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WATERSHED SIMILARITY CONDITIONS FOR PEAKFLOW TRANSPOSITION - A STUDY OF RIVER BASINS IN THE WET ZONE OF SRI LANKA

by

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Abstract

The majority of construction works in developing countries like Sri Lanka require engineers to work with ungauged watersheds. Such works often require extrapolation of peakflow from a gauged watershed using the different characteristics of each watershed. Though some attempts of peakflow transposition for different parts of the world are available, this has to be addressed for Sri Lankan watersheds. The annual peakflow of four main watersheds in the Wet Zone were studied to identify the feasibility of transposition. This study established a peak flow similarity index and three main criteria. It was identified that annual peakflows of similar watersheds can be transposed satisfactorily with the relationship that peakflow from a watershed is propotionate to the 0.8th power of its area. Peakflow transposition between similar watersheds within the same river basin indicated an average error of 35% whereas similar watersheds between river basins in the Wet Zone indicated an average error of 55%.

1. Introduction

The present trend in watershed studies is to utilize physically based spatially distributed continuous mathematical models. The data demands for these models are so high that modellers are often restricted from using them to their full potential. The time taken for data collection and processing, demand for skilled personnel and the high cost involved are other factors that limit their usage. Moreover, most or almost all these sophisticated models do not prove valuable for applications in ungauged watersheds.

The majority of construction works in developing countries like Sri Lanka require engineers to work with ungauged watersheds. Such works often require extrapolation of peakflow from a gauged catchment using some characteristics such as watershed area. Peakflow Estimation is a very important exercise in planning for drainage and related protection measures. Proper selection of the design estimates influences the safety and the cost of engineering measures that are planned for the safety of the public and the environment. Therefore, it is necessary to use reliable methods for such estimations. Though there are many methods cited in the literature for the extrapolation of streamflow from one watershed to another, limited work has been done in this regard for Sri Lankan watersheds. Most peakflow transposition methods cited in literature often require similarity between watersheds to overcome the issue of watershed heterogeneity. The Wet Zone of Sri Lanka that has a significant similarity in rainfall, wind directions, land use, topography, etc., was selected to carry out a comparative study to identify the best methodology for peakflow extrapolation between watersheds. Measured annual peakflow of four major river basins, Kelani, Kalu, Gin and Nilwala (Table 1, Figure 1) that cover more than 80% of the Wet Zone, were used for the computations. The parameters identified through this study enable the extrapolation of annual peakflows from a gauged watershed to an ungauged one.

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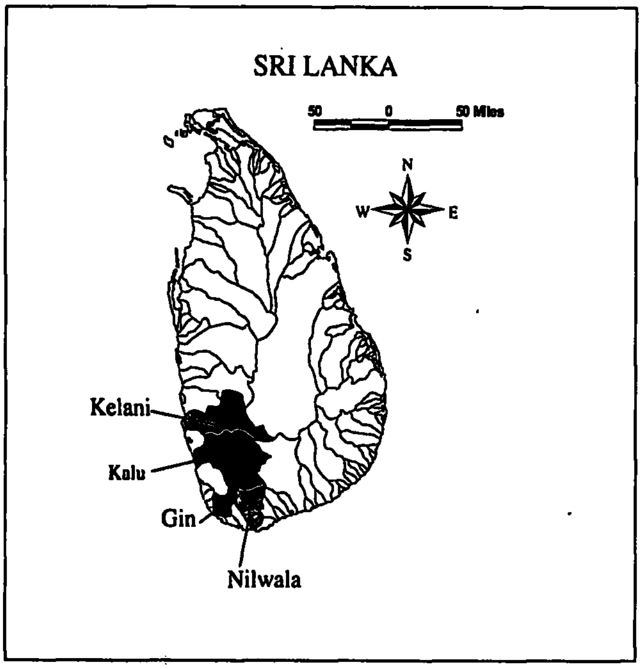

Figure 1: Locations of Selected River Basins

River Basin	Gauging Station	Watershed Area (km2)	Slope (%)	Shape (m/m)	Annual Rainfall (mm)	Length of Record
Kelani	Glencourse	1463	4.0	0.3	4060	1948 - 1984
	Metiyadola	606	4.6	0.1	4100	1948 - 1981
	Deraniyagala	152	2.2	0.4	5000	1948 - 1976
	Kithulgala	388	5.1	0.2	3620	1947 - 1984
	Imbulana	329	1.5	0.6	3525	1948 - 1973
Kalu	Putupaula	2598	1.5	0.5	3970	1943 - 1981
	Millakanda	769	1.5	0.2	4110	1950 - 1977
	Malawala	329	4.0	1.0	4100	1954 - 1978
	Nambapana	629	3.3	0.3	3745	1956 - 1978
	Ellagawa	1393	2.1	0.4	3910	1956 - 1980
	Dela	220	1.8	0.2	2610	1956 - 1984
Gin	Agaliya	696	1.5	0.5	3970	1941 - 1984
	Thawalama	361	1.5	0.2	4110	1973 - 1984
Nilwala	Boppagoda	442	20	1.0	3400	1940 - 1982
	Bingimahara	333	18	0.6	3240	1973 - 1984

Table 1: Details of Selected River Basins

2. Data

Monthly streamflow, rainfall and annual flood peak records for the selected basins from 1940-1985 were plotted and observed for discrepancies, and compared with adjacent watersheds (CEB 1985). Data sets with missing periods were avoided as far as possible. No data filling was carried out since the study was an attempt to look at the peakflow which was difficult to relate to adjacent temporal data. A comparison of different combinations of flood peaks, though they showed a similarity, were reflecting an irregular behavioral pattern (Figure 2) even within the same river basin indicating a probable influence of other factors such as slope, shape and rainfall. Correlation computed between annual peakflow of different catchment combinations also indicated the same. This indicated the absence of a direct and straightforward relationship between annual floods.

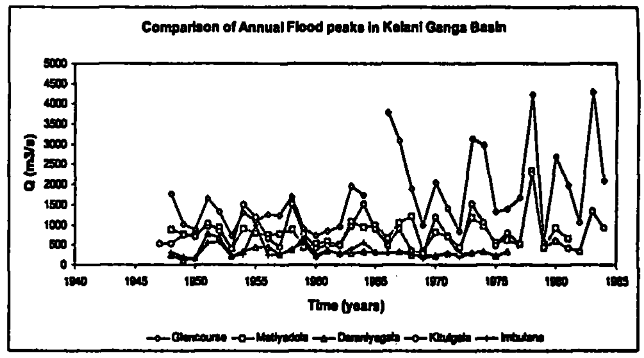

Figure 2a: Comparison of Flood Peaks in Kelani Ganga Basin

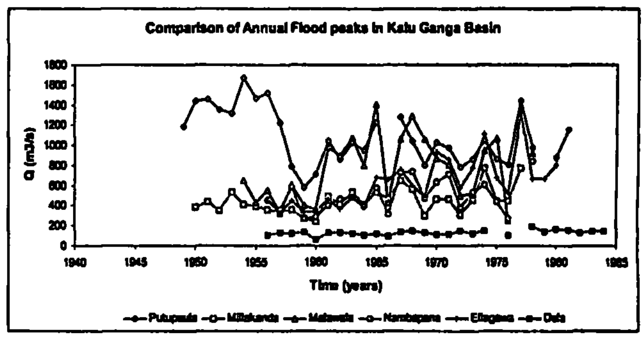

Figure 2b: Comparison of Flood Peaks in Kalu Ganga Basin

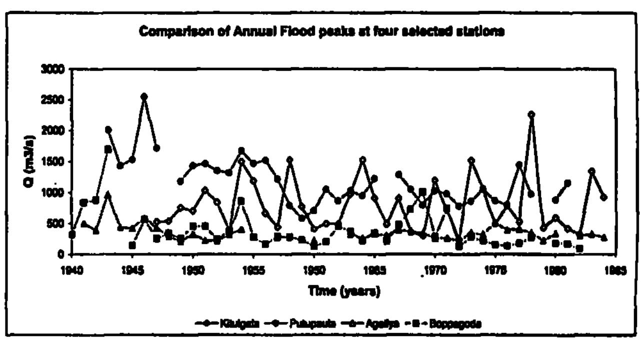

Figure 2c: Comparison of Flood Peaks in Four Selected River Basins

3. Analysis

3.1 Watershed Area and Peakflow

There are a vast number of empirical formulae in the published literature indicating the direct relationship of watershed area to the peakflow from a watershed. Out of those formulae, the most widely used in South India are Ryve's formula and Dicken's Formula (Murthi 1977). There are some others such as the rational formula which also involve rainfall intensity, slope of the catchment, land use, etc. The identification of peak flow extrapolation was attempted with the commonly used approach in the abovementioned methods. It was taken that $Q_p=CA^n$ where Q_p and A are peakflow and catchment area respectively. C and n are constants where n is said to vary between 0.2 and 0.9 (Chorley 1969). C is the constant of proportionality and varies from region to region. Peakflow transposition using this relationship assumes that the watersheds under comparison are similar.

In this study, peakflow assessments in seventy-nine possible pairs of watershed combinations from identified river basins were compared with the use of a numerical indicator. The indicator, Mean Ratio of Absolute Error (MRAE) is as shown below.

$$MRAE = (1 / N) \sum [ABS (Q_{cal}-Q_{obs}) / Q_{obs}] \times 100 \ \% \quad (1)$$

where Qobs is the observed peakflow and Qcal is the calculated peak flow, and N is the number of events in consideration. The error in estimation for each watershed combination and optimum n value with minimum error was computed. Computations showed that the value of n varied widely. More than 75% of the n values were between 0 and 1. For some combinations, the n values were less than zero and for a few it was greater than one.

3.2 Other Key Factors

The values of exponents from the comparison of selected watersheds showed a dissimilarity of watersheds. In the literature, rainfall (intensity, duration & distribution), stream slope, shape and land use have been identified as key factors affecting the peak runoff. Slope and shape have significant influence over the peak runoff whereas it has been identified that peakflow has no significant relationship to drainage density and basin elevation once the slope and shape have been taken into account. Effect of land use has pronounced effect only in small watersheds. Based on the information extracted from a literature survey especially work done for the Indian subcontinent (Abeynayake 2000), mean annual rainfall, main stream slope, and shape of the catchment had been identified as the key factors for watershed comparison. Annual rainfall, slope, and shape of watershed were computed for each watershed in the study and were used as base data. Slopes of different stream segments were averaged to calculate the average slope for a particular watershed. Shape was taken as the ratio of width and the length of the watershed. Length is the axial length from outlet to the remotest part of the watershed and width is the average width of watershed along the axial length. Average annul rainfall of a particular watershed was taken as the Thiessen average (Wilson 1969) of long term averaged point rainfall. For this study a 40-year average rainfall was utilized. Values pertaining to the above are in Table 1.

3.3 Peakflow Similarity Index

Attempts were made to identify watershed similarity for peakflow transposition using the spatial extent of the watershed. The similarity between watersheds for peakflow estimation was taken as a function of similarities in rainfall, slopes, and shapes of those watersheds. Rainfall is directly responsible for peakflow and other than this, the slope is the most prominent characteristic that affects the peakflow reaching a gauging station. Considering these, an index called peak flow similarity index that is the simple average of rainfall and slope factors was defined:

$$\text{Peakflow Similarity Index (PSI)} = \tfrac{1}{2}\,(\text{Rainfall 2} / \text{Rainfall 1} + \text{Slope 2} / \text{Slope 1}) \quad (2)$$

Qualifying criteria were incorporated in PSI. This was to eliminate the possibility of extreme ratios of rainfall, slope and shape making the index stray from pointing to watershed similarity. The first criterion required this PSI to have a value closer to unity for the watersheds to be similar.

3.4 Criteria for Rainfall

Computed exponent values indicated that extreme values of rainfall and slope ratios could also lead to PSI values close to unity thus satisfying the criterion for similarity. In order to overcome this, the second criterion that requires rainfall ratio to be near unity was introduced into the computations. Though the results of peakflow transposition were improved to a great extent due to the exclusion of the extreme cases, a wide variability in the computed exponent could still be observed. This pointed to the need for incorporating a similarity criterion for watershed slope and shape.

3.5 Catchment Slope and Shape

In steep slopes, the discharge rate is usually rapid and higher. The runoff rate from mild slopes is generally slower and lower. Compact watersheds for which breadth to length ratio is high show rapid and high peaks. Elongated watersheds of which breadth to width ratio is low show slower and lower peaks. Peakflow from elongated watersheds with steep slopes are likely to show characteristics similar to mild compact watersheds. Similarly flood peaks of elongated watersheds with mild slopes are likely to show characteristics similar to steep compact watersheds. At the same time steep compact watersheds might show significant high peaks in the steep compact ones when compared with mild elongated watersheds. This behaviour is taken into consideration for the third criterion. The third criterion consists of three components. When both the ratios of slope and shape of a set of watersheds indicate either increasing or decreasing values then the peakflow characteristics could be considered as similar. As such for watershed similarity in peakflow, it is necessary for the ratios of slopes and shapes to be equal or close to unity. This is the first component of the third criteria. The second and third are that the watersheds would behave similarly when the slope ratio is greater than one and the shape ratio is less than one and vice versa.

Watershed combinations in the study area were compared using the above three criteria and after a comparison of the results, the criteria were modified to cater to reality by enabling the ratios to deviate 25% from unity. The final criterion for watersheds having peakflow similarity used in the study are as follows:

Criterion 1: $0.75 < PSI < 1.25$ (3)
Criterion 2: $0.75 < Rainfall\ 2 / Rainfall\ 1 < 1.25$ (4)
Criterion 3: $0.75 < Slope\ 2 / Slope\ 1 < 1.25$ and $0.75 < Shape\ 2 / Shape\ 1 < 1.25$ (5)
$Slope\ 2 / Slope\ 1 < 1$ and $Shape\ 2 / Shape\ 1 > 1$ (6)
$Slope\ 2 / Slope\ 1 > 1$ and $Shape\ 2 / Shape\ 1 < 1$ (7)

4 Results

4.1 Similar Peakflow Characteristics

Based on the above criteria, watersheds with similar peakflow characteristics were identified. It was observed that eighteen combinations out of seventy-nine were found to have similar peakflow characteristics (Table 2).

No.	Catchment (to)	Catchment (from)	Optimum Exponent n	Mean Ratio of Absolute Error %	Criterion 1 PSI	Criterion 2 Ratio of Rainfall	Criterion 3 Ratios of Slope and Shape	Similar Watershed Combinations
	Combinations within a River Basin							
1	Metiyadola	Glencourse	0.80	29	1.09	1.01	1.16 & 0.45	#
2	Deraniyagala	Glencourse	0.80	41	0.89	1.23	0.56 & 1.21	#
3	Kitulgala	Glencourse	0.80	41	1.09	0.89	1.28 & 0.64	#
4	Imbulana	Glencourse	1.20	39	x	0.87	0.37 & 1.91	
5	Deraniyagala	Metiyadola	0.80	34	0.85	1.22	0.48 & 2.67	#
6	Kitulgala	Metiyadola	0.20	28	0.99	0.88	x	
7	Imbulana	Metiyadola	1.80	23	x	0.86	0.32 & 4.20	
8	Deraniyagala	Kitulgala	1.30	41	0.91	x	0.43 & 1.90	
9	Imbulana	Kitulgala	6.50	40	x	0.97	0.29 & 3.00	
10	Deraniyagala	Imbulana	0.00	25	x	x	1.50 & 0.63	
11	Millakanda	Putupaula	0.70	26	1.01	1.04	1.00 & 0.42	#
12	Malawala	Putupaula	0.30	44	x	1.03	x	
13	Nambapana	Putupaula	0.30	23	x	0.94	2.27 & 0.56	
14	Ellagawa	Putupaula	0.90	29	1.22	0.98	1.46 & 0.68	#
15	Dela	Putupaula	0.80	23	0.95	x	1.24 & 0.42	
16	Millakanda	Ellagawa	0.60	22	0.87	1.05	x	
17	Malawala	Ellagawa	0.00	36	x	1.05	x	
18	Nambapana	Ellagawa	0.30	25	x	0.96	1.36 & 0.97	
19	Dela	Ellagawa	0.90	27	0.76	x	x	
20	Malawala	Millakanda	-0.30	31	x	1.00	x	
21	Nambapana	Millakanda	-0.30	21	x	0.91	x	
22	Dela	Millakanda	1.10	17	0.95	x	1.25 & 1.00	
23	Malawala	Nambapana	-0.40	26	1.14	1.09	x	
24	Dela	Nambapana	1.40	20	x	x	x	
25	Dela	Malawala	5.00	28	x	x	x	
	Combinations between River Basins							
26	Glencourse	Putupaula	-0.10	38	x	1.02	3.35 & 0.62	
27	Metiyadola	Putupaula	0.30	29	x	1.03	3.89 & 0.28	
28	Kitulgala	Putupaula	0.40	40	x	0.91	4.30 & 0.40	
29	Imbulana	Putupaula	0.70	37	1.07	0.89	1.25 & 1.19	#
30	Deraniyagala	Putupaula	0.50	33	x	x	1.86 & 0.75	
31	Metiyadola	Ellagawa	0.10	39	x	1.05	3.10 & 0.42	
32	Kitulgala	Ellagawa	0.20	44	x	0.93	3.43 & 0.58	
33	Imbulana	Ellagawa	0.60	35	0.95	0.90	0.99 & 1.75	#
34	Deraniyagala	Ellagawa	0.60	33	x	x	x	
35	Metiyadola	Millakanda	-1.50	30	x	1.00	3.14 & 0.68	
36	Kitulgala	Millakanda	-0.20	41	x	0.88	3.47 & 0.95	
37	Imbulana	Millakanda	0.50	28	0.93	0.86	0.99 & 2.86	#
38	Deraniyagala	Millakanda	0.30	31	x	1.22	x	
39	Metiyadola	Nambapana	-10.00	26	x	1.09	1.75 & 0.43	
40	Kitulgala	Nambapana	-0.40	42	x	0.97	1.93 & 0.60	
41	Imbulana	Nambapana	1.00	30	0.75	0.94	0.56 & 1.80	#
42	Deraniyagala	Nambapana	0.40	28	1.09	x	0.84 & 1.14	
43	Imbulana	Malawala	*	167	0.78	0.86	x	
44	Deraniyagala	Malawala	1.60	39	1.13	1.22	1.05 & 0.40	#
45	Deraniyagala	Dela	-2.20	20	x		x	
46	Ellagawa	Glencourse	26.00	24	x	0.96	0.37 & 1.09	
47	Millakanda	Glencourse	2.00	29	x	1.01	x	
48	Nambapana	Glencourse	1.60	38	0.79	0.92	0.67 & 1.06	#
49	Malawala	Glencourse	0.70	48	0.77	1.01	0.53 & 3.03	#
50	Malawala	Metiyadola	-0.60	38	x	1.00	0.46 & 6.67	
51	Malawala	Kitulgala	4.00	48	0.77	1.13	0.41 & 4.76	#
52	Malawala	Imbulana	*	59	x	1.16	x	
53	Dela	Glencourse	1.60	42	x	x	x	
54	Dela	Metiyadola	2.00	29	x	x	0.40 & 1.47	
55	Dela	Kitulgala	3.50	42	x	x	0.36 & 1.05	
56	Dela	Imbulana	2.40	27	0.99	x	1.24 & 0.35	
57	Agaliya	Glencourse	2.80	33	x	0.94	x	
58	Agaliya	Putupaula	2.40	22	1.14	0.96	1.32 & 0.42	#
59	Agaliya	Ellagawa	1.20	30	1.01	0.97	1.05 & 0.61	#
60	Agaliya	Millakanda	4.50	19	1.00	0.92	1.07 & 1.00	#
61	Metiyadola	Agaliya	-5.80	37	x	1.08	2.94 & 0.68	
62	Kitulgala	Agaliya	-0.80	44	x	0.95	3.25 & 0.95	
63	Imbulana	Agaliya	0.20	30	0.93	0.93	0.94 & 2.86	#
64	Deraniyagala	Agaliya	0.10	28	x	x	x	
65	Nambapana	Agaliya	-4.00	29	x	0.99	x	
66	Malawala	Agaliya	-0.70	41	1.21	1.08	x	
67	Dela	Agaliya	0.80	18	x	x	1.17 & 1.00	
68	Bopagoda	Glencourse	1.80	48	x	x	0.51 & 3.03	
69	Bopagoda	Metiyadola	4.00	32	x	x	0.44 & 6.67	
70	Bopagoda	Putupaula	1.50	35	1.19	x	x	
71	Bopagoda	Ellagawa	2.50	46	1.02	x	x	
72	Bopagoda	Milakanda	1.50	42	1.02	x	x	
73	Bopagoda	Nambapana	2.00	28	x	x	0.76 & 2.86	
74	Kitulgala	Bopagoda	-3.50	61	x	x	2.54 & 0.21	
75	Imbulana	Bopagoda	2.00	59	1.02	x	x	
76	Deraniyagala	Bopagoda	0.50	53	x	x	1.10 & 0.40	
77	Malawala	Bopagoda	-2.00	41	x	x	1.05 & 1.00	
78	Dela	Bopagoda	1.40	47	0.94	0.96	x	
79	Bopagoda	Agaliya	1.10	48	1.00	x	x	

*Note: X-Criteria Not Satisfied; *-Did not Converge; # Similar Watersheds*

Table:2: Key Parameters with respect to Watershed Combinations

4.2 Comparison of Exponent n with Peakflow Similarity Index

Comparing the variation of transposition exponent n with PSI indicated that there is a wide variation in n values within the entire set of watershed combinations (Figure 3). Even for the watersheds with a PSI of unity, the n value showed a wide scatter. However, a cluster near n = 0.8 could be observed for many values of PSI.

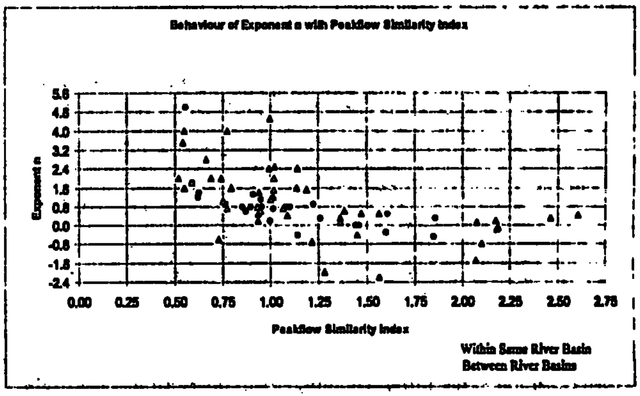

Figure 3: Comparison of Exponent n with Peakflow Similarity Index for all Watersheds

An attempt to look at the peakflow behaviour was made by dividing the watershed combinations into two categories, (1) transposition within same river basin and (2) transposition from other basins.

4.3 Flood Transposition within the Same River Basin

Comparing the exponent n with PSI for watersheds within the same river basin indicated that when the PSI is greater than one the n value decreased from 0.8 and when the PSI is less than 1 the n values increased from 0.8 (Figure 3). The best-fit n value becomes closer to 0.8 when the PSI is between 0.75 and 1.25. These cases (Figure 4) were assigned an exponent value of 0.8 and the error in peakflow transposition was computed using the Mean Ratio of Absolute Error. These values indicated that the average error in estimation has reduced from 60% to 34% when the peakflow similarity index concept is introduced (Table 3). For watersheds within the same river basin having similar peakflow characteristics the variation of error in estimation is between 27% and 41%.

4.4 Flood Transposition between River Basins

Flood transposition using watersheds from other river basins in the Wet Zone was attempted. Figure 3 shows a wide scattered nature in the behaviour of the values of exponent (n) for each case. However there is a

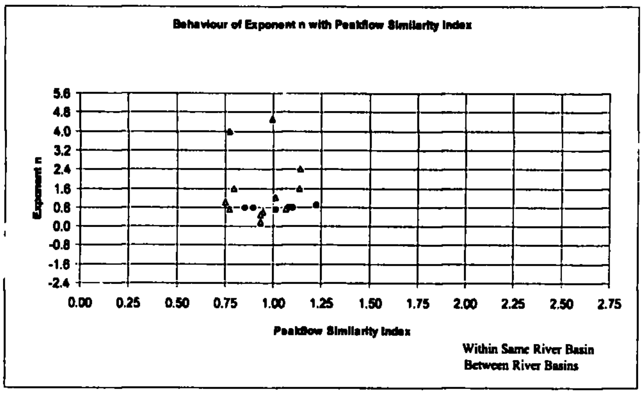

Figure 4: Comparison of Exponent n with Peakflow Similarity Index for Similar Watersheds

No:	% Error in all combinations	%Error for similar watersheds	No:	% Error in all combinations	%Error for similar watersheds
1	29	29	26	51	
2	41	41	27	53	
3	41	41	28	63	
4	70		29	39	39
5	34	34	30	62	
6	40		31	56	
7	54		32	63	
8	56		33	42	42
9	125		34	39	
10	45		35	50	
11	27	27	36	59	
12	69		37	32	32
13	36		38	61	
14	31	31	39	40	
15	23		40	53	
16	23		41	32	32
17	72		42	46	
18	36		43	167	
19	29		44	66	66
20	66		45	69	
21	26		46	132	
22	40		47	113	
23	58		48	93	93
24	73		49	48	48
25	336		50	40	
Average	60	34	51	62	62
			52	59	
			53	220	
			54	183	
			55	301	
			56	92	
			57	230	
			58	128	128
			59	38	38
			60	41	41
			61	62	
			62	68	
			63	44	44
			64	66	
			65	42	
			66	41	
			67	18	
			68	175	
			69	146	
			70	96	
			71	95	
			72	45	
			73	54	
			74	67	
			75	65	
			76	55	
			77	62	
			78	65	
			79	80	
			Average	80	55

Table 3: Error in Peakflow Transposition with 0.8 as the Exponent
(1-25 Within same River Basin26 -79 Between River Basins)

similarity when compared with the values observed from the comparison for the same river basin. The value of the exponent changes in the same manner when the PSI is either greater or less than unity. Exponent (n) values are less than 0.8 when the PSI is greater than one whereas n values are higher than 0.8 when the PSI is less than one.

The exponent of similar watersheds indicated a wide variation of values though a cluster could be observed around 0.8 (Figure 4). The error in estimation of peakflow was checked when a value of 0.8 was used for n. It was identified that the average error in estimation reduced from 80% to 55% in all cases of the similar watersheds. In similar watersheds between river basins, the variation of error in transposition of peakflow showed to be between 32% and 93% with an average error of 55. Case 58 which was the Agaliya - Putupaula watershed combination, indicated a very high error in transposition and this created an increase of the average. It is necessary to study the data and the watersheds in detail to identify the cause.

5 Conclusions

1. Annual peakflow transposition, considering that annual peakflow is directly proportionate to the nth power of the watershed area, produced good estimation of peakflows for similar watersheds. The Peakflow Similarity Index (PSI) and the associated criteria developed could be effectively used to identify similar watersheds for peakflow transposition. The three criteria of PSI adequately incorporate the similarities pertaining to rainfall, slope and shape of the watersheds in the Wet Zone of Sri Lanka

2. Superior peakflow estimates could be obtained when watersheds from the same river basin to when adjacent river basin watersheds are used for transposition. Reasonable estimates could be made even with adjacent watersheds of which peakflow characteristics are similar.

3. Flood transposition between similar watersheds using the watershed area as the only parameter, showed that the annual peakflow is proportionate to 0.8th power of watershed area.

4. Errors in estimation of peakflow using this 0.8th power showed an average estimated error of 35% for similar watersheds within the same river basin whereas an average error of 55% was recorded for any other watersheds from the Wet Zone. Users therefore need to consider the objective of their use of peakflow data and then select the coefficients and watersheds accordingly.

5. The results obtained from the Wet Zone were based on a data series range from 23 years to 43 years of annual peak flow records. It may be good to obtain more data to perform similar analysis for a lengthier data series.

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