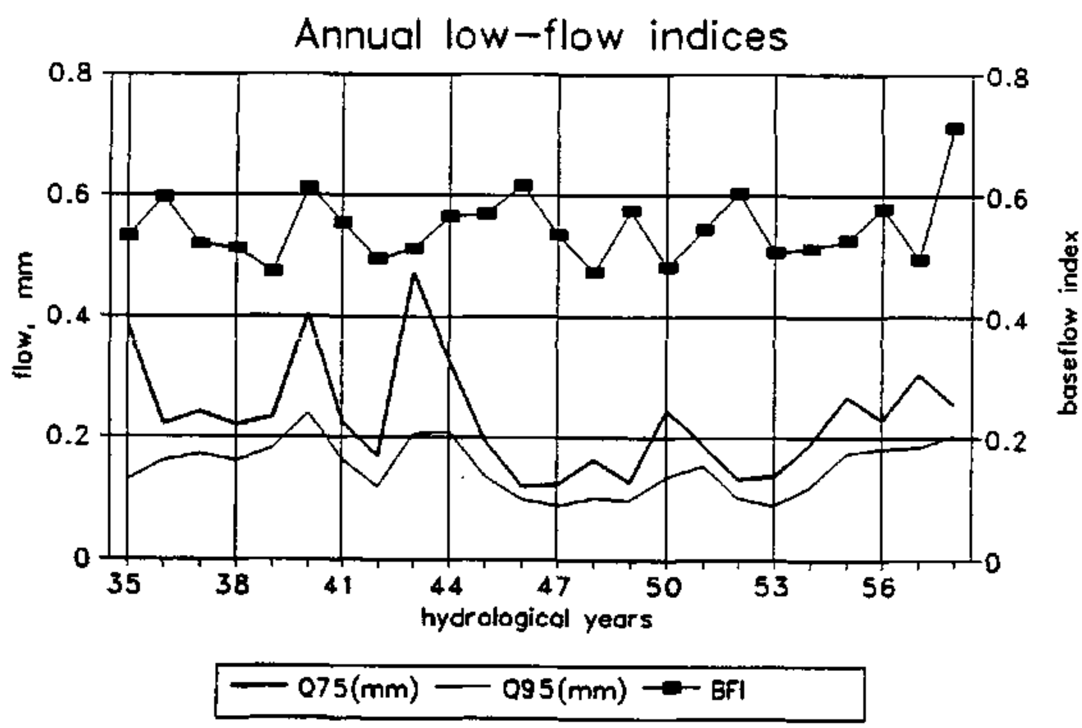
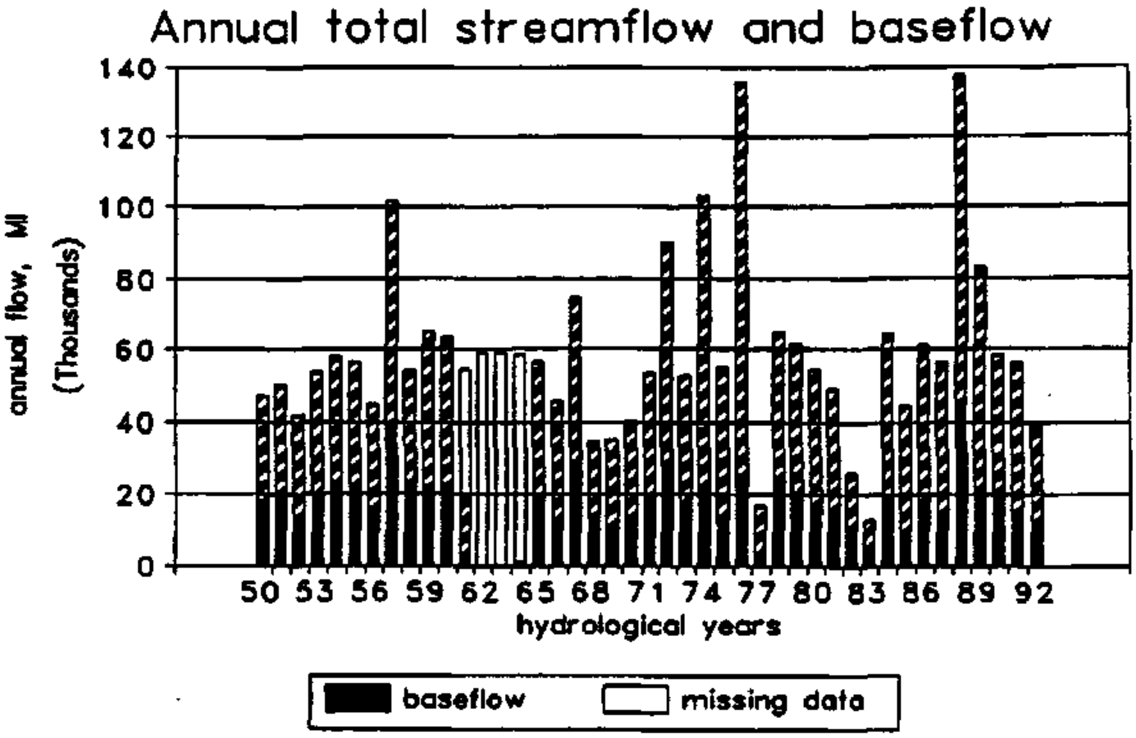


Figure E2.11. Gauge T5H002



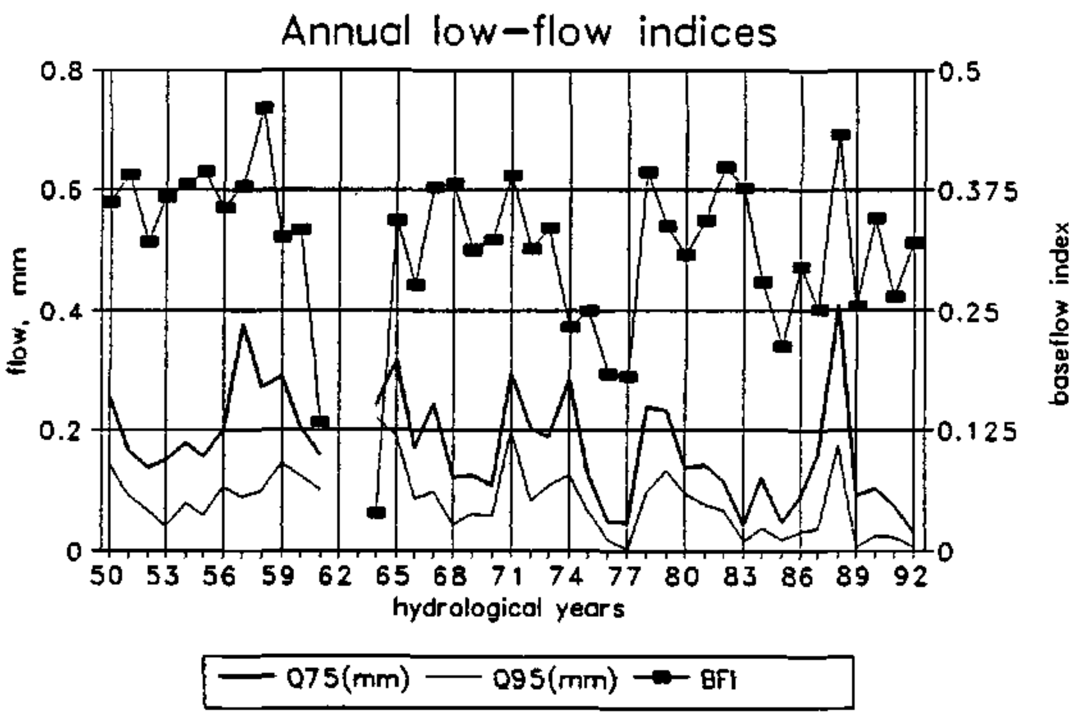
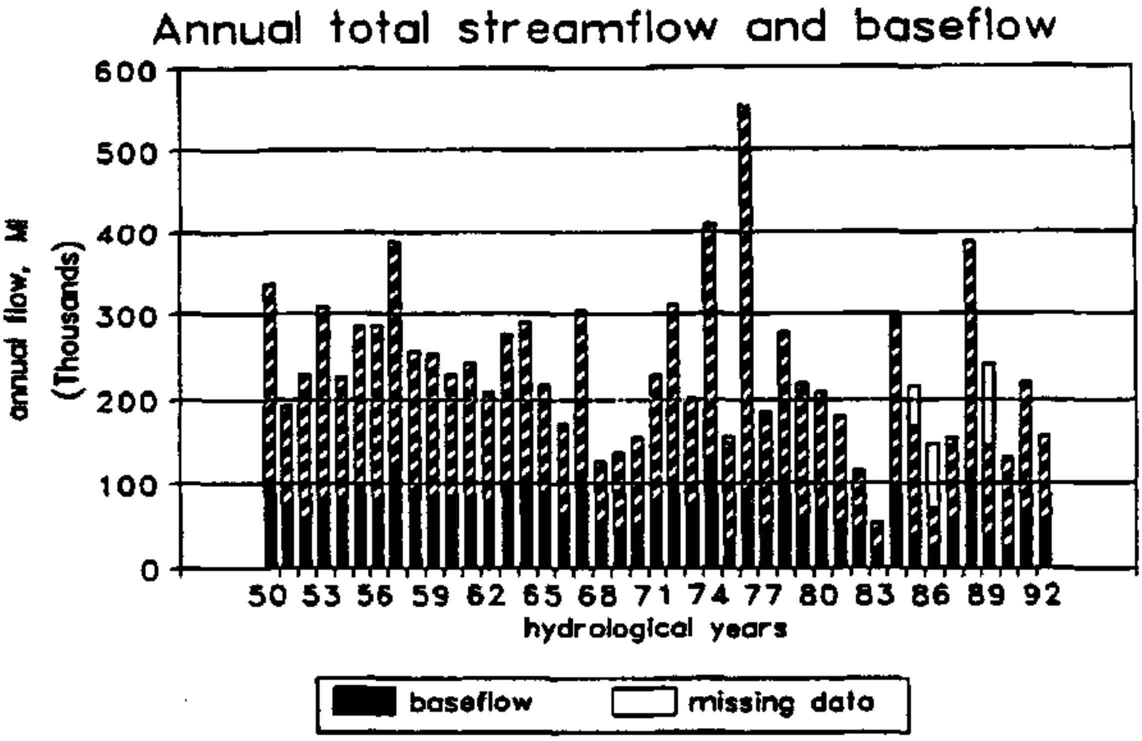


Figure E2.12. Gauge T5H003



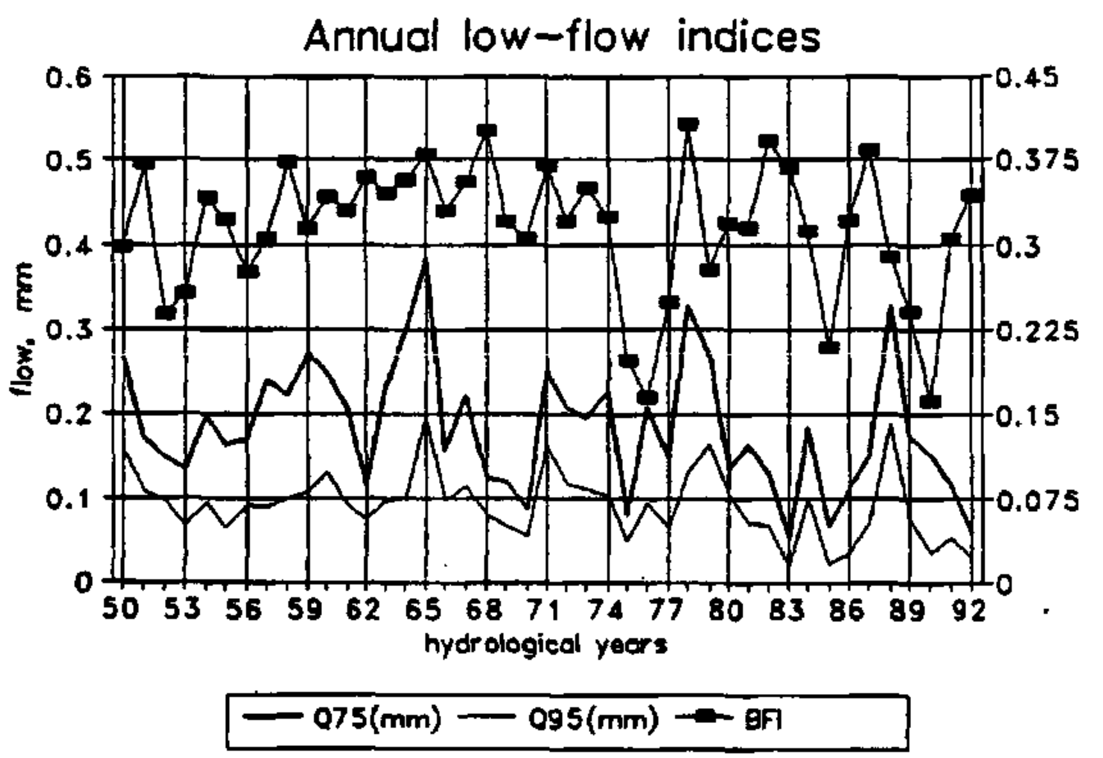
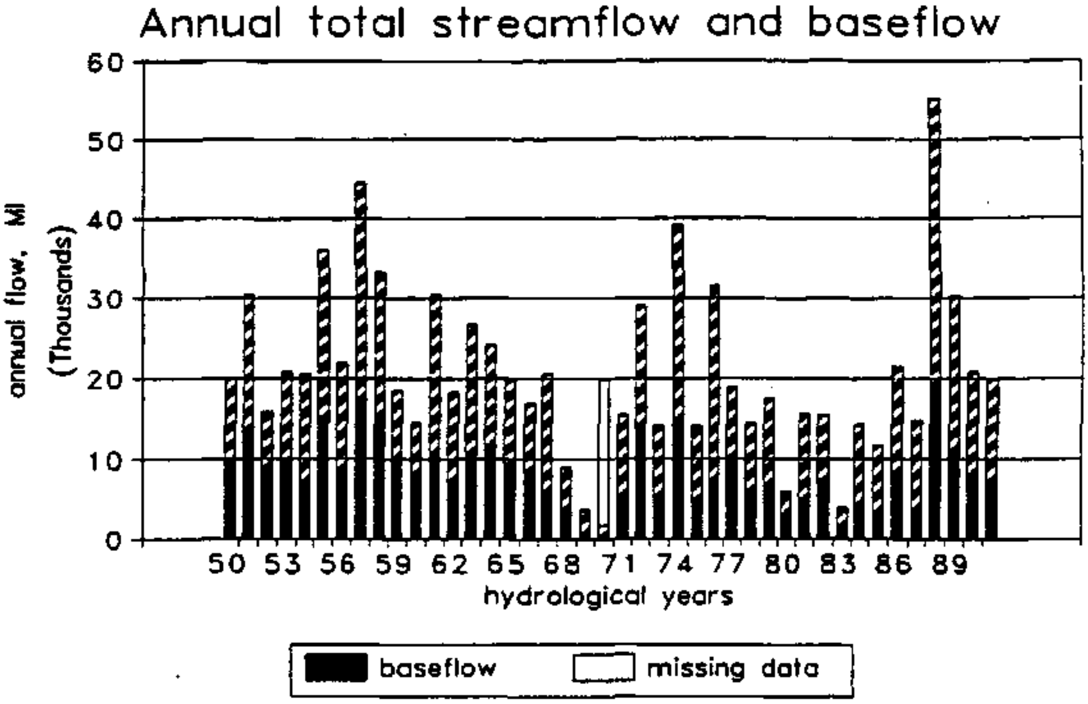


Figure E2.13. Gauge T5H004



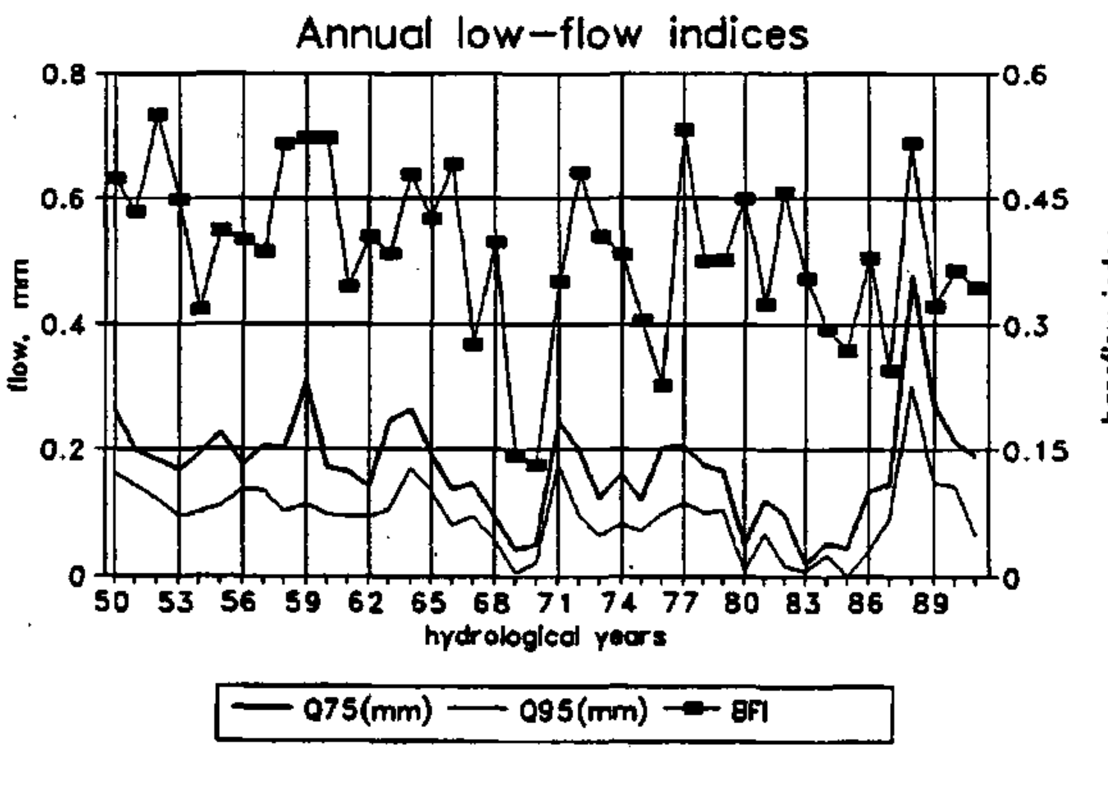
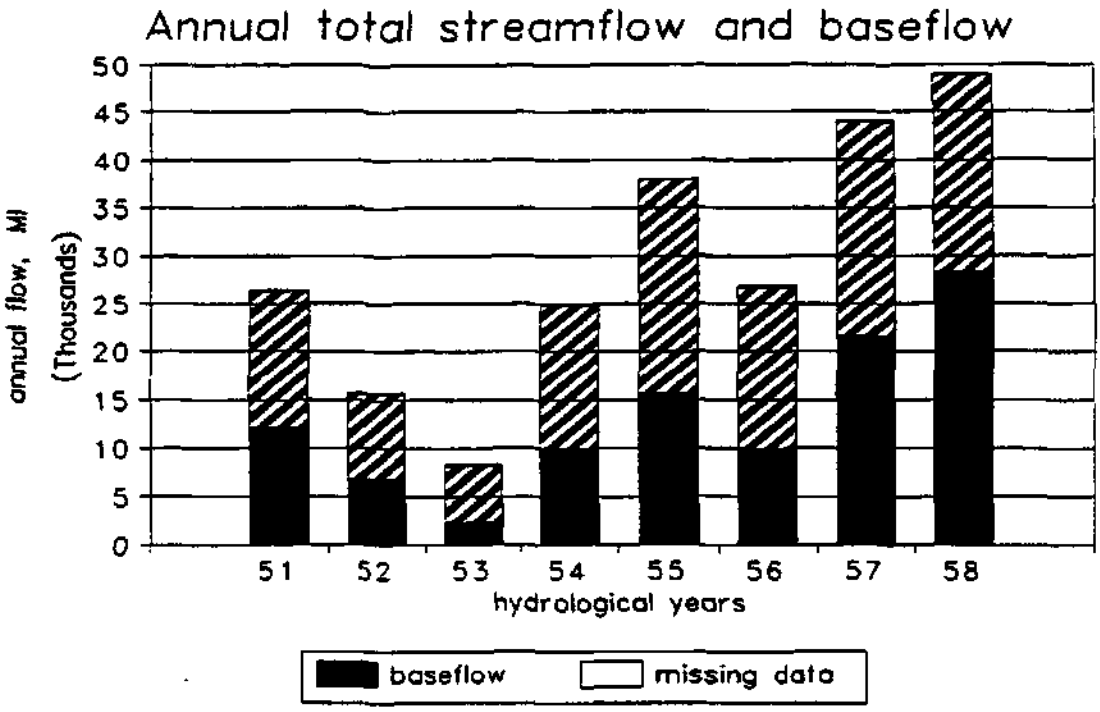


Figure E2.14. Gauge T5H005



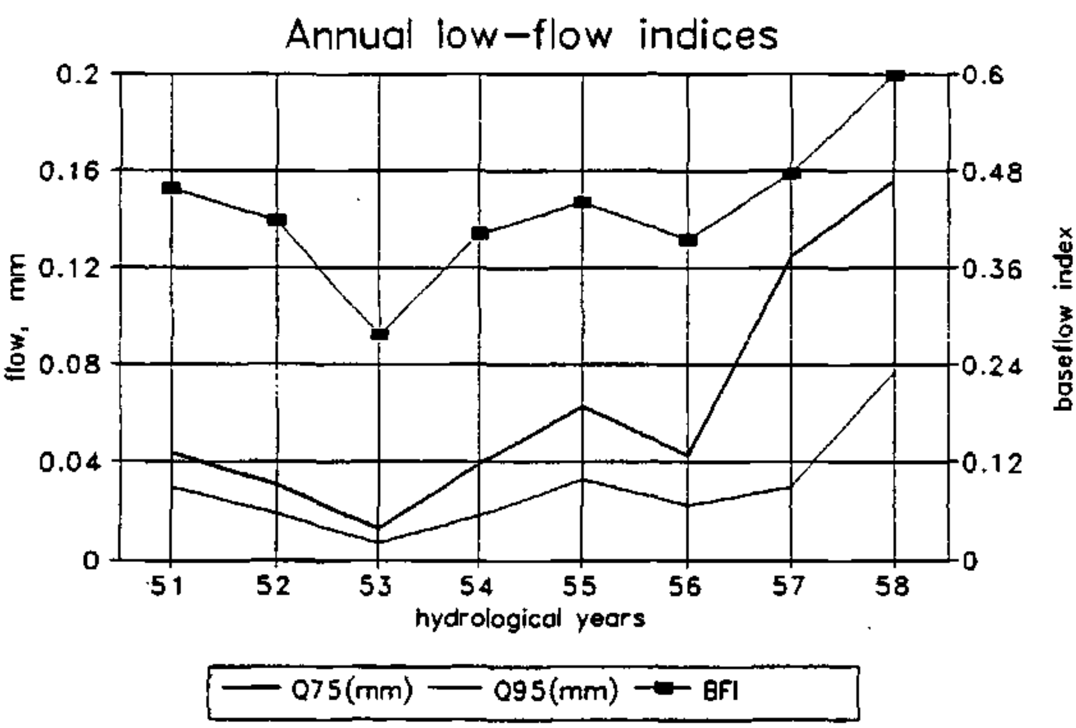
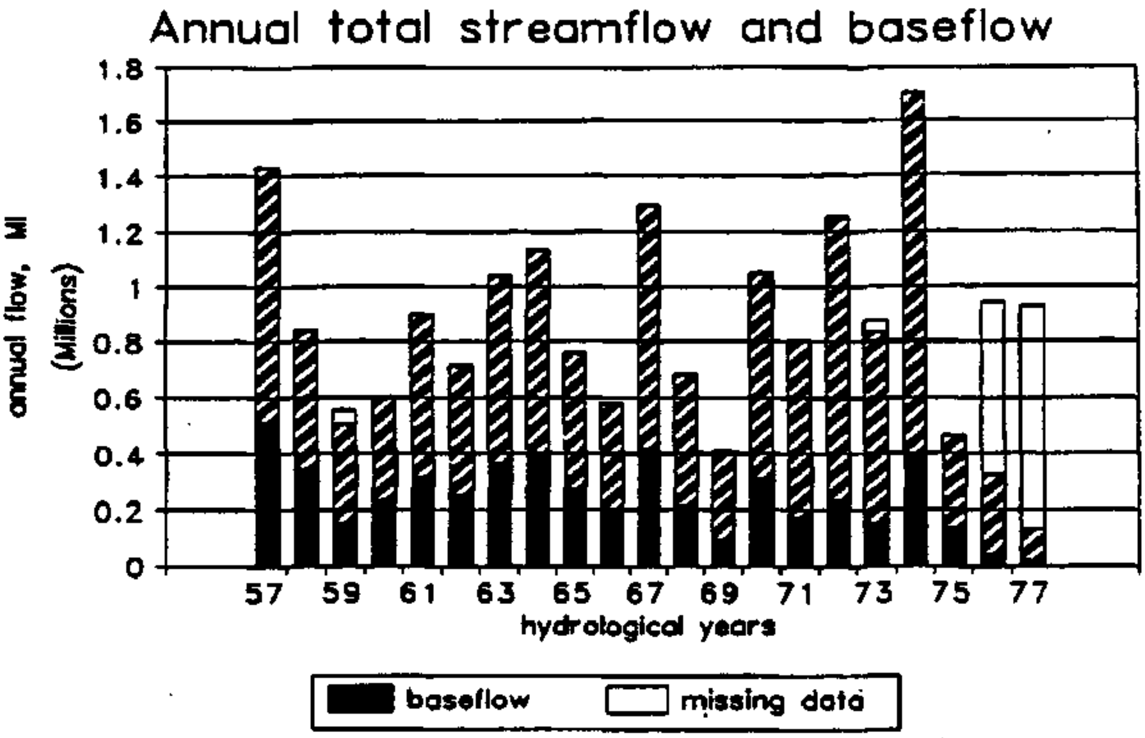


Figure E2.15. Gauge T5H006



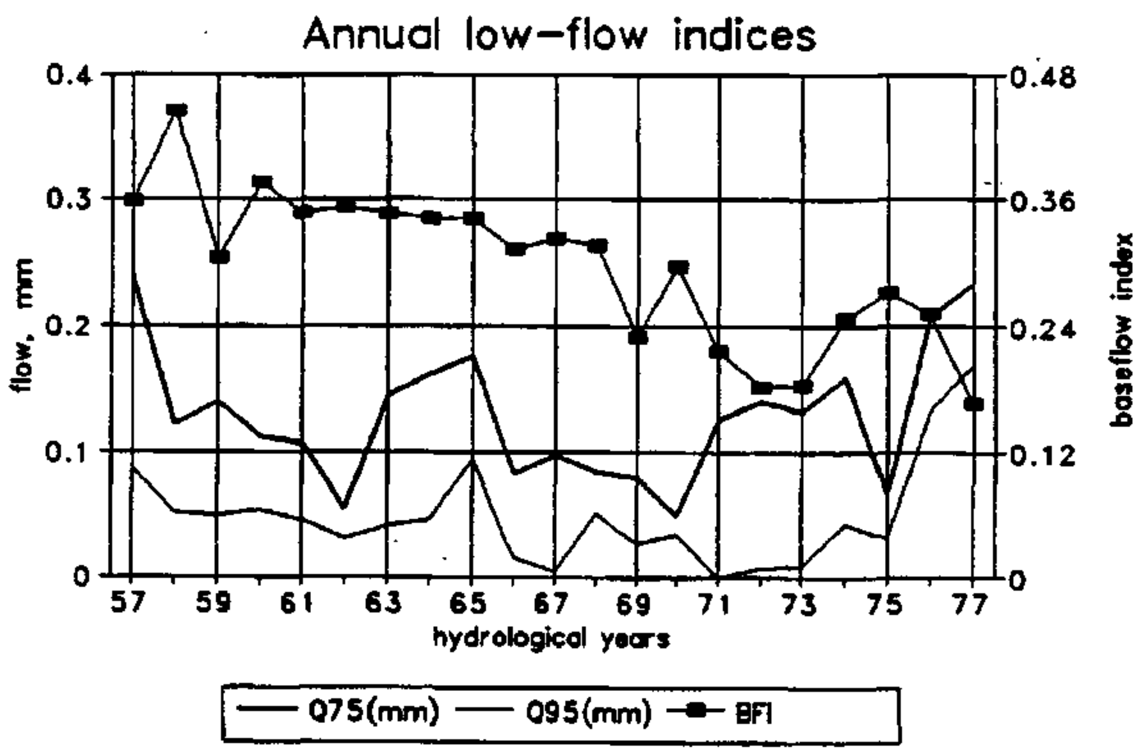


Figure E2.16. Gauge T5H007

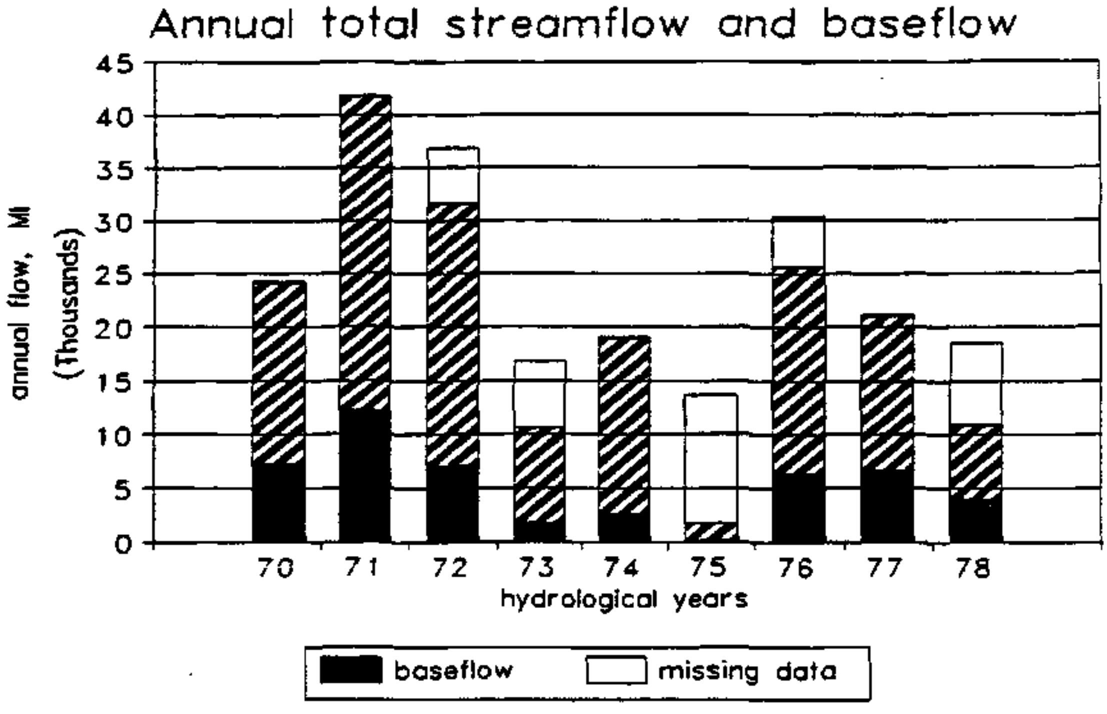


Figure E2.17. Gauge T6H001

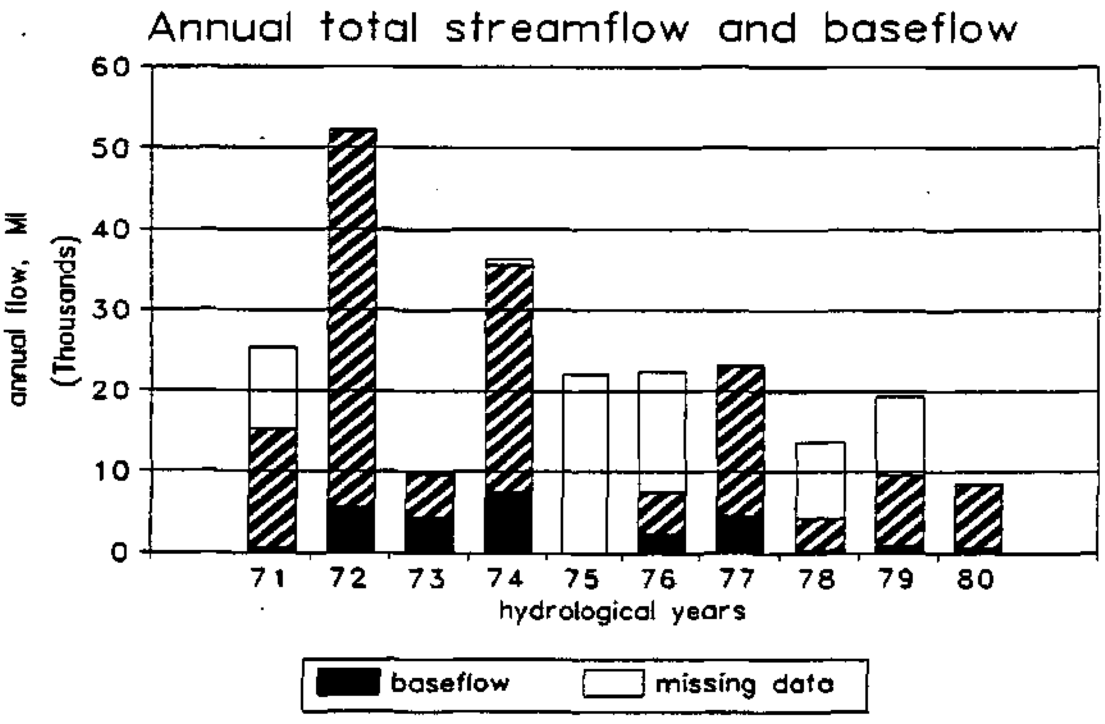


Figure E2.18. Gauge T7H001

APPENDIX F1

Low-flow estimation in the Olifants River catchment (Northern Province)

F1.1 INTRODUCTION.

The problem of low flows in the Olifants river catchment has been addressed by means of regional estimation methods. First the attempt was made to establish regional regression relationships of selected low-flow characteristics with physiographic and climatic parameters of the drainage basins. The approach is widely used in the world low-flow studies (Chapter 2, Vol. 1) and the possibility of its application in South African conditions could not be ignored. Two different variations of the regression approach have been tested. In the first, the regression was attempted without *a priori* grouping of catchments into smaller, relatively homogeneous 'clusters'. In the second, the regression was attempted at the scale of smaller drainage subregions. The attempt to establish regression relationships within 'flow groups' emanating from the UCT river classification studies has also been made.

The second technique applied was the regionalisation of daily flow duration curves (the similar approach was followed in the case of the T drainage region). However, the shape of non-dimensional curves constructed on the basis of observed data appeared to be more variable than in the case of the T drainage region. Therefore, the attempt was made to group them and on the that basis to establish the boundaries of geographically contiguous regions where the simple averaging of the observed flow duration curves can be justified. This Appendix presents some preliminary results of low-flow regionalization. To increase the number of catchments included in regional analysis both regionalization techniques used additional observed daily data from catchments adjacent to the Olifants River Basin.

As in the case of all previous catchments, the available observed daily streamflow data have first been examined by means of the HYMAS data analysis routines and the existing low-flow conditions throughout the Olifants river system have been illustrated in terms of several standard low-flow indices.

F1.2 CATCHMENT DESCRIPTION.

The total area of the Olifants River catchment is approximately 54 575 km^2 and the total length of the main river is about 770 km. The topography of the catchment varies between undulating country side in the south and south-west, with altitudes varying from 900 m and 1800 m above sea level. The Strydpoort mountains and the Transvaal Drakensberg form the boundaries of the catchment on the north-western and south-eastern sides, with altitudes from 1500 to 2400 m above sea level. The escarpment drops rapidly on the eastern flank to the plains where altitudes vary from 900 m close to the Drakensberg to 300 m at the Mozambique border. The general topographic features of the Olifants river catchment are illustrated by Figure F1.1, constructed on the basis of the information obtained from the CCWR.

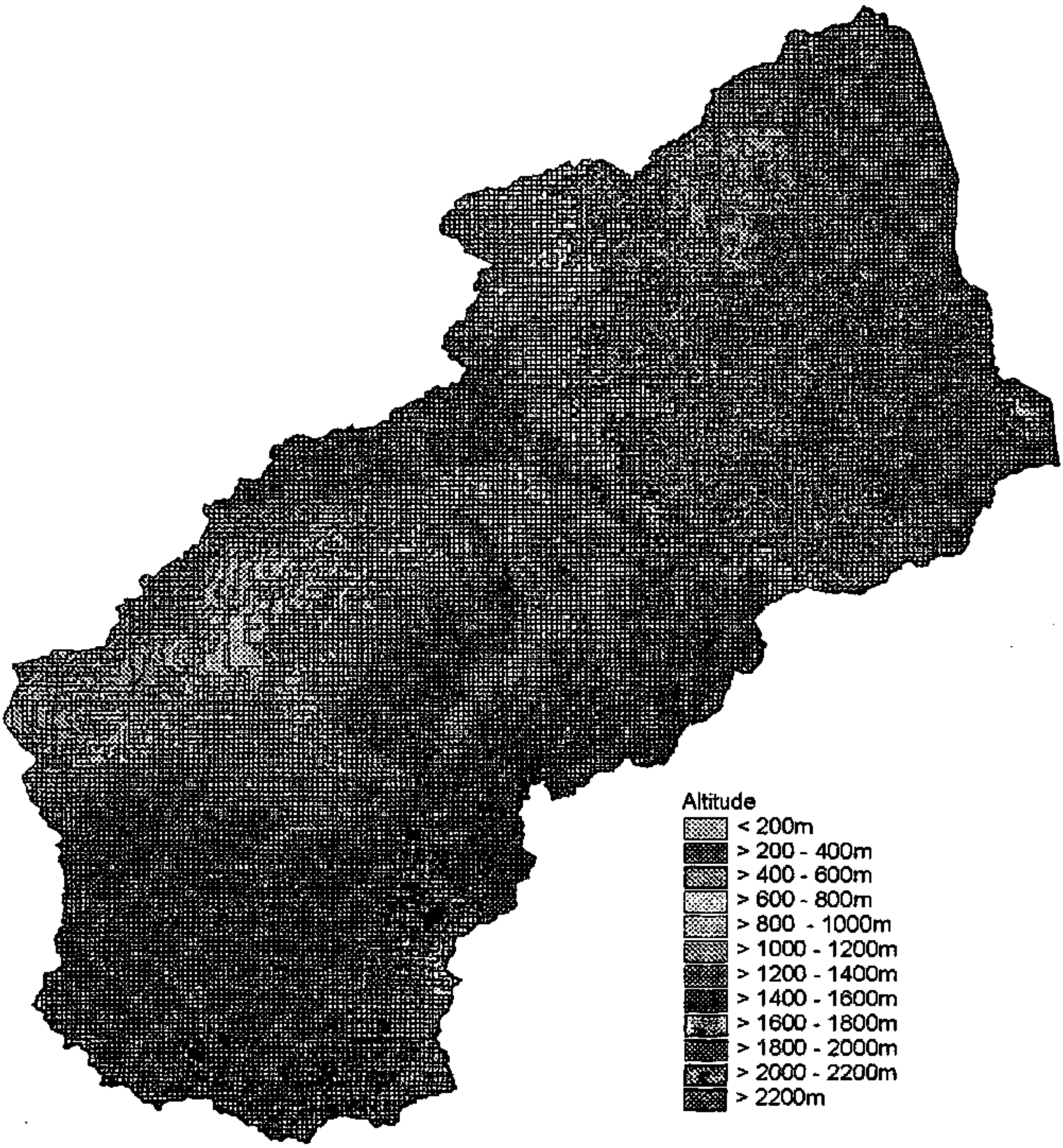


Figure F1.1 1' X 1' grid altitude data (m) for the Olifants River catchment.

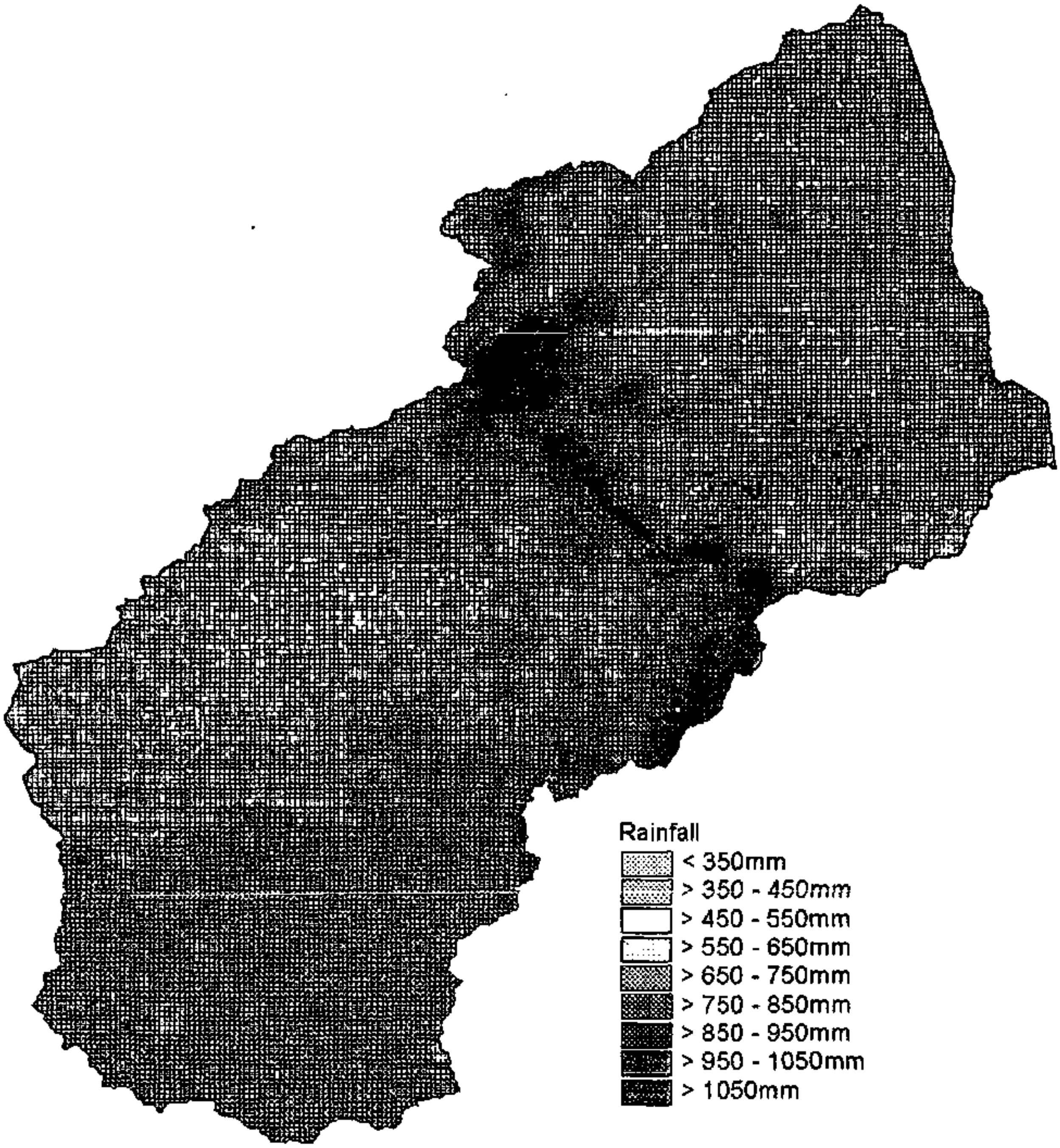


Figure F1.2 1' X 1' grid MAP data (mm) for the Olifants River catchment.

The MAP varies from about 950 mm at Pilgrim's Rest to as little as 400 mm in the Kruger National Park. Along the escarpment, rainfall is in the order of 1900 mm. The spatial distribution of MAP within the catchment is illustrated by Figure F1.2. Further details regarding the physiographic and climatic conditions of the Olifants River basin as well as the description of the different sectors of water usage may be found in the Olifants River Basin Study Report (DWAF, 1991).

F1.3 OBSERVED STREAMFLOW DATA.

The streamflow in the catchment is (or was) measured at more than 100 gauges. The data for 70 gauging stations were actually available from the DWAF. Some of them record flow in canals and are of little relevance to the present study. Some detail about the gauges in the catchment are summarised in Table F1.1 while their approximate positions are shown on Figure F1.3.

All data sets have been examined by means of the HYMAS data analysis routine which allows annual flow volumes for each gauge to be calculated from the original daily data and plotted as a time series. This provides an easy way of looking at the quality of the data since the procedure identifies and graphically displays "bad years" with the potential amount of "missing flow". This allows the usable period of record for each gauge to be selected and the necessity and possibility to patch the records to be determined.

Temporal changes in low-flow regimes have been investigated by extracting similar low-flow indices for each year of record and plotting them as a time series. This provides the possibility of detecting temporal trends in low-flow regimes themselves, as opposed to annual flow totals. Low-flow indices used were the same as in the previous cases: 1-day Q75 and Q95 flows extracted from each year flow duration curve, annual baseflow volumes and baseflow index values estimated by means of the digital filter. The graphs of annual flow totals and annual low flow for each gauge in the catchment are presented in the APPENDIX F2.

Most of the records in drainage region B1 appeared to be stationary with the exception of gauge B1H004 (Fig. F2.1, APPENDIX F2) which demonstrates an increasing trend in both annual total flows and annual low flows. The gauges in the region B2 (except B2H001) generally have rather short records and therefore allow no firm conclusions about temporal changes in low- flow regimes to be made.

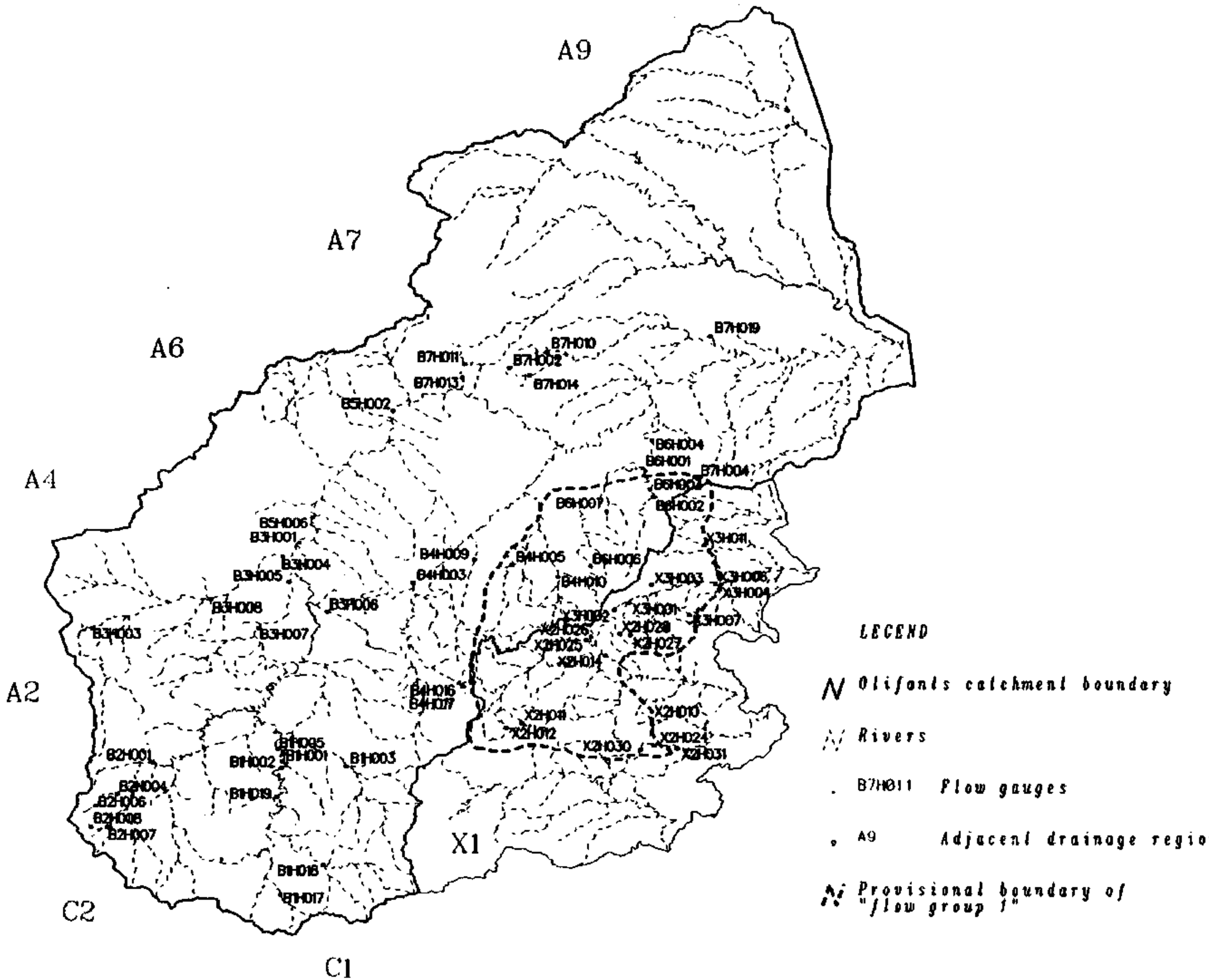
Most of the gauges in drainage region B3 are located downstream of various impoundments and/or irrigation schemes and therefore record modified flow regimes (Table F1.1). The major source of water in the main river in this region are spills and compensation releases from the Loskop Dam constructed in the late 1930s. However, no low flows exist downstream of the dam (gauge B3R002, Fig. F2.17). The record at gauge B3H001 (Fig. F2.11) located further downstream of the Loskop Dam (at the confluence with Elands),

Table F1.1 Flow gauges in the Olifants River basin.

Code	River	Area, km²	Rec. period	Comments
1	2	3	4	5
B1H001	Olifants	3904	1904-1951	prior to Witbank dam
B1H002	Spookspruit	252	1956-1992	
B1H003	Klein Olifants	1576	1957-1966	prior to Middleburg dam
B1H004	Klipspruit	376	1959-1993	
B1H005	Olifants	3989	1972-1994	
B1H010	Olifants		1953-1991	
B1H015	Klein Olifants	1577	1980-1992	close to B1H003; after Middleburg dam
B1H017	Steenkoolspruit	387	1989-1994	short record; extended to 1972: R^2=0.64; CE=0.63
B1H018	Olifants	985	1989-1994	short record; extended to 1972: R^2=0.8; CE=0.76;
B1H019	Noupoortspruit	88	1990-1994	short record
B2H001	Bronkhorstspruit	1594	1904-1951	prior to Bronkhorst dam
B2H003	Bronkhorstspruit	1574	1981-1994	*after Bronkhorst dam*
B2H004	Osspruit	123	1984-1994	short records; cannot be extended
B2H006	Osspruit	54	1984-1994	
B2H007	Koffiespruit	317	1985-1994	
B2H008	Koffiespruit	100	1985-1994	
B2H009	Koffiespruit	86	1985-1994	
B3H001	Olifants	16553	1938-1991	1942-1966 missing;cannot be patched
B3H003	Elands	1050	1965-1972	short record
B3H004	Elands	6133	1966-1987	prior to Rhenosterkop dam
B3H005	Moses	1673	1969-1986	
B3H006	Diepkloofspruit	244	1970-1988	
B3H007	Moses	971	1980-1994	
B3H008	Elands	4083	1981-1985	short record;
B3H014	Elands	1147	1981-1993	downstream the Rust de Winter dam
B3H017	Olifants	12286	1986-1993	short record; downstream the Loskop dam
B3H019	Selons	606	1983-1984	short record
B3H020	Elands	3656	1984-1992	downstream Rhenosterkop dam
B3R002	Olifants	12285	1937-1993	Loskop dam
B3R005	Elands	3655	1985-1986	Rhenosterkop dam
B4H003	Steelpoort	2240	1983-1993	

Table F1.1 (cont.) Flow gauges in the Olifants River basin.

Code	River	Area, km²	Rec.period	Comments
1	2	3	4	5
B4H005	Waterval	188	1960-1992	
B4H007	Klein Spekboom		1968-1993	
B4H009	Dwars	448	1966-1992	
B4H010	Dorps	526	1979-1993	
B4H016	Tondeldoos	58	1962-1994	Dam upstream (B4R001)
B4H017	Vlugkraal	14.7	1962-1992	Dam upstream (B4R002)
B4H021	Waterval	278	1972-1993	Downstream the Waterval dam
B4R004	Waterval	278	1980-1994	Waterval dam
B5H002	Olifants	31416	1948-1977	
B5H004	Olifants	24791	1987-1992	short record
B6H001	Blyde	518	1911-1992	
B6H002	Treur	97	1909-1939	
B6H003	Treur	92	1959-1992	
B6H004	Blyde	2241	1950-1993	Blydepoort dam upstream since 1973
B6H005	Blyde	2204	1958-1993	
B6H006	Kranskloofspruit	43	1968-1993	
B6H007	Vyehoek	86	1973-1979	short record, extended 1968-1993: $R^2=0.85$, CE=0.81
B7H002	Ngwabitsi	58	1960-1994	extension of record at B7H023
B7H003	Selati	84	1948-1972	
B7H004	Klaser	136	1950-1992	
B7H007	Olifants	46583	1966-1993	
B7H008	Selati	832	1956-1992	
B7H009	Olifants	42472	1960-1991	
B7H010	Ngwabitsi	318	1960-1992	
B7H011	Mohlapitse	262	1963-1988	
B7H013	Mohlapitse	263	1970-1994	close to B7H011
B7H014	Selati	83	1973-1992	extension of record at B7H003
B7H015	Olifants	49826	1987-1994	short record
B7H019	Ga-Selati	2268	1988-1994	short record
B7H023	Ngwabitsi	58	1948-1960	



A9
A7
A6
A4
A2
C2
C1
X1
B7H019
B7H010
B7H011
B7H002
B7H013
B7H014
B5H002
B6H004
B6H001
B7H004
B6H002
B6H007
B5H006
B3H001
B3H004
B3H005
B4H009
B4H003
B4H005
B6H006
B4H010
X3H011
X3H003
X3H006
X3H004
B3H008
B3H006
X3H001
X2H028
B3H003
B3H007
X2H025
X2H027
X2H014
B4H016
B4H017
X2H011
X2H012
X2H010
X2H024
X2H030
X2H031
B1H005
B1H001
B1H002
B1H003
B2H001
B2H004
B2H006
B2H008
B2H007
B1H019
B1H018
B1H017
LEGEND
Olifants catchment boundary
Rivers
B7H011 Flow gauges
A9 Adjacent drainage region
Provisional boundary of "flow group 1"

demonstrates an abrupt decrease in low flows in the early 1980s. This could be the result of the latest water resource developments (e.g. construction of the Rhenosterkop Dam on the Elands river), but most probably can be explained by a severe drought at the beginning of the 1980s. A similar trend is present in some other records: B3H004, B3H005, B3H006. The latter records flow from a small catchment which generates no low flows (Fig. F2.18). The only "unregulated" records in the region are those at gauges B3H003, B3H005, B3H006 and B3H007. No possibility exists for the patching and/or extension of the records. Overall, most of the records in the B3 drainage region are not suitable for regional analysis.

The gauges in the drainage region B4 generally record stationary flow regimes which are not or only slightly affected by water resource development. The major river is the Steelpoort. Irrigation is concentrated mostly on the catchment of its right-hand tributary - the Dwars River. Most of the gauges record low-flows from relatively small catchments (Table F1.1) with the exception of gauge B4H003, located on the Steelpoort river itself. Most of the records may be considered suitable for regional analysis.

The flow gauges in drainage region B6, in many cases, record relatively unaffected flows. Plots of annual totals and low-flows do not demonstrate any obvious trends. However, the Blyde river in its upstream reaches, went dry twice during the last 10 years, which had been never recorded before (Fig. F2.27). Records at gauges B6H002 and B6H007 may be considered together since they effectively are the earlier and the latter parts of flow observations at almost the same location on the Treur river. Until 1973 both gauges B6H004 and B6H005 recorded unregulated flow in the Blyde river. The short record at gauge B6H007 was extended using data from gauge B6H006 (Table F2.1). Gauge B6H012 is located below the Ohrigstad Dam and records a regulated flow regime. Most of the records in this region (or parts thereof) may be considered suitable for regional analysis.

Apart from the three gauges located on the Olifants River itself, gauges in drainage region B7, record flow from relatively small catchments characterised by varying degrees of water resource development. Gauges B7H023, B7H002 and B7H010 record flow in the Ngwabitsi river. The earlier record in the upstream part of the catchment (gauge B7H023, Fig. F2.47) is characterised by on average, much higher annual totals and low flows than the latter one (gauge B7H002, Fig. F2.43), while low flows at the downstream gauge B7H010 are only recorded in the most wet years (Fig. F2.41). Gauges B7H003, B7H014 and B7H008 record flow in the Selati River. The earlier record in the upstream reaches of Selati (B7H003) is of poor quality (Fig. F2.37) while the latter record (B7H014) demonstrates a decreasing trend in both annual totals and low flows (Fig F2.42). Many run-of-river abstractions and minor impoundments cut off all low flows from reaching gauge B7H008 (Fig. F2.39). Gauges B7H011 and B7H013 are located almost at the same position. Their records demonstrate differences in flow sequences during this overlapping period (Figs F2.44 and F2.45). Overall, some records in region B7 could be used for regional analysis but care should be taken in selecting a gauge or part of its record period.

F1.4 REGIONAL REGRESSION ANALYSIS OF LOW-FLOW CHARACTERISTICS.

The most common technique used in low-flow studies elsewhere, is the application of the multiple regression approach whereby a low-flow characteristic is related to the catchment physiographic and climatic parameters. A relationship of this kind is established on the basis of observed flow data and therefore is very sensitive to their amount and quality. If this relationship is strong, it may be applied to any ungauged catchment in a region for which it was established.

It has been demonstrated in a number of studies (e.g., Vladimirov, 1970, 1976; Regionalization in Hydrology, 1990) that low-flow characteristics are often very strongly related to the catchment area and mean annual precipitation (MAP). In South Africa these parameters for many catchments may be found in Basin Study Reports, System Analysis Reports and Surface Water Resources of SA (1981 and/or 1994). On the other hand, these parameters are also available for each of the quaternary subcatchments (WR90). This implies that if a regional relationship for a required low-flow index is established on the basis of observed data, this index may then be calculated, at least at the scale of quaternary catchments in a region, to create a spatial picture of low-flow conditions. This does not however imply that the established relationship cannot be used at subquaternary scale.

Table F1.1 illustrates that there is not many observed daily data sets in the Olifants River system that can be used in regional analysis. Many of the gauges have either short records or record regulated flow regimes. Also in some parts of the catchment there is a critical paucity of data. Therefore, it was decided to use additional data from several adjacent drainage regions. The possibility of using data from subregions A2 - A6, X2 and X3 has been investigated. Most of the usable data were found to be concentrated in drainage subregion X2 while the others supplied an additional 1-2 gauges.

The analysis concentrated initially on the relationship of Q75(7) with the catchment area and MAP, using primarily the most widely used logarithmic regression model. If this exercise is successful, it may justify further similar regional low-flow studies. The areas of selected catchments were in the range from about 10 to several hundred km^2 to justify the applicability of a possible future relationship at both quaternary and subquaternary catchment scales.

The first attempt to apply the regression technique for all selected gauges resulted in very low coefficient of determination (R^2 < 0.3). It was suggested that some preliminary classification of gauges into smaller groups would be necessary. However, such a classification itself may be a time consuming process and eventually may not result in any physically meaningful groups. Another complexity is that such a classification is efficient only if the number of the catchments being classified is large. If it is initially small, classification may result in groups containing only few catchments and that would make the establishment of regression relationships within each group unreliable. Therefore, the suitability of already existing groups or geographical regions for regional analysis was investigated.

The first possibility for such a grouping would be to use the hydrological zones outlined in WR90. These groups have been established on the basis of the similarity between the Deficient Flow - Duration - Frequency curves constructed using synthetic monthly data for quaternary catchments. However, there exist too many hydrological zones in the study area and not enough observed data sets within each such zone.

The second possibility is to establish regression relationships within each of the drainage subregions (or combinations thereof) within the whole Olifants River system. Table F1.1 and section F1.3 of this Appendix demonstrate that only subregions B4 and B6 taken together, may provide a basis for such an approach. These regions are located geographically close to each other, remain relatively untouched by human influences, have data of reasonable quality and the gauged catchment areas vary in the required range. The following prediction equation has been obtained from regression:

$$\ln (Q75_7) = -33.6 + 3.91 * \ln(MAP) + 1.13 * \ln (AREA); \qquad (F1.1)$$
$$(R^2 = 0.72; \quad s.e. = 1.12)$$

where Q75(7) is in m^3/s, MAP is in mm and AREA is in km^2. MAP and catchment area therefore explain 72% of variability in Q75(7) in these two drainage subregions.

Table F1.2 contains gauge codes, the values of independent variables as well as Q75(7) values observed and calculated by regression. Some calculated values are very different from the observed and the standard error is also high. This may partly be explained by a very high Q75 flow value at gauge B6H001 as well as by the inclusion of the gauges B4H016 and B4H017 which have small dams upstream. The analysis of such outliers as well as the consideration of other independent catchment parameters will most probably increase the reliability of the regression relationship in this case.

The third possibility is to use the groups emanating from the UCT river classification studies (King and Tharme, 1995). This classification undertaken on the scale of the whole country resulted in 6 seasonal and 7 'flow' groups of rivers. Seasonal groups have been established through the analysis of the seasonal distribution of various rivers and are of little relevance to the present study. Flow groups have been established on the basis of the various characteristics of the flow regimes of rivers and may be of interest in the current analysis. Unfortunately, not many flow gauges from the Olifants river system have been classified into flow groups. The analysis has therefore been performed on all 'classified' gauges in the Olifants basin and adjacent drainage regions listed above. Only groups number 3, 5 and 7 of the UCT classification appeared to have a reasonable number of gauges which are used in the regression. The following regression equations have been obtained for each of these groups:

Group 3:

$$\ln (Q75_7) = -26.3 + 0.88 * \ln (AREA) + 3.04 * \ln (MAP); \qquad (F1.2)$$
$$(R^2 = 0.908; \quad s.e. = 0.475)$$

Group 5:

$$\ln (Q75_7) = -22.0 + 0.60 * \ln (AREA) + 2.49 * \ln (MAP); \qquad (F1.3)$$
$$(R^2 = 0.836; \quad s.e. = 0.676)$$

Group 7:

$$\ln (Q75_7) = 42.2 + 0.626 * \ln (AREA) - 7.45 * \ln (MAP); \qquad (F1.4)$$
$$(R^2 = 0.472; \quad s.e. = 1.40)$$

Table F1.2 The data and results of regression analysis in drainage regions B4 and B6.

Code	MAP, mm	AREA, km^2	Q75(7), obs, m^3/s	Q75(7),calc,m^3/s
B4H005	676	188	0.251	0.116
B4H009	650	448	0.076	0.265
B4H016	691	58	0.023	0.033
B4H017	691	14.7	0.006	0.007
B4H021	676	278	0.333	0.180
B4H010	773	526	0.501	0.627
B6H006	766	43	0.012	0.035
B6H007	778	97	0.070	0.095
B6H003	1229	97	0.379	0.571
B6H001	1094	518	2.436	2.400
B6H005	800	86	1.069	0.093

Table F1.3 The data and results of regression analysis based on UCT flow groups.

Code	Group	Area, km^2	MAP, mm	Q75(7),obs, m^3/s	Q75(7), calc.,m^3/s
B1H002	7	252	695	0.018	0.041
B4H005	7	188	676	0.251	0.042
B6H006	7	43	766	0.012	0.007
A4H008	7	504	600	0.720	0.190
A5H004	7	629	622	0.167	0.166
A6H011	7	73	653	0.025	0.030
A6H020	7	43	633	0.008	0.027
B6H003	3	97	1229	0.379	0.519
X2H025	3	25	999	0.131	0.083
X2H026	3	14	999	0.052	0.050
X2H027	3	78	833	0.260	0.131
X2H028	3	5.7	999	0.016	0.022
X2H011	3	402	757	0.562	0.418
X2H012	3	91	757	0.098	0.112
X2H014	3	250	989	0.790	0.619
X3H001	3	174	1241	0.606	0.897
X3H003	3	52	1294	0.485	0.351
A2H050	3	148	750	0.072	0.168
A6H019	3	16	598	0.012	0.012
B7H004	5	136	1022	0.158	0.195
X2H024	5	80	1111	0.267	0.141
X2H005	5	642	1163	0.599	0.960
X2H010	5	126	1101	0.371	0.208
X3H006	5	766	1151	2.706	1.840
X3H007	5	46	1178	0.060	0.096
A6H018	5	12	600	0.010	0.009
X2H031	5	262	1040	0.124	0.358

The results suggest that satisfactory relationships may be established for groups 3 and 5, while for group 7 other catchment parameters may be required as independent variables. Further analysis, using the data from all classified gauged catchments in the country, would add more clarity to the prospects of using the flow groups as a basis for low-flow regionalisation. However, it should be taken into account, that flow groups have been identified on the basis of measured flow characteristics which are not available for ungauged catchments. Therefore, it would be necessary to develop an approach which would predict the group membership of an ungauged catchment.

F1.5 REGIONALIZATION OF FLOW DURATION CURVES.

In technical terms the method used to establish regional FDC is similar to that used in the T drainage region and includes two steps: i) construction of a non-dimensional FDC for a gauge by dividing discharges from a curve by the mean daily flow and ii) superposition of all individual FDCs on one plot and the construction of an average regional non-dimensional FDC. Each individual FDC has been constructed using the relevant HYMAS program module. The procedure allows the curves to be automatically normalised by the mean flow and several fixed percentage points with corresponding non-dimensional ordinates to be printed or written to a file for further simultaneous display using other software.

Since the number of suitable flow records for this type of analysis in the Olifants River catchment itself is very limited, flow records from adjacent catchments (particularly in drainage regions X2 and X3) have also been utilized. Only annual FDCs have been considered at this stage.

The shape of individual non-dimensional FDCs in the whole study area appeared to vary considerably throughout the whole range of flows. This could be expected since the study area is extensive and may embrace a variety of daily flow regimes. Therefore, the grouping of curves is required before averaging of ordinates of the individual curves. Normally these groups are established *a priori* by means of classification techniques based on the analysis of the similarity of the physiographic characteristics of the drainage basins. However, the approach does not guarantee that the catchments will be eventually classified into physically meaningful and readily distinguishable groups.

The alternative ("inverse") approach is to try to establish the groups of catchments based on their flow characteristics first. If such groups are established (for example, the shape of flow duration curves within each group are similar), it should effectively point to the existence of the physiographic similarity of the catchments included in each group. The catchments may then be analyzed for example, in terms of their geographical neighbourhood - whether they form a geographically contiguous region(s) or not. Alternatively, the similarity between the grouped catchments should be explained in terms of their physiographic and climatic parameters. That would allow for the application of the defined regional or group flow characteristics to physiographically similar ungauged catchments in the study area.

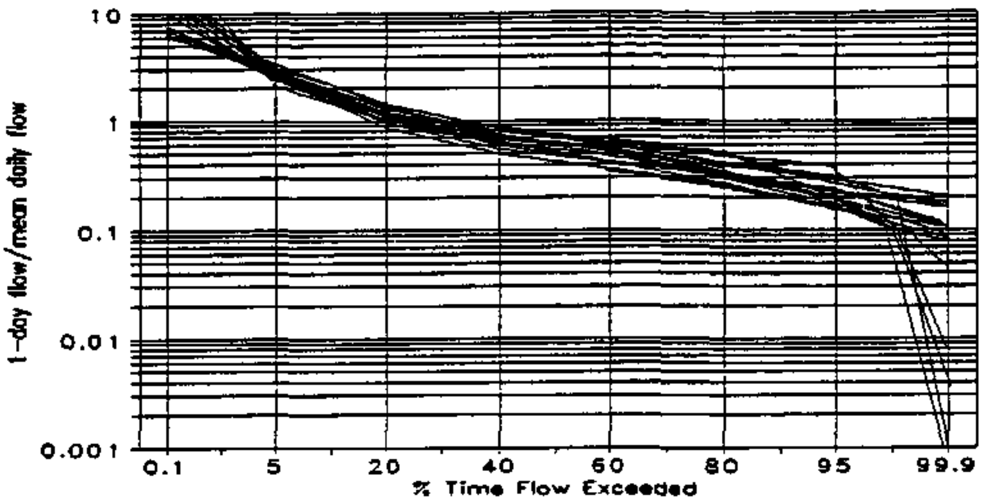


Figure F1.4 Superimposed 1-day annual flow duration curves in Group 1.

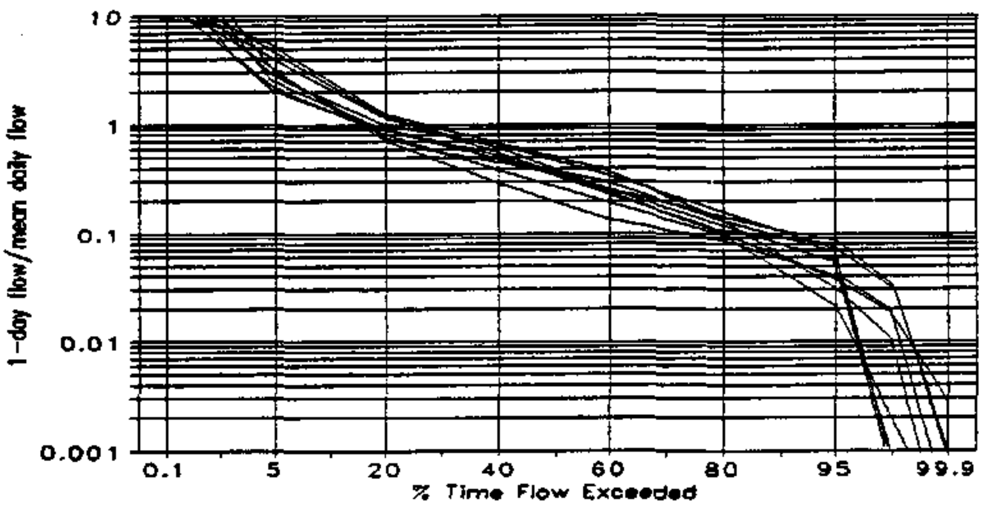


Figure F1.5 Superimposed 1-day annual flow duration curves in Group 2.

The analysis of non-dimensional annual flow duration curves has demonstrated that two rather distinctive groups of catchments can be defined. The first group (Fig. F1.4) is formed by gradually sloping curves with high relative contributions of low flows (the daily flows exceeded 95% of the time do not drop below 10% of the mean daily flow). The second group includes catchments with steeper flow duration curves and smaller contributions of low flows (less then 10% of the mean flow - Fig. F1.5).

The regional normalized FDCs for each group can be established by a simple averaging of the ordinates of all individual FDCs. The actual required FDC for an ungauged site which may belong to the group defined may be calculated by multiplying back the non-dimensional ordinates of a group FDC by the estimate of mean daily flow. The latter may be obtained from the estimates of MAR presented in WR90 as described in Appendix E1. However, it is first necessary to establish whether the groups defined are geographically contiguous.

The catchments from the first group appeared to form a relatively contiguous geographical region which is shown on Figure F1.3. This region embraces most of the drainage subregions B4 and B6 as well as the upstream parts of subregions X2 and X3. The gauged catchments which fall into this group are listed in Table F1.4. Two catchments from drainage region B7 also form part of the group. However, the lack of suitable gauged records in this region do not allow firm conclusions about the extension of the group boundaries into region B7 to be made.

Table F1.4 Gauged catchments grouped by 1-day annual flow duration curves.

Group 1		Group2	Others
B4H005	X2H010	B1H002	B1H003
B4H010	X2H011	B1H019	B1H005
B6H001	X2H012	B2H001	B1H017
B6H002	X2H014	B2H006	B1H018
B6H003	X2H024	B2H007	B3H006
B6H006	X2H025	B2H008	B3H007
B6H007	X2H026	B4H003	B7H003
X3H001	X2H027	B4H009	B7H010
X3H002	X2H030	B7H004	
X3H003	X2H031	X3H008	
X3H004	B7H011		
X3H006	B7H013		

The catchments which form the second group are more spatially scattered and do not integrate themselves into an easily distinguishable geographical region. It should however be taken into account that this group includes catchments with mostly very short records (e.g.

B1H019, all gauges in B2 drainage subregion) and therefore the shape of their flow duration curves cannot be considered accurate. Consequently, this group itself is very arbitrary defined.

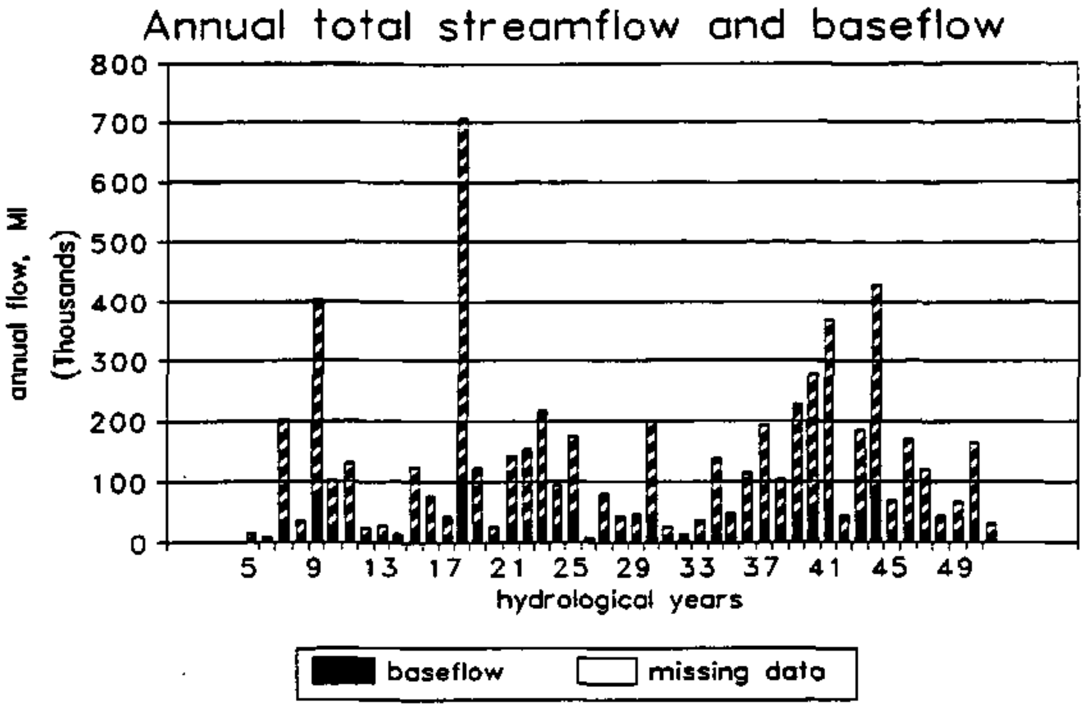
Several catchments included in the third column of Table F1.4 demonstrate high variability in the low-flow part of the flow duration curve (e.g. the time with zero flows varies from 50% to 20%) and therefore cannot be grouped. This variability is likely to relate to a different degree of artificial influence in the catchments which cannot be quantified and catered for without the appropriate data, even if the stream is unregulated and the record is stationary.

Overall, despite the tendency for the catchments in regions B4, B6, X2 and X3 to group together, the other catchments in the area do not lend themselves to simple geographically contiguous grouping. The main reason for this is the lack of reasonable data for regional analysis in most parts of the Olifants River system. To increase the number of usable records in the catchment, they should be naturalised by adding back all existing abstractions in the catchments. If the data on such abstractions are made available, it might be possible to get more success out of the regionalization techniques without attracting more complex simulation methods. It may be suggested that the same applies to other regions of the country as well.

APPENDIX F2

Annual flows and low-flow indices in the Olifants catchment

Note : each year on graphics is from October of the previous calendar year to September of the next calendar year (the year 1952 is from October 1951 to September 1952).



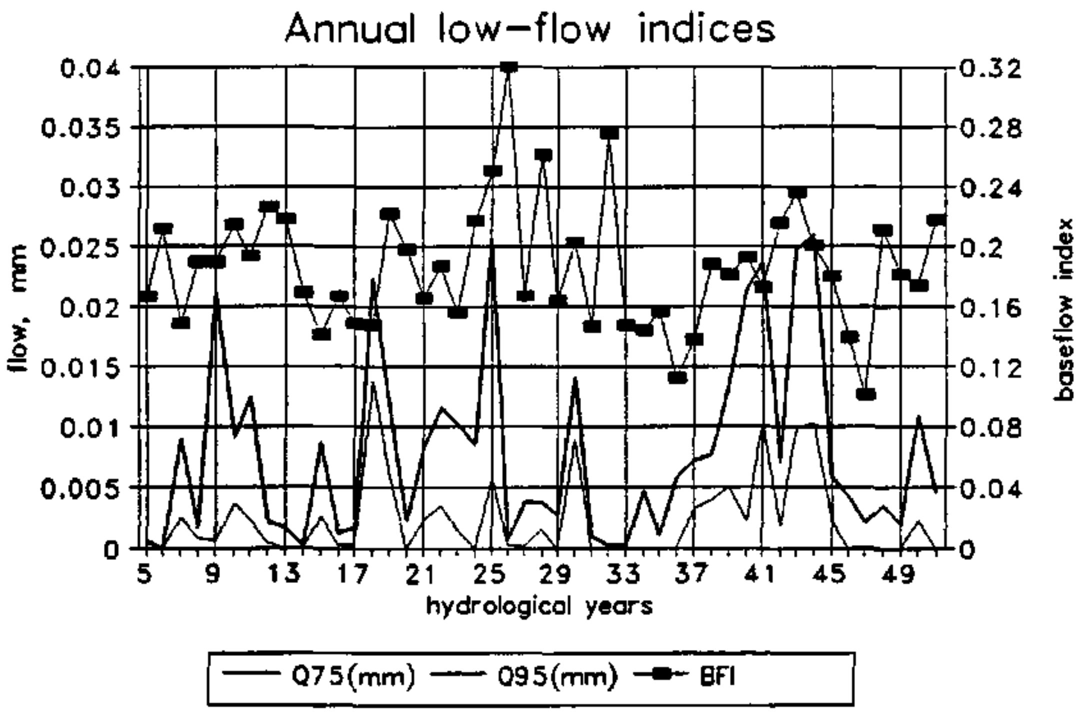
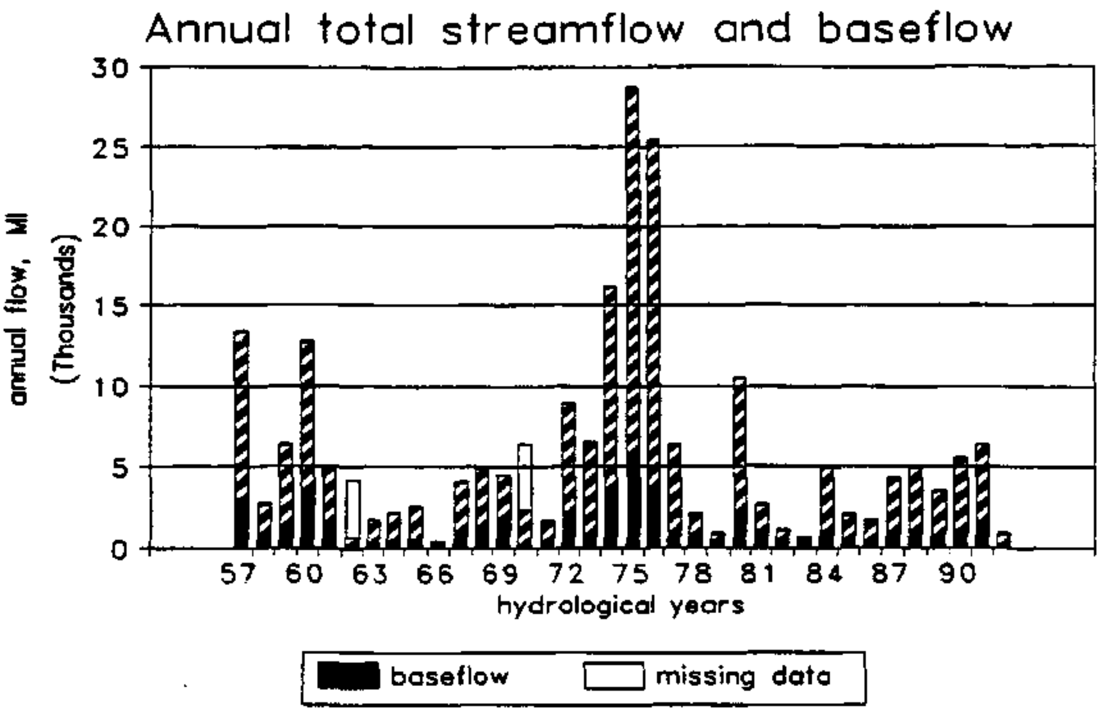


Figure F2.1. Gauge B1H001



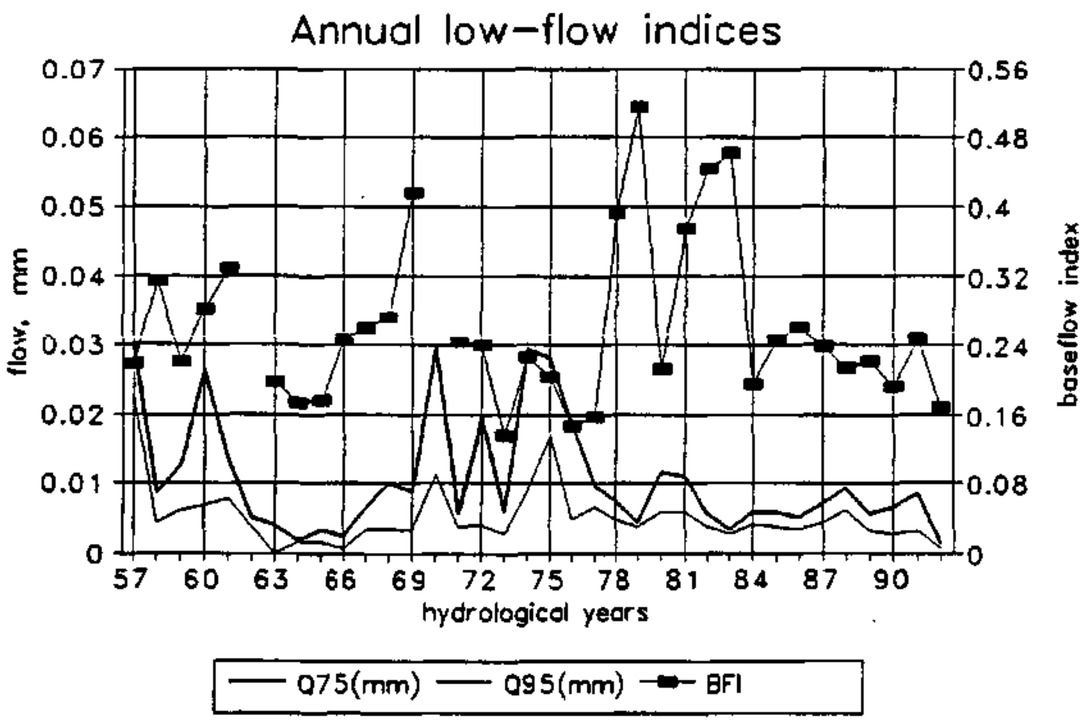
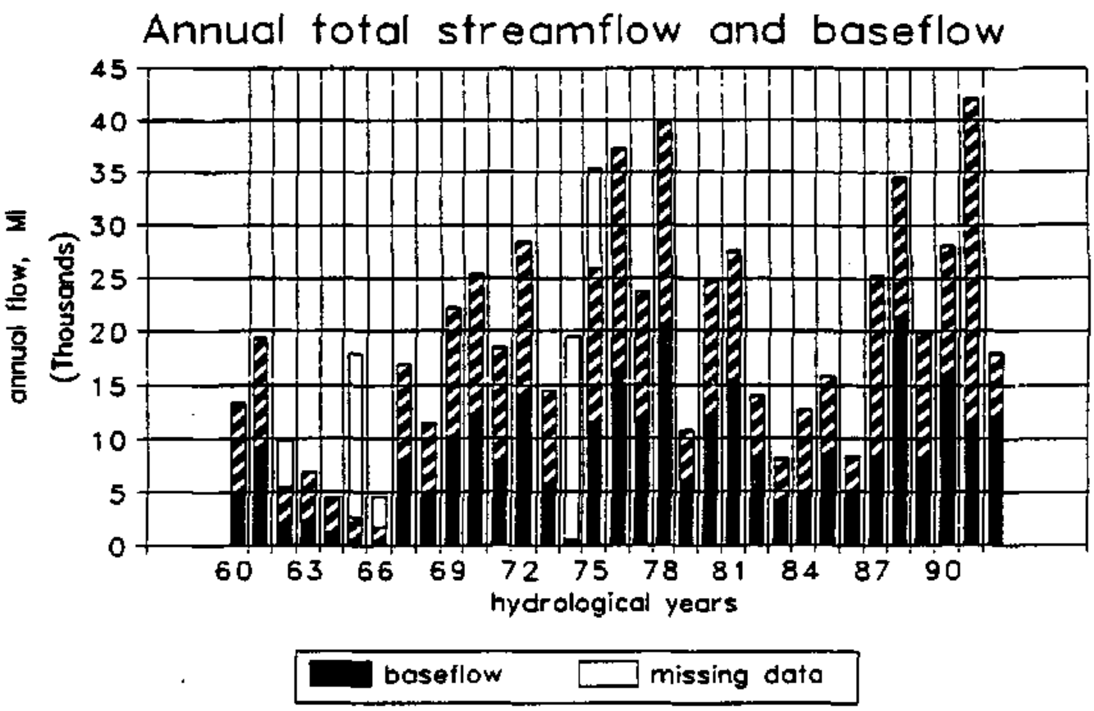


Figure F2.2. Gauge B1H002



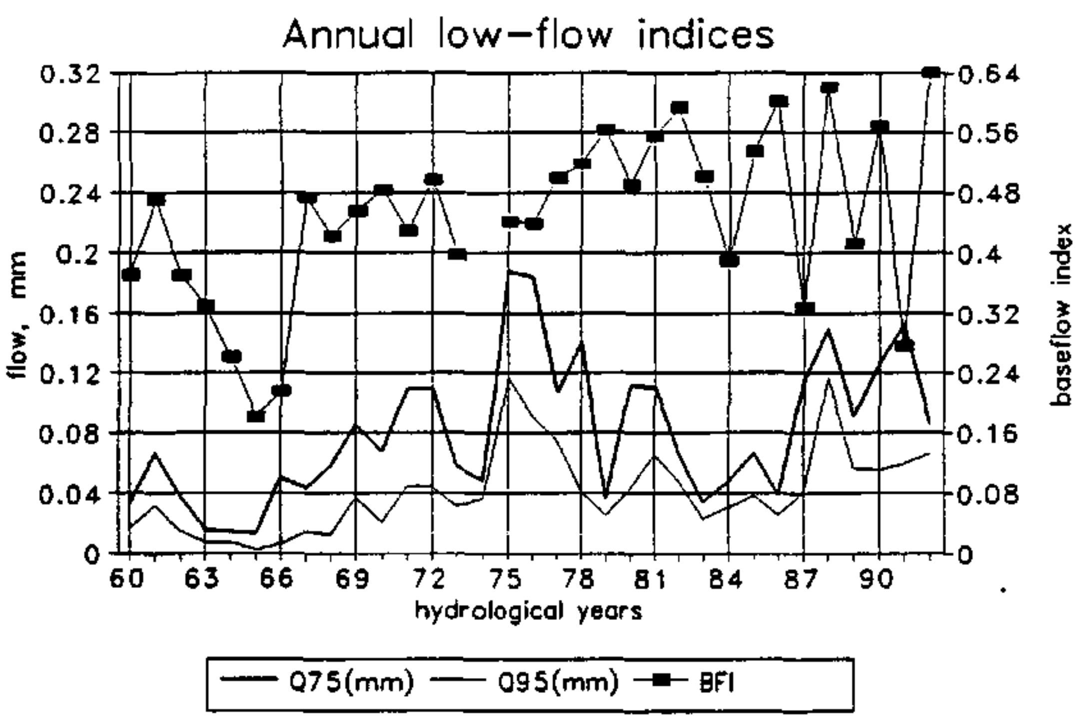
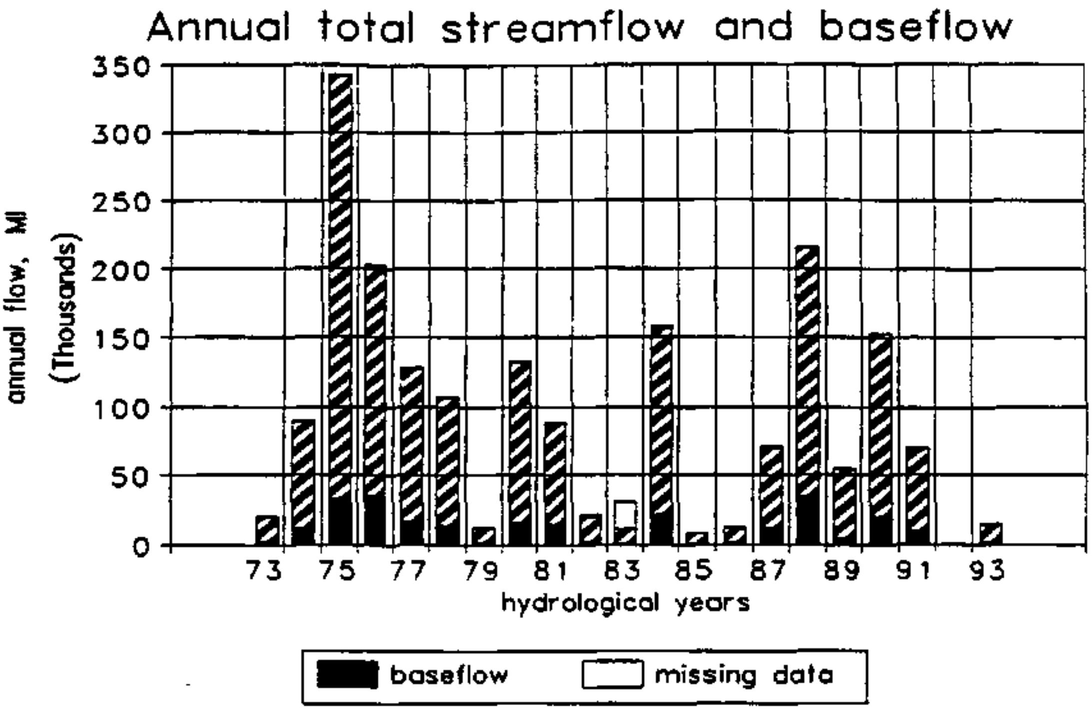


Figure F2.3. Gauge B1H004



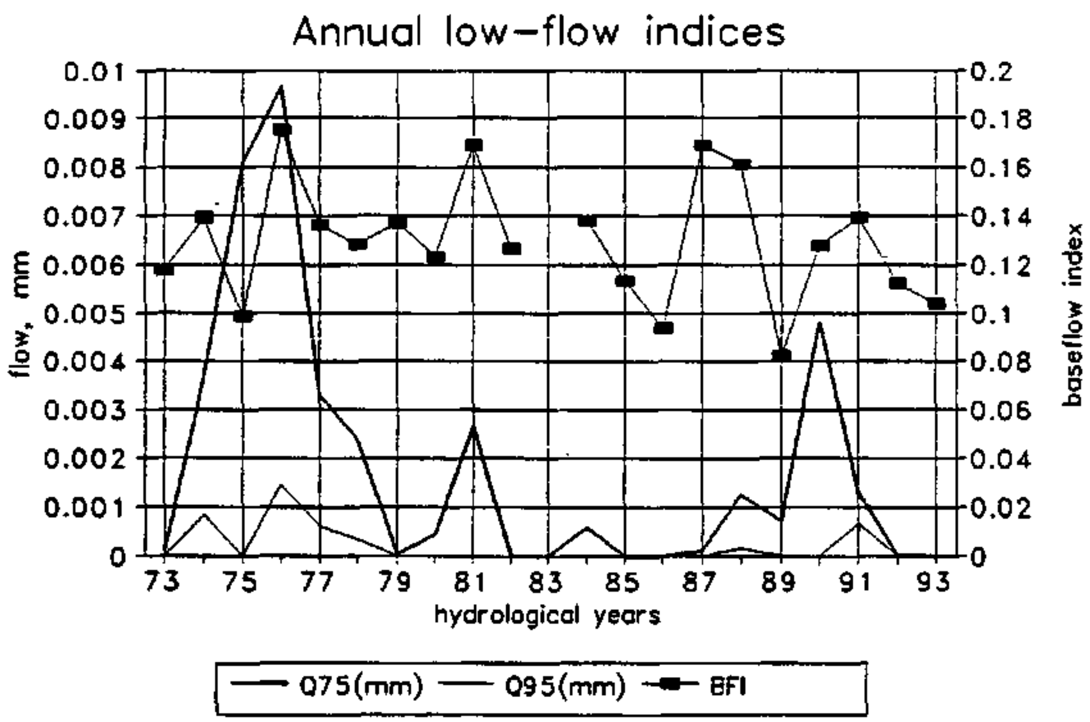


Figure F2.4. Gauge B1H005

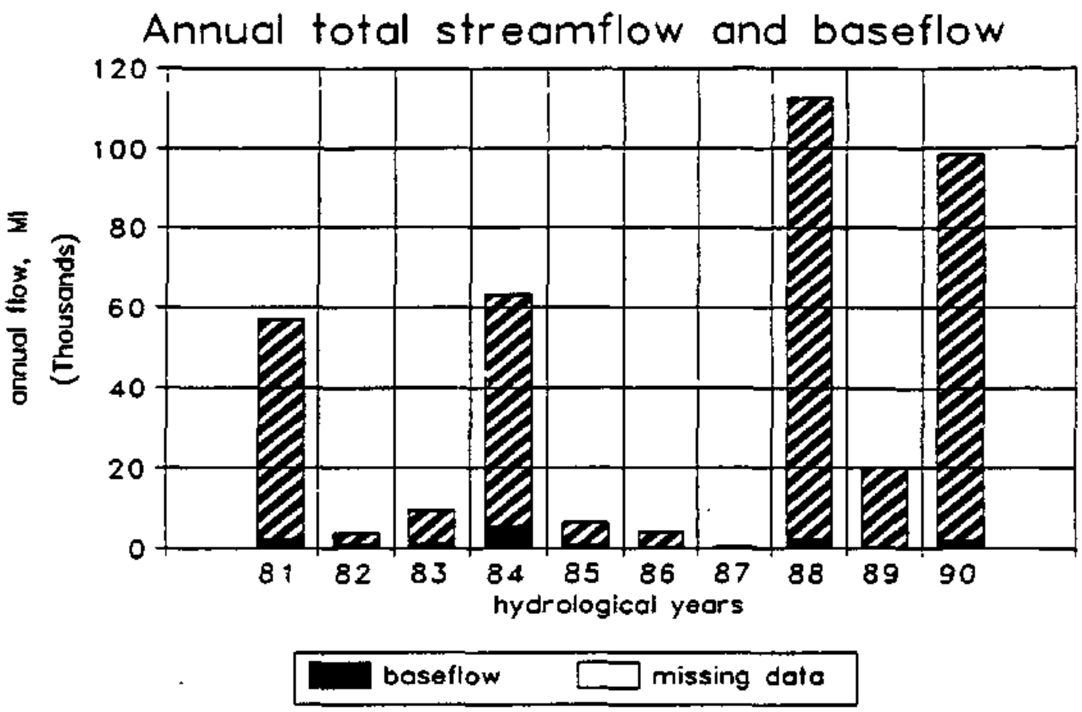
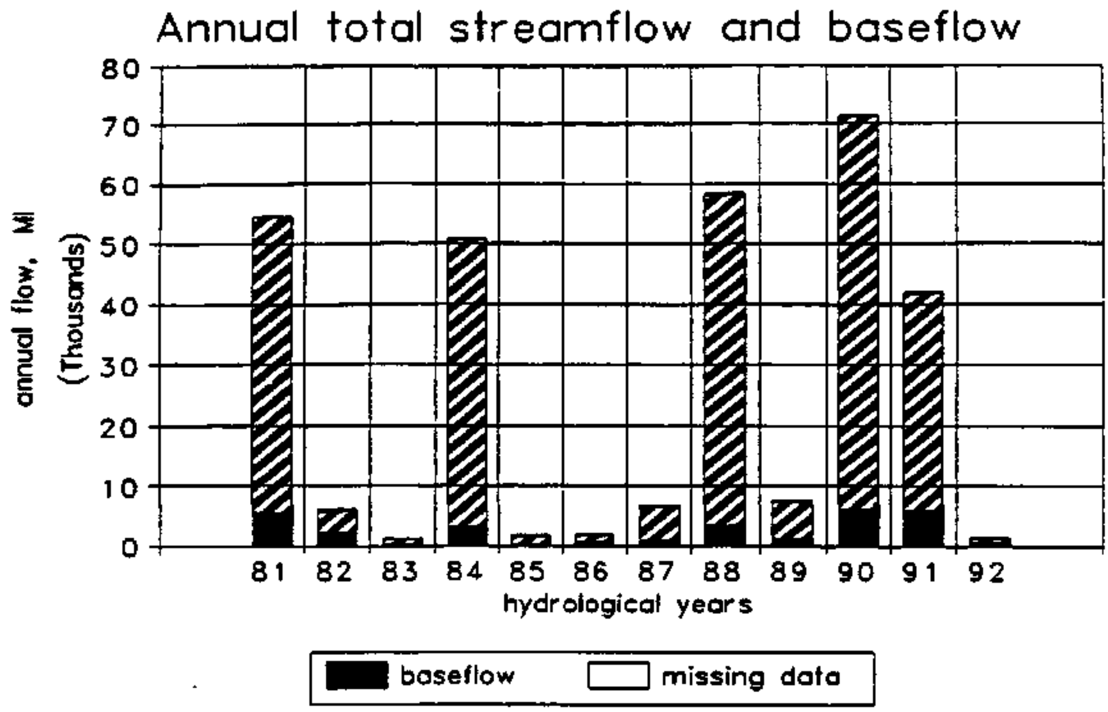


Figure F2.5. Gauge B1H010



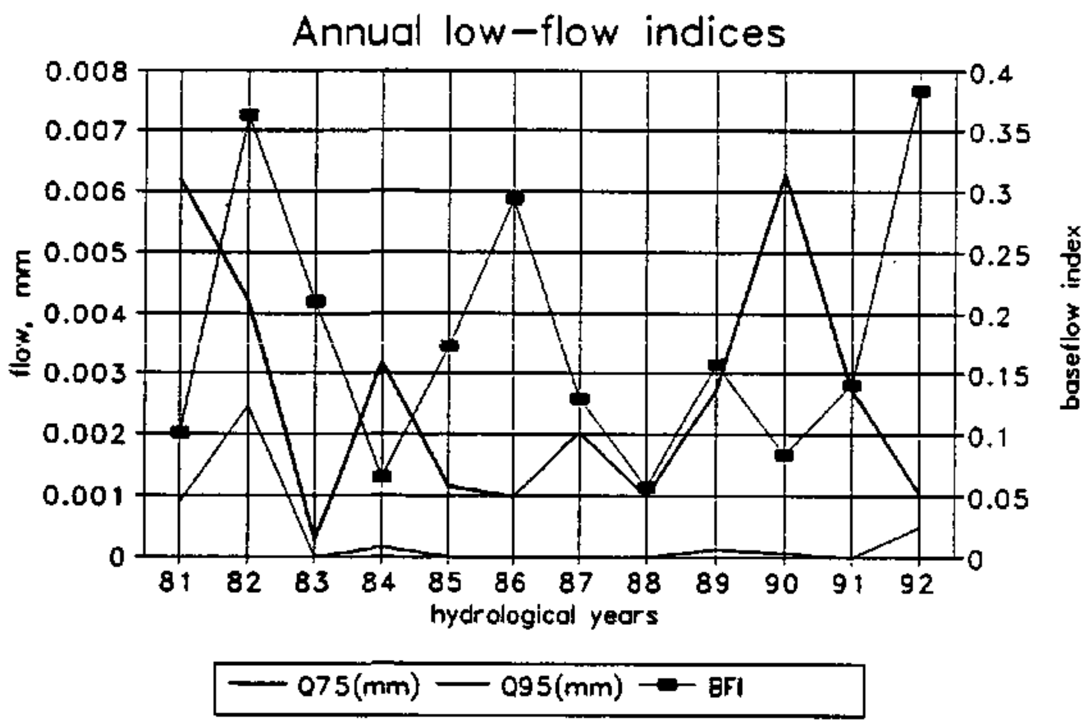
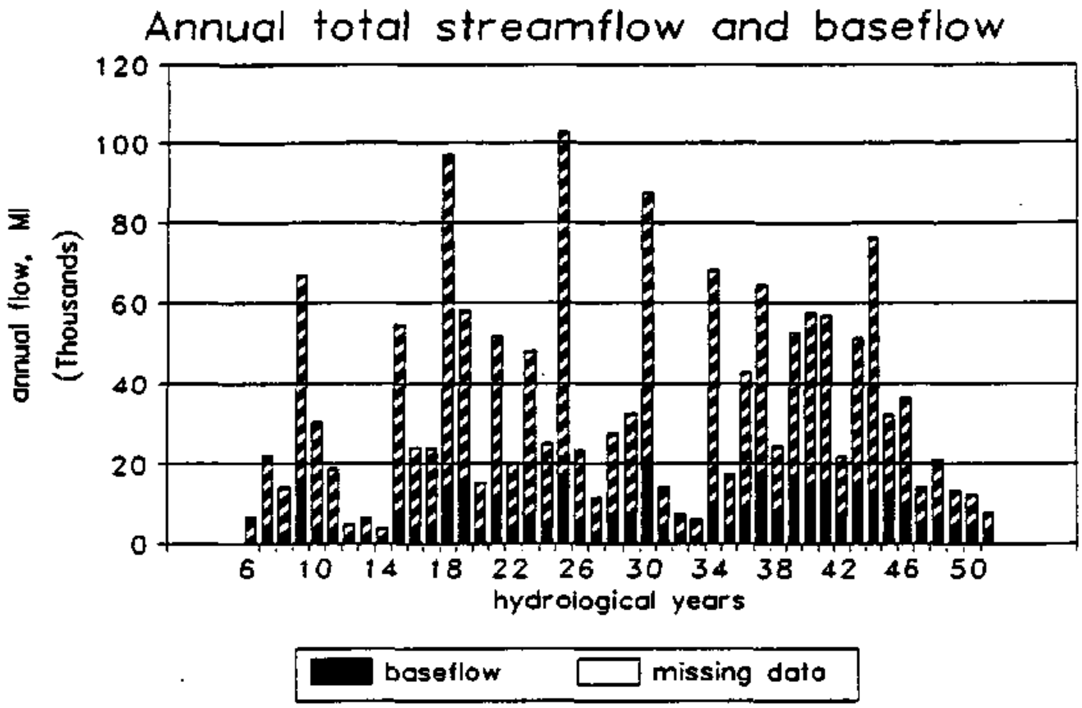


Figure F2.6. Gauge B1H015



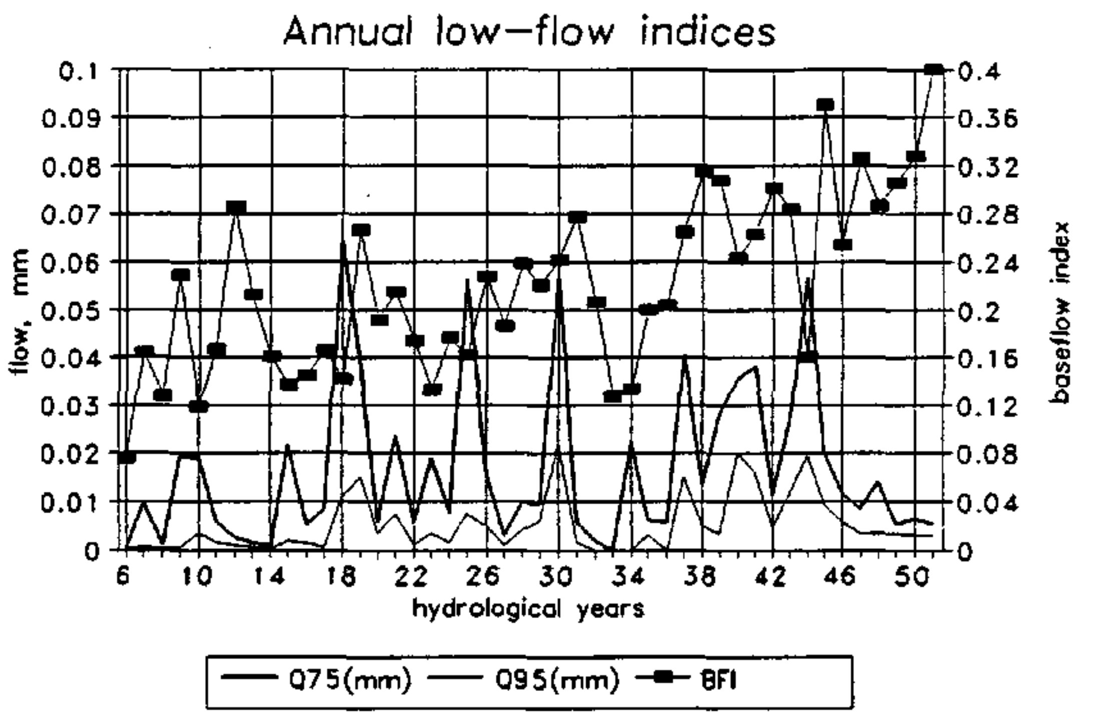
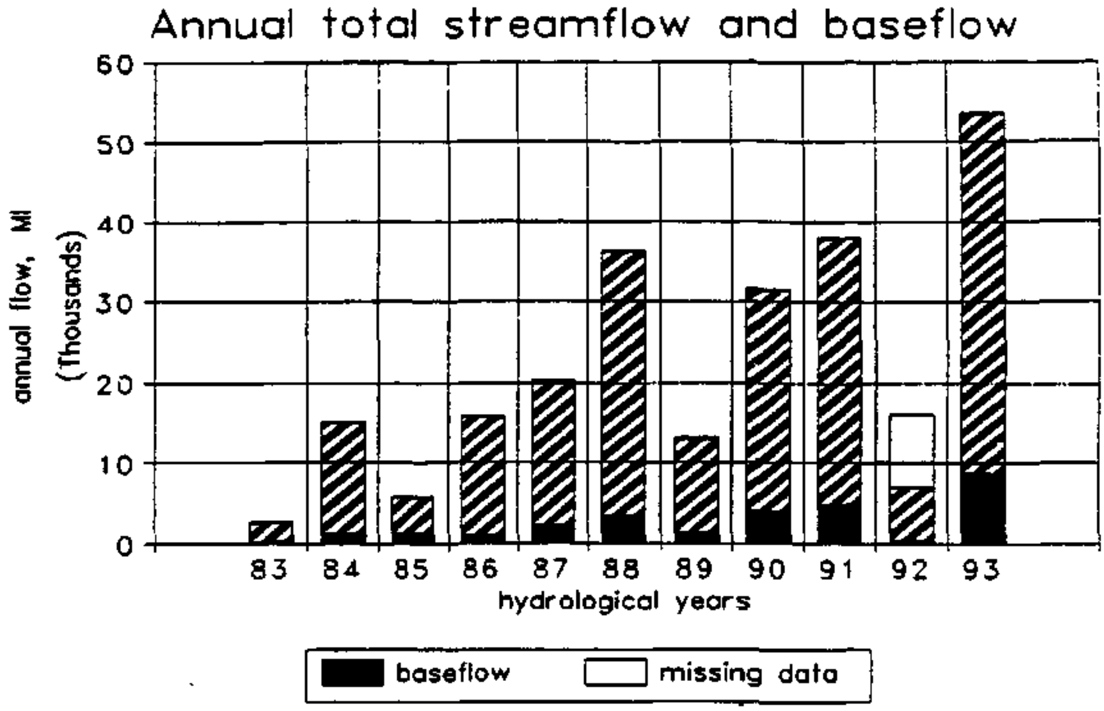


Figure F2.7. Gauge B2H001



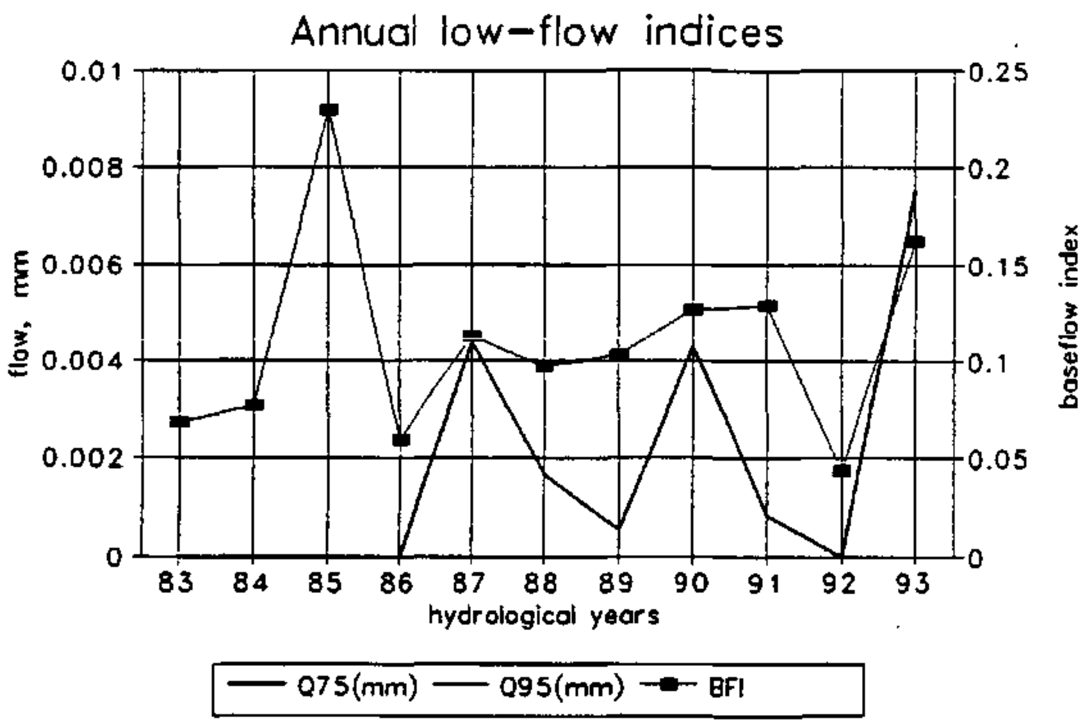
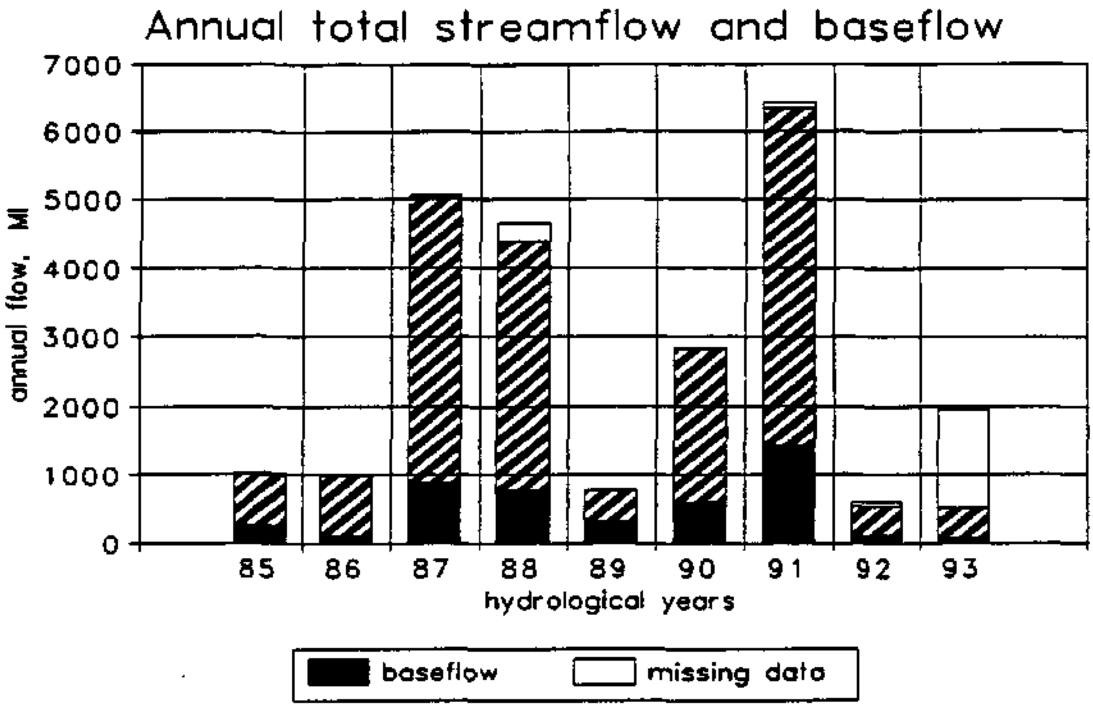


Figure F2.8. Gauge B2H003



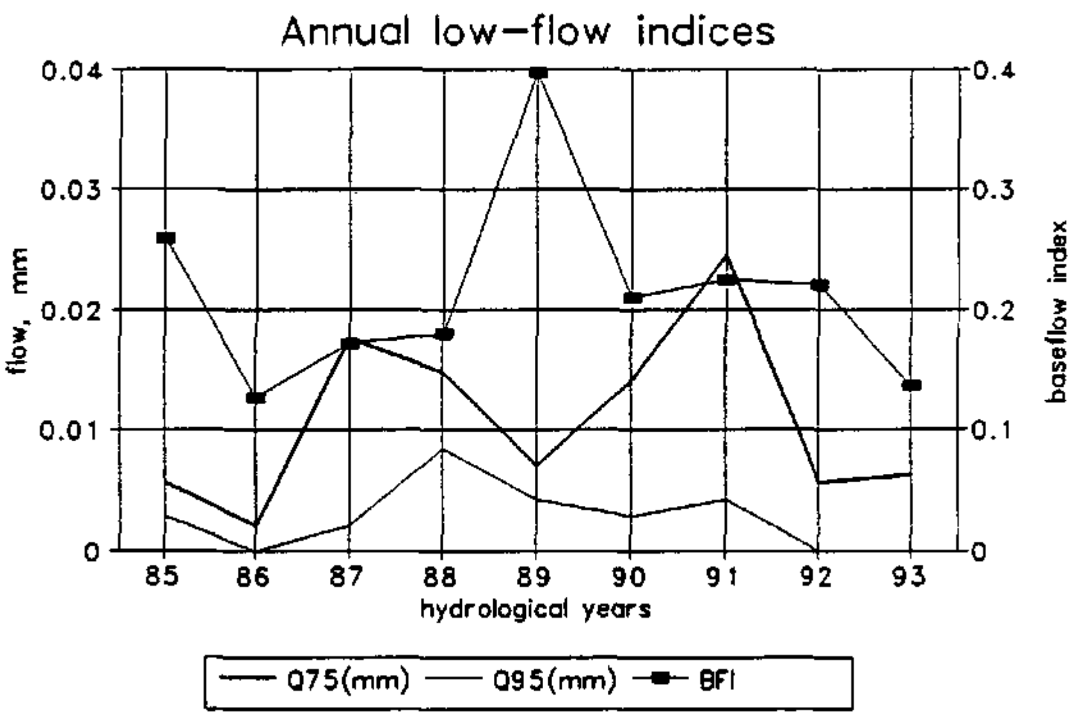
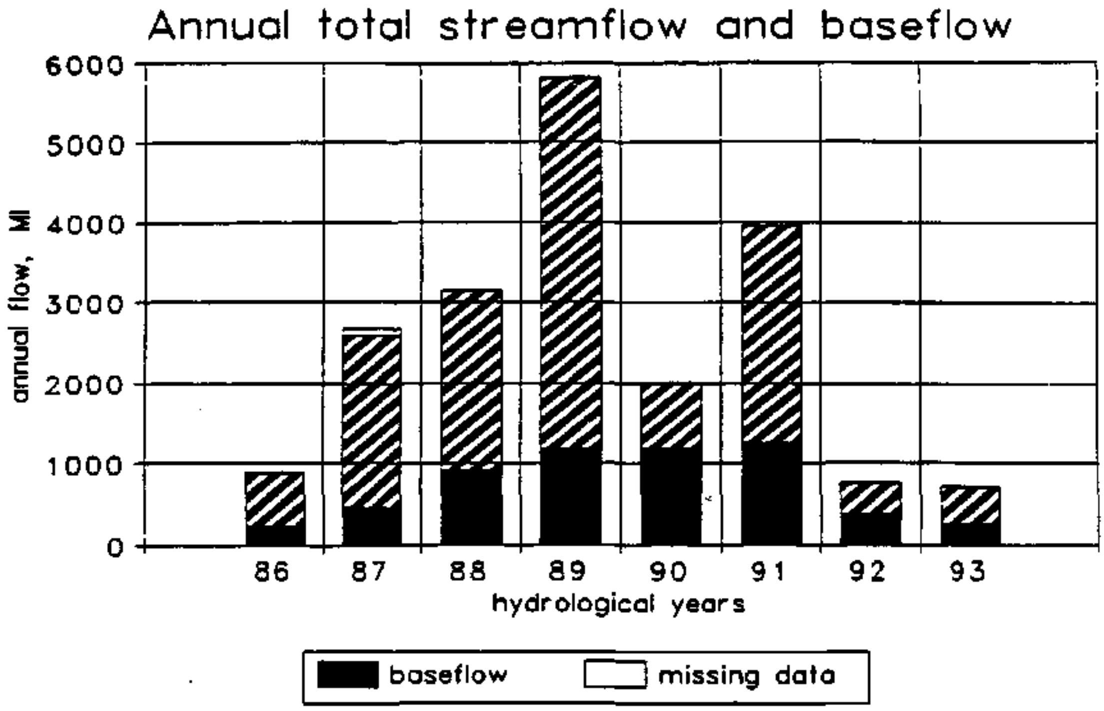


Figure F2.9. Gauge B2H004



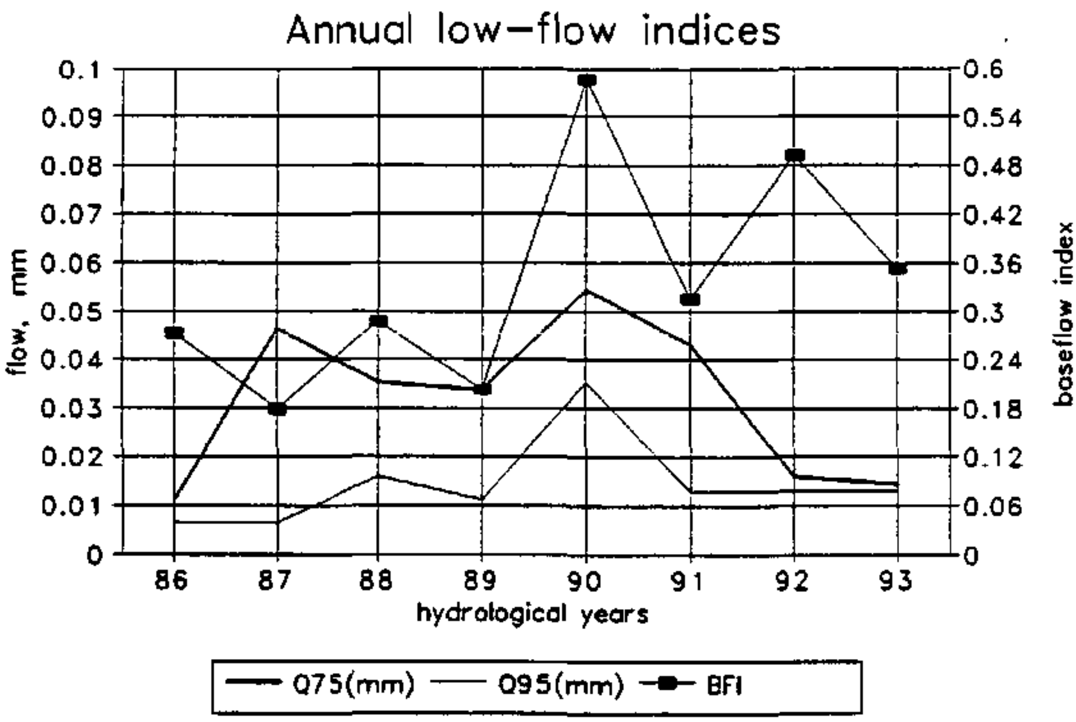
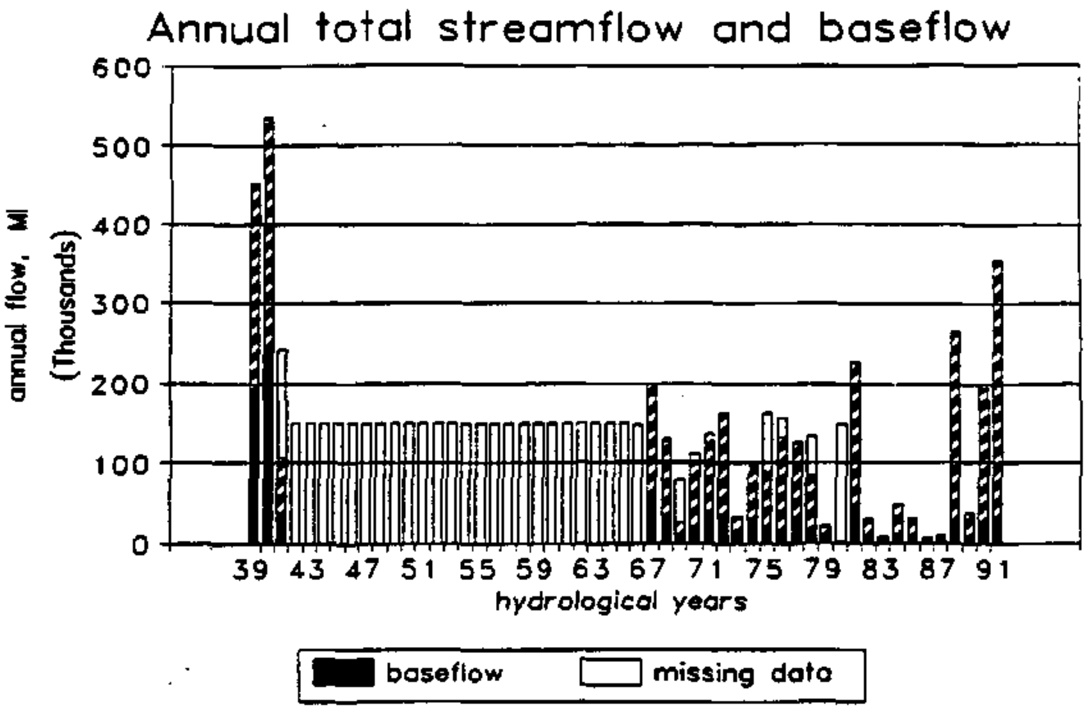


Figure F2.10. Gauge B2H006



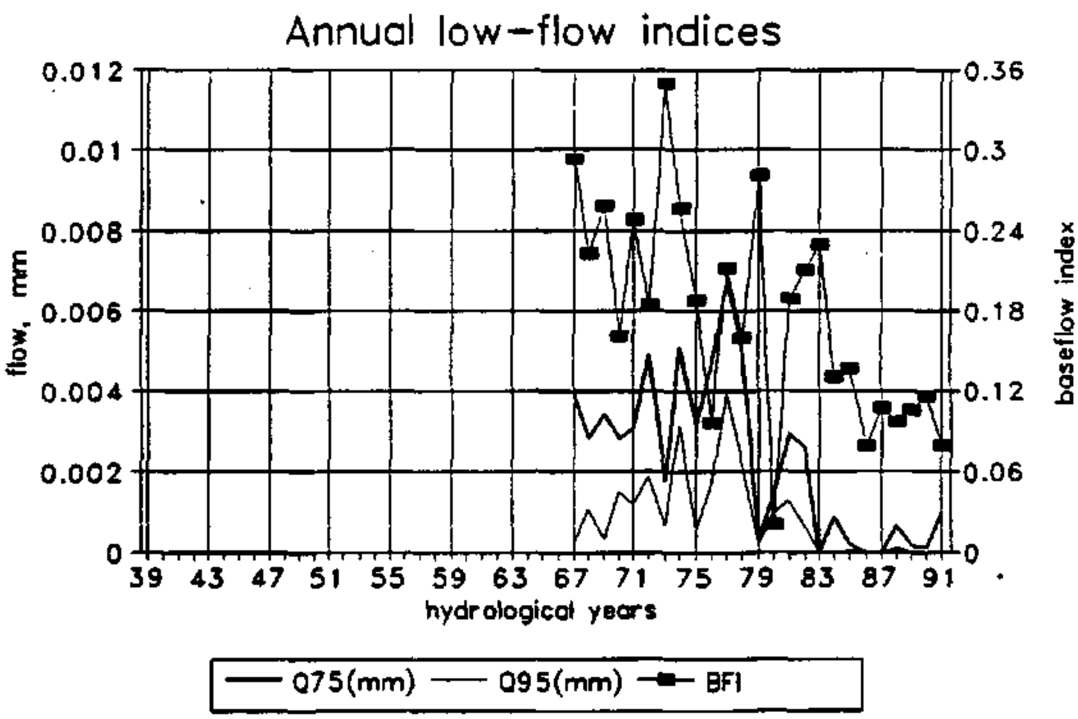
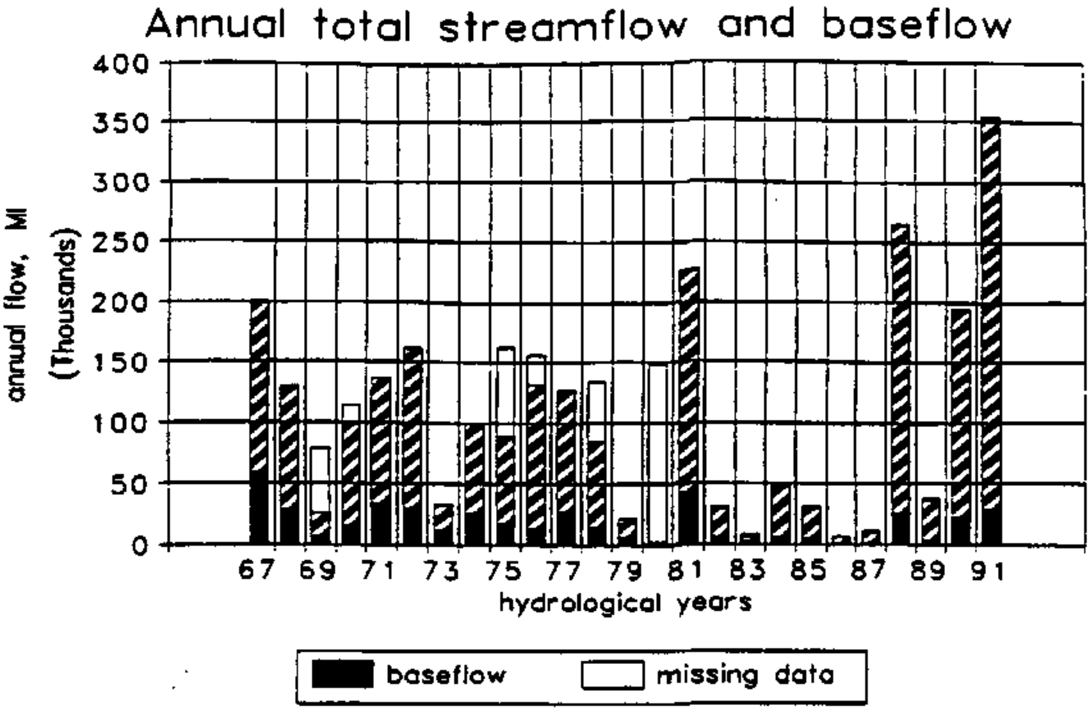


Figure F2.11. Gauge B3H001



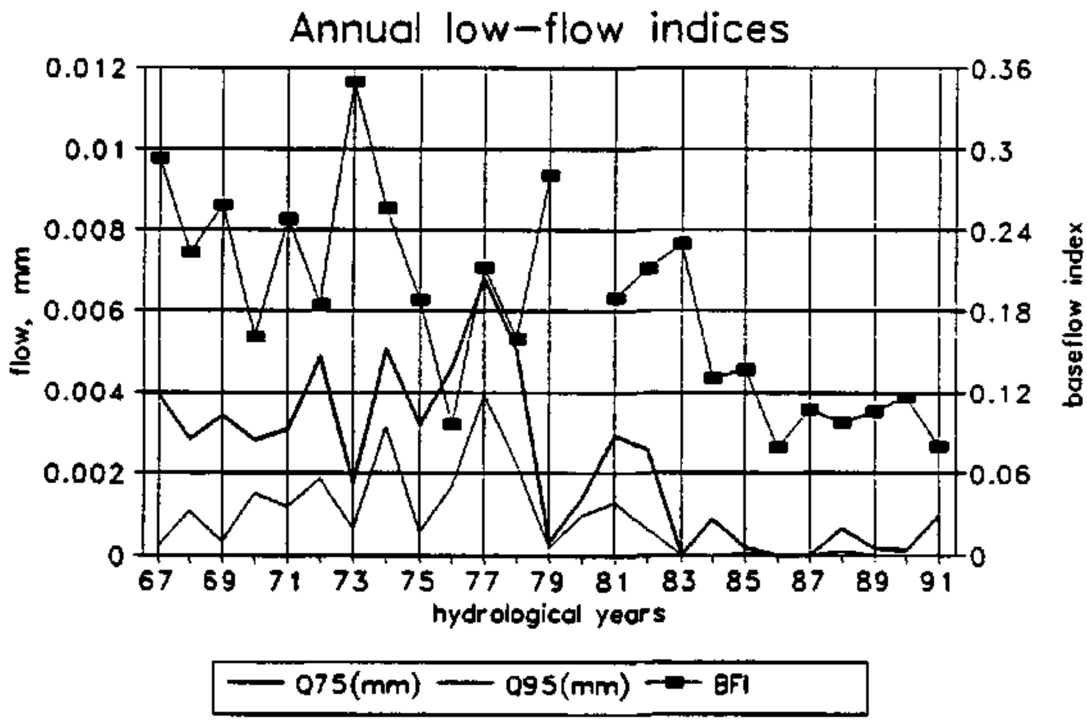
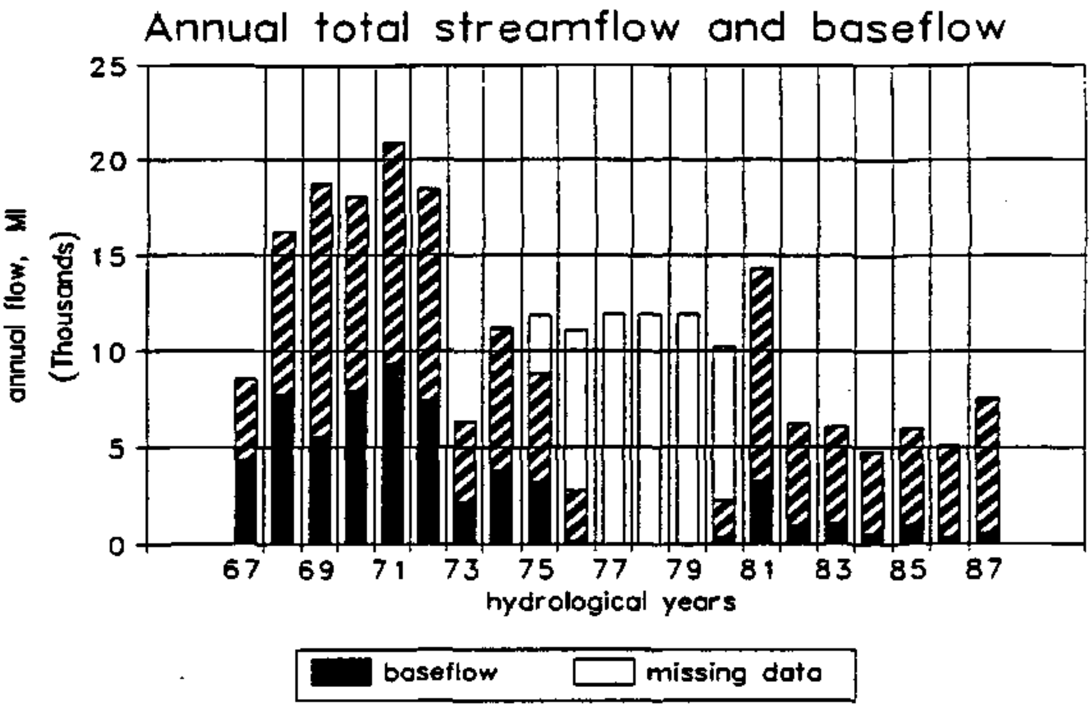
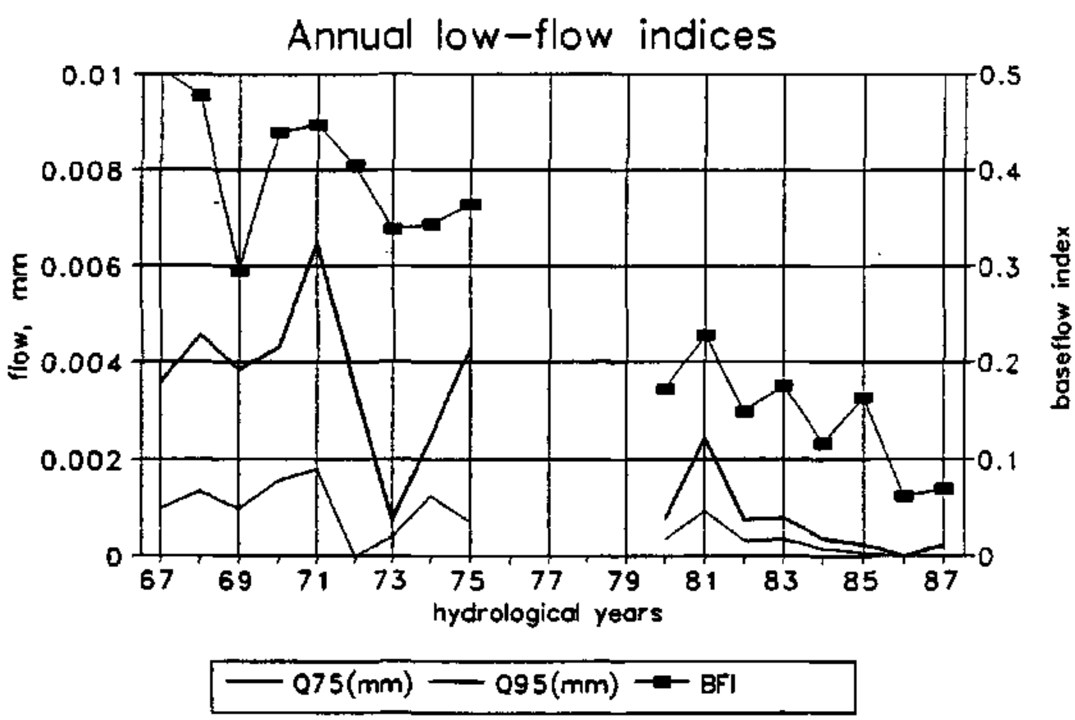


Figure F2.12. Gauge B3H001





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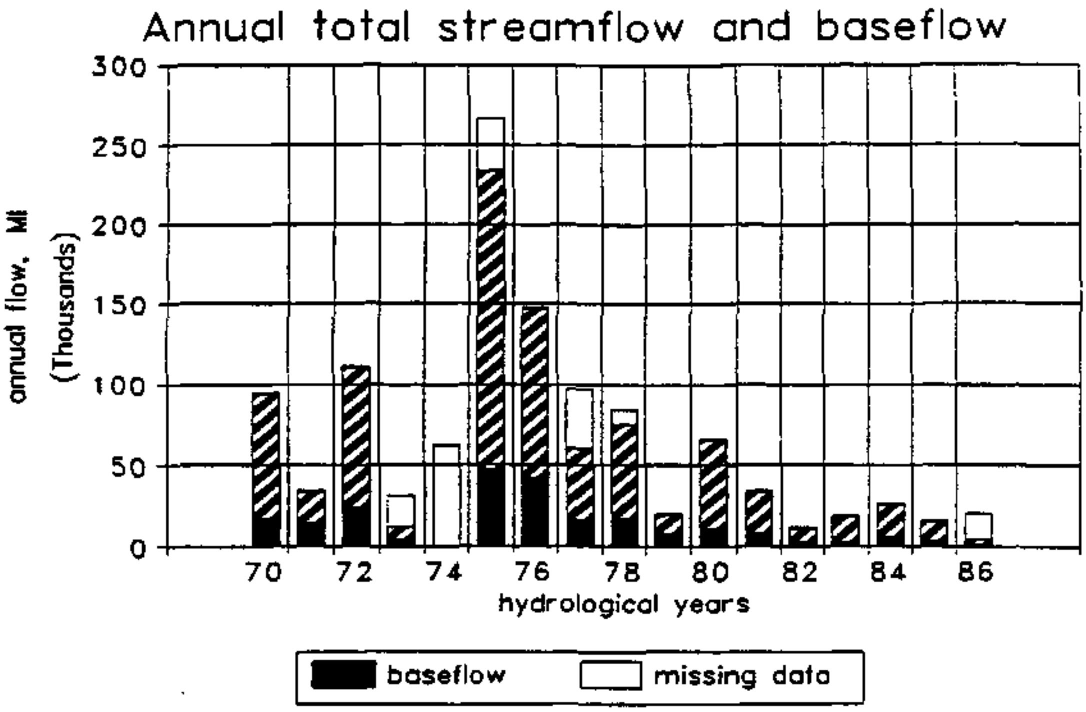

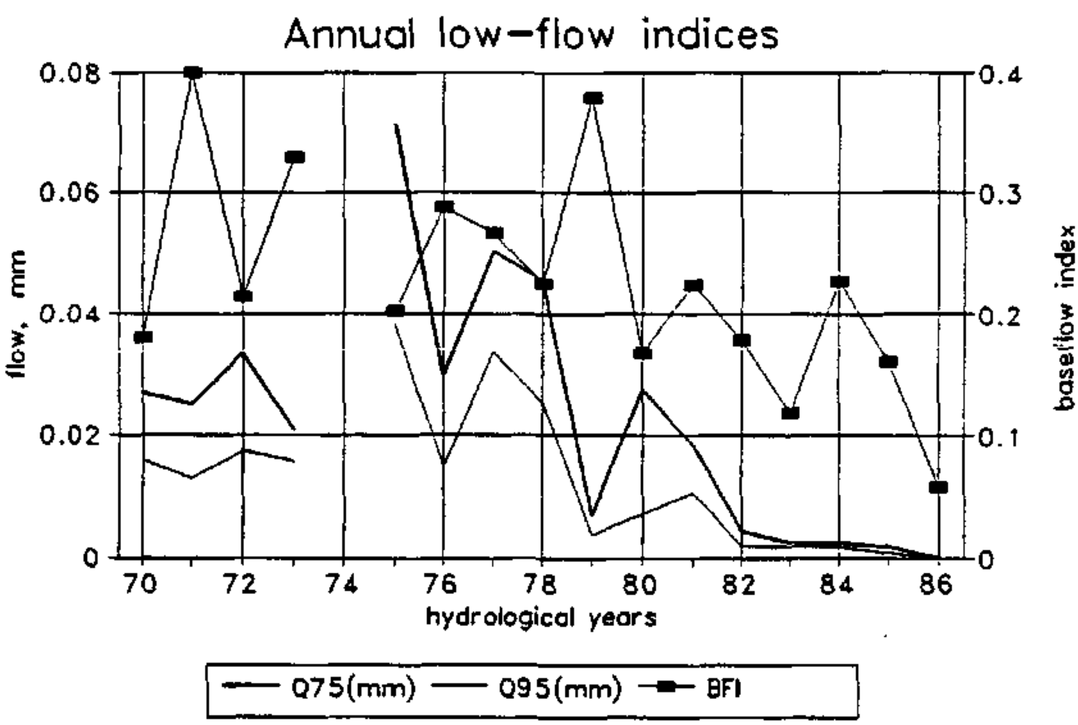

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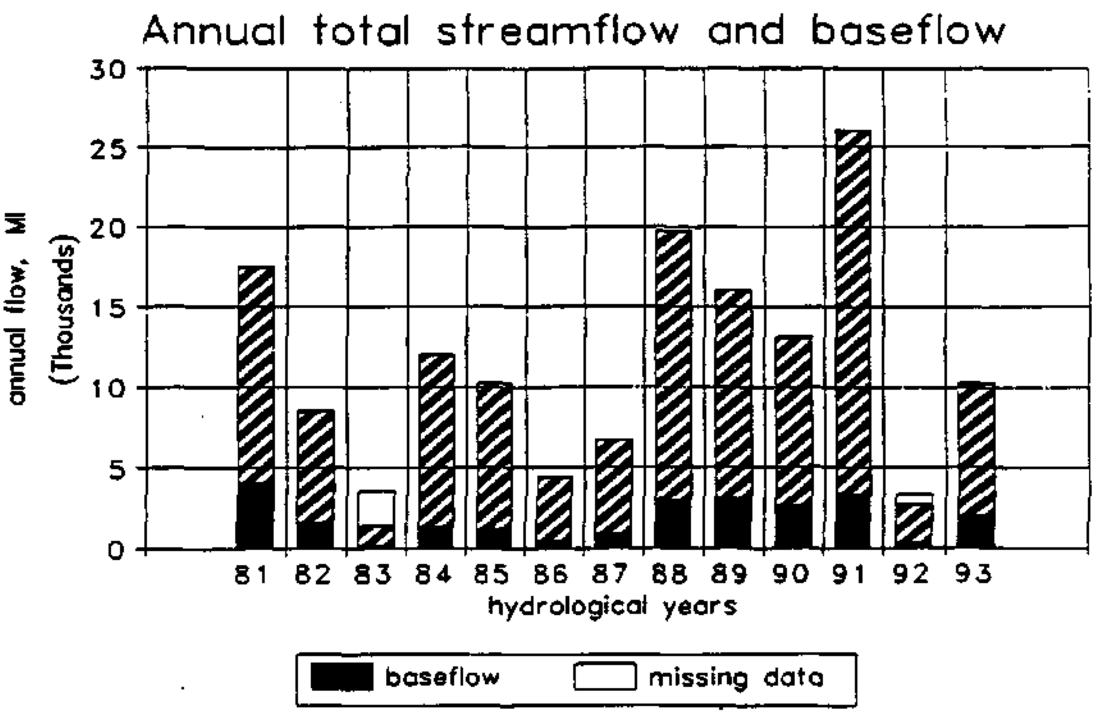


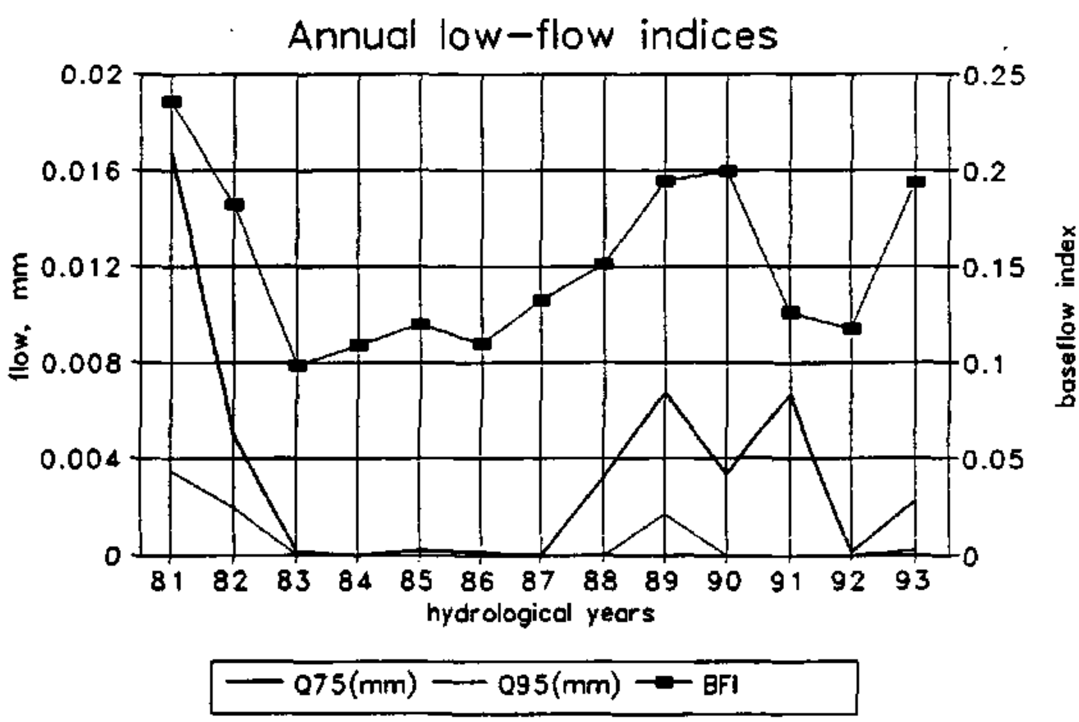
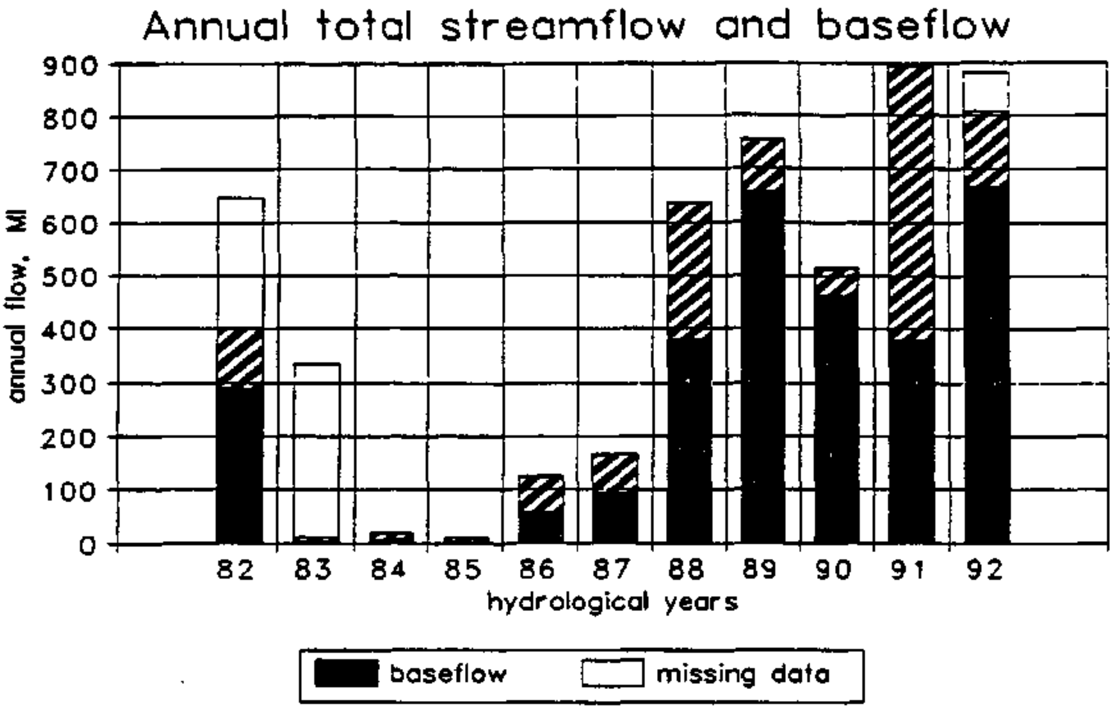


Figure F2.15. Gauge B3H007



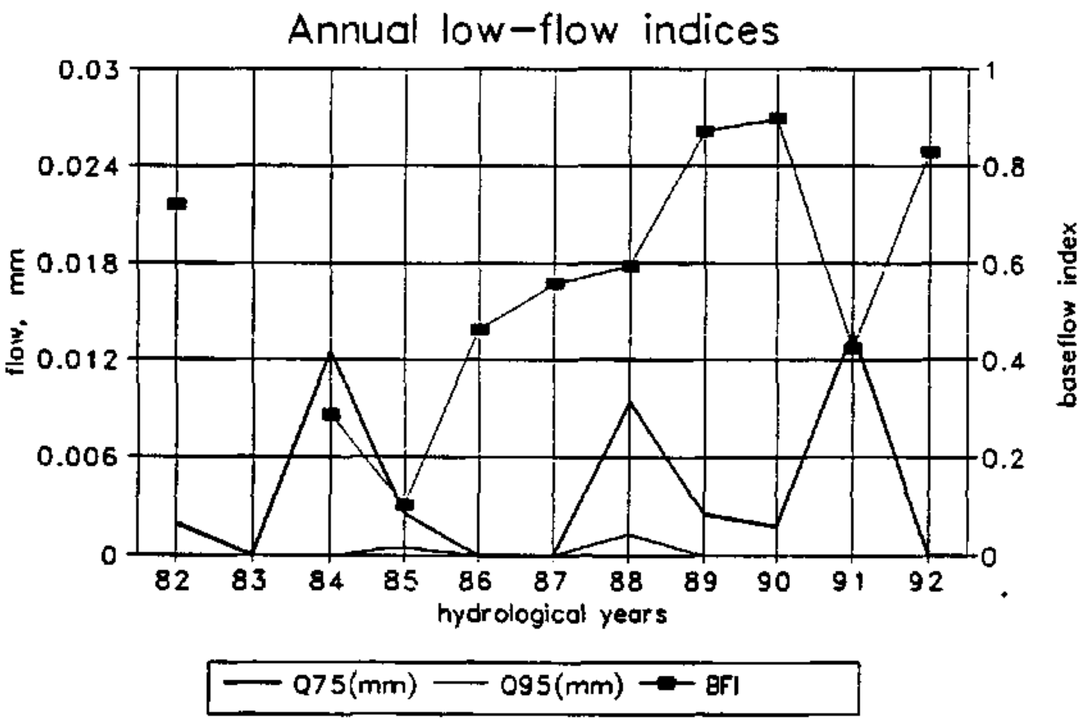


Figure F2.16. Gauge B3H014

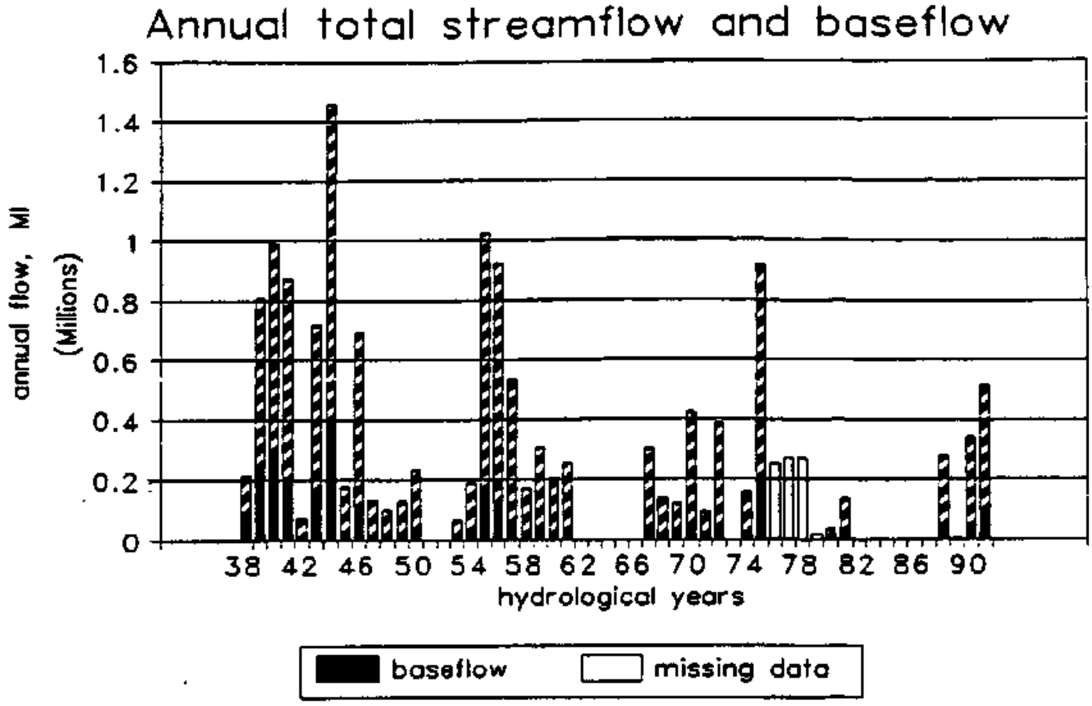


Figure F2.17. Gauge B3R002

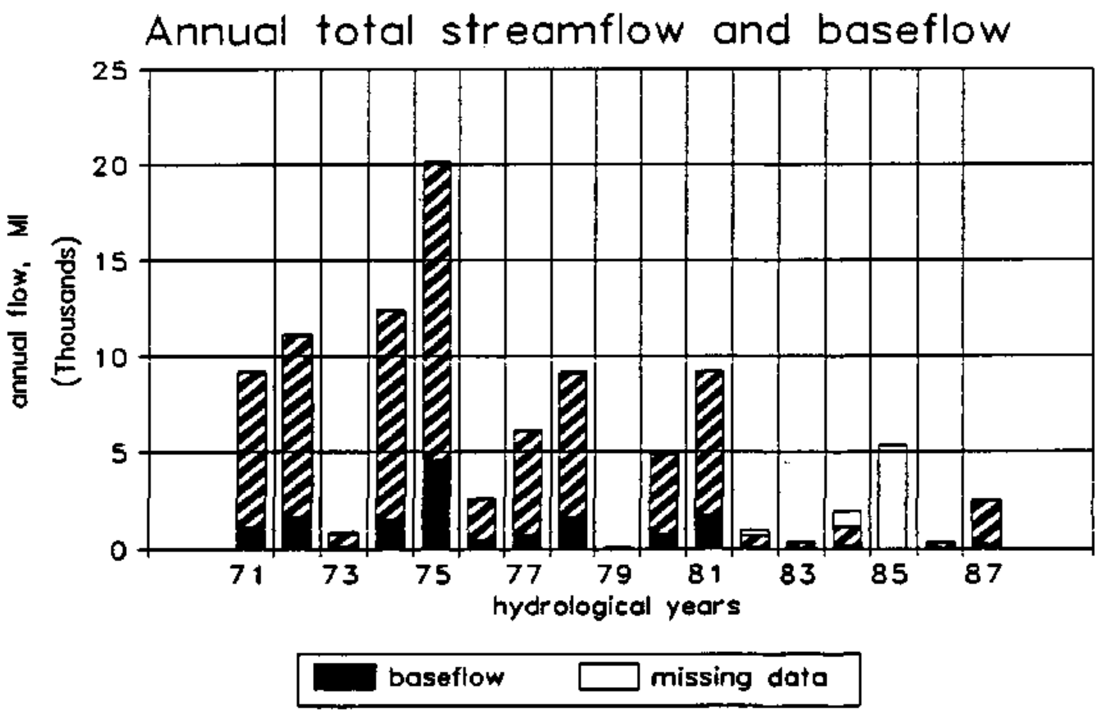
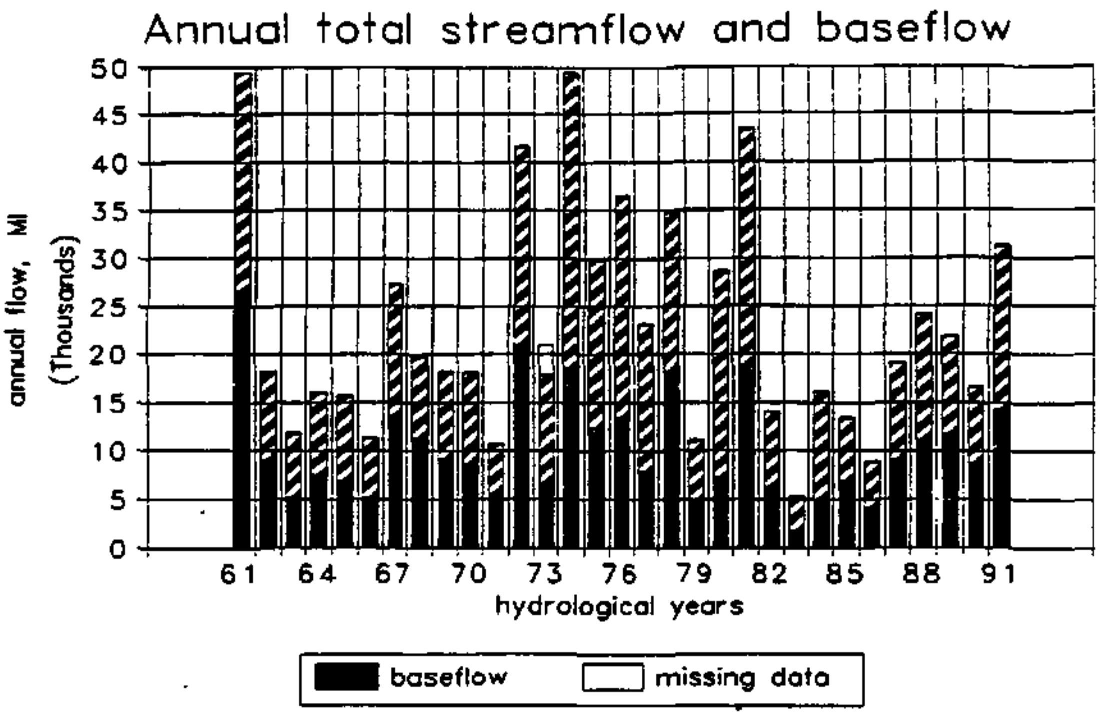


Figure F2.18. Gauge B3H006



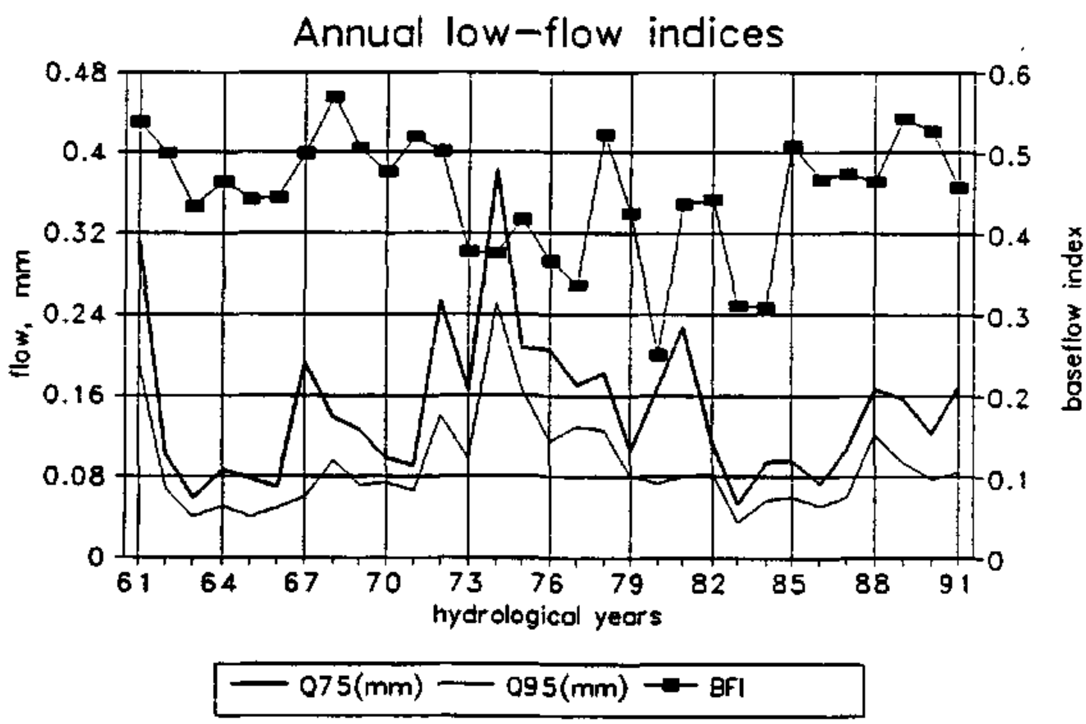
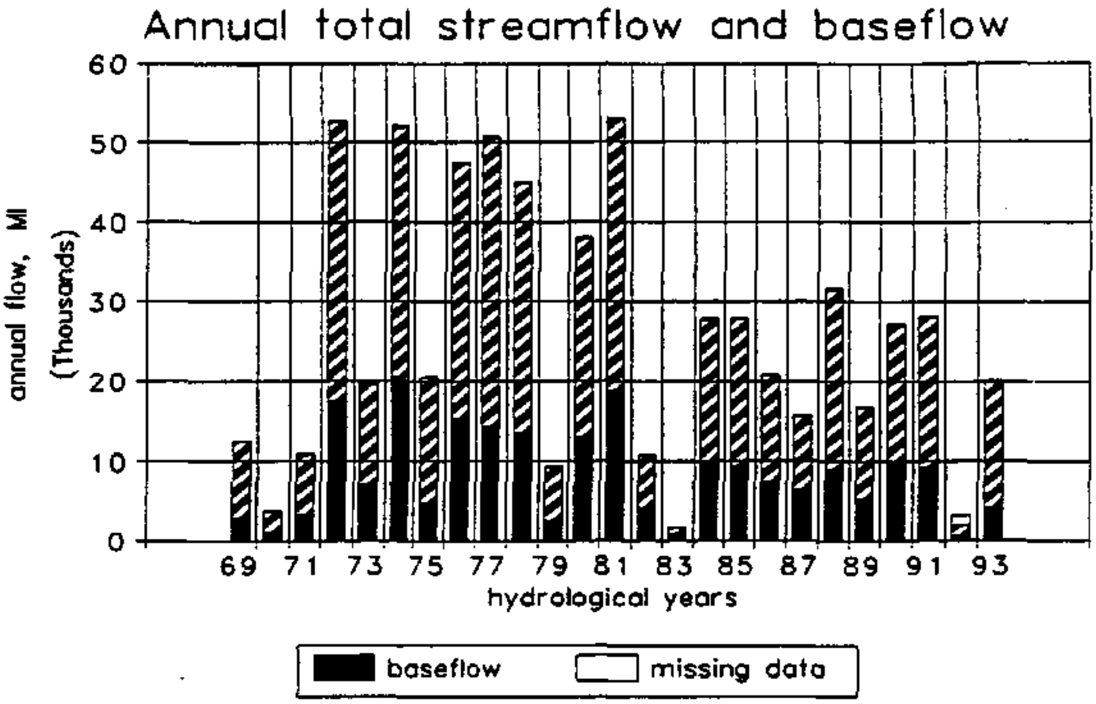


Figure F2.19. Gauge B4H005



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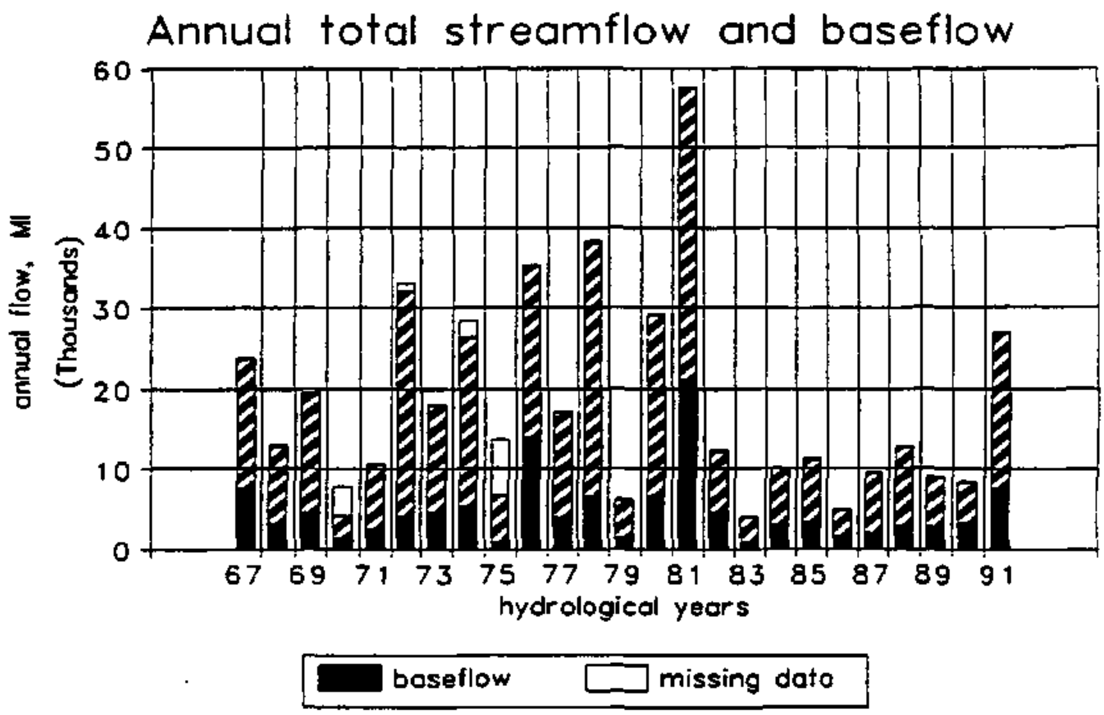


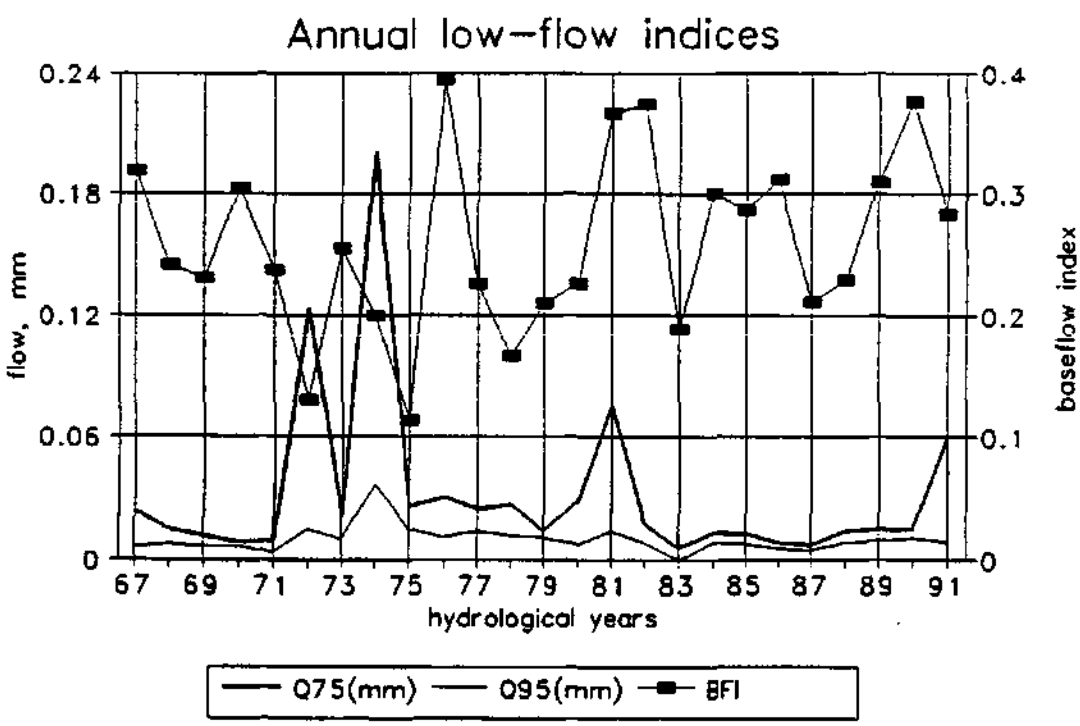
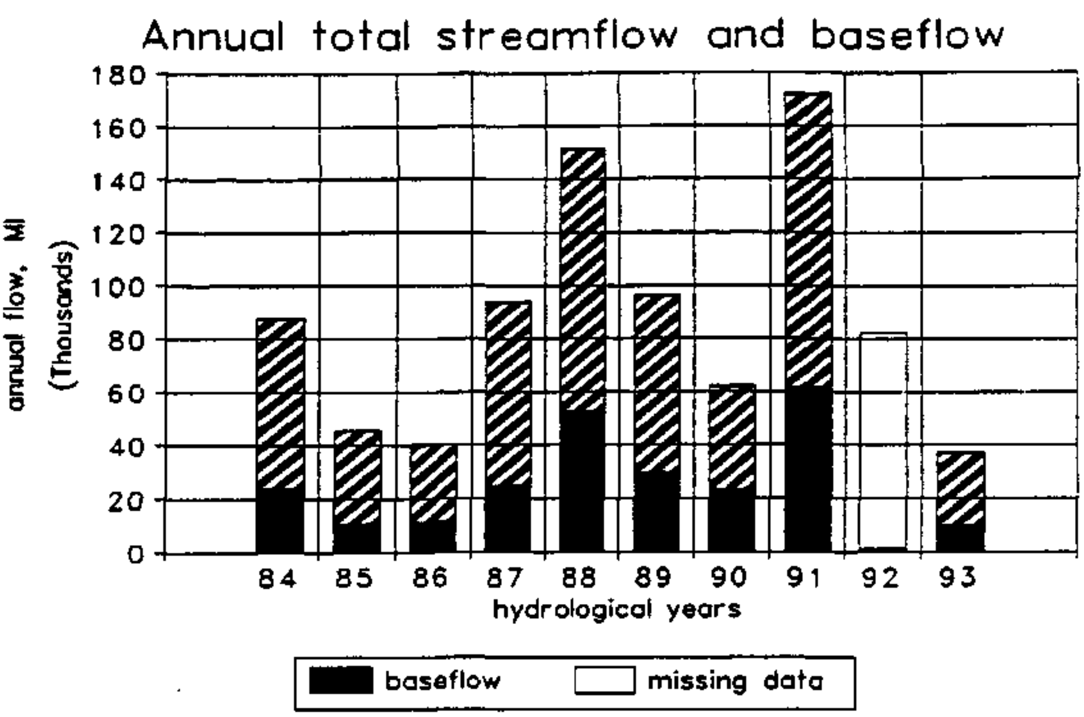


Figure F2.21. Gauge B4H009



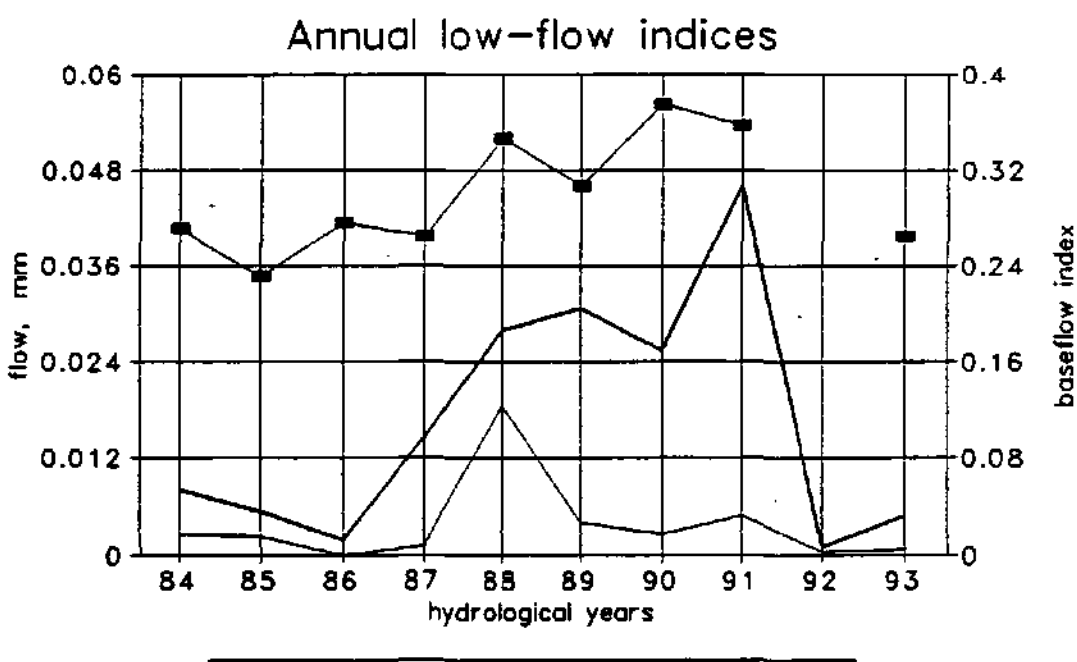
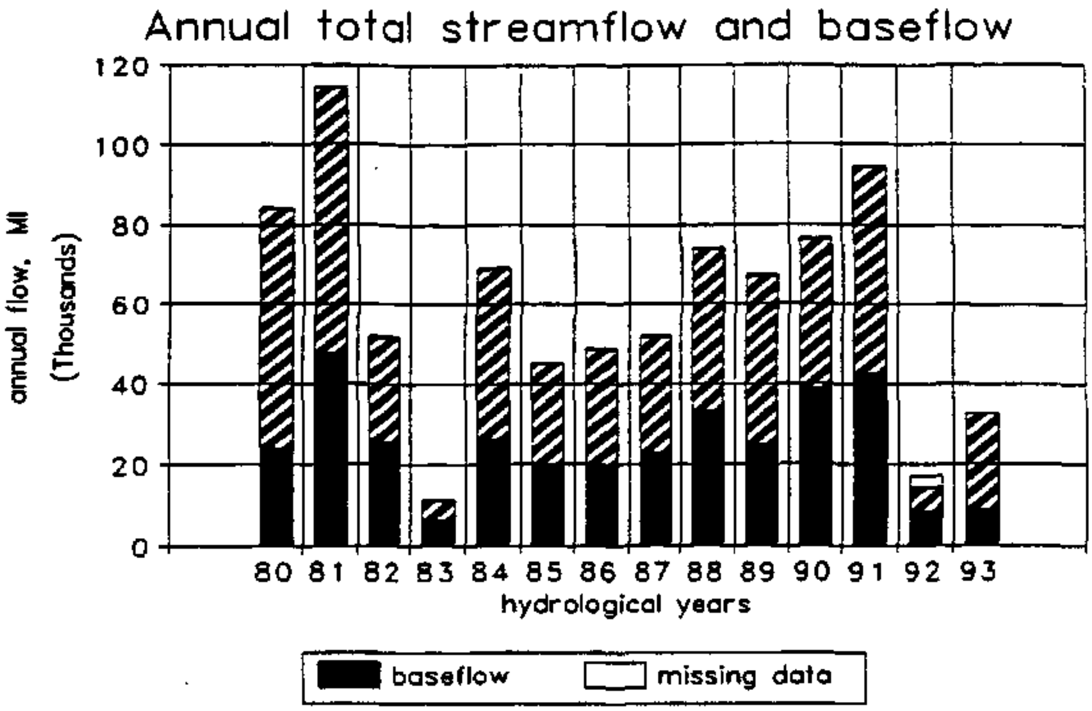
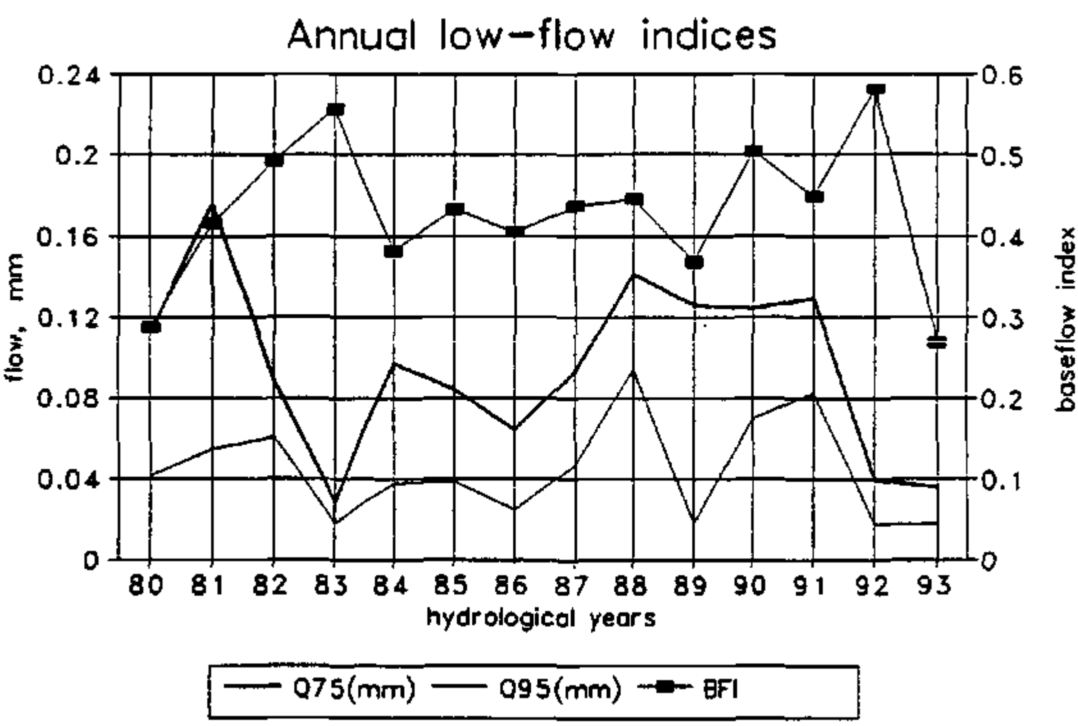


Figure F2.22. Gauge B4H003





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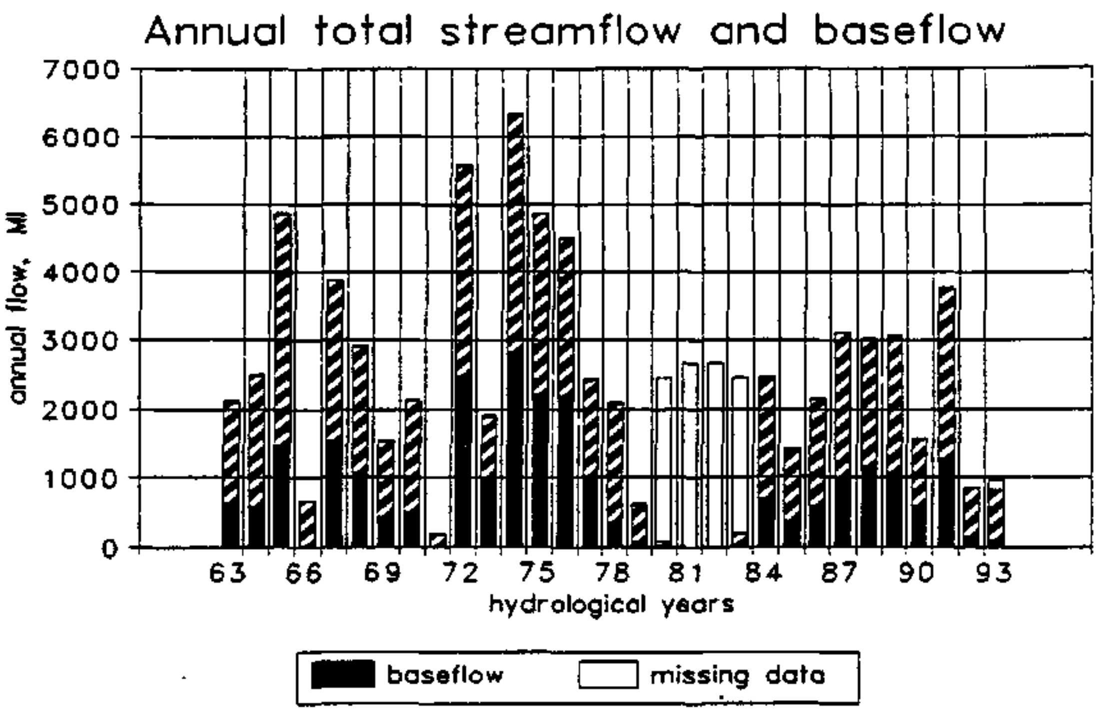


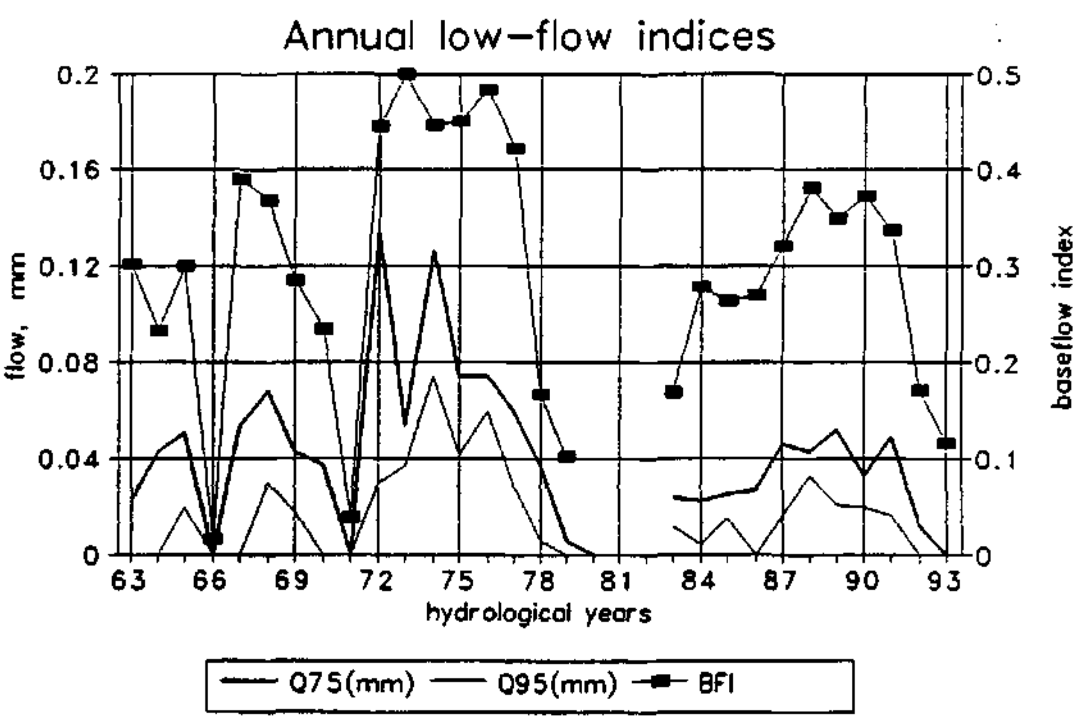
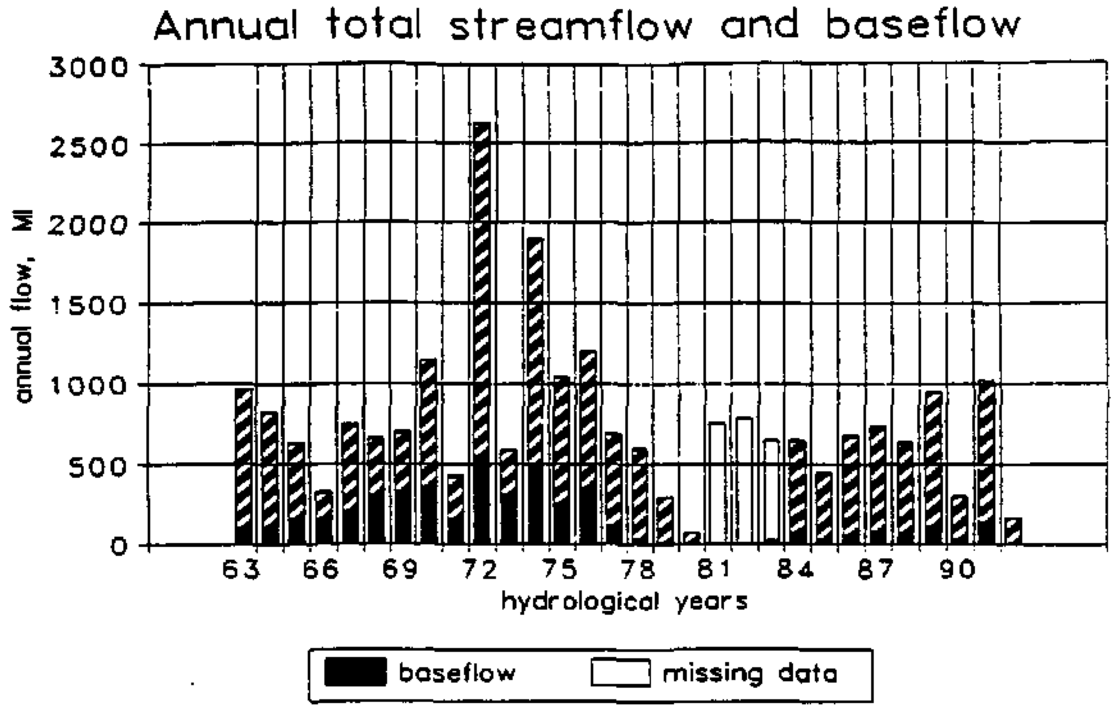
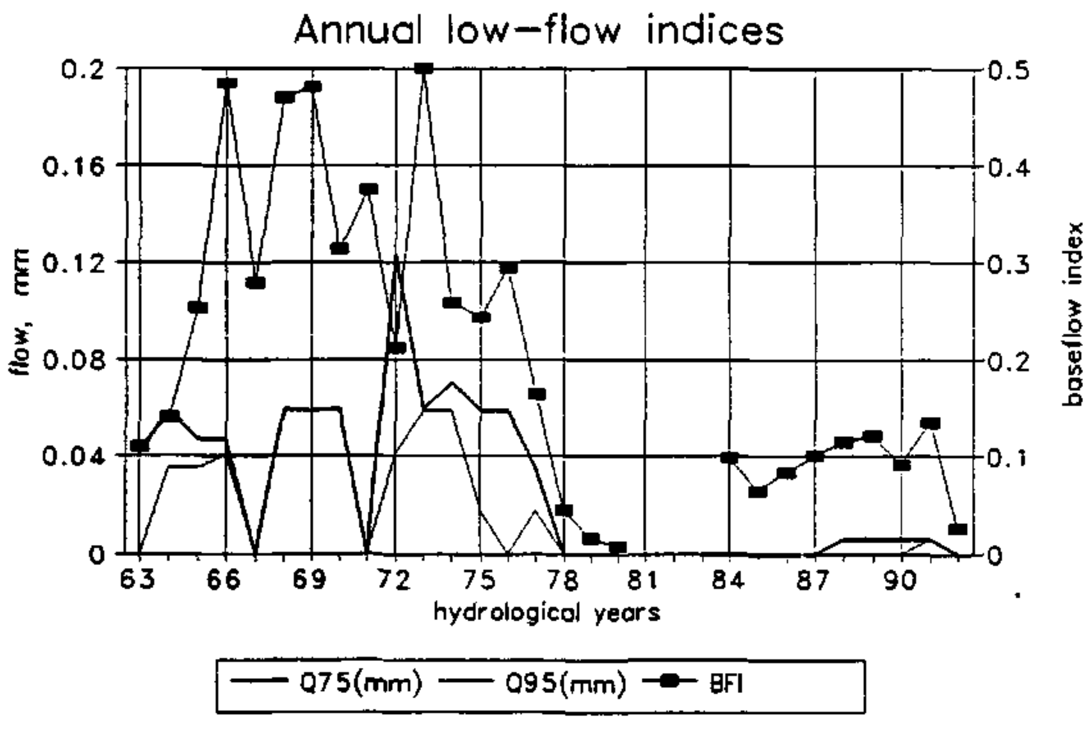


Figure F2.24. Gauge B4H016





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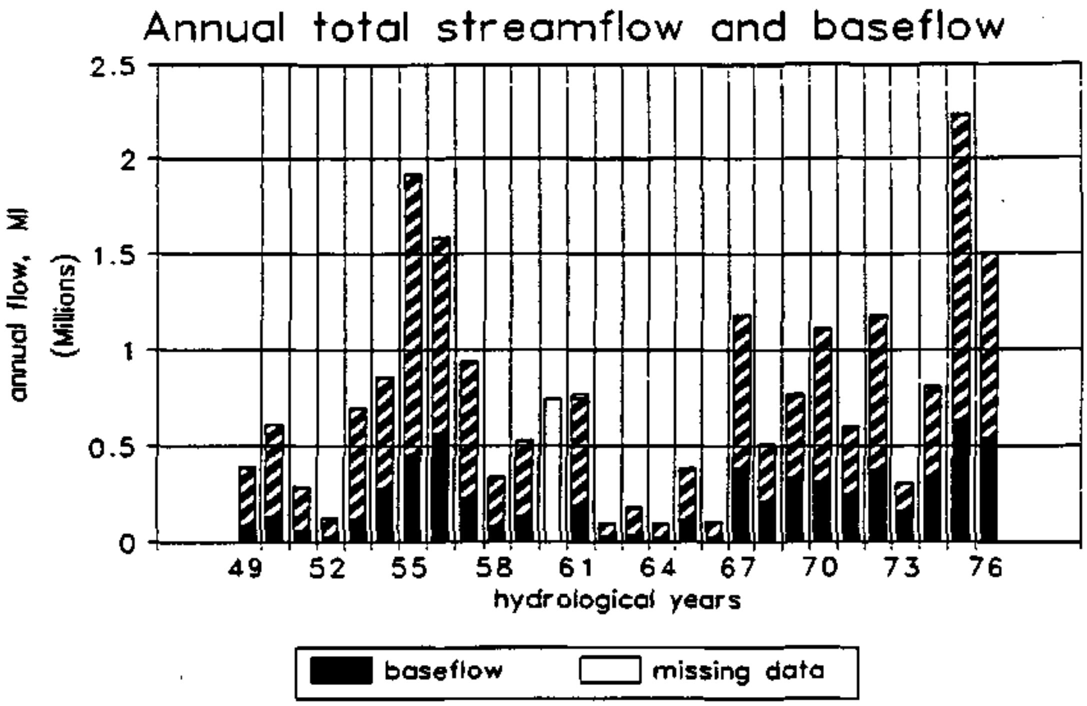


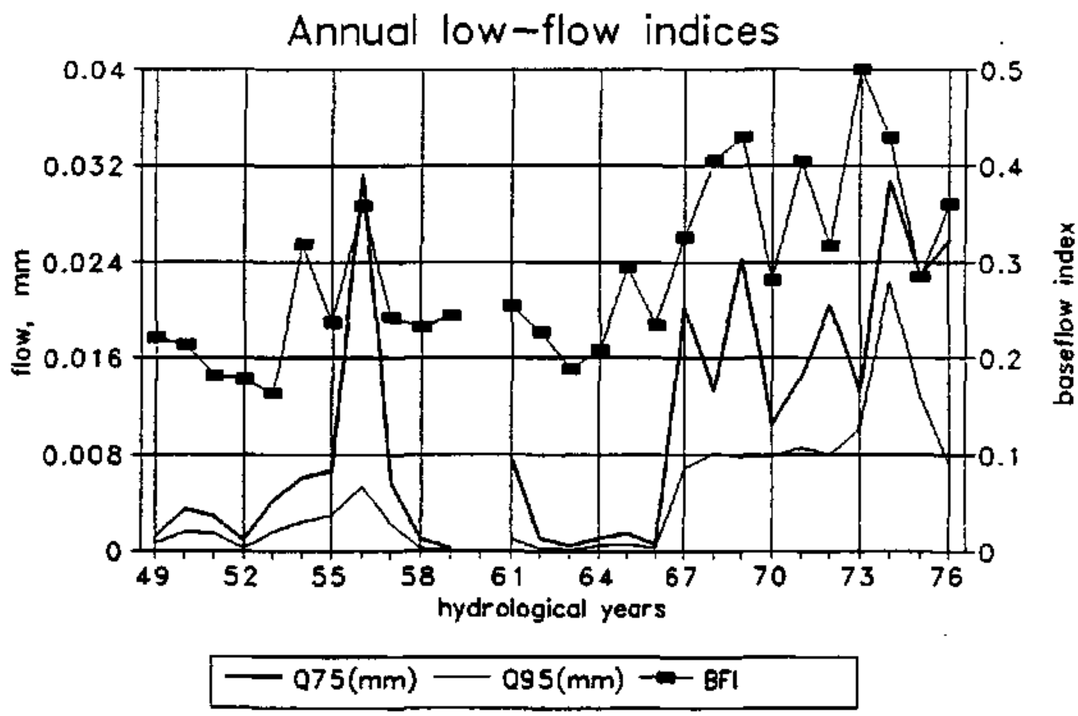
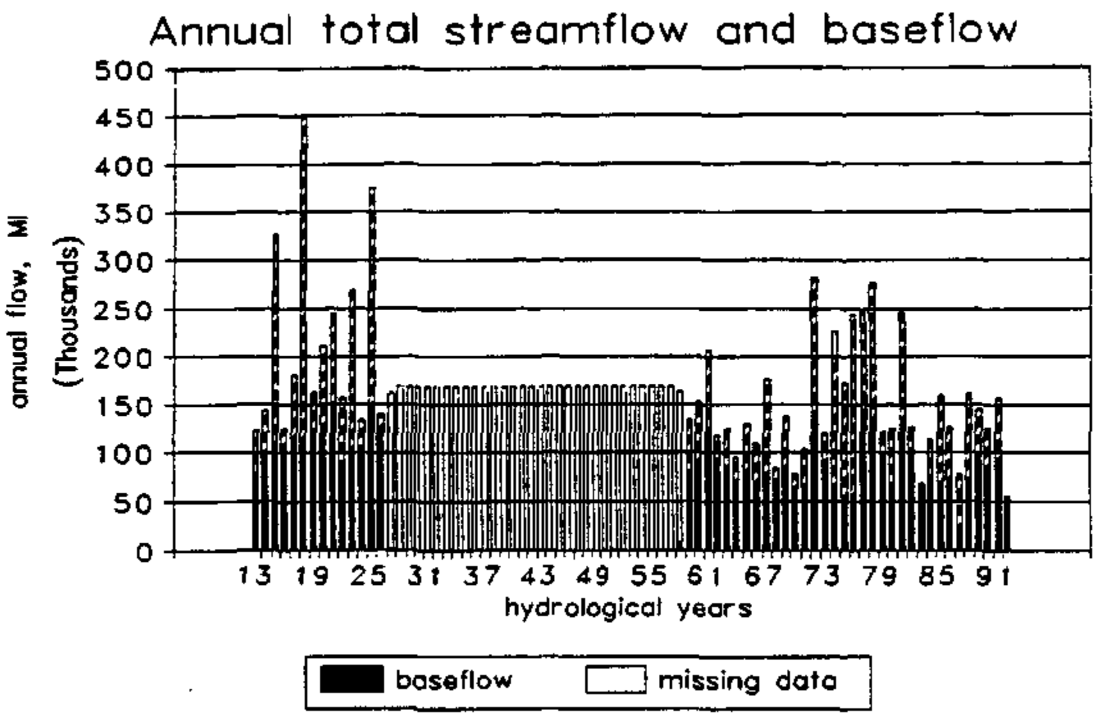


Figure F2.26. Gauge B5H002



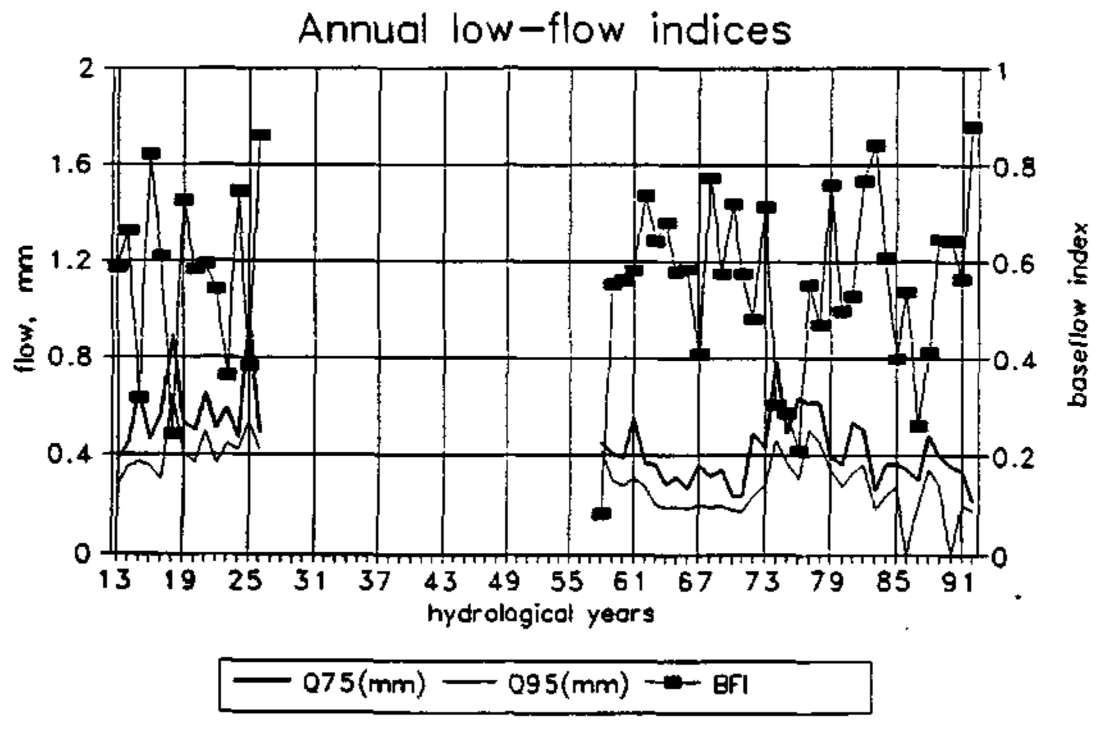
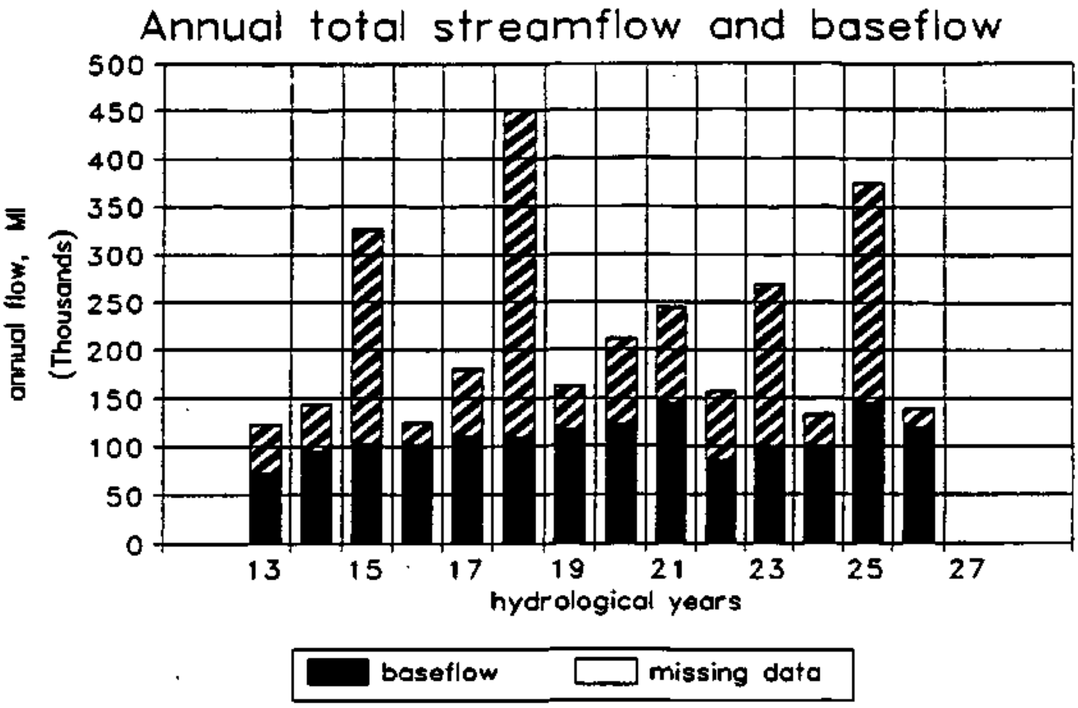


Figure F2.27. Gauge B6H001



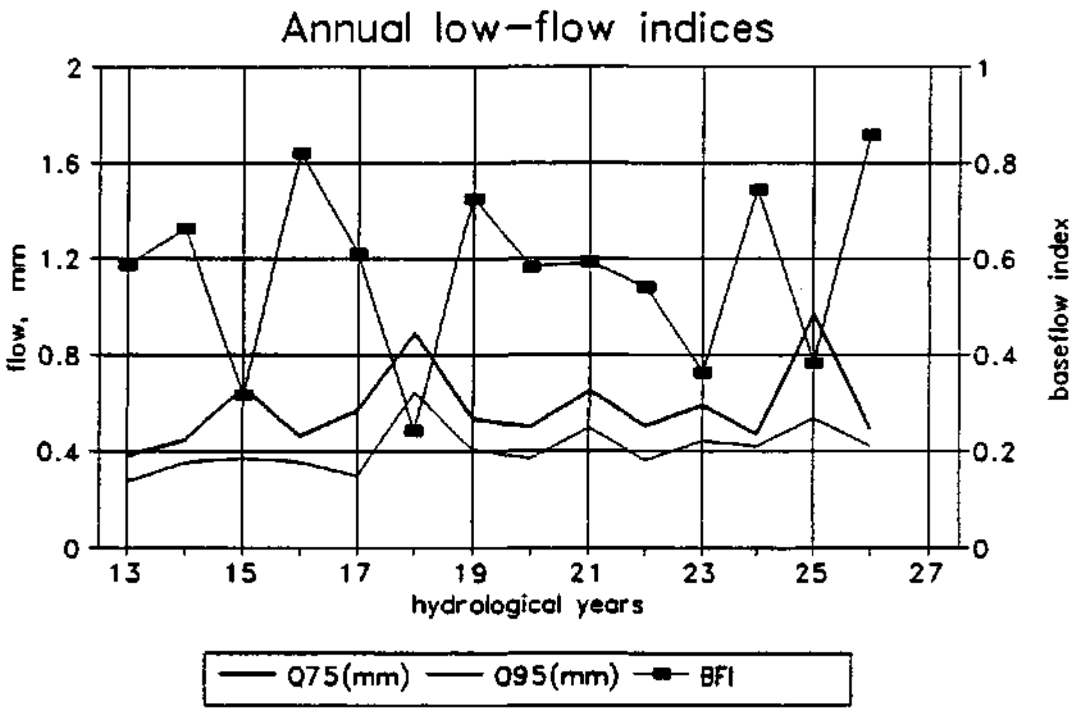
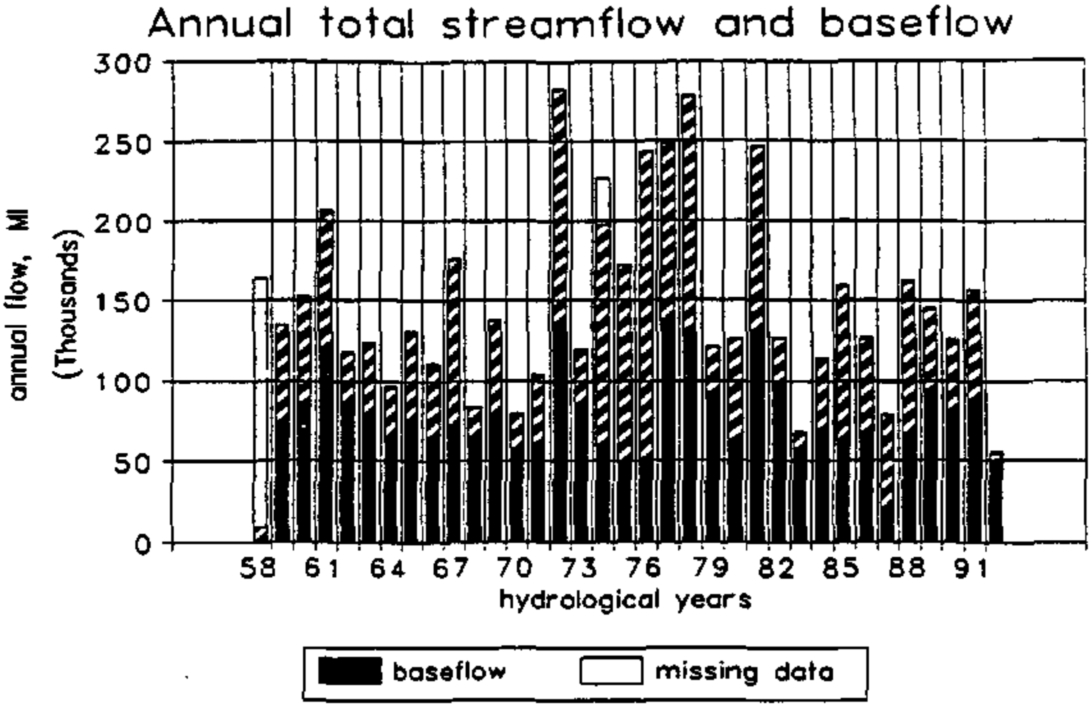


Figure F2.28. Gauge B6H001



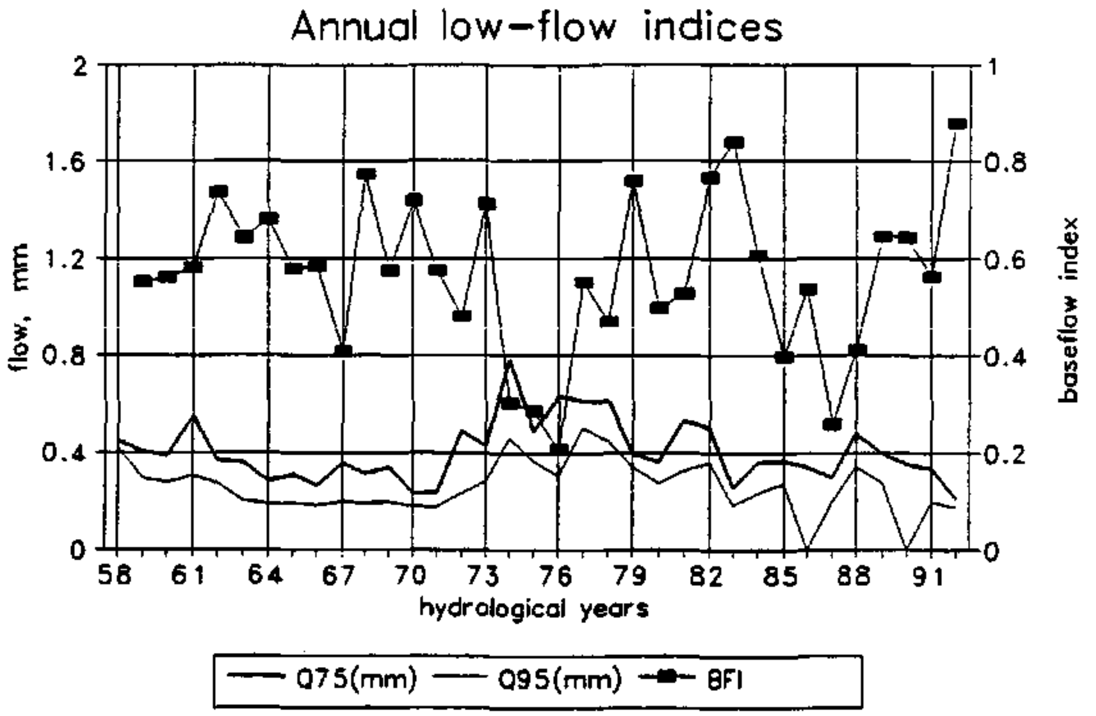
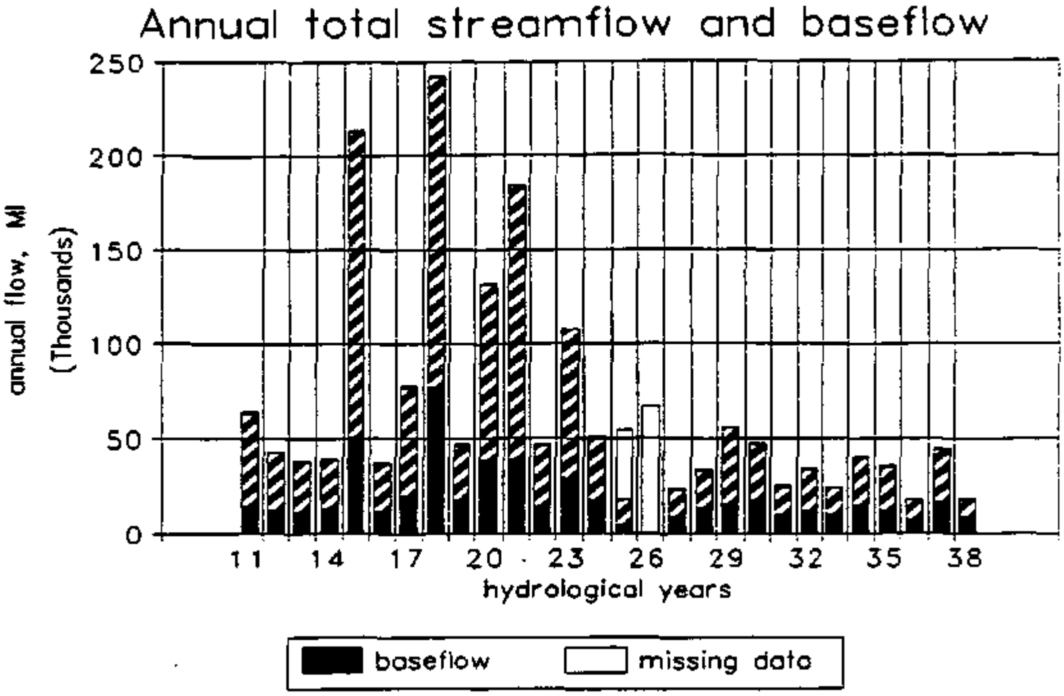


Figure F2.29. Gauge B6H001



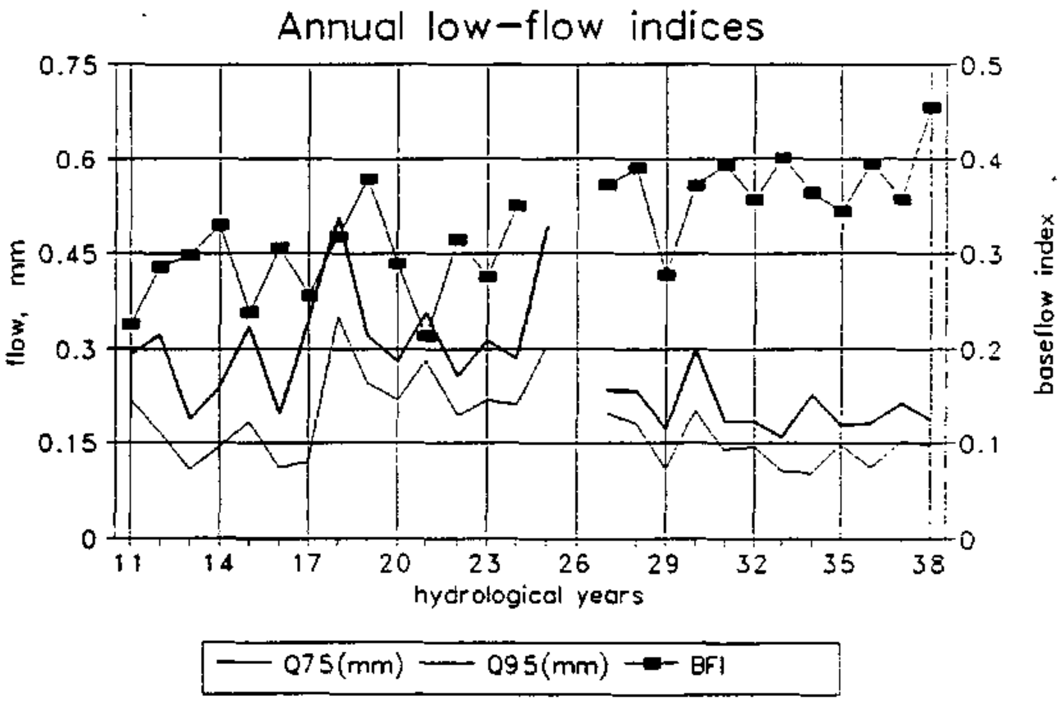
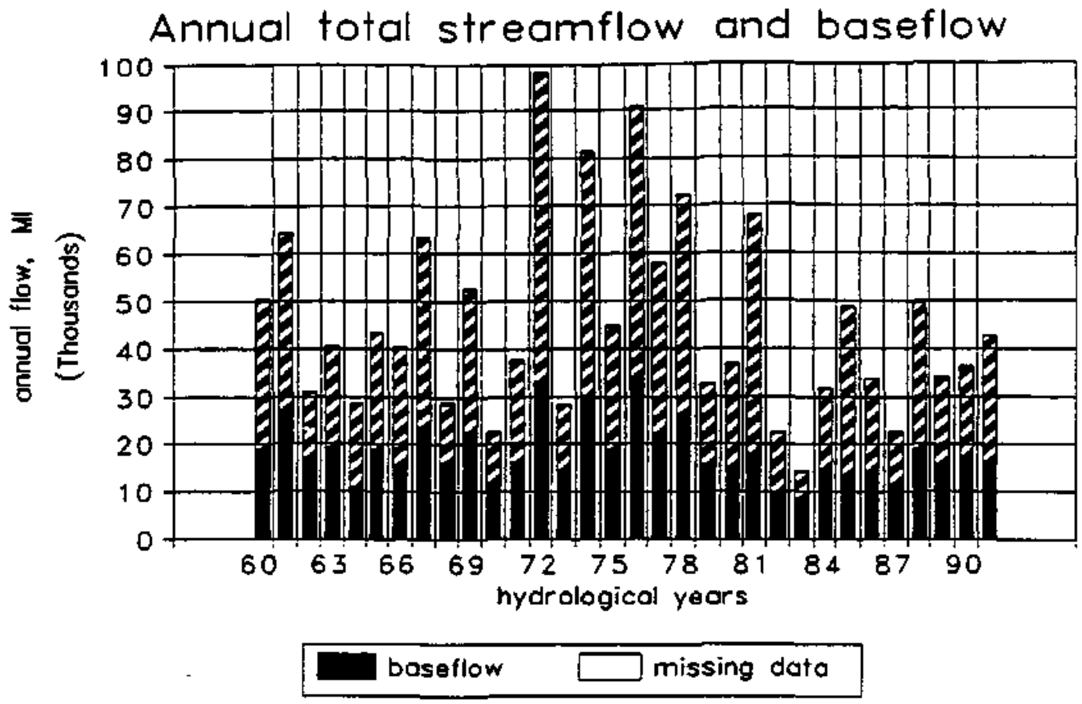


Figure F2.30. Gauge B6H002



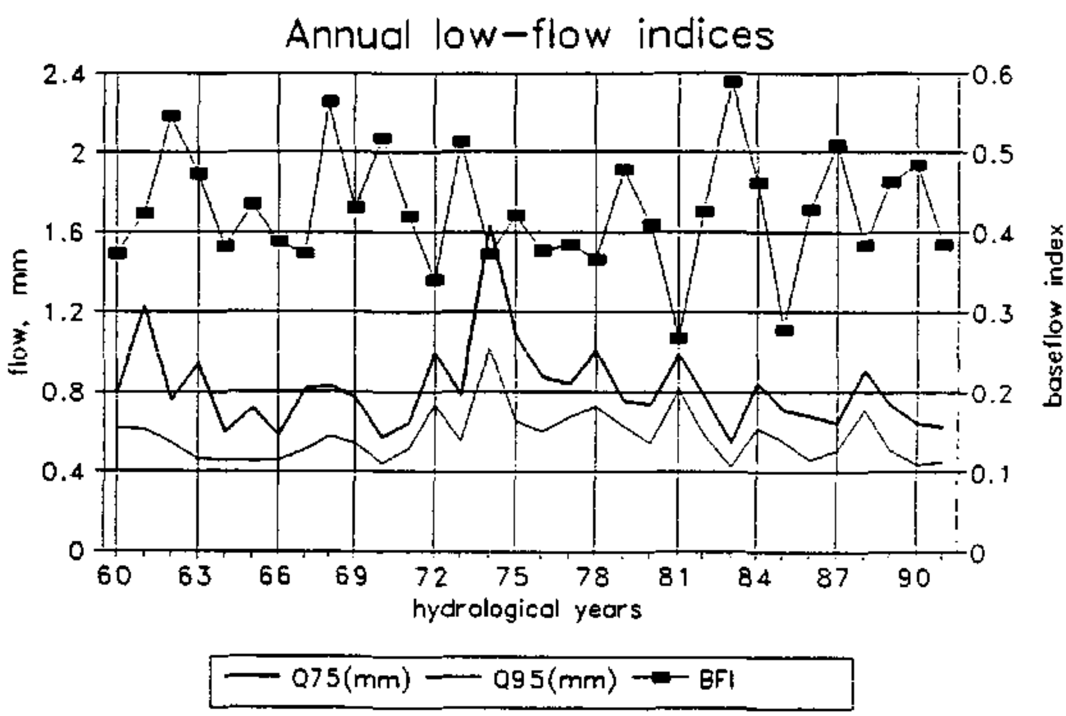
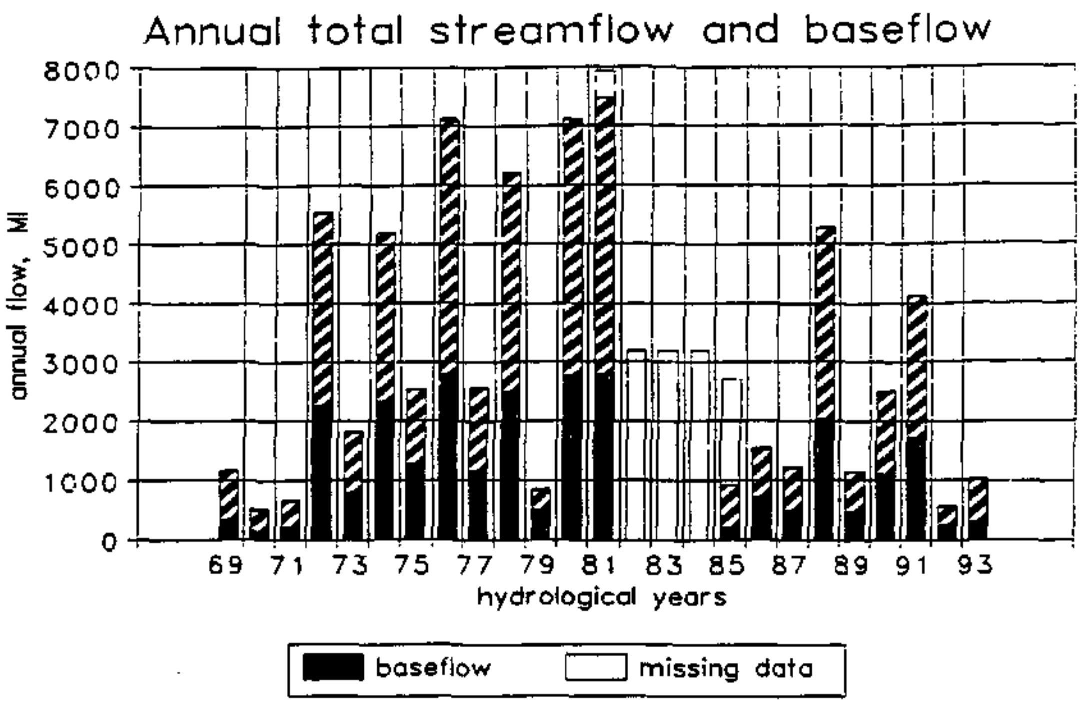


Figure F2.31. Gauge B6H003



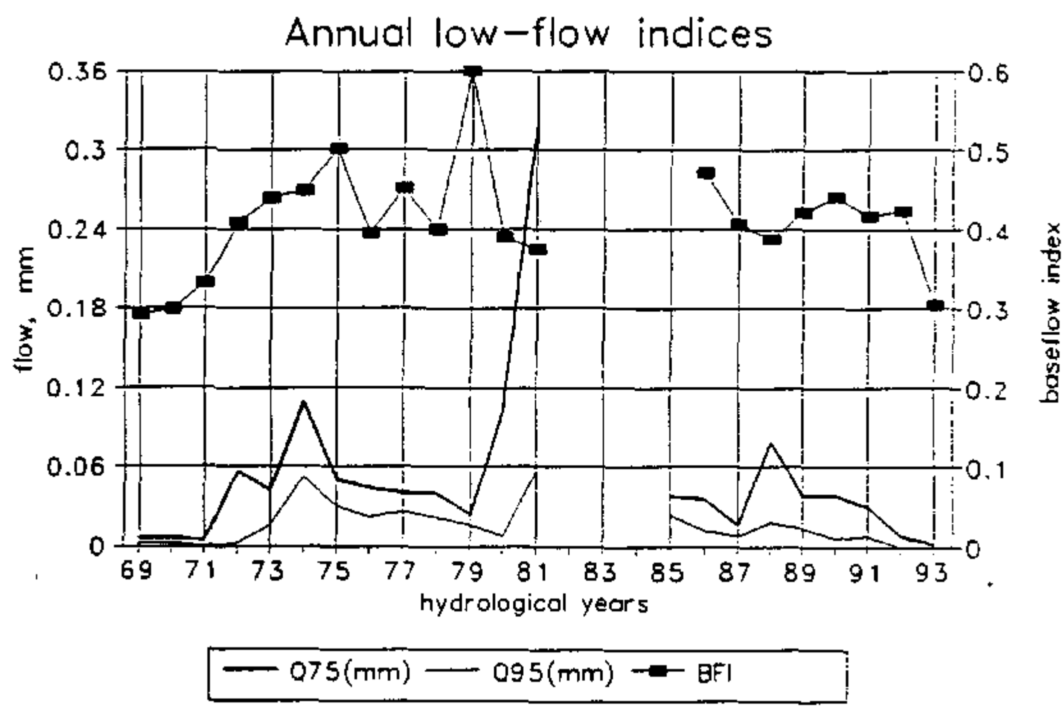
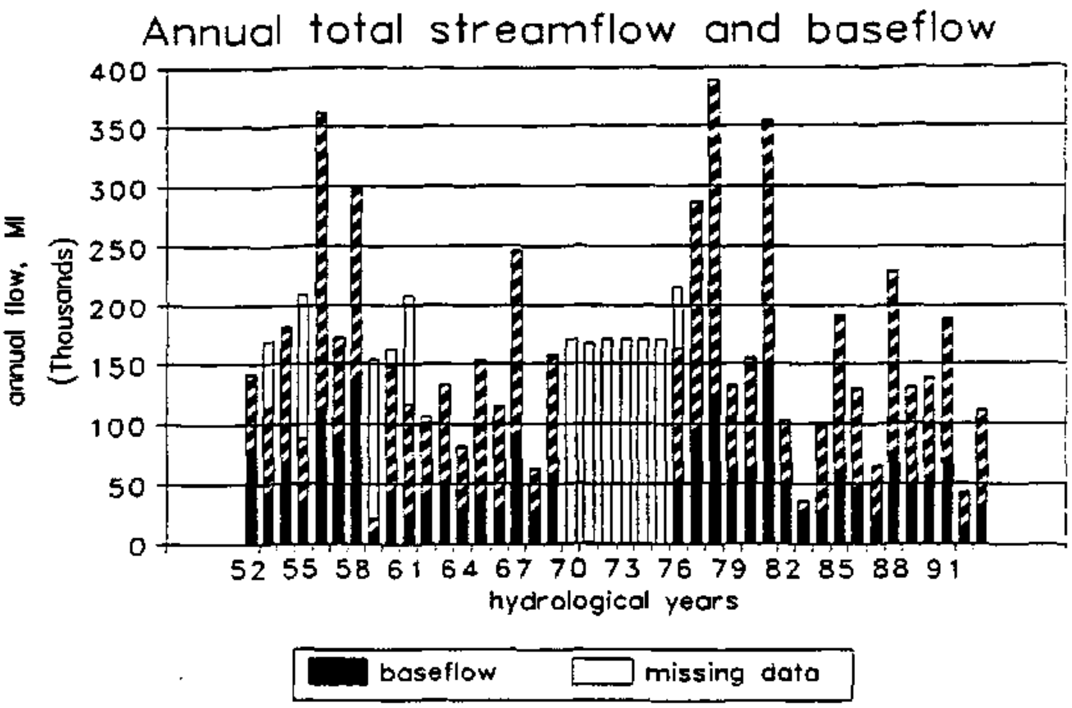


Figure F2.32. Gauge B6H006



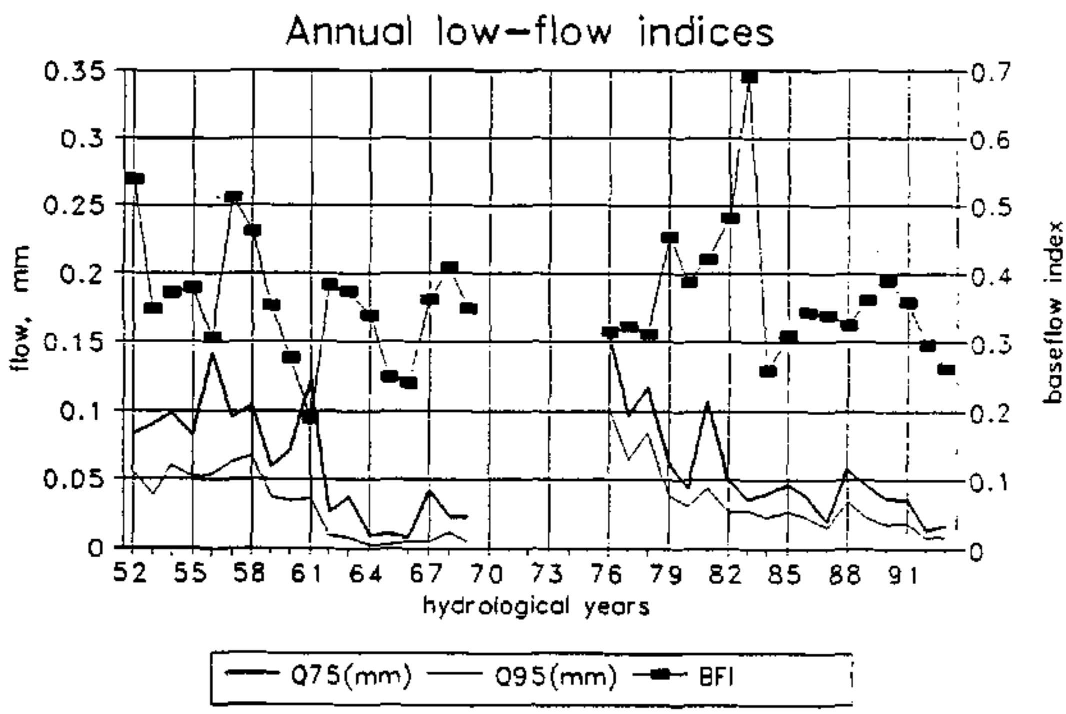
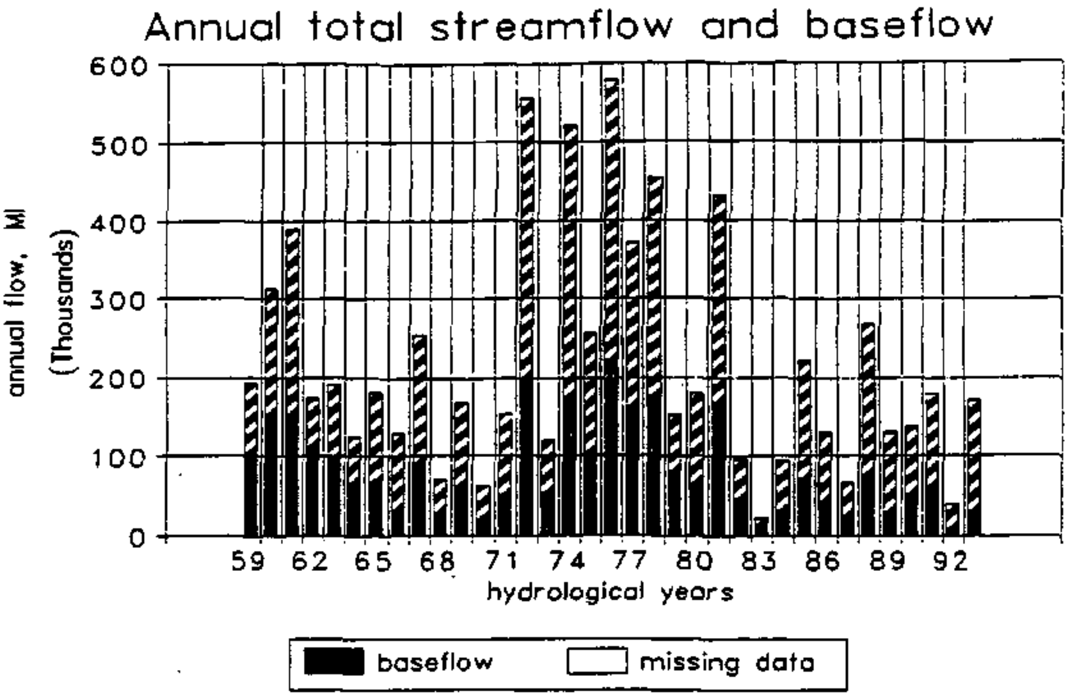


Figure F2.33. Gauge B6H004



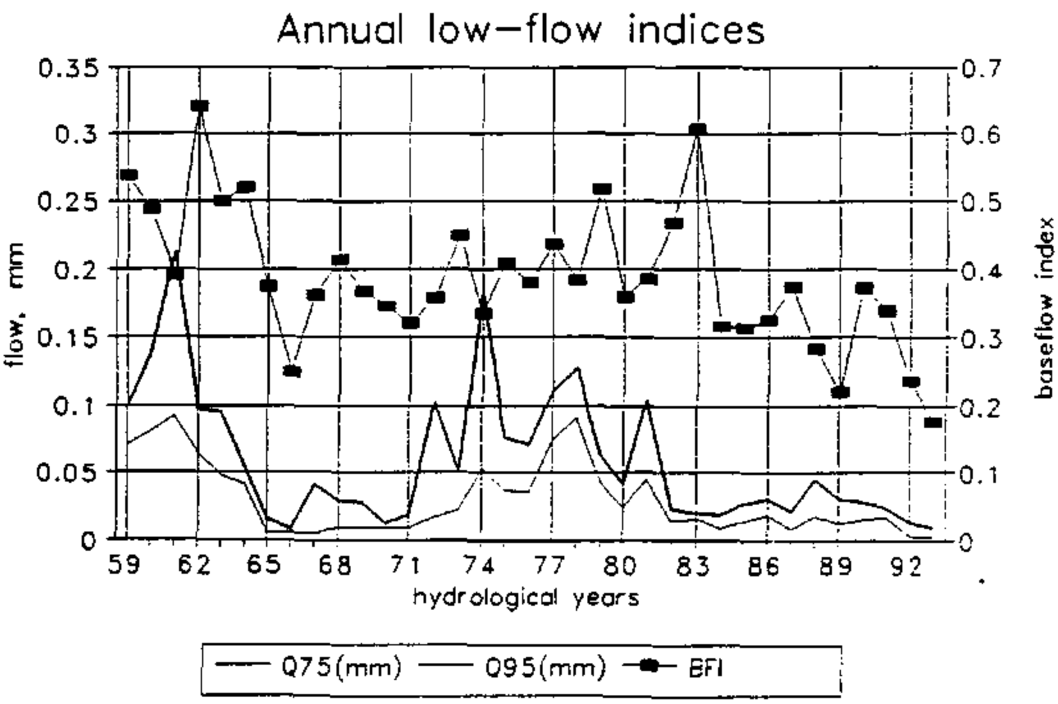
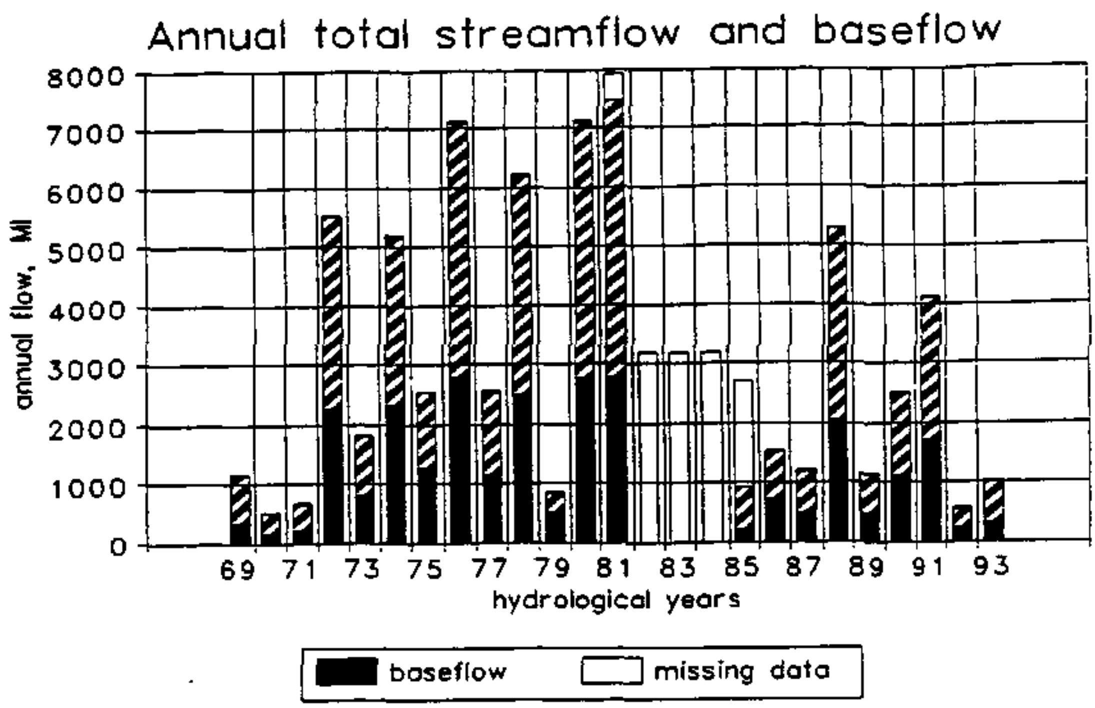


Figure F2.34. Gauge B6H005



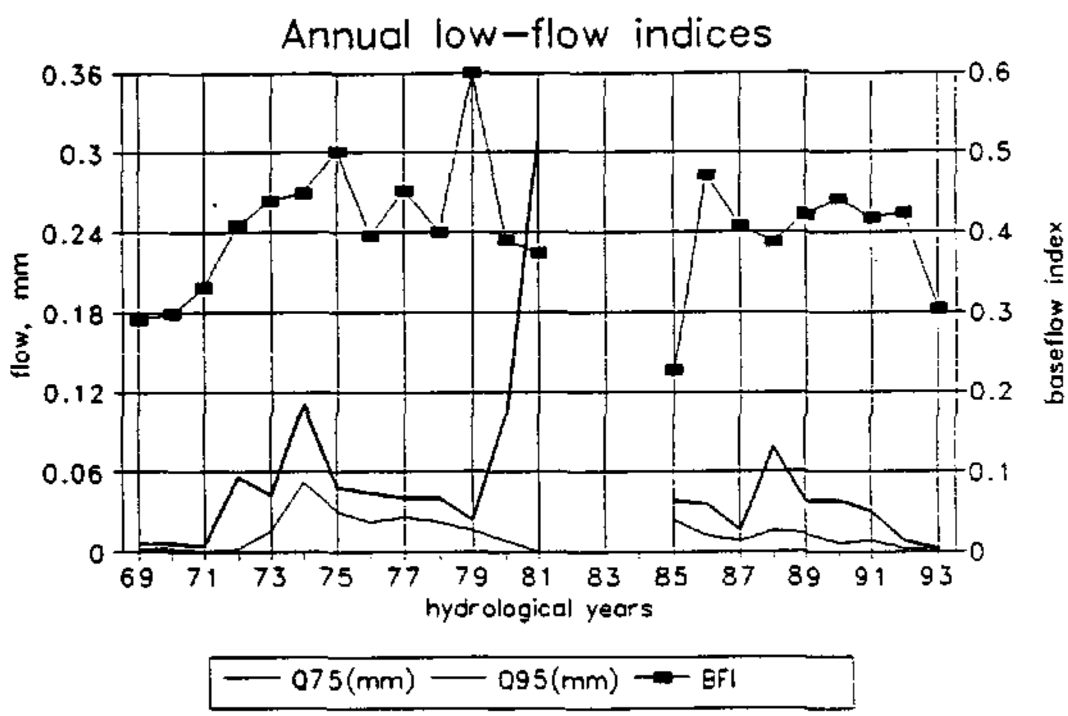


Figure F2.35. Gauge B6H007

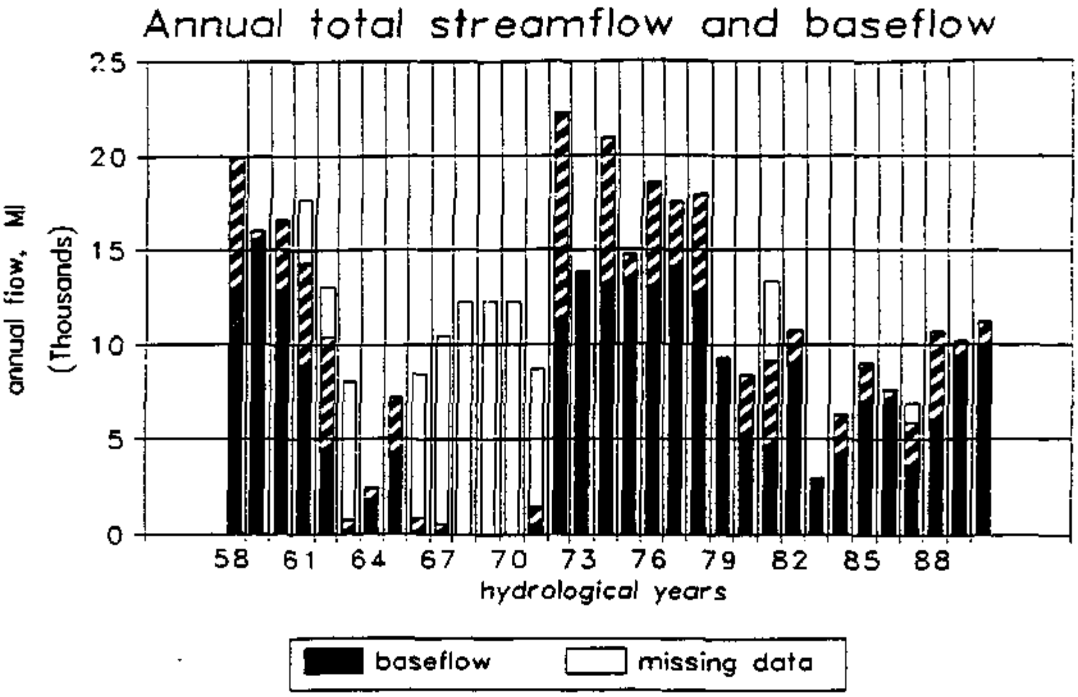
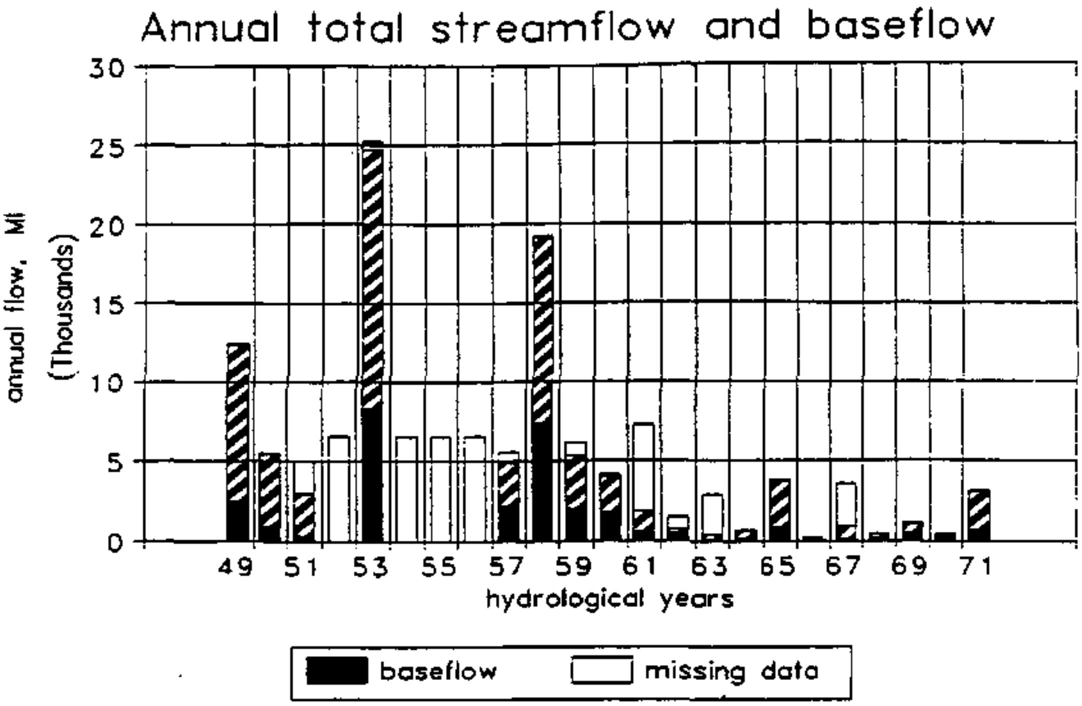


Figure F2.36. Gauge B6H012



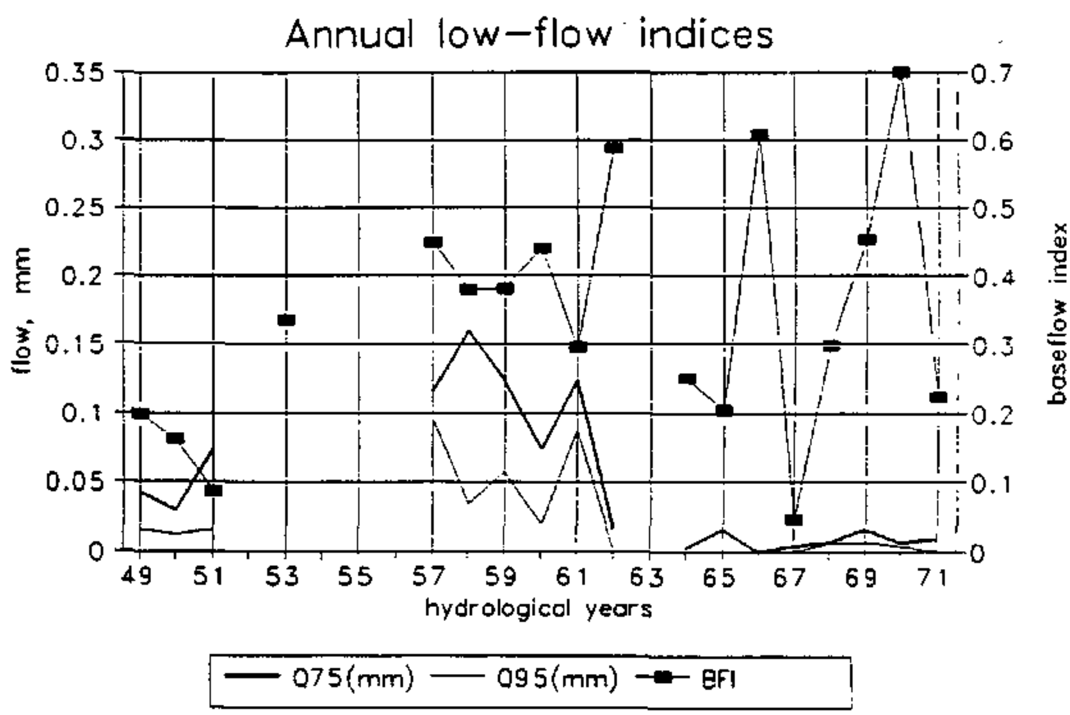
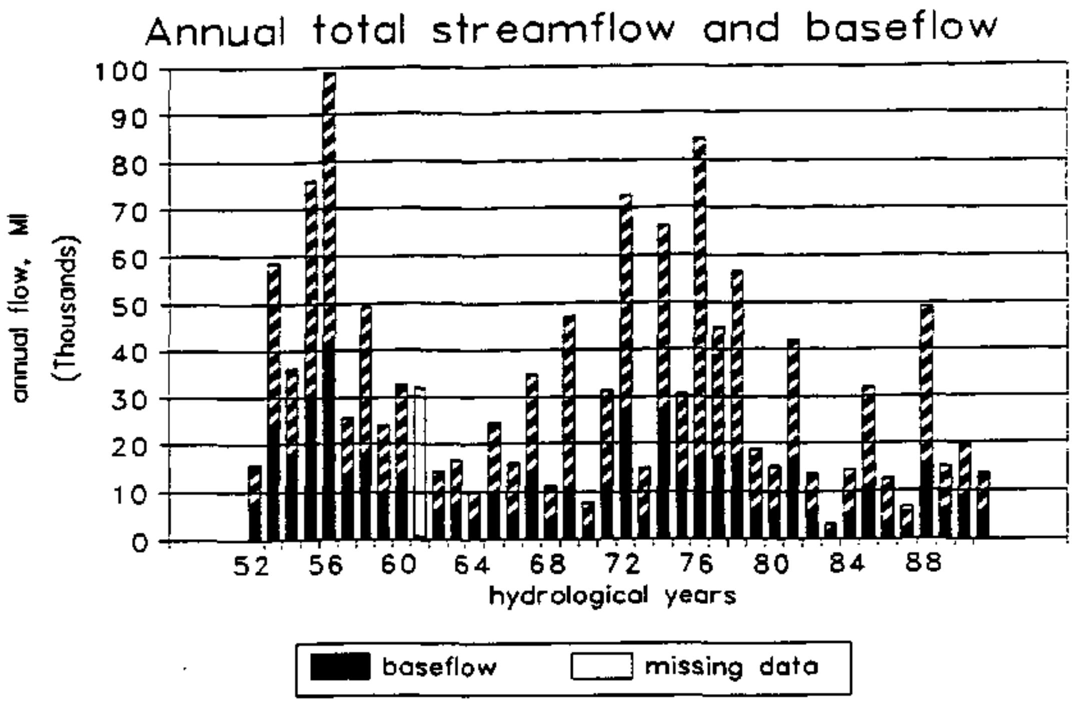


Figure F2.37. Gauge B7H003



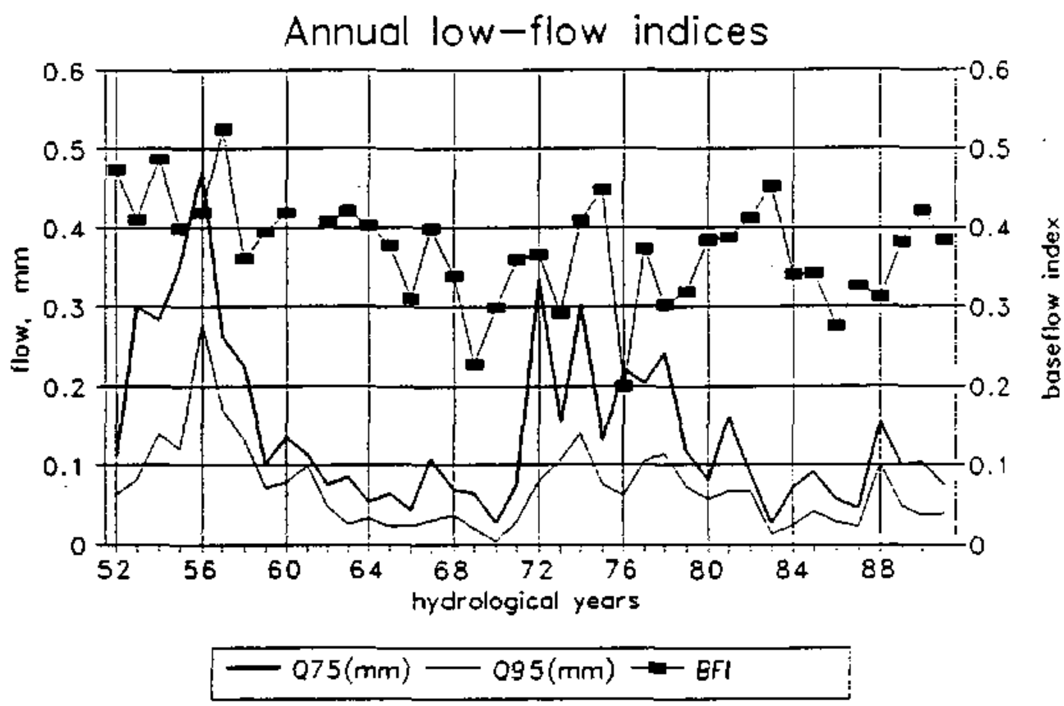


Figure F2.38. Gauge B7H004

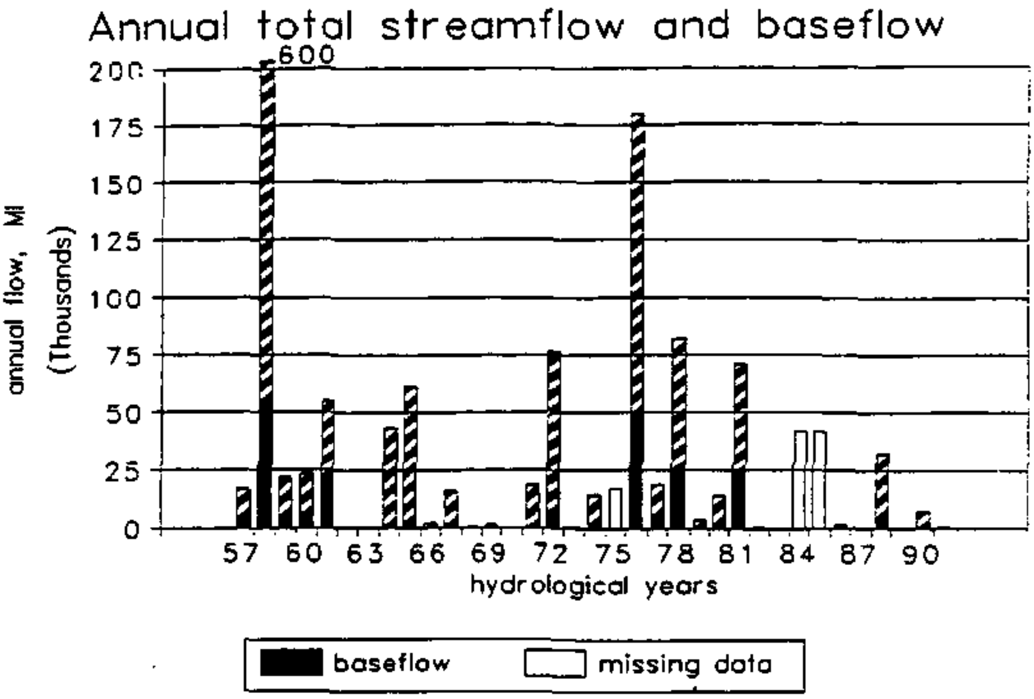
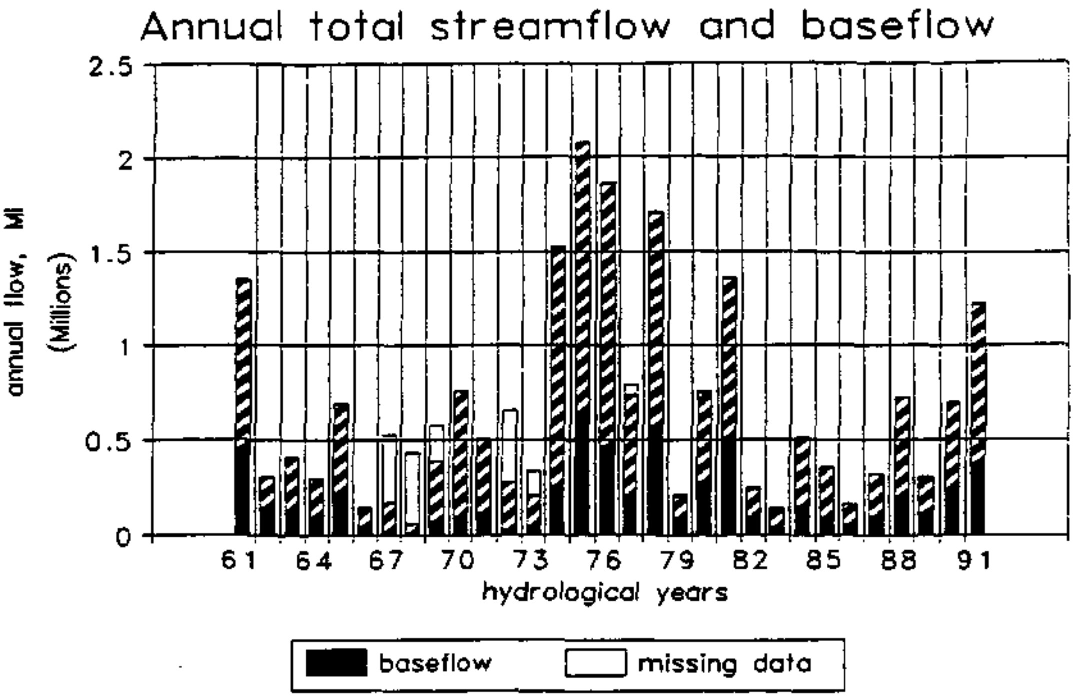


Figure F2.39. Gauge B7H008



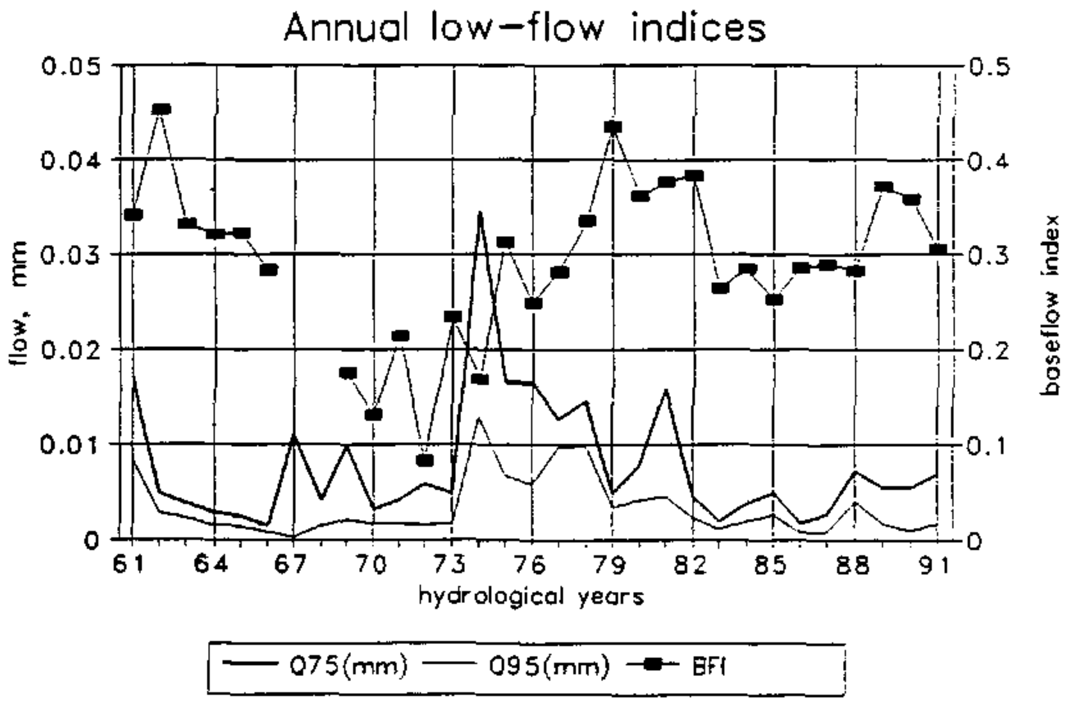
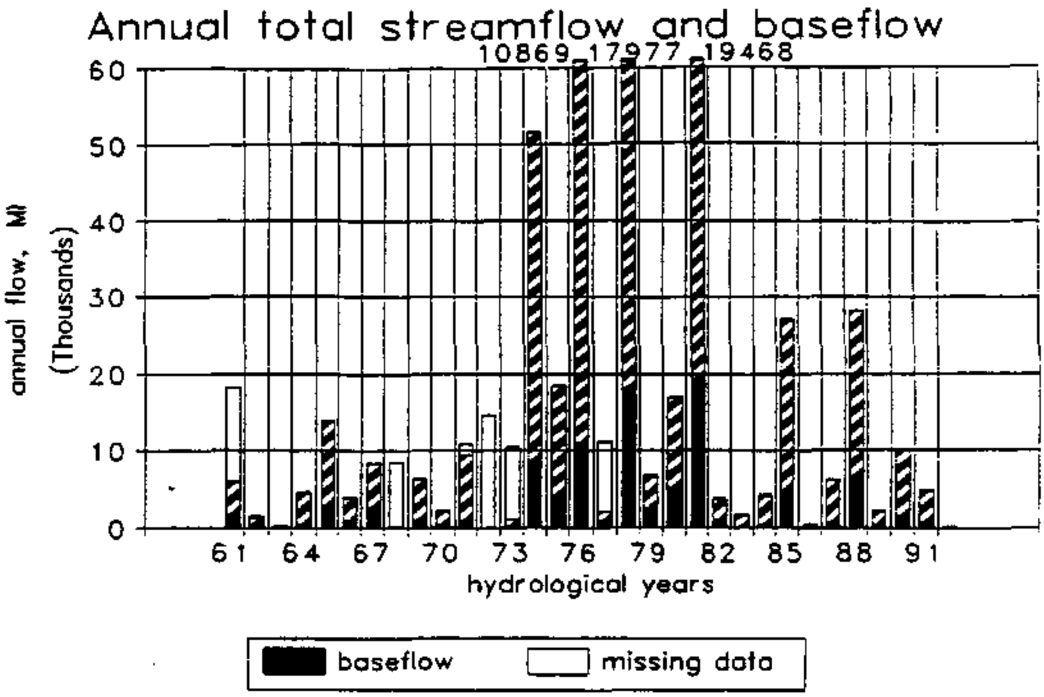


Figure F2.40. Gauge B7H009



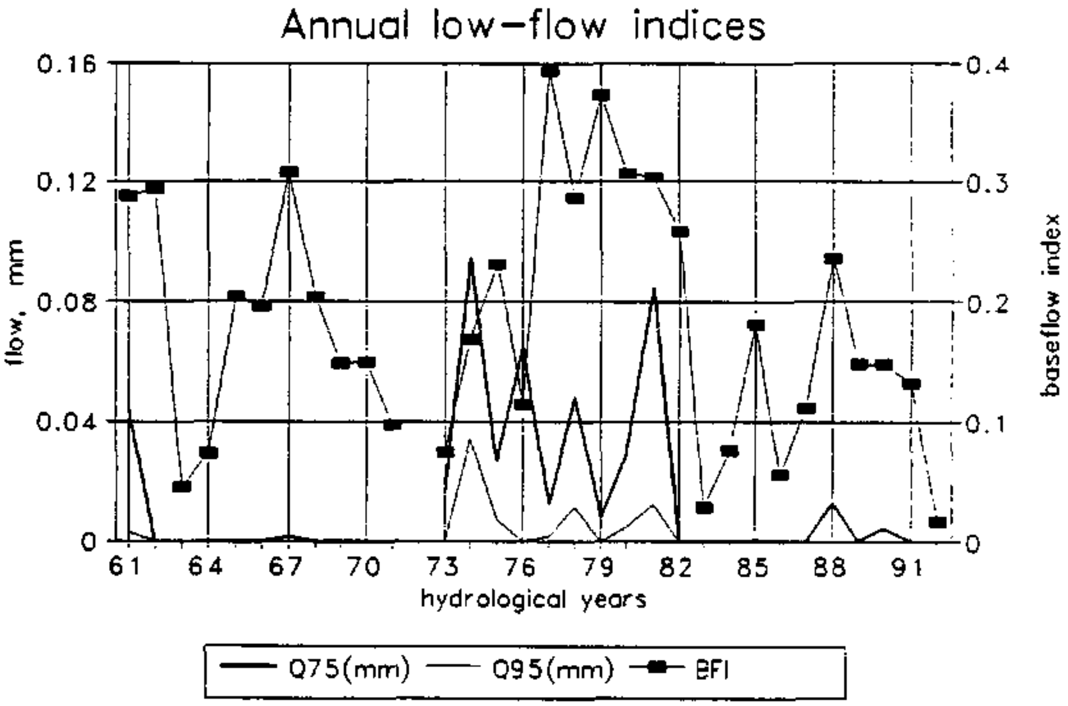
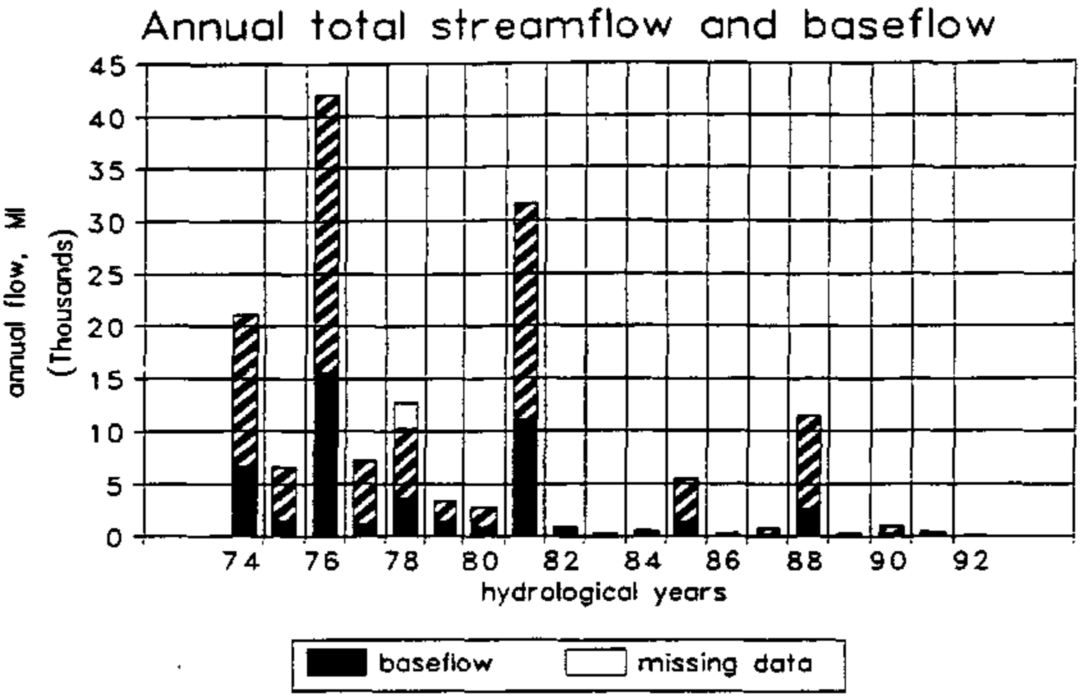


Figure F2.41. Gauge B7H010



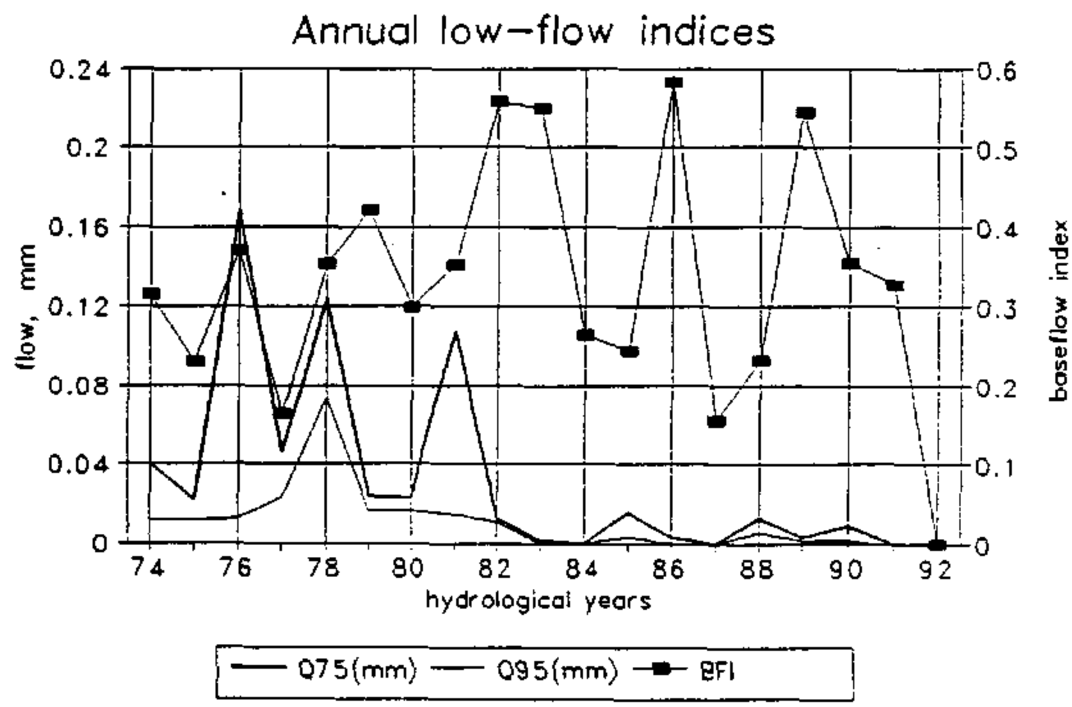
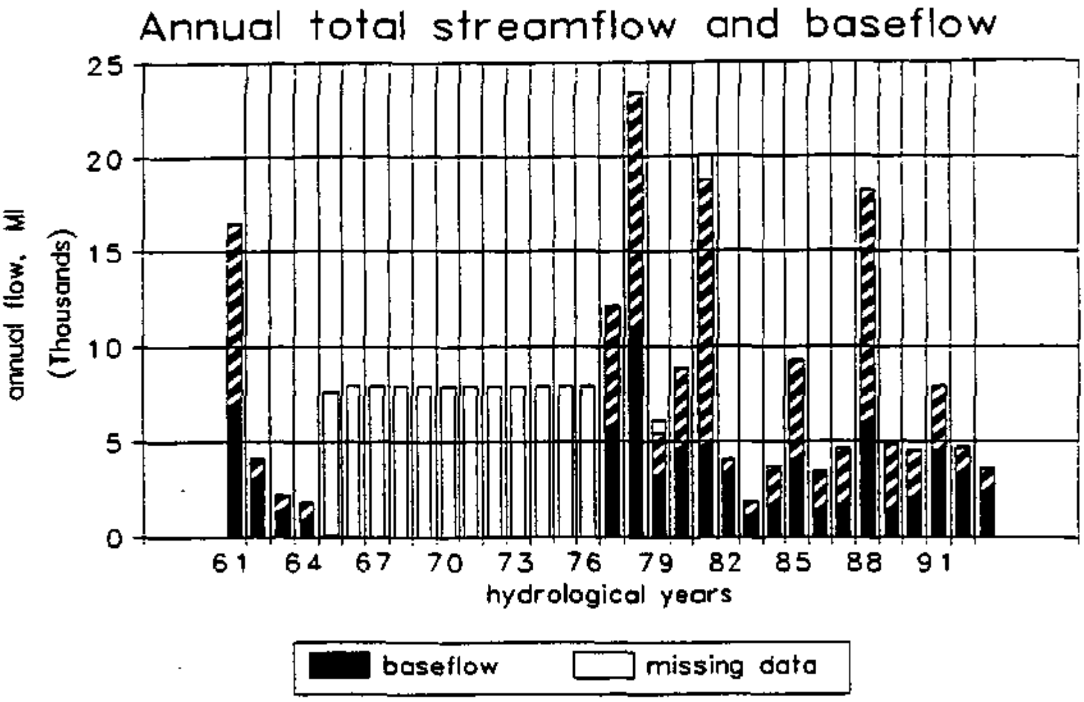


Figure F2.42. Gauge B7H014



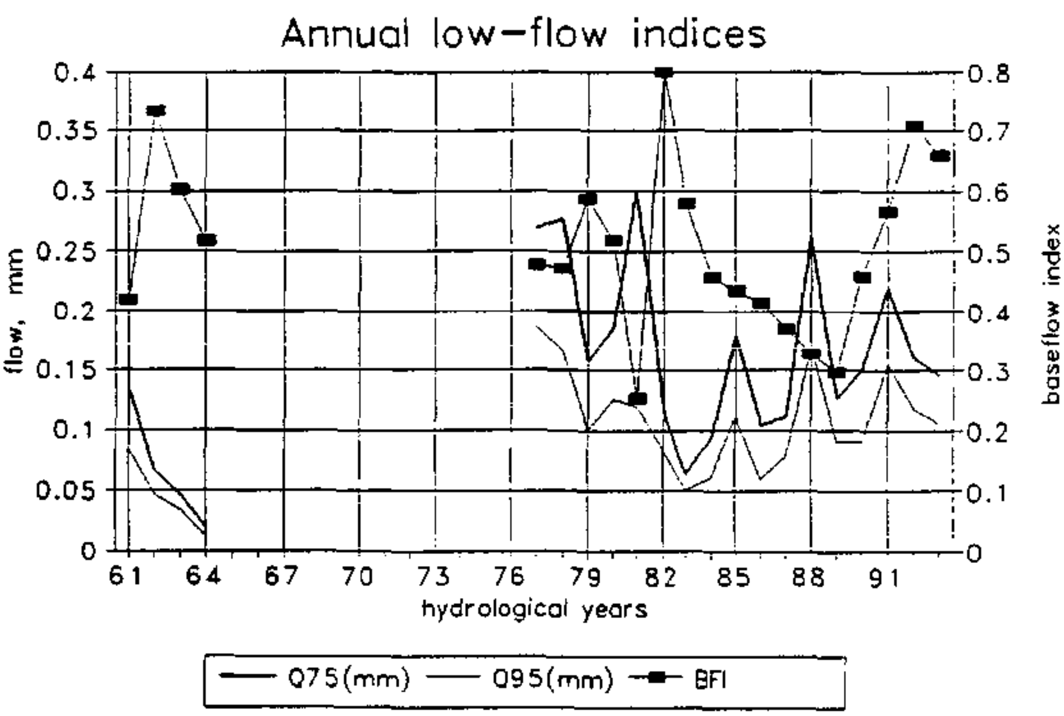
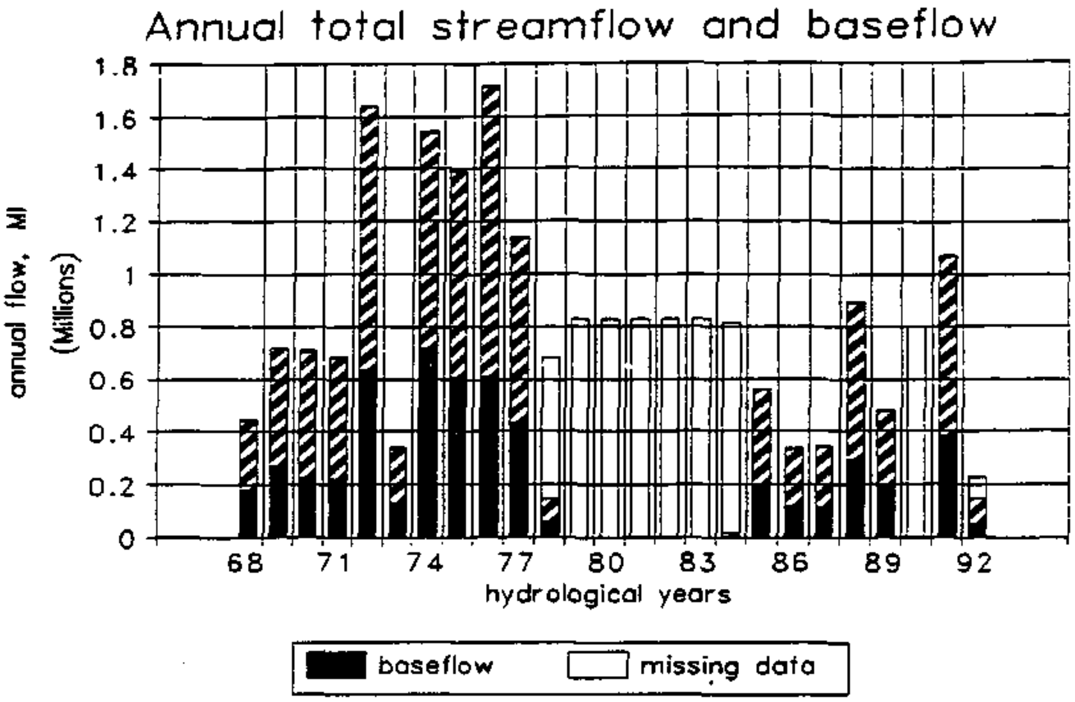


Figure F2.43. Gauge B7H002



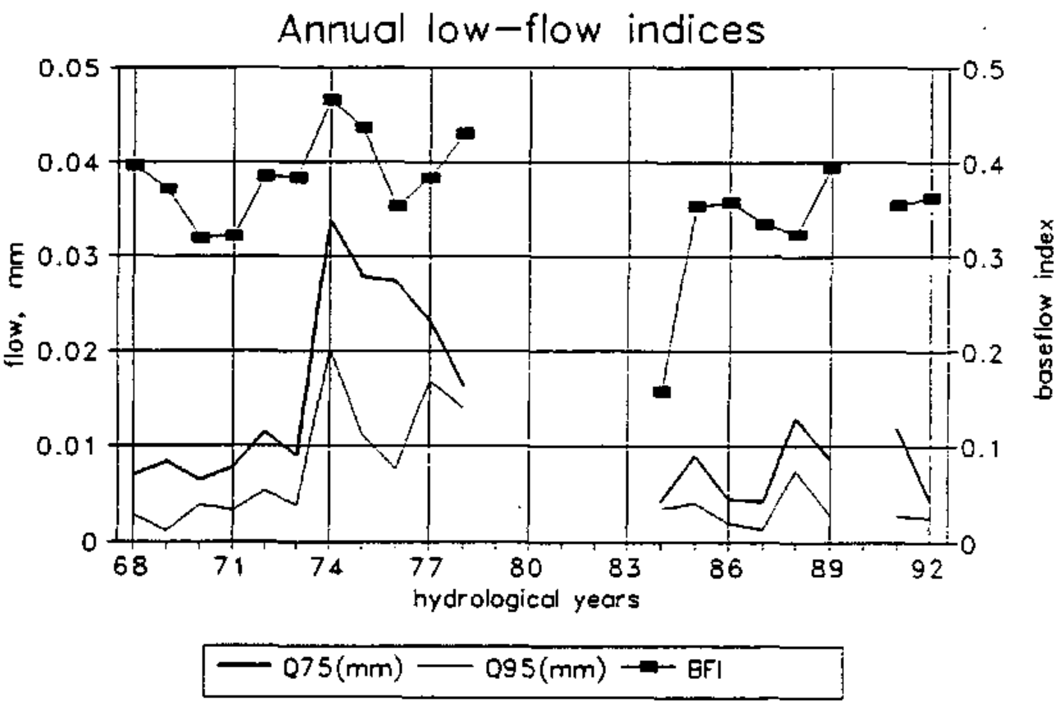
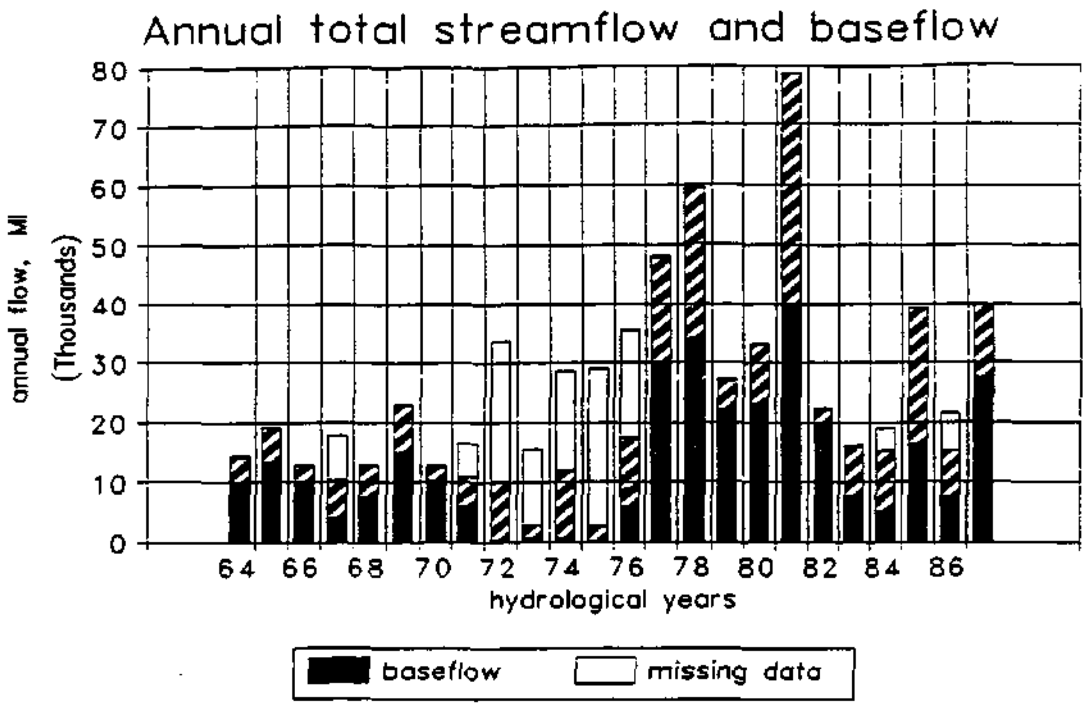


Figure F2.44. Gauge B7H007



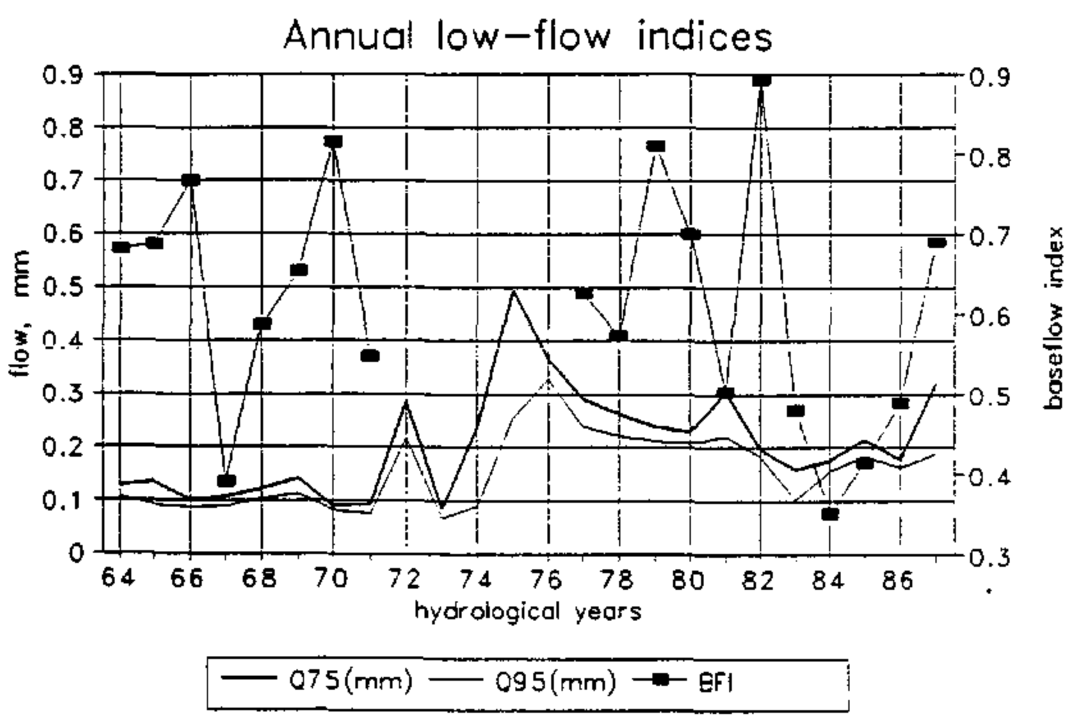
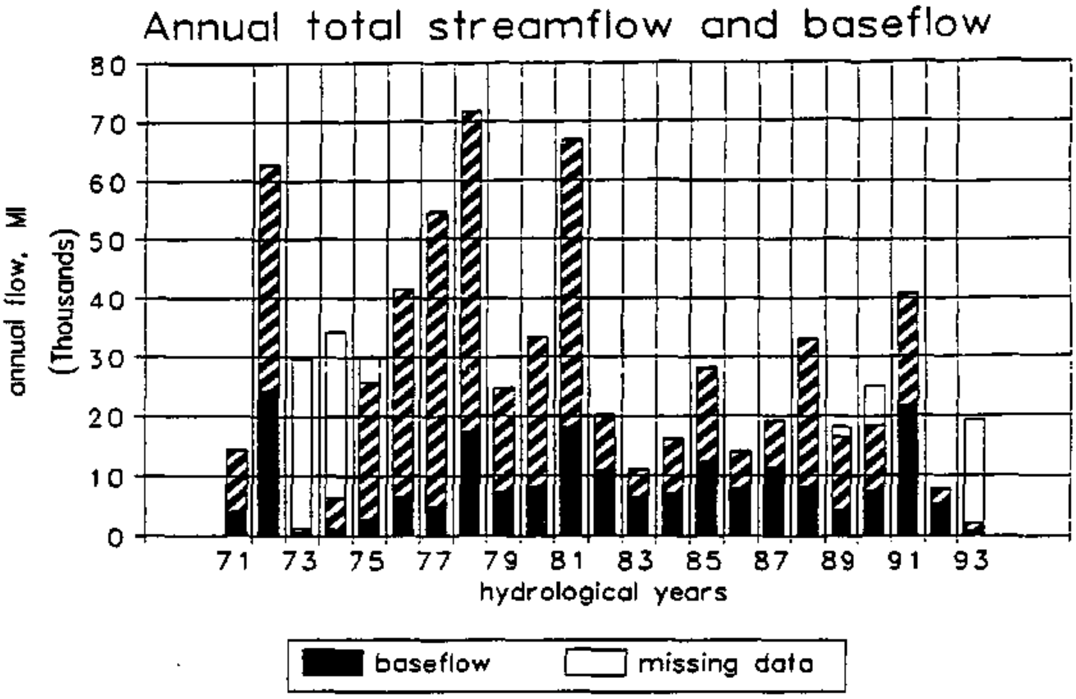


Figure F2.45. Gauge B7H011



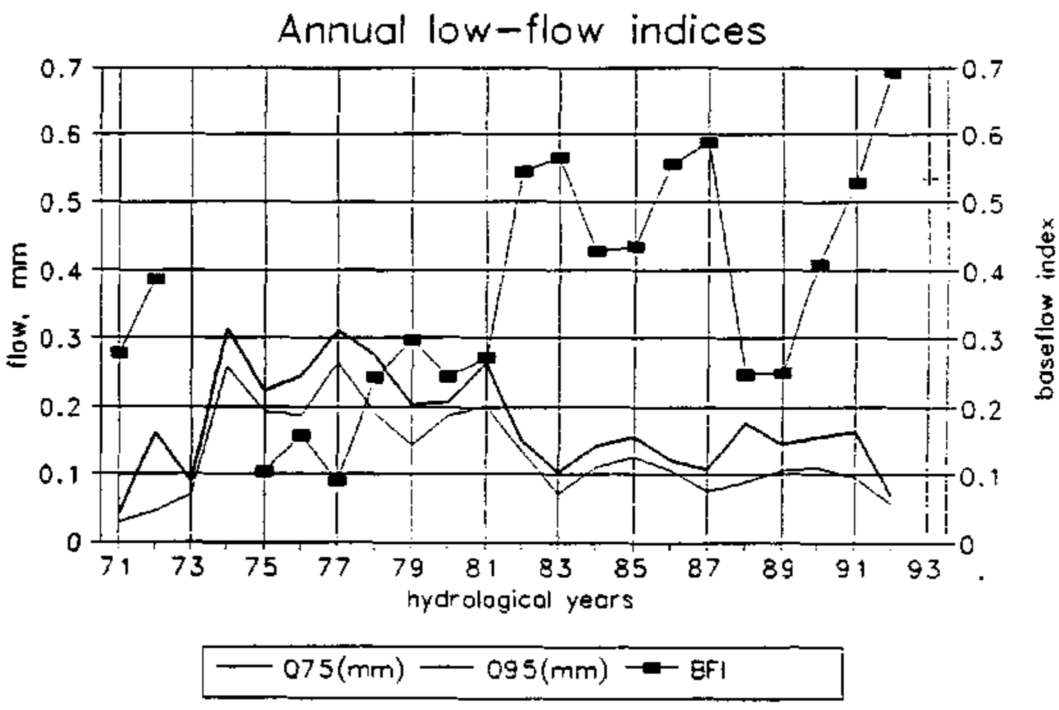
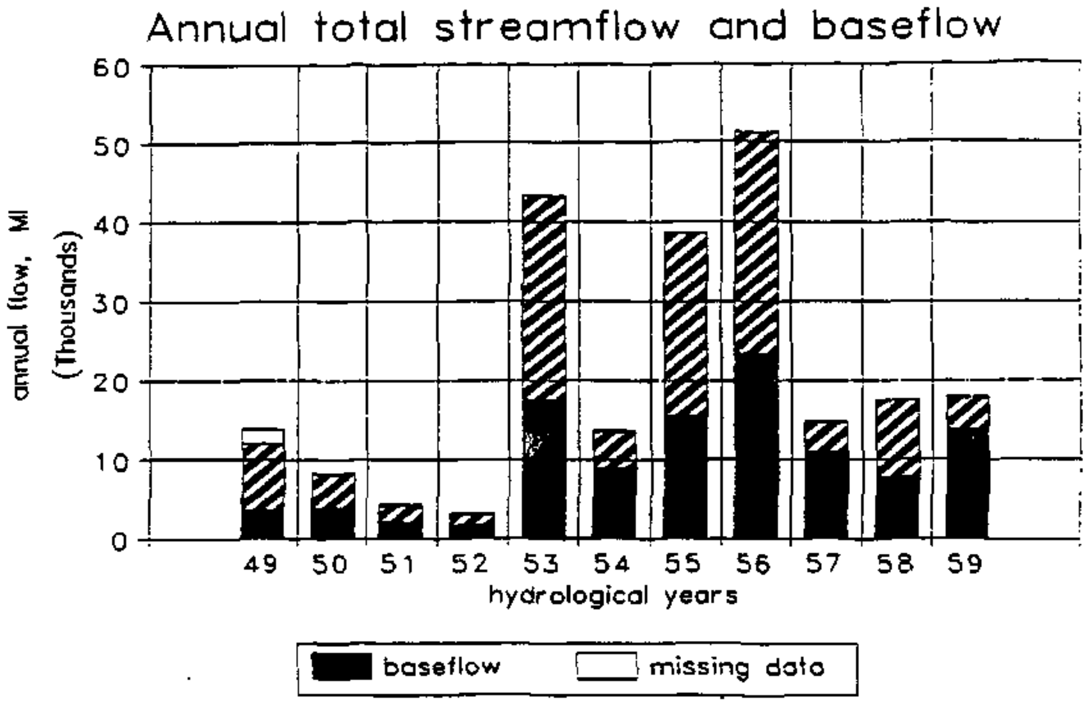


Figure F2.46. Gauge B7H013



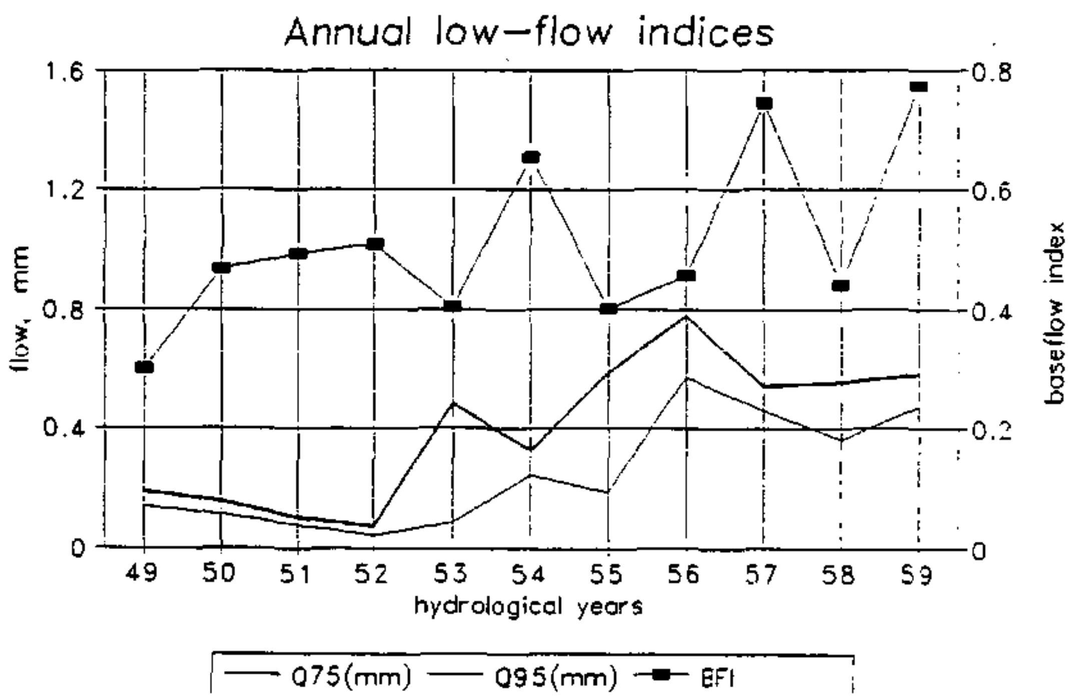


Figure F2.47. Gauge B7H023