ANALYSIS OF REGIONAL HOMOGENEITY OF CATCHMENTS IN SRI LANKA BY L-MOMENTS

by

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Abstract

This paper examines the regional homogeneity of catchments in Sri Lanka. A "region" is a group of sites each of which is assumed to have data drawn from the same frequency distribution. The basic idea behind regional frequency analysis is to make use of similarities in the characteristics of floods at different sites in a region. Consequently, regional homogeneity is essential for such an analysis. L-moments are used in this study to investigate the regional homogeneity. Cachments are divided in to regions by considering area, elevation, and using a clustering algorithm. Regional homogeneity is tested by using two statistical measures: a discordancy measure, for identifying unusual sites in a region; and a heterogeneity measure, for assessing whether a proposed region is homogeneous.

1.0 Introduction

In flood frequency analysis objective is to estimate a flood quantile magnitudes for different return periods at a station or at a number of stations in a river system. An understanding of the hydrologic characteristics of a catchment is essential in order to obtain a reliable estimate of the relationship between extreme flood quantiles and the associated return periods. A difficulty associated with flood frequency analysis is the lack of sufficient data. Consequently, it is difficult to identify the parent distribution from which a sample is drawn. Large standard errors of estimates result because of small sample sizes. In such situations, regional flood frequency analysis entails using information from a group of sites to estimate the extreme flow quantiles at the site of interest. Records from nearby stations are used to substitute spatial to temporal characteristics. In this way, data from nearby stations compensate, at least in part, for short records from a single site (National Research Council 1988).

The importance of regional homogeneity for flood frequency analysis has been demonstrated by, among others, Geris and Wood (1981), Hosking et al. (1985), and Lattenmaier et al. (1987). Lettenmaier et al., (1987) have shown that regional analysis results in more accurate estimates of the flood quantiles than at-site estimates in moderately heterogeneous regions based on the Index Flood Method combined with the method of Probability Weighted Moments (PWM). The method results in biased estimates at-site with coefficient of variation (C_v) deviating from the regional mean, but with an overall reductiontof the regional error of estimates, and confirms the value of a regional approach even in the presence of weak heterogeneity (Gustard et al. 1989). However, a major requirement for effective regionalization is that the region under consideration should be sufficiently homogeneous in terms of statistical properties of data from different stations, although a moderate degree of heterogeneity is often accepted (Cunnane 1986).

The delineation of regions traditionally has been based on geographic, political, administrative, or physiographic boundaries. The resulting regions were then assumed to be homogeneous in terms of hydrologic response, but this will generally not be the case if there is a large amount of spatial variability in the physiographic or hydrologic characteristics of the catchments in the region. Residuals from a regional regresion model, used to estimate flow characteristics at ungauged catchments, have been used to create geographically contiguous regions based on grouping catchments with residuals of a similar sign and magnitude (Wandle 1977). Cluster analysis has also been used as a method of creating regions (Tasker 1982). The intent with cluster analysis is to identify clusters (groups) of catchments such that the catchments within a cluster are similar while there is dissimilarity between the catchments in different clusters.

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The aim of this study is to investigate the regional homogeneity of the selected river basins in Sri Lanka by using L-moments. This paper describes the screening of data, identification of homogeneous regions, choice of a frequency distribution, and estimation of the frequency distribution. The main features of the present analysis are the use of cluster analysis to tentatively identify homogeneous regions, and constant attention to hydrological reasoning in order to ensure that regions obtained by statistical procedures are also physically meaningful.

2.0 Probability Weighted Moments and L-Moments

Probability weighted moments (PWM) were introduced by Greenwood et al. (1979) and has received considerable attention since its inception (Landwehr et al. 1979a,b; Hosking et al. 1985; Hosking 1986). In particular PWM allow parameter estimates to be obtained for distributions which are defined only in inverse form, such as Wakeby distribution which was introduced as a general flood frequency distribution model by Houghton (1978).

Probability weight moments Mp,r,s are defined by Greenwood et al. (1979) as in (1).

$$M_{p,r,s} = E\{[x(F)]^p F^r [1-F]^s\} = \int_0^1 [x(F)]^p F^r (1-F)^2 \, dF \qquad (1)$$

where,

p, r, and s are real numbers
F = cumulative probability distribution function
x = Flood magnitude

In particular, the following two moments are considered:

$$M_{1,0,s} = \alpha_s = \int_0^1 x(F)(1-F)^s \, dF \qquad (2)$$

$$M_{1,r,0} = \beta_r = \int_0^1 x(F) F^r \, dF \qquad (3)$$

Both α_s and β_r are linear in x and are of sufficient generality for parameter estimation. Also, α_s and β_r are related to each other, as in (4) and (5)

$$\alpha_s = \sum_{k=0}^{s} \binom{s}{k} (-1)^k \beta_k \qquad (4)$$

$$\beta_r = \sum_{k=0}^{r} \binom{r}{k} (-1)^k \alpha_k \qquad (5)$$

Hosking (1986, 1990) has defined the L-moments. The L-moments are analogous to conventional moments and are estimated by linear combinations of order statistics. L-moments can also be expressed by linear combinations of PWM. Thus, the procedures based on PWM and L-moments are equivalent. However, L-moments are more convenient because they are directly interpretable as measures of the scale and of the shape of probability distributions (Hosking 1986). Hosking (1990) has used L-moment ratio diagrams to identify underlying parent distributions and L-moment ratios for testing hypotheses about different probability distributions. Hosking and Wallis (1993) extended the use of L-moments and developed statistics that can be used for regional frequency analysis to measure discordancy, regional homoginity, and goodness-of-fit. The L-moments λ_{r+1} are defined by Hosking (1986, 1990) in terms of PWMs α_s and β_r as in (6)

$$\lambda_{r+1} = (-1)^r \sum_{k=0}^{r} p^*_{r,k} \alpha_k = \sum_{k=0}^{r} p^*_{r,k} \beta_k \qquad (6)$$

where

$$p^*_{r,k} = (-1)^{r-k} \binom{r}{k} \binom{r+k}{k} \qquad (7)$$

For a given ordered sample of flood magnitudes $x_1 \le \ldots \le x_i$, n>r and n>s the unbiased sample PWMs are calculated (Hosking 1986) by equations (8) and (9).

$$a_s = n^{-1} \sum_{i=1}^{n} \left[\binom{n-i}{s} \Big/ \binom{n-1}{s} \right] x_i \qquad (8)$$

$$b_r = n^{-1} \sum_{i=1}^{n} \left[\binom{i-1}{r} \Big/ \binom{n-1}{r} \right] x_i \qquad (9)$$

where,

n = numbers of records
r and s are real numbers

Alternatively, consistent, but not unbiased, plotting position estimators are obtained by using (10) and (11)

$$a_s = \hat{\alpha}_s = n^{-1}\sum_{i=1}^{n}(1-p_{i:n})^s x_i \qquad (10)$$

$$b_r = \hat{\beta}_r = n^{-1}\sum_{i=1}^{n} p_{i:n}^r x_i \qquad (11)$$

where,

Pi:n = plotting position.
xi = i th flood magnitude in the ordered sample

Sample L-moments are calculated by using (6) and (7), replacing α_s and β_r with their sample estimates a_s and β_r from (10) and (11). L- moments ratios are defined by Hosking (1986, 1990) in (12) and (13)

$$\tau = \frac{\lambda_2}{\lambda_1} \qquad (12)$$

$$\tau_r = \frac{\lambda_r}{\lambda_2}; \qquad r = 3, 4, \cdots. \qquad (13)$$

where λ_r is the mean of the distribution, a measure of location; λ_2 is a measure of scale; λ_3 is the measures of skewness (LCs); λ_4 is the measure kurtosis (LCk); and λ is analogous to the usual coefficient of variation (LCv).

The discordancy statistics for site i (Di) of Hosking and Wallis (1993) is defined as

$$D_i = \frac{1}{3}(u_i - \bar{u})^T S^{-1}(u_i - \bar{u}) \qquad (14)$$

$$u_i = \left[\tau^{(i)} \tau_3^{(i)} \tau_4^{(i)}\right]^T$$

where $u_i = \left[\tau^{(i)} \tau_3^{(i)} \tau_4^{(i)}\right]^T$ be a vector containing the τ, τ_3 and τ_4 values for the site i; $\bar{u}$ be the group average

$$\bar{u} = n^{-1}\sum_{i=1}^{n} u_i \qquad (15)$$

where n= number of sites in the sample

S is the sample covariance matrix defined as

$$S = (n-1)^{-1}\sum_{i=1}^{n}(u_i - \bar{u})(u_i - \bar{u})^T \qquad (16)$$

If it is assumed that the u_i are drawn from independent identical multivariate normal distributions, then for regions the statistics 3Di have, approximately, independent chi-square distributions with 3 degrees of freedom, and approximately 3% of the Di values exceed 3. Thus a site is considered to be unusual if the discordancy measure Di is larger than 3 (Hosking and Wallis 1993).

The homogeneity test is based on the idea that in a homogeneous collection of catchments, all catchments should have the same population L-moments. This is, however, not true for the sample L-moments due to the sampling variation. The question arises as to whether differences in sample L-moments indicate different populations or arise from sampling error. Therefore, the level of sampling, or random, error has to be determined. Simulations can be used to establish an acceptable variability level. The homogeneity test has three different levels that are evaluated by the variation of L-moments of different order. In this study, the homogeneity test based on the L-CV is used. The test is base on a weighted variance of L-CV, V, such that the statistics calculated is

$$V = \frac{\sum_{i=1}^{N} n_i\left(\tau_{(i)} - \bar{\tau}\right)^2}{\sum_{i=1}^{N} n_i} \qquad (17)$$

where n_i = record length at site i; N = number of sites in the region. It is necessary to determine the mean and the standard deviation of V to calculate the homogeneity measure. This can be done through simulation where a realization of the statistic, labled V_k, is calculated from the kth simulation. The mean and standard deveation of the simulated population of the V_k values are defined as μ_v and σ_v respectively. The homogeneity measure is then defined as

$$H = \frac{V - \mu_v}{\sigma_v} \qquad (18)$$

Acording to Hosking and Wallis (1993), a region can be declared homogeneous if the value of *H* is less than 1, Possibly homogeneous if the value of *H* is greater than or equal to 1 but less than 2, and definitively heterogenous if the value of *H* is greater than or equal to 2.

3.0 Data Selection and Initial Screening

Data were obtained from Master Plan for the Electricity Supply of Sri Lanka (1987). A total of 127 catchments of Sri Lanka are listed in the Master Plan for the Electricity Supply of Sri Lanka (1987). Out of this set of catchments, 68 passed the screening criteria of having at least 10 years of observation. It should be noted that the record length threshold selected (10 years) is not intended to signify that reliable at-site flood frequency analysis could be conducted for catchments having a record length as short as the threshold value. It should also be noted that during the period of the available data set, discharge of some of the catchments were regulated by upstream reservoirs or by a large number of small tanks (Master Plan for the Electricity Supply of Sri Lanka 1987). Therefore it is also decided to exclude those catchments from the analysis. Some variables that might be expected to influence the frequency distribution, such as the underlying geology of the basin or the basin is forested or urbanized, are not available. 46 gauging sites are selected for this study after final screening.

The reliability of data is not analyzed in this study. Of the 46 stations selected for this study, some of the stations were closed down before 1985.

Locations of the 46 sites selected after screening are shown in Figure 1. The selected data set contains a total of 979 streamflow observations of the period 1940 to 1985, with sample sizes at the 46 sites varying from 10 to 42. The at site sample LCv ranges from 0.139 to 0.513. The average valve for LCv is 0.3319 and for LCs is 0.3309.

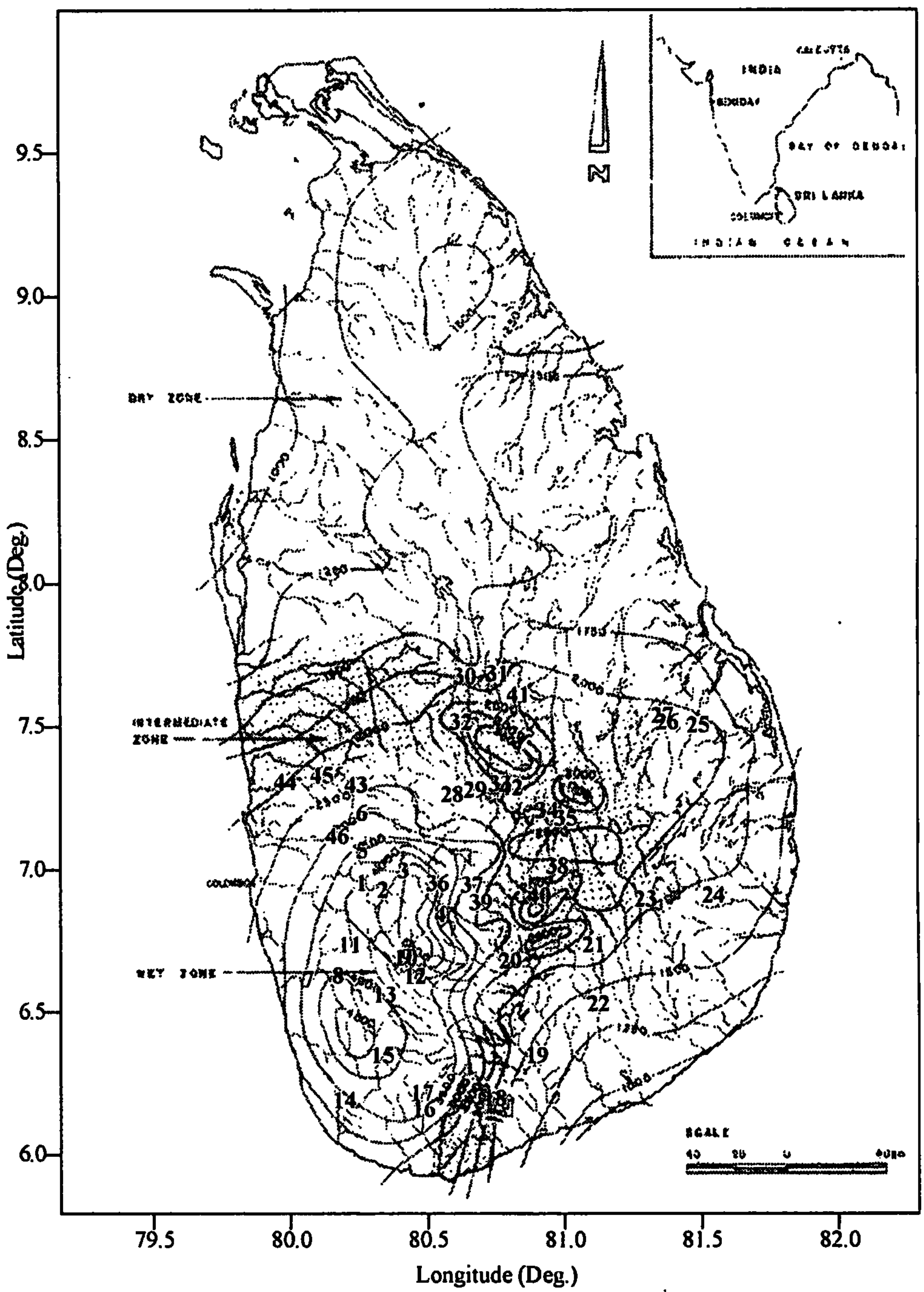

Fig. 1 - Selected streamflow gauging stations
(Base Map Source: Master Plan for the Electricity Supply Supply of Sri Lanka (1987)

The LCv and LCs of the data are shown in Figure 2. Treating the entire set of 46 sites as a single region, the discordancy statistics Di of Hosking and Wallis (1993) was calculated for each site (Table 1). Two sites stand out as being particularly discordant, with Di are equal to 4.51 at Dela, 3.04 at Talawakanda. To some extent the low L-skewness at sites Dela occur because the period of gauging included one year that had particularly low maximum flow compared to the second lowest maximum flow. There were no significant interventions of upstream flow of Dela site and therefore, considering the number of data records of the site, it is decided to retain the site in the data set.

for regional frequency analysis would therefore be a subdivision of the set of sites, according to their drainage areas, into groups of not much more than 20. The set of sites was accordingly divided into three groups of approximately equal size according to the sites' drainage area. These group regions are termed as Regions A-C The heterogeneity measure was calculated for each regions data. A summary of results is contained in Table 2. The heterogeneity measure H indicates that homogeneous regions were achieved for sites with drainage area less than 200 km^2. It appears that homogeneity is determined by more factors than drainage area alone.

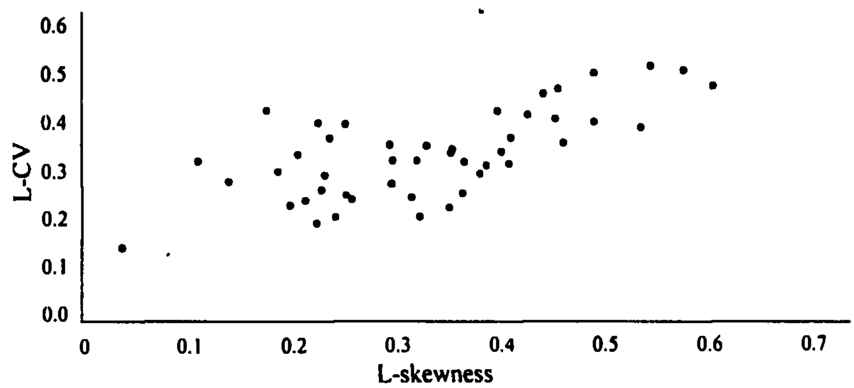

Figure 2 - L-moment ratios for the streamflow data.

Tekkam site has 12 years of records varying from 63 m^3/s on 06th January 1963 to 769 m^3/s on 24th December 1957. Next highest discharge value was 224 m^3/s and recorded on 21st February 1960. To some extent this high gap between largest flood and second largest flood is responsible for high values of L-CV and L-skewness of this site. Other checks on the data were inconclusive. There are no obvious trends or changes in level apparent in the data. Some sites have high sample L-CV and L-skewness, but the data appear to be correct.

4.0 Formation of Regions

Treating the entire set of 46 gauging sites as a single region, the heterogeneity measure was calculated to be H = 2.93. The entire set of sites is therefore far from being homogeneous. The main reason is that the theory and practice of hydrology imply that the frequency distribution is likely to depend on the drainage area of the basin. Regional frequency analysis should therefore be applied only to regions whose basins cover a fairly small range of drainage area. A further point is that in regional frequency analysis there is little to be gain by using regions containing more than about 20 sites (Hosking and Wallis (1993)). A reasonable starting point

The set of sites was divided in to three groups of approximately equal size according to the sites' gauge elevation. These group regions are termed as Regions D-F. A summary of results is given in Table 3. The heterogeneity measure H indicates that homogeneous regions were achieved for sites with higher gauge elevations. Region D is heterogeneous with H value is equal to 2.65. The heterogeneity measure was calculated after removing the highest discordant site, site (12) Dela with Di = 2.55, in the Region D. The Heterogeneity measure of the new region with 14 sites reduced to 1.75. The site (16) Bopagoda was found to be discordant with Di= 2.70 among the 14 sites of the new region. The heterogeneity measure of Region D after removing the sites 12and 16 was calculated to be 0.41. It appears that gauge elevation along can be used to identify homogeneous regions.

The set of site was divided in to clusters using Ward's method (Ward, 1963; Mojena, 1988). This is an "agglomerative hierarchical" clustering procedure: each site is a cluster by itself, and clusters are then merged one by one until all sites belong to a single cluster. The assignment of sites to clusters can be determined for any number of clusters, and there is no formal measure of an "optimal" number of clusters. Choice of a suitable number of clusters is therefore subjective. The number

Table 1 - Calculated L-coefficient of variation, L-skewness, L-kurtosis, and the discordancy statistics treating the entire set of 68 sites as a single region.

Site	Catchment	River	n	Area (km^2)	Elevation (m r.m.s.l.)	LC_V	LC_S	LC_K	D_i
1	Algoda	Sitawaka Ganga	15	345	26	0.2207	0.3501	0.4410	1.19
2	Deraniyagala	Sitawaka Ganga	28	152	82	0.2507	0.3629	0.4212	0.75
3	Kitulgala	Kelani Ganga	12	388	56	0.3201	0.2962	0.2052	1.09
4	Mousakelle	Maskeli Oya	18	122	1158	0.2393	0.2568	0.3140	0.38
5	Imbulana	Gurugoda Oya	26	329	26	0.2913	0.3799	0.3756	0.43
6	Holambuwa	Gurugoda Oya	15	155	53	0.3975	0.2249	0.2036	1.35
7	Putupaula	Kalu Ganga	37	2598	2	0.2022	0.2409	0.2685	1.05
8	Millakanda	Kuda Ganga	28	769	17	0.1885	0.2230	0.3615	1.00
9	Malwala	Kalu Ganga	24	329	18	0.2773	0.1389	0.1697	1.06
10	Nambapana	Kalu Ganga	22	629	13	0.2269	0.1976	0.2649	0.54
11	Ellagawa	Kalu Ganga	26	1393	4	0.2474	0.2515	0.2769	0.44
12	Dela	Wey Ganga	27	220	29	0.1391	0.0366	0.3781	4.51
13	Kekulegama	Kukule Ganga	10	334	200	0.3165	0.3650	0.4781	0.79
14	Agaliya	Gin Ganga	38	696	10	0.2023	0.3216	0.3821	1.22
15	Jesmin	Gin Ganga	10	361	27	0.3208	0.1097	0.2482	2.13
16	Bopagoda	Nilwala Ganga	42	442	18	0.4049	0.4532	0.3159	1.04
17	Bingimahara	Nilwala Ganga	12	333	26	0.2369	0.2122	0.3505	0.65
18	Julampitiya	Urubokka Oya	14	141	62	0.3517	0.2937	0.3729	0.44
19	Embilipitiya	Walawe Ganga	22	1580	31	0.3353	0.3523	0.3112	0.21
20	Samanalawewa	Walawe Ganga	16	353	364	0.3661	0.2360	0.2298	0.73
21	Wellawaya	Kirindi Oya	11	160	154	0.4569	0.4416	0.4824	1.41
22	Kuda	Kuda Oya	17	291	81	0.4216	0.3972	0.3081	0.56
23	Nakkala	Kumbukkan Oya	10	216	160	0.3492	0.3287	0.3522	0.04
24	Siyambalandu	Heda Oya	20	295	55	0.4239	0.1759	0.1257	2.88
25	Periya aru	Magalwatuwan Aru	32	119	36	0.4665	0.4560	0.3992	0.77
26	Nilobe	Rumbukkan Oya	24	159	44	0.3329	0.2053	0.1507	1.30
27	Maha	Maha Oya	11	300	39	0.3086	0.3861	0.4865	0.78
28	Peradeniya	Mahaweli Ganga	39	1167	463	0.2891	0.2311	0.1879	0.93
29	Gurudeniya	Mahaweli Ganga	33	1418	425	0.3368	0.4007	0.3652	0.26
30	Nalanda	Nalanda Oya	10	126	243	0.5134	0.5446	0.5606	2.54
31	Elehera	Amban Ganga	29	774	133	0.3426	0.3536	0.3224	0.12
32	Morape	Kotmale Oya	32	555	640	0.3863	0.5354	0.4697	1.06
33	Teldeniya	Hulu Ganga	23	160	411	0.3978	0.4904	0.4407	0.55
34	Randenigala	Mahaweli Ganga	20	2365	141	0.2585	0.2275	0.2988	0.27
35	Kandaketiya	Badulu Oya	17	387	126	0.3192	0.3198	0.4111	0.34
36	Watawala	Mahaweli Ganga	18	65	829	0.3548	0.4609	0.4103	0.55
37	Talawakelle	Kotmale Oya	28	297	1200	0.5037	0.5767	0.4575	1.52
38	Talawakanda	uma Oya	12	520	575	0.4718	0.6052	0.6454	3.04
39	Holbrook	Agra Oya	18	121	1346	0.4134	0.4264	0.3130	0.72
40	Welimada	Uma Oya	17	179	1070	0.4986	0.4904	0.3942	1.18
41	Wellewela	Kalu Ganga	12	194	140	0.2975	0.1863	0.3540	1.39
42	Moragahamull	Galmal Oya	16	73	427	0.3652	0.4100	0.3700	0.19
43	Alawwa	Maha Oya	23	804	49	0.3117	0.4080	0.3691	0.56
44	Badalgama	Maha Oya	30	1360	12	0.2716	0.2948	0.2900	0.39
45	Giriulla	Maha Oya	21	1191	27	0.2424	0.3138	0.3532	0.54
46	Karasnagala	Attanagalu Oya	14	53	28	0.3956	0.2512	0.3024	1.09

(m r.m.s.l.) Elevation in meters relative to mean sea level

Table 2 - Summary of regions defined in terms of drainage area.

Region	Range of Area (km^2)	Sites	Number of Sites	H
A	< 200	46, 36, 42, 25, 39, 4, 30, 18, 2, 6, 26, 21, 33, 40, 41	15	0.24
B	200 - 400	23, 12, 22, 24, 37, 27, 5, 9, 17, 13, 1, 20, 15, 35, 3	15	2.28
C	>400	16, 38, 32, 10, 14, 8, 31, 43, 28, 45, 44, 11, 29, 19, 34, 7	16	1.67

Table 3 - Summary of regions defined in terms of catchment elevation.

Region	Range of Elevation (m)	Sites	Number of Sites	H
D	< 30	7, 11, 14, 44, 10, 8, 9, 16, 5, 17, 1, 15, 45, 46, 12	15	2.65
E	30 - 150	19, 25, 27, 26, 43, 6, 24, 3, 18, 22, 2, 35, 31, 41, 34	15	0.09
F	>150	21, 23, 13, 30, 20, 33, 29, 42, 28, 38, 32, 36, 40, 4, 37, 39	16	-0.16

of sites in a cluster should be large, to obtain the maximum benefit of regionalization, but the range of drainage areas of the site in a cluster should not be too large, for otherwise it would not be reasonable to expect the clusters to be homogeneous. The clustering algorithm was applied in a sequential manner until no further improvements could be obtained in the homogeneity of the regions formed.

Clusters are numbered 1-3 in increasing order of average drainage basin area of the sites in the cluster. Region 1 contains 15 sites with very small drainage area and high elevation. Regions 2 and 3 span a range of drainage area and contain mostly low-elevation sites. These distinctions are not exact, because the remaining variables, latitude and longitude, also affect the clustering. Their effect can be seen in Figure 3, which shows the geographical location of the sites in each cluster.

The discordancy, and heterogeneity measures of Hosking and Wallis (1993) were calculated for each region's data. Summary statistics for the regions are contained in Table 4. The heterogeneity measure H indicates that homogeneous regions were achieved in regions 1 and 3. Region 2 is possibly heterogeneous with H value as high as 1.88, but should yield quantile estimates more accurate than those obtained from single-site frequency analysis. The heterogeneity measure Region 2 was calculated after removing the highest discordant site, site (12) Dela with Di = 2.65, in the Region 3. The Heterogeneity measure of the new region with 18 sites reduced to 0.56.

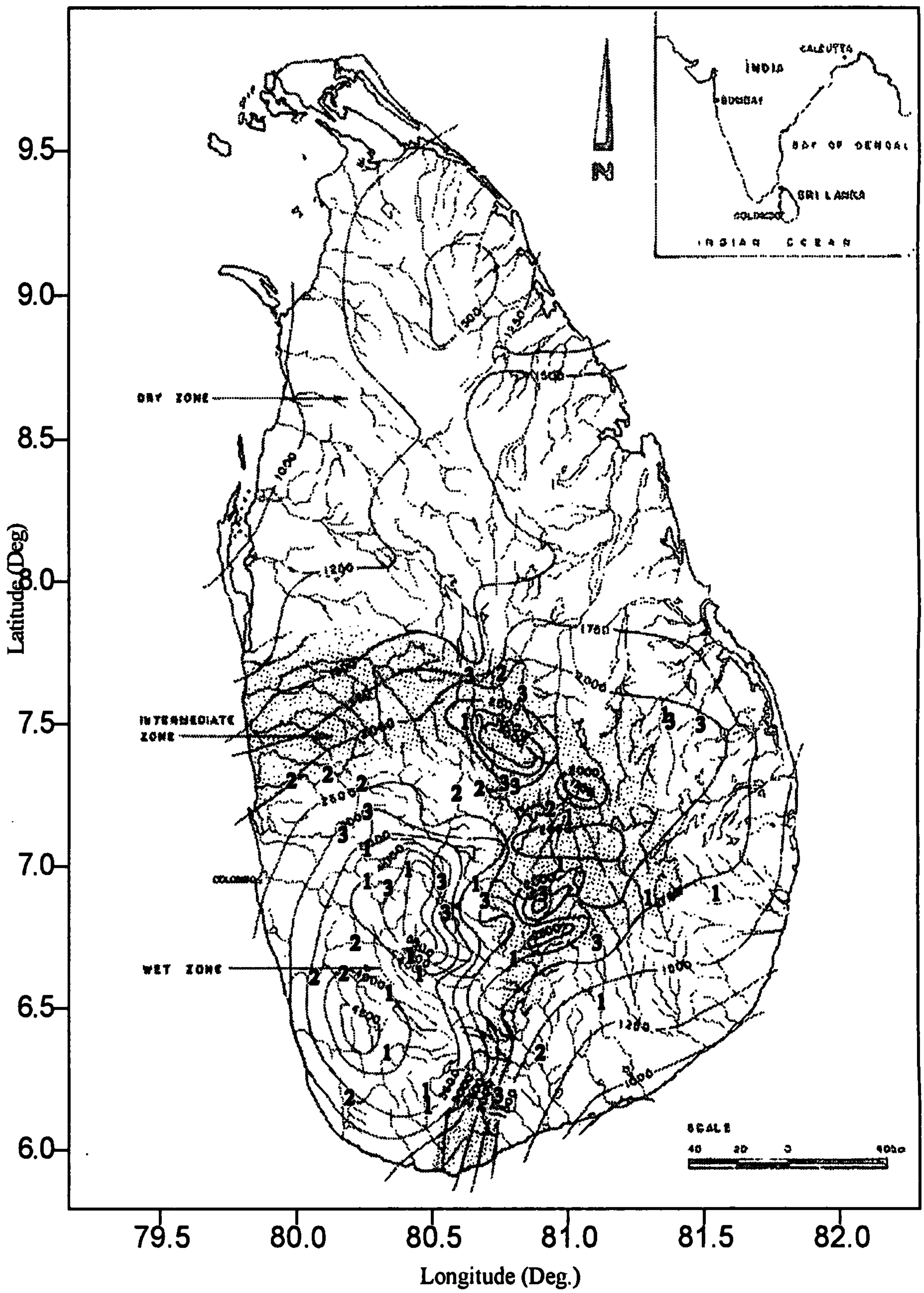

Figure 3 - Location of the sites in each cluster of streamflow gauging stations in Sri Lanka.

Table 4 - Summary of regions defined by cluster analysis.

Region	Average Area (km^2)	Average Elevation (m)	Sites	Number of Sites	H
1	124.3	289.28	2, 4, 6, 18, 21, 25, 26, 30, 33, 36, 39, 40, 41, 42, 46	15	0.22
2	351.18	121.15	1, 3, 5, 9, 10, 12, 13, 15, 16, 17, 20, 22, 23, 24, 27, 32, 35, 37, 38	19	1.88
3	1230.7	65.97	7, 8, 11, 14, 19, 28, 29, 31, 34, 43, 44, 45	12	0.38

5.0 Summary and Conclusion

Annual maximum flow data from 46 sites in Sri Lanka were analyzed using L-moments to study regional homogeneity. The region as a whole is heterogeneous. The region was further divided into three regions defined in terms of drainage area. Homogeneous regions were achieved for sites with drainage area less than 200 km^2. Regions with catchment areas grater than 200 km^2 were found to be heterogeneous.

The region was then divided into three regions in terms of catchment elevation. Division of regions based on catchment elevation was found to be acceptably homogeneous. Geography of Sri Lanka is such that the catchments with higher elevation are scattered hence, can be considered as a single region. Therefore division of regions based on gauge elevation alone formed acceptably homogeneous regions.

More information was introduced into the procedure for forming regions. The four available site characteristics, drainage area, gauge elevation, gauge latitude and gauge longitude, were used in a cluster analysis procedure. The regions formed were found to be homogeneous after excluding one discordant site from the data set. Further adjustments to these clusters may be desirable, but would require further study of the reliability of the data from different gauging sites, detailed knowledge of local factors such as urbanization, reclamation etc. that might affect the climate or hydrology of each drainage basin, and more data on other site characteristics that could be used as the basis for forming regions.

6.0 Acknowledgements

Author would like to thank Professor D. C. H. Senarath, Department of Civil Engineering, University of Moratuwa for the constructive comments on the manuscript.

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