Estimating daily flow duration curves from monthly streamflow data

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Abstract

The paper describes two techniques by which to establish 1-day (1d) flow duration curves at an ungauged site where only a simulated or calculated monthly flow time series is available. Both methods employ the straightforward relationships between daily and monthly flow characteristics. These relationships are first established on the basis of observed streamflow data and then used to convert synthetic monthly flow data into1d flow duration curves. The paper suggests the conversion equations and describes step-by-step calculation procedures which may be applied to generate 1d flow duration curves at quaternary catchment level of spatial resolution.

Abbreviations

FDC	Flow duration curve
MAR	Mean annual runoff
MAP	Mean annual precipitation
MAE	Mean annual evaporation
Q95	Discharge exceeded 95% of the time
T_0	% of the time with zero flow conditions in a river
SE	Standard error
R^2	Coefficient of determination
HYMAS	HYdrological Modelling Application System
1 d	1-day
1 m	1-month

Introduction

Monthly streamflow volume time series data have been traditionally used in South Africa for management and development of water resources. These data are available as:

- Observed records cumulated with a monthly time step
- Monthly inflow volumes to major dams calculated by the water balance method
- simulated time-series from system analysis and basin study reports commissioned by the Department of Water Affairs and Forestry.

After the update of the nation-wide study on the surface water resources of South Africa (Midgley et al., 1994) synthetic monthly data are also available for 1 946 small and normally ungauged incremental drainage subdivisions (‘quaternary catchments’) throughout the entire country. The average area of quaternary catchments is 650 km^2 but it varies from 80 to100 km^2 in humid regions to 2 000 km^2 in arid regions. It may be concluded that monthly streamflow data are available at the level of spatial resolution which would satisfy most of the large and medium water projects. However, an increased attention to environmental considerations in water resources management on one hand, and development of small water supply schemes (e.g. in rural areas) on the other, has led to the growing demand for analyses based on daily streamflow data.

Characterisation of daily flow regimes in South Africa (and almost any other country) from observed data is possible only at a limited number of sites. At the same time, even the existing observed daily flow records are not always suitable for direct use since they

- often contain large gaps due to missing data;
- may be non-stationary because of the time variant land-use effects or water abstraction pattern;
- may be available only for a very short observation period;
- are rarely coincident in time with the time series from other sites within a basin and may therefore represent different sequences of dry and wet years.

Generating a time series of daily flows by deterministic rainfall-runoff models is a commonly used but rather expensive and time consuming approach. On the other hand, given a wide availability of monthly streamflow data in the country, a cost-effective methodology may be developed which allows daily streamflow characteristics to be derived from synthetic monthly flow records.

Ideally, the outcome of such method should be the continuous synthetic streamflow time series of daily discharges for all quaternary catchments for some standard period (e.g. similar to that of the synthetic monthly time series - 70 years, from 1920 to 1990). At the same time, for many practical purposes a FDC is a valid substitute for a complete time series. FDC is a relationship between any given discharge value and the percentage of time that this discharge is equaled or exceeded. It gives a summary of the flow variability at a site and represents perhaps the most informative method of displaying the complete range of river discharges from low flows to flood events. FDC is frequently used in water quality calculations, design of run-of-river abstraction schemes, estimation of required environmental flows etc. It is logical in this context to investigate the possibilities of deriving FDCs representing daily flow regimes from synthetic (or calculated) monthly flow time series. Once this task is completed, the techniques for the conversion of established curves into a complete daily flow time series may also be suggested.

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FDC may be constructed from either daily (1d FDC) or monthly (1m FDC) data. Both 1d and 1m FDCs may be calculated on the basis of the whole available record period or on the basis of all similar calendar months from the whole period (e.g. all Januaries). The former curves are sometimes referred to in the literature as either "period of record FDC" (Vogel and Fennessey, 1994), or "long-term average annual FDCs" (Smakhtin et al., 1997) and the latter as either "long-term average monthly FDC" (Smakhtin et al., 1997) or FDC of a monthly "window" (Mngolo, 1997). In this paper, 1d FDC for the whole year is referred to as 1d annual FDC, while 1d FDCs for each calendar month of the year are referred to as 1d monthly FDCs.

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

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

Explicit "ratio curves" approach

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

For any site in a river, the variability of daily flows is higher than that of monthly flows. In high-flow months, maximum daily average discharges are higher than the monthly average. In low-flow months minimum daily average discharges may be much lower than the monthly average. The implication for FDCs is that the 1 d FDC generally has a larger slope than the 1 m FDC (Fig.1) Consequently, daily discharges are higher than monthly discharges in the area of low probabilities of exceedance and lower than monthly discharges in the area of high probabilities. This in its turn implies that the ratios of daily to monthly flows for the 17 fixed percentage points may be calculated and plotted against the percentage point values thus producing the '*ratio curve*' for a site. Similarly to FDCs themselves, such ratio curves may be established for each calendar month of the year or for the whole year (Fig. 2).

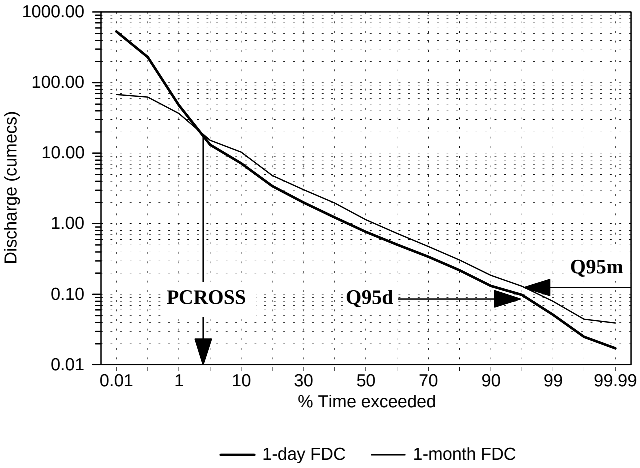

Figure 1
Annual 1d and 1m FDCs for the Mooi River at gauge T3H009 (catchment area 307 km^2) in the Eastern Cape showing daily and monthly Q95 flow values and the percentage point at which two curves cross (PCROSS)

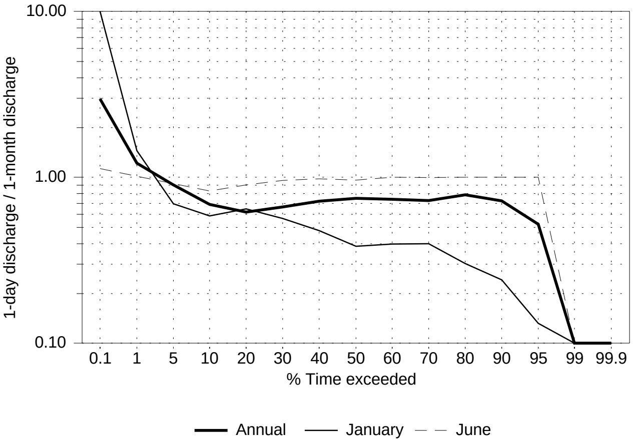

Figure 2
Ratio curves for the whole year (Annual), wet month (January) and dry month (June) for the White Mfolozi River at gauge W2H009 (catchment area 432 km^2) in Natal

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

- In the vicinity of the site of interest identify a representative streamflow gauge(s) with good quality data. The size of the gauged catchment(s) should ideally be similar to that of the catchment upstream the site of interest.
- Construct both 1 d and 1 m FDCs using this gauge's data (for the whole year and/or for each calendar month)
- Calculate ratios of 1 d flows to 1m flows for 17 fixed percentage points. These ratios may also be plotted against the percentage point values to visualise the resultant "ratio curve" for a site. If several representative flow gauges are identified in the adjacent area, the exercise should ideally be repeated for each gauge in order to calculate the average "ratio curve".
- The established "ratio curve" represents a conversion function from 1 m to 1 d FDC. It can now be used in combination with synthetic streamflow data in the area to establish 1 d FDC.

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

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

The approach based on the relationships between specific daily and monthly characteristics (implicit ratio curve method)

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

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

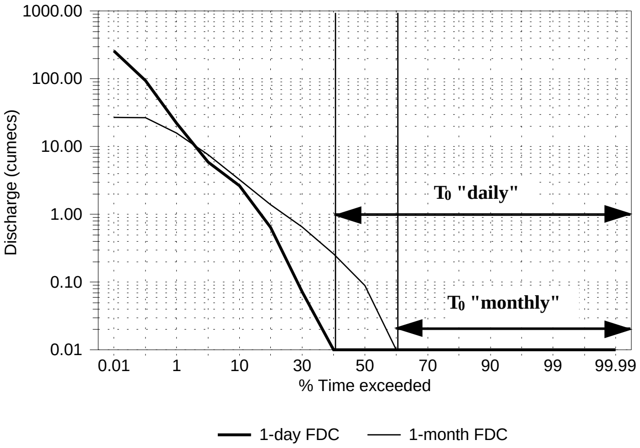

Figure 3

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

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

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

The following information has been derived from observed streamflow time series for each gauge.

- Daily and monthly flows exceeded 95% of the time throughout the year (Q95 flows from 1 d and 1 m annual FDCs, Fig. 1).
- The percentage of time with zero-flow conditions (T_0, %) from 1 d and 1 m annual FDCs. T_0 may be read directly from the FDC graph at a point where the curve intersects the time axis (Fig. 3). This index is important for distinguishing between perennial and non-perennial streams.
- A smaller subset of 55 randomly selected flow gauges from different physiographic regions was used to construct the actual plots of i) 1 d and 1 m annual FDC and ii) 1 d and 1 m FDCs for each calendar month of the year. Altogether, the 13 graphs with pairs of curves have been constructed for each gauge. These graphs gave the full-scale view of the relation-

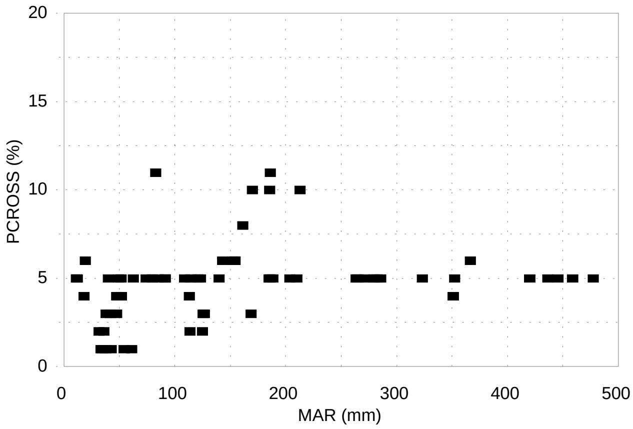

Figure 4
Scatter plot of the relationship between the percentage point at which 1d and 1m annual FDCs cross (PCROSS) and the MAR.

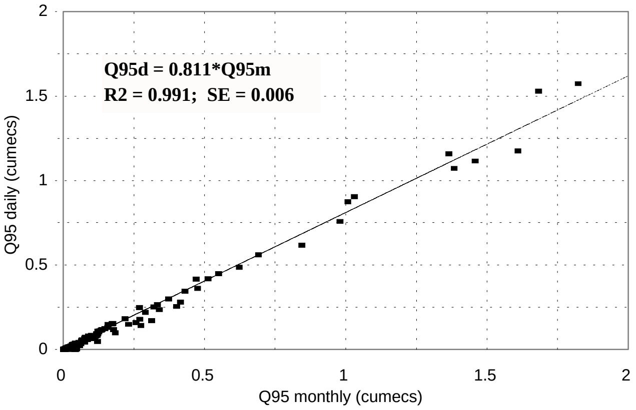

Figure 5
Relationship between Q95 flow values estimated from 1d and 1m annual FDCs.

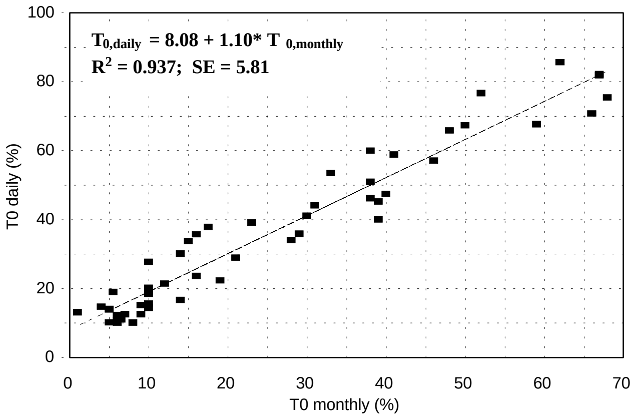

Figure 6
Relationship between T_0 values extracted from 1d and 1m annual FDCs for non-perennial rivers.

ship between two curves on the month-by-month and annual basis. They have also been used for the estimation of another important characteristic - the percentage point at which 1 d and 1 m FDCs cross (PCROSS - Fig. 1).

The details of the gauges used, and some of the calculated indices for all gauges (e.g. 1 d Q95 flow values and "daily" T_0) are listed in Smakhtin and Watkins (1997). The study has shown that the two curves normally cross between the 1% and 10% time exceedance points. With a few exceptions, this is valid for pairs of curves constructed for both the whole year and for individual calendar months. The attempts have been made to investigate the possible relationships of the PCROSS (for annual FDCs) with characteristics which may be easily obtained from the *Surface Water Resources of South Africa 1990* volumes (Midgley et al., 1994). These characteristics included: catchment area, unit MAR, MAP, MAE and several combinations of those (e.g. MAP/MAE). PCROSS has not been found to be related to any of these parameters. On the other hand, the majority of cases studied indicate that the PCROSS may be approximated as a constant which is equal to 5% (Fig. 4). This assumption may be feasible considering that the data sets used normally have measurement errors and observation periods which are different in length and not always overlapping. It also has to be taken into account that in the area of high flows some of 1 d FDCs are "truncated" which results from low discharge table limits of gauges (1 m curves are also affected by this limit, but to a lesser extent). This may also affect the accuracy of PCROSS calculation. The assumption of a constant PCROSS value has a convenient implication for the estimation of 1 d FDCs. It means that the first point for the 1 d FDC may be read directly from the 1 m FDC at the 5% exceedance level.

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

$$Q95_d = 0.811{*}Q95_m \qquad (1)$$
$$(R^2 = 0.991; \quad SE = 0.006)$$

where $Q95_d$ and $Q95_m$ are flow values exceeded 95% of the time and estimated correspondingly from 1 d and 1 m annual FDCs. This relationship is also illustrated in Fig. 5.

The rest of the data set has been classified as non-perennial rivers. These rivers have zero "monthly" Q95 values and Eq. (1) is not applicable. The focus should be shifted to the estimation of the time spent at zero-flow conditions (T_0). For non-perennial rivers, "monthly" $T_0 > 5\%$. The corresponding "daily" T_0 values are even larger (Fig. 3). This is explained by the fact that in semi-arid and arid catchments a river may dry up completely for most of the low-flow month, while the average monthly discharge will remain non-zero. Both monthly and daily T_0 values increase with the increasing aridity of the area (e.g. decreasing MAP). The following relationship between "daily" and "monthly" T_0 values has been derived (also illustrated in Fig. 6):

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

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

$$DQ_{j,d} = \exp \; \ln DQ_{j,m} - \ln(Q95_m / Q95_d)*(\ln DT_j - 1.61)/ 2.94 \qquad (3)$$

where:

$DQ_{j,d}$ and $DQ_{j,m}$ are 1d and 1m flow values at the j percentage point DT_j

1.61 is the natural log of the constant PCROSS (5%)

2.94 equals to (ln95 - ln5).

The already mentioned 17 fixed percentage points may be used to define the curve (in this case j = 1,2,..17). But Eq. (3) may also be used to calculate flow values for any other percentage point(s) on the curve.

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

$$DQ_{j,d} = \exp \; \ln DQ_{j,m} - \ln(Q_{m\,(1-To,d)} / Q_{d\,(1-To,d)}) * \ln(DT_j / 5) / \ln((1-T_{0,d}) / 5) \qquad (4)$$

where $Q_{m\,(1-To,d)}$ and $Q_{d\,(1-To,d)}$ are 1m and 1d flow values exceeded $1 - T_{0,d}$ per cent of the time. Naturally, $Q_{d\,(1-To,d)}$ is zero and a closest non-zero substitute value is required to use Eq. (4). The most convenient substitute is 1% of the MAR, converted to discharge units. This value may easily be calculated using the quaternary catchment information from Midgley et al. (1994). The study has shown that the "daily" values of $(1 -T_0)$ and $(1 - T_{0.01\,MAR})$ in the majority of cases are almost indistinguishable. The final form of the interpolation equation for non-perennial rivers them becomes:

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

The suggested approach for 1d FDCs estimation may be summarised as follows:

- Construct 1m annual FDC for an identified quaternary catchment using the standard 70-year long synthetic monthly flow record.
- Estimate $Q95_m$ flow value. If it is non-zero, use Eq. (1) to calculate $Q95_d$ flow value and Eq. (3) to calculate 1d flows for other percentage points.
- If $Q95_m$ flow value is zero, estimate $T_{0,\,m.}$ Then use Eq. (2) to calculate $T_{0,\,d}$.
- Estimate 1% of the MAR from quaternary catchment data and convert it into discharge units. Use Eq. (5) to calculate non-zero 1 d flow values at all percentage points smaller than 1- $T_{0,\,d}$. Assign zero values to all flows exceeded more than 1- $T_{0,d}$ per cent of the time.

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

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

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

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

Implications for generating actual daily flow time series at quaternary level of spatial resolution

One of the possible and the most attractive areas of application of the proposed approach is to generate daily flow time series at the ungauged sites without using a sophisticated deterministic modelling technique. Hughes and Smakhtin (1996) described a simplified algorithm initially developed to patch and/or extend observed time series of daily streamflows. In an attempt to account for possible non-linearities in streamflows at different sites, even within similar parts of the same basin, this spatial interpolation algorithm has been based on 1d FDCs and the assumption that flows occurring simultaneously at sites in reasonably close proximity to each other correspond to similar percentage points on their respective FDCs. In the original form of this algorithm, the FDCs were calculated for each calendar month of the year, but the method is equally applicable if only annual FDC is used.

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

This model has been extensively tested in different physiographic zones within Southern Africa. It has been demonstrated that the resulting streamflow simulations in the majority of cases compare favourably with those obtained using a semi-distributed, physically-based, daily time step, rainfall-runoff model (Hughes and Sami, 1994) which represents a more labour-intensive and time-consuming technique.

Smakhtin et al. (1997) described how the algorithm may be used for the generation of daily streamflow time series at ungauged sites in a data-poor region. Smakhtin (1999) illustrated the application of the method to the restoration of natural flow sequences in regulated rivers. Using the approach for the estimation of 1 d FDCs described in the present paper and the spatial interpolation algorithm suggested by Hughes and Smakhtin (1996), daily streamflow time series may in principle be generated for any quaternary catchment throughout the entire country. Such time series data will represent natural streamflow regimes and may be put to various uses. The limiting requirement for the application of the spatial interpolation approach would be the presence of at least one suitable source flow gauge with daily data in the vicinity of each quaternary catchment. However, as has been shown by Hughes and Smakhtin (1996), the selection of such gauges is often possible, and in many cases the choice is obvious.

The other attractive and feasible alternative is to use the more readily available daily rainfall data in a catchment instead of source daily streamflows. This would considerably extend the limits of application of spatial interpolation approach. Smakhtin and Masse (2000) suggested a method for continuous daily streamflow generation using the 1d FDCs and duration curves of rainfall- related index, which reflects the daily fluctuations of "wetness" of the catchment and is similar to the antecedent precipitation index.

Conclusions

The approaches described in the paper are designed as simple tools to generate 1d FDCs at ungauged sites for which synthetic monthly flow volume data are available from elsewhere (e.g. synthetic data for quaternary catchments from Midgley et al. (1994). The established curves may have many direct practical applications. At the same time, the curves may be converted into the actual daily streamflow time series representing natural flow conditions in a river catchment. The methods may further be developed to adjust the established curves to incorporate the effects of catchment and water resources development on the curve and, through the curve - on the resultant daily time series. The suggested techniques are designed to contribute to the availability of much needed detailed streamflow time series information.

The methods are developed within the context of South African information environment. But, their main principle (establishing relationships between 1 d and 1 m streamflow characteristics) may equally successfully be applied in other regions, provided that a time series simulated by any monthly rainfall-runoff model or obtained from water balance calculations is available. The proposed scheme of monthly to daily data conversion may be particularly relevant for a developing country where the application of economical monthly rainfall-runoff models represents one of the few feasible options for assessment of surface water resources.

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