Preliminary analysis of low-flow characteristics of South African rivers

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Abstract

Information on low-flow characteristics is required for many research, design, planning and management purposes in both water quality and quantity fields. The paper examines different user requirements for low-flow information and describes the set of automated procedures for low-flow analysis developed by the Institute for Water Research which estimate various low-flow indices of different time exceedance and frequency, analyse the duration and deficit of consecutive low-flow events, calculate recession and baseflow characteristics of a stream, etc. The paper also refers to some aspects of the spatial variability of low-flow indices in South Africa.

Nomenclature

ADF	:	average daily flow
BFI	:	baseflow index - the ratio of baseflow to total streamflow;calculated by baseflow separation techniques for a year or several years of daily flow record
MAM1	:	mean annual 1-d minimum flow; calculated from a series of daily minima extracted from each year of flow record
MAM10, MAM30	:	mean annual 10-d (or 30-d) minimum flows; calculated from a series of 10-d (or 30-d) averaged minima extracted from each year of record
MAR	:	mean annual runoff
MMDEF50	:	mean of annual maximum deficits built during consecutive low-flow events below a referenced discharge of 50% of ADF
MMD50	:	mean of annual maximum durations the river continuously stays below a referenced discharge of 50% of ADF
REC50	:	50 percentile recession ratio estimated from a distribution of ratios of current discharge to the discharge one day previously
Q75, Q90, Q95	:	flows extracted from flow duration curve and exceeded 75, 90 and 95% of the time respectively.

Introduction

The frequent droughts in South Africa place the efficient utilisation of water resources in sharp focus, highlighting amongst others, problems associated with the hydrology of rivers and catchments during periods of limited flow. Low-flow hydrology poses a variety of questions, the most general ones being :

- What is the best way to quantify low flows in different regions of the country and for different purposes?
- How should changing low-flow conditions at different scales be represented?
- How sensitive are low-flow regimes to various anthropogenic effects and physical processes in the catchment?
- How should low flows for natural conditions be estimated when most of the observed records include at least some anthropogenic effects?
- How should the low-flow characteristics of ungauged streams be estimated when no flow records are available?

Different specialists in water-related fields may have different answers, perceptions and requirements for low-flow information. The term "low flows" could mean different things to different interest groups. To many it may be considered as the flows occurring during the dry season, while others may be concerned with the length of time and the conditions occurring between flood events in semi-arid flow regimes. Consequently, there exist a broad variety of measures and indices which have been presented in the literature (Beran and Gustard, 1977; Institute of Hydrology, 1980; Task Committee, 1984; FREND, 1989) and which potentially can be used for characterising low flows in South Africa.

Recently there seems to be a tendency to encourage specialists dealing with low-flow problems to communicate using common terminology. To support and promote this tendency the variety of existing low-flow criteria, potentially required in different water-related areas, should be assessed and evaluated in a local context. It also seems logical that the following basic steps should be undertaken before extensive low-flow studies are undertaken in South Africa.

- Examine the state-of-art of low-flow hydrology in South Africa and specify the requirements of all potential users of low-flow information.
- Develop a multipurpose tool which allows the low-flow characteristics required by different water-related disciplines to be estimated.
- Examine the variability and sensitivity of different low-flow characteristics and decide what is the most appropriate time and spatial resolution to be used.

The paper refers to these three issues and describes some results obtained from initial attempts to address them.

Low-flow survey

In order to define the community of users of low-flow information, to outline the problems experienced in low-flow hydrology and to

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Received 22 September 1994; accepted in revised form 14 February 1995.

clarify the requirements of users and ways of improving data acquisition, the Institute for Water Research (IWR) conducted a survey on low-flow information requirements during 1993. The questionnaire was directed at different institutions in South Africa and several neighbouring countries - water authorities, engineering consultants, research groups and environmental bodies. The set of issues raised in the questionnaire was designed to cover a wide range of low-flow problems. It 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. Of the 58 questionnaires sent out, 20 replies were received (34% return rate). Of the 20 respondents, 8 are researchers, 8 engineers and 4 university lecturers. These respondents represent 8 universities, 7 consulting agencies and 2 government departments (in South Africa and Namibia). The authors assume that these respondents and institutions can be considered to represent 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, 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

Seventy per cent 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. Generally, most of the respondents felt that the duration, frequency and magnitude of low-flow events already cover the range of low-flow characteristics. Both monthly and daily data are the most common required time resolutions of low flow with a slight preference for daily data.

Application of low-flow data

Eighty per cent 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.

Alternate methods used when low-flow information is not available

Seventy per cent of the respondents tend to use (or construct) generalised or regional relationships, 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%).

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 as to between natural low flows and low flows influenced by abstraction and/or augmentation. The need for natural low-flow characteristics was emphasised.

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. Sixty five per cent of the respondents would like to have standard procedures for low-flow analysis. Many respondents stressed the necessity to develop regionalised relationships between low-flow characteristics and catchment or climatic parameters, while others considered that low flows should preferably be addressed in terms of deterministic modelling.

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) is 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.

It has also 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.

There were requests to standardise 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 database 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.

Low-flow analysis software

The results of the survey imply that a software package is required to calculate the variety of low-flow indices from data sets of different size and time resolution. Such software has been undergoing development at the IWR. It includes the construction of flow duration curves along with facilities to extract related flow duration indices, different types of analysis of consecutive low-flow intervals and deficiency volumes (spell analysis), low-flow frequency analysis, procedures to calculate baseflow and recession characteristics and some other options. While some of these methods (flow duration curves and spell analysis) are applicable to more than just low flows and could meet the requirements of those users who are interested in analysing the characteristics of several different aspects of the complete flow regime of a river, others are related directly to low flows (low-flow frequency analysis, baseflow and recessions).

The modules are written in 'C' code, make extensive use of computer graphics, are entirely menu driven and designed to be part of the HYMAS package - Hydrological Model Application Software - which has been developed at the IWR and represents a flexible environment in which to set up and run hydrological models and to analyse observed and simulated hydrological variables. The current version of the software for low-flow calculation together with HYMAS has already been distributed to several research institutions and consultancy companies in South Africa. Most of the low-flow procedures and some of their applications have already been described by Smakhtin and Hughes (1993) and only a brief summary and some recent developments are given here.

The majority of the analyses can be carried out using the complete time series available or a shorter period within it. Similarly, all months of the year or specific months can be selected for analysis.

Flow duration curves

The flow duration module allows flow duration curves to be constructed for data with daily, monthly or a variable time resolution. 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 (or months). The flows for the curve may be expressed in the original data units or as percentages of mean flow. 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 co-ordinates of the curve can be written to a file or printed for further analysis if required.

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 the duration and the deficit (deficiency flow volume) which would be required to maintain the flow at a given threshold. Spell analysis deals with the frequency distribution of these two variables and treats them separately.

The software includes two different modules 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. The actual flow volumes during the dry spells can also be extracted. This option gives an impression of spell variability, or how responsive the river is, and the cumulative frequency curves may be perceived as showing the probability that a low-flow sequence below the selected threshold will last for a given duration (or longer). The module is conveniently linked with the flow-duration curve from where the set of threshold discharges can be selected.

The second part of spell analysis deals with the annual series of maximum spell duration and deficiency 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 thresholds are selected from a menu of fixed values representing percentages of either mean daily (daily data) or mean monthly (monthly data) flow. The analysis, as in all previous cases, may be carried out for specific months or seasons and for any part of the entire time series.

Low-flow frequency analysis

This module analyses the annual flow minima series and is applicable to the full range of data time resolutions. A moving average approach is provided to allow minima of 3 to 183 d duration to be estimated. The flows may be expressed either in actual data units or as a percentage of mean daily/mean monthly flow (depending on the data used). The program optionally fits the Weibull distribution to the data which is often referred to in the literature as being the most acceptable for analysis of low-flow extremes (at least in case of daily data -FREND, 1989; Institute of Hydrology, 1992;). The program allows the construction of up to 5 low-flow frequency curves at a time (for the same river but for minima of different averaging intervals). It also calculates ordinary sample statistics and calculates the absolute minimum flow for the period of record in use.

Recession analysis

This module works only with daily data and includes two options. The correlation method (Beran and Gustard, 1977) is used to estimate the baseflow recession constant and half-flow period (time required for the baseflow to halve). The second method involves the calculation of "recession ratios" - the ratios of the current discharge to the discharge n-days (usually 1 d) ago. The ratios are calculated for all recession periods found in a record for each day when discharge is less than ADF. These ratios are used to construct a frequency diagram and a cumulative frequency curve from which the ratio exceeded by 50% of recession ratios (REC50) is derived. This index shows the average rate of recession and can clearly illustrate the differences in recession rates for catchments with contrasting geology for example (FREND, 1989), or serve as a criterium of the representativeness of low flows simulated by any daily model (Smakhtin and Hughes, 1993).

Baseflow analysis

The baseflow analysis is confined to the separation of baseflow from the original streamflow hydrograph. Two separation techniques are used and designed to estimate the baseflow on a continuous basis (for a year or for the whole record) rather than for a single event. The methods involved do not attempt to simulate actual baseflow conditions but are aimed at the derivation of an objective index related to general baseflow response. This baseflow index is calculated as the volume of baseflow divided by the volume of total streamflow and has been widely used in low-flow studies elsewhere (Institute of Hydrology, 1980; 1992) to illustrate the effect of catchment geology on low flows.

The first separation method uses a set of automatically determined "nodal points" - the ends of known recession periods, where the quickflow is assumed to be zero and thus discharge is generated by baseflow only. The program simply interpolates between these values to obtain the values for the other days. The second method makes use of a digital filter originally used in signal analysis and first introduced to hydrology by Nathan and McMahon (1990). The filter separates "high-frequency" quickflow from the original streamflow. The difference between these two variables gives the estimate of "low-frequency" baseflow.

Flow cycles

This is a simple facility for plotting annual flow volumes as a time series. 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 the mean annual flow); differential mass flow curves (the cumulative deviation from the mean annual flow); and normalised differential mass flow curves (the cumulative deviations from the mean 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, the cyclical structure of annual flows to be examined, dry and wet periods to be detected, and fluctuations of annual flows for rivers with different variability to be compared.

This program also gives the user an 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 thus showing "bad years" if any. This allows the user to decide what period should be used in further analysis.

Monthly distribution

This option allows mean monthly flow totals to be plotted either in Mℓ or as percentages of MAR. It also calculates and plots coefficients of variation (CVs) for each month's flow. The means and CVs 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 especially while working with a large number of gauging stations. It can also be potentially used to analyse the monthly distribution of other hydrological variables - included in the model output files for example.

Residual flow diagrams

This module provides a straightforward and yet very illustrative facility to look at the changing flow (not only low-flow) conditions at different positions within a catchment. Initially, a data file containing the same flow index (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.

Residual flow diagrams were originally used by Pirt and Simpson (1983) for the analysis of low flows in the Trent River catchment in the UK. In the IWR low-flow software the format of the diagrams is slightly different and is designed to be applicable to observed, simulated and mixed data sets. Residual flow diagrams are mostly useful for analysis of 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. The options associated with this module are currently being extended to improve flexibility.

Estimation of low-flow indices

The low-flow estimation methods described (except the last two) 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 and develop the low-flow software on different subsets of daily data with different characteristics.
- 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 grow as data from more stations are processed. It may then be used in management practices, by aquatic scientists, or for large-scale regional analysis of low flows if such studies are required at a later stage.
- 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.

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 South African gauging stations which record reasonably natural flow. 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. The stations selected were generally situated upstream of all major impoundments or abstractions and had a mean record period of 20 years. The data for all these stations were tested for non-homogeneity at UCT and all non-homogeneous stations were excluded from the calculations of low-flow indices to ensure that the indices extracted represent stationary regimes.

Since some of the flow gauging stations had short periods of record (less than 15 years) the estimates of low-flow indices might not represent "true" low flows if the record span falls entirely within either wet or dry flow cycles only. To ensure that the low-flow estimates are reasonably reliable, the annual flows for stations with short periods of record have been compared with longer annual series from one of the nearby stations using the annual flow cycle analysis briefly described in the previous section. In most cases the examined data sets were demonstrated to be suitable for the estimation of most of the low-flow indices. Stations with fewer

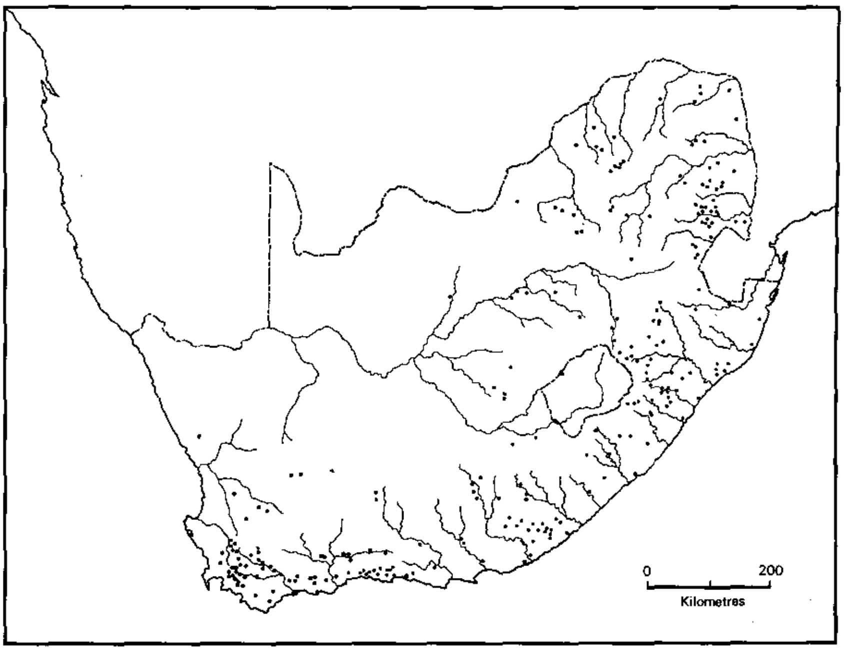

Figure 1
Flow gauging stations used for estimation and mapping of low-flow indices

than 10 years of record were not used in estimations of low-flow frequency and spell frequency indices. In total, about 240 gauging stations were used in the analysis and subsequent mapping of the indices (Fig.1).

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 exceedance. Of these, the 95 percentile flow (Q95) is commonly used to distinguish between drought and non-drought conditions and in some countries (UK) for surface water licensing policies. It may also be considered as a good criterium for water quality dilution calculations with the implication that downstream water quality will decrease below prescribed values on about 18 d/a on average. Q90 is sometimes assumed to be a rough measure of the groundwater contribution to streamflow (Searcy, 1959). The ratio of Q90/Q50 can provide an estimate of the slope of the lower part of the duration curve and may represent the proportion of streamflow originating from subsurface stores, excluding the effects of catchment area. The problem with indices of high percentage of time exceedance is that many rivers in SA have relatively long zero-flow periods and lower percentile flows (for example, Q75) may be of greater value. The extracted indices were expressed in cubic meters, percentages of average daily flow and millimetres per day from a unit area of the catchment. For each gauge the percentage of time at zero-flow conditions has also been estimated as a measure of the degree of flow intermittency.

Spell indices provide additional information about the duration characteristics of a stream as they refer to continuous periods below (in a low-flow context) any particular flow value of interest through the period of record. Spell analysis may further indicate acceptable rates of waste disposal into the stream, allowable abstractions, basin water withdrawals and are considered by the authors to be of value for the specialists dealing with instream flow requirements, designing water supply schemes, etc. The indices extracted describe the frequency of occurrence of spell maxima below threshold flows of 80, 50 and 20% of ADF (the duration of spells was expressed in days and the deficiency volumes in Mℓ, and percentage of MAR). The means of annual spell duration maxima as well as spell deficit maxima and spell indices for several return periods have also been calculated.

Low-flow frequency analysis was confined to the estimation of mean annual minima of 1, 7, 10, 30 and 60-day duration and events with return periods of 5 and 10 years. The indices were calculated in cubic meters and then normalised by the ADF and catchment area.

Estimation of the recession characteristics of the stream was limited to the REC50 since estimates of recession constant by the correlation method appeared to be rather subjective and time consuming. Both baseflow separation techniques were used in the derivation of a baseflow index and both were found to produce generally acceptable baseflow hydrographs (Smakhtin and Hughes, 1993). Digital filtering nevertheless has a tendency to overestimate the baseflow index especially for highly intermittent streams as it often creates excessive baseflow for isolated relatively short-term flood events. The method of nodal points may underestimate baseflow for sluggish (slow response) streams or streams with long flood events. In general terms, both methods may be used equally well for streams with frequent short-term floods. For streams with long duration floods preference should be given to the digital filter approach, in other cases the nodal points method is acceptable.

Mapping of low-flow indices

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 gridding procedures are provided to create a regular grid of a specified density (the detailed description of these methods may be found in SURFER, 1990).

A series of draft maps have been constructed for each low-flow index considered. 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. Small- and medium-size catchments (with an area less than 1 000 km^2) dominated the data

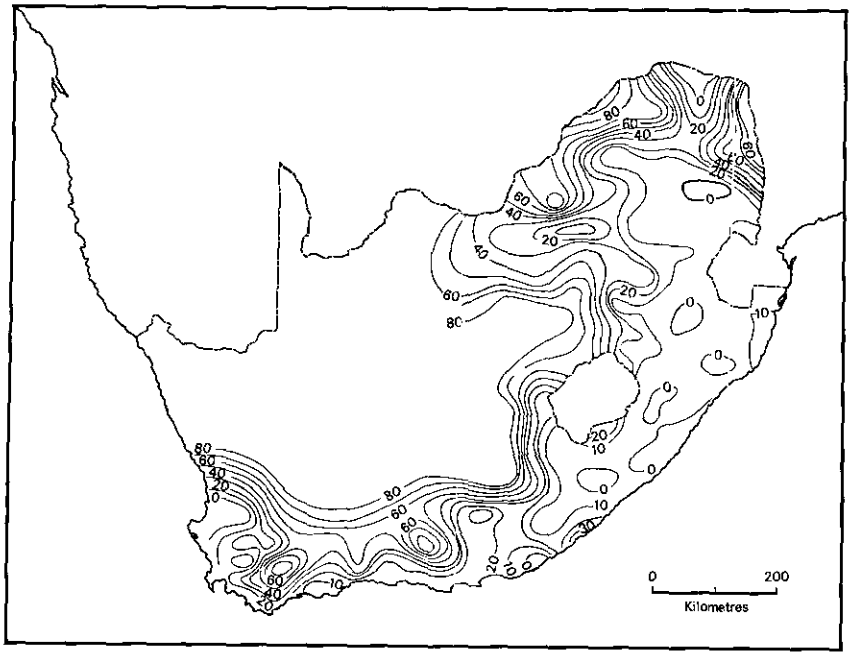

Figure 2
Spatial distribution of the percentage of time with zero flows

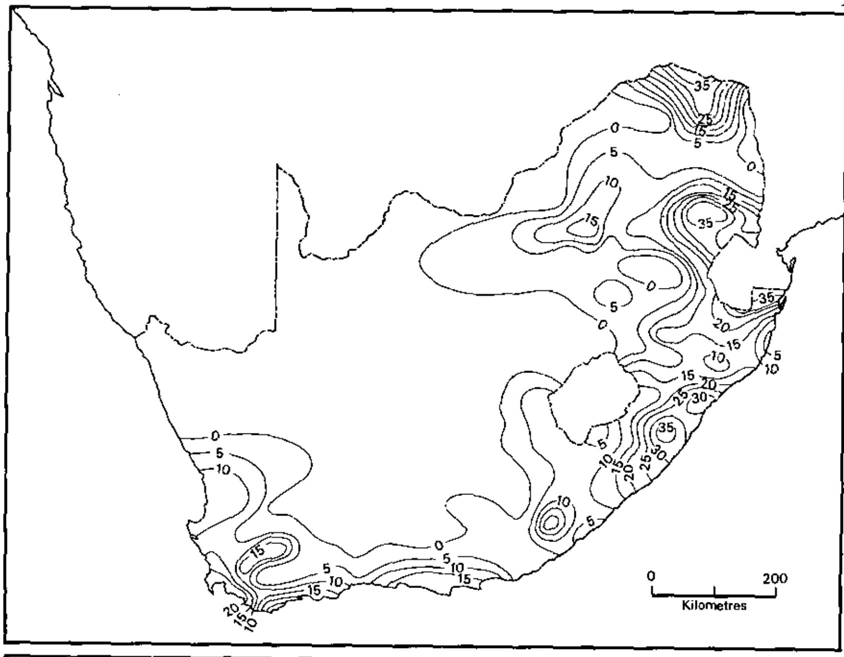

Figure 3
Spatial distribution of 1-day 75-percentile flow (percentage of ADF)

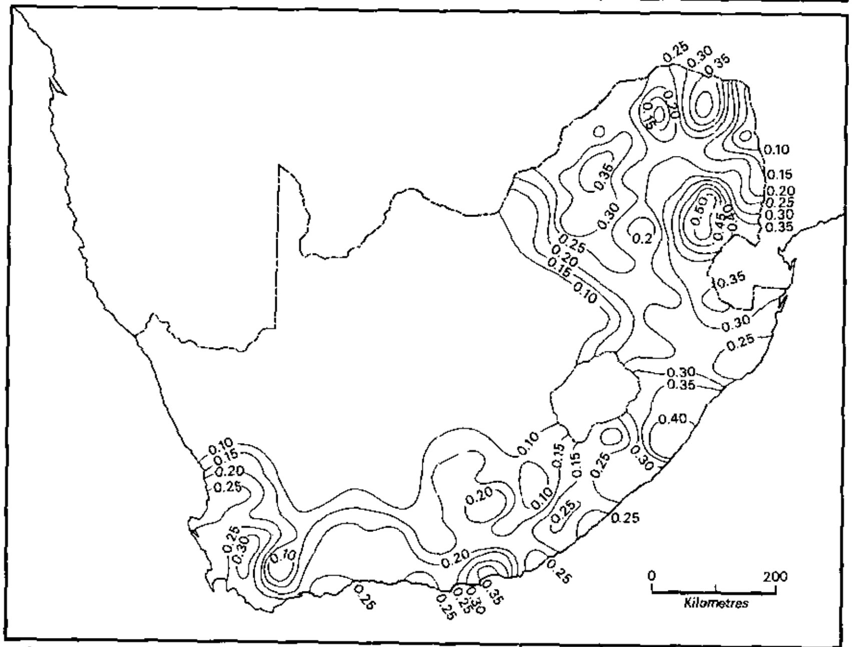

Figure 4
Spatial distribution of baseflow index

set used for mapping purposes. All the rivers with catchment areas of more than 10 000 km^2 were excluded from the mapping procedure. The catchments with areas in the range 1 000 to 10 000 km^2 (about 40 rivers) have been used mostly in the regions of scarce data if they were not regulated, were found to have stationary flow records and were not suspected to cause regional anomalies. The exclusion of more rivers led to the reduction of the initially small data set and was found to result in physically less meaningful maps. The resultant set of maps has been redrawn manually for better presentation.

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 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 Eastern Transvaal 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. 2). 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 Eastern Transvaal 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 Organisation (1974) like "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 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-d flow equalled or exceeded 75% of the time (Q75) is obviously restricted to the regions with predominantly perennial streamflow regimes (Fig. 3). 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 ADF. They increase to 30 to 35% of ADF in the coastal part of Natal while the highest values occur in the Eastern Transvaal (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. 4) 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 Eastern Transvaal (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 1).

TABLE 1
SPATIAL VARIABILITY OF SELECTED NATURAL LOW-FLOW INDICES IN SA

Low-flow index	Mean	Standard deviation	Coefficient of variation
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

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 MAM10, expressed as percentage of ADF, is shown in Fig. 5. 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 the EasternTransvaal. The pattern corresponds reasonably well with the baseflow index (Fig. 4) throughout most of the country, emphasising 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-d minimum flow) 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

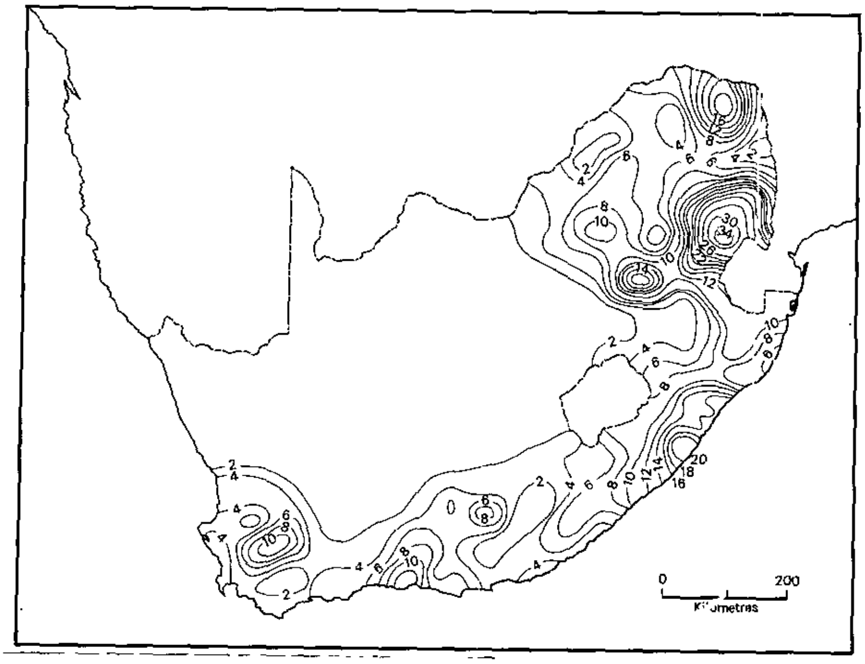

Figure 5
Spatial distribution of mean annual 10-day minimum flow (percentage of ADF)

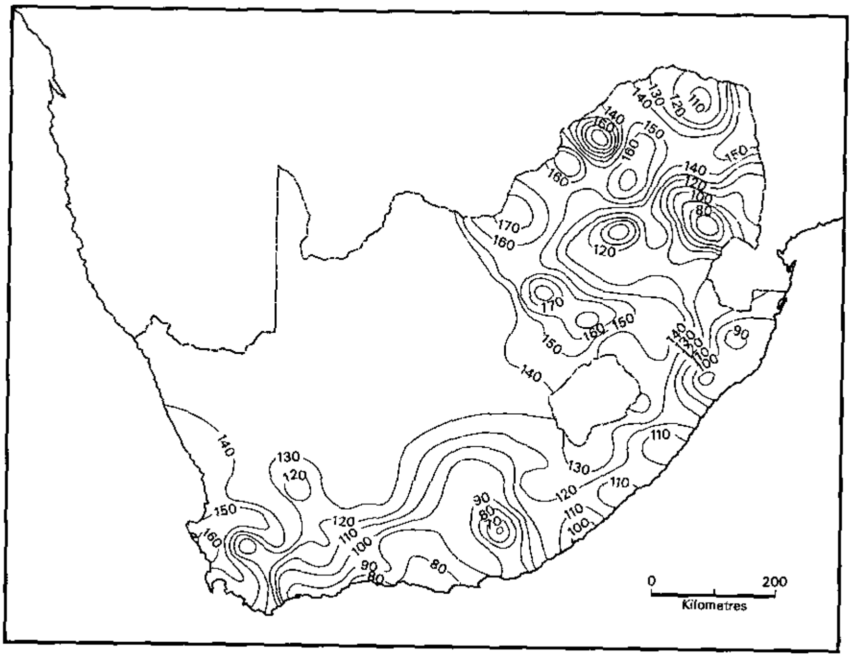

Figure 6
Spatial distribution of mean annual maximum duration of low-flow spells below 50% ADF (days)

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 Fig. 6 and Fig. 7 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 d 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 d 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 old Transvaal. For the threshold of 50% ADF, the mean maximum duration of spells in these regions varies from as little as 50 to 60 d to as large as 160 to 180 d, 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 1).

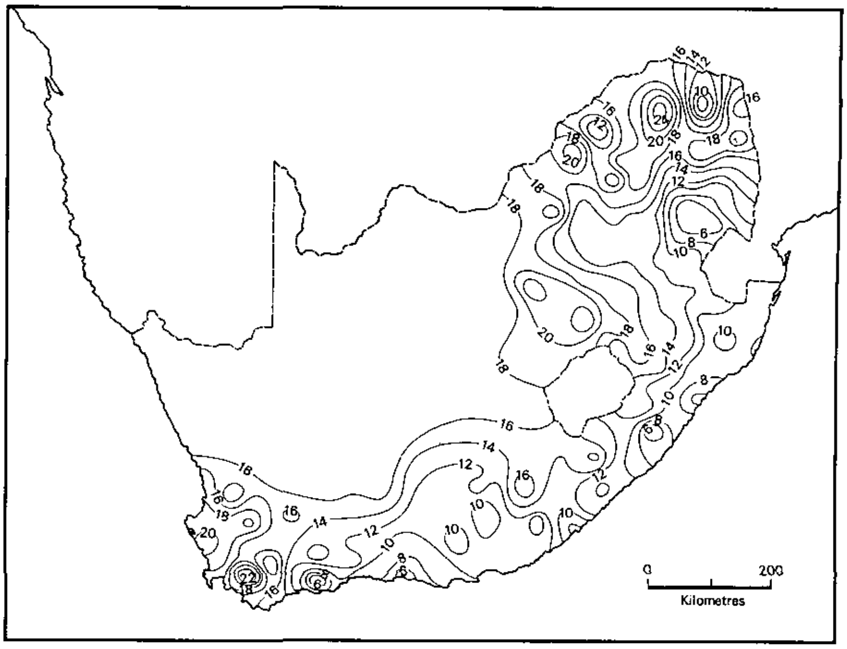

Figure 7
Distribution of mean annual maximum deficiency volume below 50% ADF (percentage of MAR)

Conclusions

A survey of low-flow information requirements allowed the community of potential users to be defined, helped to clarify their requirements and highlighted the need to improve data acquisition.

To meet the needs of different water-related fields facing low-flow problems, a set of automated procedures for low-flow analysis has been developed. The techniques involved work with data sets of different origin, quality, and time resolution. They allow various low-flow characteristics (duration and frequency of low-flow events, baseflow conditions, etc.) to be estimated. The software has been intensively tested on a large number of daily data sets from different parts of the country in the process of estimating various low-flow indices. Several subordinate routines (annual flow cycles, monthly distribution, residual flow diagrams) have been developed to support the low-flow analysis.

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 regionalise 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. This also implies that the development of low-flow prediction methodology, either on a national or 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 this 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.

Further research is currently concentrated on low flows within several major river basins drawn from different parts of the country (Tugela in KwaZulu/Natal, Olifants and Sabie in the Eastern Transvaal, Fish in the Eastern Cape, Gourits in the southern Cape, Berg in the Western Cape). This research is 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 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.

Acknowledgements

The authors gratefully acknowledge the financial support of Water Research Commission. We thank all the respondents to our questionnaire. We thank Dr J King and Mrs Alison Joubert of the Freshwater Research Unit at the Zoology Department, University of Cape Town for their valuable assistance in the identification of the set of flow gauging stations used in that preliminary analysis. The authors are grateful to the Department of Water Affairs and Forestry for supplying the daily flow data used in this study.

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