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Drought studies in Kala Oya basin, Sri Lanka[1]

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Abstract

Introduction: Kala Oya basin is the third largest basin in Sri Lanka. The basin receives an average annual rainfall of about 1192 mm and the mean annual potential evapotranspiration is about 1514 mm. Major part of the basin is within the dry zone and only 3% of the basin area is in the intermediate zone, where the river emanates in central mountains.

Materials and Methods: Drought is a common feature of the climate in the Kala Oya basin. Drought in this region had occurred mainly due to erratic behaviour of monsoon, especially due to long breaks in monsoon, high-intensity shorter duration rain etc. In this study, seasonal and annual rainfall departures have been calculated using 15 rainfall stations for the period of 1960 to 2018. Seasonal and annual rainfall departure analysis indicates a seasonal and annual rainfall deficiency during a drought year.

Results: The analysis showed that the departure of annual rainfall follows the trend of seasonal rainfall indicating that the drought events in basin are largely governed by the monsoon seasonal rainfall. The average frequency of basin drought does not follow a clear frequency pattern. Then probability distribution analysis has been carried out considering long term (i.e., 59 years) records for 15 stations. The standardised precipitation index (SPI) represents a statistical z-score or the number of standard deviations (Following Gamma probability distribution transformation to normal distribution). SPI has been applied in basin to quantify annual and seasonal precipitation deficit anomalies on multiple time scale. The estimated values of SPI demarcate precipitation events over a specified period into surplus (heavy precipitation). The analysis revealed that the drought condition in the area is dominantly driven by the total rainfall during the period from September to December. Monthly departure values indicated that May, Jun, July, August, and September months are

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the dry months of basin. Whereas, 2nd inter monsoon and northeast monsoon heavy rainfall was received in October, November, December, January and February. The average wet days in the basin were about 136 days. The average SPI results confirmed that the drought condition in the basin was "nearly normal" (-0.99<SPI<0.99). The probability of obtaining "nearly normal" results for the fifteen rain gauge stations was 53%. Similarly, almost all rain gauging stations show a declining trend, which is an indication that drought may occur more frequently in the future. Severe drought occurred in the basin during the period of 2003-2004. The basin has a good overall probability of receiving a moderate quantity of rainfall, but its erratic distribution in time and space had played major role in advancement of drought hardship in Kala Oya basin. The basin had a sufficient number of wet days (on average about 136 days). The study provides information on the potential for future droughts due to climate change.

Conclusions: Studying the long-term drought will provide guidance for future water resources planning and management. Precipitation data analysis using SPI and the rainfall departure provides the adequate information on past droughts. More than 50% of the Kala Oya basin is used for paddy cultivation. Therefore, it is especially important to understand the drought in a basin-like Kala Oya and manage water sources to supply water for cultivation and other activities. This study provides a guide for water resource managers to plan cultivation quantitatively and in a timely manner. An analysis of 59 years of long-term data shows that the basin receives a moderate amount of average rainfall (near normal rainfall). As there is a greater tendency for drought, efforts should be made to promote the crop diversification rather than conventional paddy cultivation.

Keywords: Kala Oya, Drought, Rainfall departures, Standard Precipitation Index, Sri Lanka.

1. Introduction

Droughts are a regional recurring feature of climate. Drought refers to the relative deficiency of water caused by the shortage in usual rainfall and hence in normal water supply. It is thus a temporary aberration, unlike aridity which is a permanent feature of the climate. Drought is viewed as a sustained and regionally extensive occurrence of appreciably below average natural water availability, either in the form of precipitation, surface water runoff or ground water. Drought is categorised into four types, namely, meteorological, agricultural, hydrological, and socio-ecological droughts (Malakiya & Suryanarayana, 2016; Abeysingha & Rajapaksha, 2020). Quantifying rainfall variability has been an area of great interest for many researchers studying drought. The droughts have some distinct characteristics such as slow onset and creeping phenomenon which make it difficult to determine the onset and end of event (Prasad & Hayashi, 2005).

Droughts cause innumerable problems immediately or with the lag as the economy gradually experiences the adverse shock of the phenomenon. Because of their potentially long duration, the droughts need to be monitored continuously through climate and water supply indicators. The occurrence of low rainfall is governed by various regional climate phenomena. Beran & Rodier (1985) explained the possible causes of deficient precipitation over a region attributed to (a) over seeding of clouds by dust particles from earth surface; (b) an increase in albedo; (c) a decrease in the availability of biogenic nuclei in rain drop formation; (d) the reduced plant cover, and similar such factors. The albedo lowers surface temperature which, in turn, decreases the lift of air masses, resulting in a decrease in precipitation (Panu & Sharma, 2000). Another important causative factor of drought is the oceanic water circulation described by the average of current and heat storage that affects both weather and climate.

Numerous definitions of drought have been proposed from time to time depending on the nature of moisture deficit for specific activities and subject of researcher's interest. Indices make it easier to communicate information about climate anomalies to diverse user audiences and allow scientists to assess quantitatively climate anomalies in terms of their intensity, duration, frequency and spatial extent (Tabari *et al*., 2011). Among the available indices, no single index is capable of fully describing all the physical characteristics of drought. The Standardised Precipitation Index (SPI) is a drought indicator used by many authors to measure drought. SPI is usually defined as the arithmetic mean of the normalised precipitation recorded at several stations over a region of interest where the standard deviation computed at each station over a period of reference is used as the normalising factor (Ali & Lebel, 2009). It is common to use this indicator to determine whether a basin or region can be considered wet or dry for a given year. This index is often used in a very simplistic way by assessing that the rainy season is wet if the SPI>0, and dry if the SPI<0 (Ali & Lebel, 2009). The purpose of this paper is to explain the drought in the Kala Oya Basin in Sri Lanka using SPI. The continuous SPI method can provide better means of quantifying rainfall variability and correlating it with changes of shallow water table levels since it is based on continuous statistical functions comparing rainfall variability over the entire rainfall record (Khan *et al.*, 2008). In this study, the degree of wetness has been quantified using monthly, seasonal and annual rainfall data of fifteen rainfall gauges in the Kala Oya basin.

2. Description of Study Area and Data

The Kala Oya basin covers an area of about 2, 870 square kilometres. Kala Oya begins at an altitude of about 870 m above sea level (AMSL). As the Kala Oya basin belongs to the dry zone, the basin experiences a severe water shortage most of the year. The majority (about 52%) of the catchment area is located in the North Central Province, and about 30% of the catchment area is located in the North Western Province (Iresh *et al.*, 2021). About 97% of the basin is located in the dry zone plains and the remaining 3% is in the intermediate zone consisting of steep slopes. Fifteen historical records of 1960-2018 daily precipitation data were collected from the Department of Irrigation, Sri Lanka for the study. Daily data are aggregated into seasonal (1st inter monsoon, 2nd inter monsoon, southwest monsoon and northeast monsoon) and annual data series. A detailed map of Kala Oya basin is shown in Figure 1.

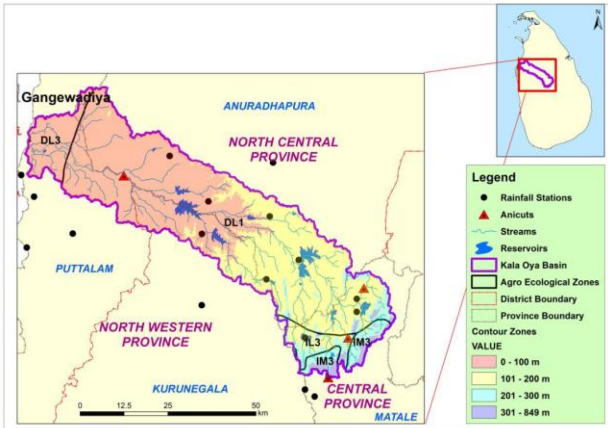


Figure 1. Location Map of the Kala Oya Basin (adopted from Iresh *et al.*, 2021)

3. Methodology

The methodology of the study includes the analysis of hydro-meteorological data, involving the analysis of long-term annual, seasonal and monthly rainfall data to asses frequency and severity of past drought events using the rainfall departure and SPI estimates.

3-1. Computation of rainfall departures (Annual, Seasonal and Monthly)

The computation of rainfall departures was carried out using annual, seasonal and monthly rainfall data. This computation was carried out for the assessment of drought. Drought is a temporary climate phenomenon occurring predominantly due to lesser values of precipitation, soil moisture, river runoff or groundwater as compared to their average values. The meteorological classification of Sri Lanka is based on the spatial variation of the mean annual rainfall of an area/region. The mean annual rainfall at a given rain gauge station was obtained as the arithmetic average of annual rainfall values over the period of record. The annual rainfall departures were computed as the deviation of the rainfall from mean divided by mean rainfall for the station as follows.

$$ADR_i = \frac{(AR_i - \overline{AR})}{\overline{AR}} \quad (1)$$

where, ADR_i = annual rainfall departure in ith year; AR_i = annual rainfall of ith year; $\overline{AR}$ = average annual rainfall.

The year having annual departure value more than or equal to -25% is considered as a drought year. The sum of rainfall from June to October has been taken as the seasonal rainfall. Similarly, seasonal rainfall departures were also estimated. For estimating monthly departures, the average rainfalls of all the 12 months were estimated and the monthly rainfall departures were obtained as shown below.

$$MDR_{ij} = \frac{(MR_{ij} - \overline{AMR_J})}{\overline{AMR_J}} \qquad (2)$$

where, MDR_{ij} = monthly rainfall departure of jth month in ith year; AMR_j = average rainfall of jth month; I = 1, 2, …. n; and j = 1, 2, …, 12. Estimation of departure from mean precipitation i.e., the departure of rainfall across the catchment gives an indication of wet and dry conditions for the respective observation station.

3-2. Standardized Precipitation Index

The Standardised Precipitation Index (SPI) was developed by McKee *et al*. (1993). It is primarily a tool for defining and monitoring drought events. It allows an analyst to determine the rarity of drought at a given time scale (temporal resolution) of interest for any rainfall station with historic data (Edwards & McKee, 1997). It can also be used to determine periods of anomalously wet events. Mckee *et al*. (1993) designed SPI, basically to quantify the precipitation deficit for multiple scales. Though the Palmer Drought Severity Index is widely used in the United States of America (USA), the SPI is also being used in the USA and many other counties for drought monitoring. SPI is more representative of short-term precipitation and soil moisture variation and hence a better indicator of drought. SPI can be used to monitor drought condition on 1-, 3-, 6-, 12-, 24- and 48-month time scales. This temporal flexibility allows the SPI to be useful in both short-term agricultural and long-term hydrological applications.

3-2-1. Classification of SPI

The SPI calculation for any location is based on the long-term precipitation record for the desired period. This long-term record is fitted to probability distribution, which is then transformed to a normal distribution so that the mean SPI for the location and desired period is zero. The positive SPI values indicate greater than median precipitation, while negative values indicate less than median precipitation. Because the SPI is normalised, wetter and drier climate can be represented in the same way and wet periods can also be monitored using the SPI. Classification system given by Mckee *et al.* (1993) is shown in Table 1, which is used to define drought intensities resulting from estimated of the SPI for various stations in the Kala Oya basin.

Mckee *et al*. (1993) also defined the criteria for a 'drought event' for any time scale. A drought event occurs any time when the SPI is continuously negative and reaches an intensity where the SPI is 1.0 or less. The event ends when the SPI becomes positive. Each drought event, therefore, has a duration defined by its beginning, end and intensity for each month that the event continues. The accumulated magnitude of drought is drought severity, and it is the positive sum of the SPI for all the months within a drought event.

3-2-2. Calculating SPI

Computing of the SPI involves fitting a gamma probability density function to a given frequency distribution of precipitation totals for a climate station. Gamma distribution is defined by its frequency or probability density function (PDF):

$$g(x) = \frac{1}{\beta^{\propto}\Gamma(\propto)} \chi^{\propto -1} e^{-x/\beta} \qquad (3)$$

The $\propto$ and β parameter of the gamma probability density function are estimated for each station, for each time scale of interest (1- month, 3-month, 6-month, and 12-month). The maximum likelihood solution is used to optimally estimate $\propto$ and β:

$$\propto = \frac{1}{4A} (1 + \sqrt{1 + \frac{4A}{3}}) \qquad (4)$$

$$\beta = \frac{\bar{x}}{\propto} \qquad (5)$$

where, $A = \ln(\bar{x}) - \frac{\sum \ln(x)}{n}$ (6)

n = number of precipitation observations. The resulting parameters are then used to find the cumulative probability of an observed precipitation event for the given time scale for the station in question. The cumulative probability is given by:

$$G\ (x) = \int_0^x g\ (x)dx = \frac{1}{\beta^{\propto}\Gamma(\propto)} \int_0^x x^{\propto -1}\ e^{-x/\beta}\ dx \qquad (7)$$

Letting $t = x/\beta$ the equation become the incomplete gamma function:

$$G\ (x) = \frac{1}{\Gamma(\propto)} \int_0^t t^{\propto-1}\ e^{-b} \qquad (8)$$

Since the gamma function is undefined for $x = 0$ and a precipitation distribution may contain zeros, the cumulative probability becomes:

$$H = q + (1 - q)G\ (x) \qquad (9)$$

Where, q is the probability of zero. The cumulative probability function (CDF) *H(x)* is then transformed to the standard normal random variable Z with mean zero and variance of one, which is the value of the SPI.

$$Z = SPI = -\left(t - \frac{c_1 + c_1\, t + c_1\, t^2}{1 + d_1 t + d_2\, t^2 + d_3\, t^3}\right) \qquad for\ 0 < H(x) \leq 0.5 \qquad (10)$$

$$Z = SPI = +\left(t - \frac{c_1 + c_1\, t + c_1\, t^2}{1 + d_1 t + d_2\, t^2 + d_3\, t^3}\right) \qquad for\ 0.5 < H(x) \leq 1.0 \qquad (11)$$

Where, $t = \sqrt{\ln\left(\frac{1}{(H(x))^2}\right)}$ $for\ 0 < H(x) \leq 0.5$ (12)

$$t = \sqrt{\ln\left(\frac{1}{(H(x))^2}\right)} \qquad for\ 0.5 < H(x) \leq 1 \qquad (13)$$

$c_0 = 2.515517$ $c_1 = 0.802853$ $c_2 = 0.010328$
$d_1 = 1.432788$ $d_2 = 0.189269$ $d_3 = 0.001308$

Monthly precipitation records of 15 rain gauge stations in the Kala Oya basin were used to estimate SPI values for 1-, 3-, 6-, and 12-month time scales. The monthly data for a given stations in basin were available for the period of 59 years.

4. Results

Kala Oya basin is one of the drought-affected basins located in the dry zone of Sri Lanka. The average annual rainfall in this basin is about 1192 mm. the mean annual potential evapotranspiration is about 1514 mm. 64% of the basin area belongs to the dry zone, whereas 32% and 3% area belongs to semi-arid and intermediate zones respectively.

Table 1. Classification of SPI

SPI values	SPI Condition
2 and above	Extremely wet
1.5 to 1.99	Very wet
1.0 to 1.49	Moderately wet
- 0.99 to 0.99	Nearly normal
- 1.0 to - 1.49	Moderately dry
- 1.5 to -1.99	Severely dry
- 2.0 and less	Extremely dry

4-1. Analysis of Annual and Seasonal Rainfall Departures

Fifteen rainfall gauge stations 59 years (1960-2018) data were used for the analysis. Annual rainfall departure analysis indicated that the annual rainfall deficiency during the drought year had varied from -75% to -35%. The results of annual and seasonal rainfall departures at Kala Oya basin are given in Tables 2, 3 and 4. Figures 2, 3 and 4 show the annual rainfall, southeast monsoon and northeast monsoon rainfall departures at Mahailuppallama rain gauge station. From Table 2 it can be seen that year 1974, 1992, 2007, 2013, and 2016 were the wide spread droughts recorded years at the maximum number of stations in the basin with maximum value of annual rainfall departure up to -0.75. Table 3 shows that year 1976, 1999, 2006, 2009 and 2012 were the wide spread drought recorded during southwest monsoon. Table 4 shows that year 1987-1988, 1988-1989, 1996-1997, 2003-2004, and 2017-2018 were the drought recorded seasons for the northeast monsoon.

The analysis showed that the departure of annual rainfall follows the trend of seasonal rainfall indicating that drought events in the basin are largely governed by the monsoon season rainfall. Generally, monthly departure values indicated that May, Jun, July, August, and September months are dry months of the basin. Whereas, October, November, December, January and February received the 2nd inter monsoon and Northeast monsoon to the basin.

4-2. Drought Severity Assessment using SPI

The SPI represents the statistical z-score or the number of standard deviation (following the gamma probability distribution transformation to a normal distribution). SPI has been applied in the study basin to quantify monthly precipitation deficit anomalies on multiple time scales. The estimated values of SPI values demarcate precipitation events over a specified time period into surplus, medium/normal and low/deficit precipitation. The plot of SPI for 12-month (annual) time scale is shown in Figure 5 for Mahailuppallama rainfall gauge station. The greater value of SPI closer to 1 and above indicates the wet event. The values >2.0 shows very heavy precipitation over the specific time scale. The value of SPI between 1 and -1 shows the near normal precipitation events.

Table 2. Identification of Annual Drought Years in Different Stations

Station	Mean annual rainfall	Minimum annual departure (MAD)	Drought year for MAD	Average spatial rainfall estimate
Mahailuppallama	1266	-0.483	2013	92
Kalawewa trank	1291	-0.346	2003	110
Mahagalkadawala	1296	-0.400	1992	102
Siyabalangamuwa	1117	-0.414	2013	87
Pelwehera	1450	-0.424	1983	72
Dewahuwa	1230	-0.675	2016	101
Kandalama	1302	-0.444	1983	87
Nochchiyagama	1123	-0.413	1992	0
Karaitivu	1066	-0.494	2007	110
Karandipooval	1077	-0.556	2007	44
Nachchaduwa	1041	-0.541	1989	0
Tabbowa	1179	-0.752	1974	44
Millawana-lulcade	1220	-0.396	2016	7
Millawana-Estate	1120	-0.456	2016	7
Mediyawa tank	1100	-0.479	1987	1

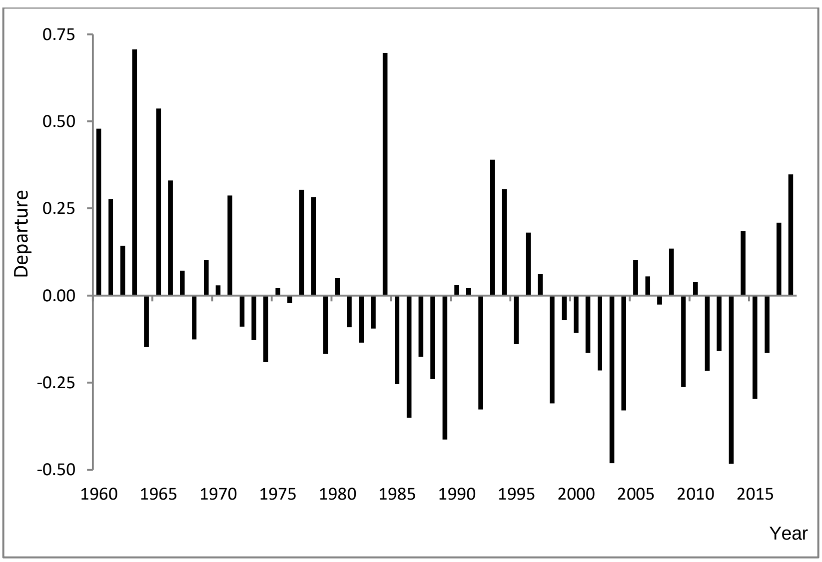


Figure 2. Annual Rainfall Departure at Mahailuppallama Rain Gauge Station

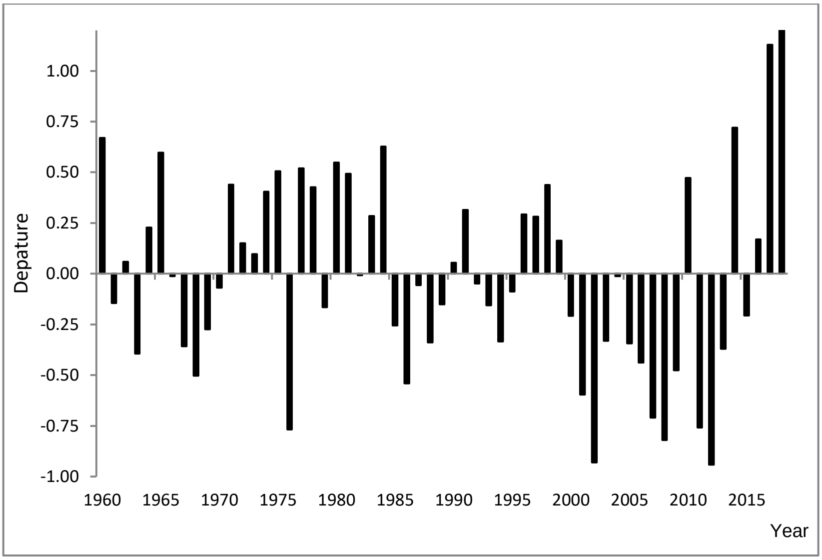


Figure 3. Southwest Monsoon Rainfall Departure at Mahailuppallama Rain Gauge Station

Table 3. Identification of Droughts During Southwest Monsoon (May-September)

Station	Average southwest monsoon rainfall (ASMR)	Minimum southwest monsoon departure	Drought year	Spatial rainfall estimate for ASMR
Mahailuppallama	306	-0.942	2012	28
Kalawewa trank	385	-0.914	2012	34
Mahagalkadawala	329	-0.983	1999	31
Siyabalangamuwa	289	-0.923	2012	27
Pelwehera	524	-0.901	1994	22
Dewahuwa	496	-0.773	2012	31
Kandalama	588	-0.803	1969	27
Nochchiyagama	274	-0.793	1976	1
Karaitivu	242	-1.000	1971	34
Karandipooval	294	-0.949	2009	13
Nachchaduwa	314	-0.868	2006	0
Tabbowa	234	-1.000	1974	14
Millawana-lulcade	485	-0.803	2012	2
Millawana-Estate	485	-0.818	2012	2
Mediyawa tank	266	-0.918	1976	1

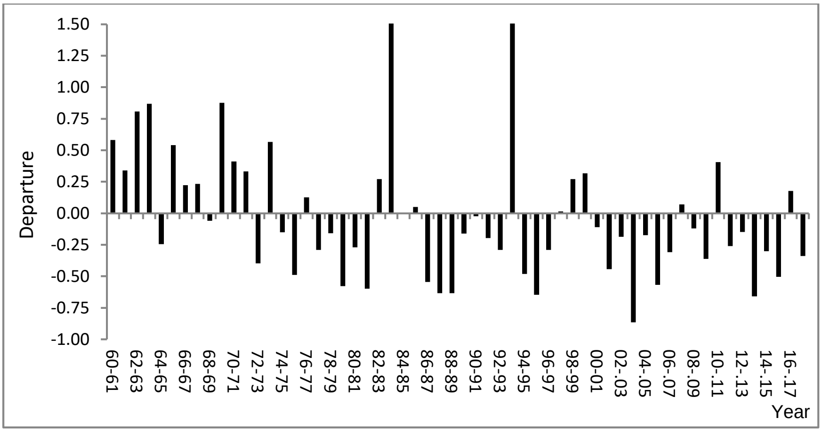


Figure 4. Northeast Monsoon Rainfall Departure at Mahailuppallama Rain Gauge Station

Table 4. Identification of Droughts during Northeast Monsoon (October-November)

Station	Average northeast monsoon rainfall (ANMR)	Minimum northeast monsoon departure	Drought season	Spatial rainfall estimate for ANMR
Mahailuppallama	306	-0.866	2003-2004	0.40
Kalawewa trank	385	-0.874	2003-2005	26.79
Mahagalkadawala	329	-0.815	2003-2006	31.15
Siyabalangamuwa	289	-0.858	2003-2007	13.66
Pelwehera	524	-0.791	1987-1988	31.08
Dewahuwa	496	-0.764	2017-2018	2.13
Kandalama	588	-0.823	1987-1988	26.73
Nochchiyagama	274	-0.806	1987-1989	33.83
Karaitivu	242	-0.867	2003-2004	2.04
Karandipooval	294	-0.919	2003-2005	22.17
Nachchaduwa	314	-0.903	2003-2006	31.27
Tabbowa	234	-0.850	2003-2007	28.42
Millawana-lulcade	485	-0.752	1996-1997	69.77
Millawana-Estate	485	-0.767	1996-1998	0.07
Mediyawa tank	266	-0.890	1993-1994	13.48

When the value of z-score goes lower than -1.5 it is an indication of severe drought conditions. Table 5 shows the estimated SPI probabilities for different classifications. From Table 4, it is clear that the basin drought condition is nearly normal. All fifteen rain gauge stations data have more than 53% probability for the nearly normal condition. Similar to Mahailluppallama, SPI values at all of the other stations show a tendency toward a downward trend, indicating that droughts may be more frequent in the future.

Table 5. Estimated SPI Probabilities for Annual data (12-month)

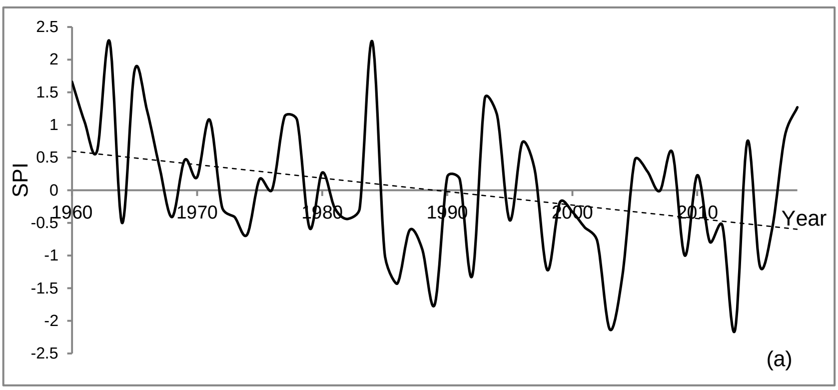
Station	Probabilities for SPI Conditions (%)						
	Extremely wet	Very wet	Moderately wet	Nearly normal	Moderately dry	Severely dry	Extremely dry
Mahailuppallama	3	3	14	64	10	2	3
Kalawewa trank	5	3	7	68	15	2	0
Mahagalkadawala	3	5	5	71	8	7	0
Siyabalangamuwa	3	5	8	63	14	7	0
Pelwehera	3	3	14	68	7	3	2
Dewahuwa	3	2	10	76	2	3	3
Kandalama	3	3	8	68	15	2	0
Nochchiyagama	1	2	6	71	12	5	3
Karaitivu	2	3	12	71	3	5	3
Karandipooval	2	5	8	71	7	3	3
Nachchaduwa	2	3	9	72	8	4	2
Tabbowa	2	3	10	73	10	0	2
Millawana-lulcade	3	8	3	73	7	5	0
Millawana-Estate	3	10	2	76	3	3	2
Mediyawa tank	3	9	2	76	3	4	2

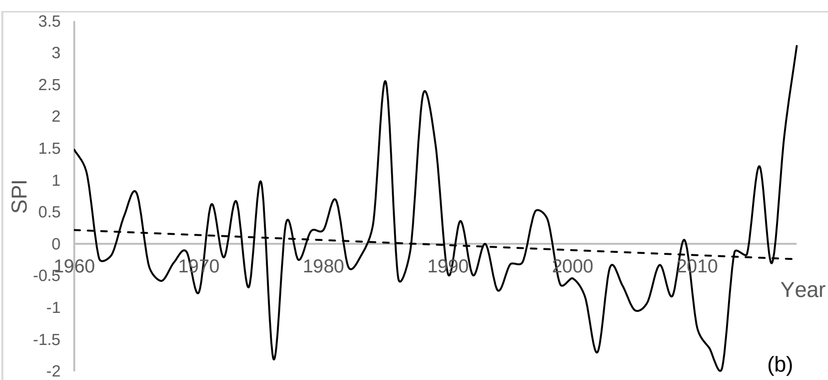
5. Discussion

The results of the annual departure and annual SPI indicate that the years 1986, 1989, 1992, 1998, 2003, 2004, 2013 and 2015 had been the dry years with seasonal rainfall deficiency in the order of 47-55% and had caused moderate water stress in Kala Oya basin. Analysis of annual and seasonal rainfall records indicated that the Kala Oya basin does not follow a drought pattern (average frequency of occurrence). However, analysis of southwest monsoon rainfall records indicate that the drought had occurred with an average frequency of every 5 years. Severe drought occurred in the basin during the period of 2003-2004. The basin has a good overall probability of receiving a moderate quantity of rainfall, but its erratic distribution in time and space had played a major role in advancement of drought hardship in Kala Oya basin. The basin had a sufficient number of wet days (on average about 136 days). The study provides information on the potential for future droughts due to the climate change.

6. Conclusions

Drought is a common phenomenon, especially in the dry zone of Sri Lanka. Studying the long-term drought will provide guidance for future water resources planning and management. Precipitation data analysis using SPI and the rainfall departure provides adequate information on the past droughts. More than 50% of the Kala Oya basin is used for paddy cultivation. Therefore, it is especially important to understand the drought in a basin-like Kala Oya and manage the water sources to supply water for cultivation and the other activities. This study provides a guide for water resource managers to plan cultivation quantitatively and in a timely manner. An analysis of 59 years of long-term data shows that the basin receives a moderate amount of average rainfall (near normal rainfall). As there is a greater tendency for drought, efforts should be made to promote crop diversification rather than conventional paddy cultivation.





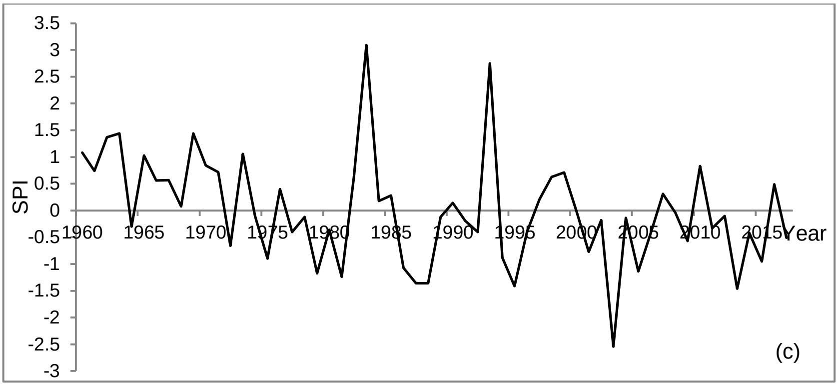


Figure 5. Estimated SPI at Mahailuppallama (a) Annual (b) Southwest Monsoon (May-September) (c) Northeast Monsoon (October-November)

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