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Runoff variability: a global perspective

T.A.McMahon (1), B.L.Finlayson (2),
A.Haines (1), & R.Srikanthan (3)
(1) Department of Civil and Agricultural Engineering, University of Melbourne, Australia
(2) Department of Geography, University of Melbourne, Australia
(3) CSIRO Division of Land and Water Resources, Canberra, Australia

ABSTRACT A data base consisting of monthly and annual flows, peak annual instantaneous flows and monthly precipitation has been assembled from around the world to allow analysis of streamflow characteristics at the continental scale. At the annual level, the major intercontinental differences are in terms of variability. Australia and Southern Africa are distinguished from the rest of the world by their high variability and the observed differences persist even when the comparisons are made between areas of like climatic characteristics and the same latitudes. For any given precipitation variability, the runoff variability in Australia and Southern Africa is much higher than for the rest of the world. Analysis using a single linear storage model suggests that it is the higher variability of effective precipitation in Australia and Southern Africa, which results from high evaporative demand there, which is one of the major causes of the observed differences in runoff variability.

RESUME Nous avons assemble les donnees de base suivantes relevees dans diverses parties du mond: debits mensuels et annuels, debits annuels maximum, et quantite mensuelle de pluie. Ces donnees nous ont permis de mesurer les caracteristiques debit/ecoulement a l'echelle continentale. Au niveau annuel, les differences intercontinentales les plus marquees se situent au niveau de la variabilite. L'Australie et la partie sud du continent africain se distinguent du reste du monde par leur niveau eleve de variabilite. De plus, les differences que nous avons observees persistent, meme lorsqu'on les comparaisons sont etablies avec des regions de climat semblable et de meme latitude; et de climats similaires. Pour n'importe quelle variabilite de precipitation, la variabilite de l'ecoulement en Australie et dans le sud de l'Afrique est beaucoup plus haute que dans le reste du monde. Une analyse pour laquelle nous avons utilise un modele unique de reservoire lineaire, semble suggerer que la plus grande variabilite de precipitation effective - resultant d'une evaporation intense dans ces regions - est une des causes majeures des différences que nous avons observées dans la variabilité de l'écoulement des eaux.

Introduction

The work of McMahon (1975,1978,1979,1982a,1982b) has shown that significant differences exist between the flow characteristics of Australian streams and those of the rest of the world and that the global relationships postulated by Kalinin (1971) do not fit the Australian data. Though the data sets used by both Kalinin and McMahon were inadequate with respect to the southern hemisphere continents, McMahon's early results indicated the possibility of there being substantial differences between the hemispheres. A data base has been established which enables the questions of interhemispheric and intercontinental differences to be addressed.

The present data set contains the world data as used by McMahon (1982a) extensively supplemented with records from all continents. The streamflow records consist of monthly flows, annual flows, and annual peak instantaneous discharges from 87 countries. Monthly and annual flows are available from 938 gauging stations with an average record length of 33 years (a total of 30,800 station years) and the peak instantaneous flows are available for 921 stations with an average record length of 31 years (28,500 station years). These data have been acquired from a variety of published and unpublished sources and less frequently on magnetic tape from national water authorities. Rainfall records for 424 stations worldwide have been extracted from magnetic tapes from the National Center for Atmospheric Research (Boulder, Colorado). The origins of the data and the structure of the data base are described in more detail in Finlayson *et al.* (1986) together with a map showing the locations of the stream gauging stations and raingauges. The most serious deficiency in the data set is the relatively small number of rainfall stations and it is planned to increase this substantially in the current phase of the study.

For this paper the data have been analysed in eight continental groups. Europe (EUR), Asia (AS), North America (NAM), South America (SAM) and Australia (AUS) are as normally defined; Southern Africa (SAF) and Northern Africa (NAF) are separated by the Equator; and South Pacific Islands (SP) data are mainly from New Zealand. Where all the data have been analysed together the results are referred to as "World" (WOR), where "Rest of World" (ROW) is specified, this refers to the world data minus Australia and South Africa (jointly ASAF).

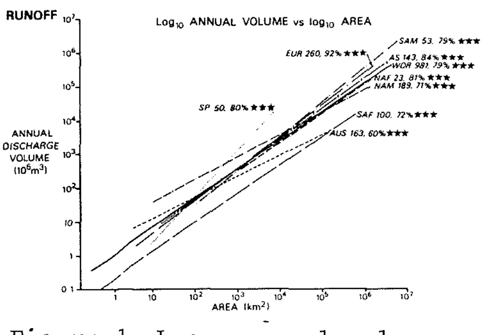
Analysis of the data base is planned in several parts. The first, part of which is reported in this paper, consists of broad intercontinental comparisons using the annual flows, annual rainfalls, and the annual peak discharge data. The second main phase of analysis will look at the monthly data and particularly at regional rainfall runoff relationships. Other studies will include time series analysis and the definition of seasonal river regime types at the global scale. Ultimately it is hoped that this work will lead to a better understanding of global hydrology and to the definition of a set of world regions for model transferability.

Intercontinental comparisons

Annual runoff

Figure 1 shows the relationship between annual flow volume and catchment area by continents and for the world data. In all cases the correlations are significant at the 1% level and area explains a high proportion of the variance, the lowest being AUS at 60%. The regression lines shown in this and all other figures in this paper are least squared fits and in each case the number of data points, the value of R , and the level of significance are given. Most of the relationships cluster around the world one with minor exceptions for SP, AUS and SAF. Lower flow volumes for AUS and SAF, especially for the larger catchments, are as would be expected for continents in their latitudinal positions. NAF lies close to the WOR line even though it is a predominantly arid area because the data for NAF comes mainly from the humid area bordering the Gulf of Guinea.

Figures 2 and 3 show the relationships between coefficient of variation of annual flows (Cvr) and mean annual runoff (MAR) and area respectively. Cvr is calculated as the standard deviation divided by the mean. Since at the annual level runoff represents the difference between precipitation and evaporation, MAR is a climatic indicator representing the level of aridity or humidity of the climate. In Figure 2 AUS and SAF, while following the world trend of decreasing Cvr with increasing MAR, are notable in having higher Cvr than the other continents. MAR explains considerably more of the variance in Cvr for AUS and SAF and there is also a substantial difference between these two. This situation appears anomalous and certainly needs further explanation.



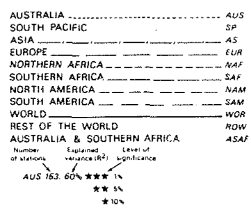


Figure 1 Log_{10} annual volume vs. log_{10} area.

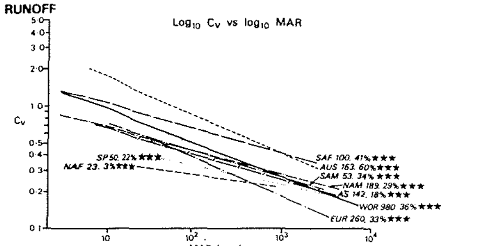


Figure 2 Log_{10} Cv vs. log_{10} MAR.

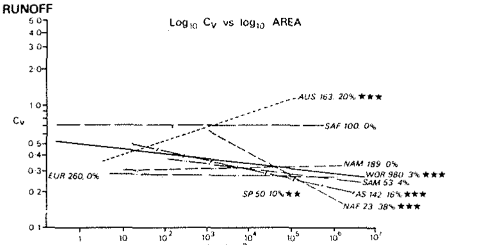


Figure 3 Log_{10} Cv vs. log_{10} area.

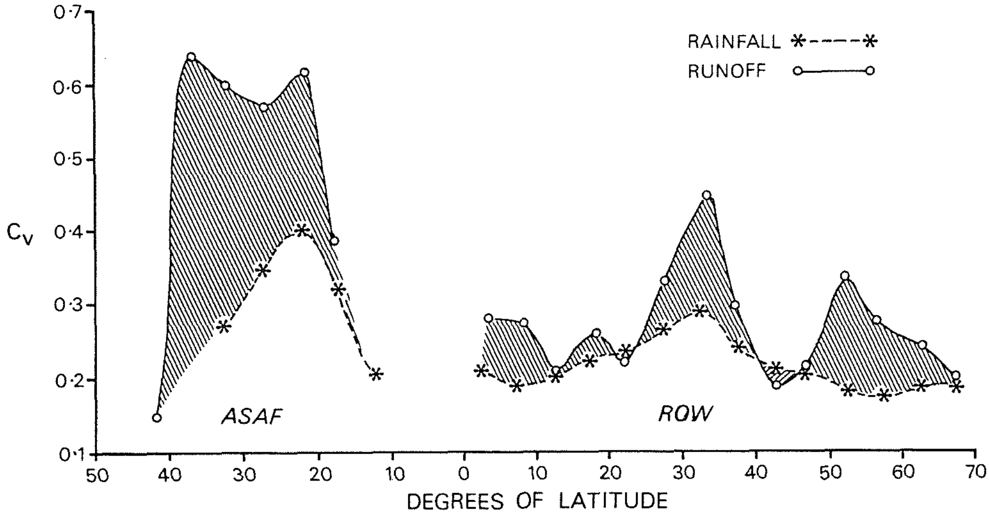


Figure 4 The distribution of variability of rainfall and runoff by latitude.

Cvr is poorly correlated with area (Figure 3) though there is a strong indication in the data that Cvr tends to decrease as area increases and this is what would be expected on statistical grounds. It should be noted however that no correlation was found between Cvr and area for SAF, NAM, EUR and SAM. AUS is a notable exception to this trend and is the only continent where Cvr increases with area. Given the relationship established in Figure 2 where Cvr increases as the climate becomes more arid, the anomalous relationship between Cvr and area for AUS can be explained in terms of the distribution of climates on the Australian continent. Humid climatic zones parallel the coast in a relatively thin strip around the northern, eastern, south-eastern and south-western coasts. Any large catchments in Australia must extend into parts of the drier interior causing an increase in Cvr.

Figure 4 shows the distribution of Cvr and Cvp (the coefficient of variation of annual precipitation) with latitude. On the left hand side of the graph Australia and Southern Africa have been plotted together and all other continents are shown jointly on the right hand side. As would be expected given the latitudinal distribution of climates Cvr and Cvp tend to peak at around 30°, the location of the subtropical high pressure cells. Here again the anomalous condition of Australia and Southern Africa is evident. The Cvr's are higher and these high values extend over a wider range of latitude than is the case for the other continents.

Annual floods

Like the annual flow volume (Figure 1), the mean annual flood ($\bar{q}$), expressed as a discharge, is strongly correlated with area (Figure 5) though AUS has the lowest value of R^2 (47%). The relationship between $\bar{q}$ and area is remarkably similar for all continents. However, when measures of the variability of flood behaviour are used (Figures 6 and 7) AUS and SAF are distinctly different to the other continents. In Figure 6, Iv, the coefficient of variation of the annual peak

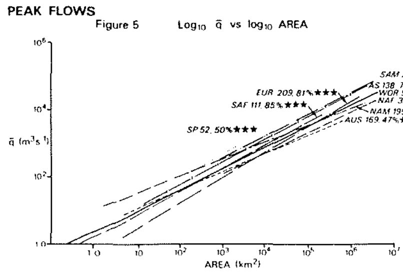


Figure 5 $\mathrm{Log}_{10}\ \bar{q}$ vs. $\log_{10}$ area.

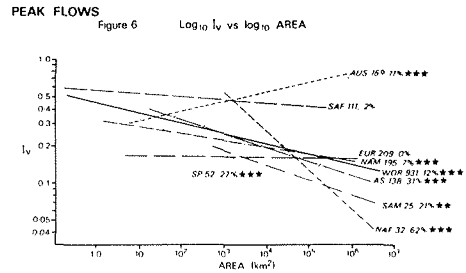


Figure 6 Log_{10} Iv vs. $\log_{10}$area.

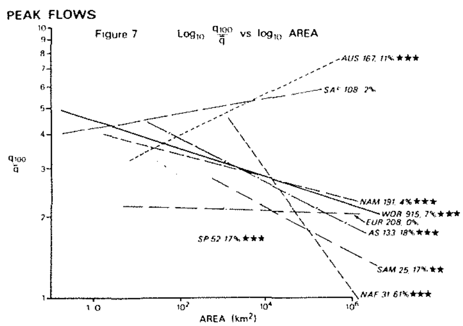


Figure 7 $\mathrm{Log}_{10} q_{100}/q$ vs. $\log_{10}$area.

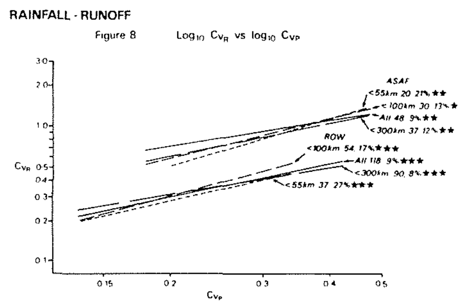


Figure 8 Log_{10}Cvr vs. $\log_{10}$ Cvp.

discharges in the log domain, is plotted against area. AUS and SAF have generally higher Iv values than the other continents, and as in the case of Cvr, AUS shows a reversal of the general trend.

The variability of flood behaviour can also be represented using the ratio $q_{100}/\bar{q}$ (Figure 7). q_{100} is calculated assuming the peak instantaneous annual discharges follow a power normal distribution (Chander et al., 1978). Here also AUS and SAF are distinguished by having generally higher ratios than the other continents and AUS again has a reversed trend. This reinforces the fact that AUS and SAF streams are highly variable when compared with those of other continents. While there is an inverse relationship between Cvr and MAR (Figure 2) no similar relationship was found to exist between Iv and $\bar{q}_s$, the specific mean flood, or between $q_{100}/\bar{q}$ and $\bar{q}_s$. Under flood conditions catchment area alone appears more important than the other parameters examined.

Australia and Southern Africa are more variable than the other continents in terms of both annual flows and annual floods. Australian streams also consistently show a typical behaviour when measures of variability are related to catchment area. It should be noted, however, that small catchments (<100 km^2) in Australia have similar Cvr to the rest of the world (Figure 3). These catchments have been discussed by McMahon (1986). Given that MAR is a climate related variable, for any given climate Australian and Southern African streams are more variable (Figure 2) and this can also be shown by comparing streams in similar climatic zones. Table 1 shows, for catchments in the range 1000 - 10,000 km^2, mean values of both Cvr and Iv for ASAF and ROW and their ratios for Koppen climatic zones. In all cases where sample sizes are large enough for reliable comparisons to be made, ASAF streams are more than twice as variable

Table 1 Annual flow variability and peak discharge variability stratified by climatic type for catchments in the size range 1000 - 10,000 km^2

Climatic region	ASAF No.	ASAF Cv	ROW No.	ROW Cv	Ratio	ASAF No.	ASAF Iv	ROW No.	ROW Iv	Ratio
Am	-	-	-	-	-	1	.36	3	.12	(3.0)
Aw	1	.76	8	.21	(3.6)	-	-	-	-	-
BSk	9	.86	9	.43	2.0	8	.70	4	.38	1.8
Cfa	24	.95	14	.56	1.7	24	.54	18	.25	2.2
Cfb	15	.72	32	.29	2.5	12	.45	29	.19	2.4
Csa	-	-	-	-	-	1	.45	6	.45	(1.0)
Csb	2	.61	1	.50	(1.2)	5	.55	15	.26	2.1
Cwa	7	.92	5	.29	3.2	6	.57	6	.19	3.0
Cwb	15	.72	2	.39	(1.8)	11	.39	2	.18	(2.2)

(-) Parentheses indicate sample size very small

as ROW streams in the same climate zone. This is true also for catchments <1000 km^2 in area (see Finlayson et al., 1986).

Sources of variability in runoff

While the results presented so far do not support the hypothesis that a significant difference in mean values exists between the hemispheres, they do show that AUS and SAF are different to the other continents when measures of variability are involved. In exploring the sources of variability the data have been split into two groups, Australia and Southern Africa have been combined and the other continents grouped together. Since it is virtually impossible to determine catchment rainfalls for the streams in the data set, catchments larger than 10,000 km^2 have been eliminated and each raingauge was paired with the nearest stream gauge in order to investigate the relationship between rainfall variability and streamflow variability. Table 2 sets out the characteristics of the data used in this analysis. Raingauge/streamgauge pairs have been grouped into classes based on the distance separating them.

Table 2 Characteristics of raingauge/streamgauge pairs

Group	Australia and Southern Africa			Rest of the world		
	No.	Mean distance (km)	R^2 (%)	No.	Mean distance (km)	R^2 (%)
All pairs	48	319	9	118	298	9
<300 km	37	75	12	90	98	8
<100 km	30	50	13	54	44	17
<55 km	20	32	21	37	27	27

The influence of variability of total annual precipitation

Cvr has been plotted against Cvp on Figure 8 for each of the separation classes. Here ASAF and ROW are clearly different with ASAF having much higher Cvr for any given Cvp than ROW. For example, at Cvp of 0.25, the difference in Cvr between ASAF and ROW is 0.3. The form of this relationship is consistent irrespective of the average station separation though as station separation increases the strength of the relationship declines. In statistical terms, for all the regression lines shown on Figure 8 there is no significant difference between the regression coefficients but the intercepts are significantly different between the ASAF and ROW groups. Although the transfer of variability from precipitation to runoff is greater for ASAF than ROW, there is no difference between the two groups in terms of the amount of runoff variability explained by precipitation variability (R^2 in Figure 8 and Table 2).

Other influences

In order to investigate further the source of the differences between ASAF and ROW a storage model analysis has been carried out on those raingauge/streamgauge pairs with station separation of less than 55 km.

One thousand years of rainfall data for each station with parameters based on those of the observed data were generated synthetically using a Markov process as modified by the Wilson-Hilferty transformation (Wilson and Hilferty, 1931). Annual total rainfalls were converted to annual effective rainfalls using a constant runoff coefficient based on the observed data. For each catchment the storage effects were mimicked by routing the 1000 years of annual effective rainfall through a conceptual single linear storage model of the form:

$$S = KR \tag{1}$$

where S is catchment storage and R is annual runoff volume. The storage delay time parameter (K) in the model was optimized for each catchment so that the time series of annual flows reproduced the observed variability. The details of this methodology will be published elsewhere.

Median values of parameters from the observed data and the model results are shown in Table 3 where Cvpe , annual effective precipita-

Table 3 Median values of parameters from the observed data and the model results. (RC is the mean runoff coefficient from the observed data.)

	MAP (mm)	Cvp	Cvpe	RC	K (yr)	Cvr
ASAF	770	0.23	1.10	0.15	0.50	0.67
ROW	800	0.18	0.40	0.51	0.25	0.30

tion, and K are derived from the model. The ASAF catchments have higher storage than ROW catchments. While the values shown in Table 3 are only relative they are consistent with known storage times (T.G.Chapman, pers. comm.). In general it might be expected that higher storage would lead to less variable runoff but this does not occur here because Cvpe for ASAF is so much larger than that for ROW. The high storage in the ASAF catchments leads to a dramatic reduction in variability between Cvpe and Cvr (compared to that for the ROW data) but the Cvr is still substantially above that for ROW.

This result arises because of the lower runoff coefficients for ASAF and the values we observe are confirmed by Korzun et al. (1974). ASAF experiences relatively high evaporative demand on the world scale, partly because of the excess energy advected from their dry interiors to the humid coastal areas, and partly because of the fact that at these latitudes the southern hemisphere has a higher potential evaporation than the northern hemisphere (Baumgartner & Reichel, 1975). It is this high evaporation which leads to the lower runoff coefficients. Note from Table 3 the difference between Cvp and Cvpe for ASAF compared to ROW. While intuitively it might have been expected that ASAF would have lower storage values than ROW, because of the absence of features such as substantial snowfields, it is obvious as a result of this model analysis that other factors such as low relief and soils more than compensate for this. Paton (1978) has made a case for recognizing Australian and African soils as being significantly different to those of the other major continental areas because of the long period of continental stability and the absence of continental glaciation during the Pleistocene.

Conclusion

This paper has briefly described a new data base which has been assembled to investigate streamflow characteristics at the continental scale. While the data base contains streamflow records at the monthly level, to date only the annual data have been analyzed, both annual totals and annual peak discharges. The data base also includes precipitation records from all continents and it is intended to add to these.

Analyses of annual runoff presented here show that the most important intercontinental differences are in terms of variability. In particular, Australia and Southern Africa show levels of annual variability nearly twice that of the other continents. The same result appears in the analysis of annual peak instantaneous discharges. The observed differences persist even when the data are stratified by similar climatic types. With one exception, climatic zones in Australia and Southern Africa have variabilities of annual and peak flows approximately twice those of the rest of the world.

These differences cannot be ascribed solely to the variability of annual total rainfall though it is noteworthy that for any given precipitation variability, runoff variability in Australia and Southern Africa is significantly higher than in the rest of the world. A single linear storage model analysis carried out on catchments less than 10,000 sq.km in area for which a precipitation record was available within a 55 km radius indicates that the important factor in determining the high runoff variability in Australia and Southern Africa is the variability of effective precipitation. High variability of effective precipitation is a function of high evaporative demand in the atmosphere. An unexpected outcome of the model analysis was the high storage values for catchments in Australia and Southern Africa. While it might be expected that high storage would be associated with low runoff variability it appears that the high values of variability of effective precipitation more than compensate for the storage effects.

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