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Model parameter values and hydrological homogeneity: a study of three rivers in Botswana

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Abstract

The flow duration curves for catchments grouped into a hydrological region using the Monash Model were compared, and the statistical characteristics of the exceedance series studied. The results indicate that the three catchments grouped into the same region differ markedly from each other in their hydrological characteristics, including the 1.4-year return period flow, the mean floods above the 1.4-year flow, the number of floods per year exceeding the 1.4-year flow, the duration of the flood, the date of occurrence of the flood and the statistical distribution of their exceedance series. All three catchments however have steep flow duration curves.

Introduction

Hydrological regionalisation is a useful tool in hydrology, especially where little data are available, and the technique has received wide attention in the literature (Dalrymple, 1960; Benson, 1962; Farquharson *et al.*,1992). The first step in regionalisation is to define the region (Haan, 1977), although later studies have tended to ignore this requirement. Regional boundaries have been defined in terms of similarity of flood frequency curves or flow duration curves (NERC, 1975; Haan, 1977). It is assumed that all catchments included in a particular region have similar response characteristics. Dalrymple (1960) discusses a test for determining if flood frequency curves for a region can be considered homogeneous.

In the recent Botswana National Water Master Plan Study (SMEC, 1992), the deterministic Monash Model (Porter and McMahon, 1971) was applied to a number of catchments in eastern Botswana, and based on the results of the modelling, the catchments were grouped into regions. The results of the modelling, for the study region, indicated that three catchments, which differ in size but are geographically adjacent, returned the same values for all but two of the model parameters. In view of the limitations of deterministic models, it may be instructive to investigate the common characteristics that these catchments share.

Catchments differ in physical characteristics such as area, slope, drainage density, shape, soils, antecedent moisture condition and vegetation cover; and the characteristics of the rainfall such as duration, intensity, frequency and volume. The catchment transforms the rainfall input into runoff, and differences or similarities are reflected in the runoff hydrograph. This study focussed on the flow duration curves of the rivers, as well as the statistical characteristics of their exceedance series.

Study area and data

The three catchments chosen for this study, situated in the eastern part of Botswana (Fig. 1), are the Motloutse at Tobane, Lotsane at Maunatlala and the Mahalapswe at Madiba, all tributaries of the Limpopo. They are located south of the 20°S latitude; here the tropical controls on the rainfall process, notably the Inter Tropical Convergence Zone, weakens and 'drought-producing' anticyclones take over (Bhalotra, 1984). The catchments lie to the east of the meridionally aligned 400 mm isohyet. In this region the main influences on precipitation are the weak subsidence resulting from the marked eastward displacement of the Indian Ocean

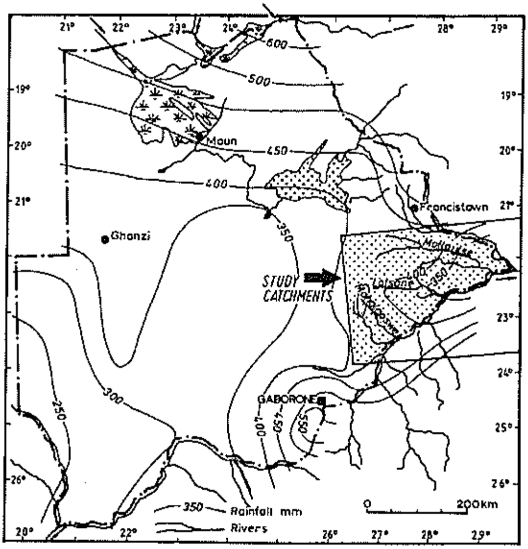

Figure 1 - Study area, eastern Botswana

anticyclone during the summer, and the onshore winds over the warm waters of the Agulhas Current. Average rainfall in this region ranges between 350 mm and 450 mm per annum, with an annual variability of 35% to 45%. The rainfall occurs during the rainy season (November to March), in spells lasting a few days at a time. These wet spells are normally associated with one dominant synoptic condition and quite often give rise to some very high flows.

The three catchments are gauged by the Department of Water Affairs. They differ in size and have varying lengths of records (Table 1). These catchments were grouped into one hydrological region on the basis of the Monash Model (Table 2) (SMEC, 1992).

Table 1 - Particulars of study catchments

Name of river	Catchment area, km²	Length of data used (years)
Motloutse at Tobane	7,930	20
Mahalapswe at Madiba	754	16
Lotsane at Maunatlala	6,385	11

Table 2 - Optimised parameter values for the study catchments

Parameter	Motloutse	Mahalapswe	Lotsane	Regional
COEFF	310	310	310	310
SMSC	175	175	175	175
DSC	3.0	3.0	3.0	3.0
EM	10.0	10.0	10.0	10.0
ADS	0.1	0.1	0.1	0.1
SUB*	0.26	0.26	0.16	0.26
CRAK	0.3	0.3	0.3	0.3
CPDAY	0.0	0.0	0.0	0.0
CINS	1.0	1.0	1.0	1.0
DM	1.0	1.0	1.0	1.0
ZDAY	0.3	0.3	0.3	0.3
ALEAK	0.0	0.0	0.0	0.0
SQ	1.5	1.5	1.5	1.5
CO	8.0	8.0	8.0	8.0
RFMIN*	18.0	25.0	27.0	20.0
SEAS	0.27	0.27	0.27	0.27
LOCAT	9.0	9.0	9.0	9.0

[Parameters whose values differ. See Appendix I for definitions of the parameters.]*

Monash model results

The Monash Model is described in detail in Porter and McMahon (1971). The method of calibration yielded the results in Table 2. In the original model, univariate adjustments and steepest ascent optimization techniques, "governed by common sense", were recommended as "the most useful means of achieving rapid convergence" (Porter and McMahon, 1971). In fitting the Monash Model to the three catchments, the optimization procedure adopted was trial and error. This can be considered a form of univariate adjustment in which the parameters were changed until certain conditions were achieved. The performance of the model (SMEC, 1992) was assessed using

- (i) simulation of average monthly runoffs and their variances,
- (ii) comparison of observed and estimated runoffs on a monthly and annual basis by time series and scatter diagrams,
- (iii) evaluation of statistical parameters including coefficients of determination and efficiency, and average bias of monthly runoffs,
- (iv) preparation of residual mass curves, and
- (v) comparison of monthly and annual flow duration curves.

Table 3 - Results of calibration of the Monash Model for the study catchments

STATISTIC	RIVER		
	MAHALAPSWE	LOTSANE	MOTLOUTSE
Monthly mean (10^6m^3):			
observed	1.02	4.4	7.1
estimated	1.01	4.0	7.2
Monthly std. dev. (10^6m^3)			
observed	3.41	20.9	21.1
estimated	4.37	19.3	20.8
Average bias (%)	-1.3	-7.3	1.5
Coefficient of determination	0.75	0.95	0.70
Coefficient of efficiency	0.57	0.96	0.67
Monthly standard error (10^6m^3)	2.2	4.17	11.5
Log mean:			
observed	0.68	1.13	1.75
estimated	0.76	1.21	1.80
Log standard deviation:			
observed	0.81	0.75	0.47
estimated	0.59	0.66	0.39

The results (Table 3) indicate that these conditions were largely satisfied using the parameter values listed in Table 2. The floods are adequately modelled by the Monash Model, in fact, they are better reproduced than the low flows. The three catchments can be modelled with virtually the same values for the parameters of the Monash Model. In an arid climate spatial variability of rainfall can impose distinctive patterns of catchment response, even in geographically adjacent catchments, and given the limitations of models, these results are interesting. What hydrological characteristics do these catchments have in common? This question is investigated by studying the observed flow duration curves of these rivers.

Methods

Flow duration curves

The methods for constructing flow duration curves are widely covered in the literature (e.g., Raudkivi, 1979; Gupta, 1989). To facilitate comparison, the mean daily flows were divided by the catchment areas.

Analysis of peak flows

If the three catchments are from a hydrologically homogeneous region, the flows recorded in each catchment may be considered as a sample from the population of flows in that region. In that case, peak flows from these rivers should have identical statistical characteristics. To investigate this hypothesis, peak flows during every wet spell for the years of data were subjected to a partial duration series analysis. The partial duration series analysis is preferred to a complete duration series analysis (i.e., one maximum event per time period, e.g. year) when data is limited. Depending on the truncation level chosen, more peaks can be included in the analysis than there are years of data. This is a desirable feature, particularly in an arid environment where flow is so variable that minor peak flows in years of good rainfall may far exceed the principal peak flow of other years. Excluding such minor peak flows from the analysis could represent a significant loss of information.

For partial duration series analysis two criteria must be defined - the truncation level and the independence of selected peaks. There are no generally accepted methods of determining either of these. The rule of thumb for determining the independence of high flow events suggested by Taesombut and Yevjevich (1978) was adopted in this paper. Consecutive events separated by days in excess of [5 + ln(basin area, km^2)] days were taken as independent. If an independent event consisted of several peaks, only the highest peak was selected. Determination of a truncation level is more problematic; there is no generally accepted method. For example, the American Society of Civil Engineers (1949) recommended that the

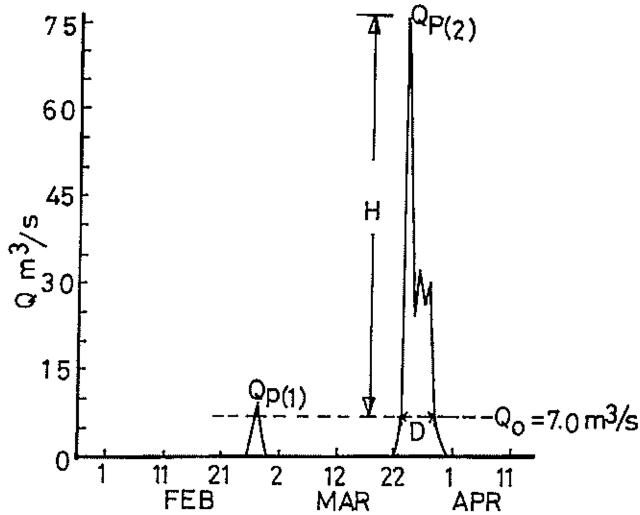

Figure 2 - Definition of exceedance terminology using flow events for the Lotsane river.

truncation level should be selected so that the number of peaks exceeding it is greater than the number of years of data, but there should be no more than 3 or 4 exceedances in any one year. The US Geological Survey recommended selecting a truncation level so that there were three times as many exceedances as there are years of data. The choice of a truncation level is even complicated by the statistical distribution fitted to the data (Tavares and da Silva, 1983; Jayasuriya and Mein, 1985; NERC, 1975). In this study, the truncation level was selected so that there is at least one flood per year of data. The threshold discharge was decided from a frequency analysis of the annual maxima series. The discharge that satisfied the above requirement for each catchment approximated to a discharge of a return period of 1.4 years. Additional truncation levels were then fixed arbitrarily at 1.6, 2.0, 2.33, 5.0, and 10.0 -year return periods.

Figure 2 illustrates the terminology associated with a partial duration analysis. A high flow event is defined as an upward crossing and a subsequent downward crossing of the truncation line. Such an event has magnitude, H, which is equal to the difference between an observed peak, $Q_{p(i)}$, and the truncation level, Q_0. The peaks above the truncation level form an exceedance series. The time between the upward and downward crossings is the duration, D. Many aspects of the exceedance series may be statistically analysed (Todorovic and Rouselle, 1971; Todorovic and

Woolhiser, 1972; Rouselle and El-Jabi, 1977; Todorovic, 1978; North, 1980; Ashkar and Rouselle, 1981; Waylen and Woo, 1983). This paper uses the time of occurrence, the peak magnitude, and the number and duration of high flow events in each year.

The number of exceedances

As Q_0 is increased, the number of exceedances, M, decreases. A Poisson process is approached as Q_0 rises. The density function of a Poisson process is:

$$p(M) = [\exp(-\Lambda) \,.\, \Lambda^{M}] / M! \qquad (1)$$

where Λ is a parameter greater than 0 and may be estimated as

$$\Lambda = K / N \qquad (2)$$

where K is the total number of crossings in N historical years of record.

The probability of observing m events up to time t, can be represented by the non-homogeneous Poisson process (Waylen and Woo, 1983) as:

$$p[m(t)] = \{[\exp[-\lambda_{(t)}]].[\lambda_{(t)m(t)}]\} / m(t)! \qquad (3)$$

where $\lambda_{(t)}$ is the expected number of crossings up to time t. $\lambda_{(t)}$ may be estimated as

$$\lambda_{(t)} = k_{(t)} / N \qquad (4)$$

where $k_{(t)}$ is the total number of events from time 0 to time t, observed in N years of record. Usually, $\lambda_{(t)}$ is estimated from the probability distribution of the time of occurrence of high flow events, $G(\theta)$.

$$G(\theta) = \lambda_{(t)}/\Lambda \qquad (5)$$

so that

$$\lambda_{(t)} = G(\theta).\Lambda \qquad (6)$$

The time of events

The times of high flow events vary from year to year because of the variability in the synoptic conditions. As the synoptic conditions tend to be repeated monotonously from year to year or from cycle to cycle, barring a change in the climate, the variability in the times at which high flows occur in Botswana rivers may be taken as a fixed variance about a long-term mean date of high flows.

In that case, the probability distribution of the times at which high flow events occur each year may be approximated by a Gaussian distribution.

$$G(\theta) = \int^{\theta}{}_{0} 1/(\sigma\sqrt{2\pi}).\exp[-(t-\mu)^2/2\sigma^2]\,dt \qquad (7)$$

where t is any number of days since the start of the rainy season, in Julian days, m is the population mean of times of occurrence of high flows, and s is the population standard deviation.

The duration of high flows

The probability distribution of the duration of high flow events may be written as (Waylen and Woo, 1983):

$$P(o \geq d) = \exp(-d/\theta) \qquad (8)$$

where q is a parameter greater than 0 and which may be estimated as the observed mean duration of high flow events.

The magnitude of high flow events

The exceedance magnitude, the difference between the truncation level and the observed high flow event, may be fitted with any distribution used in the analysis of extreme events.

Results and discussion

Characteristics of the study catchments

The flow duration curves for the three catchments are shown in Figure 3. The curves have steep slopes, indicating that the rivers have very variable discharge and that the flows come mainly from surface runoff (Raudkivi, 1979). This observation seems to confirm the result of the modelling where the parameter that represents baseflow, ALEAK, is zero for all three catchments. The threshold infiltration loss that has to be met before runoff can be generated (RFMIN) is 18 mm for the Motloutse and only 8 mm for the other two. These losses translate to 0.0023 mm km^{-2} for the Motloutse, 0.0013 mm km^{-2} for the Lotsane and 0.0106 mm km^{-2} for the Mahalapswe. Thus the modelling results suggest that all three catchments differ in their surface characteristics.

The statistical characteristics of the exceedance series

Partial duration series were extracted for flows above truncation levels corresponding to discharges of 1.4, 1.6, 2.0, 2.33, 5 and 10-year return periods. The parameters derived at the 1.4-year truncation level are listed in Table 4. At the 1.4-year return period Q_0/A for Lotsane and Mahalapswe are identical, being 0.0011 and 0.0012 $m^3s^{-1}km^{-2}$ respectively, while the Motloutse is 0.0122 $m^3s^{-1}km^{-2}$. Note that the three catchments differ in size (Table 2). The difference in Q_0/A (at the 1.4-year return period) between the Lotsane and Motloutse may reflect the localised nature of

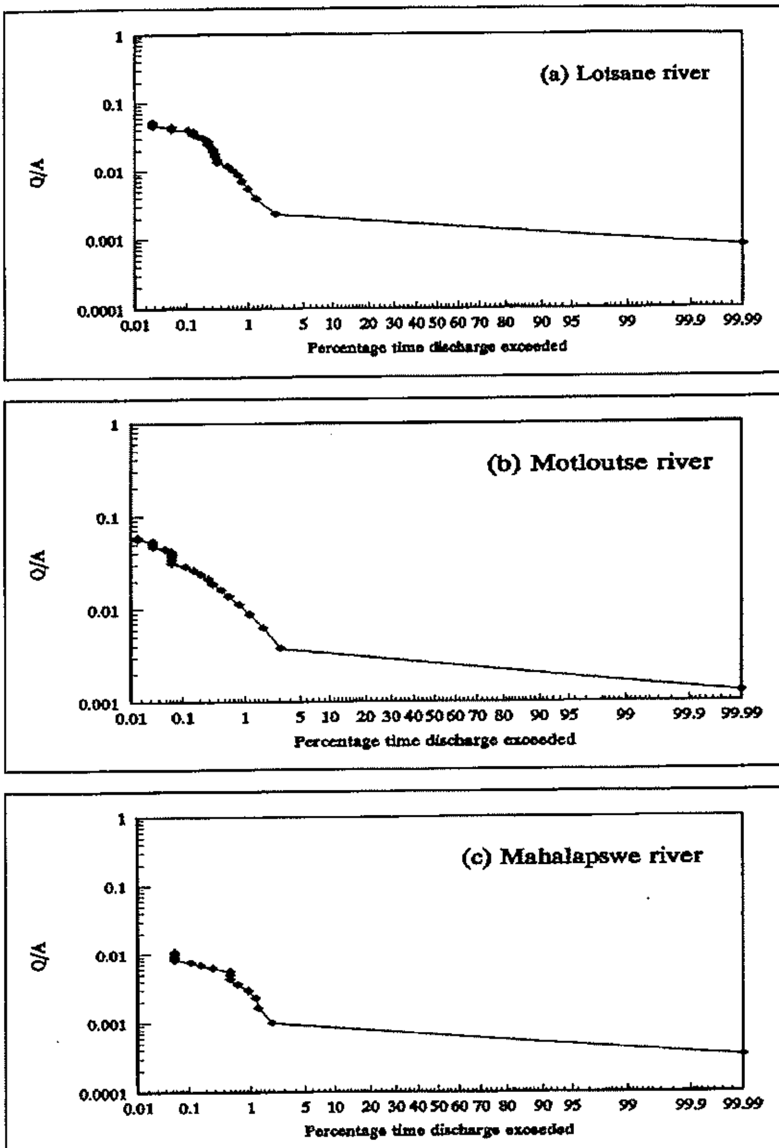

Figure 3 - Flow duration curves for (a) the Lotsane river, (b) the Motloutse river, and (c) the Mahalapswe river.

storms in semi-arid and arid areas. On the other hand, the similarity between the Lotsane and Mahalapswe suggests that catchment area is not a critical factor in the generation of the more frequent flows in semi-arid and arid areas.

All three catchments also experience very different levels of floods. The Motloutse has the highest levels of floods with a mean of 101.89 $m^3 s^{-1}$ (0.0128 $m^3 s^{-1} km^{-2}$), followed by the Lotsane with a mean of 43.71 $m^3 s^{-1}$ (0.0068 $m^3 s^{-1} km^{-2}$) and then the Mahalapswe with a mean of 1.86 $m^3 s^{-1}$ (0.0025 $m^3 s^{-1} km^{-2}$). Even the mean of floods above the 1.4-year truncation level does not reflect the influence of catchment area. The mean flood per km^2 in the Motloutse is nearly twice as high as in the Lotsane even though the catchment area of the Lotsane is 81% of that of the Motloutse. At the 1.4-year return period all three experience at least 1 flood per year (Table 4), but the Lotsane experiences two floods above the 1.4-year truncation level while the Motloutse experiences only one. Floods in the Lotsane have a mean duration of 5 days on average while those in the Motloutse last for 3 days and the Mahalapswe 2 days. In addition the mean duration in the Lotsane is very variable, compared to the other two catchments, having a standard deviation of 5 days. The mean dates on which a flood is likely to occur in these catchments are 121, 106, and 111 Julian days after October 1 (i.e. January 30, January 15, and January 20) for the Lotsane, Motloutse and Mahalapswe respectively.

Table 4 - Catchment parameters at a return period of 1.4 years

Parameters	Catchments		
	Lotsane	Motloutse	Mahalapswe
Q_0, at 1.4 year return period $m^3 s^{-1}$	7.0	97.0	0.90
Q_0/A	*0.0011*	*0.0122*	*0.0012*
Mean flood *	43.71 (83.81)	101.89 (123.95)	1.86 (1.71)
Mean flood per km^2	*0.0068*	*0.0128*	*0.0025*
Floods per year, Λ	2.0	1.10	1.44
Mean duration, days	5.05 (4.95)	2.77 (0.92)	1.78 (0.95)
Mean time of occurrence in Julian days**	121.0 (53.0)	106.0 (45.0)	111.0 (45.0)

* Figures in parenthesis are the standard deviations.

** Rounded to nearest day.

Parameters of the exceedance series at increasing truncation levels

Parameters of the exceedance series at increasing truncation levels are listed in Table 5 while Figures 4 to 6 show the application of the methods outlined earlier to the high flow variables obtained at the various truncation levels. There is correlation between mean flood and mean duration (Table 5). Generally, the longer the mean duration, the larger the mean flood. Floods of higher return periods tend to occur early in the hydrological year for both the Motloutse and Lotsane but later for the Mahalapswe.

As truncation level increases the expected number of crossings per year, L_1, which is a parameter of the non-homogeneous Poisson distribution, may be estimated as (Waylen and Woo, 1983):

$$\Lambda_1 = K_1 / N \qquad (10)$$

where K_1 is the expected number of events above the truncation level which is given by

$$K_1 = K_0 \, . \, F(H \geq \Delta Q) \qquad (11)$$

where $F(H \geq \Delta Q)$ is the probability of an observed high flow exceeding the new truncation level $(Q_0 + \Delta Q)$ and is given by

$$F(H \geq \Delta Q) = \exp\left(-\Delta Q / g_0\right) \qquad (12)$$

with g_0 being estimated as the mean of exceedances above Q_0.

Predicted mean crossings per year are shown in Table 5. The observed number of floods per year in the Motloutse and Mahalapswe can be estimated using the non-homogeneous Poisson distribution. However, the method performed poorly in the case of the Lotsane. For the Lotsane, raising the ratio $\Delta Q/g_0$ by a power, k, produced a better estimate of the number of crossings per year (Table 6). By trial and error, k was found to be 0.35. (The hydrological significance of k is being investigated.)

Figure 4 shows that the observed duration of events can be fitted with an exponential distribution (equation 8), although it did not vary sufficiently so as to define the curves adequately. Figure 5 shows the probability of a given number of events (m) occurring t days after the beginning of the hydrological year. All the curves are identical except for the Lotsane, where the curve for m(t) = 0 falls below that of m(t) = 3 in its lower values.

The exceedance magnitudes $(Q_i\text{-}Q_{0)}$ were divided by mean annual flood (MAF) to make them dimensionless. For comparison, the dimensionless exceedance magnitudes were plotted on EV1 abscissa. The plots are shown in Figure 6; the three catchments differ in the probability distribution. The plots for Lotsane and Mahalapswe show clearly that the EV1 distribution does not fit the data, while the distribution does fit the Motloutse

Table 5 - Parameters of the exceedance series

Q_0, $m^3 s^{-1}$	T yrs	mn flood $m^3 s^{-1}$	Floods /year	Duration days	Mean date
Motloutse at Tobane					
97.0	1.4	101.89 {123.95}[1]	1.0	2.77 {0.92}	106 {45}
112	1.6	111.79 {130.31}	0.9 [0.95][2]	2.72 {0.96}	114 {42}
116	2.0	107.17 {139.58}	0.55 [0.56]	2.75 {0.62}	130 {36}
173	2.33	123.36 {145.0}	0.45 [0.47]	2.44 {0.88}	119 {29}
226	5.0	192.39 {139.39}	0.20 [0.47]	2.75 {0.96}	121 {26}
468	10.0	44.43 {62.19}	0.10 [0.03]	2.10	130 {28}
Mahalapswe at Madiba					
0.90	1.4	1.86 {1.71}	1.44	1.78 {0.95}	111 {45}
1.40	1.6	1.80 {1.75}	1.06 [1.10]	1.76 {0.95}	116 {46}
1.90	2.0	1.75 {1.77}	0.88 [0.84]	1.4 {0.9}	118 {46}
2.30	2.33	1.89 {1.71}	0.63 [0.68]	1.4 {1.0}	108 {46}
4.10	5.0	1.66 {1.65}	0.25 [0.26]	1.75 {1.50}	87 {52}
5.60	10.0	1.33 {1.53}	0.13 [0.11]	1.0	70 {12}
Lotsane at Maunatlala					
7.0	1.4	43.71 {83.81}	2.0	5.05 {4.95}	121 {53}
10.0	1.6	56.16 {94.33}	1.45 [1.87]	5.44 {5.68}	121 {48}
15.0	2.0	83.75 {108.09}	0.91 [1.67]	5.50 {4.50}	127 {43}
20.0	2.33	112.91 {113.96}	0.64 [1.49]	6.14 {3.98}	124 {41}
50.0	5.0	104.95 {75.73}	0.45 [0.75]	5.0 {3.32}	136 {37}
200	10.0	71.81 {88.96}	0.18 [0.02]	2.5 {2.12}	130 {16}

Notes:

1. Numbers in { } = standard deviation.

2. Numbers in [ ] = predicted values.

(Note that in the table, Q_o = truncation level; T = return period; mn flood = mean of the exceedances above Q_o; mean date = number of days, Julian, since start of rainy season.)

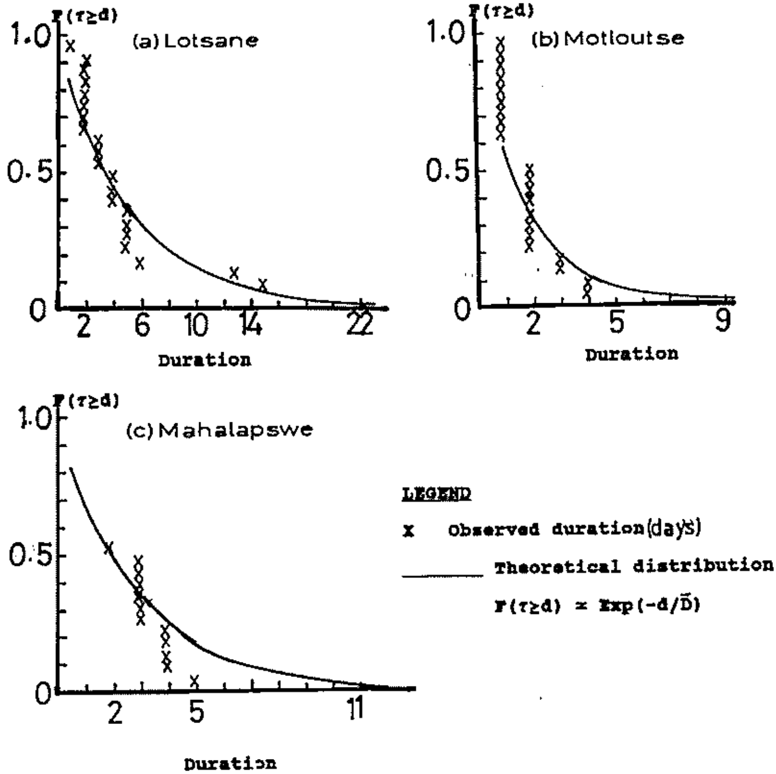

Figure 4 - Distribution of observed duration of high flow events.

Table 6 - Predicted and observed number of high flows/year for the Lotsane.

ΔQ	Observed Λ_1	Predicted Λ_1	
		k = 1	k = 0.35
3	1.45	1.87	1.35
8	0.91	1.67	1.15
13	0.64	1.49	1.04
43	0.45	0.75	0.74
193	0.18	0.02	0.37

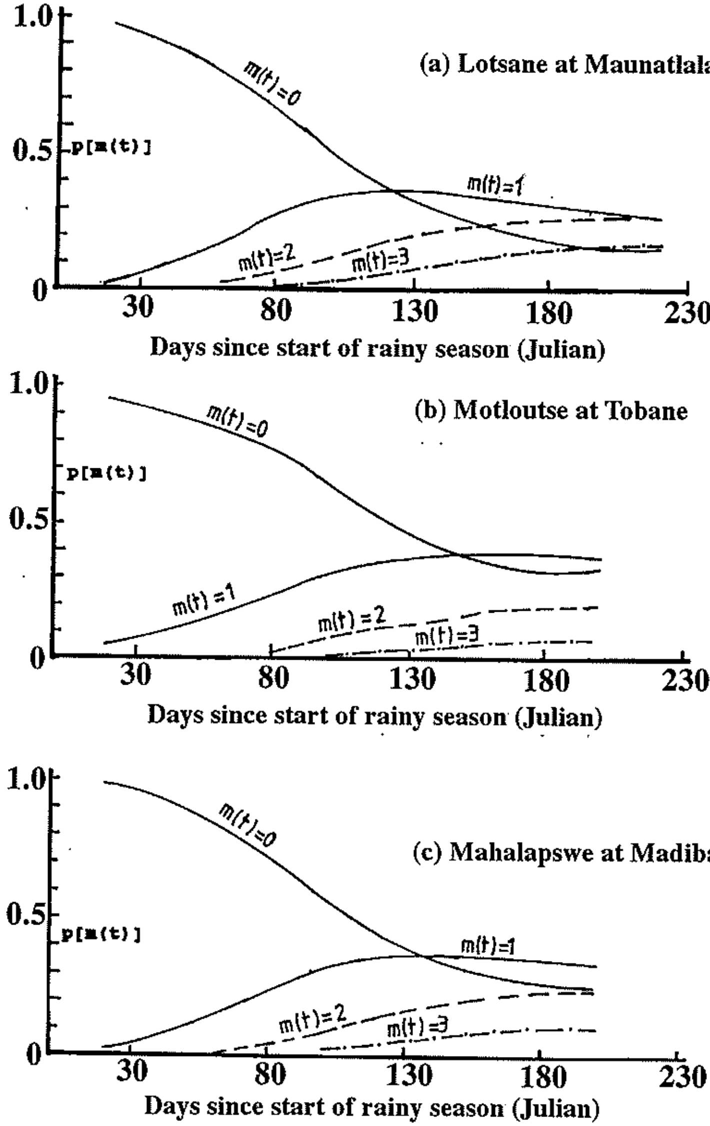

Figure 5 - Probability of occurrence of given number of events up to t days.

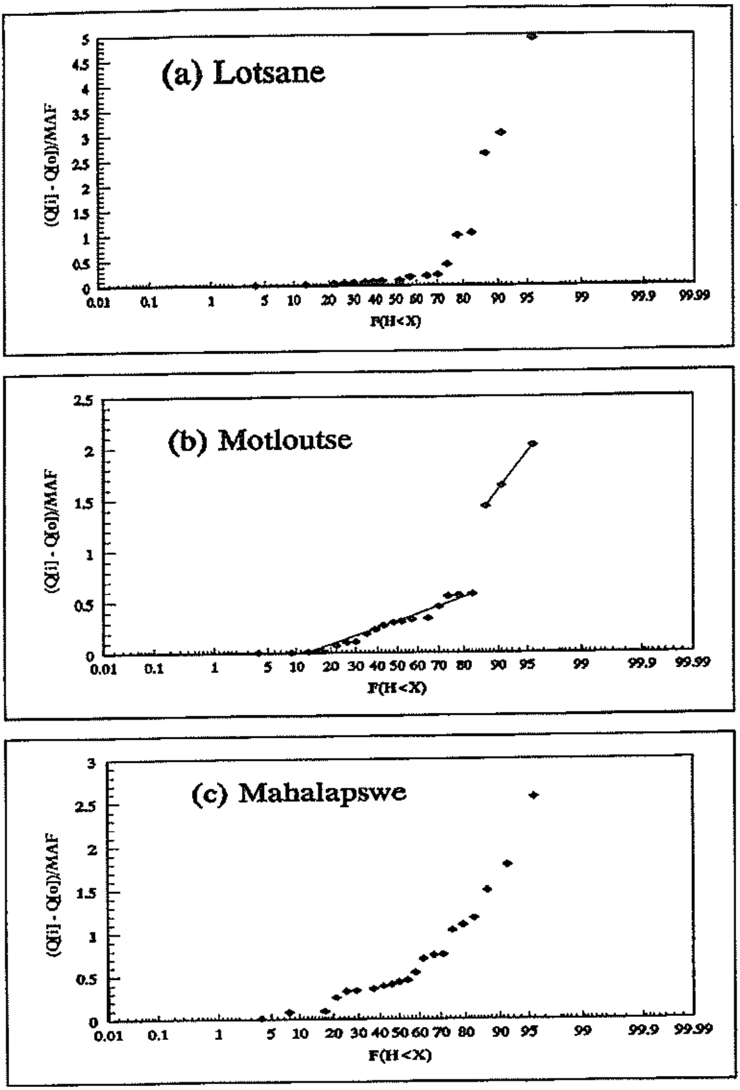

Figure 6 - Probability distribution of exceedance magnitude - (a) Lotsane river, (b) Motloutse river, and (c) Mahalapswe river.

data (Figure 6). It seems, however that there are two distinct samples in the data. From Figure 6, it can be concluded that the rare large floods giving exceedances above 300 $m^3 s^{-1}$ constitute a distinct sub-sample.

The results presented here, especially Figure 6 clearly indicate that while catchments may be modelled with the same parameter values of a hydrological model, those catchments may not necessarily constitute a hydrological region. The heterogeneity in the catchments may be masked by the structure of the model, its parameterisation, the sensitivity of the parameters and even the optimisation routine employed during model calibration. In this case, modelling was done for daily time steps, but the statistics used in fitting the model aggregated on monthly and annual time steps. This may have smoothed the daily variability and, by so doing, masked the sensitivity of the model parameters. Perhaps the observation by Klemes (1982), that models may work well but for the wrong reasons, may apply to this discussion.

Conclusion

The three catchments grouped into the same region differ markedly from each other in their hydrological characteristics: the 1.4-year return period flow, the mean floods above the 1.4-year flow, the number of floods per year exceeding the 1.4-year flow, the duration of the flood events, the date of occurrence of the flow events and the statistical distribution of their exceedance series. The only thing they have in common is the slope of the flow duration curves which indicates the dominance of surface runoff in their flood flows.

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Appendix 1: Description of parameters of the Monash Model

Parameter	Unit	Description
Catchment-wide parameters		
LOCATE	month	Month of start cycle of seasonally adjusted parameters
SEAS	-	Half amplitude of cycle, expressed as a fraction of the mean value of the seasonal parameters
Subarea parameters		
COEFF	mm/day	Maximum daily infiltration rate
SMSC	mm	Soil moisture storage capacity
DSC	mm	Depression storage capacity
EM	mm/day	Maximum possible daily evapotranspiration rate
ADS	-	Proportion of catchment draining to depressions
SUB	-	Maximum proportion of infiltrated moisture directed to interflow under saturated conditions
CRAK	-	Maximum proportion of infiltrated moisture directed to groundwater storage
CPDAY	-	Coefficient in non-linear groundwater storage/discharge relationship
RINSC	mm	Interception storage capacity
RMD	-	Exponent in relationship governing filling of depression storage
ZDAY	-	Exponent in non-linear groundwater storage/discharge relationship
ALEAK	-	Fraction of groundwater storage lost daily
SQ	-	Exponent in relationship between infiltration sensitivity and soil moisture status
CO	hour	Storage delay coefficient for runoff routing
RFMIN	mm	Daily rainfall total below which all rainfall infiltrates