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Spatial and Temporal Distribution of Rainfall and Rainy Days over the Goa State

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Abstract

Planning for water resources development in a basin or over a region requires careful assessment of the available water resources and reasonable needs of the basin/region in foreseeable future for various purposes such as drinking water, irrigation, hydro-power, navigation, etc. There are several ongoing river water disputes between different states of India, especially in the peninsular region due to decrease in rainfall during the past 15 years or so. The sharing of water of the Mondovi River is a cause of dispute between the Governments of Maharashtra, Karnataka and Goa states. An attempt has therefore, been made to study the characteristics of rainfall distribution over the Goa state using daily and monthly rainfall data. The study mostly comprises of spatial distribution of rainfall, seasonal and annual rainfall trend, relationship between rainfall and rainy days, mean daily rainfall intensity (MDI) and yearly variation of rainfall as well. The results of this study would form basis for various studies in administrating fresh water sources, projecting the investments to prevent the urban areas from the flood and proper planning of the agricultural activities in the State.

Keywords: Rainfall; Rainy Days; Goa State; Time Series Analysis; Precipitation Ratio

Introduction

Lot of discussion is going on worldwide about effect of global warming on earth's climate because some or the other part of the world facing changes in rainfall pattern, rise in sea levels, pre melting of ice and snow, etc. It is mentioned by Panandiker (2016) that by 2100 AD, global temperature is expected to rise by about 2 °C and consequently sea level ma rise by 50 cm from the current level [1]. According to the Intergovernmental Panel on Climate Change 5th Assessment Report (IPCC, 2014) the risk to low lying areas, especially along the coastal belt, is projected to increase significantly throughout the 21st century and beyond [2]. Generally, coastal regions of the world are vulnerable to natural calamities due to their proximity to the sea, large concentrations of population and economic activity. As a result, these areas are exposed to a wide variety of hazards such as sea water intrusion, coastal flooding due to storm surge, coastline erosion, water logging and an increase of sea surface temperature (Torresan *et al.*, 2008) [3]. In Asian countries also, accelerated sea level rise and increasing temperatures are apparently affecting marine as well as coastal ecosystems (Woodroffe, 2010) [4]. Specifically, South East Asian countries are believed to be at greater risk since large populations are seeking better livelihoods in these low lying fragile coastal plains.

The south Asian Country, India, has a coastline of about 5422 kms in length excluding islands ranking eighteenth longest coastline of the world. The coast of India is divided into western coast and eastern coastal plains. The Western Coast lies in between Western Ghats in the east and Arabian Sea in the west and from Kachchh (Gujarat) in the north to Kanyakumari (Kerala) in the south. Goa state, having 101 km of coastline, lie along the west coast in peninsular India Considering the economic and tourism significance, these coasts besides forming large resource of wave and tidal energy and hydrocarbons are also useful for various purposes such as drinking water, for irrigation, hydro-power, industries, navigation, etc.

In the influence of climate change, country has experienced below normal rainfall for several years in the recent past. This has resulted in several river water disputes between different states of India, especially in the peninsular Indian region. The sharing of water of the Mandovi River is a cause of dispute between the governments of Maharashtra, Karnataka and Goa. Therefore, the study of rainfall variability over short time scales is important and has a wide range of applications such as: to compare model predictions with atmospheric observations (Bell and Reid, 1993) [5]; to understand the atmospheric physics (Kishtawal *et al*, 2001) [6]; the local weather mechanisms (Hamada *et al,* 2008) [7], the drastic changes in the ecology (Pai, 2008), etc [8]. Considering this, in recent years, the study of rainfall characteristics has attracted everybody's attention as it is the most important single factor which determines the development and progress of the society and nation.

The west coast of India is one of the maximum rainfall receiving regions of the country. More than 90% of the rainfall is received during the monsoon month of Jun-Sept over the coastal region. Meso-scale analysis of daily rainfall for Maharashtra State (India), including the Western Ghats, for the two mid-monsoon months of July and August, during the 10-year period of 1971–1980 is studied by Patwardhan and Asnani (2000) [9]. Their analysis revealed that: (i) the rainfall increases rapidly from the Arabian Sea coast close to the line of maximum height of the Western Ghats; (ii) there are two rainfall maxima corresponding to the two mountain peaks parallel to the coast line; (iii) between the two mountain peaks, thereis a valley which is narrow at the western end (upwind end), broadening towards the east (on the downwind side). Because of the Western Ghats to the west side and associated heavy rainfall, the coastal region most probably between 14 °N to 16 °N band and near 19 °N is more flood-prone during the intense rainfall events (Francis and Gadgil, 2006) [10]. The state of Goa lies in the above mentioned band and is more vulnerable to flood due to heavy rainfall during the monsoon season.

Suprit and Shankar (2008) studied the spatial estimates of rainfall on the Indian west coast for calculating the surface water budget [11]. According to them the Mandovi river discharge provided a reliable and independent validation of the accuracy of the rainfall estimate as the river is purely rain-fed. Pai (2008) in his study on Biodiversity of the Mandovi valley mentioned different environmental aspects of Mandovi river basin with reference to rainfall, flora, fauna, water management, etc [8]. The rainfall features at different raingauge stations of Goa state for the period 1971-2000 showed the significant rising trend of rainfall towards the eastern parts of Goa (Metri and Singh 2010) [12].

Satya Prakash *et al.* (2013) using the gauge-adjusted multisatellite rainfall data for the period 1979–2010 investigated the long-term changes in the summer monsoon rainfall over the West Coast of India and adjoining eastern Arabian Sea (WCA) within the boundary of 10 °–20 °N and 72 °–77 °E [13]. Their results showed that time series of peak monsoon rainfall (for July and August months) averaged over the maximum rainfall showed a decreasing trend. Whereas the rainfall averaged over the WCA showed a significant upward trend since 2002. Spatio- temporal rainfall variability and rainstorm analysis over the two major river basins of Goa state viz. Mandovi and Zuari river basins has been studied by Nandargi and Mulye (2014) using rainfall data for the period 1901-2012. During 2001-2012, the state experienced 21 heavy rainspells of which 23-25 Jul. 2005 [14] and 1-3 Oct. 2009 were the most severe rainstorms occurred over the state.

For the last few years, Goa is also witnessing a change in its weather too. A TERI (2014) study on 'Climate Resilient Infrastructure Services' examined the mean sea level for Panaji for a period of 1875 to 2010 [15]. Their research showed an increasing trend of 1.26 mm/ year in sea level. Besides, a combination of outputs from 15 Climate Changes models was used in future projections (year 2100) also showed a sea level rise of 0.3 mm/year. There has been a change in the number of rainy days in Goa state. Along with this, due to high rates of urbanization, water logging and flood like situations are becoming more common. Therefore, construction and development activities need to be properly planned with at the most care.

In view of the above, an attempt has been made to understand the characteristics of rainfall distribution over the Goa state with special reference to monthly, seasonal, annual and decadal variation in the two districts using long period monthly rainfall data (1901-2017). Changes during recent period 2001 to 2017 using daily rainfall data has also been presented. The results can form very useful information to the agriculture and water sectors of this state.

Material and Methods

Study Area

Goa as a state established on 30th May 1987. The state is bordered in the north by Terekhol river which separates Maharashtra state from Goa and Karnataka state in the south and east. The Arabian Sea forms its western boundary (Fig.1). The entire eastern part of Goa State is flanked by the western slopes of the Western Ghats or Sahyadri hills that extends in the form of an arc with a length of 125 km north-south and covers an area of about 750 sq. km. The total land area of Goa has stretched across 3702 sq. kms and its coastline extends to 105 kilometers. For administrative purpose, the state is divided into two districts, North Goa and South Goa. Panaji is head quarter of the North Goa district and is also the capital of Goa state.

It is to be mentioned here that Ponda Taluka has been shifted from North Goa to South Goa in January 2015. However, on the basis of physiographic characteristics, India Meteorological Department (IMD) divided the Goa state into two districts viz. North Goa and South Goa, wherein Ponda is still considered under North Goa. Therefore, in the present study also the same classification is followed for further analysis. Sanguem Taluka has been recently divided into Dharbandora and Sanguem but rainfall data for Dharbandora station is not available yet and hence for the entire region Sanguem station data is considered. Similarly, due to non-availability of Bicholim station data from IMD, it is not considered in the Present study.

As per the Köppen climate classification, Goa comes under the tropical monsoon climate zone. Being located near the Arabian Sea and in the tropical zone, it has a hot and humid climate for most of the year. May is the hottest month (day temperatures >35 °C) contemporary with high humidity. The monsoon onset takes place over the state by about 5th June and withdraws by the end of September. Most of the Goa's annual rainfall is received during the monsoons season of June to September. However, during March 2008, the entire state was lashed with heavy rain and strong winds. This was for the first time in 30 years since it became an independent state that Goa experienced rain in the month of March.

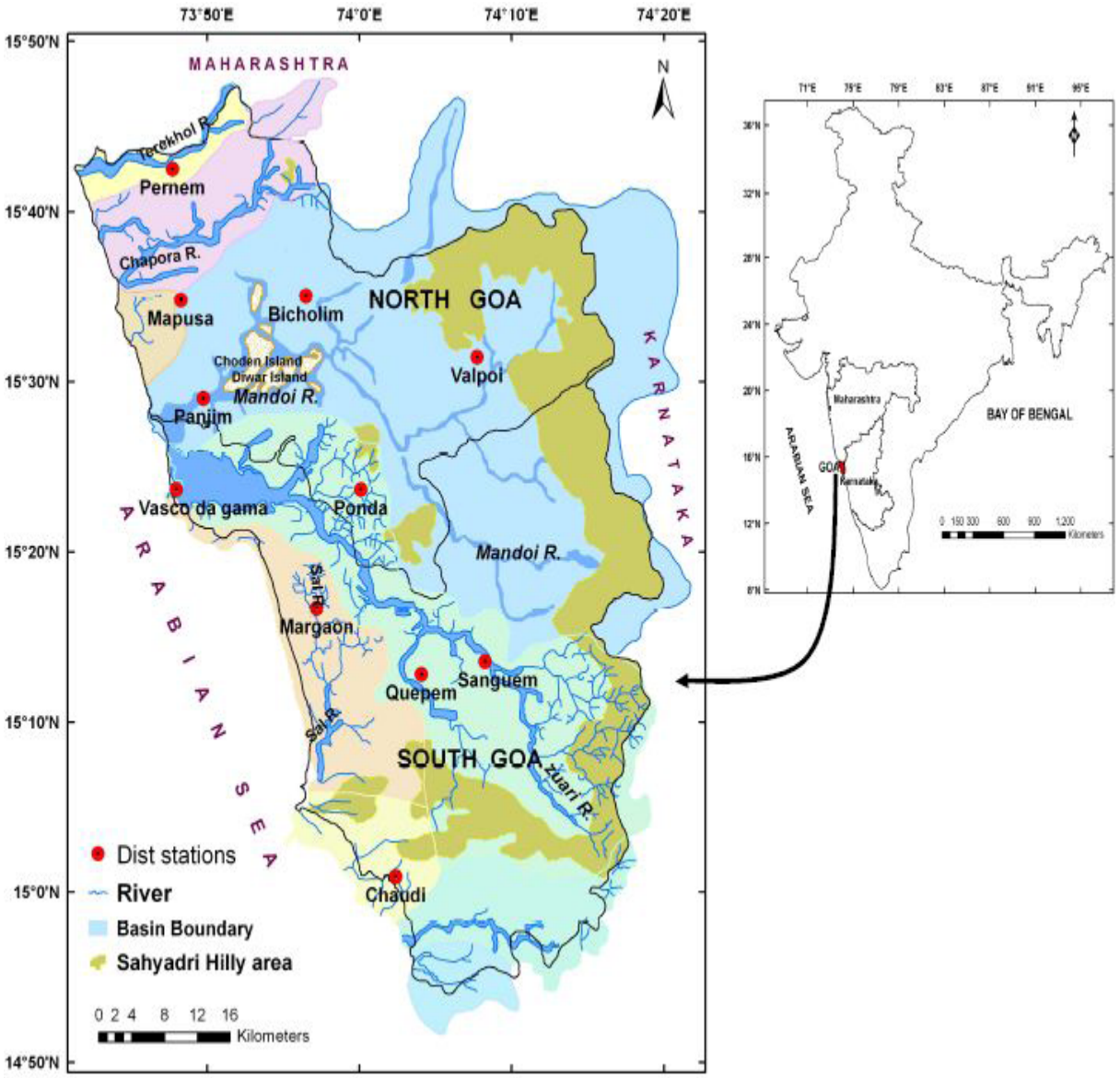


Figure 1: Goa state at a glance

As a consequence of topography, the high precipitation occurs on the west coast along the Sahyadri Mountains or Western Ghats rising to the height of above 1000 m. During the monsoon season, moisture-laden westerly winds experience uplift over the slopes of the mountains, that located at a distance of about 50 km from the coastline get cooled and precipitate their moisture. Besides, Monsoon depressions/cyclonic storms after originating in the head Bay of Bengal and crossing the eastern coast of the country move in west to northwesterly direction. When these systems move across Madhya Pradesh, often the Arabian Sea monsoon currents are strengthened, and heavy rainfall occurs over the coastal region. However, no storms or depressions from the Bay of Bengal directly affect the Goa state causing heavy rainfall over the region. Sometimes, depressions formed in the Arabian Sea cause heavy rainfall over the Goa state.

Goa's river system is unique and they are both tidal as well as Rainfed. During monsoon months, water within the watershed areas is drained out through the major rivers to the Arabian Sea. The rivers are influenced by the tidal influx up to the distance of about 40 km inland towards upstream. There are nine major rivers (Figure 1) in Goa viz. Terekhol, Baga, Chapora, Mandovi, Zuari, Galgibag, Sal, Saleri, Talpona flow from Western Ghats (East) to Arabian Sea (West) except Sal River. Of these rivers, about 70% (2553 Sq. Km) of the total geo-graphical area of Goa is drain by Mandovi and Zuari rivers. Rivers Terekhol and Chapora have originated in Maharashtra state and Mondovi in Karnataka state, flow through the state forming an intrinsic part of Goa. Out of nine rivers, six originate and flow exclusively inside the state boundaries and not having any interstate consequences.

Daily rainfall data from 2001 to 2017 for the five raingauge stations, Pernem, Mapusa (Mapuca), Panjim, Ponda (Fonda), Valpoi located in the North Goa (Figure 1) and six stations, Marmugao, Dabolim, Margao, Quepem, Sanguem, Canacona located in the South Goa are considered for the analysis. Besides, monthly rainfall data for the period of 1901 to 2000 of North and South Goa districts are obtained from the IMD forms the major data source.

Statistical Analysis

On the basis of the monthly rainfall data for the state, long term mean monthly, seasonal and annual rainfall was calculated for the individual stations and for the two districts, North and South Goa along with the standard deviation and coefficient of variation (CV) for the period of 1901 to 2017 and their spatial distribution have been shown using GIS technique. CV (Relative Standard Deviation) is a relative measure of variation that explains the deviation in data series from its central tendencies. It is defined as the ratio of standard deviation (σ) to the mean ($\bar{X}$) as expressed in the following equation-

$$CV = \frac{S.D.}{\bar{X}} * 100$$

Where, CV is the coefficient of variation, S.D. is the standard deviation, and $\bar{X}$ is the mean Time series analysis has also been carried out for the two districts by moving average method.

Trend Analysis

A complete trend analysis includes determining the direction and magnitude of change in the mean value of a particular time series. A popular nonparametric Man- Kendall test has been worked out for studying the spatial variation and temporal trends of hydro-climatic series. Mann-Kendall test had been formulated by Mann (1945) as non- parametric test for trend detection and the test statistic distribution had been given by Kendall (1975) for testing non-linear trend and turning point [16,17].

For a given a dataset consisting of x values with sample size n, the Mann-Kendall calculation begins by estimating the S statistic.

Null Hypothesis: There is no trend in the series meaning data are independent and randomly selected. S statistic is calculated as

$$S = \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} \text{sign}\,(X_j - X_i) \text{ for } j > 1 \quad \text{.....(1)}$$

Where, x_i and x_j are the values of the data at time i = 1,2…., n-1 and j = i+1, 2,…., n respectively. Each of the data point x_i is taken as a reference point which is compared with the rest of the data points x_j so that,

$$sign(X_j - X_i) = \begin{cases} -1 \text{ for } (X_j - X_i) < 0 \\ 0 \text{ for } (X_j - X_i) = 0 \\ +1 \text{ for } (X_j - X_i) > 0 \end{cases} \quad \text{.....(2)}$$

Whenn ≥ 8, the statistic S is approximatelynormally distributed with the mean E(S) = 0 and variance is given as

$$\text{Var(S)} = \frac{1}{18} n(n-1)(2n+5) - \sum_{p=1}^{q} t_p \left(t_p - 1\right)\left(2t_p + 5\right) \quad \text{.....(3)}$$

Where, t_p is the number of ties for the p^{th} values and q is the number of tied values. The test statistics Z_c is computed as

$$Z_c = \begin{cases} \frac{S-1}{\sqrt{\text{Var(S)}}} & \text{if } S>0 \\ 0 & \text{if } S=0 \\ \frac{S+1}{\sqrt{\text{Var(S)}}} & \text{if } S<0 \end{cases} \quad \text{.....(4)}$$

Here Z_c follows a standard normal distribution. A positive value of Z signifies an increasing trend and negative value as decreasing trend.

The magnitude of trend is predicted by the Sen's slope estimator.

$$T_i = \frac{X_j - X_k}{j-k} \text{ for } i = 1, 2.....N \quad (j>k) \quad \text{.....(5)}$$

Where T_i is Sen's Slope, x_j and x_k are data values of the same observational unit at time j and k respectively. The median of these N values of T_i is represented as Sen's estimator of slope which is given as:

$$Q_{median} = \begin{cases} \frac{T_{(N+1)}}{2} & \text{if N is odd} \\ \frac{T_{\frac{N}{2}} + T_{\frac{(N+2)}{2}}}{2} & \text{if N is even} \end{cases} \quad \text{.....(6)}$$

The sign of Qmedian reflects the data trend direction and its value gives the magnitude of slope of the trend.

The drawback of the Mann-Kendall test (distribution free test) is that it is only able to detect monotonic trend in the data. In order to assess the trend in the rainfall series from 1901-2017 for the two districts of Goa, viz. North and South, second degree polynomial was found to be best fit for a large variable data set of rainfall.

Precipitation Ratio

The abnormalities of rainfall at any location may be brought by a simple ratio of precipitation. It is the difference between maximum and minimum rainfall of the annual rainfall series expressed in terms of mean.

$$P_R = \frac{P_{Max} - P_{Min}}{P_{MAR}} \times 100 \quad .....(7)$$

Where, P_R = Precipitation Ratio, P_{Max} = Maximum mean annual rainfall
P_{Min} = Minimum mean annual rainfall and P_{MAR} = Mean annual rainfall

This ratio may give the stability of rainfall with special relationship. Higher the ratio, higher is the abnormality in rainfall and vice versa (Rathod and Aruchamy, 2010) [18].

Results

Temporal and Spatial Distribution of Rainfall

Month/Season	North Goa	South Goa
January	0.7	3.6
February	1.2	1.2
March	10.2	10.8
April	4.8	8.0
May	62.3	73.4
June	873.3	821.4
July	1016.4	908.8
August	682.7	638.8
September	401.5	371.8
October	166.9	163.8
November	34.5	30.3
December	2.6	3.2
Annual Total	3257.2	3035.2
Seasonal rainfall as % of annual		
Jun-Sept	91	90

Table 1: Mean monthly, seasonal and annual rainfall (mm) over north and South Goa

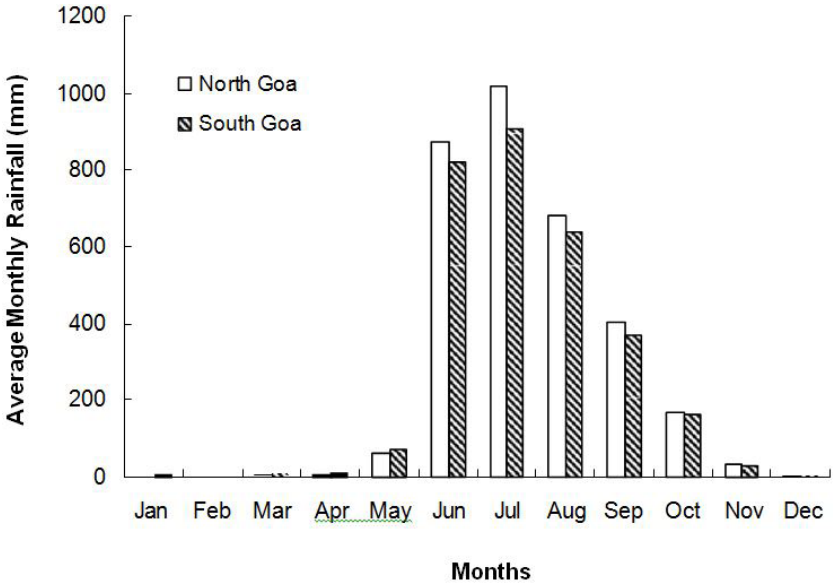


Figure 2: Average monthly rainfall distribution over North and South Goa

On the basis of available daily rainfall data of all the stations in the north and south Goa for the period 2001 to 2017, the mean seasonal rainfall over the North Goa and South Goa is of the order of about 2974.3 mm and 2740.8 mm respectively, declining from July to October. The mean annual rainfall over the two districts varies from 3257.2 mm and 3035.2 mm in the north and south districts respectively. This is also supported by the long period data (1901-2017) results of the mean annual rainfall over the two districts which vary from 3122.7 mm and 3010.6 mm in the north and south districts respectively. The northern district receives comparatively heavy rainfall due to topography influence. June and July are the two major contributing months to the annual rainfall followed by the August month (Table 1 and Figure 2). More than 60 % of the seasonal rainfall occurred in these two months. It is seen from Table 1 and Figure 2 that about 91% to 90% of the annual rainfall is contributed during June to September monsoon months.

The effect of altitude on seasonal and annual rainfall of the stations in the two districts showed that altitudinal variation is more effective in north Goa than in the south Goa both during seasonal and annual rainfall (Figure 3). Average rainfall recorded at higher altitudes is comparatively less than that of at lower altitudes.

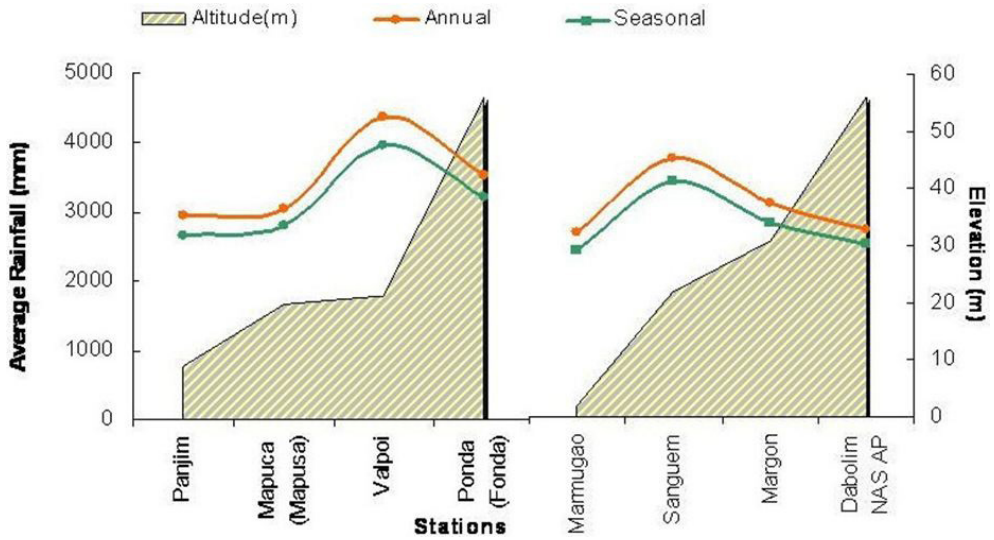


Figure 3: Effect of altitude on the variation of rainfall

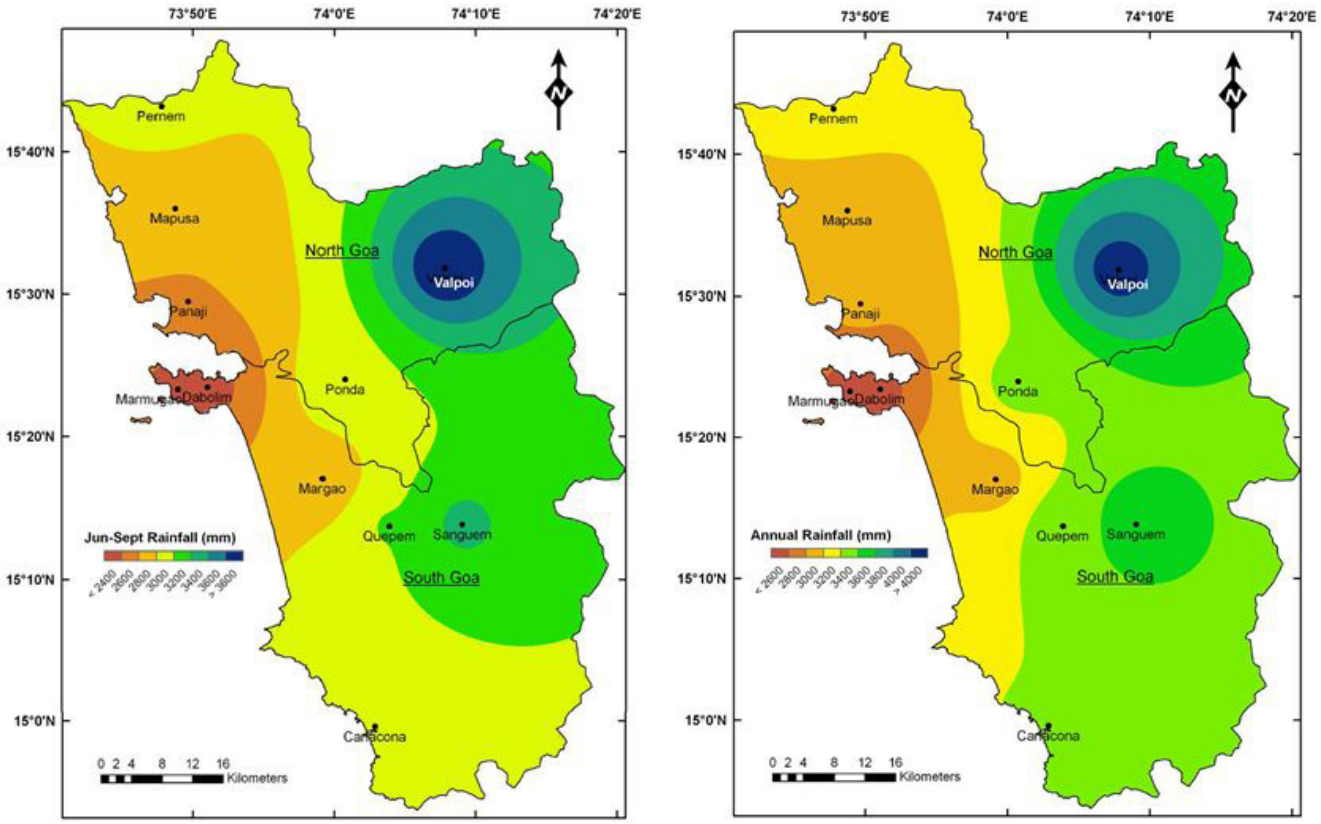


Figure 4: ESpatial distribution of Seasonal and Annual Rainfall distribution over the Goa state

The spatial distribution of annual and seasonal (June to September) rainfall for the entire state is more or less same, as 90% of annual rainfall is received during the four monsoon months (Figure 4). Mapusa and Panaji stations in North Goa and Marmugao, Dabolim and Margao stations in South Goa received comparatively less mean annual and seasonal rainfall which is mostly because these stations lie in a low lying region along the coast. On the contrary, Valpoi station in Satari Taluka of North Goa which is nearer to Western Ghats recorded highest mean annual rainfall (4123 mm) in 122 rainy days and seasonal rainfall (3760 mm) in 97 rainy days and its monsoon season rainfall was 91 % of the annual. In South Goa Quepem and Sanguem stations recorded 3001 mm and 3273 mm rainfall in monsoon months of Jun-Sept respectively that is 91 % of the annual rainfall.

The statistical analysis of the long period (1901-2017) variation of average annual rainfall using MK Test over North and South Goa districts has shown linear increasing trend (Table 2). This is also supported by Kendall's tau and p-value indicating strong positive correlation between rainfall and duration. But fitting second degree polynomial distribution to long period annual rainfall shows increase in rainfall up to 2000 year and thereafter there is decrease in both annual and monsoonal rainfall (Figure 5).

	Annual Rainfall				Jun-Sept Rainfall			
Districts	Kendall's tau	p- valuueue	Sen's slope	MK Test	Kendall's tau	p- value	Sen's slope	MK Test
	τ		Q	Z	τ		Q	Z
North Goa	0.23	0.00	6.52	3.73	0.24	0.00	6.15	3.77
South Goa	0.26	< 0.0001	4.95	4.06	0.22	0.00	4.81	3.48

Table 2: Results of Mann-Kendall test with Sen's slope (Q, mm/year) for annual andSeasonal rainfall over North and South Goa

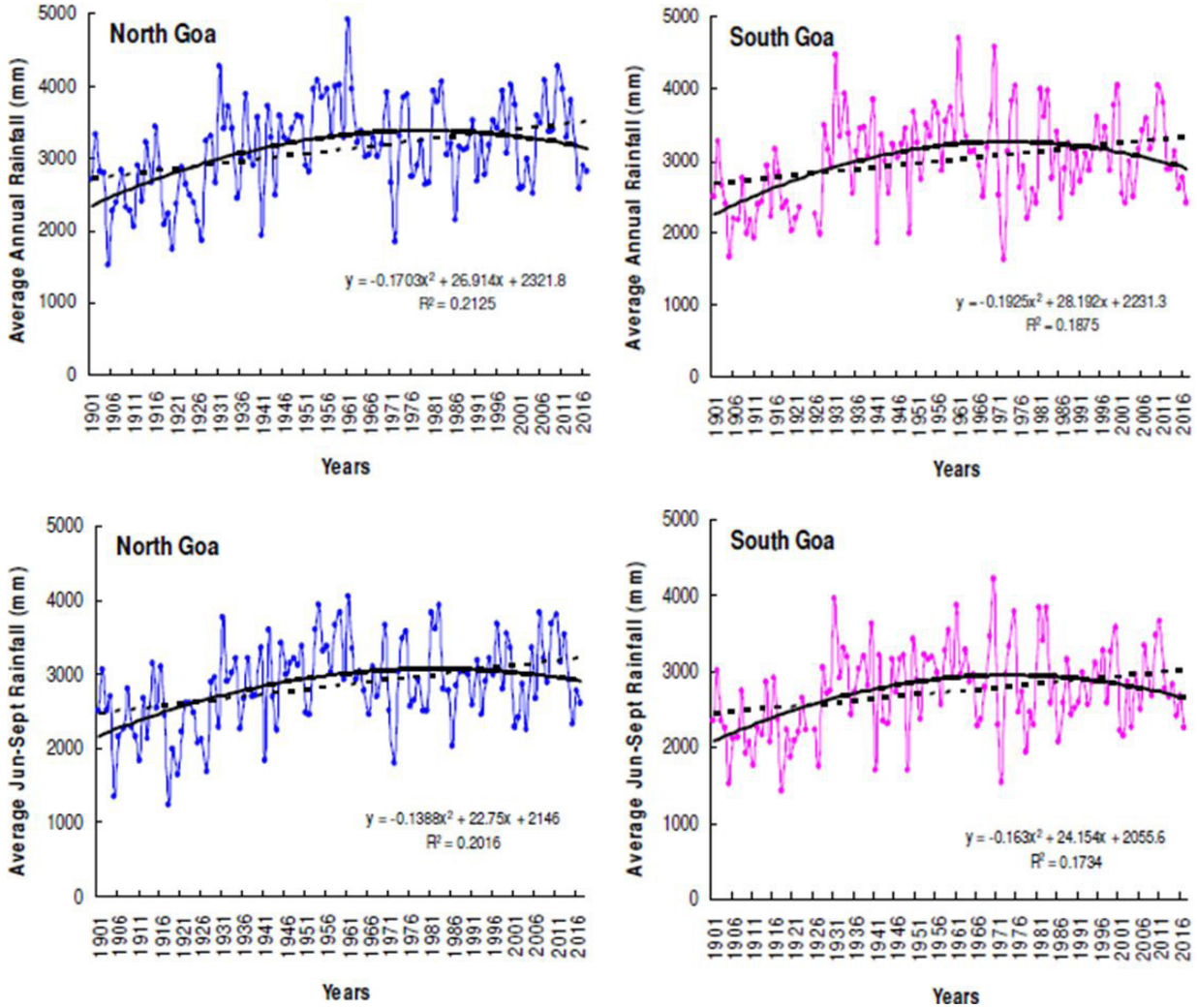


Figure 5: Yearly variation of average annual and Jun-Sept rainfall over North and South Goa
Note: Dotted line indicates linear increasing trend and solid line indicates second degree Polynomial fit

In order to know long term trends or cycles in a given time series of annual rainfall over the state, a moving average method was also applied and 3, 5, 7 and 9-year running averages have been worked out for north and south Goa districts (Figure 6). Broadly both the districts displayed a similar characteristic of cyclic trend except the magnitude for most of the Period. The cyclic trend

clearly shows that average annual rainfall was below normal up to 1935 and was highest during the period 1950 to 1970. Thereafter, it remained more or less to near normal.

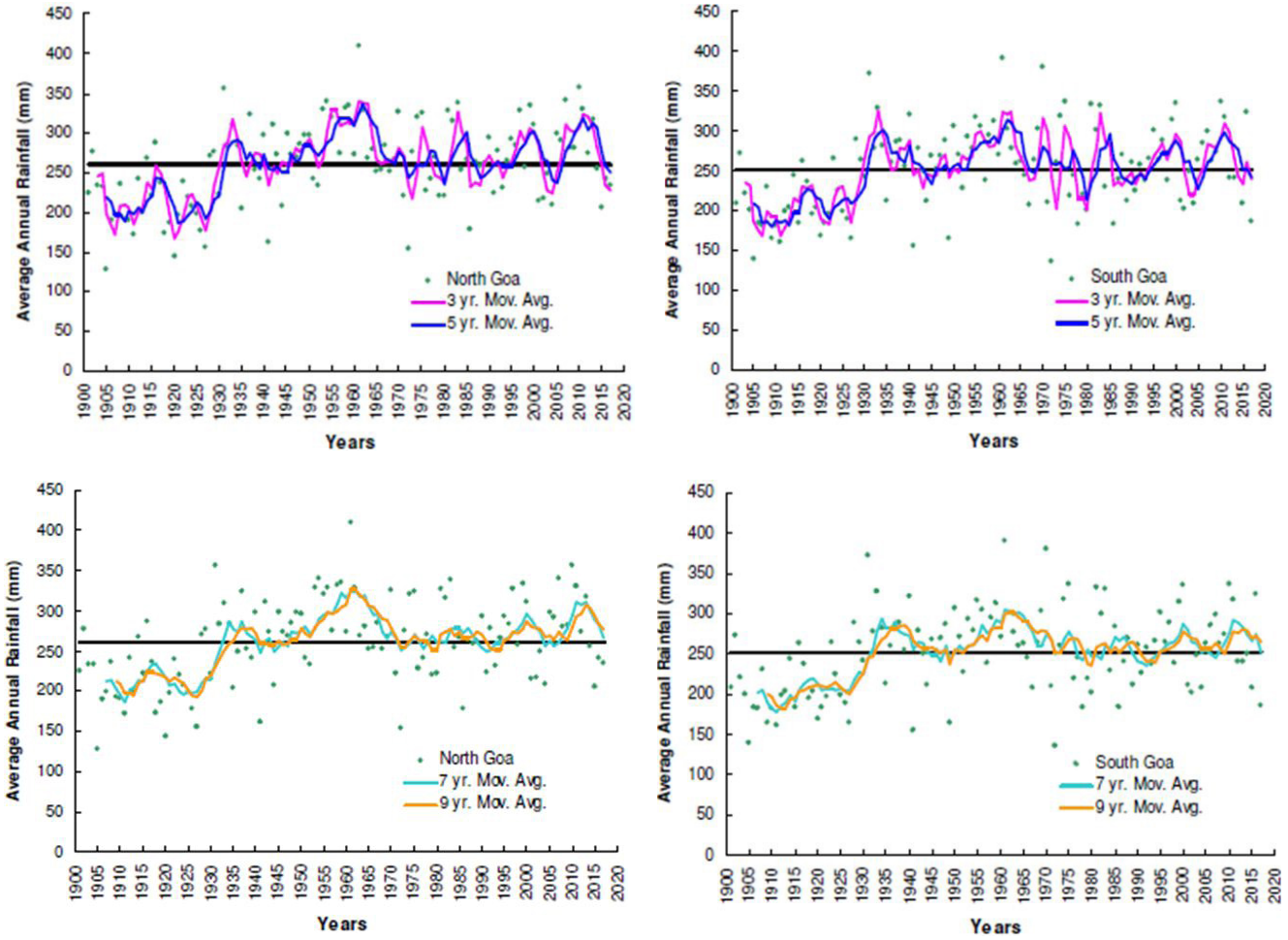
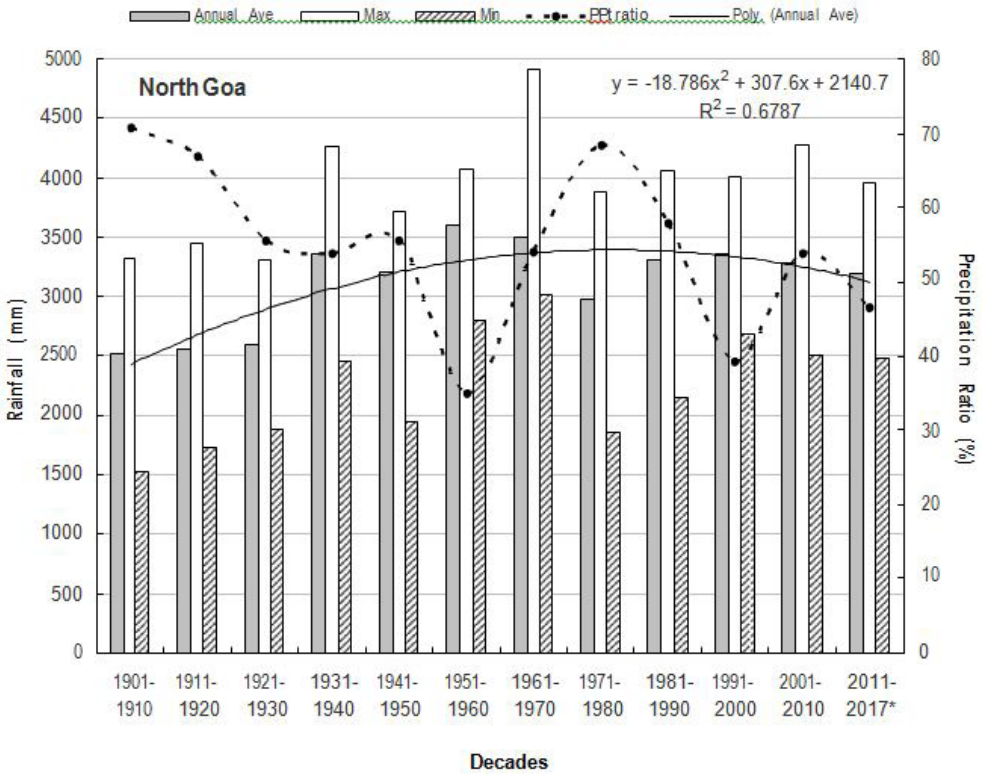


Figure 6: 3, 5, 7 and 9-year running averages of annual rainfall over North and South Goa



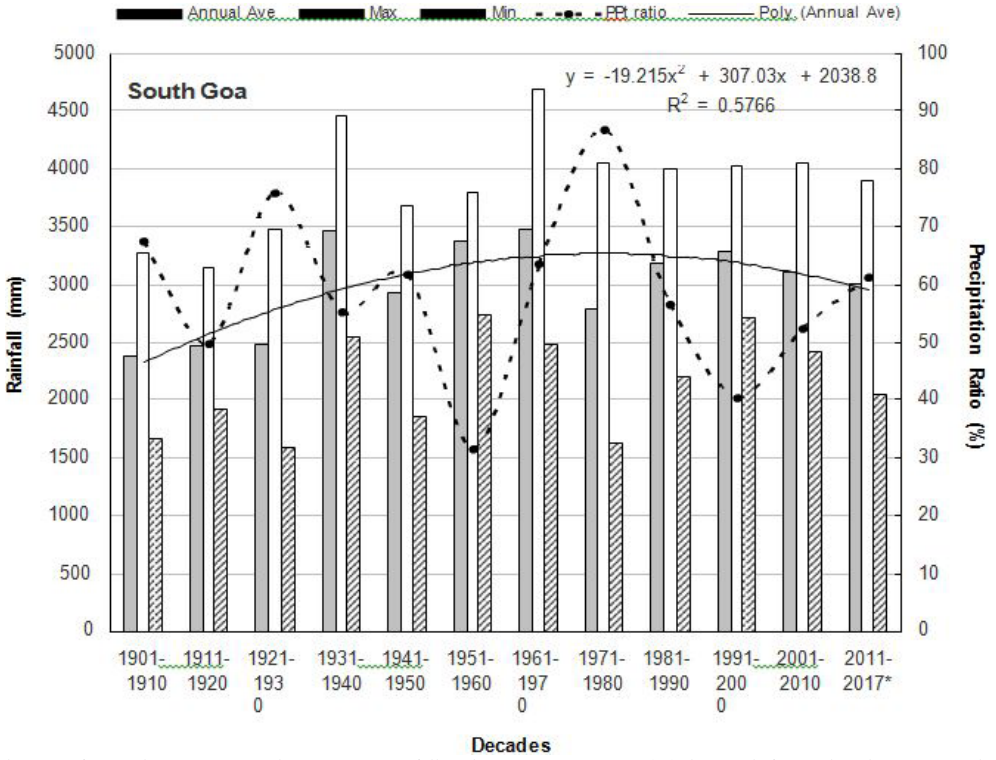


Figure 7: Distribution of annual, maximum and minimum rainfall with Precipitation ratio (%) during different decades over North and South Goa

As shown in Figure 7, the average annual rainfall increased from the 1901-1910 decade to 1951-1960 decade and remained more or less steady till 1991-2000 decade. Thereafter there is decrease in rainfall. In North and South Goa, 1931-1940, 1941-1950, 1951-1960, 1961-1970 and 1991-2000 decades, July month contributed more than 1150 mm of rainfall. However, in North Goa 1911-1920 and 1981-1990 decades; and in case of South Goa during 1901-1910, 1981-1990 decades and 2011-2017 period, June month has recorded more rainfall than the July month.

The maximum July rainfall was recorded in the 1951-1960 decade in both the districts. Heavy rainfall in the month of August was recorded during 1981-1990 decade. Similarly, September month has recorded heavy rainfall during 2001-2010 decade than the other decadal periods. The 2011-2017 is not a complete decade but it was found that some heavy rain spells were recorded during this period. The maximum annual rainfall was recorded during the 1951-1960 decade in north Goa and 1961-1970 decade in south Goa followed by the 1931-1940 and 1991-2000 decades (Figure 7). 1961-1970 decade has recorded maximum rainfall of 4913.1 mm in north Goa and 4691.2 mm in south Goa. The minimum annual rainfall was also to the higher side in 1961-1970 decade followed by 1951-1960 decade in north Goa whereas in case of south Goa 1951-1960 decade recorded higher minimum annual rainfall followed by 1961-1970 decade.

In North Goa district, maximum abnormality (i.e. Precipitation ratio 71%) was recorded during 1901-1910 decade (Figure 7) and then 1971-1980 decade during which the district as a whole recorded less annual rainfall. Similarly, in South Goa district, maximum abnormality (i.e. 87%) was recorded during 1971-1980 decade (Figure 7) during which the district recorded very less annual rainfall in the drought year of 1972 and highest maximum rainfall was recorded in the 1975 year giving high precipitation ratio of 87%. Both the districts recorded minimum precipitation ratio during 1951-1960 decade (35 % for North Goa and 32 % for South Goa) indicating more or less stable annual rainfall throughout the decade (Figure 7). In the recent period of 2011-2017 though it is not a full decade, North Goa has recorded increase in rainfall activity showing lesser precipitation ratio whereas, South Goa has recorded higher precipitation ratio of 61 % indicating decrease in rainfall over the South Goa district during this period.

From the foregoing it is seen that Jun and Jul are the main rainfall contributing months. However, assessment of highest 24-hr rainfall during the entire monsoon season is essential from flood forecasting, agricultural management point of view. Stations in the Goa state have recorded the highest 24-hr rainfall for the monsoon months in the range of 128 mm to 433 mm (Table 3). Highest 24-hr Jun-Sept rainfall for each station with date of occurrence during 2001 to 2017 is given in (Table 4). In 2009 which was a drought year over rest of the India, many stations in Goa state recorded highest 24-hr rainfall in the monsoon months of June, July and September. In the month of August, years 2008 and 2014 contributed highest 24-hr rainfall. Highest 24-hr rainfall of 432.6 mm was recorded by Sanguem station (South Goa) on 7 June 2009 while Valpoi station (North Goa) recorded 360.3 mm on 25 July 2005.

Month	June	July	August	September
Highest 24-hr rainfall range (mm)	200-433	200-360	153-261	128-308

Table 3: Magnitude of highest 24-hr rainfall during monsoon months over the Goa state

District	Station	Jun-Sept	Date of Occurrence
North Goa	Pernem	294.4	18/06/2012
	Mapusa	301.4	02/07/2009
	Panaji	260.8	20/06/2003
	Ponda	242.2	07/06/2009
	Valpoi	360.3	25/07/2005
South Goa	Marmugao	242.2	19/06/2012
	Dabolim	207.4	22/06/2005
	Margao	238.2	25/07/2005
	Quepem	230.8	14/09/2006
	Sanguem	432.6	07/06/2009
	Canacona	279.0	20/06/2003

Table 4: Highest 24-hr rainfall recorded by stations in Goa (2001-2017)

North Goa and South Goa districts and Goa state as a whole showed overall decrease in highest 24-hr rainfall during 2001 to 2017 monsoon months and annual as well. However, increasing trend from 2005 to 2011 and thereafter sharp decreasing trend is observed. South Goa has contributed highest 24-hr rainfall of greater magnitude than the North Goa.

Monsoon starts receding from the month of September, and at the same time northeast monsoon sets in over the Peninsular India which causes some heavy rainfall over the coastal regions also. Because of this October month (post-monsoon) has recorded heavy range (140- 380 mm) of highest rainfall. Similarly, during pre-monsoon months on 30-31 May 2006 all the stations, except Marmugao recorded heavy rainfall and highest of 322.5 mm was recorded by Margao station.

Rainfall and Rainy days over the Goa state

It is well known that the bulk of the rainfall during any given period is recorded on a relatively small proportion of the days of rain. The statistical features associated with the daily rainfall distribution at different stations over an extended area are interesting and important aspects of rainfall climatology. Variations in the frequency of rainfall amounts on these heavier rainfall days may, therefore, be expected to exert a major control on rainfall totals. The rainy days' study can provide the information regarding frequency and intensity of rain events during different weather conditions. For example, drought season may be marked by both fewer rain days and less rain per day as compared to periods of normal and above-normal rainfall. Therefore, in the present study, the days of heavier rains over the two districts of Goa for 2001 to 2017 period have been identified to determine the relative importance of rain day frequency and intensity changes for monthly, seasonal rainfall totals.

The monthly, seasonal and annual rainfall at a station is contributed by a small percentage of the total number of rain days (NRD) with large rain amounts. On an average, the number of rain days (i.e. ≥ 0.1 mm of rainfall) varied from 112 (Quepem, South Goa) to 123 (Panaji, North Goa and Marmugao, South Goa) during June to October months of the monsoon season (Table 5).

North Goa					
Pernem	**Mapusa**	Panaji	Ponda	Valpoi	
115.6	120.1	123.1	118.8	122.4	
South Goa					
Marmugao	**Dabolim**	Margao	Quepem	Sanguem	Canacona
123.3	118.3	113.5	111.9	119.4	115.1

Table 5: Average number of rain-days ≥ 0.1 mm of rainfall for the stations in the North and South Goa districts

The frequency of rain days for the annual series for the state as a whole having less rain days in the years, 2002, 2005, 2008, 2009, 2012, 2014 and more number of rain days in the years, 2004, 2006, 2007, 2010 and 2013 (Figure 8). After 2014 an erratic behavior of rain days has been noted during 2015 to 2017. Margao and Quepem stations recorded less number of rain days respectively in the years 2016 and 2017 while Marmugao, Sanguem and Panaji stations recorded more than 120 rain days during 2016 and 2017. Rest of the stations recorded number of rainy days between 100 and 120. Frequency distribution of daily rainfall against number of rain days is shown in Figure 9 for North and South Goa.

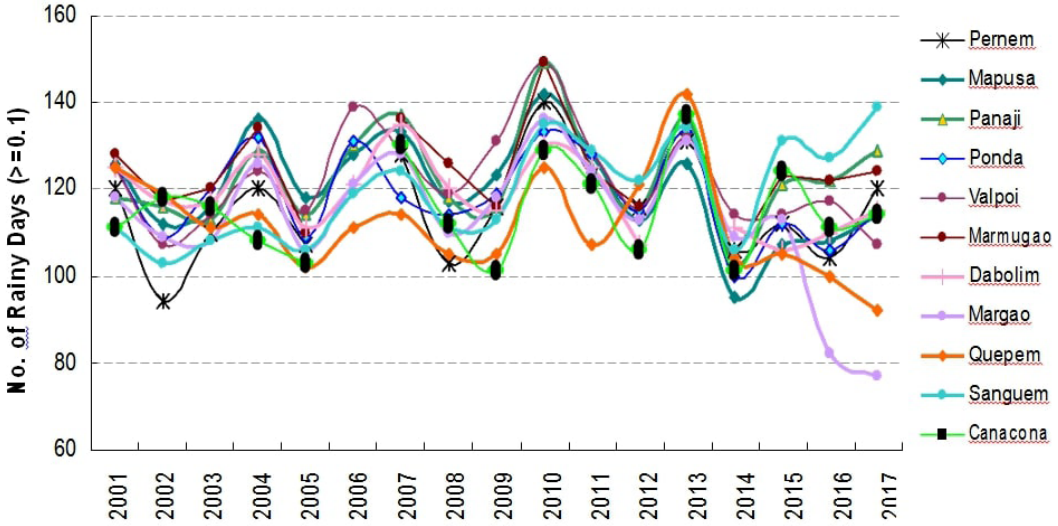


Figure 8: Yearly frequency of number of rain days (≥ 0.1) in North Goa and South Goa

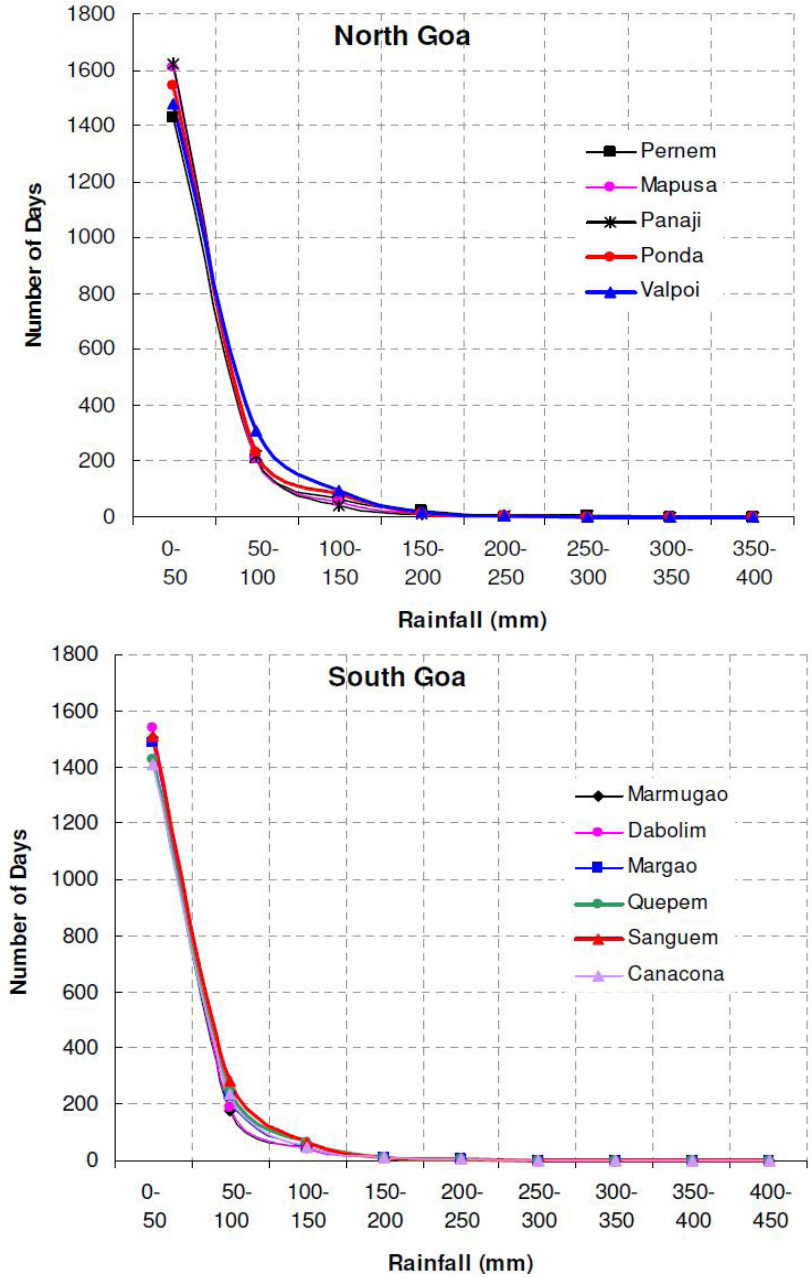


Figure 9: Yearly frequency of number of rain days (≥ 0.1) in North Goa and South Goa

The Goa state, being located in the hilly terrain of Western Ghats and close to the Arabian Sea, receive heavy to very heavy rainfall all through the monsoon season. Therefore as per the India Meteorological Department (IMD) a rainy day is defined as a day with rainfall of 2.5 mm or more rainfall. IMD further defines that rainfall for a station is called heavy if it is > 650 mm and 'very heavy' when it is > 1300 mm. Pursuing this criterion mean number of rainy days in all the three categories have been calculated for Jun-Sept monsoon months of 2001 to 2017 period for the two districts in Goa state (Table 6).

The frequencies of heavy and very heavy rainy days noted by each station in the Goa state are comparatively very less, varying between the ranges of 0 to 5 whereas the rainy day with 2.5 mm of rain vary from 20 (Mapusa and Pernem} to 24 (Valpoi) in North Goa and from 20 (Dabolim) to more than 23 (Sanguem) in South Goa. In association with the heavy rainfall in July month, maximum numbers of rainy days are recorded in rainy category (i.e. ≥ 2.5 mm) of the July month followed by the August and June months respectively in North and South Goa (Table 6). In Heavy rain day's category (i.e. ≥ 650 mm) June and July months recorded equal number of rainy days followed by the August month in both the districts. In very heavy rain day's category (≥ 1300 mm), only June and July months recorded one-one events.

Rain category	June		July		August		September	
	North	South	North	South	North	South	North	South
Rainy (≥2.5 mm)	22	21	28	27	25	24	16	15
Heavy (≥650 mm)	5	4	5	4	3	2	1	1
Very heavy (≥1300 mm)	1	1	1	1	0	0	0	0

Table 6: A Frequency of rainy days during June to September (2001-2017) over north and south districts of the Goa State

In order to realize the rainfall condition over the state, the relationship between the season total rainfall, NRD and Mean Daily Intensity (MDI) (Nandargi & Mulye, 2012) [19] has been exercised (Table 7). This may give some broad measure of intensity of rain and indication of frequency of occurrence of rain over the state being significant from hydrological as well as agricultural perspective. The two types of relationships have been examined between –

a) Average seasonal rainfall versus NRD (Figure 10 North Goa and Figure 12 South Goa)

b) Average seasonal rainfall versus MDI (Figure 11 North Goa and Figure 13 South Goa) Here,

$$\text{Mean daily intensity} = \frac{\text{Average Seasonal Rainfall}}{\text{Number of rainy days}}$$

Station Name	Rainy Days	Ave. seasonal Rainfall (mm)	Mean Daily Intensity (MDI)
North Goa			
Pernem	89.4	97.6	1.1
Mapusa	88.4	86.8	1.0
Panaji	85.4	86.9	1.0
Ponda	92.6	99.5	1.1
Valpoi	97.0	127.0	1.3
South Goa			
Marmugao	81.3	80.2	1.0
Dabolim	80.1	83.6	1.0
Margao	85.5	90.3	1.1
Quepem	89.1	99.2	1.2
Sanguem	92.9	107.7	1.2
Canacona	92.0	96.4	1.0

Table 7: Comparison of Number of rainy days (NRD) and mean daily intensity (MDI) with average seasonal rainfall for the stations in the North and South Goa

Goa (Figure 10, 11, 12 and 13) showed that the logarithmic relationship was observed to be superior than the linear relationship despite there is a very marginal difference in the R^2 values. Here R^2 values used to assess the differences between linear and logarithmic equations which were very minute and non-significant. Therefore, taking into consideration the topography and heavy rainfall over the study region, logarithmic relationship may be considered being more superior to the linear relationship.

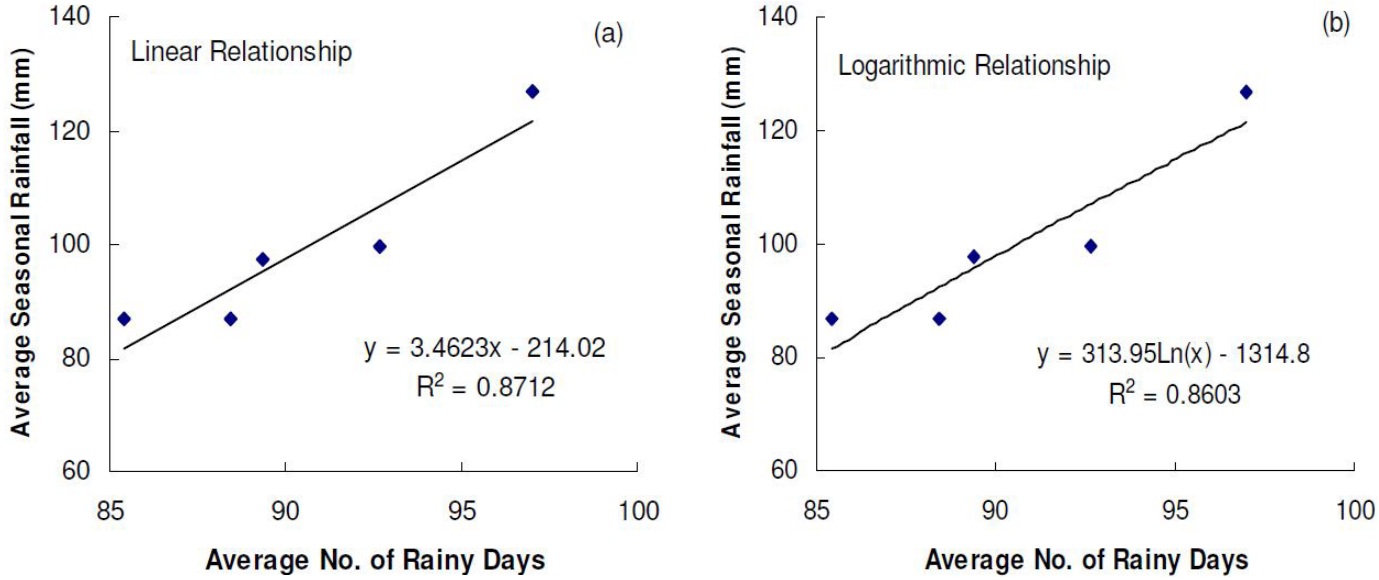


Figure 10: Relationship between Average seasonal rainfall and NRD over North Goa

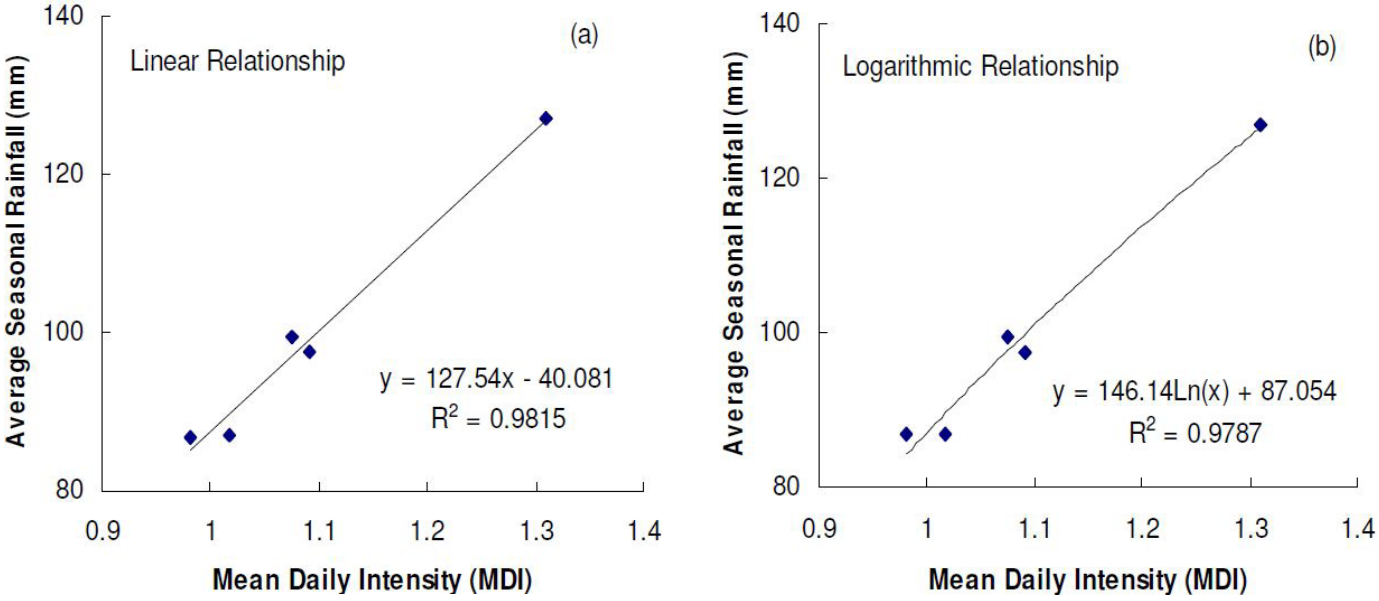


Figure 11: Relationship between Average seasonal rainfall and MDI over North Goa

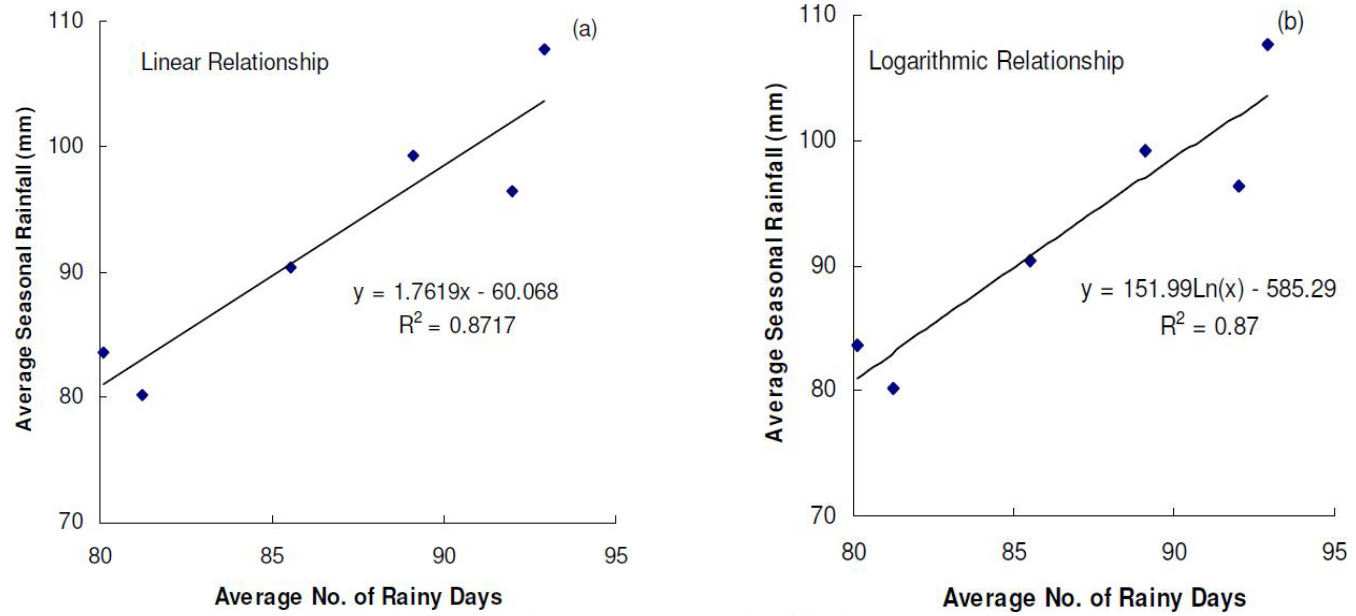


Figure 12: Relationship between Average seasonal rainfall and NRD over South Goa

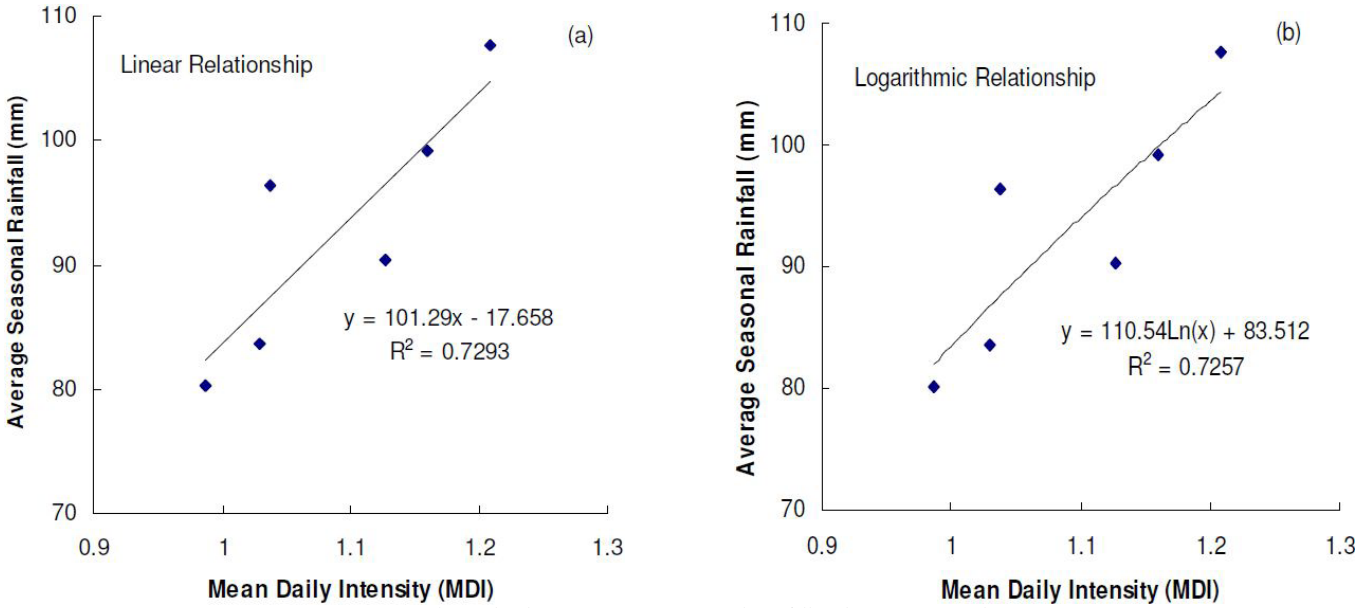


Figure 13: Relationship between Average seasonal rainfall and MDI over South Goa

		Pernem			Mapusa					Panaji		
	n	r	s	CV	n	r	s	CV	n	r	s	CV
Jun	22.5	37.1	42.8	115.6	24.9	33.1	37.8	114.4	25.3	34.5	42.4	123.1
Jul	28.0	34.8	37.6	108.0	30.4	29.6	35.6	120.3	30.1	27.6	32.0	115.8
Aug	26.8	21.6	26.9	124.7	28.2	19.5	24.3	124.5	27.6	20.5	27.5	134.2
Sept	17.4	21.5	29.8	138.8	19.1	17.8	23.4	131.6	20.2	18.2	25.9	142.4
Jun- Sept	**94.7**	**29.2**	**35.4**	**121.2**	**102.7**	**25.5**	**32.0**	**125.7**	**103.2**	**25.5**	**33.3**	**130.4**

		Ponda				Valpoi		
	n	r	s	CV	n	r	s	CV
Jun	24.1	36.2	37.1	102.3	23.7	40.0	38.6	96.7
Jul	30.1	34.2	34.5	101.0	30.1	43.9	39.0	89.0
Aug	27.7	24.9	27.9	112.2	28.7	34.1	35.8	105.0
Sept	18.9	20.9	25.3	120.9	20.0	26.0	31.3	120.2
Jun-Sept	**100.8**	**29.6**	**32.5**	**109.6**	**102.4**	**36.7**	**37.2**	**101.2**

n = the mean no. of rain days, r = the mean rain amount per rain day (mm), s = standard deviation (σ) and cv = 100˚(s.d./r)

Table 8: Statistical parameters of rainfall series of stations in the North Goa

Relationship between monthly totals (T), rain days (RD) and mean daily rainfall intensity (MDI) were examined on monthly and seasonal scale. It is seen from (Table 8 and 9) that except Pernem station (95 days), all the stations recorded more than 100 rain-days in North Goa whereas only Sanguem station recorded more than 100 rain-days in South Goa and rest all the five stations recorded less than 100 rain-days during the monsoon season. In the North Goa, the lowest intensity (i.e. mean rainfall/day) in monsoon season has been recorded by Mapusa and Panaji stations (25.5 mm/day) being situated nearer to Arabian Sea and the highest intensity occurred over the Valpoi station (36.7 mm/day) situated close to the Western Ghats.

		Marmugao			Dabolim				Margao			
	n	r	s	CV	n	r	s	CV	n	r	s	CV
Jun	22.4	32.2	38.7	120.2	22.7	30.5	35.1	115.2	24.1	33.6	37.9	112.8
Jul	26.8	26.7	33.3	124.6	28.5	26.1	32.5	124.6	28.4	30.7	34.4	112.1
Aug	26.2	18.2	24.5	134.4	27.2	19.9	25.9	129.8	26.1	23.0	27.0	117.6
Sept	19.1	15.1	20.8	138.0	19.4	16.7	22.6	135.1	18.2	19.5	24.0	123.2
Jun-Sept	**94.5**	**23.3**	**31.0**	**133.2**	**97.7**	**23.5**	**30.1**	**127.9**	**96.8**	**27.2**	**32.2**	**118.3**

		Quepem				Sanguem				Canacona		
	n	r	s	CV	n	r	s	CV	n	r	s	CV
Jun	23.2	39.6	38.3	96.9	23.2	37.4	40.6	108.1	22.9	36.8	41.4	112.4
Jul	29.5	34.8	33.9	97.6	29.9	38.2	36.0	94.2	27.6	32.0	31.9	99.7
Aug	26.4	25.5	27.1	106.4	28.1	29.2	29.9	102.3	25.4	25.0	27.5	110.0
Sept	16.4	23.4	27.3	116.7	19.9	22.2	24.3	109.2	17.1	22.3	23.2	104.0
Jun-Sept	**95.5**	**31.4**	**32.6**	**103.8**	**101.1**	**32.4**	**34.1**	**105.3**	**93.0**	**29.5**	**32.6**	**110.3**

n = the mean no. of rain days, r = the mean rain amount per rain day (mm), s = standard deviation (σ) and cv = 100*(s.d./r)

Table 9: Statistical parameters of rainfall series of stations in the South Goa

In the South Goa, the lowest MDI has been recorded by Marmugao station (23.3 mm/day) which is also situated nearer to Arabian Sea and the highest intensity observed for the Sanguem station (32.4 mm/day) situated nearer to the Western Ghats (Table 9). MDI values are less in South Goa than North Goa which experience heavy rainfall during the monsoon season (Table 7).

As stated earlier, the CV of the daily rain amounts is a symbolic parameter of the daily rainfall distribution. The CV of the daily rainfall at the 5 stations in North Goa varies from 101% to 130% and in South Goa; CV of the daily rainfall at the 6 stations varies from 104% to 133% during June to September monsoon season respectively (Table 8). It is seen that CV values of monthly series for North Goa range from a minimum of 89% for the July rainfall of Valpoi to a maximum of 142.4% for September rainfall of Panaji. In South Goa, CV values range from 94.2% for the July rainfall of Sanguem to a maximum of 138.0% for September rainfall of Marmugao.

Discussion

On the basis of 30 years (1971-2000) data Metri and Singh (2010) [12] showed that Goa state recorded more than 92 % of rainfall. The results of the present study also agree with this. However, it is seen that during 2001-2017 there is slight increase in rainfall activity over the North Goa. The highest seasonal rainfall is recorded during the month of July followed by June and August months which is comparable with the results of Metri and Singh (2010) [12]. Of all the stations, Valpoi station in the North Goa receives maximum rainfall during southwest monsoon season due to its orographic nature. The elevation of Sahyadri hills rising steeply just east of Valpoi, which lies at the foot hill of the Sahyadri range, is one of the main reasons of high precipitation over Valpoi (Nandargi and Mulye, 2014) [14].

The Goa state as a whole received about 3050 mm of rainfall during monsoon season of 1971-2000 (Metri and Singh, 2010) [12]. The present analysis revealed that the state received 2881 mm and 2791 mm of monsoon rainfall during 2001-2017 and 1901-2017 respectively which is definitely less indicating decrease in rainfall activity (Figure 5). The study of precipitation trends is critically important for a country like India whose food security and economy are dependent on the timely availability of water. Fitting second degree polynomial distribution to the yearly average annual rainfall over north and south Goa district showed increasing trend in rainfall up to 1991 to 2000 decade and thereafter there is decrease in rainfall (Figure 5).

The eastern parts and the southern plain region of the state showed less variation in daily rain amounts which is reflected in low values of CV over these regions. This is mostly due to the orographic effect of Western Ghats. The high values of CV are recorded by the stations in the western part along the Arabian Sea coast, falling in the low rainfall region when compared to the eastern region influenced by topography. It is also seen that many number of rain-days contributed a small fraction to the season total rainfall and with less intensity and few days of heavy rain intensity contributed significant amount of rainfall.

Temporal variation of CV for each station showed very much different picture than studies made by Metri and Singh (2010) [12]. The present study shows an increase in June rainfall for the stations Pernem, Mapusa, Panaji, Ponda, Valpoi (North Goa), Margao, Sanguem and Canacona stations (South Goa) and decrease in rainfall during July month. On the contrary, Marmugao, Dabolim and Quepem stations showed increase in July rainfall during 2001- 2017. All the stations recorded maximum CV in the month of September as a result of less consistency of rainfall during this month. The increase in June rainfall and decrease in July rainfall over the North Goa is also supported by the comparative variation of CV and average rainfall during June to September between long period data for 1901-2000 and present data 2001-2017. Over all North Goa has shown increase in rainfall activity during 2001-2017 compared to 1901-2000. This is also true for South Goa except the month of June showing slight decrease in rainfall. However, average rainfall variation during the four monsoon month over the South Goa showed that there is decrease in June and July rainfall during 1901-2000 and increase during 2001-2017.

Magnitudes of highest rainfall recorded by a station are the basic tools in the estimation of Probable Maximum Precipitation (PMP) and are useful in the assessment of design flood as well. June to September monsoon months are the major contributing months to annual rainfall. Therefore, it is necessary to analyse the salient features of the rainfall in the recent past to minimize the impact of such intense precipitation event.

In the recent past exceptionally rainfall occurred over the Goa causing severe rainstorm during 23-25 Jul. 2005 over the Mandovi basin (north Goa) with Valpoi as a centre (Nandargi and Mulye, 2014) [14]. Although most of the heavy rainfall occurs during monsoon season, in October, 2009 Canacona Taluka in South Goa experienced flash flood on 2nd October. On this day about 271 mm of rain fell between approximately 9.30 am and 4.30 pm causing floods in Talpona and Galjibag Rivers. There is no historical record available to verify flooding of this magnitude in the past over the state (Report on the Canacona Flash Floods Study Committee constituted by the Government of Goa, Oct.2009). Nandargi and Mulye (2014) analysed this heavy rainstorm and found that although 1-3 Oct. 2009 was a southwest coastal storm (Centre: Canacona, South Goa), it has given widespread heavy rainfall over the entire state for all the three durations (Figure 14).

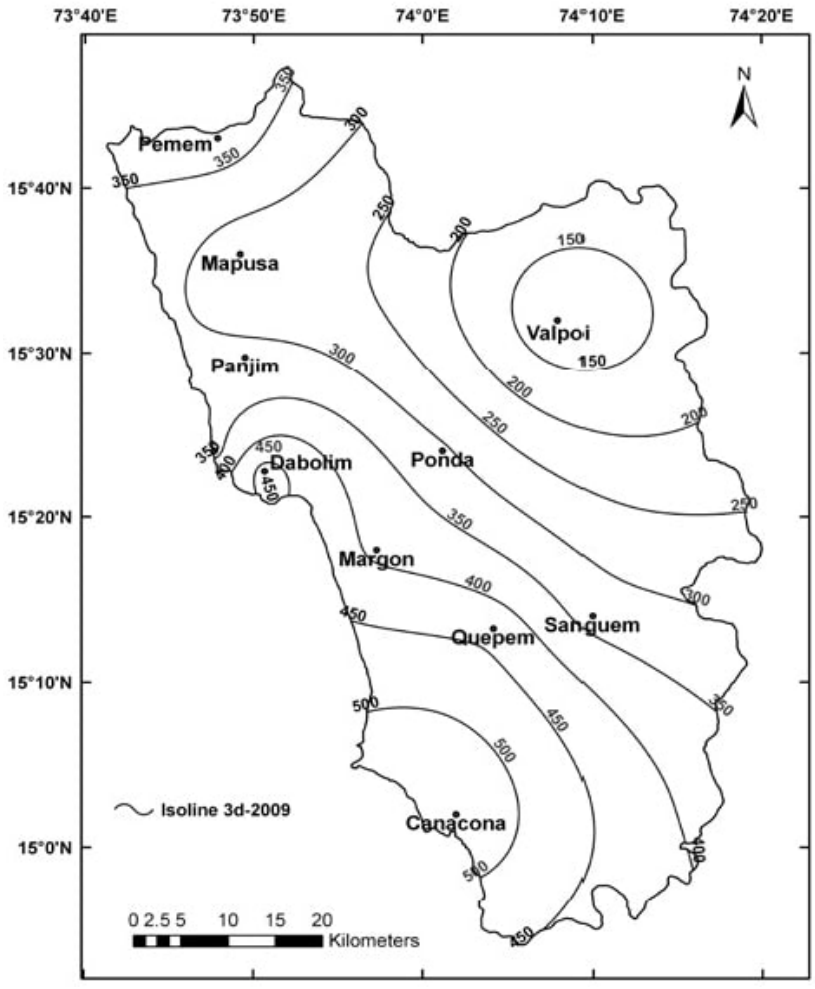


Figure 14: 3-day isohyetal pattern of 1-3 Oct. 2009 rainstorm over the Goa state

A noteworthy change in the number of rainy days is observed over the state. Of the annual rainy days only 85% to 88% rainy days receive ≥ 2.5 mm of rain during the monsoon season. The state as a whole have less rainy days in the years, 2002, 2005, 2008, 2009, 2012, 2014 and more number of rainy days in the years, 2004, 2006, 2007, 2010 and 2013. After 2014 there is erratic behavior of

rainy days from 2015 to 2017. This may be due to high rate of urbanization along the west coast. This in turn can cause water logging due to filling up of low-lying areas beyond their natural absorption capacity and hence lead to flood like situation. Therefore, it is a warning situation for proper planning for construction and developmental activities to overcome any climatic disaster.

Conclusion

The rainfall over Goa is a determining factor to meet the demands of industry, tourism, agriculture and other human activities in the state. In the present study efforts have been made to evaluate different characteristics of monsoon rainfall over the two districts of the Goa state and the state as a whole, especially variability and trend in rainfall and rainstorm analysis. The study can be helpful to planners, agriculturists, hydrologists, flood control authorities, tourists, etc in rapidly developing Goa state for better planning and to meet their requirements.

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