A Non-stationary Hydrologic Drought Index Using Large-Scale Climate Indices as Covariates

Arya Sajeev and Subrahmanya Kundapura

Abstract The dry and wet periods can be analyzed based on different drought indices. Most existing drought studies are based on stationary assumptions, and environmental changes are not considered. This study proposes a non-stationary streamflow-based drought index, incorporating large-scale climate indices to study hydrological drought for 45 years. Climate indices are used as covariates for building the non-stationary model fitted to streamflow. Correlation analysis is carried out to determine the best covariates for the streamflow in the Netravati River basin in India. The Southern Oscillation Index (SOI) exhibited a significant influence on streamflow at all time scales. The non-stationary model is compared with the stationary model, and the best model is chosen based on the Akaike information criterion (AIC). Under statistical measures, non-stationary models performed better than stationary ones at all time scales. The generalized additive model for location, scale, and shape (GAMLSS) is used for non-stationary modeling. The models are developed for short-term (3 and 6 months) and long-term (12 and 24 months) droughts. The influence of climate variables on drought classes is analyzed, and more severe drought is observed under the non-stationary scenario. The deficiency in streamflow was more than 60% in the basin in 1987 and 2002. The non-stationary drought index detected more severe drought events than the stationary index under short-term scales. Hydrological drought properties such as drought severity, duration, and peak are calculated under stationary and non-stationary scenarios, and a noticeable difference is observed. Compared to stationary models, the non-stationary model yields more logical and satisfactory findings because it effectively takes into account non-stationarities in the streamflow caused by climate change.

Keywords Stream flow · Drought · Non-stationary · Generalized additive model for location · scale · and shape (GAMLSS) · Stream flow drought index

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1   Introduction

Drought is a complicated natural phenomenon that occurs due to the deficiency in the availability of rainfall, and it is also associated with a deficiency in the runoff, groundwater level, agricultural production, and socio-economic situations [9, 18, 26]. Hydrological drought is related to a deficiency of streamflow [4]. It is represented by using various drought indices such as Streamflow Drought Index (SDI) [15], the Standardized Streamflow index (SSI) [19], Standardized Terrestrial Water Storage Index (SWSI) [28]. The calculation of those indices is based on the stationary assumption, but in the changing climate, non-stationarities in the streamflow cannot be ignored, and stationary indices lead to inaccurate results [12]. Previous research has established the impact of large-scale climate variables on the rainfall pattern in India [1].

Recent research has mostly focused on drought studies using non-stationary indices, like the Non-stationary Standardized Precipitation Index (NSPI) [14], time-dependent Standardized Precipitation Index (SPIt) [24], and non-stationary Reconnaissance Drought Index (RDI_N) [6]. These indices were developed for the analysis of meteorological drought. The hydrological drought is associated with streamflow deficiency, so it is also essential to consider climate change in the hydrological drought index. Because of its simplicity, Standardized Streamflow Index (SSI) has been used by various researchers globally for drought studies [3, 10, 19]. Various researchers examined the influence of the Southern Oscillation Index (SOI) and ENSO index on the Indian climate [1, 2, 27]. In non-stationary modeling, the generalized additive model for location, scale, and shape (GAMLSS) is a widely used algorithm [5, 20, 25].

In terms of the geographical area experiencing drought, Rajasthan is first, with Karnataka coming in second [21]. Most of the droughts were reported in arid regions. Although Dakshina Kannada experiences heavy rain during the monsoon, recent years have reported drought situations throughout the summer [8]. Water scarcity exists due to the extensive expansion of industries during the past two decades. Revadekar et al. [16] examined a declining trend in heavy rainfall along the coastal region of Karnataka in the future. Dakshina Kannada's economic development is significantly influenced by the Netravati River. There is no research on the Netravati River basin's drought conditions. So, it is necessary to study the drought situations in the river basin and to implement necessary water management programs to reduce the water scarcity problems. The primary goal of this research is to create a non-stationary standardized streamflow drought index using climate indices for the Netravati River basin. It is compared with the traditional hydrological drought index. Drought severity, peak, and duration are also calculated and compared under both scenarios.

2 Study Area

2.1 Overview of the Basin

The Netravati River basin covers 3401 km^2 and is chosen as the study area. It origi-nates in the Indian state of Karnataka's Western Ghats and flows west. The basin is situated between 12°30′ N and 13°10′ N latitude and 74°50′ E–75°50′ E longitude. The gauging station of the river is located in Bantwal. The annual average rainfall is 3076 mm, and the temperature is 20–26 °C. The monsoon season begins in June and lasts until September. The water from the river is mainly used for agricultural purposes, and the main crop in the region is paddy. Sandy clay loam and clay loam are the main types of soil found in the region [13]. This river is the primary water source for nearby cities such as Mangalore, Bantwal, Dharmasthala, and Puttur (Fig. 1).
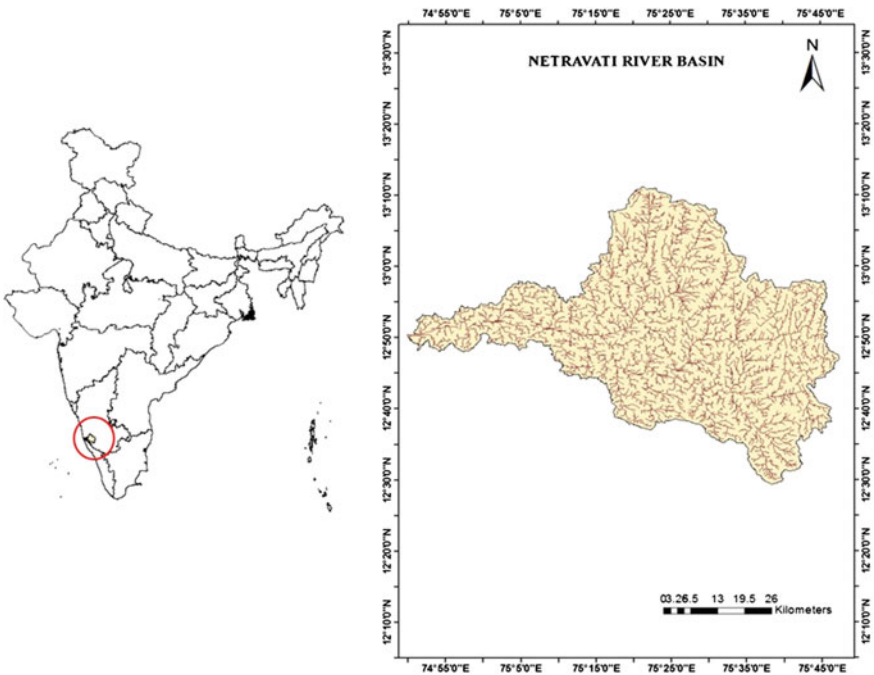
Fig. 1 Location of the Netravati river basin

2.2 Data Used

The monthly streamflow data of the Netravati River are obtained from the Water Resources Information System, India, database (http://www.india.wris.nrsc.gov.in). It is the observed data at the Bantwal River gauging station from 1971 to 2016. The climate indices such as Sea Surface Temperature (SST), Southern Oscillation Index (SOI), and Indian Ocean Dipole (IOD) are obtained for the same period from www. esrl.noaa.gov.

3 Methodology

3.1 Percentage Departure of Streamflow

The streamflow's departure from its long-term mean is measured as a percentage departure in streamflow, and it can be obtained using Eq. (1). Annual and seasonal departure with respect to long-term (45 years) mean values are calculated.

$$Departure(\%) = \frac{y_i - \overline{y}_i}{\overline{y}_i} \times 100 \tag{1}$$

where y_i = streamflow for the season i; and $\overline{y}_i$ = long-term average for the considered period.

3.2 Climate Indices

In this study, three climate variables, such as IOD, SOI, and SST, are taken as covariates for constructing non-stationary models. The streamflow data are arranged to 3-, 6-, 12-, and 24 months time scales. The monthly data of climate indices are arranged to 0–12-month lag. The Kendall correlation test is performed at a 5% significance level to find the best lag of climate data correlated with the streamflow data arranged on different time scales. Different combinations of selected climate indices are also checked to find the best combination for non-stationary modeling.

3.3 Hydrologic Drought Index

This study defines the hydrological drought using the streamflow-based Standardized Streamflow Index, and a new drought index based on climate variables is developed. The SSI is calculated based on the SPI concept. The first step is to identify the

Table 1 Classification of drought

Index values	Class	
$-1 \leq \mathrm{SSI} < 0$	Mild drought	C1
$-1.5 \leq \mathrm{SSI} < -1$	Moderate drought	C2
$-2 \leq \mathrm{SSI} < -1.5$	Severe drought	C3
$\mathrm{SSI} < -2$	Extreme drought	C4

marginal distribution that fits the data the best. For instance, the gamma distribution is selected as the best-fitted probability distribution [3]. The probability density function of a Gamma distribution shape parameter α and scale parameter β is given as:

$$g(x) = \frac{1}{\beta^\alpha \Gamma(\alpha)} x^{\alpha-1} e^{\frac{-x}{\beta}} \tag{2}$$

Its cumulative probability density is given below:

$$F(x) = q + (1 - q)G(x) \tag{3}$$

where $G(x)$ is the cumulative distribution function for the non-zero streamflow q is the probability of zero values. The cumulative distribution is then changed to a normal distribution with zero mean value and unit standard deviation to get SSI values. The drought is classified into different categories and is given in Table 1 [23].

3.4 Calculation of the Non-Stationary Index

The generalized additive model for location, scale, and shape (GAMLSS) is used for non-stationary modeling [17]. The non-stationary gamma distribution with linearly varying location parameters is used to calculate the non-stationary Standardized Streamflow Index (NSSI), and it is given as follows:

$$X_t \; gamma \, (\mu_t, \, \sigma) \tag{4}$$

$$\mu_t = c_0 + c_1 I_1(t) + c_2 I_2(t) \ldots\ldots\ldots + c_n I_n(t) \tag{5}$$

where, constants are $c_0, c_1, .., c_n$, and the covariates are $I_1, I_2, .., I_n$ at time t. The parameters are computed using the maximum likelihood approach. NSSI is classified similarly to SSI (Table 1) and can monitor drought events on various time scales.

The stationary and non-stationary indices based on drought properties are calculated. The duration is defined by the number of consecutive months with an index value below the threshold, where the threshold value is typically -1. The severity is

Table 2 Significant lag of climate indices

Climate oscillations	SST	SOI	IOD
Time scale			
3 months	–	9	11
6 months	–	0	–
12 months	2	1	0
24 months	0	1	2

the total of those index values for that duration. Peak is the index's lowest value for that specific period.

4 Results and Discussion

4.1 Significant Lag of Climate Indices

For the time scales of 3, 6, 12, and 24 months, the cumulative streamflow data are calculated. The lag of the climate oscillations ranges from 0 to 12 months. The correlation between streamflow on various time scales and climate oscillation on 0–12 lags was tested using the Kendall correlation method at a significance level of 5%. The significant lag obtained is listed in Table 2. At all time scales, only SOI exhibited a significant influence on streamflow. SST had no significant correlation on streamflow at 3-month and 6-month time scales. Except for the 6-month time scale, IOD showed a significant correlation at all other time scales, and at the 12-month time scale, there was a concurrent association between IOD and streamflow. There was a concurrent association of SST and SOI with the flow at 24- and 6-month time scales, respectively. So, the climate oscillations with significant lag are taken as a covariate for developing a non-stationary index.

4.2 Non-Stationary Drought Index

The gamma distribution is identified to be the best fit for streamflow data in this study. The stationary model is made using gamma distribution with both parameters as constant. For the non-stationary model, the distribution's location parameter is considered to be varied linearly with the selected covariates. Various combinations of climate oscillations at significant lags are tested to find the best model based on AIC values, and the results are tabulated in Table 3. The table also includes the AIC values of stationary and non-stationary models. Combination of SST and IOD was the best for non-stationary models at 12- and 24-month time scales. At all time scales, the AIC values of non-stationary models were less than the stationary models. The

Table 3 Selected covariates and AIC values of models

Time scale	Selected covariates and lag	AIC value of non-stationary	AIC value of stationary
3 months	IOD_{11}	8053.60	8230.86
6 months	SOI_0	9486.72	9592.23
12 months	SST_2, IOD_0	9445.99	9482.70
24 months	SST_0, IOD_2	9774.04	9813.20

Table 4 Equations of Mu and Sigma values

Time scale	Equations
3 months	$\mu(t) = 6.92615 - 0.29054\ IOD_{11}(t)$ $\sigma = 1.701114$
6 months	$\mu(t) = 7.692151 + 0.007906\ SOI_0(t)$ $\sigma = 1.121142$
12 months	$\mu(t) = 8.36594 - 0.07928\ SST_2(t) + 0.18086\ IOD_0(t)$ $\sigma = 0.3568845$
24 months	$\mu(t) = 9.06111 - 0.09120\ SST_0(t) + 0.18638\ IOD_2(t)$ $\sigma = 0.2914951$

non-stationary model is selected as better than the stationary model at all scales based on the statistical measure.

The non-stationary gamma with constant sigma and linearly varying Mu is taken for calculating the non-stationary hydrologic drought index NSSI. The equation of Mu and Sigma is given in Table 4. The distribution parameters are computed using the Maximum Likelihood Estimation (MLE) approach.

4.3 Comparison of Drought Classes

The drought classes, based on the index values based on Table 1, are mild (C1), moderate (C2), severe (C3), and extreme (C4) droughts. Fig. 2 compares and illustrates the frequency of occurrence of various drought classes under stationary and non-stationary conditions. Based on both approaches, C1 has a higher percentage of occurrence at all time scales. C2 has a higher frequency based on non-stationary than stationary index at all scales except 24-months. At all time scales, the occurrence frequency of all types of drought classes for stationary and non-stationary indices varies; hence it can be postulated that climate oscillations influence the drought class in the basin.
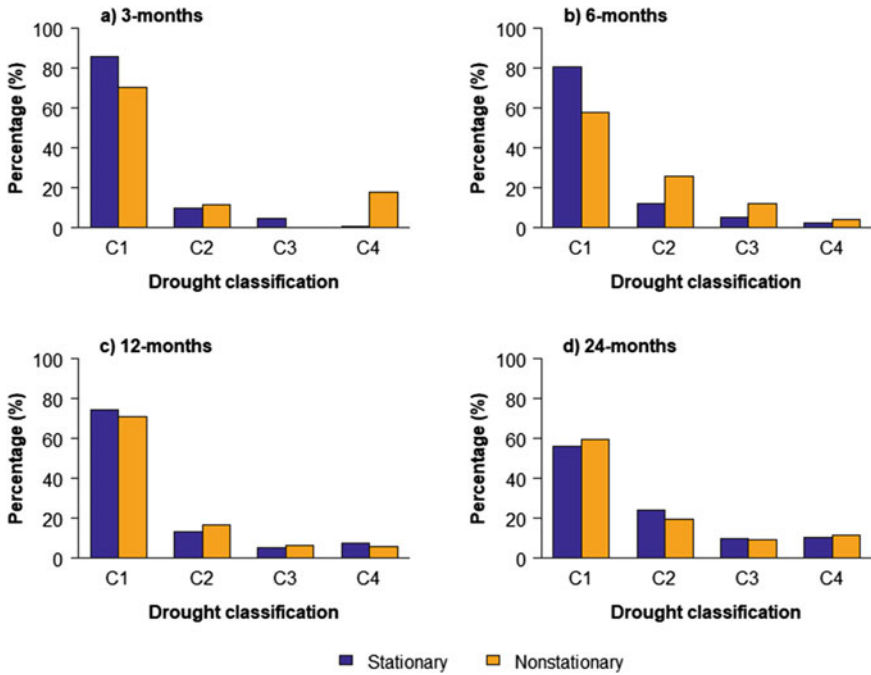
Fig. 2 Percentage occurrence of drought classes

4.4 Comparison of Drought Properties

The peak, severity, and duration of drought events are calculated from SSI and NSSI values, and its statistical characteristics are given in Table 5. The mean duration, severity, and peak values obtained from NSSI are higher than those obtained from SSI at all the time scales except at 12 months. In every case, drought properties under stationary conditions differ from non-stationary conditions. For the comparative study, the density plot of drought duration is also plotted in Fig. 3. At all the time scales, a noticeable difference is observed in the density plots of duration. The density plot for non-stationary is shifted towards the right of the stationary plot at the time scales of 6-month and 12-month. This variation shows the association of climate indices to vary drought properties.

Table 5 Statistical characteristics of drought properties

	SSI			NSSI		
	Duration (in months)	Severity	Peak	Duration (in months)	Severity	Peak
3 months						
Mean	1.71	2.35	1.33	2.38	4.17	1.57
Maximum	4.00	6.85	2.13	4.00	8.80	2.24
Minimum	1.00	1.01	1.01	1.00	1.00	1.00
6 months						
Mean	2.16	3.09	1.35	2.22	3.46	1.88
Maximum	7.00	13.47	2.29	4.00	7.55	3.89
Minimum	1.00	1.00	1.00	1.00	1.00	1.00
12 months						
Mean	9.25	14.17	1.49	5.92	9.12	1.46
Maximum	26.00	41.61	2.30	24.00	40.70	2.50
Minimum	1.00	1.00	1.00	1.00	1.01	1.01
24 months						
Mean	13.62	21.42	1.44	16.00	26.27	1.72
Maximum	48.00	80.31	2.52	49.00	79.13	2.68
Minimum	1.00	1.02	1.02	1.00	1.22	1.17
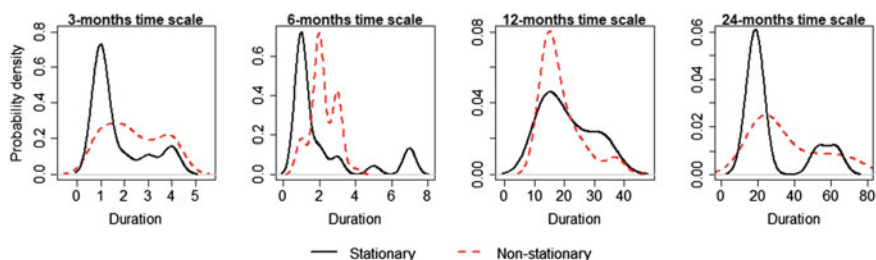
Fig. 3 Probability density of duration

4.5 Departure Analysis of Streamflow and Comparison with Historical Droughts

The annual and seasonal departure of streamflow of the Netravati basin is computed using Eq. (1), plotted in Fig. 4. Cyclic up and down behavior can be observed in the graph. The maximum deficiency observed in seasonal and annual rainfall was 69.68% and 64.37%, respectively, in 2002. In 1987 also, the deficiency was more than 60%. A continuous deficiency was observed in the annual and seasonal flow from 1984 to 1989, 1999 to 2004, and 2011 to 2016. According to the Indian meteorological department, 110% of long-period average seasonal rainfall was obtained in India in

Fig. 4 Annual and seasonal departure of streamflow

1994; hence, excess flow can be observed in the river in the same year. Both stationary and non-stationary indices were plotted and depicted in Fig. 5. The deficiency in the streamflow is the primary reason for hydrological drought in a basin. From Fig. 5, the drought events can be observed during the streamflow deficiency years.

India experienced the worst drought situations in 1917, 1918, 1965, 1966, 1986, 1987, 2002, 2009, and 2012 during the last century [7]. According to previous studies, Karnataka faced severe drought from 2001 to 2004, 2009, and 2012 [11, 22]. In the same years, the deficiency in the streamflow of Netravati can be observed. NSSI also clearly showed the drought conditions during the same period (Fig. 5). The drought events number is higher under short-term compared to longer-duration drought in the basin. Even though Dakshina Kannada receives much rain during the monsoon, recent years have been noted as drought conditions throughout the summer [8]. After 2000, the severity of drought is observed to be increased in the basin, and this is well captured by NSSI than SSI.
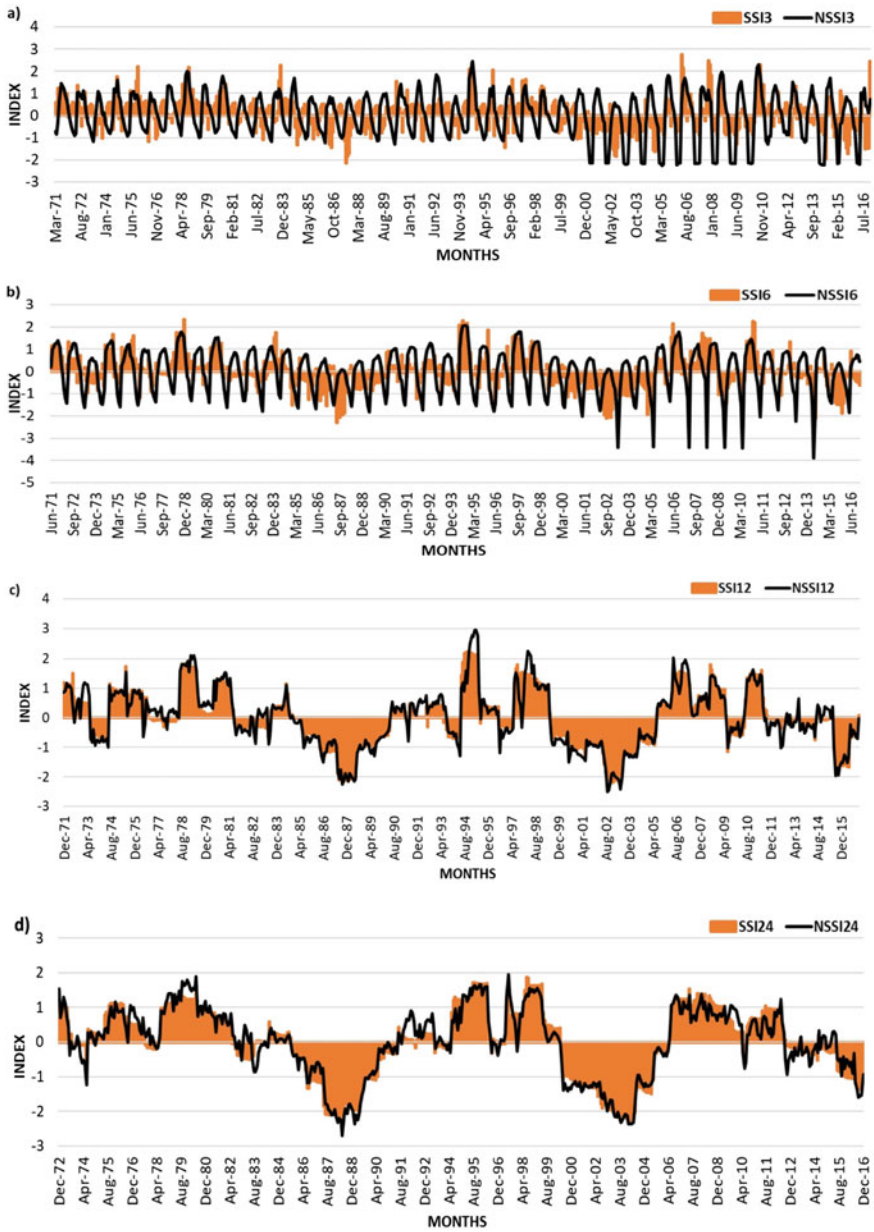
Fig. 5 Stationary and non-stationary indices

5   Conclusion

The streamflow at various time scales significantly correlated with various climate indices with different lags. Hence, the non-stationary models were constructed with the GAMLSS algorithm and compared with the traditional stationary models. From statistical measures, non-stationary models were the best at all the time scales. The influence of climate variables on drought classes, drought properties, and probability density plots was observed. From the comparison of NSSI with streamflow departure and historical drought events, it was found that the NSSI is better than SSI at detecting more severe drought events at short-term scales.

Further analysis based on the non-stationary index will be more helpful in reducing drought risk in the future. The hydrological drought in the basin was the main focus of this study. Many factors other than streamflow lead to drought in a region. Hence, future studies on drought should focus on other types of droughts. In addition, for water resource policymakers to effectively manage water resources, it is crucial to investigate the joint behavior of drought properties and determine the drought return periods in the basin.

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