Continuous baseflow separation from time series of daily and monthly streamflow data

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Abstract

Continuous baseflow separation procedures have been frequently used to differentiate total flows into the high-frequency, low-amplitude 'baseflow' component and the low-frequency, high-amplitude 'flood' flows. In the past, such procedures have normally been applied to streamflow time-series data with time steps of 1 day or less. However, there are applications in South Africa (notably related to setting instream flow requirements) where the only available data for natural flow conditions are monthly flow volumes. A relatively experienced hydrologist can be expected to successfully calibrate a separation model using daily data, coupled with a conceptual understanding of the hydrological processes prevailing in the catchment. The same cannot be said for monthly data, as the majority of the information on short-term flow variability has been lost. As part of a regional study covering the whole of South Africa, this paper presents some example results of comparisons between daily and monthly separations. While it can be concluded that it is possible to determine regionalised parameters for monthly data separations that are useful, further information on the processes involved would be of great value to validate the methods and parameter values. This information could also form the basis for the further development of baseflow separation methods for South African flow regimes.

Introduction

From a hydrological process point of view, baseflow is considered to be that component of the total flow hydrograph that is derived from runoff processes that operate relatively slowly. Thus many of the traditional hydrograph separation approaches have focused on trying to distinguish between rapidly occurring surface runoff, slower moving interflow and even slower discharge from groundwater (Freeze, 1972). However, the conceptual basis for such distinctions can only really apply in small catchments where differential travel times, due to distance from the catchment outlet, play a minor role. In larger catchments the situation is far more complex and hydrograph shapes can be affected by a multitude of processes, some dominated by topography, others by subsurface (soils and geology) characteristics and others by spatial variations in rainfall inputs.

Further complexity is added when runoff processes are considered in more detail. A number of field studies have demonstrated that subsurface runoff processes in some catchments can operate at quite rapid rates (Ward, 1984; Putty and Prasad, 2000), while surface runoff on hillslopes may be re-infiltrated further downslope. It soon becomes apparent that, apart from a very few experimental catchments which are comprehensively instrumented, it is extremely difficult to determine what component of the total flow hydrograph can be considered as baseflow. Chemical and isotope tracing studies (Marc et al., 2001), as well as simulation modelling (Haberlandt et al., 2001) offer alternative methods for process-based hydrograph separations, however, they all require extensive time and manpower resources.

Smakhtin and Watkins (1997) and Smakhtin (2001) outline a useful separation approach that was originally reported by Nathan and McMahon (1990). Although this approach does not take any account of the source of the two separated flow components it is useful in that it separates total flows into the high-frequency, low-amplitude 'baseflow' component and the low-frequency, high-amplitude 'flood' flows. This distinction can be of great importance in some applications and specifically in the determination of the quantity component of instream flow requirements. The identification of instream flow requirements of rivers is part of the current water resource legislation for South Africa and forms part of the ecological reserve.

The ecological reserve for rivers is frequently determined using the 'Building Block Methodology' (BBM- King and Louw, 1998), which attempts to divide the instream flow requirements of rivers into four main blocks. The process is based on the use of expert opinion and involves several different ecological specialists (focusing on riparian vegetation, fish, invertebrates and geomorphology) identifying the water requirements of the river. The four blocks are the seasonal distributions of drought and maintenance low flows, and drought and maintenance high flows. Drought conditions are considered as the minimum flows that should occur, while the maintenance flows are those that are expected to occur under 'normal' conditions. The frequency with which normal conditions can be expected in a specific catchment will depend upon the magnitude-frequency characteristics of the natural flow regime (Hughes, 1999). Hughes (2001) outlines some of the hydrological procedures that are used to support the determination process and refers to the need for information on the natural flow regime characteristics, so that the flow requirements determined by the specialists can be evaluated. One of the requirements of the hydrological procedures is the ability to determine the seasonal distribution of natural low flows, as well as the likely frequency of occurrence of different size baseflows in individual calendar months. Frequently this information is required when the only source of natural flow data is time series of simulated monthly flow volumes.

This paper is designed to build on the work reported in Smakhtin (2001), critically evaluate the continuous baseflow separation approach as used with monthly data and to ultimately

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Received 3 January 2002; accepted in revised form 30 September 2002.

generate regional parameters for the separation equation. It formed one component of a re-assessment and re-calibration of the parameters of the so-called ‘Desktop Reserve Model’ (Hughes and Hannart, 2003), widely used in South Africa for initial estimates of the quantity component of the ecological reserve for rivers.

The separation algorithm

With a slight modification, the algorithm for the digital filtering separation approach discussed in Smakhtin (2001) can be represented by:

$$q_i = \alpha q_{i-1} + \beta\ (1 + \alpha)\ (Q_i - Q_{i-1}) \tag{1}$$

$$QB_i = Q_i - q_i \tag{2}$$

where:

Q_i = total flow time series
q_i = high-flow time series component
QB_i = baseflow time series component
i = time step index
α, β = separation parameters ($0<\alpha<1$, $0<\beta<0.5$)

The baseflow component (QB) for each time step is constrained to be never less than 0 or greater than the total flow (Q). The only differences between this equation and the equation reported in Smakhtin (2001) are that the time step here is not fixed to a month and that the β parameter was fixed at 0.5 in Smakhtin (2001).

Applied to daily time-step data, there does not appear to be any reason to change the β parameter from the fixed value of 0.5, as there is more than enough flexibility in the setting of the α parameter to achieve an acceptable result. Parameter α effectively controls the volume of baseflow, with high values resulting in relatively low baseflow volumes and low α values generating high proportions of baseflow relative to total flow. The actual proportion of baseflow resulting from a specific α parameter value is very dependent upon the shape of the natural hydrograph variations (through time series Q). The original (Nathan and McMahon ,1990) application of the method suggested that several iterations of Equation 1 could be applied, with the time series of QB being set to a new time series of Q at the end of each iteration. Thus even a relatively low value of parameter α could result in quite low baseflow proportions after several iterations. While this approach offers advantages in terms of generating smoother baseflow response results, it also introduces a further parameter to the application of the equation.

For a large number of observed daily flow time series in South Africa Smakhtin and Watkins (1997) determined that a fixed value of 0.995 for the α parameter can be considered suitable. This study, which investigated fewer time series, concluded that there are many catchments where slightly higher α values (up to 0.997) are more appropriate. However, the differences are quite small.

In making use of the separation method for the more generally available monthly flow data (Midgley et al., 1994) in South Africa, Smakhtin (2001) suggested using the same equation (i.e. with β retaining its fixed value of 0.5) and calibrating α until the same baseflow volume is achieved as a separation based on daily data. One of the results that can be discerned from the graphical results presented in Smakhtin (2001) is that the daily separation often generates a higher peak baseflow, as well as a higher baseflow volume in the early part of the wet season.

Determination of seasonal baseflow distributions

The comparisons between the separations based on daily and monthly data referred to in the previous paragraph were investigated more thoroughly in the present study. The reason for this was that the objective of this study was to develop regionalised parameters for the separation equation using monthly data and it was clear from Smakhtin (2001) that there would be much less stability in the parameter values for monthly data than for daily data. One of the results that was required from the study was a method of deriving mean seasonal baseflow distributions for any of the 1946 quaternary catchments in South Africa, without the need for calibration of the separation equation by the user. If the result noted from Smakhtin (2001) is reasonably consistent for a range of South African rivers, there is the potential that the seasonal distributions of baseflow derived from monthly data would be less peaked and skewed towards the late part of the wet season, compared to those derived from daily data.

It has already been made clear that this type of separation is not based on any real knowledge of the hydrological processes involved. The question could therefore be asked, ‘why compare results from a separation based on monthly data with those based on daily data, when the daily results are considered to be less than hydrologically meaningful?’. The first part of the answer to the question is that, amongst South African hydrologists there is a reasonable conceptual understanding of the type of hydrological processes that lead to streamflow in different parts of the country (even if the specific nature of the processes is not fully understood). It is also quite clear that there are differences in short-term streamflow response between catchments, even in the wetter parts of the country. Some of these areas have quite strong seasonal baseflow responses with relatively small high-flow responses superimposed upon them. In other areas, there is a lower seasonal baseflow response, but more frequent high-flow events. These differences can be clearly distinguished in daily time series, but are much more difficult to detect in monthly time series, where the flow volumes due to the frequent events are aggregated. The implication is that it is not always easy for even an experienced hydrologist to determine what would be a ‘reasonable’ baseflow separation given only monthly data.

In an attempt to determine regionally acceptable baseflow separation parameters, it is therefore logical to calibrate the separation parameters for daily data and then repeat the exercise for monthly data on the following basis:

- Achieve similar long-term average baseflow responses for the two methods.
- Ensure that there is no systematic difference between the mean seasonal distributions for the baseflows generated by the two methods.
- Ensure that the shapes of the baseflow calendar month duration curves are similar.

It became apparent early in the study that the second objective was not possible with fixed values for both the α and β parameters and that β would have to be set at a value of less than 0.5. The alternative of varying the number of iterations was considered, but rejected on the basis of the fact that it also appeared to suffer from the same problem of having a fixed β value and would still have resulted in at least two regionally varying separation parameters. While all three objectives were assessed during the study, this paper focuses on the first two.

TABLE 1 Gauging stations, catchment areas and parameters used in the graphical examples (Fig. 1 to 6)						
DWAF station number	Catchment area (km^2)	Mean annual rainfall (mm)	Mean baseflow proportion (% total flow)	Daily α value (β = 0.5)	Monthly α:β values	Monthly α value (β = 0.5)
X3H003	52	1252	62.0	0.997	0.960 : 0.44	0.930
G4H014	252	722	30.0	0.995	0.955 : 0.43	0.900
T3H002	2101	765	26.3	0.995	0.975 : 0.44	0.930
J3H012	688	325	18.3	0.997	0.988 : 0.45	0.960
Q6H003	814	494	9.5	0.997	0.995 : 0.47	0.975
W5H005	804	846	39.0	0.995	0.955 : 0.44	0.915

Results

While some 70 observed flow records were analysed in the full study, only results for a few representative stations are presented here. The records were chosen to be relatively free of missing data and from catchments that have fewer artificial influences on their flow regimes than most South African rivers. Table 1 lists the example stations (using their Department of Water Affairs and Forestry (DWAF) station codes), their catchment areas, mean annual precipitation, the 'calibrated' mean baseflow proportion, as well as the parameters that were used for the daily and monthly separations. The values for α when β was fixed at 0.5 in the monthly separations are also included in the table. The information displayed on the six graphs (Figs. 1 to 6) includes the observed daily flows and the separated daily flows, both aggregated to monthly volumes. The baseflows derived from the monthly separations using a variable and a fixed (=0.5) β parameter are also displayed. For convenient reference in the text below, the monthly separations using a variable β parameter are referred to as M1, while those with β always set to 0.5 are called M2.

X3H003 – Mac-Mac River

This is a tributary of the Sabie River and has a very high baseflow response of greater than 60%. The daily time series demonstrates a very strong, and quite rapidly responding, wet season baseflow response with relatively small events superimposed. This suggests that the differences between separations based on monthly and daily data should be smaller than in other river systems. However, the tendency toward a late wet season skew of the separated baseflows for the M2 separations is still evident (Fig. 1). The peak of the mean seasonal baseflow distribution based on daily separations is in March, while for the two monthly separations it is in February (M1) and May (M2). The peak of the total flows is in February and it is considered unreasonable to suggest that the baseflow peak would be as late as

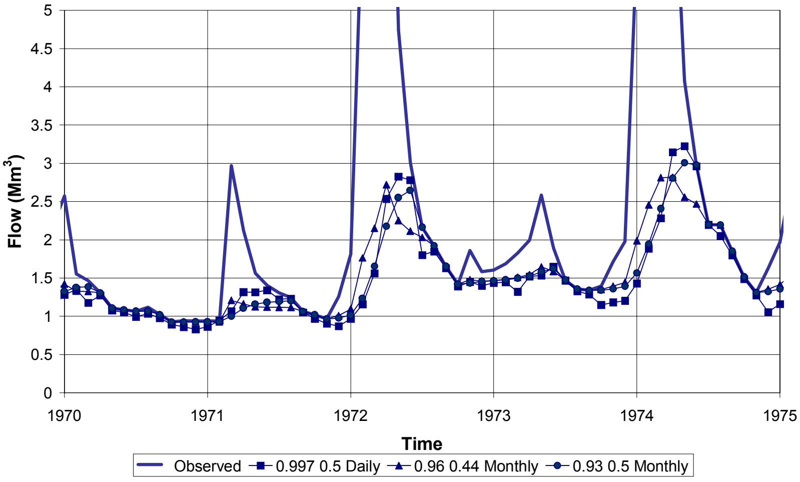

Figure 1
Observed flows and separated baseflows for gauge X3H003

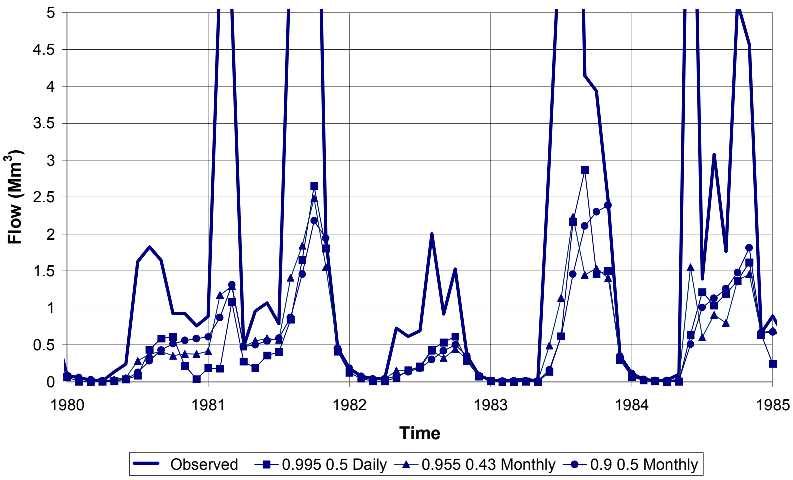

Figure 2
Observed flows and separated baseflows for gauge G4H014

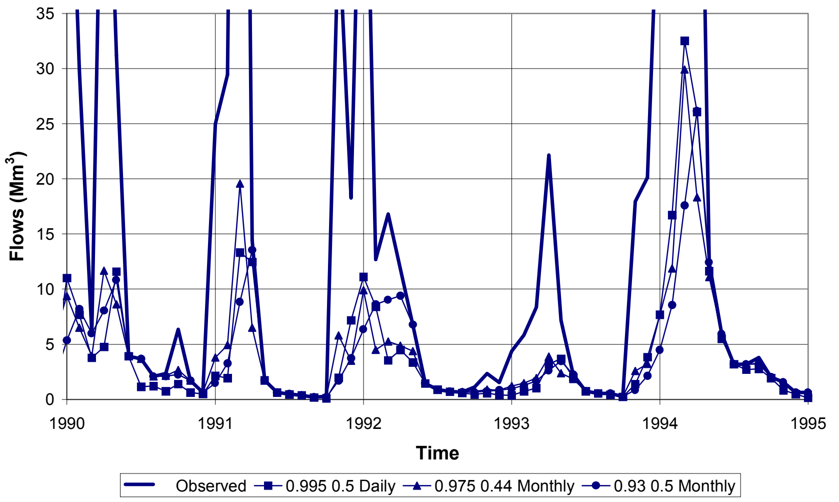

Figure 3
Observed flows and separated baseflows for gauge T3H002

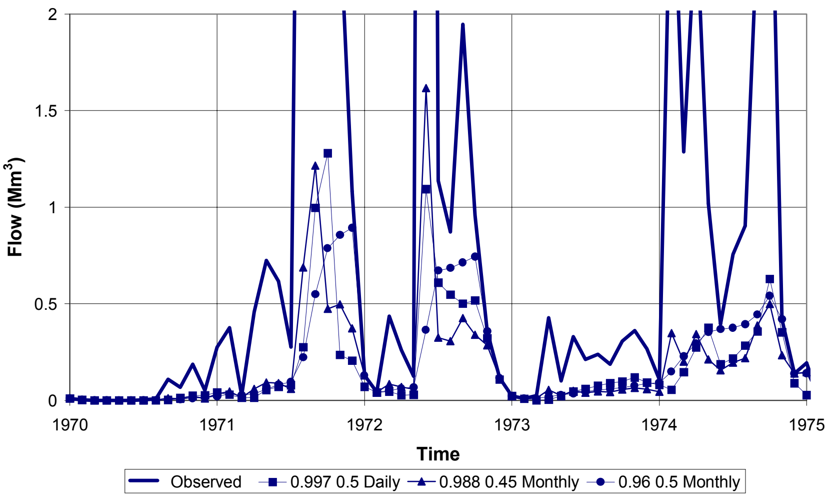

Figure 4
Observed flows and separated baseflows for gauge J3H012

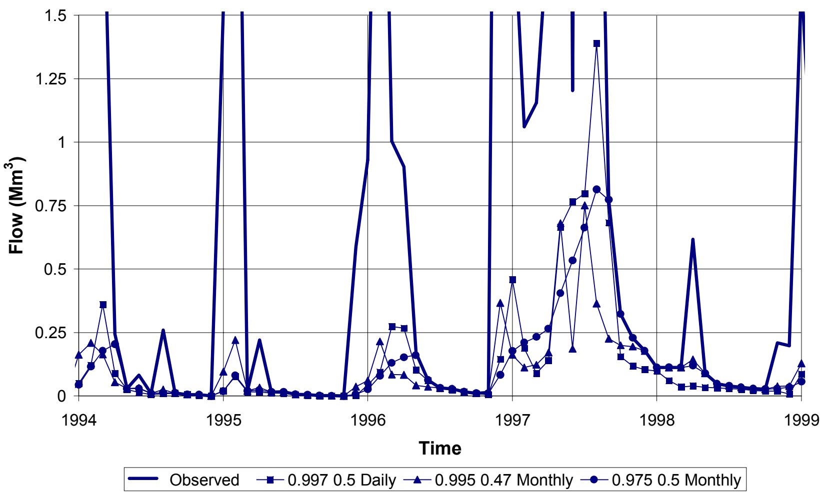

Figure 5
Observed flows and separated baseflows for gauge Q6H003

May in a catchment where the baseflow response appears to be quite rapid.

G4H014 – Bot River

This is a Western Cape river, where the seasonal total flow peak is in August. Both the daily and the monthly M1 separations produce baseflow peaks in August, while the M2 separation gives a baseflow peak in October. Figure 2 illustrates that the shift of baseflows toward the end of the wet season for M2 is not always as apparent as it is for 1983. This suggests that the biggest differences between M1 and M2 will occur in years with consistently wet winters, rather than those years (such as 1982 and 1984) which are drier or have dry periods during the winter. This is an important issue from the perspective of setting low flows for instream flow requirements. If the M2 separations were to be accepted it may be concluded that low flows in dry years would have a different seasonal distribution to low flows in wet years.

T3H002 – Kinira River

The Kinira River drains the Eastern Cape Drakensberg and is a tributary of the Mzimvubu River. The daily time series are characterised by frequent events superimposed on a baseflow response that is not as persistent as for X3H003. The late wet season skew of the M2 is much more evident for these data (Fig. 3). Relative to the daily separations, the M2 seasonal baseflow distribution is heavily shifted to the right.

J3H012 – Groot River

This is a Karoo river that drains the Swartberg Mountains and can be characterised as an event driven system that experiences baseflows during, and for a relatively short period after, main events. Consequently, it has a quite low baseflow proportion (Table 1) and suffers from the same problems as T3H002 when the M2 baseflow separation is applied (Fig. 4).

Q6H003 – Baviaans River

The Baviaans River is a tributary of the Great Fish River in the Eastern Cape and is the most arid example used in this paper. While it appears to be very difficult to get satisfactory agreement between daily and monthly baseflows using either monthly model (Fig. 5), the M1 approach generates a seasonal distribution which is more similar to the results based on daily data.

W5H005 – Hlelo River

The Hlelo River is a South African tributary of the Great Usutu River that flows through Swaziland. It has characteristics that are midway between X3H003 and T3H002, with a relatively strong seasonal baseflow response but more frequent and relatively larger events than X3H003. There are very slight differences in the shapes of the seasonal distributions, although the M1 separations result in a shape slightly more similar to the daily separations (Fig. 6).

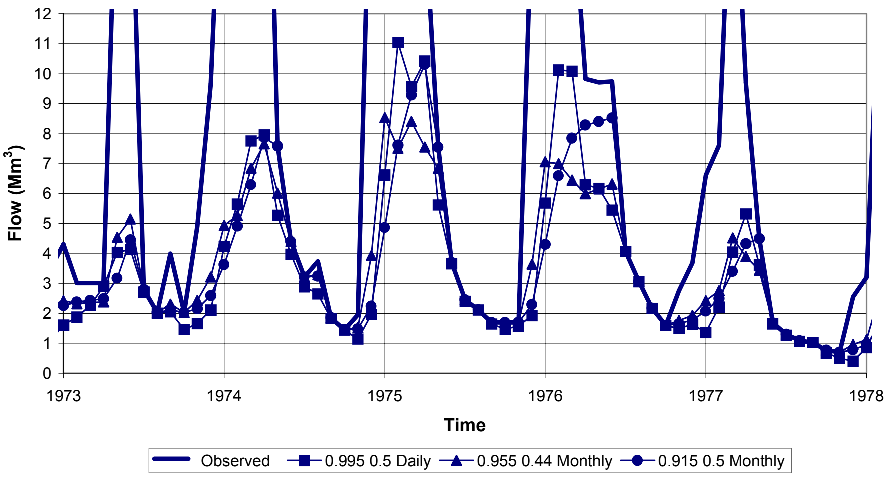

Figure 6
Observed flows and separated baseflows for gauge W5H005

General

In catchments such as X3H003, it is possible that many of the early wet season baseflows are under-represented by the daily separations, particularly during wet years. This is related to the format of the separation equation and the fact that the whole wet season gets treated as a single high-flow event. The fact that the M1 separations generate earlier peaks than the daily could therefore be an advantage.

The biggest differences between M1 and M2 appear to occur when the wet season flows are largely made up of quite frequent high-flow events, separated by relatively low baseflows. Examples can be seen in Fig. 3 (1992), Fig. 4 (1971 and 1972) and Fig. 6 (1976). In the daily separations, the early wet season baseflow response is made up of individual event baseflows, which are then aggregated to monthly values. The M2 separation procedure is not able to respond quickly enough in the season to reproduce this pattern, as the whole wet season appears as a single event. Given the constraint of having to reproduce the same mean volume of baseflows as the daily results, an excessive volume of baseflow is therefore generated for the late wet season.

Although the differences in β for the six gauging stations referred to in Table 1 appear to be relatively small, they are nevertheless important. For example, if the β parameter for Q6H003 is changed to 0.44 (closer to the value for the other gauges) the mean baseflow proportion changes to almost 15% of total flows. The effect of differences in β for the wetter catchments, where the α parameter value is generally lower, are much smaller suggesting that the sensitivity of the results to variations in β will increase with the aridity of the catchment and with increases in parameter α.

Discussion and conclusions

There seems to be little doubt that the separation equation is designed to work most effectively with short time-step data and that even a daily time step is too long in some catchments. This is largely because, like most baseflow separation procedures, it was originally designed to operate on individual events, which may have multiple peak flows, but has one main baseflow event. As soon as flow data are aggregated, individual events become obscured and at the scale of monthly data, a single season looks like a single event.

There is no simple solution to this problem, although the introduction of the second parameter (β) certainly improves the monthly baseflow separations in most flow regime types, while in others there is very little difference between the M1 and M2 separations. The examples provided in this paper are part of a country-wide regionalisation study that was designed to quantify baseflow separation parameters (α and β) for the 22 regions of South Africa that are currently defined within the Desktop Reserve model (Hughes and Hannart, 2003). The conclusions of the study have been that the regional separation parameters for monthly data are satisfactory, given the limitations of our knowledge and of the separation algorithm itself.

Despite the comments made earlier that there is a conceptual understanding of runoff generation processes for South African rivers, there are some deficiencies and most of them are related to the source and relative importance of baseflows. In particular, greater clarity is required about the interactions between surface- and groundwater in those areas where baseflows appear to contribute substantially to the total flow (X3H003 is an example). This information is not essential for the river component of the ecological reserve, as the instream flow requirements are related to what is in the channel and not why or how it got there. However, it is important in some areas for linking the groundwater and river components of the reserve and for developing sustainable strategies for the integrated development of surface- and groundwater. Such information, even for a limited number of representative catchments, would also provide the necessary quantitative support for the calibration and application of simple separation methods as discussed in this paper.

In the introduction it was stated that process-based separation methods are resource intensive. However, there is a clear need for further studies of this type, not only to validate existing continuous separation procedures but also to provide a quantitative basis for the further improvement of simple separation techniques that can then be used with greater confidence for a variety of applications.

Acknowledgements

A large part of the hydrological research that is undertaken by the Institute for Water Research is funded by the Water Research Commission of South Africa. This study forms part of the 'Reserve Programme' of the WRC.

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