Problems of estimating hydrological characteristics for small catchments based on information from the South African national surface water resource database

DA Hughes
Institute for Water Research, Rhodes University, Grahamstown 6140, South Africa

Abstract

Rapid assessments of water resource availability in South Africa have been facilitated by the availability for a number of years of a national data set of naturalised monthly flow time series. However, these data are only available for moderate to large catchments (referred to as quaternary catchments). In the absence of further information it has often been the practice to apply a simple catchment area-based scaling factor to estimate subquaternary scale flow characteristics. This has proved to be problematic in many studies. The paper presents a comparison of quaternary and subquaternary flow data using 41 gauged catchments and develops a simple approach to scaling based on estimates of the mean annual rainfall characteristics for the two areas. The use of the scaling method in a model designed to provide preliminary, low-confidence, estimates of environmental flow requirements suggests that it represents an improvement. However, there is still a need for a method that allows flows of different magnitudes and frequencies of exceedance to be scaled differentially.

Keywords: flow regimes, small catchments, scaling, environmental flows

Introduction

The *Surface Water Resources of South Africa* publications (WR90 – Midgley et al., 1994) have provided a valuable source of baseline regional hydrological and water resource information for many years. Part of its value is that the data were generated using consistent approaches and cover the whole of South Africa, Lesotho and Swaziland based on a spatial subdivision into 1 946 so-called quaternary catchments, varying in size from 50 to 18 000 km^2 (with a median size of 445 km^2). The database includes 70-year time series (based on a standard period of 1920 to 1989) of naturalised monthly streamflow volume and monthly rainfall depth for each quaternary catchment, as well as naturalised flow data for all the Department of Water Affairs and Forestry (DWAF) streamflow gauging stations that had more than about 5 years of data prior to 1989. The quaternary streamflow data were generated using the WRSM90 version of the Pitman (1973) monthly rainfall-runoff model based on regionalised parameter values.

While there have been some questions about the representativeness of the WR90 flow data in some parts of the country, the database has nevertheless proved to be one of South Africa's major water resource information assets. However, there is one major problem for some water resource assessments and that is the extent to which the data can be used to estimate the natural hydrological characteristics of catchments smaller than the quaternary scale. This issue has been frequently highlighted during recent studies to determine the environmental instream flow requirements of rivers with subquaternary scale catchments. A number of these studies have been undertaken in recent years as part of the process of implementing the new South African National Water Act (No. 36 of 1998). Hughes and Hannart (2003) report on the development of a model that makes use of time series of natural flow data and a set of regional parameters to provide an initial estimate of the environmental flow requirements for different levels of protection. The basis of the model is that the requirements are expected to vary with the magnitude and variability characteristics of the natural flow regime of the river. The WR90 streamflow database provides the default natural flow data to use with the model (i.e. in the absence of any updated or revised flow data) and the only facility within the model for modifying these data is a simple linear scaling function. Therefore if the model is to be applied at the subquaternary scale it is necessary to be able to estimate the proportion of the total quaternary catchment runoff that is generated above the point of interest.

The relationship between flow volumes from a subcatchment and the total flow volume for the whole catchment will depend upon a wide range of factors, the following being some examples:

- Rainfall variations over the total catchment and particularly the rainfall gradient from the lower parts of the total catchment to the upstream areas. The extent to which these variations are consistent over time will also be of importance.
- Evaporation variations due to elevation and slope differences, as well as differences in vegetation cover.
- The variations in soil, geology and land-cover characteristics and the way in which these all influence runoff generation processes.

These factors will clearly affect the relative total volumes of runoff generated from the subcatchment and total catchment, but they could also affect different components of the flow regimes (high and low flows for example) in different ways. There will therefore be no simple and consistent relationship between the quaternary catchment flow and the subcatchment flow and certainly the commonly used method of scaling the runoff volume on the basis of the ratio of catchment areas is unlikely to be adequate in most

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☎+2746 622-4014; fax: +2746 622-9427; e-mail: denis@iwr.ru.ac.za
Received 3 July 2003; accepted in revised form 31 March 2004.

cases. While information on the catchment characteristics of the area may be available with sufficient spatial resolution to distinguish between the total catchment and subcatchment, translating that information into quantitative flow regime differences is less straightforward. A rainfall-runoff modelling approach could be used, but there would always be a measure of uncertainty about the validity of the model parameter values due to the lack of flow data against which to assess the simulations. Any method used will generate results with uncertain confidence and therefore it is appropriate to suggest that a relatively simple and easy-to-use approach could be just as good as a more complex and time-consuming one.

This brief contribution presents the results of a short study to investigate the relationships between flow volumes generated from gauged subquaternary size catchments and the total flow for the associated quaternary catchment.

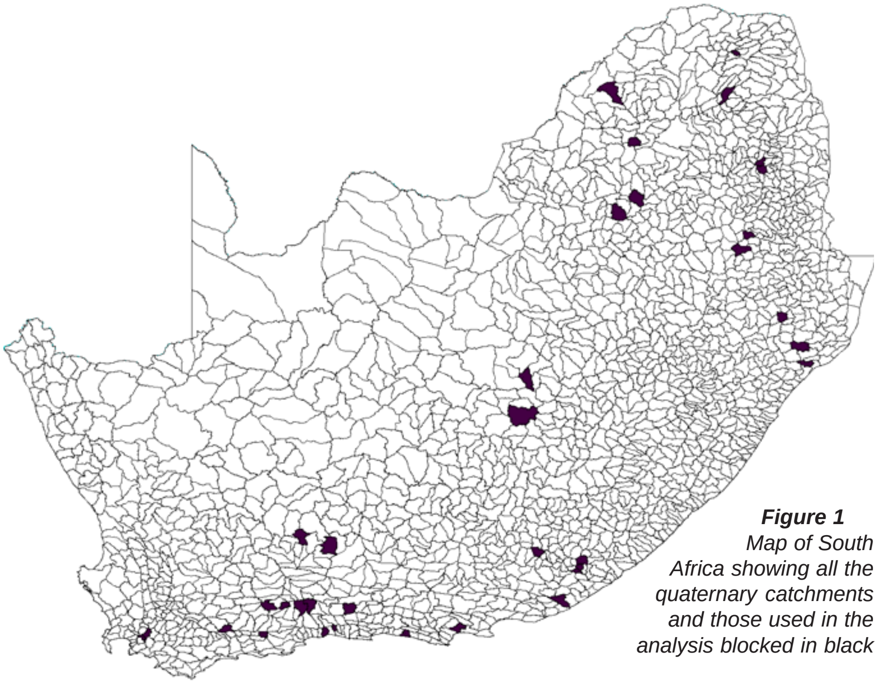

Figure 1
Map of South Africa showing all the quaternary catchments and those used in the analysis blocked in black

Data and methods

It is important that the data for the tributary catchments and the total quaternary catchments are as consistent with each other as possible. It also has to be recognised that most of the gauged catchments in South Africa have undergone some form of anthropogenic alteration, either to the land cover, or directly to the flow regime. The WR90 database includes naturalised data for a large number of gauged catchments and 41 of these represent subquaternary scale catchments (with areas between 15 and 593 km^2) with more than 10 years of data. The flow data are far from perfect and some of them have been patched where missing data occur. However, they are consistent with the quaternary scale simulated flow data that also forms part of the database. The same naturalisation process (removal of artificial impacts on the flow regime) was used in the generation of the two data sets. The gauge data were also used during the Pitman model calibration process that formed the basis of the regional model parameters and that were used to generate the quaternary catchment flows. The two sets of time series data (naturalised, patched gauge data and simulated quaternary data) should therefore be sufficiently comparable to be used in an assessment of flow regime differences.

The complete analysis was undertaken using the facilities available with the SPATSIM (Spatial and Time Series Information Modelling) software package (Hughes, 2002). SPATSIM combines a system for accessing time series and other data through a spatial data interface with a wide range of data processing, display, analysis and modelling tools. It is a very efficient tool for undertaking the type of simple, but repetitive, analyses that have formed the major component of this short study. The standard application of SPATSIM used at the IWR for a wide range of analyses and model applications already included the majority of the WR90 data. The following data were extracted or generated using the SPATSIM database and analysis utilities:

- Gauged and quaternary catchment areas
- Quaternary catchment mean annual precipitation (MAP).
- Mean monthly runoff (MMR) volume for the gauged and quaternary catchment streamflow time series over the gauged period (between 10 and 69 years)
- Mean value of the natural logarithms of non-zero monthly runoff volumes over the gauged period (which allows the medium to low flows to have a stronger influence on the mean than if non-transformed flow data are used), back transformed to a flow value (MMLR)
- The 1-month flow duration curve (FDC) data for the quaternary and gauged flow volumes.

These data were then used to generate the ratios of the gauged and quaternary areas and the ratios of gauged and quaternary MMR, MMLR and flow at various FDC % points. The flow ratios were then divided by the area ratio to generate values that represent the degree to which the gauged subcatchments generate more (or less) runoff per unit area.

In order to generate a representative value for average rainfall over the gauged areas, the gridded 1’ x 1’ mean annual rainfall data database (grid-point locations and data values), developed by the School of Bioresources Engineering and Environmental Hydrology at the University of Natal, Pietermaritzburg (Dent et al., 1988), was imported into SPATSIM. The catchment areas of the gauged tributaries were roughly identified with the assistance of 1:250 000 scale topographic maps and all the 1’ x 1’ grid points lying within the boundaries identified. An estimate of the mean annual rainfall for the gauged catchments was taken to be the arithmetic average of the entire grid mean annual rainfall values. The ratio of gauged to quaternary mean annual rainfall was then calculated for all the catchments. One possible criticism of the method is that the mean annual rainfall for the gauged and quaternary data is drawn from two different sources. However, both sources are based on the same original information and several checks suggested that there would not be substantial differences between the quaternary MAP values derived by the two methods.

Figure 1 illustrates the distribution of the catchments used in the analysis and Table 1 lists all the DWAF station identification numbers, associated quaternary catchment name and ratio values.

Results

Figure 2 indicates that there is a large scatter in the relationships between the area ratios and the ratios of MMR and MMLR. Figure 3 illustrates the relationship between the ratio of the gauged to quaternary MAPs (MAP Ratio) and the ratio of the MMR ratio to the Area ratio (which is the ratio of gauged to quaternary runoff per unit area), while Fig. 4 represents the equivalent diagram for the analysis based on log- transformed flow values. In Fig. 3 the five data points which have MMR/Area ratios of greater than 3.0, or less than 0.4, have been excluded from the diagram and the estimated regression equation. These were found to constitute outliers, which prevented the regression line from adequately representing the relationship for the other points. In Fig. 4, the same three high-ratio value points were found to be outliers, but there were an additional two points (with MMLR/Area ratios of greater than 5) that were also excluded. It is clear that the relationship based on MMR is better than that based on MMLR.

TABLE 1
List of gauged catchments, equivalent quaternary catchment and the ratio data used in the analyses

Gauge	Quat	Area Ratio	MMR Ratio	MMLR Ratio	MMR/ Area Ratio	MMLR/ Area Ratio	MAP Ratio
J2R001	J25D	0.18	0.73	1.17	4.14	6.67	1.13
J3H015	J35A	0.16	0.53	1.10	3.24	6.74	1.17
H7H004	H70C	0.10	0.31	0.69	3.22	7.10	0.86
R2H012	R20C	0.12	0.37	0.38	2.95	3.09	1.44
J3H016	J33A	0.07	0.18	0.27	2.46	3.76	1.34
L9R001	L90C	0.46	1.12	2.39	2.44	5.18	1.13
J3H014	J35A	0.35	0.82	1.83	2.33	5.19	1.17
R2H001	R20A	0.21	0.43	0.50	2.05	2.41	1.31
Q9H013	Q93D	0.09	0.19	0.27	1.99	2.89	1.07
B8R003	B81B	0.13	0.26	0.28	1.99	2.08	1.20
J2R004	J21A	0.11	0.23	0.36	1.99	3.16	1.22
J2R003	J22G	0.25	0.45	0.75	1.81	3.03	0.99
S6R001	S60A	0.07	0.12	0.11	1.69	1.57	1.12
J3H018	J35D	0.27	0.45	0.84	1.66	3.11	1.27
A6H011	A61A	0.19	0.30	0.45	1.57	2.37	1.02
A2H042	A21C	0.54	0.78	0.58	1.46	1.08	1.04
S6H001	S60A	0.27	0.39	0.39	1.43	1.42	1.12
H6H007	H60B	0.22	0.31	0.54	1.43	2.48	1.07
H6H008	H60A	0.52	0.72	1.18	1.39	2.26	1.19
H9H004	H90A	0.28	0.38	0.36	1.38	1.30	0.87
K8H001	K80C	0.19	0.24	0.25	1.31	1.36	0.96
K3H001	K30C	0.25	0.31	0.25	1.26	1.02	1.06
W1H005	W12C	0.08	0.10	0.12	1.25	1.51	1.06
A2H028	A23A	0.24	0.29	0.26	1.24	1.09	1.01
A2H027	A23A	0.52	0.63	0.58	1.21	1.11	0.99
W5H004	W53A	0.84	0.96	0.82	1.15	0.98	0.99
K8H002	K80C	0.19	0.19	0.18	1.04	0.98	0.96
W2H007	W22B	0.23	0.24	0.26	1.04	1.09	1.14
X2R003	X22D	0.23	0.24	0.21	1.03	0.91	1.05
Q9H014	Q92A	0.76	0.77	0.67	1.01	0.88	0.97
A2H029	A23A	0.19	0.18	0.20	0.94	1.05	1.00
J2H005	J25B	0.64	0.58	0.49	0.91	0.77	1.08
A9H007	A91D	0.36	0.32	0.33	0.91	0.94	1.05
A6H006	A61A	0.44	0.38	0.50	0.85	1.14	0.99
W1H004	W13A	0.07	0.06	0.05	0.84	0.73	1.01
C5H007	C52F	0.51	0.42	0.47	0.82	0.94	0.98
C5H008	C51B	0.35	0.27	0.54	0.77	1.54	1.06
K4H003	K40A	0.83	0.56	0.47	0.68	0.56	0.99
X3H002	X31A	0.24	0.12	0.11	0.48	0.45	0.95
W5H001	W55B	0.07	0.02	0.02	0.26	0.27	1.07

Figure 5 illustrates the relationship between the MMR/Area ratio and the MMLR/Area ratio, which is surprisingly good. In this diagram none of the previously excluded points have been left out. It is apparent that the relationship between the ratios based on MMR and MMLR is extremely good for MMR/Area ratios up to about 3.0, but less good for catchments where the smaller catchment contribution is much greater (relative to catchment area) than the quaternary catchment. This is a result that is intuitively understandable. As the contribution of a subcatchment increases relative to the total contribution of a quaternary catchment, there are potentially a wider range of range of conditions that could cause that increase, such as:

- Relatively greater high flows due to higher rainfall, steeper slopes and thinner soils.
- Relatively greater low flows due to more sustained baseflows in wetter headwater areas.
- Relatively greater low flows due to transmission losses in drier downstream areas.

The relative importance of any of the above effects (or others not listed) will be dependent upon the specific topographic, climate, soil and vegetation variations that occur within the quaternary catchments. Figure 6 illustrates the relative importance of the different percentage points of the flow duration curves in terms of contributing to the differences in flow response of the gauged and quaternary catchments. The values plotted on the vertical axis are the ratios (gauged to quaternary catchments) of the flows per unit catchment area for the defined FDC % points normalised by dividing by the MMR/Area ratio (see Table 1). A value of 1 therefore represents a relative contribution to the flow differences that is equivalent to the mean monthly difference. Values higher than 1 suggest a relatively greater contribution. For Q9H014 (MMR/Area ratio = 1.01) the moderate to high flows (10 to 30% exceedance) appear to dominate. For H6H007 (MMR/Area ratio =

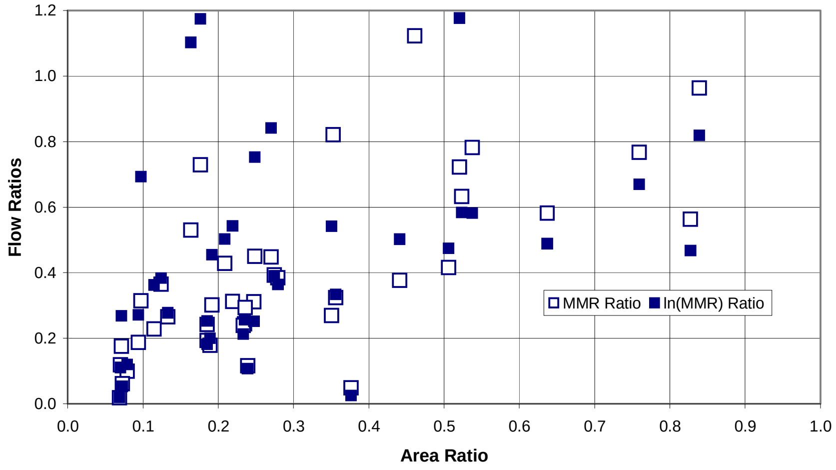

Figure 2
Relationships between the ratios of catchment area to ratios of both MMR and MMLR for all the combinations of gauged and quaternary catchments listed in Table 1

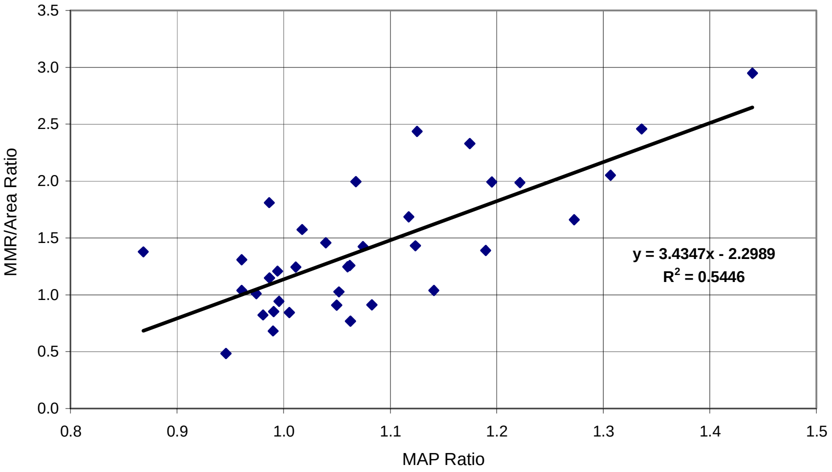

Figure 3
Relationship between the MAP Ratio and MMR/Area ratio

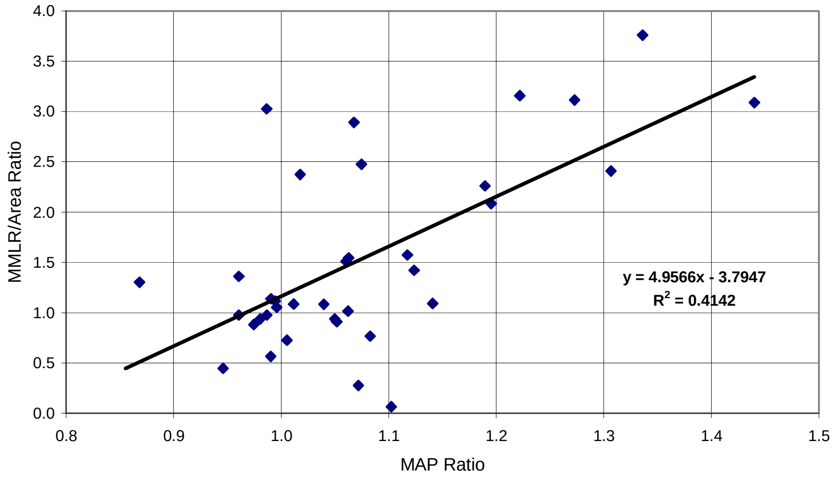

Figure 4
Relationship between the MAP Ratio and MMLR/Area ratio

1.43) the relative difference in flow is largely related to enhanced low flows. For J2R004 (1.99), the moderate to low flows appear to play the major role. For some of the catchments (R2H001: ratio = 2.05, A6H006: ratio = 0.85, for example) both the high and the low flows contribute relatively less than the moderate flows. This could be the result of other tributaries in the total quaternary catchment having more dominant high- and low-flow impacts than the gauged tributary. In the case of R2H001, a large proportion of the total quaternary catchment is within an area of steep topography and high rainfall. A6H011 is within the same quaternary catchment as A6H006 but has a much higher MMR/Area ratio (1.57).

Table 2 presents some results of using the relationships derived during this study for the purposes of obtaining preliminary, low-confidence, estimates of the low-flow components of the ecological Reserve (environmental flow requirements) for rivers. Hughes and Hannart (2003) discuss the background to and details of the so-called Desktop Reserve Model. The basis of the model is to make use of a time series of natural monthly flows to derive the flow variability and magnitude characteristics of a river at a specific point. The flow variability characteristics are based on a hydrological index, which is calculated from a combination of monthly coefficients of variance (standard deviation/mean) and an estimate of the contribution that baseflows make to total flows (Hughes et al., 2003). This index is used together with the mean annual runoff and a set of regional parameters to estimate the drought and maintenance low-flow environmental requirements. The drought and maintenance requirements provide the basis for estimating the full range of flow requirements for different levels of assurance (or different frequencies of occurrence). An option is provided in the model to scale the time series of flows in case they are associated with a different location on the river. Note that the hydrological index is the same when the quaternary data are used, as the scaling factor is always linear.

As an illustration, the ratio of catchment areas for gauge R2H001 is 0.21, while the MAP ratio is 1.31 (Table 1). The estimated MMR/Area ratio based on an MAP ratio of 1.31 is 2.2, suggesting that the quaternary flows should be scaled by 0.21*2.2 = 0.46 to obtain a more representative time series of subquaternary flows for this catchment. The '*Gauge Data*' requirements are based on using the gauged time series, the '*Quat. Area Adj*.' requirements are based on a area ratio scaling factor (0.21 for R2H001), while the '*Quat. New Adj*.' requirements are based on the corrected scaling factor (0.46 for R2H001).

Discussion and conclusions

While the analyses presented suggest that the ratio of MAPs over the tributary to the total quaternary catchment can explain some of the differences in runoff per unit area, there is a substantial scatter in this relationship. Where the tributary runoff per unit area is much greater (more than 3 times) than the quaternary catchment, there is even greater scatter. Given the available data on subquaternary flows, it is difficult to generalise about the relative contributions of different components of the flow regimes (based on flows at different FDC % points). This means that there is no basis for developing a generic approach to differentially adjusting the components of a quaternary catchment flow regime to create a more representative time series at the subquaternary scale.

Table 2 summarises the results of using the regression equation provided in Fig. 3 to derive an adjustment to the ratio of catchment areas from the ratio of MAPs for the subquaternary and quaternary catchments. The objective is to improve the estimate of the scaling factor used with quaternary flows within the Desktop Reserve Model to obtain more representative estimates of environmental flow requirements at the subquaternary scale. It is clear from Table 2 that in four out of the six examples the estimates are greatly improved, while in the other two cases (Q9H014 and X3H002) there is little difference between the simple adjustment based on area vs. that based on the new method. It can be seen that in some cases the hydrological index value is similar for the quaternary and for the gauged tributary; however, in other cases (H6H007 and J3H016) they are very different. In the case of H6H007 the new adjustment provides a good approximation of the gauge MAR but the higher hydrological index value associated with the quaternary catchment flow regime results in still quite poor estimates of the flow requirements. The results for Q9H014 reflect the same effect but to a lesser degree and in this case the over-estimation of the MAR is compensated for by the higher hydrological index.

The only way to resolve the issue of adjusting the hydrological index value as well as the MAR is to apply a differential adjustment to flows depending on their position on the FDC (for example). It can be seen from Fig.6 that the application of such an approach to gauge H6H007 would have reduced the quaternary catchment low flows to a much lesser extent than the moderate to high flows. This would have generated higher low flows for the subquaternary area and had a substantial impact on the baseflow estimation approach used within the Desktop Reserve Model. The results would have been a reduced hydrological index of the adjusted quaternary catchment time series. While for this catchment the overall result would have been better, it was noted in the first paragraph of this discussion that there is no generic basis for a differential adjustment of flows.

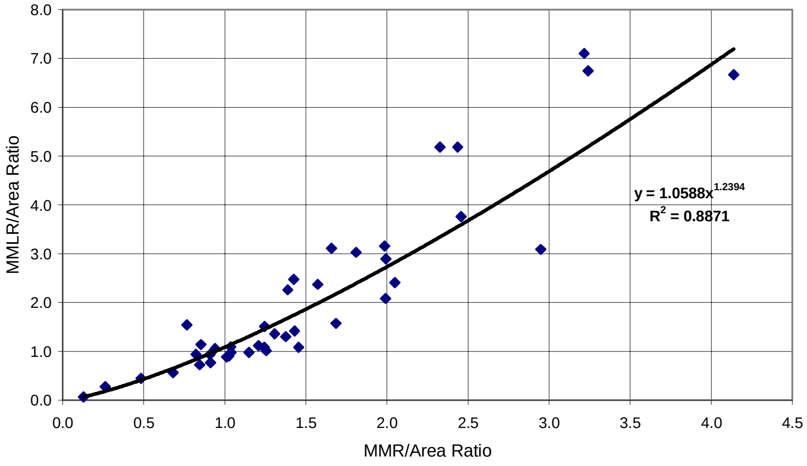

Figure 5
Relationship between the MMR/Area Ratio and MMLR/Area ratio

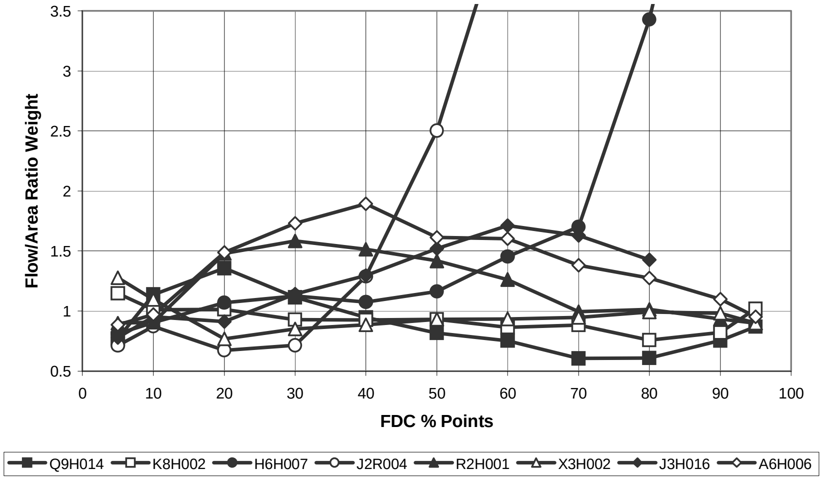

Figure 6
Relative importance of different % points of the flow duration curves in terms of contributing to the differences in flow response of the gauged and quaternary catchments (see text for an explanation of the vertical axis)

The analyses undertaken for this study have been based on imperfect data and the confidence in the results should reflect that fact. However, these are the same data that are often relied upon in relatively rapid water resource analyses, especially those designed to provide a preliminary estimate of the environmental flow requirements of rivers. The analyses suggest that the proposed new scaling method for assessments at the subquaternary scale can generate improved estimates and are not worse than results given using a simple catchment area based scaling approach. It is clear that differential scaling of flows, rather than a fixed scaling factor, would be beneficial. Under such situations, not only would the MAR be adjusted, but so would the variability characteristics and hence the hydrological index used in the Desktop Reserve Model. Similar improvements in estimation accuracy can be expected from other models that are dependent upon a reasonable representation of the flow regime variability characteristics (such as estimating yields and runoff-river abstraction reliabilities). The method is appropriate to rapid appraisals of small-scale water abstractions such as might be used in the initial design of rural water supply schemes.

The data required to apply the methods discussed are all readily available and can be applied without complex software and analytical methods. A differential adjust-

TABLE 2

Results from the Desktop Reserve Model using gauged tributary flows and quaternary flows adjusted by catchment area and by the regression equation given on Fig. 3 (the percentage difference values are the values of the quaternary based estimates compared to the estimates based on gauged data and the bold values indicate improvements of the new adjustment).

Gauge ID No.	R2H001	H6H007	Q9H014	X3H002	B8R003	J3H016
Gauge Data						
MAR (m^3*10^6)	10.22	36.60	13.73	14.46	51.60	0.83
Hydro. Index	7.89	3.32	9.00	2.05	2.51	14.89
Drought (m^3*10^6)	0.28	2.97	0.49	1.48	4.83	0.00
Maint.(m^3*10^6)	1.86	9.65	2.37	4.74	15.44	0.12
Quat. Area Adj.						
MAR (m^3*10^6)	4.92	26.08	16.52	31.66	30.26	0.51
Hydro. Index	11.66	8.97	10.67	1.75	2.44	24.43
Drought (m^3*10^6)	0.14	1.12	0.52	3.56	2.88	0.01
% Difference	-50	-62	6	141	-40	N/A
Maint.(m^3*10^6)	0.77	4.52	2.67	11.17	9.16	0.06
% Difference	-59	-53	12	136	-41	-48
Quat. New Adj.						
MAR (m^3*10^6)	10.78	35.56	16.95	30.43	55.87	0.82
Drought (m^3*10^6)	0.31	1.53	0.53	3.41	5.32	0.01
% Difference	**11**	**-48**	8	130	**10**	N/A
Maint.(m^3*10^6)	1.68	6.16	2.74	10.70	16.91	0.10
% Difference	**-10**	**-36**	15	126	**10**	**-17**

ment could be made to the monthly flows based on local knowledge, but this would require a greater level of hydrological experience. It is the intention of the author to continue with the study and to make use of additional information (that is less readily available) to investigate the possibility of regionalising the differential scaling factors of flows at different FDC percentage points.

Acknowledgements

This study was undertaken as part of two Water Research Commission funded projects associated with the determination and implementation of environmental flow requirements (the ecological Reserve).

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