Determination of Water Resources Sustainability of the Upper Mahaweli Catchment by Time Series Analysis

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ABSTRACT. *The main objective of this study was to test the hypotheses that large scale settlements and expansion of subsistence agriculture in the Upper Mahaweli Catchment Area (UMCA) and construction of a massive reservoir system within the main river network of Mahaweli have caused any significant changes in the rainfall regime of the area. It is argued that the discharge volumes of the Mahaweli river have been significantly diminishing during the last two or three decades due to the changes made in the structure and composition of the catchment jeopardizing the expectations of the Mahaweli Development Programme. If these questions are left unanswered and the degree of hydrological variability is not properly assessed, it would not be possible to use the historical hydrological records for further design and maintenance purposes. Further, a large amount of national wealth has been spent on this programme and its success basically depends on the hydrological stability of the catchment.*

In this study, rainfall and discharge data of 15 gauging stations in three sub catchments within the catchment boundary were statistically analyzed to investigate the presence of trends and shifts (jumps) of the mean or variance in the monthly time series. It was found that there are no significant trends or jumps in the monthly time series although they exhibit a significant increase in variance. However, it is observed that more time series data should be incorporated to arrive at more meaningful conclusions.

INTRODUCTION

Sustainability of water resources is basic to the sustenance, security, and welfare of a nation especially, in a country like Sri Lanka where the economy is much dependent on agriculture. It is strongly emphasised that the watershed boundaries must be considered as the basic hydrological unit for any water related studies. In this context, it would be very useful to select sub catchments to develop basic hydrological models with sufficient flexibility that modifications, updating and creation of new data layers could be routinely accomplished. This approach will facilitate effective planning methodology to be formulated, implemented and monitored for the long term sustainability of the water resources in the country (Premalal, 1990).

Problem identification

Mahaweli is the longest river in Sri Lanka and its total length is 330 km. It originates from the central highlands located in the upcountry, passes though the mid country and finally reaches the sea on the north east coast. The total catchment area of the river Mahaweli is about 10,400 square km and this catchment is divided into two main areas based upon the elevation. The Upper Mahaweli Catchment (UMCA) is the area located above 150 m above mean sea level and covers an extent of 3100 square km. The major contribution of water to the river is received from the UMCA and therefore, it is very important to conserve this area to ensure a continuous water supply to the dry zone of the country.

The Mahaweli Development Programme was implemented aiming at providing Mahaweli water to the dry zone of the country and generating hydropower to meet the increasing local demand. Under this massive development program, seven major reservoirs have been constructed across the Mahaweli river. Thus a large amount of households had to be replaced and a considerable area of agricultural land was inundated. Resettlement programmes were launched since 1965 and the lands at the UMCA were allotted for the displaced peasants.

With the initiation of the new settlements in the upper catchment, large scale deforestation was unavoidable. Large extents of land, including steep slopes were put under cultivation without proper land and water conservation measures. A question is often raised that hydrological regime in the UMCA has been adversely affected by the settlement schemes and land development under the Mahaweli Development Programme. It is also arguable that the discharge volume of the Mahaweli river has been diminishing during the last two decades due to the changes made on the structure and composition of the catchment, jeopardising the expectations of the Mahaweli Development Programme. If these questions are left unanswered and the degree of hydrological variability is not estimated, it is not possible to use the historical climatological records for any design or maintenance purposes in the UMCA. A tremendous amount of national wealth has been spent on the Mahaweli Development programme and the success of this endeavour is basically dependent on the hydrological stability and sustainability of the catchment. Therefore, it is imperative to study the temporal and spatial distribution of rainfall with reference to the historical records to verify the reliability of the past data with the existing conditions. Further, it is also important to analyze the river flow data to determine any significant changes occurred after 1965.

The Meterological Department of Sri Lanka monitors an extensive rain gauge network throughout the UMCA. The stream gauging network is also well established. In this study, it was anticipated to collect the rainfall and discharge information of UMCA for at least 40 years.

It was expected to estimate the missing data by simple interpolation of existing data from adjacent stations. The consistency of the collected data was also verified. Once the consistent data format was obtained, it was proposed to conduct time series analysis to determine positive or negative trend surface overlying the data. Statistical tests were also employed in order to check the presence of shifts or jumps of the statistical parameters of the time series.

METHODOLOGY

Selection and description of the study area

Three sub catchments within the UMCA were selected for this study representing the climatic variability, structural and land use changes, topographical discrepancies and established conservation networks of the entire upper catchment (Figure 1).

These selected sub-catchments namely Bawagama, Hanguranketa, and Welimada are located between longitudes $80^{0}30'$ to $81^{0}30'$ and latitudes $6^{0}45'$ to $7^{0}15'$. The elevations of these sub-catchments vary from 300 m to 1500 m above mean sea level and the topography is moderate to steep slopes. The mean annual rainfall ranges from 1500 mm to 3000 mm in these areas.

Bawagama sub-catchment - The catchment is located in Hatton administrative district (Figure 2) and its total land extent is 94.01 sq. km.

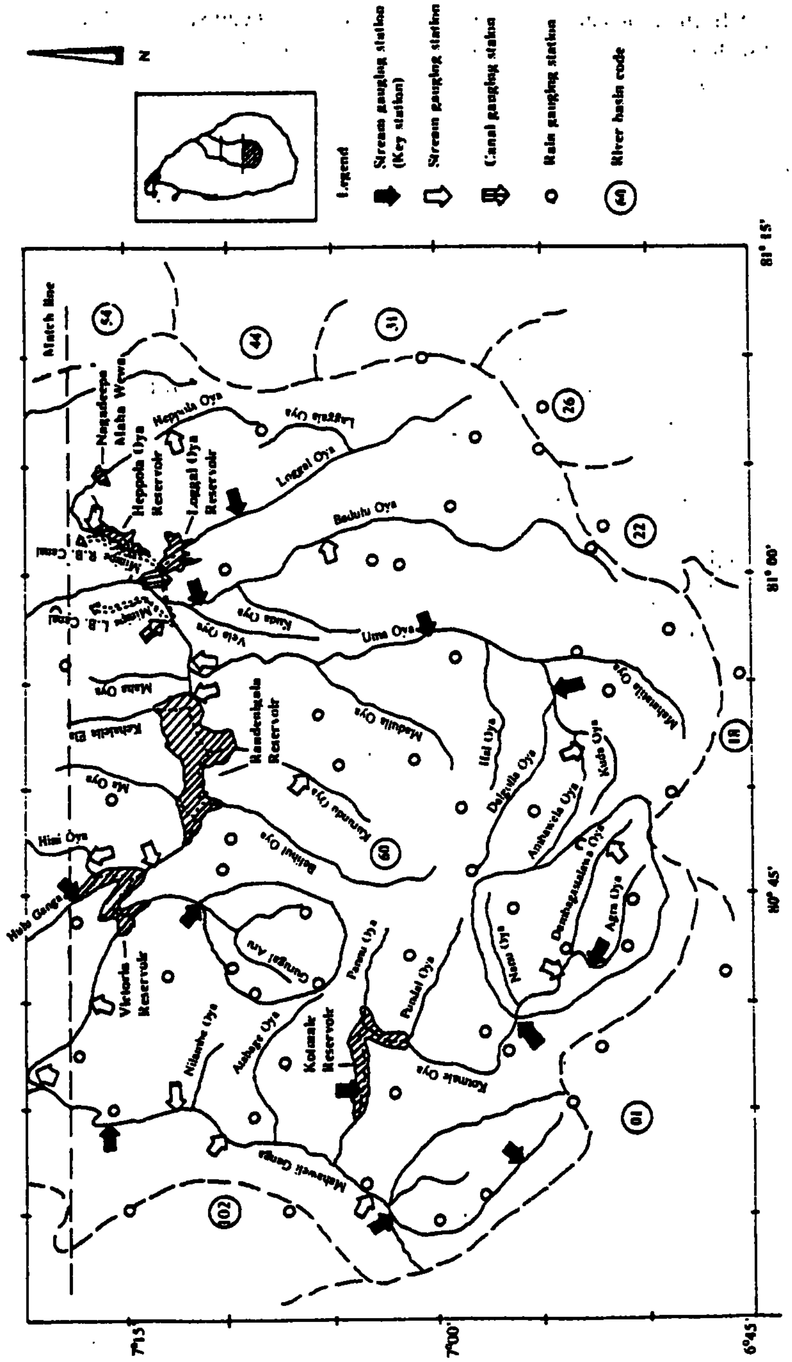

Figure 1. Upper Mahaweli catchment area

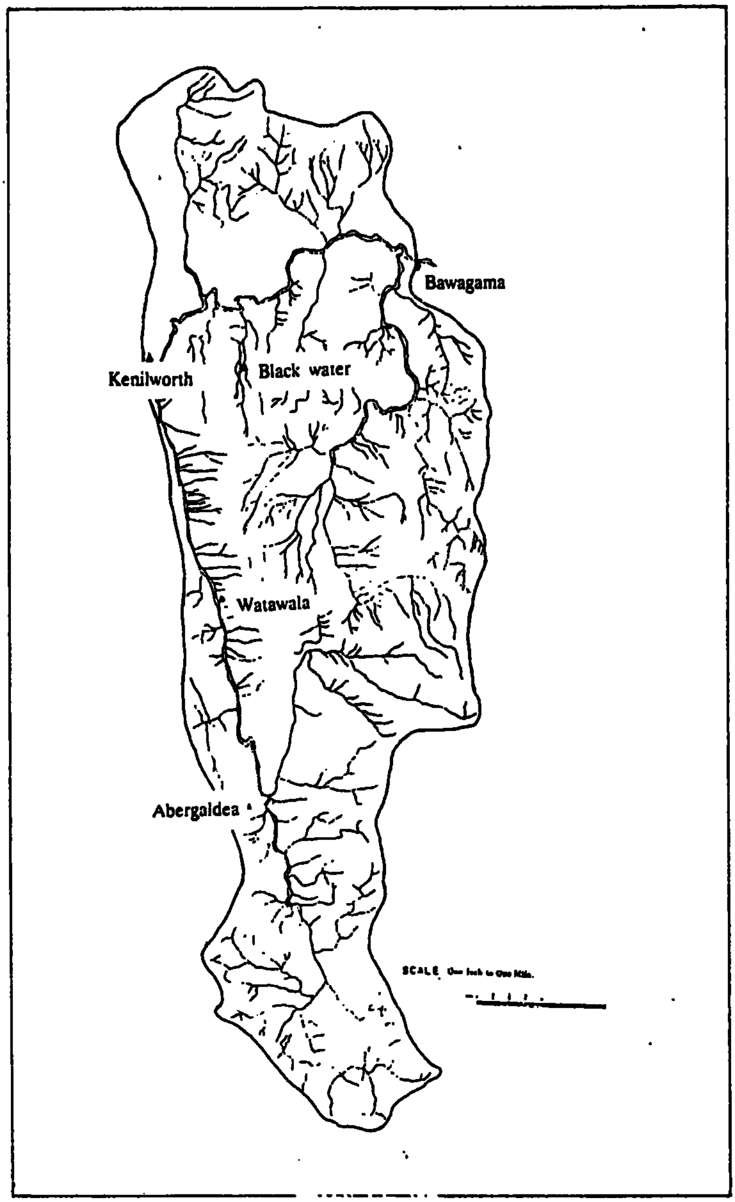

Figure 2. Bawagama sub-catchment

Four major rain gauging stations were selected for the study *i.e.* Blackwater, Abergaldea, Watawala and Kenilworth. The highest rainfall in Sri Lanka has been recorded at Watawala rain gauging station.

Hanguranketa sub-catchment - This sub catchment is situated at Hanguranketa (Figure 3) and has a total area of 68.49 sq.km. Two sub streams, namely Gurugal Aru and Mul Oya which are connected together at Pallegammedda to create the main stream Maha Oya. The discharge data were obtained from the station located on Maha Oya. Rainfall data were collected from Meeritenna, Hope Estate, Bulugahapitiya and Deltota meterological locations.

Welimada sub-catchment - This is found to be located within the boundaries of Nuwara Eliya administrative district (Figure 4) and its total land extent is 113.11 sq.km. The main stream gauging station is located at Uma Oya at Welimada. Dologaolla Oya, Ambewela Oya, and Kuda Oya are sub streams which feed Uma Oya. The rainfall data were obtained from five stations namely, Hakgala, Welimada, N-Eliya, Erabedda and Ambewela.

It is observed that historical long term records are not available consistently in all stations. Meterological stations and corresponding periods of data available are given in Appendix 01. The rainfall and discharge data were not continuous for the considered time lap. Therefore, it was necessary to estimate the missing rainfall data using the values of adjacent stations and historical records by Normal Ratio method. The effective areal coverage for each gauging station was estimated using the Thessien Polygon method. For the estimation of missing discharge data, it was assumed that the respective areal rainfall values are directly related to the discharge as the time scale of the data is high (monthly). The historical precipitation data were searched to find a similar value of precipitation with respect to the month of missing discharge data and the corresponding discharge value was substituted to fill the missing data.

Prior to time series analysis, the collected data were checked for consistency to avoid any systematic errors which may occur due to changes in instrumentation, location, and observers. The double mass curve technique was adopted for this purpose by comparing the locally integrated data from a selected station with the areal integrated data from the adjacent stations. Whenever discrepancies were found modifications were made to generate a unified consistent data sequence.

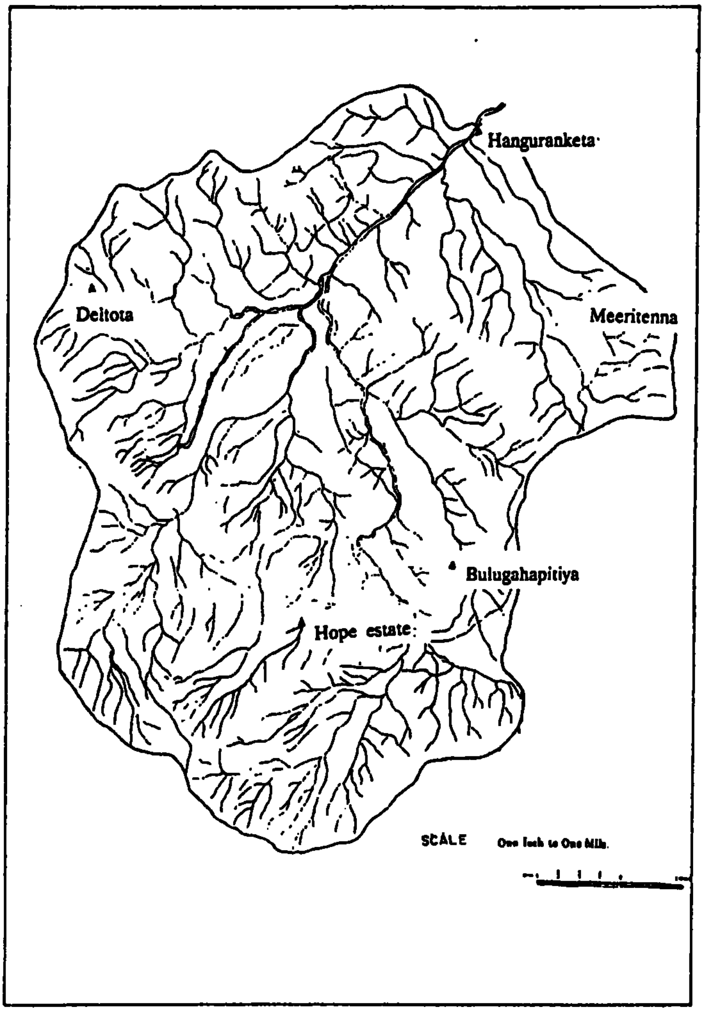

Figure 3. Hanguranketa sub-catchment

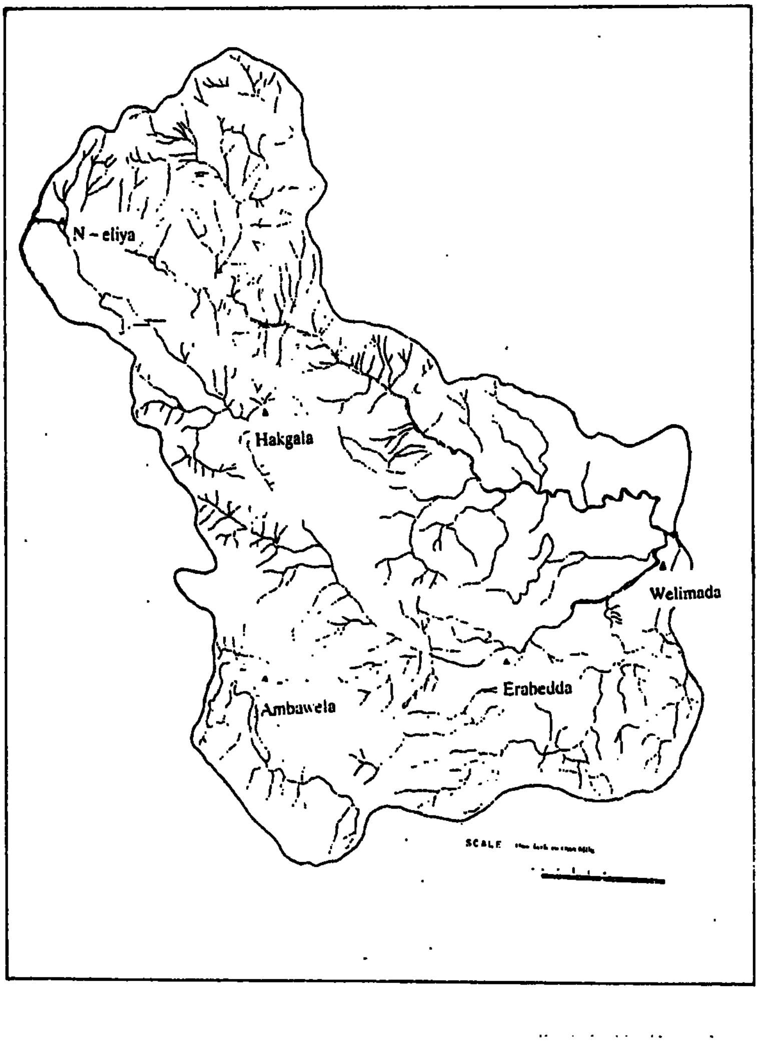

Figure 4. Welimada sub-catchment

Determination and testing for trends

A number of parametric and non-parametric tests for determination of trends have been suggested in literature. Some of these tests are relatively simple under certain assumptions, while others are more complex requiring modelling of the underlying time series such as in the so-called intervention analysis (Box and Tiao, 1975; Hipel *et al.*, 1975). In this study, a simple test for the detection and estimation of linear trend was conducted as summarized below.

Assuming that Y_t, t=1,2, ...N is a time series with N sample size, if Y_t has a linear trend, it could be conveniently written as a simple linear regression model as a function of t (Equation 1).

$$Y_t = a + bt \qquad (1)$$

where a and b are the parameters of the regression model.

If it has no significant linear trend, the value of b should be equal to 0. Then, testing the hypothesis that Y_t has no significant trend is the same as testing the hypothesis that b=0 in the model (Equation 1). Thus, a rejection of the hypothesis b=0 was considered as a detection of a linear trend.

According to Salas and Ormijana (1992), the hypothesis b=0 could be rejected if

$$T_c = \left| \frac{\hat{r}\sqrt{N-2}}{\sqrt{1-\hat{r}2}} \right| \qquad (2)$$

Where $\hat{r}$ is the cross correlation coefficient between the sequence Y_1, Y_2, ...Y_N and 1,2, ...N.

T(1-α/2) (N-2) is the (1-α/2) quantile of the student t-distribution with N-2 degrees of freedom.

Monthly series of data were divided into two time series representing the periods prior to 1965 and after 1965. For each sub series, estimation of cross correlation coefficient between the sequences Y_1, Y_2, ...Y_N and 1,2, ...N series were conducted using a Lotus 1-2-3 Macro programme. The test statistics (T_c) were calculated by introducing cross correlation coefficient and sample size as input parameters into the equation 2.

Mann-Whitney test for shift in the mean

Two monthly time series $Y_1, Y_2, \ldots, Y_{N1}$ and $Y_{N1+1}, Y_{N1+2}, \ldots Y_N$ of sizes N1 and N2 respectively are separated so that N1+N2=N. The decision was made in such a way that it divides the complete time series into two time periods before 1965 and after 1965. A new series, Z_t, t=1,2, ...N was defined as the series with the observations of series Y_t arranged in increasing order of magnitude. The hypothesis that the mean of the first sub series is equal to that of the second, was tested by using the statistics as detailed by Snedecor and Cochran (1980).

$$Uc = \sum_{t=1}^{N1} \frac{R_{(Y_t)} - N_1(N_1+N_2+1)/2}{N_1 N_2 (N_1+N_2+1)/12} \qquad (3)$$

Where $R(_{Y_t})$ is the rank of the observation Y_t in ordered series of Z_t. The hypothesis of equal means of the two sub series cannot be rejected if

$$|U_{(\alpha/2)}| \leq |U_c \leq U_{(1-\alpha/2)}|$$

where $|U_{(1-\alpha/2)}|$ is the (1-α/2) quantile of the standard normal distribution and α is the significance level of the test. When the test statistic of U_c is greater than $|U_{(1-\alpha/2)}|$, the hypothesis of equal means could be rejected. A Lotus 1-2-3 Macro program was used for the calculation of U_c.

F-test for shifts in the variance

Even when there is no apparent trend in the time series, a shift in the variance could occur due to changes in the hydrologic regime. A simple test on the F-distribution was adopted to detect changes in variance of the monthly time series.

The complete time series Y_t, t=1,2,...N was divided into two sub series representing the periods prior to 1965 and after 1965. The first sub series was defined as Y_t, t=1,2,....N1 and assumed to be normally distributed with mean (μ_1) and variance σ_1^2. The second sub series was defined as Y_t, t=N_1+1, N_1+2, ...N and also assumed to be normally distributed with mean μ_2 and variance σ_2^2.

The simple F-test was used to test the equality of the variance of the sub series under the following hypotheses.

$$(i) H_o: \sigma_1^2 = \sigma_2^2 \quad \text{vs} \quad H_a: \sigma_1^2 \neq \sigma_2^2$$

$$(ii) H_o: \sigma_1^2 = \sigma_2^2 \quad \text{vs} \quad H_a: \sigma_1^2 < \sigma_2^2$$

$$(iii) H_o: \sigma_1^2 = \sigma_2^2 \quad \text{vs} \quad H_a: \sigma_1^2 > \sigma_2^2$$

where H_0 and H_a are the null and alternate hypotheses.

The statistic for the F-test was defined as

$$F_c = \frac{\hat{\sigma}_1^2}{\hat{\sigma}_2^2} \qquad (4)$$

The first hypothesis of equal variances cannot be rejected if

$$F_{(\sigma/2)(N1-1,\ N-N1-1)} \leqslant F_c \leqslant F_{(1-\sigma/2)(N1-1,\ N-N1-1)} \qquad (5)$$

The second hypothesis of equal variances cannot be rejected if

$$F_c \geqslant F_{(\sigma)(N1-1,\ N-N1-1)} \qquad (6)$$

Finally, the third hypothesis of equal variance cannot be rejected if

$$F_c \leqslant F_{(1-\sigma)(N1-1, N-N1-1)} \qquad (7)$$

where $F_{(\sigma)(N1,N2)}$ is the σ quantile of the F-distribution with N_1 and N_2 degrees of freedom.

RESULTS AND DISCUSSION

Linear trends

Results of the data for Bawagama sub catchment clearly showed that there is no linear trend in the rainfall and discharge monthly series. In rainfall data, a linear trend could be detected in a few months of some gauging stations. In almost all cases, the trends were found to be negative. The detection of the linear trends can be attributed to faulty observations or measurement errors due to the fact that a negative trend could be observed even in the period before 1965. Watawala station has received the highest rainfall in the country during the last few decades. Even with these high rainfall figures, it is not possible to find a trend surface in the time series.

A linear trend could be observed in both monthly series of the Hanguranketha sub catchment before and after 1965. However, it is not possible to prove the presence of a trend in the period after 1965 though a trend could be detected in some time series. These discrepancies could be due to random errors or measurement errors. However, it can be decided that a linear trend is not shown by any monthly series of discharge and rainfall and it confirms full scale stationary nature of the time series.

In Welimada sub catchment, data at Ambewela, Hakgala and N-Eliya rain gauging stations showed no linear trend in all monthly time series while the other stations showed a trend in one or two monthly series. It is again observed that the presence of a trend surface is not accompanied by any regular pattern. In other words, the trend is not limited to the time series which represents the period after 1965.

However, it is not possible to estimate the degree of variability of the data by this simple test. Further analysis should be conducted with much longer time series to detect the nature and the degree of the trend and to arrive at a firm conclusion on the variability of hydrological phenomena. It will be helpful if the linear formulation is extended to non linear trends by fitting a non linear regression model and estimating the polynomial order.

Mann-Whitney test for shifts in the mean

In general, there is no significance shift (jump) in the mean of the monthly time series. However, in certain months, the test statistics exceeded the value of 1.645 of normal distribution mostly when the average monthly rainfall was high. Errors of measurements, occurrence of catastrophic events would have influenced towards this deviation. In fact, a few catastrophic events could result in an extraordinary high mean of the series and it may be detected as a real shift in the mean according to the calculated test statistics. Therefore, the monthly distributions should also be analyzed individually to detect the presence of such high values.

Determination of shift in variance

Even though there is no significant trend or shift found in the mean of the rainfall and discharge series, shift in the variance is very obvious. Shift in the variance is observed not only in the monthly series of high rainfall and discharge but in the series of very low figures. When the calculated value of F_c is higher than the upper limit of F-distribution value, the formulated null hypothesis of equal variances can be rejected. According to the formulated hypotheses, almost all the test statistics which are found to be outside of the defined F-range are on the high side and then the alternate hypothesis that the variance of latter series is higher than the former series can be accepted. In the data analysis, only two monthly series were found to be below the lower limit and it could be attributed to measurement errors and also to a single or a few events of catastrophe. After 1965, the variability of hydrological events of all three catchments has significantly enhanced and further statistical analyses are required to determine the degree of enhanced variability.

CONCLUSIONS

Hydrologic time series exhibit, in various degrees, trends, shifts or jumps, seasonality, auto-correlation and non-normality. The estimated values of skewness coefficient provided the information that almost all the monthly series of data are more or less normally distributed. However, most of the statistical parameters and variables defined in this study do not require the time series to be normally distributed. Further, logarithmic transformations or so-called Box-Cox transformation could be employed to render the time series to be normally distributed if required for statistical modelling. In this exercise, an attempt was made to determine the stationarity nature of the data by concentrating upon the different forms of trends and shifts which could have been yielded by the constant land use changes made in the sub catchments. Since the changes which occurred in the catchments are not instantaneous, it was found, in general, that the time scale of the data is not sufficient to provide a comprehensive understanding of this gradual process through simulation models. Further, it is necessary to conduct Bayesian analysis to detect the exact point of change and the degree of that change.

There is no significant trend observed in the time series analysis. However, an outstanding deviation from the stationarity nature was manifested in some monthly series which correspond not only with the period after 1965 but also that prior to 1965. This can be attributed to measurement errors or faulty observations. It may also be due to changes made in land use during the last few decades influencing the micro climate. However, a firm conclusion cannot be drawn on this aspect due to the limited time scale of data. The time series should be expanded further to study the effects in detail and the linear formulation of detecting trends should be extended towards assessing non linear trends with polynomial order functions.

It can be concluded that there are no significant shifts or jumps present in the monthly time series. It should be noted that single catastrophic events present in the time series can lead to yield statistics which are similar to that of a series with a shift in the mean. Therefore, the consistency format of the time series should be studied carefully to avoid possible erroneous conclusion.

It has been clearly shown that there are variations in the variance of the time series. Although the time series are more or less normally distributed throughout the period under consideration, variances of the monthly series prior to 1965 period were found to be limited to a narrow range. The high variances after the period of 1965 could be due to the change of micro climate and also by the construction of massive reservoir system on the river Mahaweli. However, it also requires more time series data to arrive at more concrete conclusions.

Since there are no significant variations in the mean of the time series, it is possible to use complete sets of historical records for identifying the parameters in extreme value distribution. Even though here are considerable changes in the variances of the time series, they do not determine the accuracy of EVI distribution parameters due to the fact that all the extreme values of the time series are employed for parameter estimation for the model. The developed extreme value distribution and predicted figures could be used for design and maintenance purposes at present but more detail investigations should be carried out with data of larger number of years to obtain a higher reliability of estimation.

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APPENDIX 1

Meterological Stations and the periods of data availability

Gauging station	Type of data	Period of data
Abergaldea	Rainfall	1949-1980
Black Water	Rainfall	1945-1985
Watawala	Rainfall	1950-1985
Kenilworth	Rainfall	1944-1984
Bawagama	Discharge	1950-1985
Bulugahapitiya	Rainfall	1950-1985
Deltota	Rainfall	1950-1985
Hope Estate	Rainfall	1949-1984
Meeritenna	Rainfall	1949-1984
Hanguranketa	Rainfall	1945-1986
Hanguranketa	Discharge	1950-1985
Ambawela	Rainfall	1952-1985
Erabedda	Rainfall	1949-1984
Hakgala	Rainfall	1949-1985
N-Eliya	Rainfall	1949-1984
Welimada	Rainfall	1949-1984
Welimada	Rainfall	1950-1985