Methods of catchment-wide assessment of daily low-flow regimes in South Africa

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Abstract

The high spatial variability of South African river flow regimes and varying availability of streamflow data imply that different methods for estimation of low-flow characteristics are required in different regions of the country. The paper introduces a catchment-wide approach for low-flow assessment and examines the applicability of various techniques for a daily low-flow estimation in South African context. The methods considered include: the application of a deterministic semi-distributed rainfall-runoff model, the spatial interpolation of observed flow records in a catchment, the regionalisation of 1 d flow duration curves and the extraction of daily low-flow characteristics from widely available synthetic monthly streamflow data time series. The advantages and limitations of each method are described using the example applications in several river catchments which differ in physiographic conditions, degree of man-induced changes and availability of hydrometeorological data.

Introduction

South Africa faces a number of problems related to 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 severe stress, water pollution becomes critical and extremely difficult to manage. In the past, more emphasis has been placed on water resource assessment for bulk water supply, which deals with large storages sized in accordance with multi-year droughts of particular return period. Consequently, seasonal low flows frequently remained outside the scale of interest. Developing concepts of streamflow management for environmental purposes as well as the focus on small (i.e. rural) water supply schemes have recently started to attract a growing attention to the low-flow part of a continuous streamflow hydrograph.

There does not seem to exist a clear cut-off point where low-flow conditions can generally be considered to start and therefore the term 'low flow' means 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, etc. Consequently, South Africa does not have the established objective guidelines as to what low-flow 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. The *Government Water Supply and Sanitation Policy* (DWAF, 1994) recommends that rural water supply 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). The viability of the proposed afforestation in a catchment is assessed by the Department of Water Affairs and Forestry (DWAF) using the concept of Mean Annual Low Flow. The latter is defined as the mean of the driest 25% of monthly flows in a standard 70 year (1920 - 1990) simulated flow record (the approach follows on from the one developed by Scott and Smith (1997)). *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, in many water-related fields the preference is often given to a complete representative streamflow time series from which a variety of low-flow characteristics describing different aspects of a low-flow regime of a river may be estimated.

Water resource assessment in South Africa has traditionally been based on monthly streamflow time series. Monthly flow time series are available from various Basin Study and System Analysis Reports commissioned by the DWAF as well as from the widely used *Surface Water Resources of South Africa* (Midgley et al., 1994). The latter contains detailed synthetic information on monthly flow characteristics for each of 1946 small drainage subdivisions - the so-called quaternary subcatchments with an average area of about 650 km^2. Low-flow estimation from monthly time-series information is normally performed using regional Deficient Flow-Duration-Frequency curves also presented in Midgley et al. (1994). However, the increasing importance of water quality and ecological considerations has led to the requirement for more detailed daily flow information.

The primary source of daily streamflow information is the observed flow records. However, the direct use of these records is frequently hampered by their inadequate quality. Also the availability of such records varies significantly in different parts of the country. These two factors limit in South African context the possibilities for the development and application of regional

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regression models widely used for low-flow assessment elsewhere (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 an integrated approach to catchment water resources planning and management.

The present paper describes different ways of low-flow assessment in South African context and provides example applications of these methods in selected South African catchments drawn from different parts of the country.

Software for low-flow analysis from time-series information

Low-flow estimation relies on the availability of either observed or simulated daily streamflow time series. To allow various low-flow characteristics to be extracted from the time series, several low-flow estimation techniques have been computerised. Low-flow estimation software forms part of the more general in-house developed computer package HYMAS (HYdrological Modelling Application System). HYMAS offers a flexible environment in which to set up and run various hydrological models and to analyse observed and simulated hydrological variables (Hughes et al., 1994). HYMAS was originally a DOS based system written in ‘C’ code. Its DELPHI-Windows version is currently under development.

Low-flow analysis software includes the following modules:

- Flow duration curve construction (along with the interactive facility to determine numerically the flow rate and the percentage of time this rate is equalled or exceeded).
- Different types of analysis of continuous low-flow intervals and their deficient-flow volumes (spell or run analysis).
- Analysis of frequency of extreme low-flow events.
- Procedures to separate baseflow from the total continuous daily streamflow hydrograph and to estimate related baseflow characteristics.
- Procedures to calculate recession characteristics of a stream (recession constant, half-flow period, distribution of recession rates).

Some of these methods (flow duration curve, spell analysis) are also applicable to analysing different aspects of the complete flow regime of a river, the others are related to low flows directly. The majority of the analyses can be done using the complete time series available or a shorter period within it. Similarly, the analysis can be performed for all months of a year or specific months or seasons. Some of the techniques are applicable to both monthly and daily streamflow data. A number of other routines is provided for plotting annual streamflow totals, analysing monthly streamflow distribution, construction of residual flow diagrams etc. The system allows a variety of analyses to be efficiently performed, which is important for processing a large number of observed or simulated data sets. Details of low-flow estimation software have been described by Smakhtin and Hughes (1993) and Smakhtin et al. (1995).

Low-flow estimation from simulated time-series

The VTI daily rainfall-runoff model

The in-house developed Variable Time Interval (VTI) model (Hughes and Sami, 1994) has been intensively used for the catchment-wide assessment of low-flow conditions. The VTI is a semi-distributed physically based model which describes the following catchment hydrological processes: interception, rainfall intensity controlled runoff, soil moisture redistribution and saturated surface runoff, evapotranspiration, various surface-subsurface water interaction processes, catchment routing including depression and small dam components, channel transmission losses and flow routing. The model has a modular structure where each module describes a separate component of hydrological cycle. The model runs within the HYMAS environment.

A catchment in the model is represented by a set of homogeneous subareas. Most of the model parameters can be derived from physical catchment characteristics. The variability of hydrological processes within each subarea is described by means of probability distribution functions of some model parameters. The subarea average rainfall input data for each subarea are calculated using the information from the nearby rainfall gauging stations, co-ordinates of these stations and co-ordinates of subarea centres by means of inverse distance squared interpolation procedure. The model normally operates with a daily time step equal to input data time resolution.

The relative contribution of low-flow generating mechanisms (e.g. spring flow, groundwater seepage) to the total streamflow hydrograph differs in different parts of the country and may be described by calibrating relevant parameter values. However, it is important to ensure that the model adequately reproduces these mechanisms. The ability of the model to simulate different aspects of low-flow regimes has been specifically examined in several catchments in South Africa which represent different physiographic environments and are characterised by different low-flow responses (Smakhtin et al., 1998).

Example applications

In the context of low-flow studies the model has been applied to the Sabie catchment in Mpumalanga Province, the Berg catchment in the Western Cape and several major tributaries of the Tugela River system in KwaZulu-Natal (Fig. 1).

The Sabie River catchment stretches from the Drakensberg mountains in the west to its confluence with Incomati River in Mozambique. The catchment can be categorised into two distinctive topographic regions. The upstream region consists of undulating to very steep topography, while in the middle and lower reaches the catchment is predominantly flat. Climatic conditions are closely associated with topography. In the upstream parts of the catchment the mean annual rainfall (MAP) increases rapidly with altitude due to orographic effects and reaches the maximum of 2 000 mm. In the lower reaches the MAP is about 600 mm. The region is characterised by summer rainfall, with 75% of the MAP falling between November to March. The average gross Symon’s pan evaporation varies from 1 700 mm in the east to 1 400 mm in the west. The catchment is underlain by several lithostratigraphic units consisting mostly of sandstones, mudstones and shales with dolomites and limestone in the upstream areas. Soils in the upstream parts of the catchment are highly variable in terms of depth, texture and structure due to varying geological substrate and slope conditions. In the lower reaches soils are moderate to deep well drained sandy loams and moderate to deep clayey soils.

The upstream parts of the catchment are extensively used for commercial forestry plantations and irrigation, while the downstream reaches lie within the Kruger National Park. The mining and timber industries account for additional abstractions in the upstream areas. The irrigation demand has resulted in the construction of several medium-sized irrigation dams as well as an extensive network of small farm dams. Direct water abstractions and several domestic supply schemes are also present (Sabie River Water Resources Development Study, 1987). Irrigation has been steadily expanding since the 1950s and that has resulted in increasing water shortages in several tributaries of the Sabie River.

There are 10 flow gauges in the Sabie catchment (Fig. 2). The maximum gauged catchment area (at gauge X3H015) is 5 713 km^2. Most of the gauges concentrate in the upper reaches while the middle and lower reaches of the Sabie River and its main tributaries are not properly gauged. Therefore, low-flow estimation from observed flow records is possible only at a very coarse spatial resolution and low flows in the catchment have been studied using a deterministic modelling approach.

The VTI model was calibrated for several interlinked subdivisions in the catchment against available observed daily data to establish representative model parameter values. Each calibration subcatchment was broken down into several subareas according to tributary structures, variations in geology, land use and rainfall. Calibration of the model was attempted over the period 1979 to 1984, with subsequent verification of the results for 1984 to 1989. The data on water abstractions, dam volumes, forestry etc. were available from the Sabie River Water Resource Development Study (1987). To account for time-dependent changes in water usage during 1979 to 1989, in some cases, water demands and dam volumes had to be changed during the calibration and verification periods.

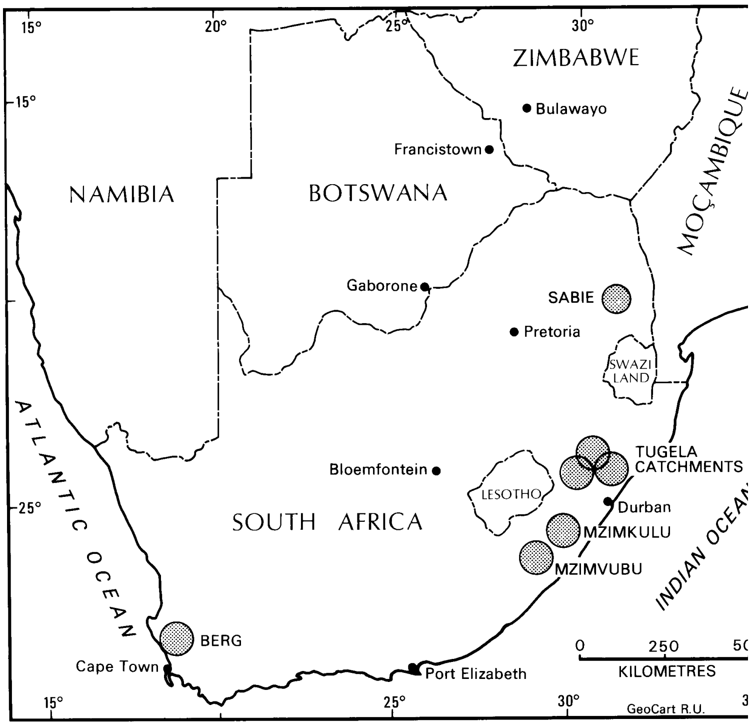

Figure 1
Location of the study catchments in South Africa

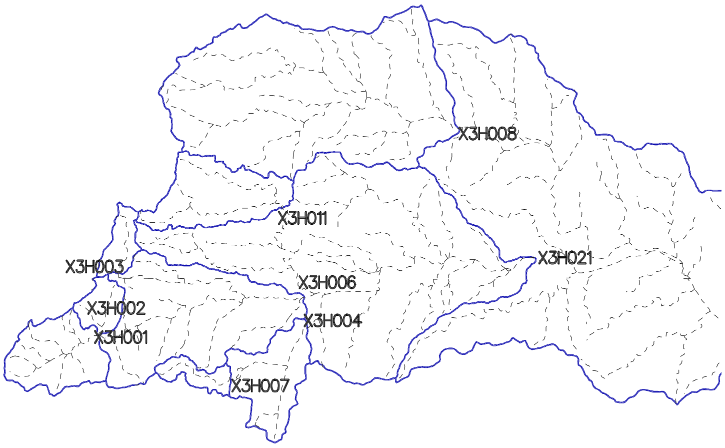

Figure 2
The map of the Sabie catchment showing the stream network, location of streamflow gauges and gauged subcatchment boundaries

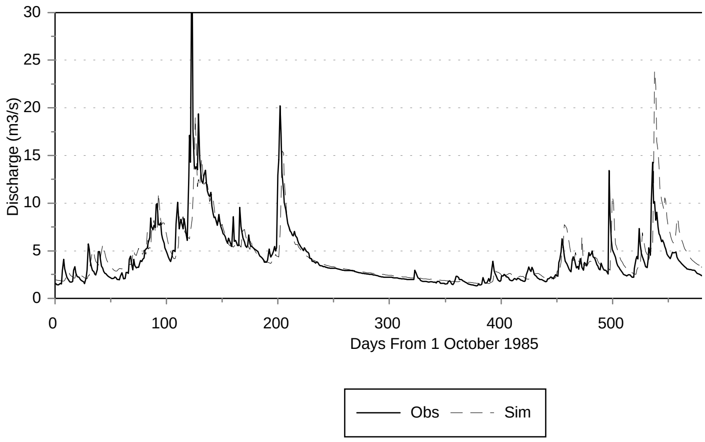

Figure 3
Observed and simulated by the VTI model daily hydrographs at gauge X3H006

TABLE 1
STATISTICS OF FIT BETWEEN OBSERVED AND SIMULATED DAILY STREAMFLOW TIME SERIES FOR GAUGED SUBDIVISIONS IN THE SABIE CATCHMENT

Gauge	Data	Untransformed[1]						Ln transformed					
		Max	Min	Mean	SD	R^2	CE	Max	Min	Mean	SD	R^2	CE
X3H001	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
X3H002	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
X3H003	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
X3H004	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
X3H006	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
X3H008	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
X3H011	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
X3H015	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
X3H021	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

[1] Maximum (Max), minimum (Min), mean (Mean) and standard deviation (SD) for untransformed flows are in m^3/s

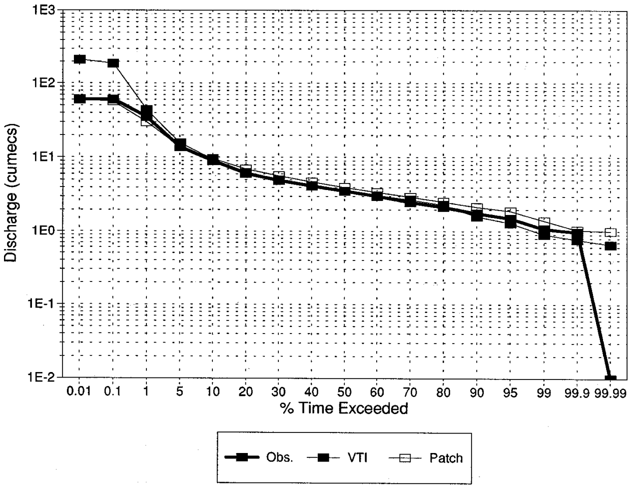

Figure 4
One day annual flow duration curves constructed from observed and simulated data at gauge X3H006 for a period of 1979-1989

A visual comparison of observed and simulated flows demonstrates that in most of the cases good fits have been achieved in terms of hydrograph peaks and shape (Fig. 3) as well as in terms of the flow duration curves (Fig. 4). This is also confirmed by the fit statistics which are the minimum, maximum and mean flow, standard deviation and coefficients of determination (R^2) and efficiency (CE) based on untransformed data as well as natural log-transformed data (Table 1; statistics are given for the whole period of simulation including both calibration and verification periods). R^2 and CE for untransformed flows were in majority of cases in the range of 0.5 to 0.7, but deteriorated in cases when the gauging structures were unable to measure high flows (as illustrated for example by the observed flow duration curve in Fig. 4). However, R^2 and CE for log-transformed flows (which place more emphasis on low flows) normally fluctuate between 0.7 and 0.9 which demonstrate that good simulation in the low parts of daily hydrographs has been achieved.

Once a calibration was completed, the simulation of flow under present-day conditions for the period 1952 to 1992 was performed in order to obtain representative daily flow time series for subsequent low-flow calculations. The daily time-series of flows in natural conditions was also simulated for this period by removing abstractions, dam volumes, afforestation areas from the model parameter set. In addition, simulation of virgin flow

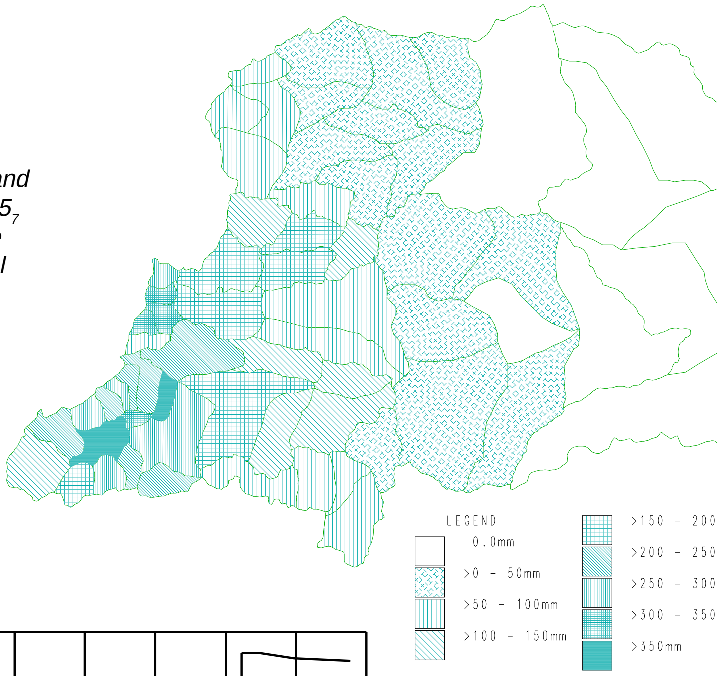

Figure 5
Subarea boundaries and the distribution of Q75$_7$ (mm/a) in the Sabie catchment in natural conditions

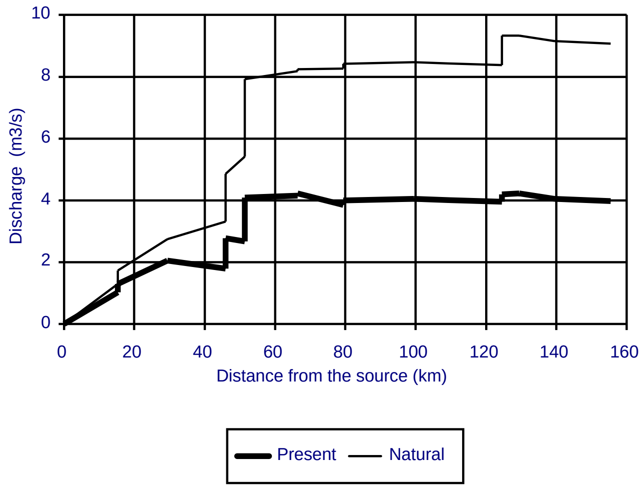

Figure 6
Residual flow diagram illustrating the availability of Q75$_7$ flow in the Sabie River in present and natural conditions

included a change in some vegetation and soil parameters in afforested subareas to account for the lower evaporative demand, lower interception losses of the natural vegetation and lower infiltration capacity of soils under the natural vegetation. These parameter changes are based on existing experience of the VTI model application to experimental catchments in Southern Africa (Hughes, 1997).

The simulated time series for each subarea may be used to calculate the variety of low-flow indices (e.g. those described in Smakhtin et al., 1995). Two such indices of different extremity have been estimated from simulated 40 yr daily flow time series to illustrate spatially changing low-flow conditions throughout the catchment: 7 d average flows exceeded 75 and 95% of the time (Q75$_7$ and Q95$_7$) on the annual flow duration curve. The use of 7 d average flows instead of actual 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 used in some sources for application to the original daily data prior to low-flow estimation (e.g. Gustard et al., 1992). In practice, however, there is very little difference between 7 d and 1 d low-flow indices.

Two different ‘types of flow’ for each exceedence level have been estimated. The first is the flow generated within each subarea (total subarea flow), which demonstrates how much water is actually flowing into a stream channel from an incremental subarea (at the selected level of exceedence) regardless of the upstream inflow to a subarea. This flow has (under 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 main-channel reaches in this subarea. The best way of looking at spatially changing low-flow conditions in the entire catchment is to construct a GIS coverage showing the distribution of estimated low-flow characteristics. Figure 5 illustrates the spatial distribution of Q75$_7$ flow values in natural conditions in the catchment (Smakhtin and Watkins (1997) also provide the actual calculated low-flow values for each subarea).

The second ‘flow type’ is the final routed runoff - the accumulative discharge at the outlet of each subarea. This flow takes into account all upstream inflows into a subarea (if those exist) and has already been subjected to direct abstractions from a stream (under present-day conditions). It therefore demonstrates how much water at a particular location is actually available in a stream channel. The availability of low flows in a river channel is best represented by a residual flow diagram (e.g. Pirt and Simpson, 1983). The example residual flow diagram for Q75$_7$ in natural and present day conditions is shown in Fig. 6 for the Sabie River.

The baseflow in the catchment is generated as springflow (from the forested headwater subcatchments) and from localised aquifers in valley bottoms where saturated conditions exist (in the remainder of the catchment, with predominantly low relief). As rainfall decreases from west to east, the conditions for low-flow generation exist predominantly in the western portion of the catchment. In the downstream reaches of the Sabie River and its main northern tributary, the Sand River (approximately from gauges X3H021 and X3H008 to gauge X3H015, Fig. 2), transmission losses begin to occur as groundwater recharge is no longer sufficient to sustain baseflow. In addition, the presence of

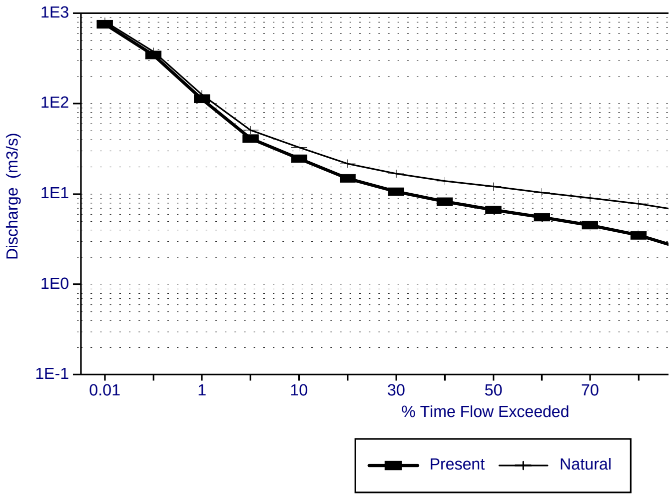

Figure 7
One day annual flow duration curves for the Sabie catchment (gauge X3H021). Constructed using the simulated daily time series.

extensive riverine vegetation (simulated as groundwater abstraction) results in the further depletion of groundwater. These two factors result in a net loss of water compared to runoff derived from upstream sources, hence no incremental discharge is generated within the lower parts of the catchment. This effect is illustrated by both Figs. 5 and 6.

The degree of changes in flow regimes due to various land-use effects and water resource developments can be assessed by comparing 1 d annual flow duration curves representing present-day and natural conditions. This comparison in the Sabie River catchment clearly illustrates that its daily flow regime has been significantly modified with the largest relative effect on low flows (Fig. 7).

The similar approach to low-flow estimation was followed (and similar results - time-series and catchment-wide maps of low-flow characteristics - produced) in the Berg River catchment in the Western Cape (for the gauged catchment area of 4 012 km^2) and in several tributaries of the Tugela River system in KwaZulu-Natal Province (Fig. 1). The parts of the Tugela catchment that have been the subject of simulation include: the Mooi River catchment (the major right-side tributary with the total catchment area of 2 890 km^2), the Sundays River catchment (one of the largest left-side tributaries with a total area of 2 425 km^2) and the central part of the Tugela basin where the river accepts most of its tributaries (the total catchment area of 3 475 km^2).

All simulated catchments differ in physiographic conditions, degree and types of artificial influence as well as in the amount and quality of hydrometeorological information and data on water resource developments which are necessary to calibrate and run the model. Problems related to specifying a representative rainfall input to the VTI model have been experienced in some headwater subareas of simulated catchments (either due to the extremely spatially variable rainfall data (the Berg River), or due to the lack of such data (the Sundays River)).

In addition, the water-use data (e.g. on a number of within-basin and interbasin transfers and abstractions in the Berg River catchment) were often either absent, inadequate or insufficient, which allowed only rough quantification of these effects in several subareas to be made. In some cases these two factors resulted in either over- or underestimation of high flows and slight overestimation of low flows in several subareas of the simulated catchments. Nevertheless, in most of the cases the model performed satisfactorily and proved to be a valuable tool for daily data simulation capable of reproducing different low-flow generation mechanisms. Smakhtin and Watkins (1997) provide the detailed description of the VTI model application and low-flow estimation in the Sabie, Berg and Tugela River catchments.

Low-flow estimation from patched/extended observed streamflow records

Spatial interpolation technique

For basin-wide low-flow analysis from observed records 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. For example, many of the available time series have gaps due to missing data which effectively shortens the record period. The time series at any site may be non-stationary due to time variant land-use effects or water abstraction patterns. This implies that, depending on the degree and the form of the non-stationarity, only part of the whole record is usable or the whole record should be rejected. Also the streamflow time series from different sites within any basin are rarely coincident in time and may represent different sequences of dry and wet climatic conditions.

To make use of observed records for the estimation of representative measures of low-flow characteristics for a number of sites within a single basin, the available records should be patched/extended and made concurrent in time. 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. One way of addressing these problems is to develop some form of spatial interpolation approach that uses the available observed daily data and manipulates them in order to patch the record at any site or extend it beyond the limits of the available (or usable) record period. Such an approach may be simple to use and could be a valuable tool if the interpolation algorithm satisfactorily accounts for non-linearities in the relationship between streamflows at different sites. One such algorithm has been described in detail by Hughes and Smakhtin (1996). This section provides only a brief overview of the developed technique.

The algorithm is based on 12 ‘typical’ 1 d flow duration curves - one curve for each calendar month of the year. The first step in the procedure is to identify relevant ‘source site(s)’ (up to the maximum of five) in the area surrounding the ‘destination

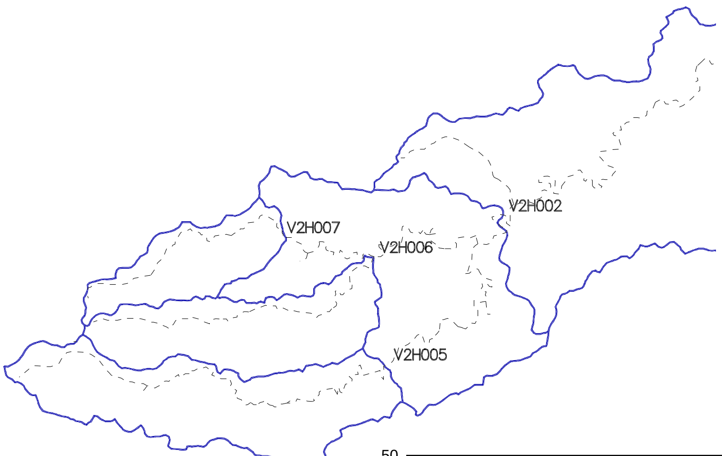

Figure 8
The map of the Mooi catchment showing main streams, streamflow gauge locations and boundaries of the gauged catchments

site' (the record of which is to be patched or extended) and to assign weights associated with the degree of similarity between the 'source' and the 'destination' site's flow regimes. The second step is to generate tables of discharge values for each site and month of the year for 17 fixed percentage points of the flow duration curves. An estimate of the streamflow on any day at the 'destination' site is then made by identifying the percentage point position on the duration curve table (for the relevant month) of the streamflows on the same day at the 'source' sites and reading off the flow value for the equivalent percentage point from the 'destination' sites duration curve table. Each estimate of the 'destination' site flow value is then multiplied by the 'source' site weight and the sum of these values is divided by the sum of the weights. For 'source' streamflows lying between the 17 defined percentage points of the duration tables, logarithmic interpolation is used to define the position. The algorithm has been set up as a model which (similarly to the VTI and some other hydrological models) runs within the HYMAS environment. The output from this model consists of the patched observed flow and the 'substitute' flow time series. The latter represents a time series made up of completely estimated values regardless of whether the original observed was missing or not. The substitute series is used for comparison with the original observed data (in a similar way that simulated series are compared with observed in conventional modelling approaches) to evaluate the quality of the spatial interpolation process as well as associated choice of 'source' sites and weights. The choice of suitable source sites is frequently limited and/or obvious. Also, the algorithm is quick and simple to run and the best weights can be determined through trial-end error type calibration.

Example application in the Mooi River catchment

The Mooi River is one of the largest tributaries of the Tugela River. It originates in the Natal Drakensberg mountains, flows north-eastward and joins the Tugela in its middle reaches. The flow in the catchment is or was (e.g. V2H001) measured at eight gauges with the maximum gauged area of 1 976 km^2. Six gauges may be considered for the application of spatial interpolation technique (Fig. 8). Observed flow records of reasonable quality are available at the five upstream flow gauges. Two downstream gauges contain many gaps due to missing data. Most of the available records are partially coincident in time.

In order to esablish a concurrent, unbroken and satisfactorily long daily time series at the available streamflow gauges, the spatial interpolation algorithm used the gauge V2H002 with the longest and the most reliable record as the 'base' source gauge and its record length of 42 years (1950 to 1992) available at that time, 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) to 1950. The record at gauge V2H004 has been extended backwards from 1960 to 1950 and patched in the latter period. 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 V2H002 and V2H004 have been used to extend the record at V2H001 (weights 0.8 and 0.2). Minor gaps in the record of the 'base' gauge V2H002 itself have been patched using the combination of V2H005 and V2H006 with equal weights.

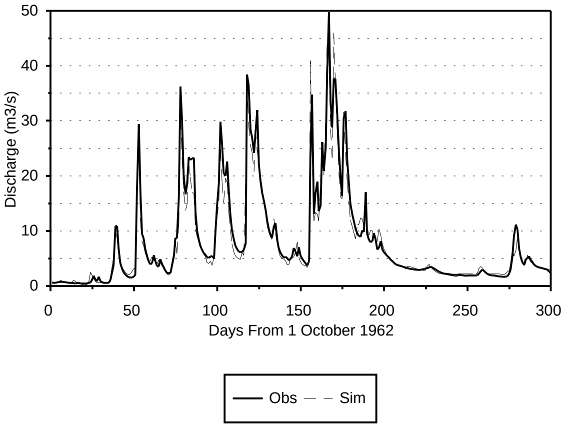

Figure 9
Observed and simulated by spatial interpolation daily hydrographs at gauge V2H004 in the Mooi River catchment

The spatial interpolation algorithm in all the cases performed exceptionally well. The observed and simulated hydrographs (Fig. 9) and corresponding flow duration curves appear to be almost indistinguishable. Table 2 summarises the results of the model application in terms of conventional fit statistics. Statistics for log-transformed flow demonstrate that low-flow parts of the total hydrographs have been especially well predicted.

As in the previous cases described, the $Q75_7$ and $Q95_7$ flows have been extracted from the extended/patched 42 year-long time series. Low-flow indices have been estimated at gauged locations and for incremental areas between gauges. Low flows for incremental area (where it is different from the total) were

TABLE 2
THE RESULTS OF SPATIAL INTERPOLATION OF OBSERVED DAILY STREAMFLOW TIME SERIES IN THE MOOI CATCHMENT

Gauge (period)	Data	Untransformed[1]						Ln transformed					
		Max	Min	Mean	SD	R^2	CE	Max	Min	Mean	SD	R^2	CE
V2H007	Obs	21.3	0.02	0.97	1.67			3.06	-3.91	-0.87	1.24		
(1972-92)	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	Obs	18.1	0.01	1.89	3.37			2.90	-4.83	-0.42	1.47		
(1972-92)	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	Obs	77.4	0.07	3.54	5.82			4.35	-2.70	-0.52	1.18		
(1972-92)	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	Obs	307	0.01	8.61	17.3			5.73	-4.20	1.24	1.33		
(1972-92)	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	Obs	243	0.00	7.95	14.5			5.49	-5.81	1.11	1.51		
(1960-92)	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	Obs	239	0.01	8.18	17.2			5.48	-4.83	1.06	1.45		
(1960-74)	Sim	243	0.03	8.67	16.6	0.72	0.70	5.50	-3.59	1.24	1.35	0.84	0.83

[1] Maximum (Max), minimum (Min), mean (Mean) and standard deviation (SD) for untransformed flows are in m^3/s

estimated by subtracting flow value(s) at upstream gauge(s) from the flow value at the downstream gauge. These flow are equivalent to total runoff from a subarea generated by the rainfall-runoff model. The results of calculations are summarised in Table 3 while the spatial distribution of low flows is illustrated by Fig. 10.

The VTI model applied to the catchment has also been found to perform satisfactorily (both R^2 and CE were normally above 0.6). However, the model generally appeared to overestimate low flows, especially in some upstream areas. Similarly, low flows in the main stream appears to be overestimated by the VTI model at the outlet of the whole catchment. This may be partially attributed to the inaccuracies in the water abstraction information used by the VTI model.

Since the observed historical records form the basis for the spatial interpolation approach, natural low-flow conditions in the catchment may not be assessed. However, the simulated by the VTI model time series for present and natural conditions reveal only slight reduction of streamflow (Smakhtin and Watkins, 1997) and indicate that despite the concentration of small farm dams in upstream areas, water resources throughout most of the catchment at present are only marginally developed.

The application of the method in the Mooi River catchment is only one example of its successful performance. The approach was extensively tested in many locations throughout Southern Africa and was found to perform at least as well as the VTI daily model (Hughes and Smakhtin, 1996). The limitations of the approach are mostly related to the ability to establish representative 1 d flow duration curves for each month of a year, which given the generally available quality of streamflow records in SA, is not an easy task in many cases. It also obviously does not allow assessment of low-flow conditions at the level of spatial resolution achievable through the use of the rainfall-runoff model, since it is by definition bounded to the streamflow gauge locations. It is also (at least at this stage) limited to the estimation at only present-day conditions, which may be represented by historical records if the latter are stationary. To be applicable to ungauged sites, procedures to establish 1 d flow duration curves at such sites should be designed. To be applicable to natural conditions, procedures to 'naturalise' flow duration curves should be developed. Despite these limitations, the algorithm is easy and simple to use and apart from the straightforward patching/extending of observed flow records has many potential applications (e.g. Smakhtin et al., 1997).

Low-flow estimation by regional methods

Regional flow duration curves

Both approaches described above are effectively related to the generation of representative streamflow records from which various low-flow characteristics may be estimated directly. The alternative approach is to use regional estimation techniques which aim at the derivation of some particular low-flow characteristic or general flow measure applicable to any ungauged location in a specified region.

One possibility is the establishment of regional flow duration curves (FDCs). The method includes two major steps: construction of non-dimensional 1 d FDCs for each flow gauge in a hydrologically homogeneous region by dividing discharges from a curve by the mean daily flow and superposition of all individual FDCs in the region on one plot to calculate a composite regional non-dimensional FDC.

Each individual FDC may be constructed using the relevant HYMAS program module which allows an FDC to be calculated from daily (or monthly) streamflow data for the whole period of record or any part thereof, for any of the 12 months of a year, any season or the whole year and allows flows for the curve to be expressed in volumetric or discharge units or as a percentage of

TABLE 3
LOW FLOW INDICES IN THE MOOI RIVER CATCHMENT CALCULATED FROM PATCHED/ EXTENDED FLOW RECORDS (1950-1992)

Gauge	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	109	0.174	0.174 (50.3)	0.098	0.098 (28.3)
V2H006	188	0.233	0.233 (39.1)	0.098	0.098 (16.4)
V2H005	260	0.702	0.702 (85.1)	0.379	0.379 (46.0)
V2H002	937 (380)	1.536	0.437 (35.4)	0.645	0.07 (5.8)
V2H004	1 548 (611)	1.653	0.117 (6.0)	0.451	0.0 (0.0)
V2H001	1 976 (428)	1.358	0.0 (0.0)	0.416	0.0 (0.0)

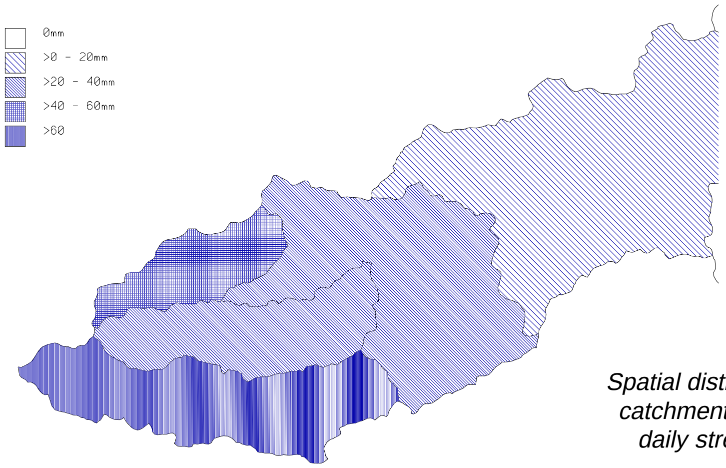

Figure 10
Spatial distribution of Q75$_7$ flow values in the Mooi River catchment estimated from patched/extended historical daily streamflow records for a period of 1950-1992

mean flow (the latter is automatically calculated from the data set in use).

Once the set of regional normalised FDCs (annual, seasonal, or for each calendar month) 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. Mean daily flow can be calculated from the estimates of mean annual runoff (MAR) presented in *Surface Water Resources of South Africa* (Midgley et al., 1994) for all quaternary catchments. The estimation of mean daily flow from the quaternary catchment flow data effectively allows the establishment of regional regression models for the mean flow to be avoided. It also links the method with the results of extensive research work that has already been done at the national scale.

Example application in the T drainage region of South Africa

The DWAF has subdivided the country into 22 primary drainage regions. Low-flow estimation using the method of regional FDCs has been performed in one of them - the T drainage region, that includes the north-eastern parts of the Eastern Cape Province to the south-east of Lesotho (Fig. 1). Most of the rivers in the region are perennial with a clear wet season during December to March followed by a long recession period with minimum flows in July to September. The water resources of the region (approximately 14.5% of the overall country's water resources - Pitman, 1995) are largely undeveloped at present. Limited areas in the north-eastern parts of the region are used for forestry plantations. The population is concentrated in a rural sector with predominant utilisation 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 to meet the requirement of the *Government Rural Water Supply and Sanitation Programme* (DWAF, 1994) and therefore a need for appropriate low-flow estimation techniques becomes particularly relevant.

Non-dimensional FDCs have been constructed for each of the 17 existing gauging stations (Smakhtin et al., 1997) which represent the only source of hydrological information in the entire region. The average observation period at these gauges is about 20 years. For each gauge the curves were constructed 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 the whole year may be split into three major periods: 4 wet (December to March), 4 dry (June to September) and 4 intermediate months (April, May, October, November).

Plots of annual normalised FDCs are illustrated in Fig. 11. The curves lie rather close to each other throughout most of the time scale. The biggest differences 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 picture is similar for all four seasons. The differences in the lowest parts 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

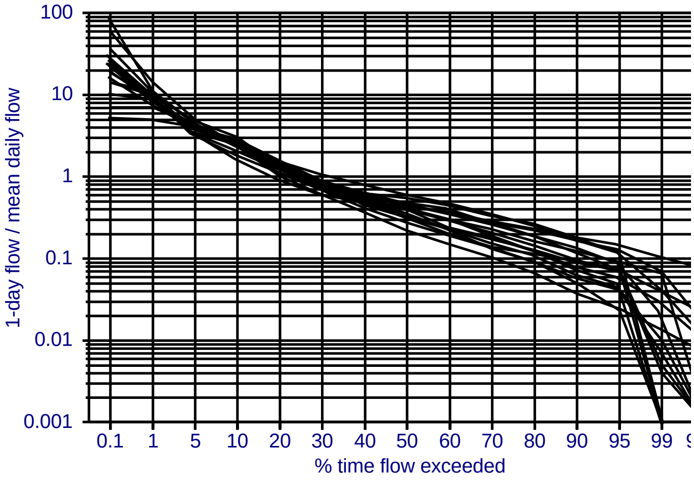

Figure 11
Normalised 1 d annual flow duration curves for streamflow gauges in the T drainage region

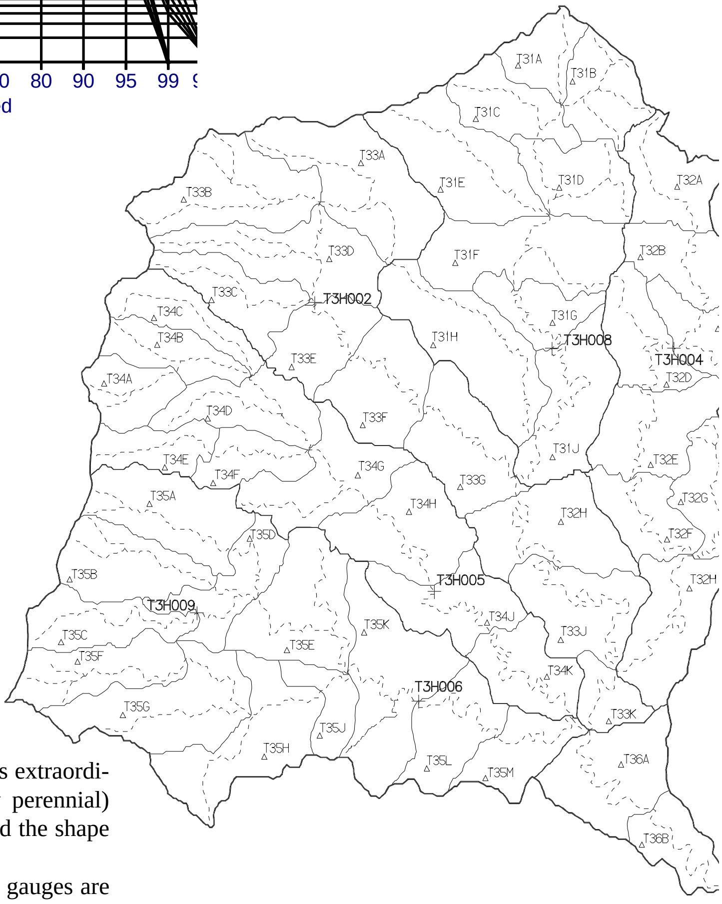

Figure 12
The map of the Mzimvubu catchment showing the main rivers, streamflow gauge locations, quaternary subcatchment boundaries and codes

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 affected the shape of some FDCs in the area of extreme low flows.

As is often the case in South Africa, some of the gauges are rather small to measure high flows and the mean daily flow calculated from the observed records is underestimated even if the gauge has a relatively long observation period. This results in overestimation of the non-dimensional ordinates of corresponding FDCs and, therefore pushes up the upper boundary of the domain of the curves. Such gauges have either been ignored completely or their highest (truncated) ordinates have not been used in the derivation of regional curves.

Low-flow calculations have been performed for two major catchments in the T region: Mzimvubu (catchment area 19 852 km^2) and Mzimkhulu (catchment area 6 678 km^2). For each of the ungauged quaternary subdivisions in these catchments the annual 1 d FDCs have been established by multiplying back the ordinates of the regional curves by the estimate of a mean flow. The latter has been calculated from the estimates of the quaternary MAR listed in Midgley et al. (1994). Since the entire region is in a relatively natural state, the shape of regional non-dimensional annual FDC estimated on the basis of observed flow data would apply for natural flow conditions (for which the estimates of MAR are given in Midgley et al. 1994). However, if water resource development is present, MAR estimates for natural conditions could be adjusted (e.g. on the basis of the catchment development information also presented in Midgley et al.(1994)).

Two low-flow indices have been estimated for Mzimvubu and Mzimkhulu catchment: 1 d Q75 and Q95 flows. The use of 1 d flows as opposed to 7 d average flows used in the previous catchment low-flow studies was dictated by the resolution of the data used to construct regional FDCs. Figure 12 illustrates the existing subdivision of the Mzimvubu catchment area into quaternary subcatchments, while Fig. 13 presents the spatial distribution of Q95 flow values in the Mzimvubu catchment. Smakhtin and Watkins (1997) present a detailed information on low-flow values in each quaternary subdivision in the two study catchments.

Besides its usefulness for low-flow estimation, the method allows the established seasonal FDCs for an ungauged site in the region to be used in combination with the spatial interpolation technique described above. This provides an opportunity to generate a complete daily time series at an ungauged site without the application of sophisticated modelling techniques (Smakhtin et al., 1997).

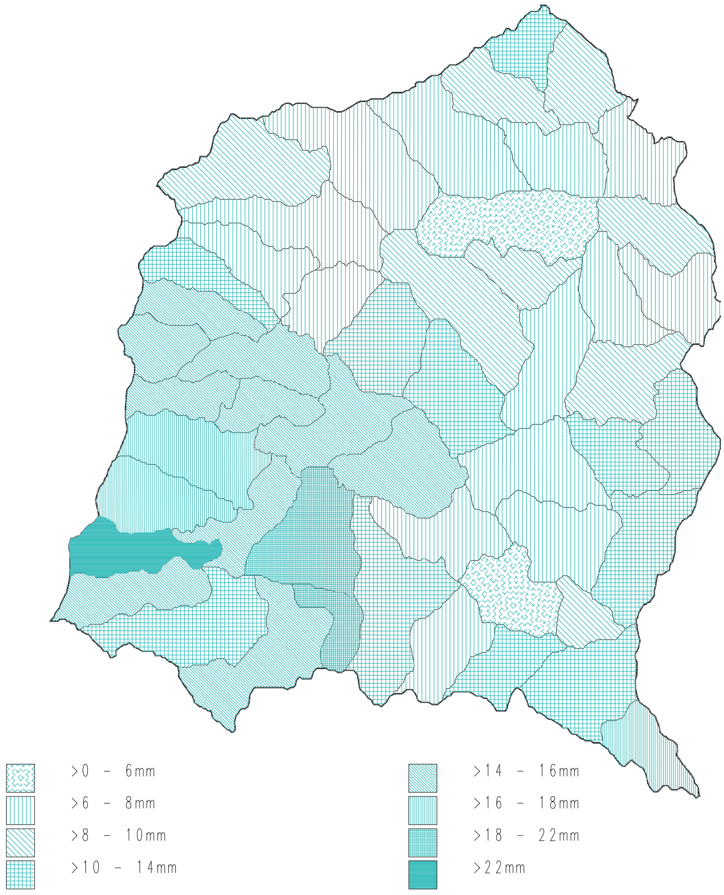

Figure 13
Distribution of Q95 flow values (mm/a) in the Mzimvubu catchment

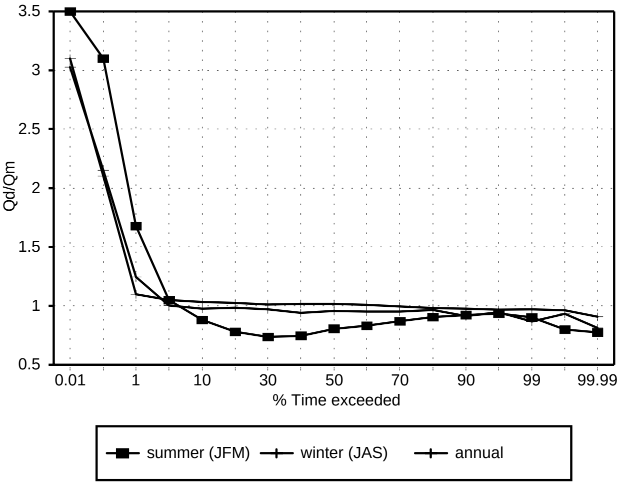

Figure 14
Averaged seasonal and annual ratio curves for the upper Sabie catchment (summer: January to March; winter: July to September)

Estimation of daily low-flow characteristics from monthly streamflow data

All previously described methods rely on the direct use of daily streamflow data time-series for estimation of low-flow characteristics. The widely used alternative approach for low-flow estimation is the construction of a regional multiple regression model which relates a low-flow characteristic to catchment and physiographic parameters. While the results may sometimes be encouraging (Nathan and McMahon, 1992), the “true” physical relationship may not always be fully uncovered by such a regression model.

On the other hand, a strong relationship is likely to exist between daily and monthly low flow characteristics. If monthly streamflow data (e.g. simulated) are already available at a site of interest, daily low-flow characteristics may be derived from them. The simplest estimation method of that kind would be a division of a monthly flow volume (e.g. during the driest month or season) into a number of days or a number of seconds in a month to obtain the average daily flow volume or average daily discharge within this month. This approach is, however, 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 in a catchment or region using observed streamflow records. In the South African context, this approach is particularly relevant since synthetic monthly streamflow time series are widely available.

The attempt was made to relate $Q75_7$ flow value with the mean monthly flow during the driest month of the year using the streamflow data in the Tugela River Basin. The data from 22 streamflow gauging stations have been selected for this analysis. Only gauges which 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 were still used when the period was long and representative.

The mean driest month’s flow (DMF) at each selected gauge was estimated using HYMAS ‘seasonal distribution’ procedure, which is a convenient facility to calculate, display and print seasonal flow characteristics. Several types of regression models were tested. The best results were obtained using the following two models:

$$Q75_7 = 0.298 * DMF \qquad (1)$$
$$(R^2 = 0.82,\ \ \text{s.e.} = 52\%)$$

$$\ln (Q75_7) = -1.616 + 1.256 * \ln (DMF) \qquad (2)$$
$$(R^2 = 0.92;\ \ \text{s.e.} = -37\% \ / \ +60\%\ )$$

Using any of these models and assuming that selected observed data sets represent reasonably natural flow regimes, it is possible to estimate $Q75_7$ 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 may easily be calculated using HYMAS ‘seasonal distribution’ procedure and used as input to the established regression model to obtain the required estimate. The illustrated results are preliminary and further steps would be necessary to investigate the reliability of regression relationships of this type for other daily low-flow characteristics and in other South African catchments.

The other possible way of utilising monthly data for daily low-flow estimation could be through the conversion of FDC-based on monthly flow volume time series to FDC based on daily discharges. The most straightforward form of a relationship between two curves may be what is further referred here as a ‘ratio curve’. The first step in the analysis is to construct 1 month and 1 d FDCs for every gauge in a selected catchment (or physiographic region) using similar units (either converting daily discharges (Q_d) to Mℓ or expressing monthly flow volumes (Q_m) as mean monthly discharges in m^3/s). The ratios of daily to monthly flows (Q_d/Q_m) for several fixed percentage points are then calculated for each gauge and plotted against the percentage point values thus producing the ‘ratio curve’ for a site. Such a ratio curve may be constructed (like in the case of a FDC) either for the whole year (annual), calendar month (typical monthly) or the combination of months (seasonal).

The next step is to group and regionalise these ratio curves. The working hypothesis of this approach is that ratio curves for similar sized catchments 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 (annual/seasonal/monthly; Fig.14) that can be applied to catchments within a homogeneous region to convert the coordinates of any 1 month FDC (derived, for example, from available synthetic monthly flow data) to the ordinates of a 1 d FDC.

Smakhtin and Watkins (1997) have demonstrated that regional relationships between two types of FDCs could possibly be established in some regions, but should be preceded by a very rigorous selection of gauged streamflow information. Also difficulties are very likely to be experienced in specifying the boundaries of homogeneous regions on the basis of limited data. However, a good motivation for further development of this method is that it could provide another possibility of establishing 1 d FDCs at an ungauged site. Such FDCs may then be used either for direct estimation of related low-flow indices, or for generation of a complete continuous daily streamflow hydrograph at a site in a combination with spatial interpolation technique in a similar way as has been described by Smakhtin et al. (1997).

Conclusions

The study has identified that the performance of each low-flow estimation method in South African conditions is essentially determined by the quality and amount of initially available data. The applicability of complex rainfall-runoff models may be limited to those areas where sufficient knowledge exists about physiographic characteristics and water resource development of the simulated catchments. Another problem related to the deterministic simulation approach is the availability of rainfall data which are scarce in many regions of the country. The daily simulation method is also a very time-consuming and labour-intensive approach and hardly practical for a large number of catchments. It requires a thorough calibration of the model parameter values before it can be reliably applied for the simulation of a representative streamflow time series. The cost and timing of small-scale water projects may not always justify the use of such sophisticated methods.

However, the rainfall-runoff modelling approach allows the simulation of daily streamflow time-series to be performed at a finer level of spatial discretisation than is normally possible using observed flow records only. This method seems to be nearly the only feasible option at present for simulating daily flow regimes at different scenarios of development (e.g. natural, present or future conditions) and for assessing the effects of these scenarios on streamflow in various parts of the study catchments.

The study has also indicated that there is a good potential for the use of simpler simulation approaches, like spatial interpolation of observed daily streamflow records, which usually performs particularly well in the low-flow portion of a hydrograph. The problems with this approach are related to the lack of straightforward techniques to account for the effects of water abstractions, discharge table limitations, limited length of the observation period and non-stationarity of streamflow records on flow duration curves. Also this method at this stage can produce results only at a coarse spatial resolution. The issues related to the extension of the applicability of this method form one of the primary directions of the future research.

It has been identified that in some cases it is possible to develop a picture of the low-flow characteristics of large basins through regionalisation of observed streamflow data, presented, for example, in the form of a flow duration curve. Regional low-flow frequency curves or low-flow spell frequency curves may possibly be derived in a similar way. The application of this method is likely to be limited to physiographically homogeneous areas with minor water resource developments and satisfactorily long representative streamflow records. The method of regional flow duration curves in combination with the spatial interpolation technique provides one opportunity for generating a continuous daily hydrograph at an ungauged site.

Low-flow conditions in large South African catchments may also be assessed through combined use of observed daily and widely available synthetic monthly streamflow data. It has been illustrated that simple relationships between daily and monthly low-flow characteristics may be established. These relationships will only be applicable at the quaternary catchment scale, since this is the level of spatial resolution of available synthetic monthly data. However, low-flow information is often required in design of small surface water supply schemes, where the catchments are frequently at sub-quaternary scales. There is not enough clarity at present about the scale dependency of low-flow indices in different regions and consequently about the procedures which should be adopted to estimate low-flow characteristics at small scales. This problem should therefore be addressed separately.

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