RAINFALL CHARACTERISTICS OF THE TAPI BASIN

A thesis submitted to

Tilak Maharashtra Vidyapeeth, Pune

For the Degree of Doctor of Philosophy (Ph.D.)

in

Geography

Board of Moral, Social and Earth Sciences Studies

By

Rajendra P. Gunjal

Under the Guidance of

Dr. Pramodkumar S. Hire

Department of Earth Sciences

January 2016

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January 2016

DECLARATION

I hereby declare that the thesis entitled "Rainfall Characteristics of the Tapi Basin" completed and written by me has not previously been formed as the basis for the award of any degree or other similar title upon me of this or any other Vidyapeeth or examining body. I understand that if my Ph.D. Thesis (or part of it) is found duplicate at any point of time my research degree will be withdrawn.

Place: Pune　　　　Rajendra P. Gunjal

Date: 26 January 2016　　　　(Research Student)

CERTIFICATE

This is to certify that the thesis entitled "Rainfall Characteristics of the Tapi Basin" which is being submitted herewith for the award of the Degree of Vidyavachaspati (Ph.D.) in Geography of Tilak Maharashtra Vidyapeeth, Pune, is the result of original research work completed by Mr. Rajendra P. Gunjal under my supervision and guidance. To the best of my Knowledge and belief the work incorporated in this thesis has not formed the basis for the award of any degree or similar title of this or any other University or examining body upon him.

Place: Pune

Date: 26 January 2016

Dr. Pramodkumar S. Hire

(Research Guide)

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Rajendra P. Gunjal

ABSTRACT

RAINFALL CHARACTERISTICS OF THE TAPI BASIN

i. Introduction to the problem

Meteorologists utilize their studies of monsoon rainfall for various social and economic as well as for purely scientific reasons (Critchfield, 1997). Various studies on Indian monsoon rainfall have been made worldwide including India to understand different facets of Indian monsoon rainfall. These studies mostly are carried out on the administrative areas such as the whole nation, state or at the district level. In comparison of the investigations of the rainfall at nation level, the similar scientific studies at small natural regions such as river basins are very limited. A small natural region, for instance a river basin can certainly reveal great variations in the distribution of rainfall on spatial and temporal scales. The basin scale rainfall studies have many important administrative, agricultural, industrial, political and environmental facets. Forming a part of the tropical monsoonal lands, the Tapi Basin situated in the central-western India displays all the significant characteristics of monsoon rainfall. The regimes of rainfall have strong influence on the natural and cultural environment of an area. Therefore, it is decided to undertake a comprehensive study of rainfall characteristics of the Tapi Basin.

ii. Introduction to the study area

The Tapi Basin is an important interstate river basin of the central India. It is situated between 20° 5′ and 22° 3′ N latitude and between 72° 38′ and 78° 17′ E longitude. The Tapi River is one of the major rivers of the peninsular India. The river rises in the eastern Satpura Range at an elevation of 730 m ASL near Multai in the Betul District of Madhya Pradesh. The river flows almost east to west and it is the second longest west flowing river of India after the Narmada River. With a total length of 724 km, the river drains a catchment of 65145 km^2 which is nearly 2% of the total geographical area of India. Flowing through Madhya Pradesh (9804 km^2), Maharashtra (51504 km^2) and Gujarat (3837 km^2), the river discharges into the Gulf of Khambhat of the Arabian Sea at Surat city in Gujarat.

iii. Main objectives of the study

Rainfall is one of the principal natural factors shaping the diversified natural systems of an area. The present study attempted to show rainfall characteristics of the Tapi Basin on the basis of the available data. Therefore, this study has four main objectives:

1. To study regime characteristics of rainfall.
2. To show the variability of rainfall on spatial scale.
3. To reveal temporal properties of rainfall.
4. To find out long-term fluctuations in the monsoonal rainfall.

iv. Research questions

The present study attempted to seek the answers to the following questions on the basis of the available data and suitable research techniques.

- What are the rainfall regime characteristics of the Tapi Basin?
- What is the normal annual pattern of the rainfall? How often excessive and deficient rainfalls occur in the basin?
- What are the spatio-temporal characteristics of the rainfall of the basin?
- Are the rainfall magnitude and its duration varying according to physiography of the basin?
- Is the pattern of the rainfall of the Tapi Basin changing?
- Are long-term changes observed in the rainfall of the Tapi Basin? If so, whether such episodic variations are associated with global synoptic conditions?

v. Hypotheses

The present study has been based on certain assumptions which have given the direction to the work. Following hypotheses are formulated for the present research work.

- The rainfall pattern of the Tapi Basin represents diverse regime characteristics.
- The rainfall pattern of the Tapi Basin is changing.

vi. Data and methodology

For any investigation of rainfall, a basic requirement is a reliable, quality-controlled, continuous data series (Kelkar, 2009). The principal objective of the present study is to understand rainfall characteristics of the Tapi Basin. Therefore, rainfall data were obtained for rain gauge stations located at taluka headquarters situated in the basin from India Meteorological Department (IMD), Pune. The Tapi Basin has 56 rain gauge stations fulfilling the aforesaid criteria. Therefore, the data of mean monthly rainfall, average annual rainfall and 24 hr highest rainfall have been procured for all the stations. The data for above-mentioned parameters have been obtained chiefly for 20th century. However, some of the stations have data more/less than a century. Almost all the stations have continuous records for over 100 years (1901-2004).

In order to achieve the objectives of the study, the following methodology has been adopted. Simple statistical parameters such as mean, standard deviation, coefficient of variation, skewness, etc. are obtained to reduce and summarize the rainfall data. The short and long-term variations in the rainfall are responsible for fluctuations in the annual rainfall series. Therefore, to ascertain short-term fluctuations and long-term trends or changes, time series analysis of the rainfall data have been undertaken. The annual variations in the rainfall have been expressed in terms of percentage departure from mean.

The Thiessen method is applied for calculating areal rainfall average of the Tapi Basin. The method for the basin under review was made possible by means of the analysis of digital data of ca. 30-m resolution of Advance Spaceborne Thermal Emission and Reflection Radiometer (ASTER). The Thiessen method is applied only for calculating areal average annual rainfall of the Tapi Basin. However, it is important to understand the areas of high and low rainfall as well as the spatial distribution of rainfall in the basin which is achieved by isohyetal method.

Since most of the heavy rainfall events in monsoonal region are associated with the passage of low pressure systems (LPS) and cyclonic storms (CS), the data regarding tracks of the cyclones were obtained from the electronic version of the Atlas of Cyclones and Depressions (2008 edition) named as the *Cyclone eAtlas* published by India Meteorological Department (IMD), Chennai.

The non-parametric Mann-Kendall test is applied to evaluate the long-term trends or changes in the annual rainfall. Student's t-test is adopted to determine the percentage change required in the mean of the future rainfall before it can be considered to be significantly different from the historical rainfall records. In order to filter short-term fluctuation and to emphasize the long-range trends in the rainfall, the normalized accumulated departure from mean (NADM) plotting as well as statistical method has been adopted.

An attempt has been made to understand natural variability in annual rainfall in the basin and its relation with El Niño and Southern Oscillation (ENSO). The method adopted by Eltahir (1996) for the Nile River has been used. In addition to this, since most of the high-magnitude rainfalls in monsoonal region are associated with the passage of low pressure systems (LPS) and cyclonic storms, the data regarding tracts of the cyclones were obtained from storm track atlas and other publications of IMD.

vii. Arrangement of the text

The present work contents five chapters. Chapter I deal with the general introduction to the research topic and the study area, that is, the Tapi Basin. An introduction to the topic, methodology adopted for analyzing rainfall data and review of previous studies in rainfall are given in this chapter. Information about physical factors of the study area such as geology, physiography, drainage and climate are also discussed in the chapter. In chapter II, an attempt has been made to show the rainfall regime characteristics of the basin. Analysis of heavy rainfall events has also been included in this chapter. Chapter III is devoted to understand variability of rainfall of the Tapi Basin. Spatio-temporal variation of rainfall in the basin is presented in this chapter. In addition, droughts and floods in basin are also reviewed. Long-term fluctuations in the rainfall over the Tapi Basin are exhibited in chapter IV. Teleconnections of rainfall over the basin are verified and also an attempt has been made to portray the future changes in the rainfall. The last chapter, that is chapter V, is the concluding section of the research work in which the major findings of the study have been summarized.

viii. Major findings of the study

The present study attempted to bring out the cohesive characteristics of rainfall of the Tapi Basin with respect to the objectives of the study. The major conclusions and contributions that have emerged from this study are as follows;

1. The average annual rainfall of the Tapi Basin is 814 mm, comprising large spatio-temporal variation. Chikhaldara is the rainiest place in the basin, receives 1596 mm average annual rainfall, which is almost double than the average annual rainfall of the Tapi Basin. Whereas, Sakri is the lowest rainfall receiving station having average annual rainfall just 511 mm. The rainfall in the Tapi Basin shows the supremacy of south-west monsoon season. The basin receives nearly 87% of its total rainfall in monsoon season (June to September) and remaining 13% in non-monsoon season (October to May). July is the rainiest month in the basin.
2. The average annual rainy days of the basin are 44 per year with high variation from one station to another. The number of rainy days at various stations of the basin varies between 30 and 70.
3. The 600.6 mm 24 hr rainfall at Amalner on July 30, 1992 is the highest one-day rainfall on record in the basin. Extreme rainfall events as well as their contribution in the seasonal rainfall (JJAS) over the Tapi Basin are increasing. Average annual rainy days are decreasing, however, average annual rainfall of the basin is neither increasing nor decreasing. The study, therefore, supports the general thought of climate change and subsequently signifies an increase in disaster potential in the basin.
4. The Tapi Basin illustrates a significant spatially diversified rainfall. Particularly, the eastern and western marginal areas of the basin show strongly non-uniform amount of rainfall than the rest of the area. The north-eastern part covered by the rugged relief of the Gawilgad Range and the extreme western area of the basin receives reasonably high rainfall. The widespread area in the central and south-eastern part of the basin, formed by the river plains receives rainfall close to the basin's average rainfall and a small pocket in the south-west of the basin, obtains low rainfall. In general, the spatial pattern of rainfall in the Tapi Basin exhibits a decreasing pattern from east to west

with abrupt rise in rainfall to the western edge of the basin.

5. The spatial distribution of rainfall in the basin is orographically controlled. The Western Ghats and its offshoots and the Gawilgad Range play a key role in rainfall diversity in the basin.
6. The rainfall over the Tapi Basin demonstrates alternating sequences of multi-decadal periods having excess and deficient rainfall. This epochal behaviour of rainfall of the basin can be summarized in three periods: (i) 1901-1930: dry epoch (ii) 1931-1960: wet epoch and (iii) 1961-1990: dry epoch. The epochal pattern of the rainfall of the Tapi Basin is quite similar to that found over the country. The Tapi Basin neither experienced any widespread severe drought nor a severe flood over the period of a century.
7. A composite picture of the long-term fluctuations of the rainfall on the basin scale point towards some significant characteristics of the rainfall.

   a. The early period of the 20th century i.e. 1901 to 1930 is associated with the below-average (low) rainfall.

   b. Above-average (high) rainfall period is observed between 1930 and 1960.

   c. (iii) Below-average (low) rainfall period is observed in the latter half of the 20th century i.e. after 1960.
8. The deviation in the amount of the rainfall clearly indicates that the major changes in the basin rainfall occurred around 1930, 1960, and 1990.
9. The monsoon rainfall in the Tapi Basin is teleconnected with some global parameters. One of the important parameters is El Niño and Southern Oscillation (ENSO). The probability of having high rainfall in the basin is more (44%) during cold ENSO conditions and very less (11%) during warm ENSO conditions and vice versa. It, therefore, indicates that during the cold ENSO (warm ENSO) events the magnitude of rainfall will be higher (lower).
10. It is observed that on the basin scale 16% change in the annual rainfall is required in the average rainfall of next 10 years to consider it different than the available rainfall record. Similarly, to determine the significant change in the rainfall of the next 20 and 50 years, the average rainfall should vary by 11 and 8% respectively than the present mean of the rainfall. Whereas, to declare the average rainfall of the present century

(21st century) significantly different than the previous century (20th century), 7% change is required in the long-term mean of the rainfall of the basin.

11. The application of various techniques to the rainfall data of the basin indicates that the monsoonal rainfall of the Tapi Basin is highly regular and consistent. Therefore, it is likely to be the same in this as well as in the next century.

The inferences regarding the rainfall characteristics arrived in the present study have been discussed for a river basin. However, as the topography, climate and geographical location within the monsoonal region are diverse; the inferences cannot be applied directly to all other natural regions within the monsoonal region. Nevertheless, such studies are beginning to provide a database and discuss the importance of rainfall studies in monsoonal environments. Hence, concluding the discussion it can be stated that in spite of few limitations, the present study attempted to bring out the cohesive characteristics of rainfall of the Tapi Basin with respect to the objectives of the study. This work therefore, certainly opens an avenue to the further research in the rainfall on regional scale.

CONTENTS

	Topic		Page No.
Chapter I	INTRODUCTION		1-31
	1.1	Introduction to the topic	1
	1.2	Main objectives of the study	3
	1.3	Research questions	3
	1.4	Hypothesis	4
	1.5	Introduction to the study area	4
	1.6	Geology	6
	1.7	Physiography	8
	1.8	Drainage	10
	1.9	Climate	12
	1.10	Data and methodology	13
	1.11	Review of Literature	18
	1.12	Arrangement of the text	30
Chapter II	REGIME CHARACTERISTICS OF RAINFALL		32-68
	2.1	Introduction	32
	2.2	Annual pattern of rainfall	32
	2.3	Monthly pattern of rainfall	38
	2.4	Rainy days	44
	2.5	Monthly distribution of rainy days	48
	2.6	Excessive rains	50
	2.7	Extreme rainfall events and climate change	54
	2.8	Trends in extreme rainfall events	57
	2.9	Contribution of extreme rainfall events in seasonal rainfall	60
	2.10	Extreme rainfall events, annual rainy days and annual rainfall of the Tapi Basin	63
	2.11	Recurrence interval of highest 24 hr rainfall	65

	2.12	Resume	67
Chapter III	SPATIO-TEMPORAL ASPECTS OF RAINFALL		69-109
	3.1	Introduction	69
	3.2	Spatial distribution of rainfall	70
	3.3	Influence of orography on the spatial variability of rainfall	76
	3.4	Temporal variability of rainfall	80
	3.5	Inter-annual variability of rainfall	83
	3.6	Variability of seasonal rainfall in climate change period	89
	3.7	Variability of monthly rainfall in the monsoon season	91
	3.8	Epochal behavior of rainfall	94
	3.9	Floods and droughts	95
	3.10	Rainfall-generating low pressure systems (LPS)	101
	3.11	Resume	107
Chapter IV	LONG-PERIOD FLUCTUATIONS IN THE MONSOON RAINFALL		110-126
	4.1	Introduction	110
	4.2	Detection of changes in the annual rainfall	111
	4.3	Testing the significance of Tau (τ)	113
	4.4	Normalized accumulated departure from mean (NADM) method	116
	4.5	Teleconnections of the rainfall with ENSO	120
	4.6	Detection of future changes in the rainfall	123
	4.7	Resume	125
Chapter V	OVERVIEW AND CONCLUSIONS		127-139
	5.1	Introduction	127
	5.2	Regime Characteristics of rainfall	128
	5.3	Spatio-temporal aspects of rainfall	130
	5.4	Long-term fluctuations in the monsoon rainfall	133
	5.5	Limitations of the study	135

5.6 Major findings of the study 136

References 140-154

LIST OF TABLES

Table No.	Title of the Table	Page No.
Chapter I		
1.1	Record lengths of the data	15
Chapter II		
2.1	Average annual rainfall of the Tapi Basin (1901-2004)	34
2.2	Average annual rainfall at different stations of the Tapi Basin	36
2.3	Monthly distribution of rainfall (mm) at different stations of the Tapi Basin	39
2.4	Distribution of rainfall in monsoon and non-monsoon season	43
2.5	Average annual rainfall and rainy days of different stations in the Tapi Basin	45
2.6	Average monthly rainy days in the Tapi Basin	48
2.7	Highest 24 hr rainfall in the Tapi Basin	52
2.8	Classification of rainfall events based on 1 day (24 hr) rainfall amount at a station	57
2.9	Average frequency of extreme rainfall events during monsoon season	58
2.10	Mean percentage of rainfall from extreme rainfall events in monsoon season	61
Chapter III		
3.1	Annual rainfall characteristics of the Tapi Basin (1901-2004)	82
3.2	Average annual rainfall (AAR) of the Tapi Basin	86
3.3	Mean monthly rainfall (mm) of the monsoon season	92
3.4	Tapi basin: flood (wet) years	96
3.5	Tapi basin: drought (dry) years	97
3.6	Tapi basin: normal rainfall years	98
3.7	Moderate drought years	100
3.8	Moderate flood years	100

Chapter IV

4.1	Scores for calculating Mann-Kendall's τ for the Tapi Basin (An illustration)	112
4.2	Nature of changes/trends in annual rainfall records based on Mann-Kendall test	115
4.3	Conditional probabilities of the monsoon rainfall over the Tapi Basin given the SST index of ENSO	122
4.4	Percent change required to identify statically significant change in AAR of the Tapi Basin	124

LIST OF ILLUSTRATIONS

Figure No.	Title of the Figure	Page No.
Chapter I		
1.1	Tapi Basin: Physiography	5
1.2	Tapi Basin: Geology	7
1.3	Tapi Basin: Drainage	11
1.4	Tapi Basin: Raingauge Stations	14
Chapter II		
2.1	Average annual rainfall of the Tapi Basin (1901-2004)	35
2.2	Average annual rainfall at different stations in the Tapi Basin	37
2.3	Distribution of monthly rainfall: Tapi Basin	40
2.4	Monthly rainfall pattern at representative stations	41
2.5	Average annual rainy days of different stations of the Tapi Basin	46
2.6	Average monthly rainy days of the Tapi Basin	49
2.7	Annual frequency of extreme rainfall events in the Tapi Basin	57
2.8	Frequency of extreme rainfall events on monthly scale in monsoon season	59
2.9	Average frequency of extreme rainfall events in monsoon season (June to September)	60
2.10	Average contribution (%) of extreme rainfall events to the total rainfall on monthly scale in monsoon season	61
2.11	Average contribution (%) of extreme rainfall events to the total rainfall of monsoon season	63
2.12	Average annual rainfall of the Tapi Basin	64
2.13	Average annual rainy days of the Tapi Basin	64
2.14	Recurrence interval of highest 24 hr rainfall over the Tapi Basin	66

Chapter III

3.1	Tapi Basin: Thiessen method	72
3.2	Tapi Basin: Isohyets	73
3.3	Tapi Basin: Physiography	78
3.4	Variation of average annual rainfall: Tapi Basin (1901-2004)	87
3.5	Departure from average annual rainfall of the Tapi Basin	87
3.6	Departure from average annual rainfall	88
3.7	Seasonal rainfall trend over the Tapi Basin	91
3.8	Trends of monthly rainfall of the monsoon season	93
3.9	Epochal pattern of rainfall of the Tapi Basin	95
3.10	Distribution of wet (flood) and dry (drought) years	99
3.11	Tracks of low pressure systems associated with heavy rainfall in the Tapi Basin	102-105

Chapter IV

4.1	Normalized Accumulated Departure from Mean (NADM) Graphs	118
4.2	Normalized Accumulated Departure from Mean (NADM) Graph of the Tapi Basin	119
4.3	Categories of annual rainfall and ENSO index of the Tapi Basin	122

CHAPTER I

INTRODUCTION

1.1 Introduction to the topic

Rainfall is considered to be an important hydrological phenomenon. It is a climate parameter that shapes the way in which manner man lives, every aspect of the ecological system, flora and fauna (Obot et al. 2010). Regime, amount and variability of rainfall are dominant natural factors that affect basically the life and economy of the people (Gadgil, 2002). Therefore, rainfall has always attracted the greatest attention of natural philosophers and meteorologists as it is one of the most important and conspicuous of all atmospheric processes and it has direct relevance to the very survival of all sorts of life (Pant and Rupa Kumar, 1997).

In a variety of climatic patterns of the world, 'monsoon' is very peculiar. Monsoons are observed in Asia, Africa, Australia and America. However, Indian southwest monsoon stands out amongst all of them. It is an important component of the earth's total climate system and has connections with the global atmospheric circulation (Kelkar, 2009). The monsoon rainfall is not uniform in time as well as its amount and its distribution is grossly uneven. The variability in monsoon rainfall is strongly linked with the society and economy of monsoon countries (Sajani et al., 2007). It is so uneven that the country has some of the wettest places as well as the driest places on earth (Kelkar, 2009). Singh et al. (2006) noticed that among all different rain bearing systems of the world, the summer monsoon of India is an exclusive weather system. It is one of the most remarkable as well as most inexplicable features of the planetary atmospheric circulation (Kale et al., 1994). Pant and Rupa Kumar (1997) noted that the rainfall of India possesses some special characteristics. The rainfall over the region is highly seasonal and is mainly concentrated in just four months of the summer monsoon season (June to September) and rest of the year is generally dry. The monsoon season accounts about 90% of the annual rainfall of the country (Agashe and Padgalwar, 2005). The north-east monsoon season (October to December) is equally important rainy season particularly for the south-eastern part of the country (Khole and De, 2003). Being an agricultural country, the monsoon plays an important role in agricultural production and development of India. Srivastav et al. (2007) stated that in spite of growing industrialization, the economy of the country still depends upon rain-fed agricultural production. Further, they added that south-west monsoon rainfall affects hydroelectric power generation and drinking water resources and thus directly influences the quality of life. In view of Kelkar (2009), the Indian monsoon is indeed '*the* monsoon'.

The features of monsoon rainfall such as its variability of onset, withdrawal and duration indeed help the agriculturists, planners, various users and also facilitate weather forecasters of the country (Ali et al., 2005). A frequent spell of drought or torrential rainfall is another common feature of monsoon. Droughts and floods are two extreme conditions of rainfall which caused mainly because of erratic nature of monsoon system. Drought conditions are formed due to weak rainfall where as excess rainfall results into flood conditions (Kalwar et al., 2005). Gregory (1991) noticed that the failure of the summer monsoon rainfall in India leads to severe problems for the society. However, due to its vagaries, monsoon rainfall also causes frequent floods in most of the Indian rivers. Every year some parts of the country face the threat of heavy loss of life and property due to monsoon floods. In recent years climate change emerges an important environmental issue. Rainfall is one of the climatic factors that can indicate climate change (Obot et al., 2010). It is the most sensitive component of the climate and therefore it is widely studied in the view of climate change.

Meteorologists utilize their studies of monsoon rainfall for various social and economic as well as for purely scientific reasons (Critchfield, 1997). Various studies on Indian monsoon rainfall have been made worldwide including India to understand different facets of Indian monsoon rainfall. These studies mostly are carried out on the administrative areas such as the whole nation, state or at the district level. In comparison of the investigations of the rainfall at nation level, the similar scientific studies at natural regions such as river basins are very limited. A natural region, for instance a river basin can certainly reveal great variations in the distribution of rainfall on spatial and temporal scales. In addition to this, the large variations in the total rainfall from one year to another may also be observed at a basin level. Therefore, the study of rainfall on basin scale is indeed more practical for water resource management within the basin. It also has many important administrative, agricultural, industrial, political and environmental facets. Kamaraju and Subrahmanyam (1984) stated that a detailed knowledge of the seasonal and annual distribution of precipitation over the basin is highly essential for any analytical work on water balance. Further they added that the rational assessment of the water potentialities of a river basin is an essential pre-requisite for the optimum utilization of the water resources for agricultural as well as hydrological purposes. In view of Prasad and Prasad (1993), the nature and distribution of rainfall in a catchment will determine its groundwater potential, the extent of its water wealth for economic exploitation and the nature and extent of flooding in the catchment. Kulkarni and Munot (2002) also opined that the study of inter-annual variations of rainfall on basin scales rather than regional scales is important from the hydrological point of view.

Thus, the rainfall studies at river basin level are quite useful to know the distribution and variability of the rainfall and also to realize trends or changes in the rainfall over the basin. Forming a part of the tropical monsoonal lands, the Tapi Basin situated in the central-western India displays all the significant characteristics of monsoon rainfall. The regimes of rainfall have strong influence on the natural and cultural environment of an area. Therefore, it is decided to undertake a comprehensive study of the rainfall characteristics of the Tapi Basin.

1.2 Main objectives of the study

Rainfall is one of the principal natural factors shaping the diversified natural systems of an area. The present study attempted to show rainfall characteristics of the Tapi Basin on the basis of the available data. Therefore, this study has four main objectives;

1. To study regime characteristics of rainfall.
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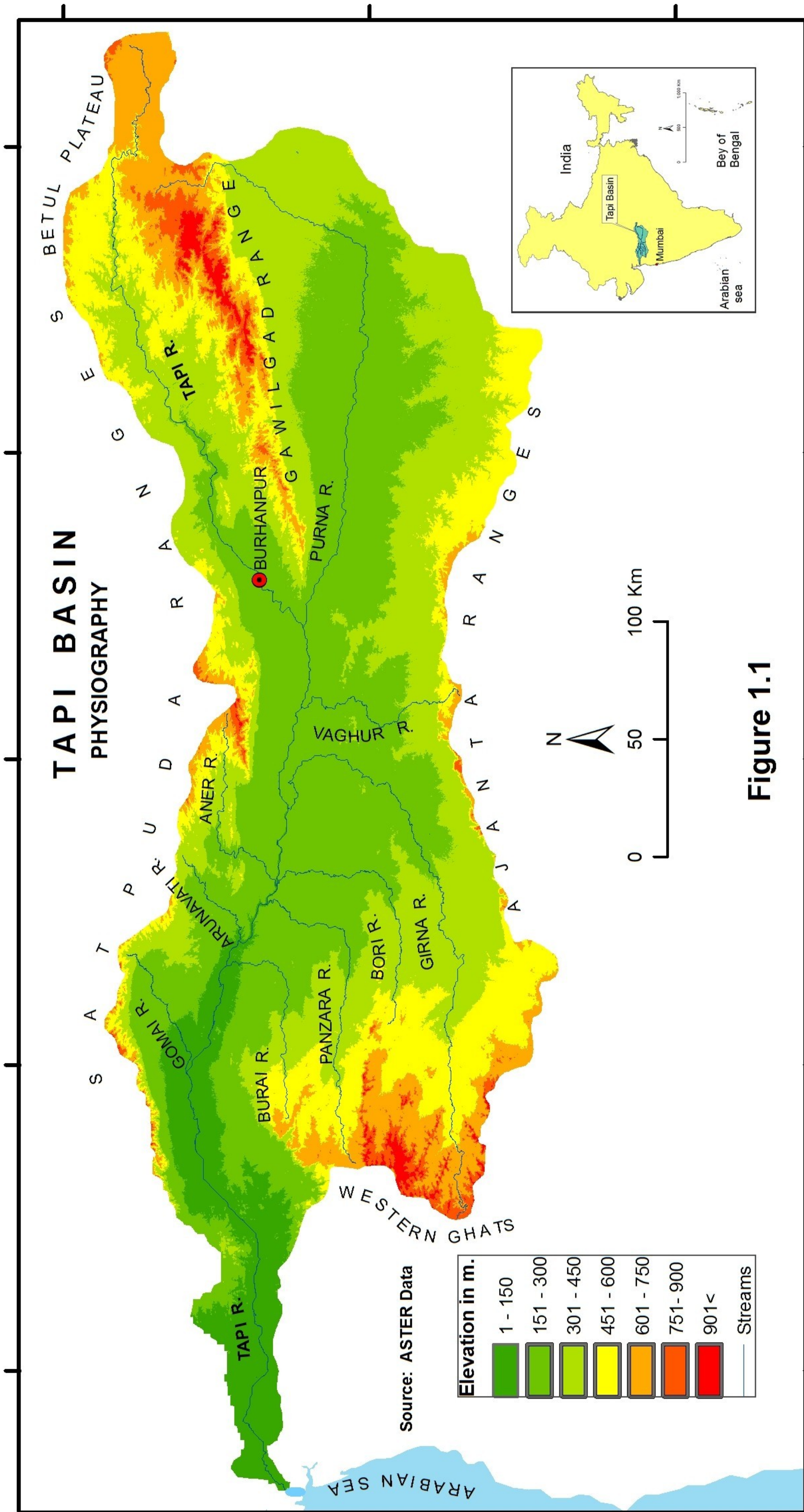
1.4 Hypotheses

The present study has been based on certain assumptions which have given the direction to the work. Following hypotheses are formulated for the present research work.

- The rainfall pattern of the Tapi Basin represents diverse regime characteristics.
- The rainfall pattern of the Tapi Basin is changing.

1.5 Introduction to the study area

The Tapi Basin is an important interstate river basin of the central India. It is situated between 20° 5′ and 22° 3′ N latitude and between 72° 38′ and 78° 17′ E longitude (Figure 1.1). The Tapi River is one of the major rivers of the peninsular India. The river rises in the eastern Satpura Range at an elevation of 730 m ASL near Multai in the Betul District of Madhya Pradesh. The river flows almost east to west and it is the second longest west flowing river of India after the Narmada River. With a total length of 724 km, the river drains a catchment of 65145 km^2 which is nearly 2% of the total geographical area of India. Flowing through Madhya Pradesh (9804 km^2), Maharashtra (51504 km^2) and Gujarat (3837 km^2), the river discharges into the Gulf of Khambhat of the Arabian Sea near Surat city in Gujarat.



TAPI BASIN
PHYSIOGRAPHY
SATPUDA RANGES
BETUL PLATEAU
GAWILGAD RANGE
AJANTA RANGES
WESTERN GHATS
ARABIAN SEA
TAPI R.
PURNA R.
VAGHUR R.
ANER R.
ARUNAVATI R.
GOMAI R.
BURAI R.
PANZARA R.
BORI R.
GIRNA R.
BURHANPUR
Source: ASTER Data
Elevation in m.
1 - 150
151 - 300
301 - 450
451 - 600
601 - 750
751- 900
901<
Streams
0
50
100 Km
N
India
Tapi Basin
Mumbai
Arabian sea
Bey of Bengal
22°0'N
20°50'N
19°40'N
73°10'E
74°20'E
75°30'E
76°40'E
77°50'E

Figure 1.1

The Tapi Basin is bordered roughly by, east-west trending Satpura Ranges to the north and by Ajanta Ranges/Hills to the south. The basin is elongated in shape having greater east-west extent than north-south. Bordered by the hill ranges from three sides, the river, along with its tributaries, flows more or less over the plains of Vidharbha, Khandesh and Gujarat (Figure 1.1). The important tributaries of the Tapi River are Purna, Girna, Panzara, Waghur, Bori and Aner.

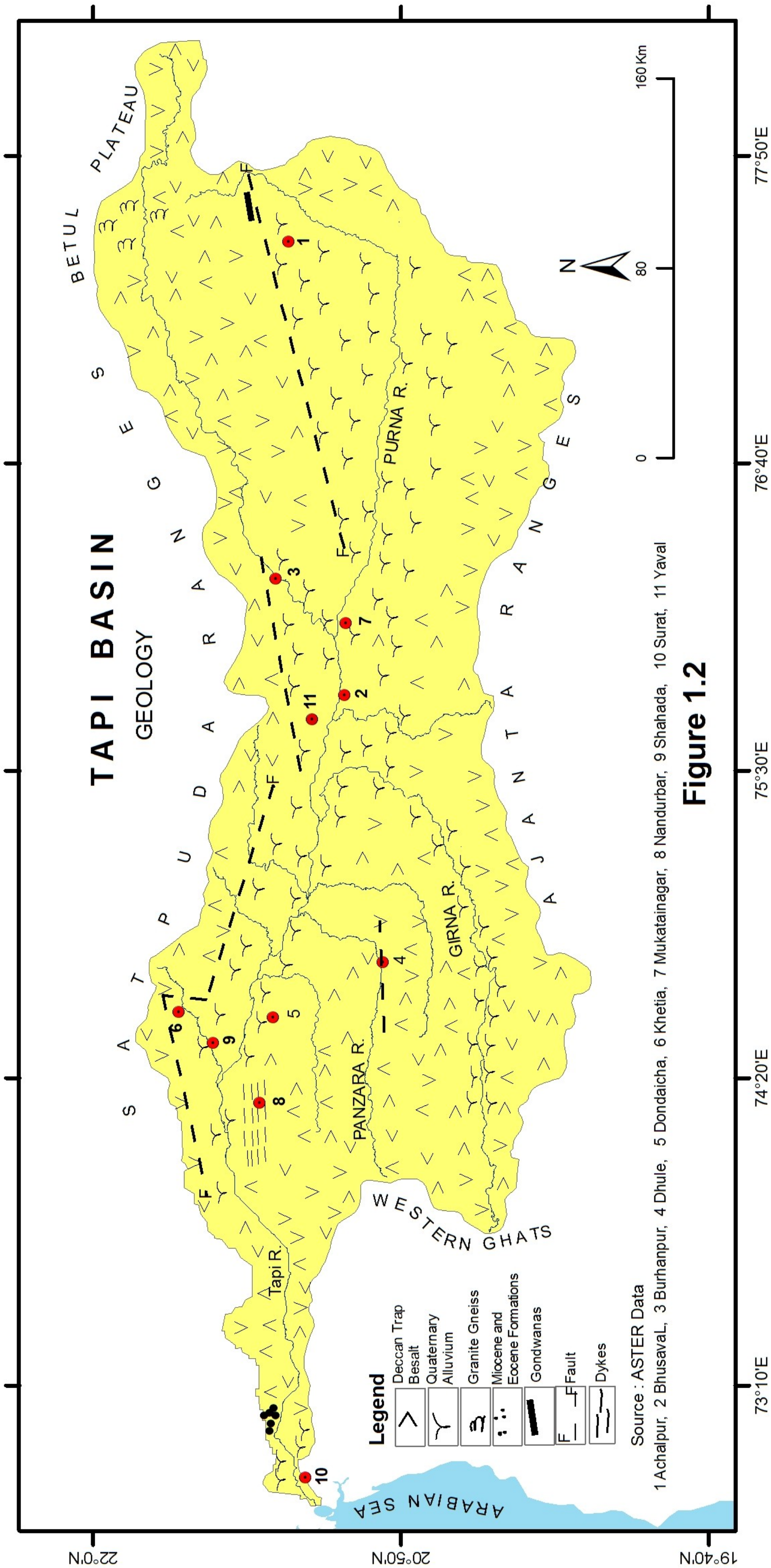
The Tapi Basin is located in an environment typical of the monsoonal tropics, with periodic high-magnitude rainfall. About 85% of the annual rainfall is received during the monsoon season (June to September). The average annual rainfall of the basin is 814 mm. The basin is located within the zone of severe rainstorms. Hence, the occasional heavy rains result from incursion of cyclonic storms and depressions originating over the Bay of Bengal or land.

The basin is predominantly underlain by Cretaceous-Eocene Deccan Trap basalts and late Quaternary alluvium. A major part of the middle and lower Tapi Basin is covered with thick alluvium of late Quaternary period.

1.6 Geology

Physiography of an area or a basin is controlled by geology of that region. Physiography, in turn, plays significant role in the amount and distribution of rainfall of the region. Therefore, it is necessary to have some idea about the geology of the Tapi Basin.

Most of the area of the Tapi Basin is underlain by late Quaternary alluvium and Cretaceous-Eocene Deccan Trap basalt (Figure 1.2). The basin is also characterized by minor inliers of granite gneisses, sandstones, Gondwanas, etc. at few locations. The thickness of the of the Deccan Trap basalt is about 1450 m in the Western Ghats and in the Satpura Ranges and it becomes thinner towards eastern margin of the basin (Jain et al., 1995). The middle and lower Tapi Basin and almost entire Purna Basin is covered by thick alluvium of the late Quaternary period. The alluvial sediments of the Tapi Basin cover about 6250 km^2 area. The depth of the alluvium ranges between 65 and 205 m till the Tertiary sequence is encountered (Jain et al., 1995).



TAPI BASIN
GEOLOGY
SATPUDA RANGES
BETUL PLATEAU
AJANTA RANGES
WESTERN GHATS
ARABIAN SEA
Tapi R.
PURNA R.
PANZARA R.
GIRNA R.
Legend
Deccan Trap Besalt
Quaternary Alluvium
Granite Gneiss
Miocene and Eocene Formations
Gondwanas
Fault
Dykes
Source : ASTER Data
1 Achalpur, 2 Bhusaval, 3 Burhanpur, 4 Dhule, 5 Dondaicha, 6 Khetia, 7 Mukatainagar, 8 Nandurbar, 9 Shahada, 10 Surat, 11 Yaval
0
80
160 Km
N
73°10'E
74°20'E
75°30'E
76°40'E
77°50'E
22°0'N
20°50'N
19°40'N

Figure 1.2

The elongated Tapi Basin forms a part of the Son-Narmada-Tapi (SONATA) lineament zone which is a megatectonic feature of India (Ravi Shankar, 1991). The Tapi Basin has several active and inactive faults. However, two major faults have been located in the northern basin. One of the major faults, namely the North Tapi Fault, extends from north of Shahada to north of Burhanpur. It runs in east-west direction and forms the southern boundary of the Satpura Ranges and the northern boundary of Tapi River alluvium (Figure 1.2). Another important fault begins from north of Muktainagar (formerly Edlabad) in the Purna Valley. It forms the boundary between Quaternary alluvium of the Purna River and Gawilgad Range (Figure 1.2). This fault is, therefore, recognized as Gawilgad Fault (Jain et al., 1995). Moreover, numerous dikes and lineaments are also present in the basin, especially in the Dhule-Dondaicha-Nandurbar area and Gawilgad Range area.

1.7 Physiography

The Tapi River rises near Multai in the Betul District of Madhya Pradesh at an elevation of 730 m ASL (Figure 1.1). The river flows for a total length of 724 km and drains into the Arabian Sea with a catchment area of 65145 km^2. It flows through three states viz. Maharashtra (79.1 %), Madhya Pradesh (15.0 %) and Gujarat (5.9 %).

The headwaters of the Tapi River and its major southern tributary, the Purna River, are situated on the Betul Plateau that ranges in altitude between 600 and 750 m ASL (Figure 1.1). The elevation of some of the area of the Betul Plateau is more than 750 m ASL and its peaks reaching up to 900 m ASL.

The basin is bordered by Western Ghats to the west, Satpura Ranges to the north, Ajanta Ranges to the south and Betul Plateau to the east. The Gawilgad Range that lies between the Tapi River to the north and Purna River to the south is connected to the Betul Plateau to the east. Besides this, most of the area of the basin is in the form of flat region of the Tapi River and its tributaries. Therefore, the Tapi Basin can be categorized into six physiographic divisions in a following manner.

1. The Western Ghats
2. The Satpura Ranges
3. The Ajanta Ranges

4. The Betul Plateau
5. The Gawilgad Range
6. Plains of the Tapi River and its tributaries

The Western Ghats: It generally is trending from north to south, ranges in elevation from 600 to 900 m ASL with some lofty peaks. The highest peak of the Tapi Basin, namely the Salher Fort, is located in the Western Ghats with an elevation of 1567 m ASL. The offshoots of the Western Ghats are running almost in east-west directions. One of the major offshoots of the Western Ghats is Satmala Range, which forms the Southern boundary of the basin up to the Manmad Gap. The area to the east of Western Ghats, locally known as *Malmatha,* ranges in elevation from 300 to 600 m ASL. Some of the major southern tributaries of the Tapi River namely Burai, Panzara, Bori and Girna have their upper basins in this area.

The Satpura Ranges: The basin is bordered by, roughly east-west trending, Satpura Ranges to the north. The elevations of the ranges lie between 450 and 900 m ASL. The Toranmal Plateau is the highest area in this region with maximum elevation of 1150 m ASL. The range is separated by Burhanpur Gap, which is one of the major gaps of the Tapi Basin. The Betul Plateau and Gawilgad Ranges, which are the parts of the Satpura Ranges as well as major physiographic divisions of the Tapi Basin, will be discussed in the following sections.

The Ajanta Ranges: These ranges form southern boundary of the Tapi Basin which starts from the east of Manmad Gap. Resembling Satpura Ranges, the elevations of the ranges lie between 450 and 900 m ASL.

The Betul Plateau: The Betul Plateau lies to the farthest east of the Tapi Basin ranges in elevation from 600 to 900 m ASL. The Tapi River rises on the Betul Plateau at an elevation of 730 m ASL near Multai. In the source region, the river flows over Betul Plateau surface for about 35 km and enters into the deeply incised gorge.

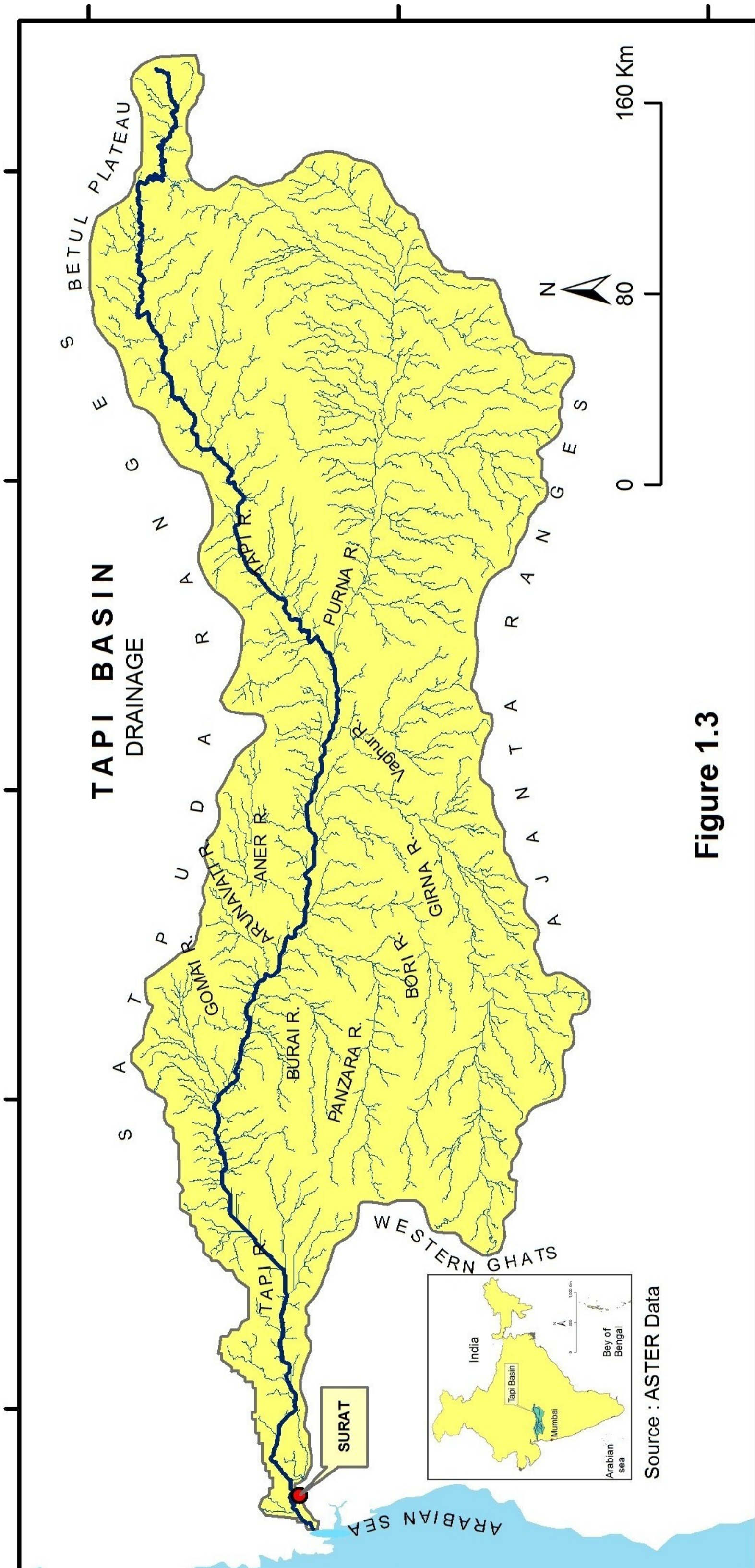
The Gawilgad Range: The range is located in the eastern part of the Tapi Basin and starts from the east of the Tapi-Purna confluence and merges into the Betul Plateau separating the Tapi River to the north and Purna River to the South. It is one of the major faults of the basin. The ranges lies in elevation from 600 to >900 m ASL. Gawilgad fort is the highest point in the ranges at an elevation of 1103 m ASL. The second highest point in the range is Chikhaldara with an elevation of 1088 m ASL. The Dabka Gap is the major gap of the range.

The plains of the Tapi River and its tributaries: Most of the area of the Tapi River and its tributaries is in the form of the plains upto an elevation of 300 m ASL. It is mainly covered by the alluviums of the late Quaternary period. The elevation of the plain in the lower reaches of the Tapi River is <150 m ASL.

1.8 Drainage

The Tapi Basin is elongated in shape with considerable east-west length than its north-south width. Furthermore, the basin is bordered by ranges from north (the Satpura) and south (the Western Ghats and the Ajanta Range) (Figure 1.3). The drainage pattern of the Tapi Basin formed by the streams and tributaries entered mainly from north and south (Figure 1.3). Many tributaries join the Tapi River on both the banks. However, the drainage system on the left bank is widespread as compared to the right bank of the river. Out of 14 important tributaries, having more than 50 km length, 10 meet to the left bank of the Tapi River while only 4 join to the right bank. Moreover, the southern tributaries are more in lengths and have greater catchment areas and vice versa.

Amongst all the tributaries of the River Tapi, the Purna is the longest tributary with 274 km length and 18929 km^2 catchment area. It originates on the Betul Plateau about 900 m ASL, very close to the source of River Tapi, and flows roughly in the north-south direction upto Murtijapur. It turns westwards near Murtijapur and flows for substantial distance to meet the Tapi River from south. The Girna, which heads in the Western Ghats about 900 m ASL, is another chief southern tributary of the Tapi River. It flow almost from west to east direction in the upper course, then smoothly turns northwards in the middle and lower course to join the Tapi River. With the total length of 260 km and the catchment area of 10061 km^2, the Girna River becomes second largest tributary of the Tapi after the Purna. These two rivers collectively cover about 45% of the total area of the Tapi Basin. The Burai, the Panzara and the Bori are other main southern tributaries of the Tapi River, have their headwaters in the Western Ghats at an elevation of 600 m ASL.



TAPI BASIN
DRAINAGE
S A T P U R D A R A N G E S
BETUL PLATEAU
A J A N T A R A N G E S
WESTERN GHATS
ARABIAN SEA
SURAT
TAPI R.
GOMAI R.
ARUNAVATI R.
ANER R.
BURAI R.
PANZARA R.
BORI R.
GIRNA R.
Vaghur R.
PURNA R.
N
0
80
160 Km
22°0'N
20°50'N
19°40'N
73°10'E
74°20'E
75°30'E
76°40'E
77°50'E
India
Tapi Basin
Mumbai
Arabian sea
Bey of Bengal
Source : ASTER Data

Figure 1.3

They reveal an uncommon stream courses. From the source, all these three rivers run almost parallel to each other in the west-east direction and suddenly, turn northwards with nearly right angle bends in their courses to meet the River Tapi. The Vaghur, the only main tributary of the Tapi River, rises in the Ajanta Range. It flows for 96 km from south to north direction and enters into the Tapi River, almost in the central part of the basin.

The Aner, the Arunavati and the Gomai are important northern tributaries of the River Tapi. These rivers have their sources in the Satpura Ranges at 450-600 m elevation ASL. The Satpura Ranges are closer (25 to 50 km) to the Tapi River, therefore, these tributaries have shorter lengths (about 50-90 km) and smaller catchments (1000-1700 km^2).

The Tapi Basin is monsoon dominated and therefore seasonal. Occasional heavy rainfall in the source regions cause floods on some of the rivers. The Tapi River and its several tributaries have been dammed for drinking and irrigation purposes.

1.9 Climate

Forming a part of the tropical monsoonal lands, the Tapi Basin is characterized by typical monsoon climate with hot summers, mild winters and seasonal rainfall. The basin displays significant regional variations in thermal conditions as well as in amount and distribution of the rainfall.

Temperature conditions: In summers, the temperature in the Tapi basin ranges from 38°C to 42°C whereas it varies from 5°C to 14°C in winters. April and May are hottest months in the basin while December and January are the coldest. The extremes of heat and cold are greater over the central part of the basin occupied by the river plains than the mountainous and coastal areas. A large area of the basin is situated at a considerable distance from the coast in consequence of it, the range of temperature, both-diurnal as well as annual, is high for most period of the year.

Rainfall conditions: Owing to its tropical location in the central India, the rainfall over the Tapi Basin is essentially seasonal. Throughout the basin, rainfall is confined to a short period- the south-west monsoon season (June to September) and the rest period of the year is generally dry. The average annual rainfall of the basin is 814 mm.

The monsoon season gives about 85% of the annual rainfall. Besides, few isolated spells occur usually in October provides occasional rain.

The average number of rainy days of the basin is 44, varying from 30 to 70. July is the rainiest month, with the largest number (12) of rainy days. The rainfall is influenced by the relief and shows noteworthy changes in the amount, in different parts of the basin. The zone of the heaviest rainfall coincides with a hilly zone of the Gawilgad Range to the east of the basin. This area receives highest annual rainfall in the basin, about 1100 to 1500 mm. The narrow western area adjacent to the mouth of the Tapi River also gains equally high annual rainfall ranging between 1100-1400 mm. The eastern and central plains are characterized by moderate rainfall about 600-800 mm per year. Whereas, to the south-west of the basin, adjoining to the Western Ghats a pocket of low rainfall below 600 mm is observed.

1.10 Data and methodology

For any investigation of the monsoon rainfall over India, a basic requirement is a reliable, quality-controlled, continuous data series (Kelkar, 2009). The principal objective of the present study is to understand rainfall characteristics of the Tapi Basin. Therefore, rainfall data were obtained for rain gauge stations located at taluka headquarters situated in the basin from India Meteorological Department (IMD), Pune. The Tapi Basin has 56 rain gauge stations (Figure 1.4) fulfilling the aforesaid criteria. Therefore, the data of mean monthly rainfall, average annual rainfall and 24 hr highest rainfall have been procured for all the stations. The data for above-mentioned parameters have been obtained chiefly for the 20th century. However, some of the stations have data more/less than a century. The name of the stations and record length of the data used in the present work has been given in Table 1.1. Almost all the stations have continuous records for over 100 years (1901-2004). However, the data for Dhamangaon, Patur, Pimpalner, and Sirpur are limited for 60 to 70 years. To understand the association of the heavy rainfall events produced due to low pressure systems (LPS) and cyclonic storms (CS), the data regarding tracks of the cyclones were obtained from the electronic version of the Atlas of Cyclones and Depressions (2008 edition) named as the *Cyclone eAtlas* published by India Meteorological Department (IMD), Chennai.

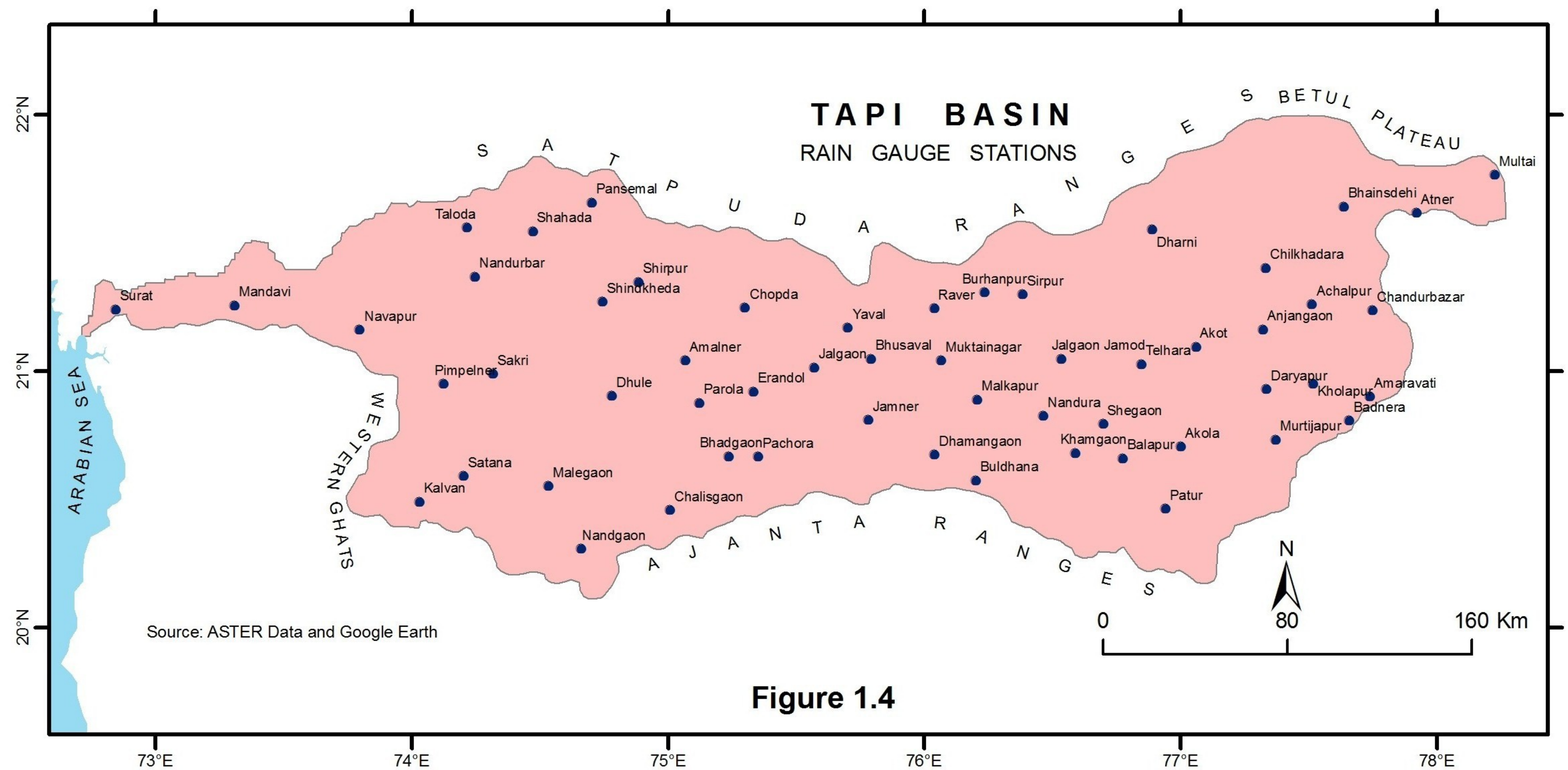

TAPI BASIN
RAIN GAUGE STATIONS
SATPUDA RANGES
BETUL PLATEAU
AJANTA RANGES
WESTERN GHATS
ARABIAN SEA
Surat
Mandavi
Navapur
Taloda
Shahada
Pansemal
Nandurbar
Shirpur
Shindkheda
Pimpelner
Sakri
Kalvan
Satana
Malegaon
Nandgaon
Dhule
Amalner
Chopda
Parola
Erandol
Jalgaon
Yaval
Bhusaval
BhadgaonPachora
Chalisgaon
Jamner
Raver
BurhanpurSirpur
Muktainagar
Malkapur
Dhamangaon
Buldhana
Jalgaon Jamod
Telhara
Akot
Nandura
Shegaon
Khamgaon
Balapur
Akola
Patur
Dharni
Chilkhadara
Achalpur
Anjangaon
Chandurbazar
Daryapur
Kholapur
Amaravati
Badnera
Murtijapur
Bhainsdehi
Atner
Multai
Source: ASTER Data and Google Earth
N
0
80
160 Km
22°N
21°N
20°N
73°E
74°E
75°E
76°E
77°E
78°E

Figure 1.4

Table 1.1 Record lengths of the data

S.N.	Station	Record Length	No. of Years	S.N.	Station	Record Length	No. of Years
1	Achalapur	1901-2004	104	29	Kholapur	1901-1990	90
2	Akola	1901-2006	106	30	Malegaon	1879-2004	126
3	Akot	1901-2004	104	31	Malkapur	1901-2004	104
4	Amalner	1901-2004	104	32	Mandavi	1901-2003	103
5	Amaravati	1901-2006	106	33	Muktainagar	1901-2004	104
6	Anjangaon	1901-2004	104	34	Multai	1867-2004	138
7	Atner	1906-2004	99	35	Murtijapur	1901-2004	104
8	Badnera	1901-1989	89	36	Nandgaon	1878-2004	127
9	Balapur	1901-2004	104	37	Nandura	1901-2004	104
10	Bhadgaon	1888-2004	117	38	Nandurbar	1901-2004	104
11	Bhainsdehi	1911-2004	94	39	Navapur	1901-2004	104
12	Bhusaval	1901-2004	104	40	Pachora	1901-2004	104
13	Buldhana	1901-2004	104	41	Pansemal	1931-2004	74
14	Burhanpur	1867-2004	138	42	Parola	1901-2004	104
15	Chalisgaon	1901-2004	104	43	Patur	1901-1963	63
16	Chandurbajar	1901-2004	104	44	Pimpalner	1921-1988	68
17	Chikhaldara	1901-2004	104	45	Raver	1901-2004	104
18	Chopda	1901-2004	104	46	Sakri	1901-2004	104
19	Daryapur	1901-2004	104	47	Satana	1888-1997	110
20	Dhamangaon	1928-1989	62	48	Shahada	1901-2004	104
21	Dharani	1901-2004	104	49	Shegaon	1893-2005	113
22	Dhule	1869-2004	136	50	Shindkheda	1901-2004	104
23	Erandol	1901-2004	104	51	Shirpur	1901-2004	104
24	Jalgaon	1901-2006	106	52	Sirpur	1901-1969	69
25	Jalgaon Jamod	1901-2004	104	53	Surat	1877-2006	130
26	Jamner	1901-2004	104	54	Taloda	1901-2004	104
27	Kalvan	1878-2004	127	55	Telhara	1901-2004	104
28	Khamgaon	1901-2004	104	56	Yaval	1901-2004	104

Data Source: IMD,Pune

In order to achieve the objectives of the study, the following methodology has been adopted. Simple statistical parameters such as mean, standard deviation, coefficient of variation, skewness, etc. are obtained to reduce and summarize the rainfall data. The short and long-term variations in the rainfall are responsible for fluctuations in the annual rainfall series. Therefore, to ascertain short-term fluctuations and long-term trends or changes, time series analysis of the rainfall data have been undertaken. The annual variations in the rainfall have been expressed in terms of percentage departure from mean.

It is important to understand the areal distribution of rainfall. Generally, average depths of rainfall for representative portions of the watershed are calculated and used for this purpose (Viessman and Lewis, 2003). One of the basic methods is to consider the arithmetic average of rainfall. This procedure, however, is suitable for uniformly distributed rain gauge stations and flat topography. Nevertheless, neither the rain gauge stations of the Tapi Basin are uniformly distributed not the topography is flat. Therefore, commonly applied methods such as the Thiessen method and isohyetal method are used for this purpose.

The Thiessen method is applied for calculating areal rainfall average of the Tapi Basin. The method for the basin under review was made possible by means of the analysis of digital data of ca. 30-m resolution of Advance Spaceborne Thermal Emission and Reflection Radiometer (ASTER). Normally, 30-m resolution ASTER data with relative accuracy can be used effectively to assist mapping geomorphic, geologic, tectonic, landform, and a range of environmental studies in remote areas of rugged terrain (Lang and Welch, 1999; Hirano et al., 2003; Figueroa and Knott, 2010). Therefore, the ASTER data were used to extract information to apply the Thiessen method to determine the areal average annual rainfall of the Tapi Basin. This was achieved by using standard procedures in ArcGIS 9.3.

The Thiessen method is applied only for calculating areal average annual rainfall of the Tapi Basin. However, it is important to understand the areas of high and low rainfall as well as the spatial distribution of rainfall in the basin which is achieved by isohyetal method. This method is based on interpolation between rain gauge stations. It is similar to the calculation of contours in surveying and mapping. This method is the most accurate approach for determining average rainfall over an area. In order to prepare isohyetal map of the Tapi Basin, the ASTER data and standard procedures in ArcGIS 9.3 have been applied.

Since the heavy rainfall events are generally caused by extraordinary synoptic conditions that deliver more rainfall to a drainage basin, the analyses of synoptic situations associated with heavy rainfall in the Tapi Basin was undertaken to understand the meteorological causes of heavy rainfall events. This included analysis of rainfall, analysis of storm tracks, and evaluation of the relationship between El Niño and monsoon rainfall in the basin.

To understand the general characteristics of the heavy rainfall events producing meteorological events, rainfall data were obtained from the India Meteorological Department (IMD). 56 raingauge stations were selected from the Tapi Basin and 24 hr highest rainfall, monthly and annual rainfall data were obtained since the inception of the sites (from 1901 to 2004). Since most of the heavy rainfall events in monsoonal region are associated with the passage of low pressure systems (LPS) and cyclonic storms (CS), the data regarding tracks of the cyclones were obtained from the electronic version of the Atlas of Cyclones and Depressions (2008 edition) named as the *Cyclone eAtlas* published by India Meteorological Department (IMD), Chennai.

The non-parametric Mann-Kendall test is applied to evaluate the long-term trends or changes in the annual rainfall. Student's t-test is adopted to determine the percentage change required in the mean of the future rainfall before it can be considered to be significantly different from the historical rainfall records. In order to filter short-term fluctuation and to emphasize the long-range trends in the rainfall, the normalized accumulated departure from mean (NADM) plotting as well as statistical method has been adopted. An attempt has been made to understand natural variability in annual rainfall in the basin and its relation with El Niño and Southern Oscillation (ENSO). The method adopted by Eltahir (1996) for the Nile River has been used. In addition to this, since most of the high-magnitude rainfalls in monsoonal region are associated with the passage of low pressure systems (LPS) and cyclonic storms, the data regarding tracks of the cyclones were obtained from storm track atlas and other publications of IMD.

1.11 Review of literature

It is pertinent to review the present state of knowledge in the field of rainfall studies. Therefore, the following section provides an appraisal of the major themes and development in the field.

Of all the meteorological elements relevant to hydrological studies, precipitation is perhaps the most essential as well as widely measured (Kamaraju and Subrahmanyam, 1984). Monsoon rainfall with its regimes is the key climatic factor and influences all components of the physical and cultural environment in the country. Therefore, it is comprehensively studied by many workers in various ways and for various purposes. Its relationship with different parameters, singularity or in association, its variability and amount have been the subject of study to various researchers (Saxena and Agrawal, 1989).

The fluctuations in rainfall, its distribution, intensity and its relation with other physical factors always remain the matter of curiosity for many workers. The assessment of some scholarly works in the field of rainfall study, especially Indian monsoon, points out five main themes:

i. Rainfall variability and distribution
ii. Heavy rainfall and floods
iii. Low rainfall and droughts
iv. Trends of rainfall
v. Teleconnections of rainfall
vi. Rainfall studies on river basins

i. Studies in rainfall variability and distribution

India forms the major part of the South Asian monsoon region. A systematic study of variability of annual rainfall over South Asia was made by Blanford (1886) for British India. The rainfall in India is highly seasonal and there is large variability in the rainfall on both, time and space. Mooley and Parthasarthy (1984) have made a countrywide mean monsoon rainfall series for India. This series shows the supremacy of south-west monsoon in the country. Sontakke et al. (1993) used the statistical scheme to objectively optimize the number of rain gauges for preparing a representative 'all India summer monsoon series'. Gadgil et al. (1993), Iyengar and Basak (1994) and Singh and Sontakke (1996) used statistical techniques such as 'cluster analysis' and 'principal components analysis' (PCA) to demarcate coherent summer monsoon rainfall zones of India. Ananthakrishnan (1970) studied the space-time variations of the Indian rainfall by examining the pentad (5 day totals) normal rainfall curves of the representative stations of different regions of the country. Shukla (1968), Ramamurthy (1972), Raghavendra (1974), Khambete and Biswas (1978), Chaudhary et al. (1979) and Sarkar and Subramanian (1995) also extensively analyzed short period, i.e. pentad rainfall.

Variability of Indian monsoon rainfall has been well documented by Pant and Rupa Kumar (1997) by using the rainfall data of 306 stations. Singh et al. (1999) present monthly and seasonal variability of monsoon rainfall over 31 meteorological subdivisions of India by utilizing the data of 34 years period from 1960 to 1993. The similar attempt of portraying rainfall variation on all-India scale has been made by Kane (2010). By examining monthly rainfall variations in India over 136 years, he concluded that there is no evidence of Indian monsoon rainfall being more erratic. De and Vaidya (1996) investigated decadal variability of monsoon rainfall in the country by using weekly rainfall departures for all meteorological subdivisions of India for a period 1960-1994. Suresh (1996) represented inter-seasonal and inter-annual rainfall variability of nine meteorological subdivisions in peninsular India. Dhar and Nandargi (2007) attempted to present the distribution of monsoon rainfall over contiguous regions of northeast India and Tibet. The North-East monsoon is important component of rainfall over India. It is the principal contributor of total amount of rainfall in the south-eastern part of the Indian peninsula. Khole and De (2003), using a long period data series 1875-1997, studied the variability of NE monsoon rainfall over south-eastern peninsular part of India.

Indian monsoon is characterized by vagaries and breaks in the rainfall is one of them. De and Mukhopadhyay (2002) examined the influence of break condition on the seasonal and monthly rainfall over the country by using 110 years data of break days for the period 1888 to 1997. Additionally, they explored the long-term trends of breaks in monsoon. Kamaraju and Subrahmanyam (1984) studied the variability of rainfall over the

Krishna Basin and suggested that a break in the rainfall is the normal behavior of monsoon rainfall.

Like the amount and distribution of rainfall, Indian monsoon also shows variation with respect to its onset and withdrawal dates. Mazumdar et al. (2002) checked the onset and withdrawal dates and the duration of southwest monsoon corresponding to various meteorological subdivisions of India for the period 1941-2000 to bring out major features of their variability. The similar study for Rajasthan and Kerala has been made by Ali et al. (2005). Pai and Nair (2009) analyzed the inter-annual variability of dates of monsoon onset over Kerala during the period 1971-2007.

Year to year variations of southwest monsoon rainfall in the various states of the country has been a matter of scientific investigation by many researchers. Ramachandran and Murali (1992) attempted to bring out the areal rainfall characteristics of Karnataka. The summer monsoon rainfall in Andhra Pradesh has been quantitatively analyzed by Sarma et al. (2007). Analysis of rainfall variability over the state in relation to cyclonic disturbances has been carried out by Pattanaik (2006). Spatial and temporal variation of summer monsoon rainfall over Chhattisgarh for the twentieth century has been presented by Sahu and Nandankar (2006). The statistical analysis of rainfall distribution in different districts of West Bengal during monsoon period for the period of 1931-1998 has been studied by Basu et al. (2004). A detailed analysis of the southwest monsoon as well as northeast monsoon rainfall over Tamil Nadu has been done by Subramanian and Thankappan (1995; 1996). The more meticulous rainfall study for the state has been made by Suresh and Sivaramakrishnan (1997). They have scrutinized the seasonal and annual rainfall data from 1901-1985 to reveal the variability of monsoon rainfall over the state. Lalita Devi (1980) attempted to assess the characteristic features of spatial distribution of rainfall over Uttar Pradesh. Several workers studied the varied features of rainfall of Maharashtra. The characteristic features of rainfall over the state are presented systematically by Gadgil (2002). The study revealed average pattern of rainfall, rainy days, rainfall variability and cyclic nature of annual rainfall, excessive rains and incidences of droughts and floods in the state. Characteristic features of daily rainfall over Madhya-Maharashtra have been studied by Agashe and Padgalwar (2005). Kulkarni (1997) and Pisharoty (1983) investigated the rainfall properties of Maharashtra.

The Western Ghats is a predominant physical factor in controlling the climate of the Maharashtra State. The effect of orography on the variation of rainfall of coastal areas and hill stations in the Ghats has been studied by Rao (1976). Apart from orography, synoptic conditions are responsible for widespread rainfall activity. Shyamala and Shinde (1999) identified the important synoptic situations that result in good monsoon rain in Maharashtra. Gadgil (1982) noted that the rainfall in the state is not dependable except Kokan coast and few districts in the state. The native calendar ties the season and climate to one of the most important series of the astrological symbol–nakshatra. In order to investigate to what extent this conceptual thinking is rational and scientific, Gadgil (1982) analyzed the nakshatra wise rainfall distribution for all the district places of Maharashtra. Correlation between nakshatras and rainfall over Maharashtra and Goa is also examined by De et al. (2004).

A close inspection of varied aspects of rainfall at a station level has been made by many workers ((Chatterjee and Ali (1993); Ramasastri et al. (1988); Ramaswamy (1972); Suresh et al. (1998); Saxena and Agrawal (1989); Seetharam (2003); Lal and Gupta (1991); Sivaramakrishnan and Prakasam (1992)). For instance, Mukhergee et al. (1980a) attempted to study in detail the distribution of rainfall over the Nasik district (Maharashtra) by evaluating daily rainfall data for the period 1901 to 1950. Later on they considered the daily, monthly, seasonal and annual rainfall data of Pune and Ahmednagar districts of Maharashtra to present the rainfall patterns of these districts (Mukhergee et al., 1980b). Gunjal (2008) attempted to describe the amount and distribution of monthly and annual rainfall of the Nashik District. Shanmugam (2007) presented a statistical study of rainfall occurrence over Coimbatore.

The change in the performance of the monsoon rainfall over the period has been a matter of scientific investigation by many researchers. The changing behavior of decadal monthly mean rainfall of Bangalore during the period 1938-1987 has been checked by Kavi (1990). Suresh et al. (1998) applied various statistical techniques to find out the variability and periodicity of rainfall between Colaba and Santacruz on the basis of monthly rainfall data for a reasonably longer period for 1901-1993 and 1959-1993 consequently.

ii. Studies in heavy rainfall and floods

Droughts and floods in India are two diverse conditions of monsoonal rainfall, which are caused mainly because of its unreliable nature. Several approaches have been used to identify and quantify the flood and drought recurrences over India. Bhalme and Mooley (1980), for instance, developed an index of drought and flood based on monthly monsoon rainfall and duration. The effects and spatio-temporal characteristics of monsoon floods in India are examined by Kale (1998). In the view of assessment of floods in the Brahmaputra Basin, Dhar and Nandargi (2000) explained the meteorological situations causing heavy rainfall over the basin.

Large numbers of studies are available on excessive rainfalls over the country or over its different parts. Rakhecha et al. (1991) have studied the heaviest recorded one-day rainfall over India. Guhathakurta et al. (2010) observed evident changes in the extreme rainfall events in the past century over India. SenRoy and Balling (2004) analyzed rainfall data of uniformly distributed 129 stations across the country with reasonably complete records from 1910 to 2000 to detect the trends in extreme daily precipitation indices. Attri and Tyagi (2010) analyzed a homogeneous data series of rainfall for the period 1901-2003 to bring out the variability and trends of extreme rainfall. By using a daily rainfall data set, Goswami et al. (2006) demonstrated that in spite of considerable year-to-year variability, there is significant increase in the frequency and the intensity of extreme monsoon rain events in central India over the period of 1951 to 2000. Krishnamurthy et al. (2009) and Vitthal et al. (2013) stated that extreme rainfall over the country shows an increasing trend especially in the later half of the 20th century.

In view of heavy rainfall and imminent floods, comprehensive study of important heavy rainfall situations leading to floods over Punjab during monsoon have been carried out by Mishra and Ravi (2003). Characteristics of extreme rainfall over Maharashtra have been examined by Gore and Potdar (2007). They utilized daily rainfall data from 1875-2000 of well distributed 342 stations of the state. Dubey and Balakrishnan (1992) have been made similar study for Madhya Pradesh for the period 1977-1997.

A low pressure system (LPS), such as depression (D), cyclonic storm (CS) and severe cyclonic storm (SCS), is an important meteorological system that bring heavy to very heavy rainfall in small duration. Lots of scientific studies have been carried out on diverse facets of LPS. Cyclonic disturbances and storms are not only associated with intense rainfall but also affect on the distribution and variability of rainfall. Hence, effect of cyclonic disturbances and storms on rainfall of the region remains a matter of concern for some researchers (Rao, 2001; Pattanaik and Thapliyal, 2002). Whereas, some scholars have tried to reveal the trends of cyclonic systems developed over the Indian Ocean (Singh, 2007). Dhar and Nandargi (1995 a) vigilantly examined 231 severe rainstorms over India for the period 1880-1990. Based on the data of 100 years for the period 1891-1990, the probabilities of cyclonic storms crossing different sections of the east coast of India have been calculated by Ganesan et al. (1994). The hydrometeorological characteristics of flood producing storms over Gujarat, for the period 1891-1970 have been studied by Puri et al. (1984). Mooley and Mohile (1986) attempted to find out the mean and maximum rainfall caused due to cyclonic storms strike the east coast of India. Abbi and Jain (1971) assessed 40 major rainstorms of various durations ranging from one to four days over the Tapi Basin. Nandargi and Dhar (2002) studied about 241 severe rainstorms that hit the Indian region during the period 1880-2000.

Several studies on heavy rainfall over the small administrative regions such as states have also been carried out by many researchers ((Gore and Potdar (2007), Dubey and Balakrishnan (1992), Bbi et al. (1981), Pandey (2007), Jayadeven and Mehajan (2006), Mohapatra and Mohanty (2005), Kalwar et al. (2005)). A few case studies of occasional one-day heavy rainfalls are carried out by some workers. Pandey (2007), tried to analyze the heavy rainfall occurrence of April 6, 2005 over Tamil Nadu and Kerala. Similar study of an exceptionally heavy rainfall event that occurred at Mumbai on July 26, 2005 has been carried out by Jayadeven and Mehajan (2006). There are, however, very few studies of heavy rainfall for the river basins of India.

iii. Studies in low rainfall and droughts

The monsoon rainfall is grossly uneven and India has some of the wettest places on earth and also the driest (Kelkar, 2009). Similar to flood, drought is extreme conditions of rainfall, caused due to erratic nature of monsoon rainfall. Droughts are associated with deficient rainfall and a predominantly agricultural economy is adversely affected by droughts. Several workers documented diverse features of droughts in India or parts of it.

Pant and Rupa Kumar (1997) have traced all-India drought years and prepared composite spatial pattern of monsoon rainfall anomalies of all drought years occurred during 1871-1990 in the country. Chowdhury and Abhyankar (1984) attempted to determine the conditional probabilities of drought/non-drought years in India by analyzing seasonal rainfall departures for the period 1875-1974. Singh et al. (1990) attempted to evolve an index for identifying a year as hydrologically drought in different parts of India taking into account daily rainfall data of monsoon season of 362 raingauge stations over the country for the period 1901-1980. India witnessed a severe drought in 2002. Mujumdar et al. (2007) and Srivastava et al. (2007) attempted independently to examine the probable causes for this unprecedented rainfall deficit by linking the drought with synoptic conditions. Das et al. (2002) studied the characteristics of drought associated rainfall variability in India. They identified drought years for the period 1875-2001 and also inspected the relationship between droughts and onset of southwest monsoon for the respective year. Gore and Thapliyal (2000) computed initial conditional probabilities for dry weeks for 30 districts of Maharashtra by using Markov Chain Model for the period 1901-1990. The water balance technique has been used by Dikshit (1983) for identification of drought-prone areas of Maharashtra. Detailed study of patterns and intensities of rainfall deficit conditions in Maharashtra over 100 years (1871-1984), has been done by Gregory (1991). Diverse characteristics of droughts in various parts of India are documented by several workers. Incidences of drought in Rajasthan are studied by Kalwar et al. (2005). Features of drought climatology of Karnataka have been revealed by Ramachandran et al. (1989); characteristics of droughts over Orissa have been identified by Shewale and Bhave (2002) whereas Ram Mohan (1984) made similar study for Tamil Nadu.

Identification of drought prone areas as well as monitoring the occurrence of drought is helpful to various fields to take remedial measures. Kore et al. (2002) devised a method to monitor droughts of three subdivisions of Maharashtra viz. Madhya Maharashtra, Marathwada and Vidharbha based on the rainfall data from 1901-1999. Gore and Sinha Ray (2002) detected major droughts over Maharashtra during 1901-1998.

They also correlated drought years of India to the states and computed the probability of occurrence of severe drought in the states. Khambete and Biswas (1984) assessed daily rainfall data of dry farming tract of the state using Markov Chain Model for better understanding of drought-proneness in Maharashtra. Similarly, Das et al. (2002) classified the dry farming track of Madhya Pradesh into severe drought prone area, moderately drought prone area and mild drought prone area using daily rainfall data for the period 1951-1995.

Failure of Indian monsoon and its connections with El Niño episodes has been investigated by several workers. Shewale (2001) examined the seasonal rainfall data during the 100 year period (1901-2000) of arid region of Saurashtra and Kutch to identify the instances of moderate and severe droughts in the region and also explored their association with El Niño incidents. The teleconnections of Pacific Ocean temperature with droughts over Andhra Pradesh are verified by Gore (2002).

iv. Studies in rainfall trends

Trends of rainfall illustrate the direction of change in the rainfall of a region, and therefore facilitate the planners in various fields. Moreover, the studies on rainfall trends are imperative to determine climatic changes. Trend analyses of rainfall of India have been reported by several workers. Rupa Kumar et al. (1992) analysed the monsoon rainfall (seasonal and monthly) over India during 1871 to 1990 to illustrate long-term trends in different parts of India. Guhathakurta and Rajeevan (2008) have been precisely examined monthly, seasonal and annual rainfall data of 36 meteorological subdivisions of India from 1901-2003 to determine the trend of rainfall over the country. They concluded that the all India summer monsoon rainfall does not show any significant trend. The investigation of Mooley and Parthasarthy (1984) also confirmed the fact that the monsoon rainfall is trendless and is mainly random in nature over a long period of time, particularly on the all India scale. Gregory (1989a) also observed that there is no significant linear trend in the Indian monsoon rainfall. Several previous studies have been made to determine the trend of monsoon rainfall over India. Subramanian et al. (1992) analyzed the monthly and annual rainfall data for 35 meteorological sub-divisions for the period of 1901-1987 to study the trends and periodicities of monsoon and annual rainfall series over India. Annual and seasonal rainfall of 35 sub-divisions and also for all districts for the period 1901-1992 were utilized by Srivastava et al. (1998) to detect the trend of rainfall over India. They concluded that all-India rainfall in general, does not show any trend. Whereas, Hamza and Babu (2007) come across differing observation. Using all-India daily monsoon rainfall from 1901-2002, they studied the long-term rainfall trends and obtained two different phases of rainfall trends. In the first phase from 1901 to 1964, the Indian summer monsoon rainfall show an increasing trend; while the second phase from 1965 to 2002 is characterized by decreasing trend.

A study of rainfall trend on regional level is a matter of concern for several workers. Basu et al. (2004) examined monsoon rainfall data of West Bengal from 1931 to 1998 to display district-wise trend of rainfall. Krishnakumar et al. (2009) using monthly, seasonal and annual rainfall data during the period from 1871 to 2005 attempted to determine long-term trend of rainfall of Kerala. Raghvendra (1974) examined the trends and periodicities of the rainfall over four sub-divisions of Maharashtra viz. Kokan, Central Maharashtra, Marathwada and Vidharbha and concluded that in all the sub-divisions the successive year's rainfall is not dependent. He also noticed an increasing trend in the rainfall over Maharashtra after 1901. Chaudhary (1992) used the moving average technique for determining the trend of rainfall over the state. Rase (1998) critically examined the seasonal rainfall data of east and west Madhya Pradesh and Vidarbha from 1875 to 1992 to find out trend and periodicity in rainfall. The analysis of the fractal behavior of annual rainfall data of Chennai for ten decades of 20th century has been carried out by Selvaraj et al. (2010) by using the fractal construction technique. In order to search for trend and periodicity in the seasonal and annual rainfall over six districts of hills of West Uttar Pradesh, Lal et al. (1993) used Mann-Kendall, Student's t-test and spectrum analysis method. Trends and periodicities in the annual, seasonal and monthly rainfall of Delhi based on data of 90 years (1901-1990) have been examined by Lal and Gupta (1991). Hire and Gunjal (2006) attempted to find out long-term trends in the annual rainfall of the Nashik District.

v. Studies in teleconnections of rainfall

Indian monsoon is an important component of the global climate system. It has linkages with other global atmospheric as well as oceanic factors in which El Niño and Southern Oscillation (ENSO) is most significant. The relationship between El Niño event and summer monsoon over India has been extensively examined by Mooley and Parthasarthy (1983), Rasmussen and Carpenter (1983), Bhalme and Jadhav (1984), Sarkar (1988) and Chaudhary and Mhasawade (1991) and Kale (1999). The investigation by Ropelewski and Halpert (1987), and Simpson et al. (1993) shows that El Niño and Southern Oscillation (ENSO), is the major reason of rainfall variability in many parts of the world, including India. Bhalme and Jadhav (1984) and Burn and Arnell (1993) opined that the fluctuations in the monsoon rainfall are significantly related with ENSO. Datta (1987) and Gupta (1987) checked the teleconnections of southern oscillations (SO) and monsoon rainfall over India and found significant linkage between them. Khole and De (1999) observed that in general, occurrence of El Niño during the negative phase of southern oscillations proves to be conductive for poor activity of the Indian summer monsoon. The relationship between ENSO/anti-ENSO events and all India monsoon rainfall for the period 1901-1990 has been examined by Chattopadhyay and Bhatla (1996). Their study revealed that there is fairly strong association between ENSO events and deficient monsoon rains. However, there exists a weak teleconnection between anti-ENSO events and wet monsoon. Kale et al. (1996) found that number of historical as well as recent floods are related with ENSO events. Ihara et al. (2007), revealed the link between Indian summer monsoon rainfall (ISMR) with ENSO. The study of relationship between Indian summer monsoon drought of 2002 and ENSO conditions over north-west Pacific Sea is carried out by Mujumdar et al. (2007).

Sea Surface Temperature (SST) of the Pacific and the Indian Oceans is another important factor influencing Indian summer monsoon rainfall (ISMR). Many investigators demonstrated the effect of SST anomalies on Indian monsoon (Khole, 2004; Kane, 1998; Thapliyal et el., 1998; Chattopadhyay and Bhatla, 1993; Verma, 1994; Babu et al., 1989; Singh and Oh, 2007). These studies in general corroborated that SST anomalies in the Pacific are closely linked with the monsoon rainfall of India. Khole (2004) investigated the relationship between ISMR and SST over central and equatorial

Pacific Ocean and noted their strong and statistically significant relationship especially during the pre-global warming period (1951-1975) which weakened during post-global warming period (1976-2000). Kane (1998) checked the relationship of percentage rainfall deviations for ISMR with ENSO and SST events on the basis of data from 1870-1990 and noticed that unambiguous warm events of ENSO are associated with droughts and cold events with floods. Thapliyal et el. (1998) after correlating SST variations over the equatorial Pacific with ISMR and found that during deficient monsoon years SST anomalies over the Pacific show a warming trend and vice versa. Kane (1998) evaluated the association of ISMR with SST over equatorial eastern Pacific Ocean, southern oscillation and El Niño for 120 years (1871-1990). He concluded that exclusively cold SST events/years (equatorial eastern Pacific SST minima) are strongly inclined to excess ISMR. Among 36 such events/years, 34 are characterized by surplus rainfall events/years out of that 10 are flood events/years.

To seek the connection of Indian monsoon rainfall with SST anomalies over different regions of Pacific Ocean, Chattopadhyay and Bhatla (1993) examined monthly SST anomaly data during 1951-1990. Gregory (1991) studied the association between summer monsoon rainfall conditions and sea surface temperatures of the Indian Ocean. It seems that the warmer (cooler) Indian Ocean, immediately before the monsoon season was associated with an increase (decrease) in monsoon rainfall over the areas closest to the Arabian Sea. Roxy and Tanimoto (2007) have investigated the influence of SST over Indian Ocean on regional precipitation variability over the Indian Sub-continent. Rajeevan et al. (2000) also analyzed nearly 50 years of monthly SST data of Indian Ocean to find out its linkage with ISMR.

vi. Rainfall studies on river basin scale

Studies on distribution and variation of rainfall on natural regions such as river basins rather than administrative regions are more significant from the hydrological as well as environmental point of view. The Tapi Basin has been selected for the present work of rainfall study. Therefore, it is relevant to take a brief review of rainfall studies on river basins.

Studies on hydrometeorological aspects of river basins have great practical value for a variety of purposes. Therefore, several workers documented various aspects of rainfall studies on river basins in India. Ramasastri et al. (1981) analyzed the rain spells of severe intensity over some river basins in India to estimate short duration rainfall within it. In a similar point of view, Rakhecha et al. (1991) evaluated daily rainfall data from 1901-1980 of 200 stations in the various river basins of Maharashtra to predict 1-day maximum rainfall for different recurrence intervals ranging from 2 to 100 years. Kamaraju and Subrahmanyam (1984) described the characteristics of the annual and seasonal rainfall distribution and its variability over the Krishna Basin. Kulkarni and Munot (2002) made effort to delineate inter-annual variability of summer monsoon rainfall in the Godavari Basin. To take a review of climatic change in Luni Basin of arid western Rajasthan, Singh et al. (2002) illustrated the distribution and regimes of rainfall over the basin. A study of rainfall over Yamuna catchment from its origin upto Delhi for the period 1976-1990 has been made by Duggal et al. (1992). Dhar et al. (1984) prepared generalized charts of point rainfall of duration of one to three days in the Narmada Basin for the return period of 100 years.

Majority of floods in India are caused due to heavy rainfalls associated to the tropical disturbances (i.e. depressions/storms). Several workers have undertaken the studies on rainstorms over different river basins in India. Dhar and Ghose (1972) studied the spatial and sequential distributions of tropical disturbances over the major river basins in India using 80-years depressions/storms data from 1891-1970. Prasad and Sinha (1985) revealed the distribution of areal average rainfall in the upper Son catchment associated to monsoon depressions. Nandargi and Dhar (2002) prepared generalized charts of areal raindepths over India using the data of 241 severe rainstorms which occurred during the period 1880-2000. Biswas and Bhadram (1984) studied 53 rainstorms of duration one to three days over Teesta Basin occurred during the period 1960-1981 to present average isohytel depths of rainfall in the basin.

There are several studies devoted to the flood producing heavy spells of rainfall and related synoptic conditions over different river basins in India. Prasad and Das (1987) carried out hydrometeorological study of Jaldhaka Basin in North Bengal, Sikkim and Bhutan by determining distribution of monthly rainfall, number of rainy days, number of days with floods and extreme rainfall events over the basin along with associated synoptic conditions. Ghosh et al. (1982) while assessing the unprecedented flood at Delhi on the river Yamuna in August 1976 analyzed the rainfall in the river catchment along with the synoptic conditions. Prasad and Sen Sarma (1981) attempted to summarize the synoptic conditions under which flood producing heavy rains are possible in Ganga Basin of Bihar from available past records. Sharma et al. (1982) described the rainfall distribution and associated synoptic as well as geomorphological characteristics of Luni Basin which caused a devastating flood in July 1979. A study of floods in Brahmaputra Basin in India during the period 1987-1998 has been made by Dhar and Nandargi (2000). They analyzed the distribution of rainfall over the basin along with the meteorological situations causing heavy rainfall and therefore floods in the basin. Goyal and Kathuria (1984) carried out the study of return period analysis of extreme events of rainfall for selected stations of Krishna Basin utilizing one-day annual maximum rainfall data for the period 1901-1960.

1.12 Arrangement of the text

The present work contents five chapters. Chapter I deal with the general introduction to the research topic and the study area, that is, the Tapi Basin. An introduction to the topic, methodology adopted for analyzing the rainfall data and the review of previous studies in rainfall are given in this chapter. Information about physical factors of the study area such as geology, physiography, drainage and climate are also discussed in the chapter.

In chapter II, an attempt has been made to show the rainfall regime characteristics of the basin. Analysis of heavy rain showers has also been included in this chapter.

Chapter III is devoted to understand variability of rainfall of the Tapi Basin. Spatio-temporal variation of rainfall in the basin is presented in this chapter. In addition, droughts and floods in basin are also reviewed.

Long-term fluctuations in the rainfall over the Tapi Basin are exhibited in chapter IV. Teleconnections of rainfall over the basin are verified and also an attempt has been made to portray the future changes in the rainfall.

The last chapter, that is chapter V, is the concluding section of the research work in which the major findings of the study have been summarized.

CHAPTER II

REGIME CHARACTERISTICS OF RAINFALL

2.1 Introduction

Among the dominant natural factors which strongly influence the life and economy of the people is the regimes of rainfall (Gadgil, 2002). Beckinsale (1969) defined the regime of a rainfall as the variations in its amount. In addition, he stated that in its widest sense, the regime of rainfall involve all occurrences and is portrayed by a graph based on continuous observations of rainfall. The importance of the study of rainfall regime lies in its significance to recognize the variations in total amount of rainfall at different places of a region and to understand the general pattern of rainfall within it. The period and length of rainy season along with its spatio-temporal variations and varied characteristics can be well exhibited with the rainfall regime. Regime characteristics of rainfall represent the general picture of the rainfall of a place or a region and can be used for various hydrological purposes.

The monsoon of India is a distinctive weather system among all other rainfall systems of the world. An outstanding feature of monsoon rainfall of India is its seasonality and variability. To describe the rainfall regime in India, Ramamurthy (1972) carried out a detailed analysis of the pentad (five-day) totals of rainfall of over 150 stations. In the present study, however, monthly and annual totals of rainfall as well as 24 hr highest rainfall values are used to present the regime of rainfall of the Tapi Basin. The investigation has been based on the rainfall data of the 20th century of 56 rain gauge stations situated in the basin.

2.2 Annual pattern of rainfall

The Tapi Basin is situated in classic monsoonal climate of the central-western India. The basin is characterized by diverse physiography in its different parts. It is bordered by Western Ghats to the west, Satpura Ranges to the north, Ajanta Ranges to the south and Betul Plateau to the east. The Gawilgad Range lies to the eastern part of the basin connecting to the Betul Plateau to the extreme east. Besides these hilly areas, an extensive part of the basin is covered by the plains formed by the Tapi River and its tributaries. Therefore, owing to its physiography, the Tapi Basin displays uneven distribution of rainfall. Table 2.1 represents distribution of average annual rainfall in the basin and the same is represented graphically in Figure 2.1. It is to be noted that the analyses of rainfall over the basin have been carried out on the basis of monthly and annual averages of rainfall of the rain gauge stations under the study and the description of the distribution of rainfall has been presented in general to bring out the common picture of the rainfall pattern of the basin. The average annual rainfall over the basin is 814 mm ranging from about 400 mm to 1100 mm (Table 2.1, Figure 2.1). The rainfall over the Tapi Basin is characterized by variability in its amount from one year to another. However, on long-term scale it is normally distributed with standard deviation of 196 mm. However, owing to typical characteristics of the monsoon rainfall, there are some high and a few low rainfall years on record. The basin received maximum annual rainfall in 1944, which is 1158 mm, and minimum 419 mm annual rainfall in 1918. Out of 104 years under review, 48 years received more annual rainfall than average annual rainfall of the basin; whereas 56 years obtained less than average annual rainfall of the basin. It reemphasized the normal annual pattern of rainfall of the Tapi Basin (Table 2.1, Figure 2.1). The heaviness and scantiness of annual rainfall of the basin elaborately discussed further in chapter 3.

The basin covers about 2% geographical area of India and characterized by considerably extensive east-west extent than its north-south breadth. The basin extends in three states viz. Madhya Pradesh, Maharashtra and Gujarat, however, about 80% of the basin area lies within Maharashtra. Therefore, to get acquainted with the rainfall of the Tapi Basin, average annual rainfalls of India, Maharashtra and the Tapi Basin can be compared. The average annual rainfall of India and Maharashtra is 980 mm and 1350 mm respectively (Gadgil, 2002). The basin receives 814 mm rainfall per year which is less than the average annual rainfall of both Maharashtra and India.

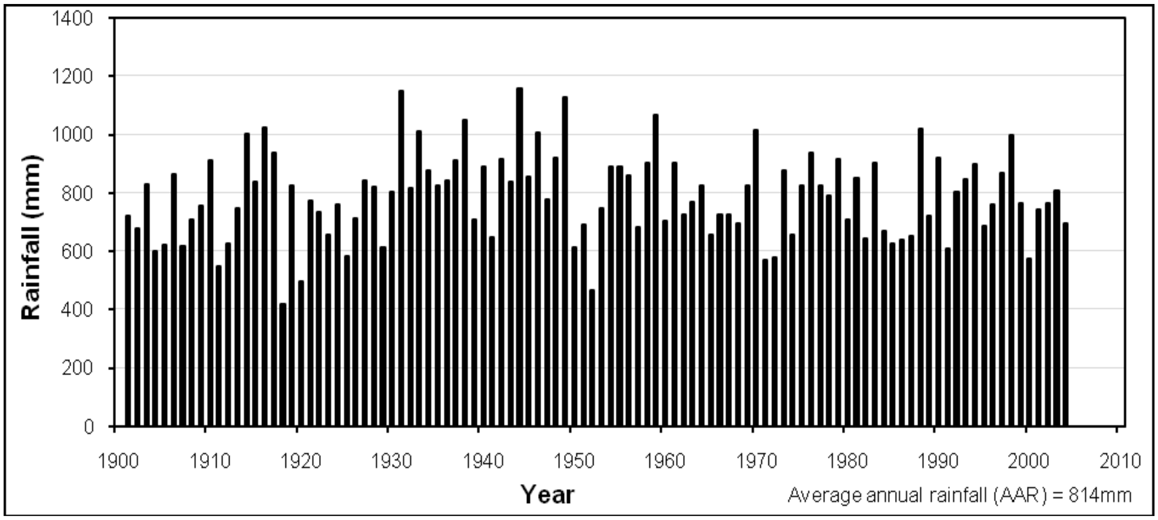
Table 2.1 Average annual rainfall of the Tapi Basin (1901-2004)

Year	AR(mm)	Year	AR(mm)	Year	AR(mm)	Year	AR(mm)
1901	721	1927	843	1953	747	1979	914
1902	677	1928	823	1954	892	1980	707
1903	828	1929	612	1955	891	1981	853
1904	600	1930	802	1956	860	1982	643
1905	622	1931	1151	1957	684	1983	904
1906	863	1932	818	1958	903	1984	669
1907	620	1933	1009	1959	1067	1985	627
1908	710	1934	876	1960	702	1986	638
1909	757	1935	825	1961	904	1987	653
1910	911	1936	844	1962	726	1988	1020
1911	549	1937	913	1963	769	1989	721
1912	625	1938	1050	1964	824	1990	922
1913	749	1939	711	1965	657	1991	607
1914	1001	1940	889	1966	726	1992	803
1915	837	1941	650	1967	724	1993	847
1916	1026	1942	917	1968	695	1994	899
1917	937	1943	839	1969	824	1995	686
1918	419	1944	1158	1970	1016	1996	759
1919	826	1945	854	1971	570	1997	867
1920	498	1946	1006	1972	581	1998	997
1921	773	1947	779	1973	879	1999	763
1922	736	1948	921	1974	658	2000	575
1923	656	1949	1128	1975	824	2001	744
1924	761	1950	615	1976	939	2002	766
1925	585	1951	692	1977	823	2003	806
1926	714	1952	469	1978	790	2004	698
						AAR	**814**

Data Source: IMD, Pune; AR = Average rainfall of the year; AAR = Long-term average annual rainfall of the Tapi basin

Unlike temporal pattern of annual rainfall, the Tapi Basin displays considerable spatial variation of annual rainfall. Majority of the rain gauge stations in the basin show deviations from average annual rainfall of the basin. There are a few stations which receive noteworthy greater or lower amount of annual rainfall than the basin's average. Particularly, the stations located on the east and west edges of the basin obtain an excess amount of rainfall than the stations amid. In contrast, the places situated to the south-west of the basin gains noticeable less amount of rainfall. The central part of the basin represents rainfall close to the average annual rainfall of the basin.

Figure 2.1 Average annual rainfall of the Tapi Basin (1901-2004)



The spatio-temporal characteristics of the basin rainfall are described in detail in chapter III. The difference between average annual rainfall figures of various stations located in different parts of the basin is significant. The average annual rainfall of the raingauge stations selected for the study is given in Table 2.2 and graphically presented in Figure 2.2. The average annual rainfall of the basin is 814 mm; varies from 511 mm to 1596 mm at Sakri and Chikhaldara sequentially (Table 2.2, Figure 2.2).

The eastern part of the basin receives more rainfall than the middle and western parts. Heaviest rainfall zone of the basin coincides with the eastern hilly area of the Gawilgad Range. The stations located in the eastern part of the basin show high range of annual rainfall of about 700 to 1600 mm. Chikhaldara is the highest average rainfall receiving station in the basin which is 1596 mm. It is about three times more than the average annual rainfall of the driest place of the basin (Sakri, 511 mm) and almost double than the average annual rainfall of the Tapi Basin (814 mm) (Table 2.2). Dharni (1159 mm) and Bhainsdehi (1023 mm), located in the vicinity of the Gawilgad Range also gain remarkably high amount of annual rainfall than the whole basin (Table 2.2).

Table 2.2 Average annual rainfall at different stations of the Tapi Basin

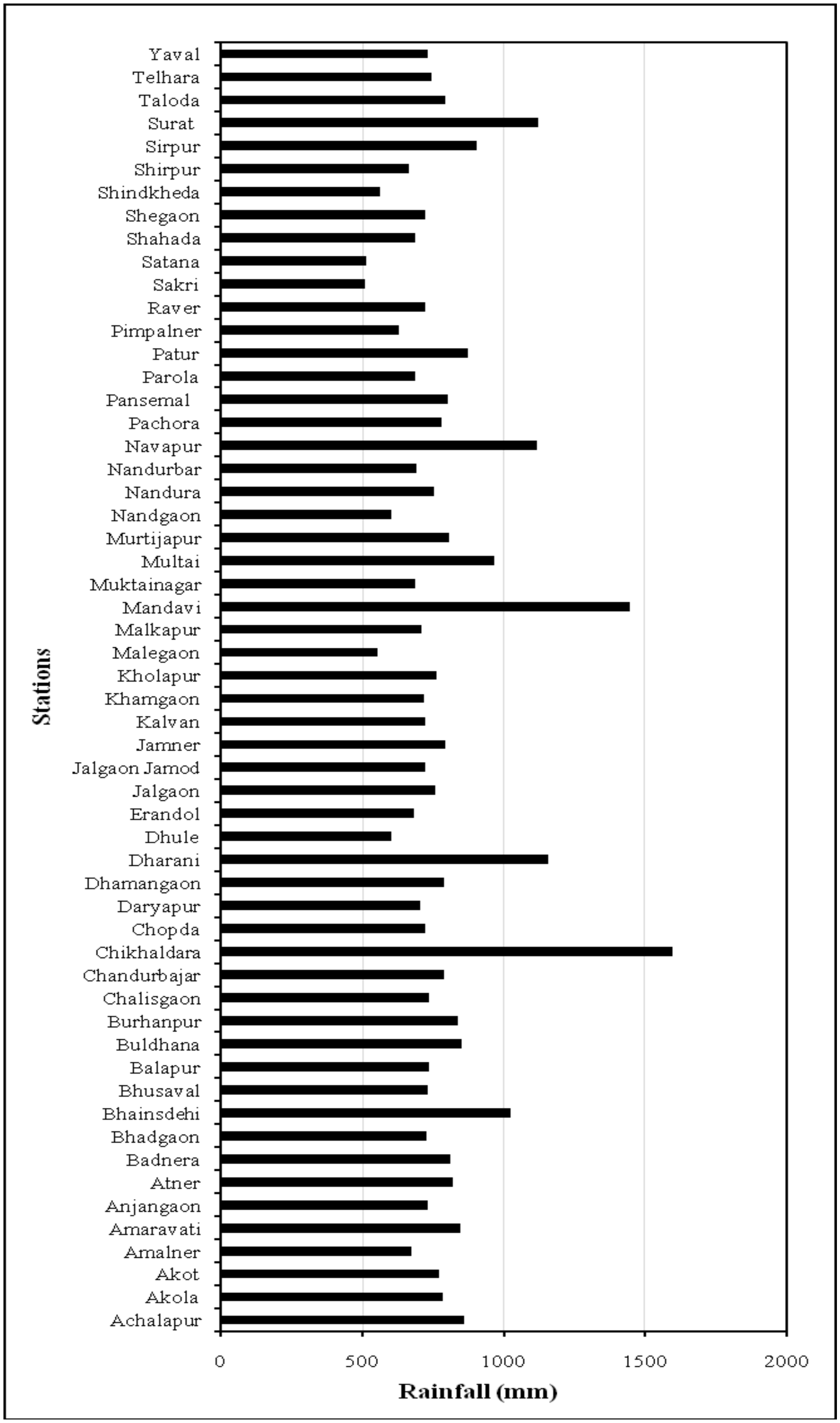
Station	AAR (mm)	Station	AAR (mm)
Achalapur	861	Kholapur	764
Akola	785	Malegaon	554
Akot	771	Malkapur	708
Amalner	676	Mandavi	1445
Amaravati	848	Muktainagar	688
Anjangaon	732	Multai	968
Atner	820	Murtijapur	808
Badnera	813	Nandgaon	605
Balapur	737	Nandura	755
Bhadgaon	727	Nandurbar	690
Bhainsdehi	1023	Navapur	1116
Bhusaval	730	Pachora	780
Buldhana	850	Pansemal	801
Burhanpur	838	Parola	686
Chalisgaon	735	Patur	874
Chandurbajar	789	Pimpalner	629
Chikhaldara	1596	Raver	721
Chopda	721	Sakri	511
Daryapur	706	Satana	514
Dhamangaon	792	Shahada	686
Dharani	1159	Shegaon	721
Dhule	602	Shindkheda	563
Erandol	684	Shirpur	667
Jalgaon	758	Sirpur	906
Jalgaon Jamod	723	Surat	1124
Jamner	793	Taloda	793
Kalvan	723	Telhara	746
Khamgaon	717	Yaval	733
Tapi Basin			**814**

Data Source: IMD, Pune

The middle section of the basin, covered by the river plain, is characterized by less variation in the annual rainfall. Most of stations in this section of the basin receive annual rainfall ranging between 700 and 900 mm which is close to the average annual rainfall of the basin. For example, the places such as Sirpur, Buldhana, Jamner, Chopda and Pachora receive annual rainfall of 906, 850, 793, 721 and 780 mm respectively (Table 2.2).

The western section of the basin shows high variability in the rainfall from one station to another. The south-western area of the basin is characterized by remarkably low amount of rainfall than the average annual rainfall of the basin. And, in fact, this area comprises the lowest rainfall receiving stations of the basin such as Sakri (511 mm), Satana (514 mm) and Malegaon (554 mm) , Nandgaon (605 mm) (Table 2.2).

Figure 2.2 Average annual rainfall at different stations in the Tapi Basin



See Figure 1.4 for location of the stations

The extreme western section of the basin shows sudden rise in amount of rainfall. The stations situated in this part of the basin receive high amount of rainfall. For instance, Navapur, Mandavi and Surat receive 1116, 1445 and 1124 mm annual rainfall in sequence (Table 2.2; Figure 2.2). Therefore, because of a sizable contribution of these few stations located in the extreme west, as a whole, this section receives a little high amount of annual rainfall than the average of the basin. Therefore, though not precisely, the Tapi Basin display decreasing amount of the rainfall from east to west with abrupt rise in the rainfall to the western perimeter.

2.3 Monthly pattern of rainfall

Being a part of classic monsoon climatic region, the Tapi Basin exhibit typical properties of the Indian monsoon. Although the basin receives rainfall throughout the year, it is exceedingly concentrated in four months of the monsoon season (June to September). Therefore, in accordance with the amount of rainfall in different months of a year, whole year can be divided into two periods viz. 'monsoon period' (June to September) and 'non-monsoon period' (October to May). The monthly distribution of rainfall at different stations in the basin as well as in the whole basin as a unit is given in Table 2.3.

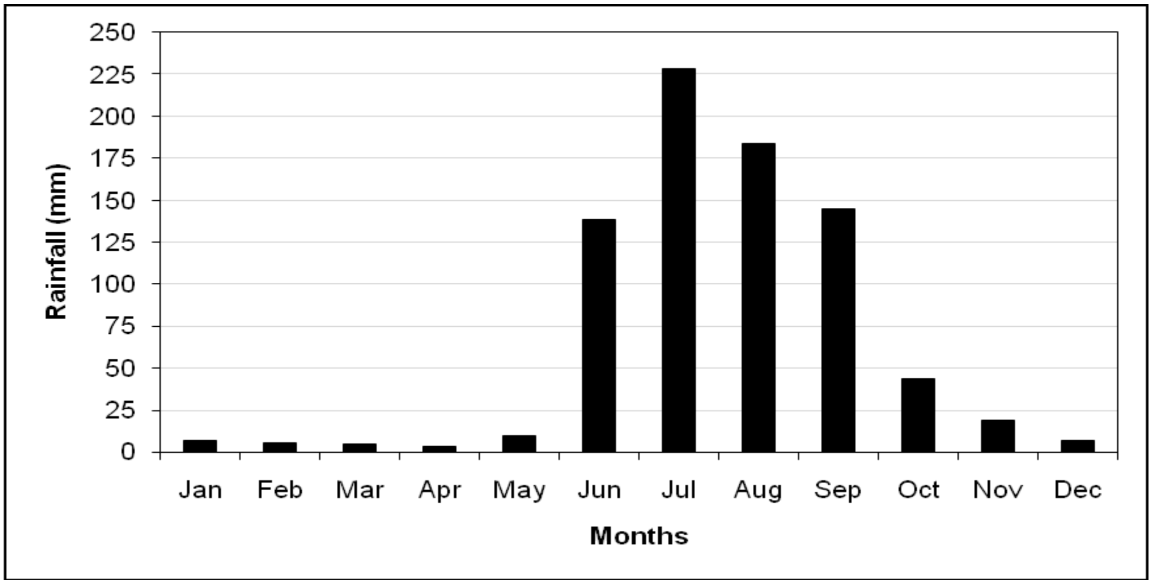
The monthly distribution of rainfall over the basin is represented in Figure 2.3. It is observed that all the months of the year receive rainfall in differential amount. It can be easily recognized from Table 2.3 and Figure 2.3 that the rainfall of the Tapi Basin is highly seasonal. The basin receives widespread rainfall in the monsoon period and rest of the year is generally dry. However, even in the monsoon period the rainfall is not evenly distributed in all the months of the season. June obtains about 17% of the annual rainfall of the basin. July is the rainiest month in the basin, contributes about 29% of the annual rainfall. August and September gains about 23% and 18% of the annual rainfall respectively. The non-monsoon period (October to May) is featured by sudden and consistent decrease in the amount of rainfall. The monthly rainfall after September declines up to April and again rises from May till the beginning of the summer monsoon season in the month of June. April is the driest month in the basin obtains a negligible amount of rainfall (about 3% of the annual rainfall of the basin) (Table 2.3).

Table 2.3 Monthly distribution of rainfall (mm) at different stations of the Tapi Basin

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
Achalapur	13.02	12.43	6.98	6.37	10.57	147.61	238.39	209.48	137.01	48.72	23.10	8.05	861.72
Akola	10.51	8.35	10.48	4.55	10.55	138.17	225.57	178.44	143.48	40.04	20.61	10.94	801.68
Akot	9.42	8.94	6.81	3.94	8.62	131.97	227.19	178.77	128.98	43.87	21.26	5.85	775.64
Amalner	4.80	2.90	3.60	2.00	6.70	128.70	194.50	149.80	119.80	43.10	17.00	4.90	677.82
Amaravati	11.20	12.09	11.80	8.24	13.07	149.01	232.50	193.91	155.50	48.90	18.31	12.43	866.95
Anjangaon	11.17	9.13	8.04	2.89	9.16	121.51	206.92	163.62	129.97	45.23	22.31	6.90	736.83
Atner	8.69	11.98	10.93	5.94	9.01	131.83	249.64	191.41	145.86	42.59	19.96	10.05	837.89
Badnera	9.61	14.07	7.87	6.30	12.08	154.50	230.31	191.33	147.90	42.00	19.91	6.40	842.29
Balapur	8.05	6.19	6.59	3.38	6.60	136.89	208.41	171.21	127.99	40.73	18.32	8.59	742.94
Bhadgaon	5.51	3.20	3.18	2.41	10.00	134.14	179.76	172.22	148.01	42.60	20.46	6.66	728.14
Bhainsdehi	10.51	9.17	11.78	6.92	9.36	146.23	286.34	266.91	190.18	64.75	24.63	8.97	1035.76
Bhusaval	5.82	4.48	3.06	1.50	9.20	134.74	212.17	167.93	125.60	40.36	18.51	7.56	730.93
Buldhana	8.16	5.74	5.39	6.20	12.35	175.53	219.56	198.69	150.34	55.48	23.55	9.44	870.43
Burhanpur	6.51	4.41	4.36	1.69	10.71	152.36	224.43	207.13	166.28	39.06	16.51	9.66	843.12
Chalisgaon	5.24	2.24	4.65	1.83	13.39	130.57	162.20	157.46	173.81	52.49	26.06	6.43	736.37
Chan.	15.28	12.61	7.45	3.88	8.51	132.02	223.82	183.32	142.24	46.15	20.69	6.05	802.02
Chik.	11.47	10.01	7.66	6.11	12.35	204.74	484.26	469.81	287.19	63.81	32.92	8.48	1596.81
Chopda	4.62	2.32	2.83	1.89	9.10	134.41	213.52	180.72	128.02	32.06	14.94	4.68	729.12
Daryapur	11.28	9.95	6.07	3.84	7.24	120.98	208.58	151.74	132.45	41.02	17.50	6.08	716.73
Dham.	5.25	10.02	8.72	4.68	9.57	141.87	211.57	190.33	145.71	48.66	22.66	10.58	809.63
Dharani	5.51	4.98	5.60	2.30	6.55	167.65	365.56	336.77	205.46	37.84	17.92	6.35	1162.48
Dhule	5.17	2.06	2.22	1.68	9.44	129.42	146.13	110.99	129.31	41.18	19.54	5.94	603.09
Erandol	4.76	2.48	2.85	0.62	7.51	119.58	196.82	171.81	118.09	39.88	17.94	5.65	688.01
Jalgaon	7.62	5.91	3.86	2.74	8.31	126.20	190.43	164.07	149.83	51.27	17.15	8.06	735.46
Jal.Jam.	6.05	2.89	4.44	1.96	8.89	137.23	230.07	187.41	128.78	39.71	18.09	8.00	773.53
Jamner	6.83	3.02	5.63	1.56	11.21	144.26	211.67	194.11	141.39	45.10	21.66	7.56	794.02
Kalvan	2.20	1.31	1.31	7.05	25.50	127.45	191.20	134.52	144.79	62.41	28.90	3.34	729.99
Khamgaon	7.22	4.97	6.86	4.71	8.67	139.52	195.23	155.48	129.29	48.99	23.37	6.48	730.80
Kholapur	10.33	12.78	6.77	5.04	9.98	135.45	218.65	162.86	139.44	43.88	19.56	7.38	772.13
Malegaon	3.66	2.15	1.69	3.60	18.44	108.56	116.08	91.17	133.95	50.60	21.33	5.88	557.13
Malkapur	7.48	4.99	4.46	2.90	8.00	126.52	190.86	167.78	130.21	40.50	19.31	9.19	712.22
Mandavi	2.42	0.80	0.91	0.15	6.06	215.10	570.37	372.55	233.12	33.27	10.54	1.36	1446.64
Mukt.	6.40	4.72	3.68	1.17	7.96	119.43	194.78	155.14	128.86	39.94	17.36	9.05	688.49
Multai	14.78	15.01	13.09	7.10	11.23	150.33	279.37	236.70	170.08	49.07	21.49	9.76	978.02
Murtijapur	9.72	9.87	7.27	6.18	10.02	147.96	235.06	171.72	142.25	49.10	20.78	6.96	816.89
Nandgaon	4.25	1.05	2.03	3.44	15.53	122.41	113.46	98.97	156.56	54.56	27.43	5.53	605.23
Nandura	9.19	5.71	7.86	4.08	10.84	130.54	204.59	166.56	139.33	45.66	21.02	8.51	753.88
Nandurbar	4.82	0.77	1.12	2.00	8.85	129.95	217.92	155.09	117.71	36.39	13.28	3.65	691.56
Navapur	3.21	1.04	0.90	1.60	4.83	158.59	408.06	305.73	176.40	42.79	12.32	2.85	1118.31
Pachora	4.47	2.16	2.64	2.76	9.26	130.04	185.69	163.24	119.84	42.26	17.11	6.27	685.73
Pansemal	1.34	0.72	0.91	1.31	4.94	122.44	254.37	224.79	169.85	41.74	9.99	4.21	836.60
Parola	4.47	2.16	2.64	2.76	9.26	130.04	185.69	163.24	119.84	42.26	17.11	6.27	685.73
Patur	8.86	8.59	10.43	8.52	14.37	155.89	255.09	182.00	161.96	41.91	20.32	8.82	876.77
Pimpalner	2.63	2.53	4.36	2.55	11.98	103.38	179.68	124.33	125.63	42.17	23.67	6.94	629.84
Raver	6.34	4.26	4.37	1.31	10.12	137.25	180.22	164.04	138.54	46.73	21.00	8.71	721.89
Sakri	4.34	1.25	2.93	3.26	11.17	109.86	126.13	85.28	103.32	39.51	19.44	5.68	511.15
Satana	3.02	0.91	1.25	3.17	17.15	101.13	100.41	79.25	125.28	50.66	26.42	3.41	514.06
Shahada	4.25	0.44	1.09	1.58	9.24	124.74	213.40	150.09	130.75	35.65	9.36	4.18	684.77
Shegaon	9.78	7.44	7.58	4.46	7.99	126.50	195.03	170.90	135.52	45.66	19.58	9.04	739.48
Shindkheda	3.79	1.65	1.19	1.61	6.35	120.55	157.34	117.05	99.27	34.49	16.63	4.15	564.06
Shirpur	3.44	1.68	2.62	1.82	10.69	122.55	205.64	146.78	119.94	34.82	12.25	3.58	665.82
Sirpur	7.61	9.66	10.08	7.53	12.45	158.85	261.45	204.01	161.02	44.78	21.96	9.31	908.71
Surat	1.50	1.56	0.83	1.95	6.50	233.89	436.94	244.11	169.26	33.24	11.33	1.94	1143.05
Taloda	3.48	1.01	0.87	1.10	8.86	130.04	268.98	195.45	140.85	28.70	11.81	2.99	794.13
Telhara	8.11	6.61	5.56	2.83	7.75	125.85	220.83	166.24	140.40	41.75	21.39	6.13	753.45
Yaval	5.32	3.23	3.51	1.86	10.40	132.78	213.71	175.34	130.04	37.69	17.54	6.35	737.78
Tapi Basin	6.79	5.40	5.07	3.48	10.03	138.39	227.97	183.57	145.10	44.05	19.38	6.74	**814**

Data Source: IMD, Pune; Chan.= Chandurbajar , Chik.= Chikhaldara , Jal.Jam.= Jalgaon Jamod , Mukt.= Muktainagar

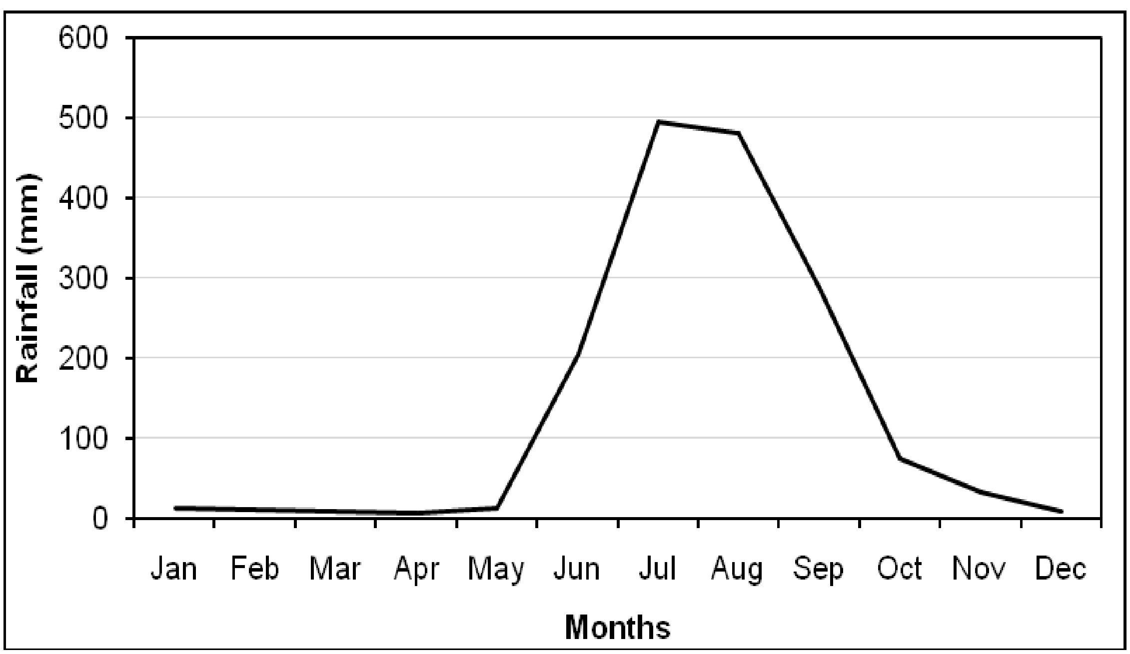
Figure: 2.3 Distribution of monthly rainfall: Tapi Basin



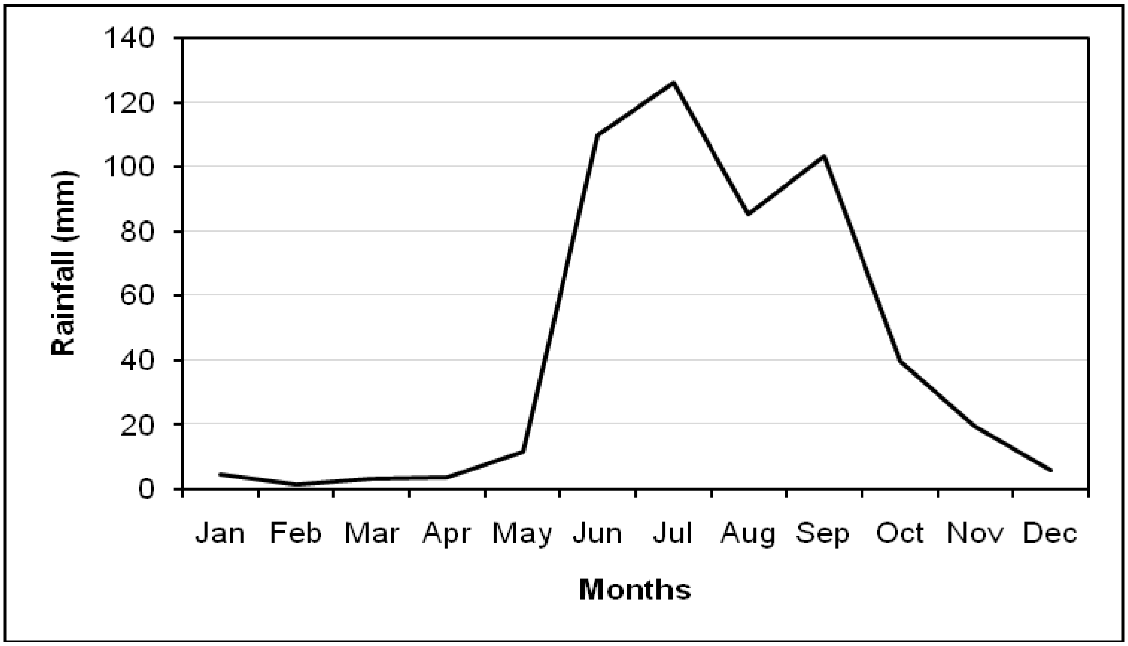
The nature of an average monthly rainfall over the Tapi Basin displays two distinct patterns at different stations. It is known that the average annual rainfall of the basin is 814 mm varies between 500 mm and 1600 mm with standard deviation of 196 mm. With reference to the average annual rainfall of the basin, the stations in the basin can be divided into two main classes- high rainfall stations and low rainfall stations. The former receives more rainfall than the total of average annual rainfall of the basin and one standard deviation and the later gains lesser amount of rainfall, less than the difference between basin's average annual rainfall and one standard deviation. These two categories exhibit quite distinctive monthly rainfall patterns. Bhainsdehi, Chikhaldara and Dharani located in the eastern part of the basin as well as Navapur, Mandavi and Surat in the extreme west receive reasonably high rainfall, lie in the first category. Whereas, the stations situated in the south-western region of the basin such as Malegaon, Nandgaon, Satana, Dhule, Sakri and Shindkheda receiving less rainfall, can be grouped into second category. The stations of both these categories exhibit diverse regime of monthly rainfall. Following the monthly rainfall pattern of the basin, July is the wettest month at high rainfall stations. Therefore, the distribution of monthly rainfall of these stations shows unimodal pattern. The rainfall attains its peak only once in a year i.e. in July and rest of the months receives less rainfall than of July. Chikhaldara, Dharani, Bhainsdehi and Surat present unimodal rainfall pattern. Figure 2.4 (a), represent the unimodal rainfall pattern at Chikhaldara. Whereas, low rainfall stations present different monthly rainfall pattern than of the high rainfall stations. These stations show rather more fluctuations in the monthly rainfall. For example, Sakri, Satana and Malegaon receive high amount of rainfall in July, low in August and again more than August in September. Therefore, the graphical representation of monthly rainfall at Sakri, Satana and Malegaon represent bimodal trend, having two peaks. Figure 2.4 (b), exhibit the bimodal rainfall pattern at Sakri. High rainfall in September particularly at low rainfall stations may be attributed to low pressure systems (LPS) originating on the land or on the sea or due to localized convectional rainfall. Every year the country experiences heavy rainstorms associated with the tropical disturbances in the form of low pressure areas, depressions, deep depressions or cyclonic storms (Nandargi and Dhar, 2002). Several of these disturbances originate over the Bay of Bengal or the Arabian Sea. They travel through the country after crossing the coasts and form moderate to severe rainstorms along and near their tracks. These disturbances that take place during summer monsoon season perhaps associated with the increase of rainfall in September.

Figure 2.4 Monthly rainfall pattern at representative stations

(a) Chikhaldara (high rainfall station)



(b) Sakri (low rainfall station)



Another distinctive aspect of rainfall of the high rainfall stations and low rainfall stations is differential proportion of monsoon and non-monsoon rainfall in the total amount of annual rainfall. Table 2.4 presents distribution of rainfall in monsoon and non-monsoon season at all rainguage stations in the Tapi Basin. High rainfall stations obtain substantial proportion of annual rainfall in monsoonal months and a lesser amount in non-monsoon season. For example, Chikhaldara, Dharani, and Surat obtain more than 90% of their annual rainfall in monsoon season and non-monsoon season contributes less than 10% of the annual total (Table 2.4). Whereas, at low rainfall stations, such as Malegaon, Satana and Sakri, monsoon season contribute about 80% of annual rainfall and non-monsoon season receives about 20% of annual rainfall (Table 2.4). The Tapi Basin as a unit obtains nearly 87% rainfall in the monsoon season and just 13% in non-monsoon season (Table 2.4), which accentuates the supremacy of seasonal rainfall in the basin.

Table 2.4 Distribution of rainfall in monsoon and non-monsoon season

Month	AAR (mm)	NMR (mm)	MR (mm)	% NMR	% MR
Achalapur	861.72	129.24	732.48	15.00	85.00
Akola	801.68	116.03	685.65	14.47	85.53
Akot	775.64	108.71	666.93	14.02	85.98
Amalner	677.82	85.00	592.82	12.54	87.46
Amaravati	866.95	136.04	730.91	15.69	84.31
Anjangaon	736.83	114.83	622.00	15.58	84.42
Atner	837.89	119.15	718.74	14.22	85.78
Badnera	842.29	118.24	724.05	14.04	85.96
Balapur	742.94	98.45	644.49	13.25	86.75
Bhadgaon	728.14	94.02	634.12	12.91	87.09
Bhainsdehi	1035.76	146.09	889.67	14.10	85.90
Bhusaval	730.93	90.49	640.44	12.38	87.62
Buldhana	870.43	126.31	744.12	14.51	85.49
Burhanpur	843.12	92.91	750.21	11.02	88.98
Chalisgaon	736.37	112.33	624.04	15.25	84.75
Chandurbajar	802.02	120.62	681.40	15.04	84.96
Chikhaldara	1596.81	150.81	1446.00	9.40	90.60
Chopda	729.12	72.44	656.68	9.94	90.06
Daryapur	716.73	102.98	613.75	14.37	85.63
Dhamangaon	809.63	120.14	689.49	14.84	85.16
Dharani	1162.48	87.05	1075.43	7.49	92.51
Dhule	603.09	87.23	515.86	14.46	85.54
Erandol	688.01	81.69	606.32	11.87	88.13
Jalgaon	735.46	104.92	630.54	14.27	85.73
Jalgaon Jamod	773.53	90.03	683.50	11.64	88.36
Jamner	794.02	102.57	691.45	12.92	87.08
Kalvan	729.99	132.02	597.97	18.09	81.91
Khamgaon	730.80	111.27	619.53	15.23	84.77
Kholapur	772.13	115.72	656.41	14.99	85.01
Malegaon	557.13	107.35	449.78	19.27	80.73
Malkapur	712.22	96.83	615.39	13.60	86.40
Mandavi	1446.64	55.51	1391.13	3.84	96.16
Muktainagar	688.49	90.28	598.21	13.11	86.89
Multai	978.02	141.53	836.49	14.47	85.53
Murtijapur	816.89	119.90	696.99	14.68	85.32
Nandgaon	605.23	113.82	491.41	18.81	81.19
Nandura	753.88	112.87	641.01	14.97	85.03
Nandurbar	691.56	70.88	620.68	10.25	89.75
Navapur	1118.31	69.54	1048.77	6.22	93.78
Pachora	685.73	86.93	598.80	12.68	87.32
Pansemal	836.60	65.16	771.44	7.79	92.21
Parola	685.73	86.93	598.80	12.68	87.32
Patur	876.77	121.82	754.95	13.89	86.11
Pimpalner	629.84	96.83	533.01	15.37	84.63
Raver	721.89	101.84	620.05	14.11	85.89
Sakri	511.15	86.56	424.59	16.90	83.09
Satana	501.06	107.93	406.07	21.00	79.00
Shahada	684.77	65.79	618.98	9.61	90.39
Shegaon	739.48	111.53	627.95	15.08	84.92
Shindkheda	564.06	69.86	494.20	12.39	87.61
Shirpur	665.82	70.90	594.92	10.65	89.35
Sirpur	908.71	123.38	785.33	13.58	86.42
Surat	1143.05	58.85	1084.20	5.15	94.85
Taloda	794.13	58.82	735.31	7.41	92.59
Telhara	753.45	100.13	653.32	13.29	86.71
Yaval	737.78	85.90	651.88	11.64	88.36
Tapi Basin	**795.96**	**100.94**	**695.02**	**12.68**	**87.32**

Data source: IMD, Pune; AAR = Average annual rainfall; MR = Monsoon rainfall; NMR = Non-monsoon rainfall

2.4 Rainy days

The number of rainy days is one of the important components of rainfall regime. The significance of the study of rainy days lies in the fact that the number of rainy days determines the length of rainy season. The monthly and annual totals of rainfall are also influenced by the number of rainy days. According to Pant and Rupa Kumar (1997) and IMD, a 'rainy day' is a day when 0.25 cm or more rainfall is recorded. The rainy days and subsequently the rainfall in the Tapi Basin display considerable unevenness. Table 2.5 represents the average annual number of rainy days at various rain gauge stations in the basin. The average annual rainy days of the basin are 44 featured by high variation from one station to another. The highly uneven distribution of rainy days of the different stations in the basin is shown graphically in Figure 2.5. The number of rainy days in the basin varies generally between 30 and 70 (Table 2.5, Figure 2.5).

The rainy days at a station has close relation with the annual rainfall of the corresponding station. Therefore, to reveal the relationship between the annual rainfall and rainy days at a station, both the parameters are compared with each other (Table 2.5). The numbers of rainy days of the various stations in the Tapi Basin are strongly associated with their annual rainfall totals and are positively correlated with each other. The pattern of rainy days in the basin follows the pattern of annual rainfall that is, high rainfall receiving stations (low rainfall receiving stations) has more number (less number) of rainy days (Table 2.5).

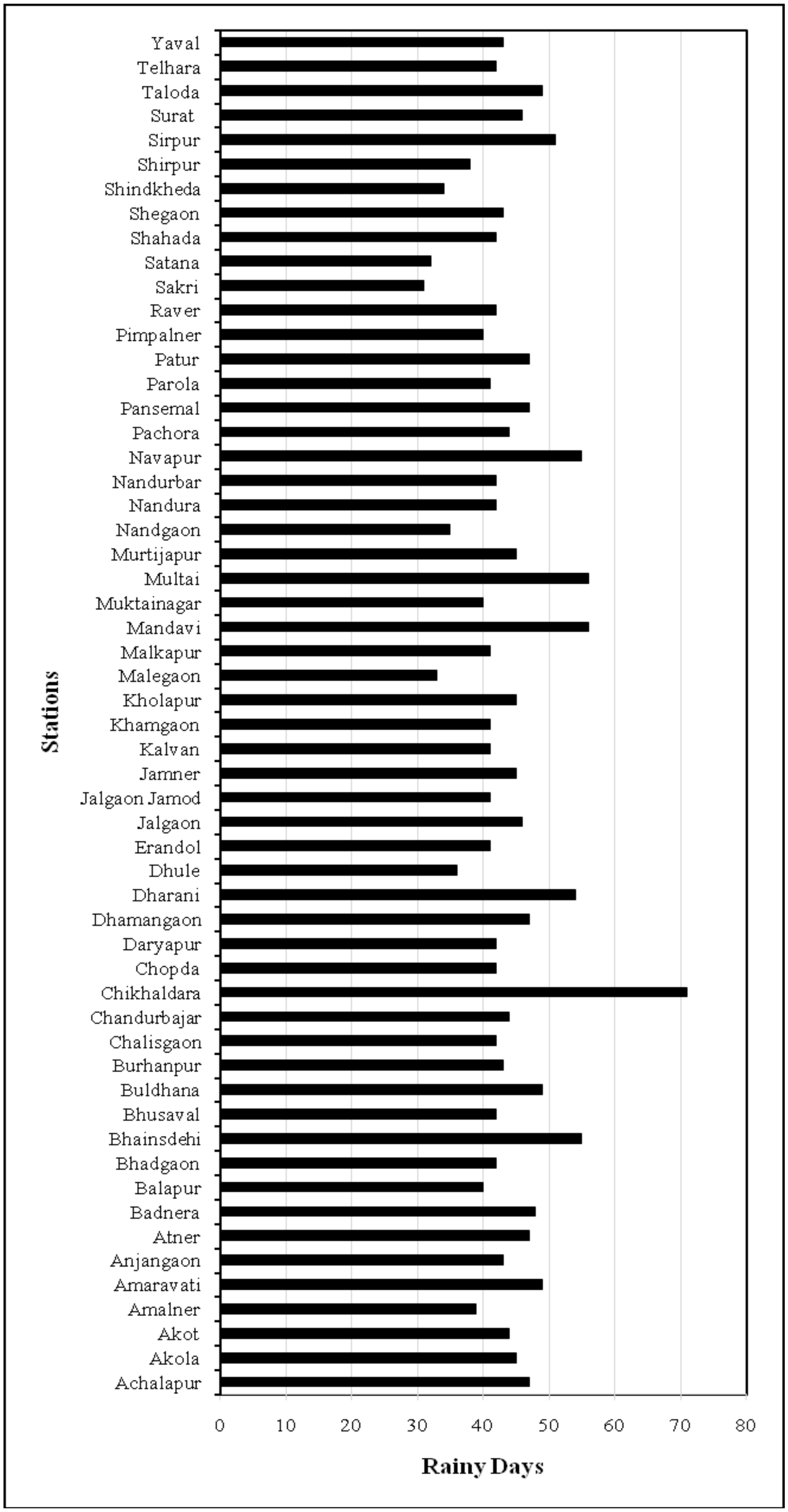
The rain gauge stations in the vicinity of the hilly region in the east, near the source of River Tapi and the stations situated to the far west, close to the mouth of the river have greater annual rainfall and consequently high numbers of rainy days. In the eastern hilly region of heavy rainfall, the number of rainy days varies between 55 and 70. The number of rainy days at Sirpur is 51, at Dharani is 54 and at Bhainsdehi and at Multai have 55 and 56 rainy days successively. Chikhaldara, the heaviest rainfall station of the basin has highest number of rainy days (71) in the basin (Table 2.5).

Table 2.5 Average annual rainfall and rainy days of different stations in the Tapi Basin

Station	AAR (mm)	RD	Station	AAR (mm)	RD
Achalapur	861	47	Kholapur	764	45
Akola	785	45	Malegaon	554	33
Akot	771	44	Malkapur	708	41
Amalner	676	39	Mandavi	1445	56
Amaravati	848	49	Muktainagar	688	40
Anjangaon	732	43	Multai	968	56
Atner	820	47	Murtijapur	808	45
Badnera	813	48	Nandgaon	605	35
Balapur	737	42	Nandura	755	42
Bhadgaon	727	55	Nandurbar	690	42
Bhainsdehi	1023	42	Navapur	1116	55
Bhusaval	730	40	Pachora	780	44
Buldhana	850	49	Pansemal	801	47
Burhanpur	838	43	Parola	686	41
Chalisgaon	735	42	Patur	874	47
Chandurbajar	789	44	Pimpalner	629	40
Chikhaldara	1596	71	Raver	721	42
Chopda	721	42	Sakri	511	31
Daryapur	706	42	Satana	514	32
Dhamangaon	792	47	Shahada	686	42
Dharani	1159	54	Shegaon	721	43
Dhule	602	36	Shindkheda	563	34
Erandol	684	41	Shirpur	667	38
Jalgaon	758	46	Sirpur	906	51
Jalgaon Jamod	723	41	Surat	1124	46
Jamner	793	45	Taloda	793	49
Kalvan	723	41	Telhara	746	42
Khamgaon	717	41	Yaval	733	43
Tapi Basin				**814**	**44**

Data Source: IMD, Pune

Figure 2.5 Average annual rainy days of different stations of the Tapi Basin



Similarly, high rainfall receiving stations located in the western boundary of the Tapi Basin such as Surat, Mandavi and Navapur are also characterized by greater number of rainy days. The number of rainy days at Surat is 46, at Mandavi is 56 and at Navapur is 55, which are greater than the average number of rainy days of the Tapi Basin (44) (Table 2.5). The geographical location of the stations seems to be influential in determining the annual rainy days of stations. Especially, higher number of rainy days at the stations mentioned above is attributed to their locations either in the vicinity of hilly terrain or nearness to the sea. Chikhaldara, Dharani, Bhainsdehi and Multai are situated in the Gawilgad Range while Surat, Mandavi and Navapur are located close to the Arabian Sea. The role of physiography and closeness of the sea on rainfall and its distribution within the basin has been assessed in chapter 3.

The places located in the eastern part of the basin, in the plain of River Purna gain moderate annual rainfall as well as moderate to high number of rainy days, about 45. For example, Akola, Shegaon, Nandura and Patur located in this region have 45, 43, 42 and 47 rainy days consequently. The central part of the Tapi Basin is designated by little less number of rainy days around 40. For example, Bhusaval, representing the central part of the basin have 40 rainy days and Erandol, Parola and Malkapur the other stations from the area have 41 rainy days each.

The south-western section of the basin comprises the lowest rainfall receiving stations of the basin. The places such as Sakri, Satana, Malegaon, Dhule and Shindkheda from this area obtain very scanty annual rain, ranging between 500 and 600 mm. Subsequently, this area accounts remarkably less number of rainy days (Table 2.5). Sakri records only 31 rainy days, which are the lowest number of rainy days in the Tapi Basin and are less than half of the highest number of rainy days of an individual station in the basin at Chikhaldara (71). Satana (32) and Malegaon (33) also featured by less number of rainy days (Table 2.5). In spite of a few stations of high rainy days in the western part of the basin, western section of the basin as a whole presents less number of rainy days than the eastern and central parts of the basin due to some stations of low rainy days.

Therefore, the spatial pattern of rainy days shows that the number of rainy days (therefore rainfall) decreases from east to west with the western tip of the basin as an exception. Considering the Tapi Basin as a geographical unit, the average rainy days in the basin are 44. Therefore, although the monsoon season extends for four months, the actual duration of the rainfall is around 37% of the total monsoon period and just 12% of the year in terms of days.

2.5 Monthly distribution of rainy days

As discussed earlier, the Tapi Basin is characterized by uneven distribution of rainfall due to varied number of rainy days in different months. The monthly distribution of rainy days in the basin is given in Table 2.6 and the same has been presented graphically in Figure 2.6. It is apparent that as the rainfall in the basin is concentrated in the monsoon months (June to September), it comprises maximum numbers of rainy days and rest of the year (non-monsoonal months) is characterized by a very few rainy days (Table 2.6, Figure 2.6).

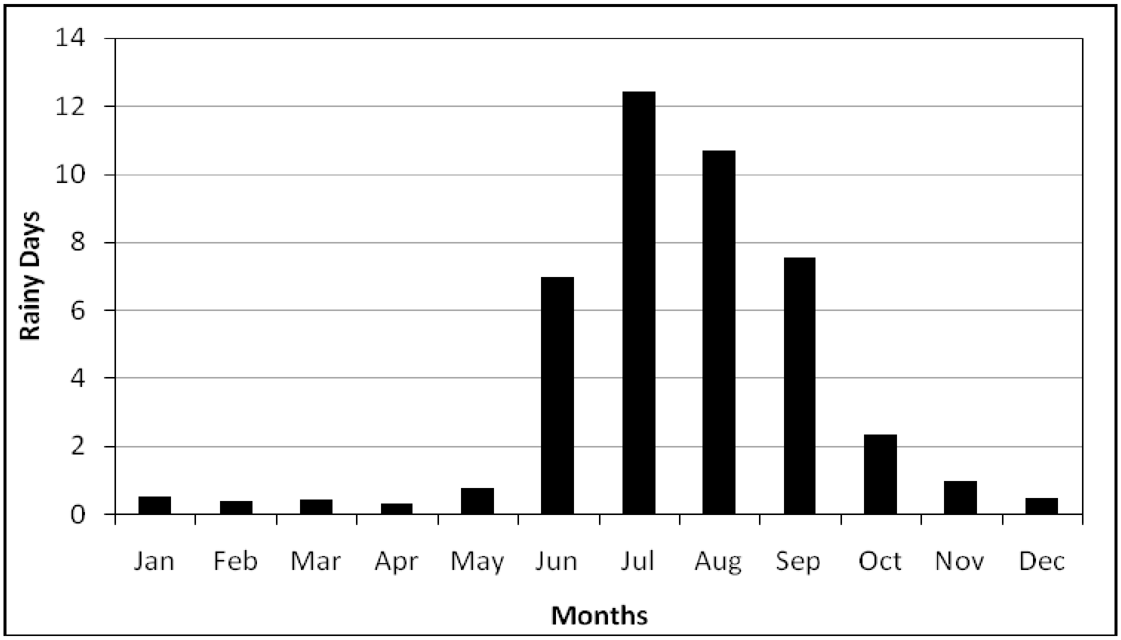
Table: 2.6 Average monthly rainy days in the Tapi Basin

Month	**Rainy Days**
January	1
February	0
March	0
April	0
May	1
June	7
July	12
August	11
September	8
October	2
November	1
December	1
Annual	**44**

Data Source: IMD, Pune

July is the rainiest month of the basin having highest (12) number of rainy days in the year followed by August with 11 rainy days. June and September has about 7 and 8 rainy days respectively (Table 2.6, Figure 2.6). Besides these monsoonal months, other months of the year shows negligible number of the rainy days. April is the driest month of the basin having almost no rain. In addition to the general pattern of the distribution of rainy days, the variation in the distribution of rainy days at different stations in the Tapi Basin is also been examined.

Figure: 2.6 Average Monthly Rainy Days of the Tapi Basin



Most of the stations in the basin receive maximum rainfall in July, therefore, it represents higher number of rainy days at almost all the stations. At the high rainfall obtaining places viz. Chikhaldara, Bhainsdehi, Dharani, Navapur and Mandavi, August gains equally high number of rainy days. However, a few stations, particularly low rainfall stations such as Sakri, Satana and Malegaon exhibit bimodal pattern of rainy days. These stations present more number of rainy days in July, August represents little less number of rainy days and again in September number of rainy days increases than that of August. Another fact can be noticed about the monthly distribution of rainy days at the aforesaid high and low rainfall receiving stations is that the high rainfall obtaining places such as Chikhaldara, Bhainsdehi, Dharani, Navapur and Mandavi, show concentration of rainy days in June to September and there is negligible number of rainy days in other months of year. Whereas, low rainfall stations viz. Sakri, Satana and Malegaon are characterized by a few number of rainy days in the months other than monsoon season also.

Average annual rainfall at the particular rain gauge station and its annual rainy days provide some important facts about the rainfall of that place. Particularly, the intensity of daily rainfall can be understood from above-mentioned two parameters. Resembling the number of rainy days in the basin, the average rainfall per rainy day is also different. On an average, there is about 20 mm rainfall per rainy day in the Tapi Basin. It is obvious that different stations located in different parts of the basin represent varied amount of rain per rainy day. The places such as Chikhaldara, Bhainsdehi, Dharani, Navapur and Mandavi having high amount of annual rainfall receive high amount of rain per rainy day, which is about 24 to 25 mm. Whereas, the low rainfall obtaining stations viz. Sakri, Satana and Malegaon receive low amount of rain per rainy day, about 16 to 17 mm. There exist a positive relationship between the number of rainy days and the annual rainfall. It suggests that the occurrence of more rain corresponds to large number of rainy days. However, it is to be taken into consideration that a few days in the monsoon season receive exceptionally heavy rains. Therefore, a large amount of rainfall is received in very short period of time, which may influence the various hydrological parameters in the basin and may turn out into flood situations. Therefore, the events of exceptionally high rains over the Tapi Basin are also studied and the results are presented in the following section.

2.6 Excessive rains

A distinct feature of Indian monsoon rainfall is infrequent heaviness of the fall in short period of time. Many places in India have recorded 40-100% or even more of their mean annual rainfall in one-day (Dhar and Mandal, 1981). For better understanding of the physical process producing rainfall, the study of short-period rainfall is important (Pant and Rupa Kumar, 1997). The heaviest recorded one-day rainfalls over India have been studied by Rakhecha et al. (1991). The heaviest falls in one-day were mostly recorded at coastal and hilly places of India, however, many stations in the rain-shadow region, as well as in dry tracts of the country have also recorded occasional heavy rainfall in a day. In this section, one-day (24 hr) rainfall data for selected stations from the Tapi Basin have been analyzed to get acquainted with the occurrences, intensity and its subsequent effects on different aspects of rainfall in the basin.

It is important to note here that, the point rainfall of a place influence the monthly and annual averages of that place and also reflect the hydrological characteristics of the region. Considering the average annual rainfall of the Tapi Basin (814 mm) and its average annual rainy days (44), on an average, there is about 20 mm rainfall per rainy day in the basin. However, many heavy to very heavy rainfall spells are on record at various locations in the basin. The details of highest recorded 24 hr rainfall events at all stations in the Tapi Basin are given in Table 2.7. The rainfall in the basin is generally made up of a large number of spells of light to moderate rainfall and a few spells of heavy to very heavy precipitation. The range of the highest daily rainfall totals at an individual stations in the basin ranges from 157 to 600.6 mm (Table 2.7). The 600.6 mm rainfall at Amalner on July 30, 1992 is the highest one-day rainfall in the basin on record. Highest one-day rainfall at Satana on June 27, 1914 is 157 mm, however, all other stations received more one-day rainfall than that recorded at Satana (Table 2.7). Considering the average annual rainfall of the basin (814 mm), any rainfall amount which is more than its 20% (162.8 mm) can be a high 24 hr rainfall event. All the stations in the basin except one (Satana), received one-day rainfall which is more than 20% of the average annual rainfall of the basin. The intensity of occasional heavy rainspells at various locations in the basin can be understood from the fact that they have comprised up to 70% of basin's average annual rainfall in one-day. For example, about 600 mm 24 hr rainfall at Amalner (600.6 mm on July 30, 1992) and Bhainsdehi (600 mm on September 11, 1988) (Table 2.7) contributed about 74% of basin's average annual rainfall. Similarly, Surat, Dharani, Multai, Mandavi, Telhara and Buldhana also gained over 400 mm 24 hr rainfall that composed nearly 50% of average annual rainfall of the basin. Many other stations obtained rainfall more than one-fourth of basin's average annual rainfall in one day (Table 2.7).

Table 2.7 Highest 24 hr rainfall in the Tapi Basin

Station	Highest 24hr. rainfall (mm)	Date of occurrence	% of basin AAR	% of station AAR	% change in AAR of the station
Amalner	600.6	30/07/1992	73.78	88.61	141.89
Bhainsdehi	600	11/09/1988	73.71	57.93	67.01
Surat	459.2	02/07/1941	56.41	40.17	-0.57
Dharani	411.2	25/08/1965	50.52	35.37	-19.36
Multai	405.2	30/07/1991	49.78	41.43	-12.33
Mandavi	397	23/09/1945	48.77	27.44	43.06
Telhara	392.3	14/09/1959	48.19	52.07	85.57
Buldhana	390.8	25/08/2002	48.01	44.90	51.70
Akola	365.4	15/09/1959	44.89	45.58	56.23
Navapur	343	05/08/1968	42.14	30.67	20.18
Pansemal	320	29/09/1954	39.31	38.25	34.19
Balapur	304.8	13/09/1959	37.44	41.03	60.69
Jamner	298.5	01/07/1941	36.67	43.53	11.76
Pachora	298.5	01/07/1941	36.67	37.59	-21.20
Badnera	293.9	23/07/1921	36.11	34.89	13.33
Chikhaldara	291.3	11/11/1936	35.79	17.88	11.60
Shegaon	288	14/09/1959	35.38	38.95	82.11
Chandurbajar	281	03/09/2002	34.52	35.04	0.87
Nandurbar	276.4	05/08/1968	33.96	39.97	-7.79
Erandol	274.4	17/08/1990	33.71	39.88	65.88
Malegaon	265	11/06/1991	32.56	47.57	51.17
Dhamangaon	264.2	01/10/1928	32.46	32.63	85.90
Patur	262	22/07/1988	32.19	35.51	85.01
Yaval	262	06/08/1968	32.19	29.88	-14.64
Jalgaon Jamod	261	15/07/1993	32.06	33.74	28.68
Burhanpur	259.1	20/07/1894	31.83	30.73	94.80
Kalvan	256	10/09/1969	31.45	35.07	23.84
Chopda	251	11/08/1998	30.84	34.43	38.93
Nandgaon	243.8	15/10/1951	29.95	40.28	16.02
Bhusaval	237.6	13/06/1970	29.19	32.51	15.03
Amaravati	235	15/09/1933	28.87	27.11	36.39
Bhadgaon	234.4	25/07/1896	28.80	32.19	11.00
Muktainagar	233.9	31/07/1933	28.73	33.97	59.22
Anjangaon	233.7	21/08/1944	28.71	31.72	93.27
Murtijapur	233	27/08/1971	28.62	28.52	-21.38
Achalapur	231.2	29/08/1978	28.40	26.83	21.01
Malkapur	227	22/08/1997	27.89	31.87	42.85
Raver	226	13/06/1970	27.76	31.31	73.16
Parola	224	06/08/1968	27.52	32.67	16.08
Jalgaon	220.8	06/08/2006	27.13	30.02	33.15
Kholapur	212.1	15/09/1933	26.06	27.47	31.26
Pimpalner	209.6	16/08/1944	25.75	33.28	69.61
Daryapur	208.8	02/07/1905	25.65	29.13	8.91
Shirpur	208.3	16/07/1920	25.59	31.28	-6.72
Shindkheda	203.2	17/08/1944	24.96	36.02	72.89
Sirpur	200.7	14/08/1959	24.66	22.09	45.51
Taloda	195.2	17/08/1990	23.98	24.58	38.63
Akot	190.8	27/08/1924	23.44	24.60	17.12
Sakri	188	06/08/1968	23.10	36.71	23.40
Atner	185.5	14/09/1998	22.79	22.14	-4.88
Shahada	185	20/08/1989	22.73	27.02	42.76
Chalisgaon	182	02/07/1984	22.36	24.72	3.07
Khamgaon	175	24/09/1970	21.50	23.95	65.57
Dhule	173.7	05/08/1968	21.34	28.80	17.05
Nandura	165.1	13/09/1930	20.28	21.90	28.83
Nandura	165.1	14/09/1959	20.28	21.90	70.80
Satana	157	27/06/1914	19.29	31.33	47.33

Data source: IMD, Pune; AAR = Average Annual Rainfall

The investigation of the highest 24 hr rainfall events in the basin reveals that in general, the heaviness of such events owes to their locations either in the hilly tracts or nearness to the sea. The eastern stations situated in the vicinity of the Gawilgad Range and Betul Plateau characterized by heavy one-day rainfalls (refer Figure 1.1 for physiography of the basin and 1.4 for location of the stations). Dharani, Bhainsdehi, Multai, Telhara, and Chikhaldara from this zone recorded 300 to 600 mm 24 hr rainfall events which contributed about 40 to 70% of basin's average annual rainfall. Pansemal, placed in the foothills of the Satpura Range also obtained over 300 mm one-day rainfall which is equal to 40% of average annual rainfall of the basin. Besides these stations located in the neighborhood of mountains, a few stations from the river plain also obtained heavy spells of one day rainfall. For instance, Badnera, Akola, Buldhana, Balapur, Patur, Shegaon, and Dhamangaon situated in the plain of River Purna and Jamner and Pachora from central plain area acquired 300 to 400 mm one-day rainfall which is about 30 to 50% of basin's average annual rainfall.

The western rain gauge stations situated close to the Arabian Sea such as Surat and Mandavi also characterized by heavy 24 hr rainfall events. About 460 mm and 400 mm one-day rainfall of Surat and Mandavi respectively (Table 2.7) is nearly 50% of average annual rainfall of the basin. Nevertheless, Navapur, located to the western part of the basin also gained about 42% (343 mm) 24-hr. rainfall of basin's average annual rainfall.

The relationship between amount of 24 hr highest rainfall events and the average annual rainfall of station represent some noticeable facts about these events. It is observed that the high rainfall receiving stations obtained less proportion of rainfall in 24 hr highest rainfall events as compared to their average annual rainfall. The low rainfall stations, on the contrary, account large proportion of rainfall from 24 hr highest rainfall events with respect to their average annual rainfall. For example, Amalner, Telhara, Malegaon, Akola, Buldhana, Jamner, Balapur, Nandgaon, Nandurbar, Erandol, Shegaon, Pachora and Sakri having moderate to low annual rainfall received heavy one-day rainfall events which contributed 40-80% of the average annual rainfall of the respective stations (Table 2.7). Whereas, heavy one-day rainfall events at high rainfall stations in the basin like Chikhaldara, Mandavi, Dharani, and Navapur contributed just 20-30% of their average annual rainfalls (Table 2.7).

It is evident that 24 hr highest rainfall events are influential in raising the annual rainfall totals of a station. Many stations in the basin show substantial rise in their annual rainfall due to 24 hr highest rainfall events. Amalner for example, witnessed about 140% increase in the average annual rainfall of 1992. This high rise in the annual rainfall total owes to 600.6 mm one-day rainfall at the station, which is highest ever recorded one-day rainfall in the basin (Table 2.7). Highest 24 hr rainfall events at several other stations such as Burhanpur, Anjangaon, Dhamangaon, Telhara, Patur, Shegaon, Raver, Shindkheda, Nandura and Pimpalner also resulted into 70-90% increase in the average annual rainfall totals of respective years (Table 2.7). Whereas, 20-40% rise in the average annual rainfall of the station due to highest 24 hr rainfall events is general in the basin. However, at some stations in the basin, highest 24 hr rainfall events did not result into increase in the annual total of the station. Few stations in the basin, in spite of gain of high rainfall in one day, show even less amount of annual rainfall than their average annual rainfall (Table 2.7).

2.7 Extreme rainfall events and climate change

Climate change is one of the major challenges of recent time. It is a complex issue and adds considerable stress to our societies and to the environment (UNEP, www.unep.org). Furthermore, it is normally judged on the basis of the behavioral changes in the precipitation amount and distribution of the area. An extremity in rainfall is often considered as a key indicator of climate change over the region. Therefore, in this section one-day extreme rainfall events in the Tapi Basin are analyzed and the results are interpreted to examine the climate change over the basin.

The impacts of climate change are felt most strongly through changes in the climate extremes, therefore, climate extremes are receiving more attention (Klein Tank et al., 2006). Being an agricultural country, Indian economy and its growth predominantly rely on the vagaries of the weather and in particular the extreme weather events (De et al., 2005). Some of the recent climate extreme events such as devastating heavy rainfall (June 17, 2013) over Kedarnath (Uttarakhand) and exceptionally extreme and recurrent hailstorms in March 2014 over extensive parts of Maharashtra are widely linked with the climate change phenomena. With considerable global warming, the frequency of occurrence of extreme events has been increased. It is broadly considered that with the increase of temperature, there will be increase of precipitation amount and intensity (Wang et al., 2008). Several heavy rainfall events in last few decades shattered the economy of different parts of the world. In India, 2005 heavy rainfall events and consequent floods caused tremendous damage in some major cities in India. The flash floods over three metro cities in the same year, i.e., Mumbai (July 2005), Chennai (October and December 2005) and Bangalore (October 2005) caused heavy loss of economy and life (Guhathakurta et al., 2010).

The investigation of short-period rainfall is important for better understanding of the physical process producing rainfall (Pant and Rupa Kumar, 1997). Moreover, the studies of extreme rainfall events with its spatio-temporal variability and trend are incredibly useful for planners and researchers in different fields. Occasional heaviness of the fall in short period is a distinct feature of the monsoon rainfall of the nation. Many places in India have recorded 40-100% or even more of their mean annual rainfall in one-day (Dhar and Mandal, 1981). Several studies are carried out on various aspects of climate on global to regional level. Investigations on climate change in last few decades have generally highlighted the changes in mean values. However, in evaluating the socio-economic impacts of climate change, studies of such changes in the occurrence of extreme weather and climatic events are important (Rupa Kumar et al., 2006). Moreover, to know the changes in extreme weather events than the changes in mean pattern is essential for better disaster management and mitigation (Guhathakurta et al., 2011).

A large number of studies are available on extreme rainfalls in the country. Rakhecha et al. (1991) have studied the heaviest recorded one-day rainfall over India. The heaviest falls in one-day were mostly recorded at coastal and hilly places of India. However, many stations in the rain-shadow region have also recorded occasional heavy rainfall in a day. Guhathakurta et al. (2010) observed evident changes in the extreme rainfall events in the past century over India. SenRoy and Balling (2004) analyzed rainfall data of uniformly distributed 129 stations across the country with reasonably complete records from 1910 to 2000 and concluded that, in general, evidence exists for an increase in the frequency of extreme precipitation over the country. Attri and Tyagi (2010) analyzed a homogeneous data series of rainfall for the period 1901-2003 to bring out the variability and trends of rainfall. They observed that the frequency of extreme rainfall (Rainfall ≥ 124.4 mm) show significant increasing trend over the country during the southwest monsoon season. Similarly on monthly scale, the frequency of extreme rainfall events show significant increasing trend during June and July. By using a daily rainfall data set, Goswami et al. (2006) demonstrated that in spite of considerable year-to-year variability, there are significant increases in the frequency and the intensity of extreme monsoon rain events in central India over the period of 1951 to 2000. Krishnamurthy et al. (2009) and Vitthal et al. (2013) stated that extreme rainfall over the country shows an increasing trend especially in the later half of the 20th century.

Several studies on heavy rainfall over the small administrative regions such as states have also been carried out (Gore and Potdar (2007), Dubey and Balakrishnan (1992), Bbi et al. (1981), Pandey (2007), Jayadeven and Mehajan (2006), Mohapatra and Mohanty (2005)). There are, however, very few studies of heavy rainfall carried for river basins of India. River basins are natural regions which can display more meaningful and practical portrayal of the rainfall features of an area than administrative regions. Therefore, the present study aims to analyze the extreme rainfall events over the Tapi Basin from western India.

In order to understand the principal characteristics of extreme rainfall events over the basin, following methodology has been adopted. As per the classifications by IMD, the rainfall events have been divided into eight different categories from ‘no rain’ to ‘extremely heavy rain’ based on the amount of rainfall in a day at a station (Table 2.8). For the present study, the IMD classification is followed. Since the present study is dedicated to extreme rainfall events, only very heavy (124.5 to 244.4 mm) and extremely heavy rainfall (≥ 244.5 mm) events are considered for the analyses. Pattanaik and Rajeevan (2010) combined very heavy and extremely heavy rainfall events for their study to make new category termed as ***‘extreme’*** rainfall events. Therefore, in the present study, one-day rainfall amounts exceeding 124.4 mm are considered as ***‘extreme’*** rainfall events. To detect the change in the extreme rainfall events, their frequencies have been tabulated and represented in graphical form along with linear trend.

Table 2.8 Classification of rainfall events based on 1 day (24 hr) rainfall amount at a station

Descriptive term used	Rainfall amount in mm
No Rain	- -
Very light Rain	0.1- 2.4
Light Rain	2.5 – 7.5
Moderate Rain	7.6 – 35.5
Rather Heavy	35.6 – 64.4
Heavy Rain	64.5 – 124.4
Very Heavy Rain	124.5 – 244.4
Extremely Heavy Rain	≥ 244.5

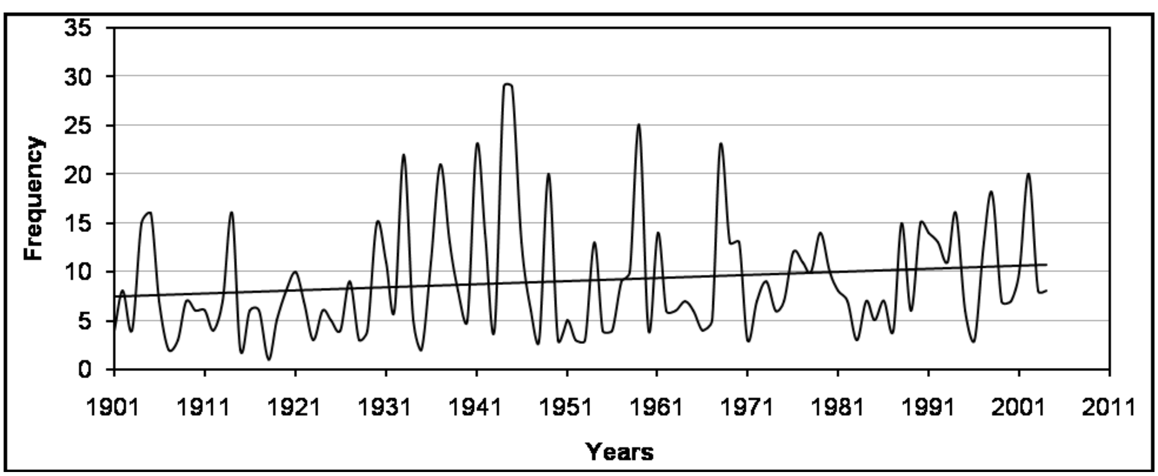
Source: IMD,Pune

To test the nature of extreme rainfall events, same methodology has been followed. The contribution of extreme rainfall events in a particular monsoon month and monsoon season has been calculated in percentage form and portrayed graphically. Further, analysis has been carried out to find out whether there is an increase or decrease in number of rainy days in the basin. In addition, average annual rainfall of the basin has also been calculated to find out the trend.

2.8 Trends in extreme rainfall events

In order to know the variability of frequency of extreme rainfall events, number of occurrences of extreme rainfall for 104 years from 1901 to 2004 are calculated and represented graphically in Figure 2.7.

Figure 2.7 Annual frequency of extreme rainfall events in the Tapi Basin



The extreme rainfall events show great variation from one year to another. It is found, however, that the rate of change is low, the extreme rainfall events represent increasing trend over the period of the century (Figure 2.7). The Tapi Basin is located in an environment typical of the monsoonal tropics, characterized by accumulated rainfall (about 85% of annual rainfall) during the monsoon season (JJAS). Apparently, extreme rainfall events are also highly concentrated in monsoon months. The total number of extreme rainfall events in the period under review is 951, out of that 898 (about 95%) are observed in monsoon months. To find out the variability of extreme rainfall events in the monsoon months, the average frequencies of extreme rainfall events during monsoon season are calculated and presented in Table 2.9.

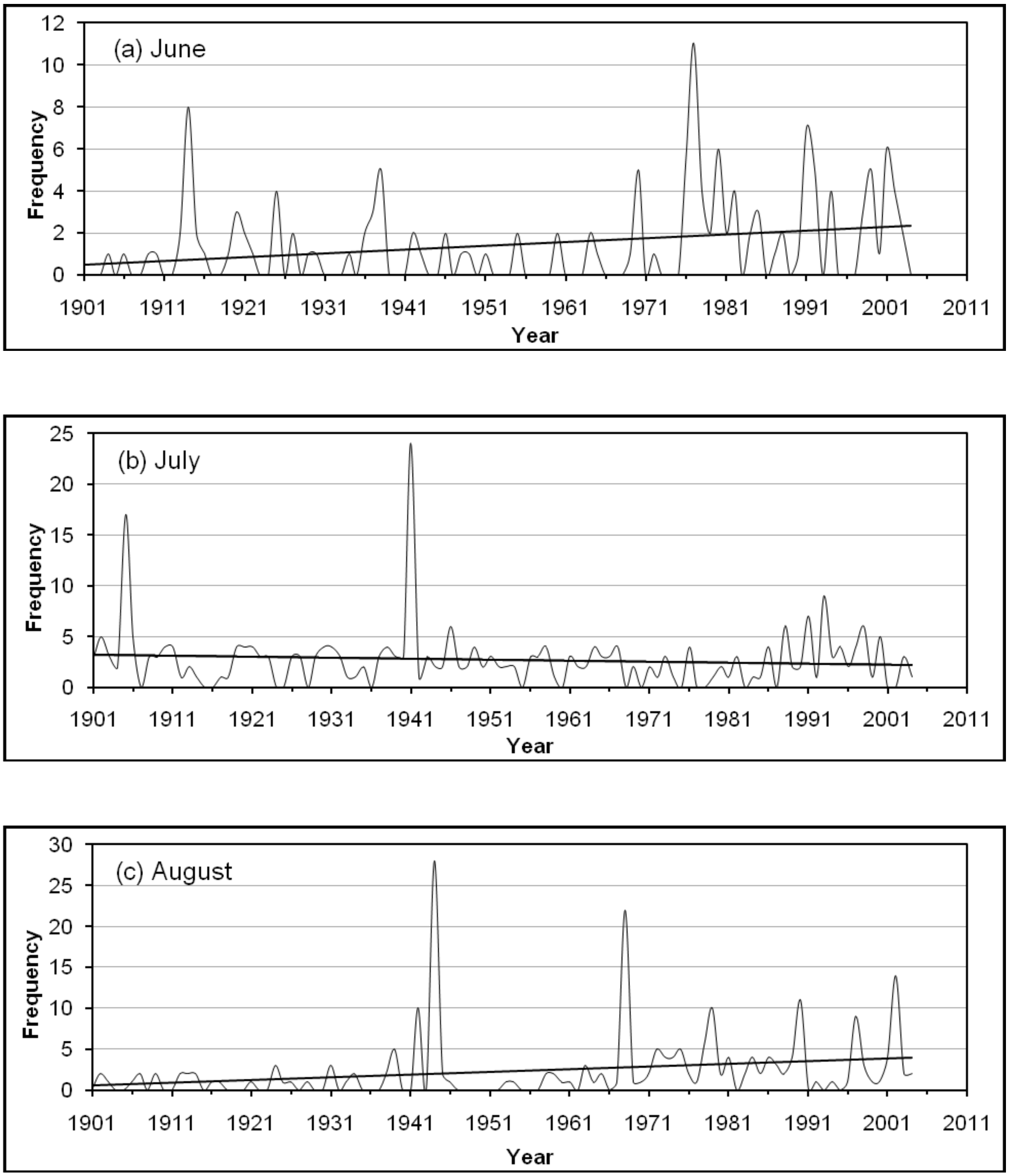
Table 2.9 Average frequency of extreme rainfall events during monsoon season

Month / Season	No. of extreme rainfall events	Average frequency of extreme rainfall events
June	146	1.4
July	281	2.7
August	232	2.23
September	239	2.3
Monsoon	898	8.63

Data source: IMD,Pune

In order to observe the inter-annual variability of *'extreme'* rainfall events during monsoon season, the frequencies of these events are plotted on monthly scale (JJAS) in Figure 2.8. The Figure indicates that the frequency of *'extreme'* rainfall events is increasing during the onset phase of monsoon in June. However, the active phase of monsoon that is July shows decreasing trend whereas, August represents an increasing trend. In the withdrawal phase of monsoon in September, *'extreme'* rainfall events illustrate again an increasing trend. Therefore, to bring out the inclusive trend of *'extreme'* rainfall events in the monsoon season, the frequencies of *'extreme'* rainfall events in four months of monsoon (JJAS) per year are plotted and shown in Figure 2.9. The Figure demonstrates an increasing trend in the *'extreme'* rainfall events. Thus, it is verified from Figures 2.8 and 2.9 that the frequency of extreme rainfall events is increasing during the southwest monsoon season in the Tapi Basin over the period of the century.

Figure 2.8 Frequency of extreme rainfall events on monthly scale in monsoon season



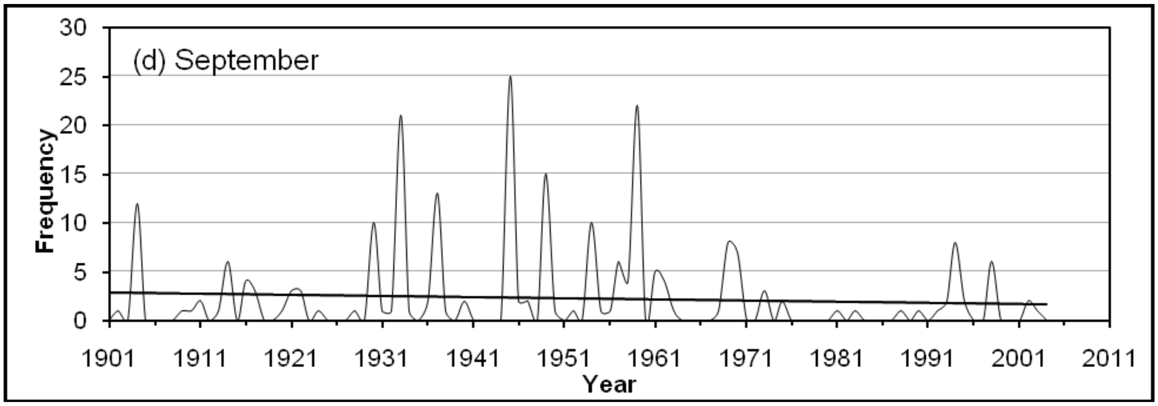
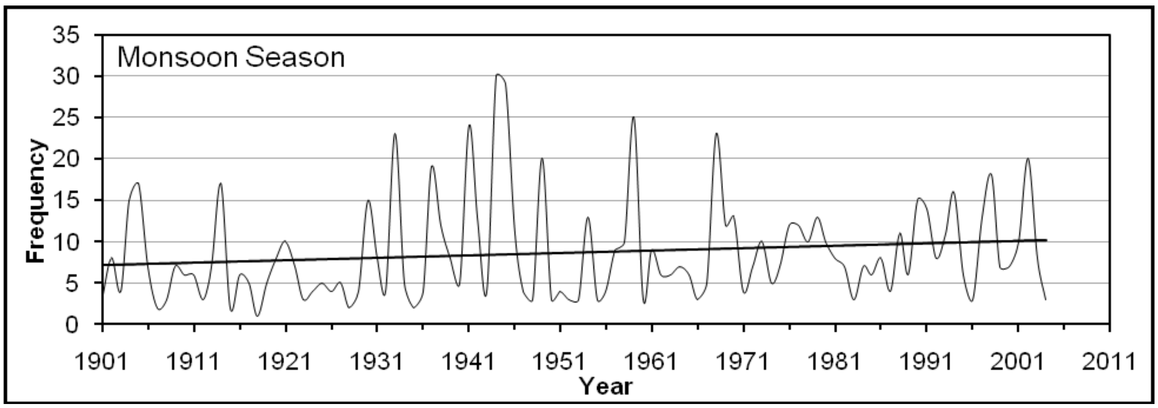


Figure 2.9 Average frequency of extreme rainfall events in monsoon season (June to September)



2.9 Contribution of extreme rainfall events in seasonal rainfall

The extreme rainfall occurrences can largely modify the annual as well as seasonal pattern of rainfall of the region by adding excess amount rainfall in short period of time. Therefore, to portrait the input of extreme rainfall occurrences in the seasonal rainfall of the basin, the mean contribution of extreme rainfall events in the monsoon months over the basin as a whole is calculated from 1901 to 2004 and is given in Table 2.10. It is seen from Table 2.10 that the monthly scale contribution of rainfall from extreme rainfall events show slight variations ranging between 2.79% and 3.66%. July and September (June and August) contributing more (less) amount of rainfall from extreme rainfall events in the total rainfall of the respective months. The whole monsoon season (JJAS) receive about 4% rainfall of the total rainfall of the season from extreme rainfall events. To recognize the trend of the contribution of extreme rainfall events in the monsoon months and season, the contribution of rainfall from extreme rainfall events on monthly and seasonal scales are plotted and presented in Figure 2.10 and Figure 2.11 respectively.

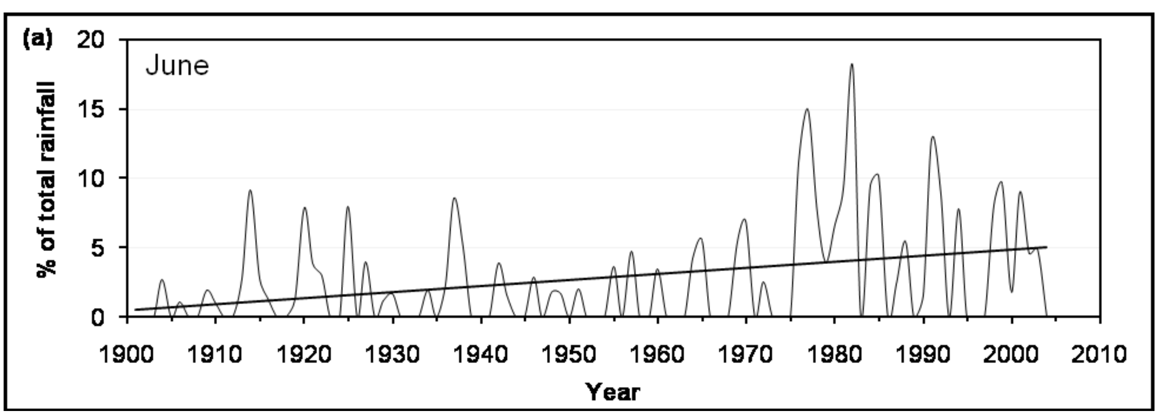
Table 2.10 Mean percentage of rainfall from extreme rainfall events in monsoon season

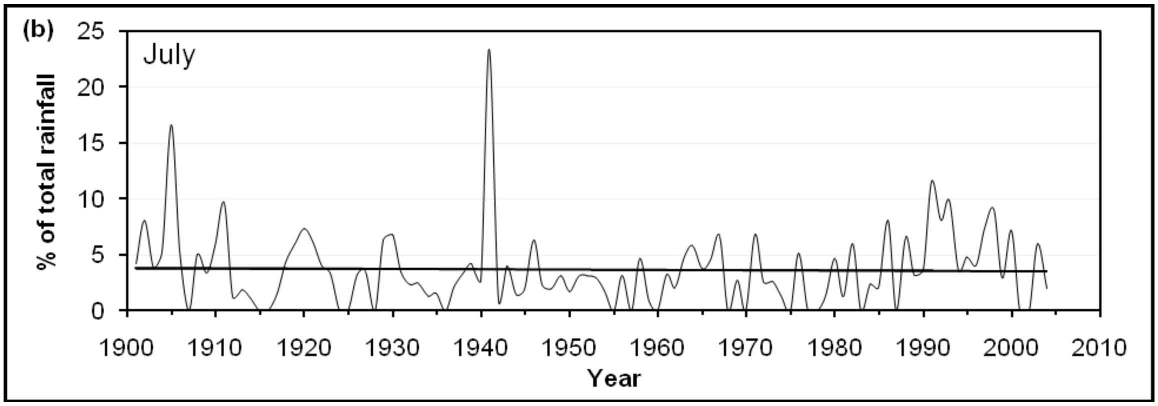
Month / Season	**%**
June	2.79
July	3.66
August	3.13
September	3.34
Monsoon	4.02

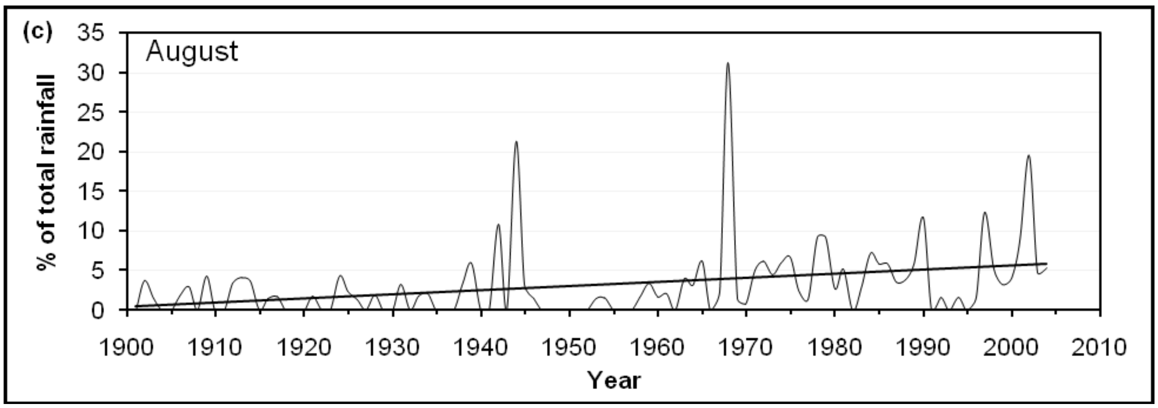
Data source: IMD, Pune

June and August (Figure 2.10 (a) and (c)) show an increasing trend in the occurrences of extreme rainfall events with respect to time. July and September (Figure 2.10 (b) and (d)) does not show increasing or decreasing trend in extreme rainfall events over the period under review. However, an average contribution of the extreme rainfall events of the monsoon season in the total rainfall of the season (JJAS) shows an increasing trend (Figure 2.11).

Figure 2.10 Average contribution (%) of extreme rainfall events to the total rainfall on monthly scale in monsoon season




(b)
July
% of total rainfall
0
5
10
15
20
25
1900
1910
1920
1930
1940
1950
1960
1970
1980
1990
2000
2010
Year


(c)
August
% of total rainfall
0
5
10
15
20
25
30
35
1900
1910
1920
1930
1940
1950
1960
1970
1980
1990
2000
2010
Year

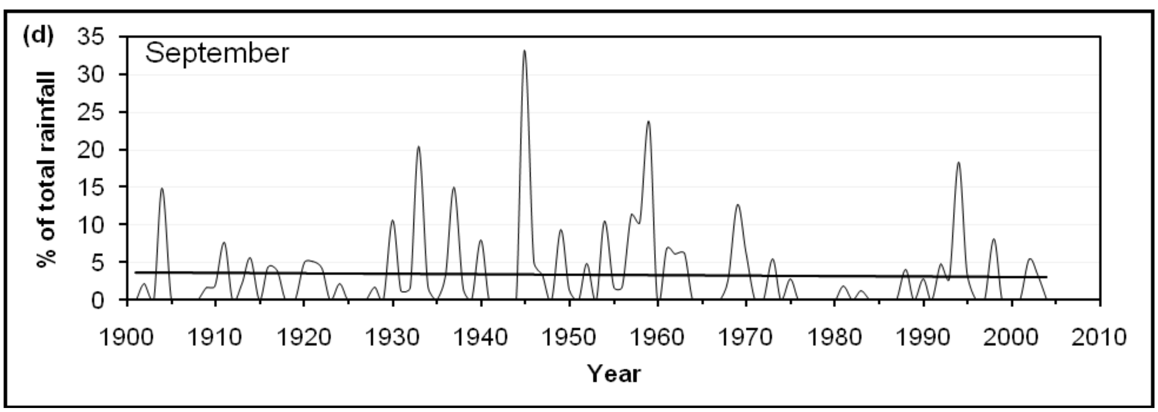
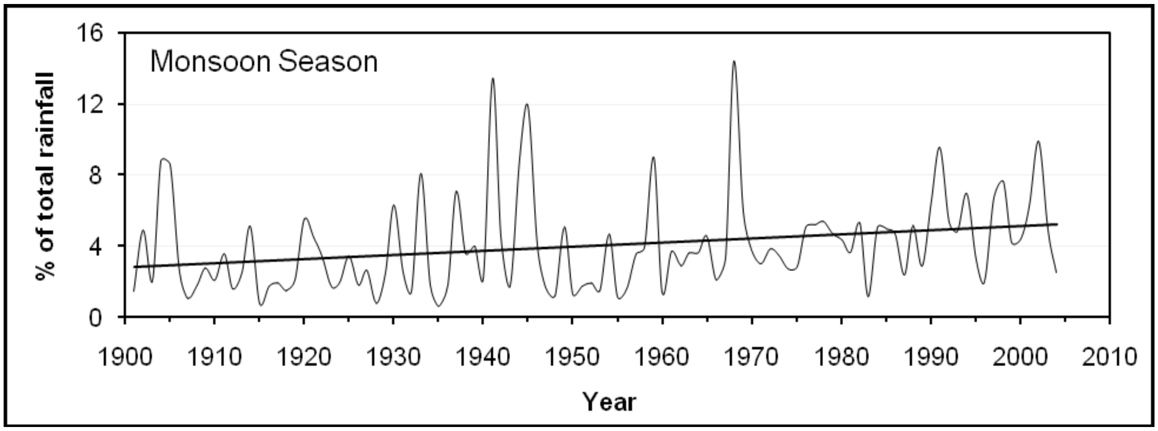

(d)
September
% of total rainfall
0
5
10
15
20
25
30
35
1900
1910
1920
1930
1940
1950
1960
1970
1980
1990
2000
2010
Year

Figure 2.11 Average contribution (%) of extreme rainfall events to the total rainfall of monsoon season



To obtain the comprehensive nature of extreme rainfall events over the Tapi Basin in the 20th century, contribution of extreme rainfall events in the seasonal rainfall (Figure 2.11), frequency of extreme rainfall events in the season (Table 2.9), its general trend with respect to time (Figure 2.9) and mean percentage of rainfall obtained from extreme rainfall events in monsoon season (Table 2.10) are compared with each other. The comparison brings out some important characteristics of extreme rainfall events over the basin. The average frequency of extreme rainfall events in the monsoon season (JJAS) over the basin is 8.63 (Table 2.9) contributing about 4% rainfall in the seasonal total (Table 2.10) representing an increasing trend (Figure 2.11). Therefore, two important characteristics of extreme rainfall events emerge from the present study: a) the frequency of extreme rainfall events over the period of the 20th century is increasing; b) the contribution of extreme rainfall events in the seasonal rainfall is also increasing. The study, therefore, supports the general thought of climate change and subsequently signifies an increase in disaster potential in the basin.

2.10 Extreme rainfall events, annual rainy days and annual rainfall of the Tapi Basin

It is evident from the previous sections that the extreme rainfall events are increasing over the Tapi Basin during the last century. Therefore, to understand its consequence on the annual rainfall of the basin, average annual rainfall of the basin for the period of 1901-2004 is presented graphically in Figure 2.12. The Figure clearly shows that the long-term trend of average annual rainfall of the basin is neither increasing nor decreasing. Thus, in spite of increasing trend of extreme rainfall events, average annual rainfall of the basin exhibit long term consistency. It, therefore, indicates that as the contribution of extreme rainfall events is increasing; the basin receives more amount of rainfall in less number of rainy days. To verify the association of annual rainy days of the basin with extreme rainfall events and annual rainfall of the basin, the average annual rainy days of the basin for the period of 1901-2004 are plotted in Figure 2.13. It is observed that the number of average annual rainy days is decreasing in the 20th century (Figure 2.13).

Figure 2.12 Average annual rainfall of the Tapi Basin

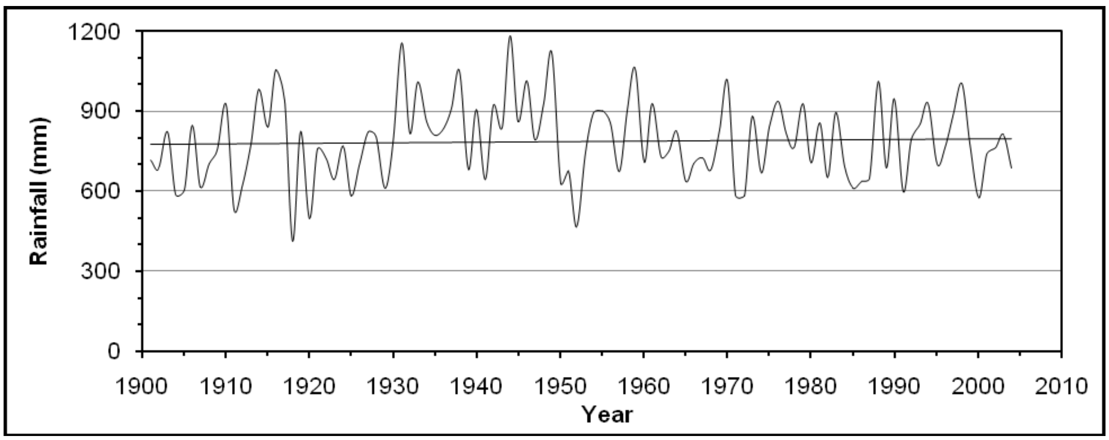
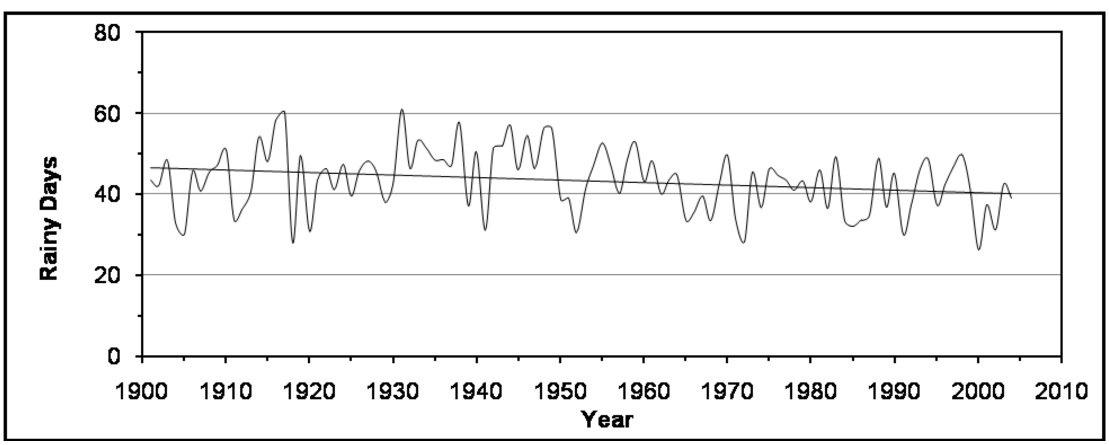


Figure 2.13 Average annual rainy days of the Tapi Basin



The study of extreme rainfall events over the Tapi Basin thus represents some important facts of rainfall regime of the basin. The extreme rainfall events over the Tapi Basin are increasing as well as their contribution in the seasonal rainfall (JJAS) is also increasing. Average annual rainy days are decreasing, however, average annual rainfall of the basin is neither increasing nor decreasing. The study, therefore, supports the general thought of climate change and subsequently signifies an increase in disaster potential in the basin.

2.11 Recurrence interval of highest 24 hr rainfall

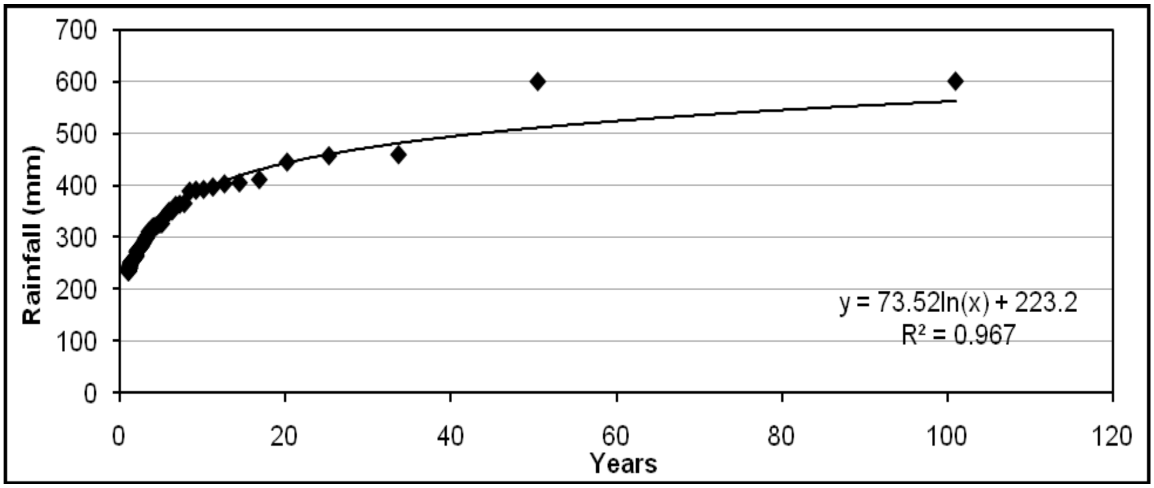
It is necessary to determine the greatest one-day rainfall that occur with a certain frequency, to understand the nature of excessive heavy rainfall events in the basin. The average time period within which a rainfall of specified amount or intensity can be expected to occur once is known as the return period or recurrence interval (Wisler and Brather, 1959). By frequency, it meant the average recurrence interval of rains equal to or greater than a certain magnitude. For instance, 10 yr frequency for a one-day rainfall is that magnitude of one-day rainfall which can be expected to equal or exceeded 5 times in 50 years or 10 times in 100 years. However, it certainly does not mean that such rain will be separated by 10 year intervals. Most likely that, two or more events will occur in 10 year period, it may occur in one year or even in one month. To estimate the recurrence interval, the one-day rainfall values are arranged in order to decreasing size such as number 1 to the largest rain, 2 to the second largest and so on. Then the recurrence interval of any rain is given by the equation;

$$RI = (N+1) / r \qquad \text{………. Eq. 2.1}$$

where, RI is the recurrence interval in years, N is the number of years and r is a rank. This Weibull's method has been proposed by Bary (1969) to calculate the return period of heaviest 24 hr rainfall.

To get acquainted with the probability of one-day maximum rainfall at certain intervals over the Tapi Basin, the record of annual maximum one-day rainfall over 100 years at all selected stations have been prepared. The data of 24 hr highest rainfall has been arrayed according to its magnitude. 100 highest 24 hr rainfall events are selected to check the probability of these events to take place again in the basin. Therefore, considering the Tapi Basin as a single unit the plot of recurrence interval of 24 hr highest rainfalls has been illustrated in Figure 2.14. This investigation has given a varied result.

Figure 2.14 Recurrence interval of highest 24 hr rainfall over the Tapi Basin



It is obvious that the heaviest 24 hr rainfall events are rare to happen as a result their recurrence interval is also high. It is observed from Figure 2.13 that one-day rainfall up to 200 mm, which is about one-fourth of the basin's average annual rainfall is quiet common in the basin and almost each year experiences 24 hr rainfall events equal to 200 mm. The possibility of 24 hr rainfall over 300 mm (nearly 40% of average annual rainfall of the basin) is after 4 to 5 years. Though a few in number, one-day rainfall about half (400 mm) of the average annual rainfall of the basin is also not unusual and shows recurrence interval of 10 to 12 years. However, the exceptional one-day rainfall events equal or more than 600 mm contributing 70 to 75% of average annual rainfall of the basin are very rare and shows recurrence interval of about 100 years. The possibility of these phenomenal rainfall events to happen is once in a century (Figure 2.14).

2.12 Resume

The principal objective of the analyses of the rainfall data of the Tapi Basin in this chapter was to identify the major regime characteristics of rainfall over the basin. The results of the analyses, presented above, emerge following general conclusions.

1. The average annual rainfall of the Tapi Basin is 814 mm comprising large spatio-temporal variation.
2. Chikhaldara is the rainiest place in the basin, receives 1596 mm average annual rainfall, which is almost double than the average annual rainfall of the Tapi Basin. Whereas, Sakri is the lowest rainfall receiving station having average annual rainfall just 511 mm.
3. The rainfall in the Tapi Basin shows the supremacy of south-west monsoon season. The basin receives nearly 87% of its total rainfall in monsoon season (June to September) and remaining 13% in non-monsoon season (October to May).
4. July is the rainiest month in the basin, contributes about 29% of the annual rainfall. Whereas, April is the driest month in the basin obtains negligible amount of rainfall.
5. High rainfall stations obtain substantial proportion of annual rainfall in monsoonal months and less in non-monsoon season. For example, Chikhaldara, Dharani, and Surat obtain more than 90% of their annual rainfall in monsoon season and non-monsoon season contributes less than 10% of the annual total. Whereas, at low rainfall stations, such as Malegaon, Satana and Sakri, monsoon season contribute about 80% of annual rainfall and non-monsoon season also receives about 20% of annual rainfall of the station.
6. The average annual rainy days of the basin are 44 per year with high variation from one station to another. The number of rainy days at various stations of the basin varies between 30 and 70.
7. The numbers of rainy days of the various stations in the basin are strongly associated with their annual rainfall totals showing positive correlations. Moreover, the pattern of rainy days in the basin follows the pattern of annual rainfall that is high rainfall stations (low rainfall stations) has more number (less number) of rainy days.

8. Chikhaldara, the heaviest rainfall station of the basin has highest number of rainy days (71) in the basin while Sakri, the lowest rainfall station has lowest number of rainy days (31) all over the basin.
9. July comprises highest number of rainy days (12) in the year followed by August (11 rainy days).
10. The 600.6 mm 24 hr rainfall at Amalner on July 30, 1992 is the highest one-day rainfall on record in the basin.
11. The investigation of the highest 24 hr rainfall events in the basin reveals that in general, the heaviness of such events owes to their locations either in the hilly tracts or nearness to sea.
12. Extreme rainfall events, as well as their contribution in the seasonal rainfall (JJAS) over the Tapi Basin are increasing.
13. Average annual rainy days are decreasing, however, average annual rainfall of the basin is neither increasing nor decreasing.
14. The study, therefore, supports the general thought of climate change and subsequently signifies an increase in disaster potential in the basin.
15. Recurrence interval of one-day rainfall up to 200 mm, which is about one-fourth of the basin's average annual rainfall, is quiet common in the basin and almost every year experiences 24 hr rainfall events equal to 200 mm. The possibility of 24 hr rainfall over 300 mm (nearly 40% of average annual rainfall of the basin) is 4 to 5 years. Though a few in number, one-day rainfall about half (400 mm) of the average annual rainfall of the basin is not unusual and shows recurrence interval of 10 to 12 years.
16. The exceptional one-day rainfalls equal or more than 600 mm contributing 70 to 75% of average annual rainfall of the basin are very rare and shows recurrence interval of about 100 years. Therefore, the possibility of such phenomenal rainfall events to happen in the basin is once in a century.

CHAPTER III

SPATIO-TEMPORAL ASPECTS OF RAINFALL

3.1 Introduction

Monsoon rain, since time immemorial has been the bedrock of India's food security and of the very survival of land and its people (Tyagi et al. 2012). It sustains the living of millions of Indian population and supports almost all the sectors of development in the country. It is a governing factor to India's economic growth. The monsoon is beautiful and captivating, but sometimes it brings misery and death. It is a regular visitor, but may turn up earlier or later than expected (Kelkar, 2009). Although the monsoons are a regular phenomenon, there are fluctuations in their intensity and spatial extent on time scales ranging from days to centuries (Pant and Rupa Kumar, 1997). In addition, it exhibits a wide spectrum of variability on daily, sub-seasonal, inter-annual, decadal and centennial time scales (Rajeevan et al. 2010).

As regards the water supply to agriculture, industry and growing urban population, the study of spatio-temporal variations in the rainfall over the country as well parts of it is of utmost importance. The variability in the monsoon rainfall occasionally leads to the extreme hydrological events such as droughts and floods which affects the huge population and national economy (Kripalani et al. 2003). Hence, the variability in the Indian monsoon especially in the global warming scenario is a topic of intense scientific debate. Several studies are carried out on the variable nature of monsoon rainfall of the country on both space and time scales.

Pant and Rupa Kumar (1997) systematically delineated spatio-temporal aspects of Indian rainfall on sub-divisional and macro-regional scales based on all-India mean rainfall. In addition, they have portrayed the variability of monsoon rainfall by giving an account of intra-seasonal variability, inter-annual variability, epochal patterns and its long-term trends. Monthly and seasonal variability of monsoon rainfall over 31 meteorological subdivisions of India, utilizing the rainfall data from 1960-1993 has been studied by Singh et al. (1999). Vines (1986) analyzed Indian rainfall figures obtained from World Weather Records to identify short to long-term cyclic pattern of Indian rainfall. Guhathakurta and Rajeevan (2008) using monthly rainfall data for the period 1901-2003 of 36 meteorological subdivisions of India presented the epochal variations in Indian summer monsoon rainfall. In addition, they also attempted to detect the trend in sub-divisional rainfall as well as in the country as a whole. Subramanian et al. (1992), Suresh (1996), Sahu and Nandankar (2006) Krishnakumar et al. (2009), and Rase (1998) also devoted their studies for trend analyses of rainfall over different parts of India. Excessive rainfall in short period is inherent feature of the monsoon rainfall. Pattanaik and Rajeevan (2010) presented the spatial and temporal variability of extreme rainfall events over India with their long-term trend.

Being a part of an inherent monsoonal region, the Tapi Basin reflects all typical features of the monsoon rainfall. The Tapi Basin receives rainfall predominantly during the southwest monsoon period and a small fraction of it is associated with rest period of the year. The rainfall over the region, therefore, is highly seasonal. Nevertheless, there is a large variability in the rainfall on both space and time scales. Therefore, a comprehensive analysis of rainfall based on the available data can present temporal fluctuations and spatial patterns of the basin rainfall. Variability, both over time and space is an important attribute of rainfall in the Tapi Basin which impinges on its resource value and utilization. To bring out the change of rainfall at different stations and to assess the variation in the basin rainfall over the period of a century, study of spatio-temporal aspects of rainfall is important. Such studies are immensely helpful for the planning of the agro-based economy of the regions like the Tapi Basin. It also provides a mosaic of rainfall over the basin along with its typical characteristics. Therefore, following the discussion on the regime characteristics of rainfall in the previous chapter, variability in the rainfall with respect to space and time has been discussed in this chapter.

3.2 Spatial distribution of rainfall

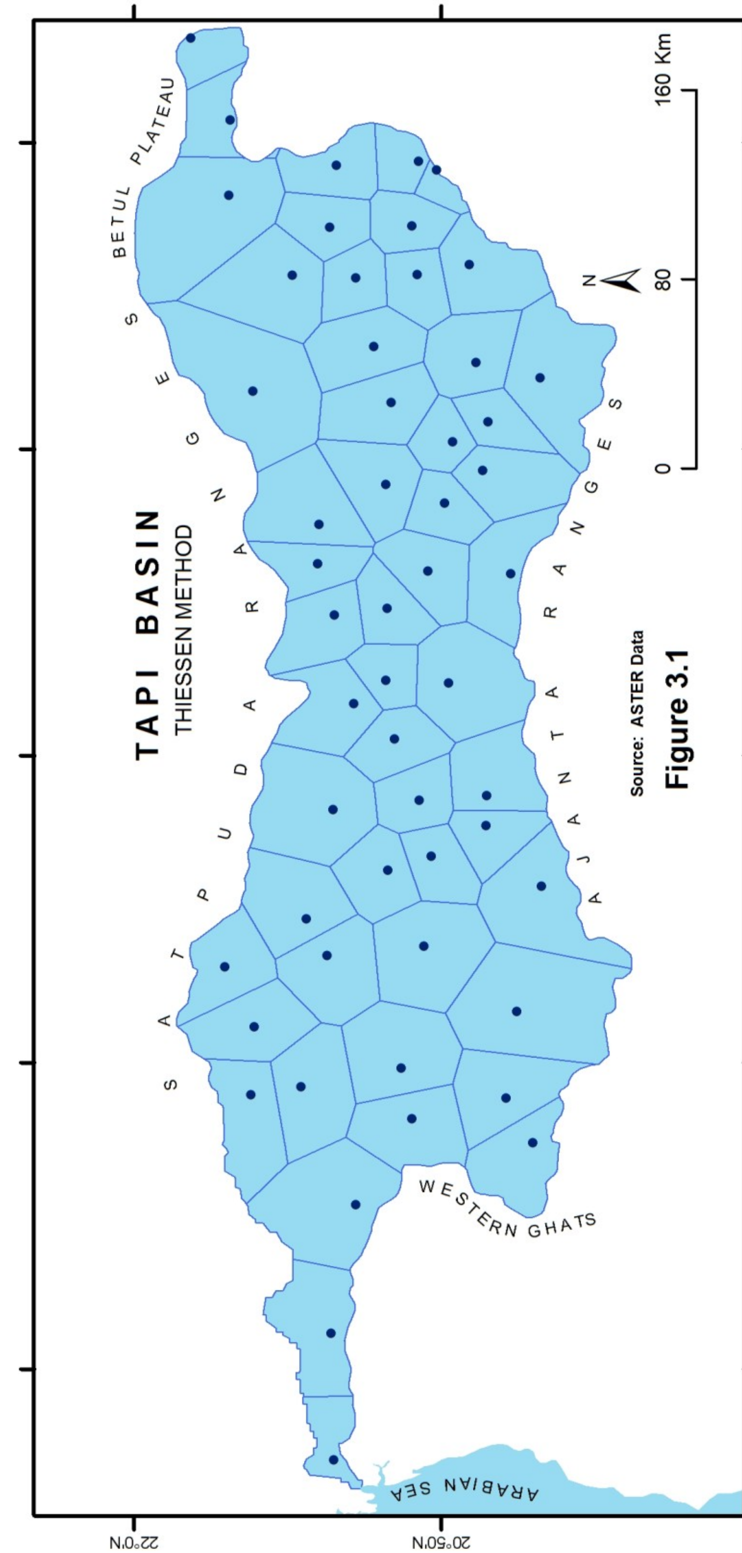
It is important to understand the areal distribution of rainfall. Generally, average depths of rainfall for representative portions of the watershed are calculated and used for this purpose (Viessman and Lewis, 2003). One of the basic methods is to consider the arithmetic average of rainfall. This procedure, however, is suitable for uniformly distributed rain gauge stations and flat topography. Nevertheless, neither the rain gauge stations of the Tapi Basin are uniformly distributed nor the topography is flat. Therefore, commonly applied methods such as the Thiessen method and isohyetal method are used for this purpose.

The Thiessen method is applied for calculating areal rainfall average of the Tapi Basin based on rainfall data of 56 raingauge stations. The method for the basin under review was made possible by means of the analysis of digital data of ca. 30-m resolution of Advance Spaceborne Thermal Emission and Reflection Radiometer (ASTER). Normally, 30-m resolution ASTER data with relative accuracy can be used effectively to assist mapping geomorphic, geologic, tectonic, landform, and a range of environmental studies in remote areas of rugged terrain (Lang and Welch, 1999; Hirano et al., 2003; Figueroa and Knott, 2010). Therefore, the ASTER data were used to extract information to apply the Thiessen method to determine the areal average annual rainfall of the Tapi Basin. This was achieved by using standard procedures in ArcGIS 9.3.

In Thiessen method, the area (basin) is subdivided into polygonal subareas using rain gauges as centers. The subareas are used as weights in estimating the average depth of rainfall of the Tapi Basin. Thiessen diagram constructed for the basin is shown in Figure 3.1. The areal average annual rainfall of the Tapi Basin determined by the Thiessen method is 814 mm. The same quantity of rainfall is used for all analyses of rainfall of the basin.

The Thiessen method is applied only for calculating areal average annual rainfall of the Tapi Basin. However, it is important to understand the areas of high and low rainfall as well as the spatial distribution of rainfall in the basin which is achieved by isohyetal method. This method is based on interpolation between rain gauge stations. It is similar to the calculation of contours in surveying and mapping. This method is the most accurate approach for determining average rainfall over an area. In order to prepare isohyetal map of the Tapi Basin, the ASTER data and standard procedures in ArcGIS 9.3 have been applied.

The variability both in space and time is the most common feature of monsoon rainfall. The Tapi Basin, a natural region of the country, shows a significant spatially diversified rainfall. Figure 3.2 shows the spatial distribution of rainfall over the basin.



Source: ASTER Data

Figure 3.1

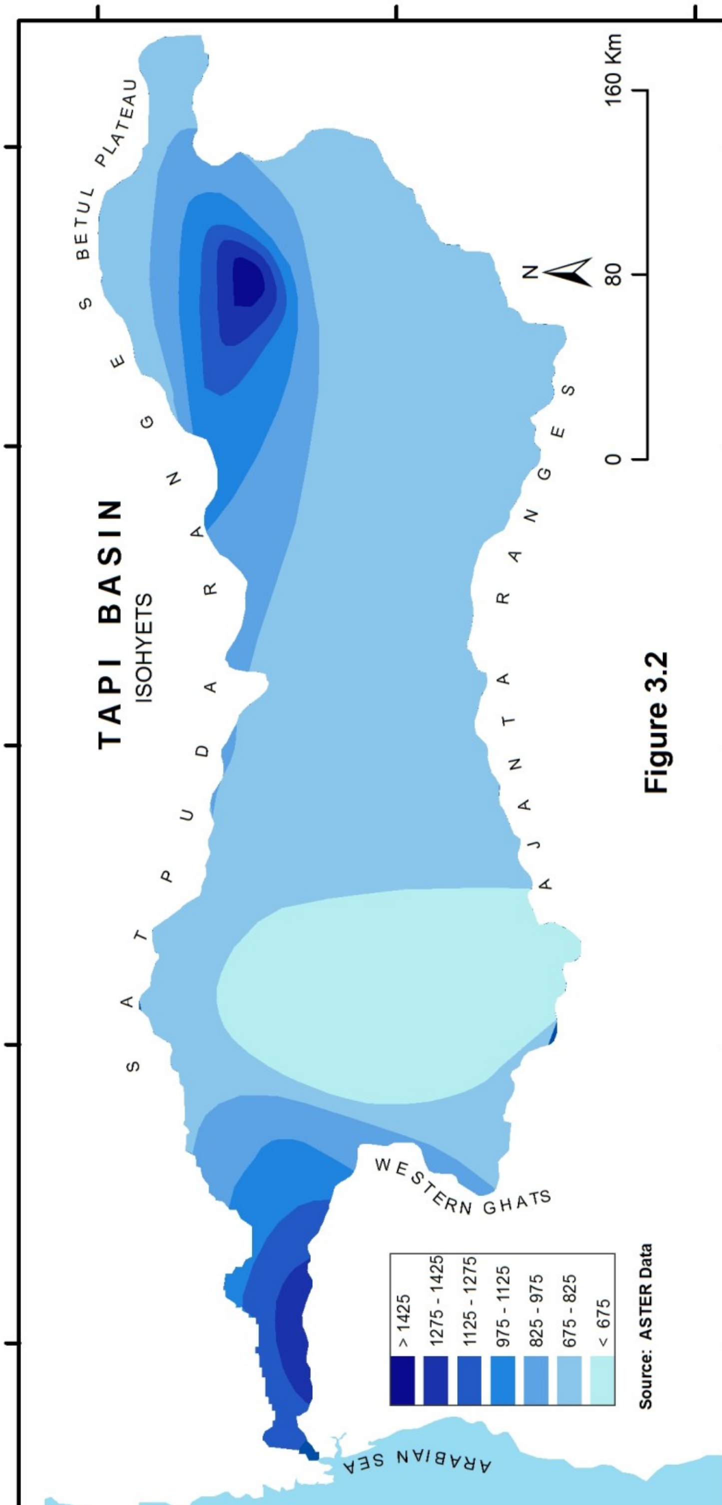

TAPI BASIN
ISOHYETS
SATPUDA RANGES
BETUL PLATEAU
AJANTA RANGES
WESTERN GHATS
ARABIAN SEA
N
0
80
160 Km
> 1425
1275 - 1425
1125 - 1275
975 - 1125
825 - 975
675 - 825
< 675
Source: ASTER Data
73°10'E
74°20'E
75°30'E
76°40'E
77°50'E
22°0'N
20°50'N
19°40'N

Figure 3.2

The figure illustrates far greater contrast in the amount of rainfall in different parts of the basin. Particularly, the eastern and western marginal areas of the basin show strongly non-uniform amount of rainfall than the rest of the basin. The isohyetal map (Figure 3.2) based on the annual rainfall totals of the 56 rain gauge stations in the basin precisely portray the spatial distribution of rainfall in the basin. It is known that the average annual rainfall of the basin is 814 mm and varies between about 500 mm to 1600 mm with standard deviation of 196 mm. With reference to the average annual rainfall (AAR) of the basin and its standard deviation (σ), the whole basin can be divided into three main zones- high rainfall zone, medium rainfall zone and low rainfall zone. The stations receiving rainfall more than the total of one standard deviation and the average annual rainfall of the basin are included in high rainfall zone ($>AAR+1\sigma$). The stations that gain the annual rainfall less than the total of average annual rainfall of the basin and one standard deviation but more than the difference between basin's average annual rainfall and one standard deviation are grouped into medium rainfall zone ($>AAR-1\sigma$ and $<AAR+1\sigma$). Whereas, the stations that obtain annual rainfall less than the difference between basin's average annual rainfall and one standard deviation are categorized into low rainfall zone ($<AAR-1\sigma$).

The north-eastern part covered by the rugged relief of the Gawilgad Range and the extreme western area of the basin receiving reasonably high rainfall, lie in the first zone (Figure 3.2). Out of 56 rain gauge stations under study, 6 stations fall in the high rainfall zone. Bhainsdehi, Chikhaldara and Dharani located in the north-eastern part of the basin as well as Navapur, Mandavi and Surat in the extreme west of the basin receive high amount of rainfall, included in this zone. Chikhaldara, situated in the mountainous tracts of the Gawilgad Range to the north-east of the basin is the highest rainfall receiving station in the basin. Average annual rainfall of Chikhaldara is 1596 mm which is nearly double than the basin's average rainfall (814 mm). Dharani and Bhainsdehi, the other stations from this zone receive the average annual rainfall 1159 mm and 1023 mm respectively. The high rainfall zone also comprises a small area located to the extreme west of the basin. The stations such as Navapur, Mandavi and Surat located in the far west of the basin with considerable high amount of rainfall, also included in this zone.

The average annual rainfall recorded at these stations is 1161 mm, 1445 mm and 1124 mm sequentially.

The widespread area in the central and south-eastern part of the basin, formed by the river plains receives rainfall close to the basin's average are categorized into second zone (Figure 3.2). The extensive area stretching from east to west, covering the whole central part of the basin obtain medium rainfall with less deviation from the average rainfall of the basin. 44 stations (about 80%) out of 56 rain gauge stations of the study area fall in the medium rainfall zone. For instance, Chandurbazar (789 mm), Akot (771 mm) and Patur (874 mm) from eastern part of the basin as well as Buldhana (850 mm), Bhusaval (730 mm) and Erandol (684 mm) located in the central part of the basin characterized by medium rainfall. The medium rainfall zone covers largest area of the basin which is much more than the total area covered by high and low rainfall zones.

A small pocket in the south-west of the basin, contiguous to the western high rainfall zone, falls in the third zone (Figure 3.2). This zone comprises six stations such as Malegaon, Nandgaon, Satana, Dhule, Sakri and Shindkheda. All these stations receive significantly less amount of rainfall comparing to the rest of the stations distributed in the basin. With respect to the average annual rainfall of the basin (814 mm) this zone gets noteworthy deficient rainfall about 25-35% less than the basin's average rainfall. A remarkable fact of the rainfall of these six stations is that all these six stations are the lowest rainfall receiving stations in the basin. All other 50 stations out of 56 raingauge stations selected for the study receives more amount of rainfall than these stations. Sakri receives lowest annual rainfall in the basin which is just 511 mm followed by Satana receiving 514 mm rainfall. Malegaon, Dhule, Shindkheda, Dhule and Nandgaon the other stations from this zone receives annual rainfall ranging between 554 mm and 605 mm. Therefore, indeed, it is an absolutely low rainfall zone in the Tapi Basin.

The high rainfall zone of the basin is characterized by great variation in the amount of rainfall in short distance. In other words, isohyets are closely spaced in this zone of the basin. The north-eastern region, nevertheless, obtains high rainfall but also characterized by rapid change in the amount of rainfall with space (Figure 3.2). The isohyets placed radially around Chikhaldara, the highest rainfall receiving station in the basin. The annual amount of rainfall in this zone ranges between 1600 to 1000 mm. Chikhaldara receives annual rainfall about 1600 mm, which decreases to about 1000 mm within the periphery of 50 to 70 km distance from Chikhaldara. The other high rainfall region of the basin situated in the west is also characterized by high spatial variation in rainfall (Figure 3.2). Whereas, the extensive river plains in the central part of the basin are characterized by almost uniform amount of rainfall. This area shows least variation in the amount annual rainfall. Therefore, isohytes are almost absent in this vast continuous tract of the basin (Figure 3.2). Similarly, the low rainfall zone of the basin in the south-west also obtains uniform amount of rainfall resulted into absence of any isohytes in the zone (Figure 3.2). In general, the spatial pattern of rainfall in the Tapi Basin exhibits a decreasing pattern from east to west with abrupt rise in rainfall to the western edge of the basin.

3.3 Influence of orography on the spatial variability of rainfall

It is well known fact that the rainfall varies from one place to another even in a small geographical area. The rainfall of a particular area results from several interacting processes principally determined by the synoptic situations of the atmosphere. However, apart from the synoptic situations, orography of a region plays an important role in the wide spread rainfall activity. Particularly in India the location and orientation of orographic barriers play a major role in modulating the distribution of rainfall during southwest monsoon season (Tyagi et al. 2012).

Many studies have been conducted to investigate the role of orography on the performance of Indian summer monsoon. Orography has a great effect on the intensity, amount and spatial distribution of rainfall. Areal distribution of rainfall is strongly influenced by orography, particularly when the diversity of relief is such as to form barriers to rain-bearing winds (Kamaraju and Subrahmanyam, 1984). The characteristic features of mountains and ghats play an effective role in modifying the rain-bearing winds and therefore can shape the rainfall pattern of an area. The mountain ranges and ghats with their height, extent and direction are responsible for differential amount of rainfall on the opposite sides of the ranges. Mountain barriers tend to concentrate precipitation on their windward slopes, by forcing ascent of moisture-bearing winds, and produce a 'rain-shadow' to the leeward (Critchfield, 1997). The places where the mountain barriers lie across the paths of moisture-bearing winds receive the greatest annual totals of rainfall. Several places in India exhibit an extremity in the amount of rainfall due to orographic effect. For example, Cherrapunji on the southern margin of the Khasi Hills in Meghalaya averages 11440 mm of rainfall annually (Critchfield, 1997). The Western Ghats region of western Maharashtra also provides an interesting example to investigate the implications of orographically controlled rainfall. The Western Ghats as a relief barrier exerts a complex and profoundly important 'gate keeper' effect on the climate mosaic of the entire Deccan (Gunnel, 2001). They have a profound influence on the wind system in the lower levels of the atmosphere which affect the distribution of rainfall. Rainfall shows great variations from the windward side to the summit and the leeward side (Gadgil, 2002). Ratna (2012) opined that the topographical barrier of the Western Ghats plays an important role in controlling the rainfall distribution, particularly over Maharashtra. It enhances rainfall on the windward side and decreases on the leeward side. The spatial distribution of rainfall in the Tapi Basin also presents an association with its orography which has been discussed in the following section and the physiography of the Tapi Basin is shown in Figure 3.3.

The geographical location of the Tapi Basin, its proximity to the Western Ghats, the Satpura Ranges, the Arabian Sea and the direction of monsoon winds all combine together to produce variable amounts of rainfall in different parts of the basin. Predominantly, the effect of the Western Ghats and the Satpura Ranges on the rainfall is evident. The basin is bordered by the Western Ghats in the south-west, trending generally from north to south and ranges in elevation from 600 to 900 m ASL (Figure 3.3). Salher Fort (1567 m ASL), the highest peak of the Tapi Basin is located in the Western Ghats. The continuity and elevation of the Western Ghats and its offshoots acts as a barrier to the south-western monsoon winds and consequentially resulted into heavy rainfall on the windward side and produce a 'rain-shadow' area to the leeward side.

A low rainfall zone mentioned in section 3.2 is in fact the 'rain shadow' area which is an outcome of orographic effect of the Western Ghats. All six stations viz. Malegaon, Nandgaon, Satana, Dhule, Sakri and Shindkheda from this zone receive lowest amount of rainfall compared to rest of the stations distributed in the basin.

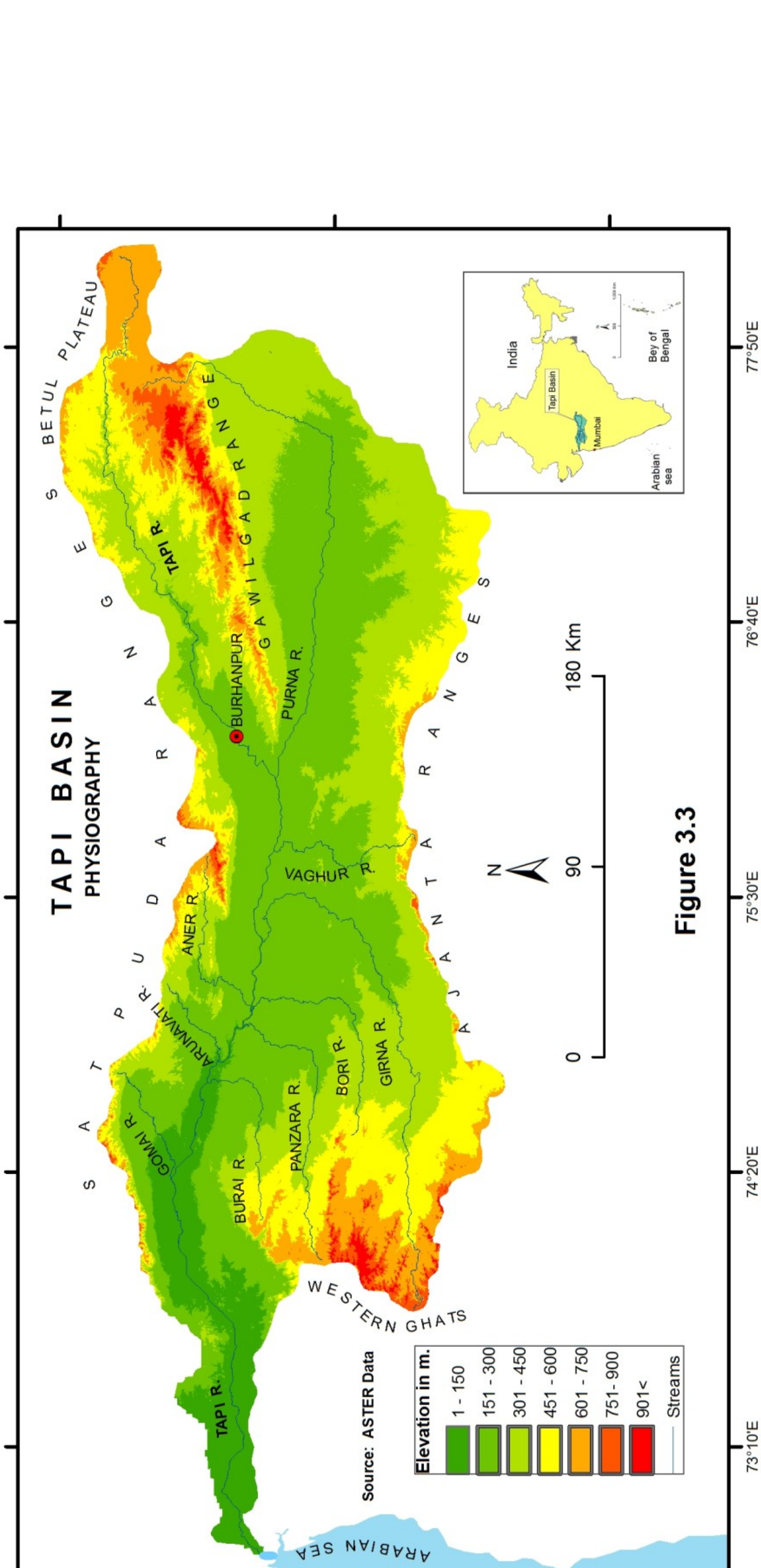

TAPI BASIN
PHYSIOGRAPHY
S A T P U D A R A N G E S
BETUL PLATEAU
GAWILGAD RANGE
AJANTA RANGES
WESTERN GHATS
ARABIAN SEA
TAPI R.
GOMAI R.
ARUNAVATI R.
ANER R.
BURHANPUR
PURNA R.
VAGHUR R.
BURAI R.
PANZARA R.
BORI R.
GIRNA R.
N
0
90
180 Km
Source: ASTER Data
Elevation in m.
1 - 150
151 - 300
301 - 450
451 - 600
601 - 750
751 - 900
901<
Streams
India
Tapi Basin
Mumbai
Arabian sea
Bey of Bengal
22°0'N
20°50'N
19°40'N
73°10'E
74°20'E
75°30'E
76°40'E
77°50'E

Figure 3.3

All the aforesaid stations from this area gets remarkably low rainfall, about 25-35% less than the basin's average rainfall (814 mm). The Western Ghats along the western boundary of the basin acts as a barrier in the path of the rain bearing winds and form the rain shadow region on opposite slope. The stations mentioned before are situated in the rain shadow region, therefore, receive considerably low rainfall. For example, Sakri receives just 511 mm annual rainfall which is the lowest in the basin followed by Satana receiving 514 mm rainfall. Malegaon, Dhule, Shindkheda and Nandgaon the other stations from this zone receives annual rainfall ranging between about 550 mm to 600 mm. The lowest rainfall at Sakri is attributed to its specific location. The Galana Range, the east-west trending offshoot of the Western Ghats runs across the path of monsoon winds and is situated in the rain shadow zone of the main rim of the Western Ghats. Therefore, it can be stated that Sakri is located in the *'secondary rain shadow area'* which is the significant reason for very low rainfall in this region. The orographic effect of the Western Ghats weaken at about 80-100 km to the east of the Western Ghats with little rise in the amount of rainfall.

To the north, the Tapi Basin is bordered roughly by east-west trending Satpura Ranges. The elevation of the ranges lies mainly between 450 and 750 m ASL (Figure 3.3). In the absence of lofty peaks, no substantial increase in the rainfall is observed on the southern slopes of the Satpura Ranges. However, the stations located in the northern plains of the Tapi River obtain more amount of rainfall compared to the stations falling in the rain-shadow area to the south-west. For example, the northern stations such as Taloda, Pansemal, Chopda and Yaval receive more than 700 mm rainfall. Whereas, the amount of rainfall of the south-western rain-shadow stations is just around 600 mm. This rise in the rainfall is perhaps due to orographic effect of the Satpura Ranges.

The effect of orography on the amount of rainfall also clearly visible in the north-eastern high rainfall zone of the basin. This part of the basin is covered by the Gawilgad Range (Figure 3.3). The range lies in elevation from 600 to >900 m ASL attains highest elevation at Gawilgad Fort (1103 m ASL) followed by Chikhaldara, the second highest place in the range with an elevation of 1088 m ASL. With its considerable length and uniformity in elevation, the area in vicinities of the Gawilgad Range gets high orographic rainfall which accounts for more than 1000 mm. Chikhaldara, situated on the crest line of the Gawilgad Range, receives highest rainfall (1596 mm) in the basin which is about two times more than the basin's average rainfall (814 mm). The range broadens to the east and terminate into a plateau, known as Betul Plateau, situated at an elevation ranging between 600 and 900 m ASL (Figure 3.3). The plateau, also receives more amount of rainfall. The stations situated over the plateau such as Bhainsdehi, Atner and Multai obtain more rainfall than the average rainfall of the basin.

The narrow belt of the Tapi Valley to the north of the Gawilgad Range obtain high amount of rainfall. This area nestles between the Satpura Range to the north and the Gawilgad Range to the south (Figure 3.3). The region receives rainfall around 1000 mm, owes to its hilly surroundings and their orographic effect. The gaps between the hill ranges also plays important role in the distribution of rainfall. For example, the moisture-bearing winds, entering through the Burhanpur Gap between the Satpura Range and the Gawilgad Range, consequently get trapped in the Tapi Valley to precipitate high amount of rainfall. For example, Dharni, located in this region accounts for 1162 mm rainfall.

Most of the area of the Tapi Basin is a plain with an elevation ranging between 150 m and 450 m ASL formed by the Tapi River and its tributaries. Due to its flat topography and absence of relief, the extensive river plains in the central and south-eastern part of the basin receives rainfall between 700 and 800 mm i.e. close to the average rainfall of the basin. However, the plain in the lower reaches of the basin receives high rainfall owing to its vicinity to the sea.

3.4 Temporal variability of rainfall

Mean values of rainfall present just a generalized portrait of rainfall of a region. Usually it simplifies the complex and diverse characteristics of rainfall. In fact, however, variability in amount for short to long period is the intrinsic aspect of the monsoon rainfall of India. In view of the various characteristics of the monsoon rainfall, in the strictest sense, each year's rainfall is unique. Therefore, the variable nature of the monsoon rainfall of India has remained the topic of inquisitiveness for many researchers. Several studies on different aspects of rainfall variability over India and its subdivisions are available. Krishnamurthy and Shukla (2000) presented intra-seasonal and inter-annual variability of rainfall over India. Pant and Rupa Kumar (1997) using rainfall data of 306 stations studied intra-seasonal and inter-annual variability of Indian monsoon rainfall. In addition they exhibited epochal pattern of the rainfall. Guhathakurta and Rajeevan (2008) also documented epochal variations of Indian monsoon rainfall using monthly rainfall data for the period 1901-2003 of 1476 well distributed rain gauge stations. Variability of monsoon rainfall on monthly and seasonal scale of 31 meteorological subdivisions of India is documented by Singh et al. (1999). Similarly, Kane (2010) attempted to represent rainfall variation of the nation by examining monthly rainfall data over 136 years. Whereas, the decadal variability of monsoon rainfall for all meteorological sub-divisions of India has been presented by De and Vaidya (1996). Apart from the studies of rainfall variability on national scale, many such studies are also carried out on regional scale. For example, inter-seasonal and inter-annual rainfall variability of nine meteorological subdivisions of the peninsular India has been studied by Suresh (1996). Many other researchers (Gadgil (2003), Lele et al. (1998), Subramanian et al. (1992), Ali et al. (2005), Das et al. (2002)) also systematically shown the variability of monsoon rainfall of India or parts of it. Owing to its inherent feature, monsoon rainfall of the Tapi Basin also shows variability with respect to time at different scales. Therefore, using monthly and annual rainfall data, the rainfall variability of the basin has been described in this section.

The analyses of rainfall figures of different stations in the basin show considerable variation in the amount of annual rainfall from year to year. The annual rainfall figures of the rain gauge stations of the Tapi Basin with their various characteristics are presented in Table 3.1. The amount of annual rainfall at many stations in the basin is found to be substantially high for a particular year and contrary very less for another. For example, maximum and minimum annual rainfall recorded at Mandavi is 2899 mm in 1976 and minimum 349 mm in 1987 respectively (Table 3.1). In comparison of average annual rainfall of the station (1446 mm), the variability of rainfall is noteworthy. Few other stations such as Chikhaldara, Surat, Shahada, Bhinsdehi, Atner, Multai, Navapur and Dharani also present high variability in annual rainfall for different years (Table 3.1).

Table 3.1 Annual rainfall characteristics of the Tapi Basin (1901-2004)

Station	AAR	Max	Year of Max	Min	Year of Min	σ	Cv	Cs
Achalpur	861.72	1615.1	1944	360.9	1952	251.58	0.29	0.69
Akola	801.68	1275.3	2006	310.3	1920	207.49	0.26	0.12
Akot	775.64	1405.2	1944	347	1952	226.45	0.29	0.47
Amalner	677.82	1639.6	1992	249.2	1911	233.61	0.34	1.64
Amravati	866.95	1533.7	1944	198.6	2004	244.74	0.28	0.20
Anjangaon	736.83	1424.1	1944	311.9	1991	228.75	0.31	0.74
Atner	837.89	1804.5	1944	154	1989	262.90	0.31	0.72
Badnera	842.29	1637.2	1979	155.1	1960	268.24	0.32	0.14
Balapur	742.94	1410.3	1988	300.8	1984	199.06	0.27	0.88
Bhadgaon	728.14	1288.4	1958	290.7	1952	205.45	0.28	0.30
Bhainsdehi	1035.76	2033.1	1944	238.2	1989	313.42	0.30	0.43
Bhusaval	730.93	1345	1931	172.7	1968	195.08	0.27	0.32
Buldhana	870.43	1392.8	1959	446.5	1984	193.29	0.22	0.44
Burhanpur	843.12	1499	1993	302.7	1952	247.04	0.29	0.36
Chalisgaon	736.37	1380.8	1956	316.2	1918	209.19	0.28	0.60
Chandurbajar	802.02	1691.5	1944	262.7	1920	216.09	0.27	0.73
Chikhaldara	1596.81	2570.3	1948	407.1	1980	441.18	0.27	0.02
Chopda	729.12	1314.3	1931	230.5	1962	197.20	0.27	0.38
Daryapur	716.73	1219.6	2001	156.3	1978	216.71	0.30	0.29
Dhamangaon	809.63	1505.1	1928	325.2	1985	230.55	0.28	0.46
Dharani	1162.48	2123.4	1990	531.5	1918	309.76	0.27	0.56
Dhule	603.09	1397.3	1949	199.3	1911	195.87	0.32	0.82
Erandol	688.01	1258.3	1914	267	1982	194.32	0.28	0.55
Jalgaon	735.46	1352	1931	391.7	1918	189.34	0.26	0.45
Jalgaon Jamod	773.53	1509	1990	193.1	1971	240.30	0.31	0.60
Jamner	794.02	1395	1979	283.7	1971	207.02	0.26	0.27
Kalvan	729.99	1581.3	1944	194.3	1961	280.76	0.38	1.18
Khamgaon	730.8	1313	1988	118.4	1986	214.05	0.29	-0.13
Kholaopur	772.13	1663	1931	279.6	1986	239.79	0.31	0.68
Malegaon	557.13	949.1	1995	197.8	1972	169.67	0.30	0.36
Malkapur	712.22	1494	1949	213.4	1972	196.58	0.28	0.60
Mandavi	1446.64	2899	1976	349.5	1987	518.01	0.36	0.62
Muktainagar	688.49	1185.6	1944	289.8	1918	171.51	0.25	0.56
Multai	978.02	1890.4	1944	243	1989	304.16	0.31	0.35
Murtijapur	816.89	1488	1990	302.7	1920	224.92	0.28	0.27
Nandgaon	605.23	1026.9	1910	116.9	1972	193.82	0.32	0.48
Nandura	753.88	1321	1980	293	1991	212.32	0.28	0.42
Nandurbar	691.56	1350	1976	203.2	1918	234.94	0.34	0.68
Navapur	1118.31	2244	1976	626.2	1941	337.47	0.30	0.79
Pachora	685.73	1571.1	1931	257	1974	232.87	0.34	0.41
Pansemal	836.6	1590	1944	203.5	1989	251.03	0.30	0.26
Parola	685.73	1270.1	1983	119.9	1962	193.14	0.28	0.21
Patur	876.77	1496.5	1959	410	1920	238.80	0.27	0.02
Pimpalner	629.84	1346.2	1976	345.1	1972	200.49	0.32	0.99
Raver	721.89	1250	1970	277.9	1907	209.47	0.29	0.25
Sakri	511.15	1127	1976	174.6	1918	146.46	0.29	0.53
Satana	514.06	965.4	1980	93.2	1962	171.97	0.34	0.40
Shahada	684.77	2166	1981	240.4	1918	251.57	0.37	2.55
Shegaon	739.48	1346.7	1959	125.5	2000	353.61	0.48	0.01
Shindkheda	564.06	975.2	1944	197.2	1918	164.80	0.29	0.26
Shirpur	665.82	1178.5	1958	268.5	1911	219.72	0.33	0.59
Sirpur	908.71	1637.6	1949	380	1920	222.70	0.25	0.36
Surat	1143.05	2298.7	1976	172.1	1985	440.55	0.39	0.57
Taloda	794.13	1308.5	1976	286	1918	207.60	0.26	0.29
Telhara	753.45	1398.2	1959	240.7	1964	235.59	0.31	0.59
Yaval	737.78	1319	1944	261.4	1974	202.84	0.27	0.50
Tapi Basin	**814**	**1158**	**1944**	**419**	**1918**	**196**	**0.30**	**0.51**

Data source:IMD; AAR:Average Annual Rainfall; Max: Maximum Annual Rainfall; Min: Minimum Annual Rainfall; σ:Standard Deviation; Cv:Coefficient of variation; Cs:Coefficient of Skewness.

The maximum annual rainfall at a station ever recorded in the basin is 2899 mm which was recorded at Mandavi in 1976. Such a huge amount of rainfall is more than three times greater than the average annual rainfall of the basin (814 mm). In contrast, the low annual rainfall, less than 200 mm (i.e. one-fourth of average annual rainfall of the basin) is recorded at Satana, Nandgaon, Khamgaon, Parola, Shegaon, Atner, Badnera, Daryapur, Surat, Bhusaval, Sakri, Jalgaon Jamod, Kalvan, Shindkheda, Malegaon, Amravati and Dhule for different years. The least annual rainfall on the record is just 93 mm, which was measured at Satana in 1962 (Table 3.1). Such extreme observations of the annual rainfall reemphasize the high temporal variability in annual rainfall of the basin.

3.5 Inter-annual variability of rainfall

An important and most immediately felt aspect of monsoon rainfall is its inter-annual variability. The monsoon rainfall is a certain and reliable source of water for the Tapi Basin. However, distinguishing to this stable picture, there are small year to year variations in the rainfall. The rainfall regimes in different parts of the basin are not identical. These small changes constitute a significant inter-annual variability in the amount of rainfall which affect on varied aspects of hydrological resources in the basin. High variability in the rainfall sometimes reflects into occurrences of droughts or floods in the basin. Therefore, annual rainfall data over 100 years for different rain gauge stations in the basin have been analyzed to know inter-annual rainfall variability in the basin and the details are given in Table 3.1.

Standard deviation (σ) is the most commonly used measure of dispersion to geographical data (Ebdon, 1977). It shows year to year deviation of annual rainfall from its mean. The standard deviation (σ) of annual rainfall of the Tapi basin is 196 mm. It is observed that the value is high for the high rainfall stations in the basin and vice-versa. For example, standard deviation (σ) of annual rainfall is more than 300 mm at high rainfall stations in the basin like Chikhaldara, Mandavi, Surat, Dharani, Bhinsdehi, Multai and Navapur. Whereas, standard deviation (σ) of annual rainfall is less than 200 mm at low rainfall stations in the basin such as Sakri, Satana, Malegaon and Shindkheda.

It is well known that the rainfall of the same region varies from one year to another. A quantitative measure of this variability is the coefficient of variation (Cv). Cv is the ratio between standard deviation and mean. Cv is useful measure of variability of rainfall. Greater value of Cv indicates high variability i.e. less reliability of rainfall while lower value represents less variation or more dependability of rainfall. Inter-annual variability of the annual rainfall in the basin is not so high, as the coefficient of variation (Cv) of annual rainfall for most of the stations in the Tapi Basin is generally observed about 30% (Table 3.1). The distribution with less Cv is said to be more uniformity, consistency or less variability (Dutta, 2006). However, Surat and Mandavi in the eastern part of the basin, greater values of Cv (39% and 36% respectively) suggests relatively high inter-annual variability of rainfall in the area (Table 3.1). Highest rainfall variability (Cv = 48%) is found at Shegaon located in the eastern plains of the basin. Kalvan and Sahada are also characterized by high inter-annual variability of rainfall. Cv at Akola, Jalgaon, Muktainagar, Sirpur and Taloda is found around 25% which represents comparatively less inter-annual variability of rainfall. Whereas, Buldhana notices 22% Cv suggesting less inter-annual variability or consistency in the rainfall than rest of the stations in the basin. The investigation of coefficient of variation (Cv) of rainfall of a station in relation to its annual rainfall does not show considerable association with each other. The low rainfall stations such as Sakri, Satana and Malegaon has average coefficient of variation (Cv) of annual rainfall suggesting less inter-annual rainfall variability. High rainfall stations like Chikhaldara, Mandavi and Surat are also characterized by average Cv (Table 3.1). The coefficient of variation (Cv) of the Tapi basin as a unit is 30% suggesting that the rainfall of the basin is less variable (Table 3.1).

Skewness is one of the most commonly used moments for the annual rainfall. It is a statistical measure used to find out the degree of asymmetry of a statistical distribution. The analysis of coefficient of skewness (Cs) of the rainfall of the Tapi Basin highlights the extreme occurrences of rainfall at different stations. The values of Cs are positive for all the stations in the basin except one (Khamgaon) and are ranging between 0.01 and 2.55 (Table 3.1). Furthermore, all the values of the skewness (Cs) are statistically significant, as they are calculated on the basis of more than 100 years data (Viessman and Lewis, 2003). The positive values propose the occurrence of one or two or a few very wet (high rainfall) years during the gauged period. It is observed that some of the low rainfall stations like Shahada, Amalner, Kalvan, Pimpalner and Dhule have highest coefficient of skewness (Cs) in the basin (the Cv of these stations is more than 30%) (Table 3.1). Therefore, it can be concluded that the apparent high inter-annual rainfall variability of these stations is mainly because of a few very high rainfall years in the gauged period. For example, highest Cs (2.55) in the basin has been noticed at Shahada which has average annual rainfall 686 mm. However, the high value of Cs at Shahada is the product of a few high annual rainfall years such as 1981 (2166 mm), 1976 (1698 mm), 1983 (1124 mm), 1933 (1124 mm) and 1933 (1060 mm). It is applied in a similar manner to rest of the stations mentioned above. The negative value (-0.13) of skewness (Cs) is observed only at Khamgaon indicating that the station received one or a few very low rainfall years. The review of annual rainfall of Khamgaon reveals that the average annual rainfall of the station is 730 mm, but it obtained just 118 mm rainfall in 1986, besides 1920, 1956, 1982 and 1991 received annual rainfall less than 400 mm. Therefore, it can be stated that these very low annual rainfall values, especially of year 1986 is responsible for negative coefficient of skewness (Cs) value of Khamgaon.

In order to understand inter-annual rainfall variability in the Tapi Basin, mean annual rainfall series for the basin has been constructed on the basis of the data for the period 1901 to 2004 and given in Table 3.2 and represented graphically in Figure 3.4. The series undoubtedly reveals the rainfall variability in the Tapi Basin from one year to another.

Two contrasting features of the rainfall can be noticed in two parts of the 20^{th} century. Investigation of the time series graph (Figure 3.4) indicates that in comparison of the rainfall in the second half of the century, rainfall in the first half of the century was more variable. Nevertheless, the first half of the century is characterized by above-average rainfall. Thereafter, less variability in the rainfall is observed. The basin received not only average rainfall but also less variable rainfall in the second half of the 20^{th} century (Figure 3.4).

The average annual rainfall of the basin over a period of 104 years (1901 to 2004) is given in Table 3.2. The long-term mean of the basin rainfall is 814 mm, however, the rainfall figures for different years show deviation from the mean. Out of 104 years on the record, 48 years received more and 56 years gained less amount of rainfall than the average annual rainfall of the basin. The average annual rainfall in the basin varies from 419 mm (year 1918) to 1158 mm (year 1944) (Table 3.2). The range of annual rainfall in the basin is 739 mm which is quite high. This deviation from the mean constitute significant inter-annual variability.

Table 3.2 Average annual rainfall (AAR) of the Tapi Basin

YEAR	AAR (mm)	YEAR	AAR (mm)	YEAR	AAR (mm)	YEAR	AAR (mm)
1901	721	1927	843	1953	747	1979	914
1902	677	1928	823	1954	892	1980	707
1903	828	1929	612	1955	891	1981	853
1904	600	1930	802	1956	860	1982	643
1905	622	1931	1151	1957	684	1983	904
1906	863	1932	818	1958	903	1984	669
1907	620	1933	1009	1959	1067	1985	627
1908	710	1934	876	1960	702	1986	638
1909	757	1935	825	1961	904	1987	653
1910	911	1936	844	1962	726	1988	1020
1911	549	1937	913	1963	769	1989	721
1912	625	1938	1050	1964	824	1990	922
1913	749	1939	711	1965	657	1991	607
1914	1001	1940	889	1966	726	1992	803
1915	837	1941	650	1967	724	1993	847
1916	1026	1942	917	1968	695	1994	899
1917	937	1943	839	1969	824	1995	686
1918	419	1944	1158	1970	1016	1996	759
1919	826	1945	854	1971	570	1997	867
1920	498	1946	1006	1972	581	1998	997
1921	773	1947	779	1973	879	1999	763
1922	736	1948	921	1974	658	2000	575
1923	656	1949	1128	1975	824	2001	744
1924	761	1950	615	1976	939	2002	766
1925	585	1951	692	1977	823	2003	806
1926	714	1952	469	1978	790	2004	698
Tapi Basin							**814**

Data source: IMD, Pune

Figure 3.4 illustrate the fluctuations in the annual rainfall and highlights wet (high rainfall) as well as dry (low rainfall) years. Though the monsoon rainfall is stable on long-term scale, it is characterized by year-to-year below or above average rainfall. These small changes in the rainfall results into deficient or excess amount of rainfall and may cause drought or flood in the region.

Figure 3.4 Variation of average annual rainfall: Tapi Basin (1901-2004)

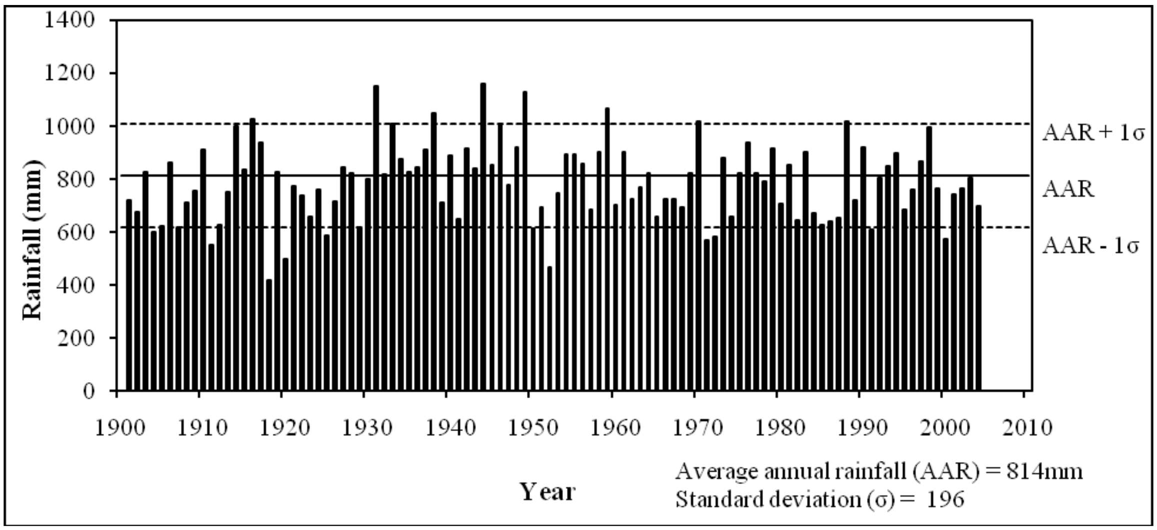
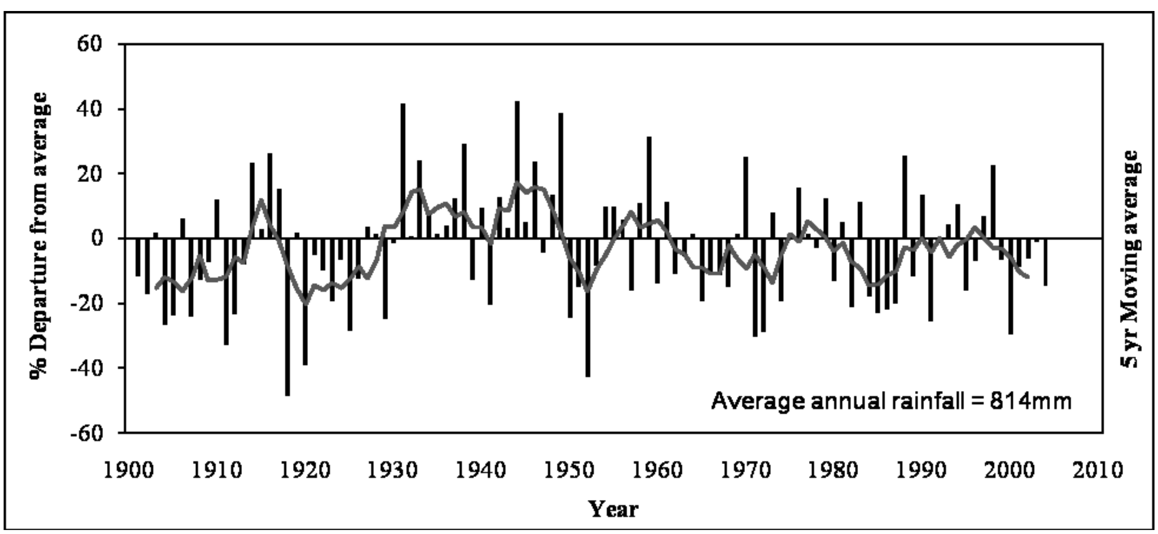
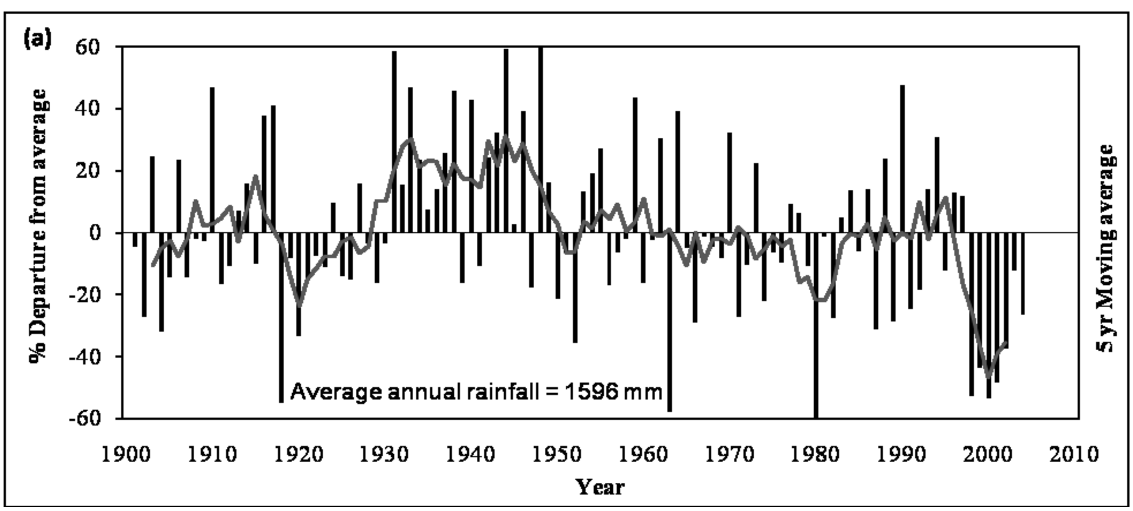


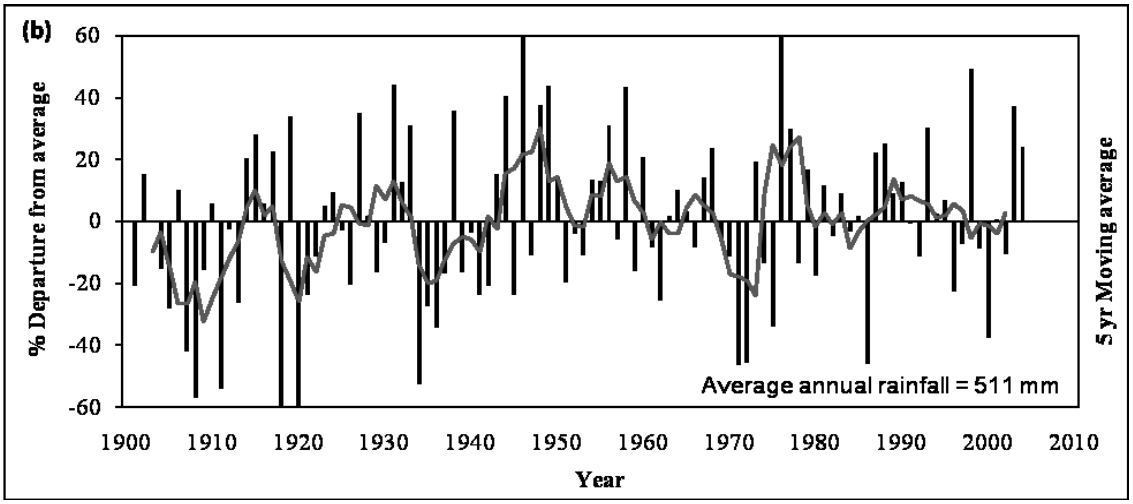
Figure 3.5 Departure from average annual rainfall of the Tapi Basin

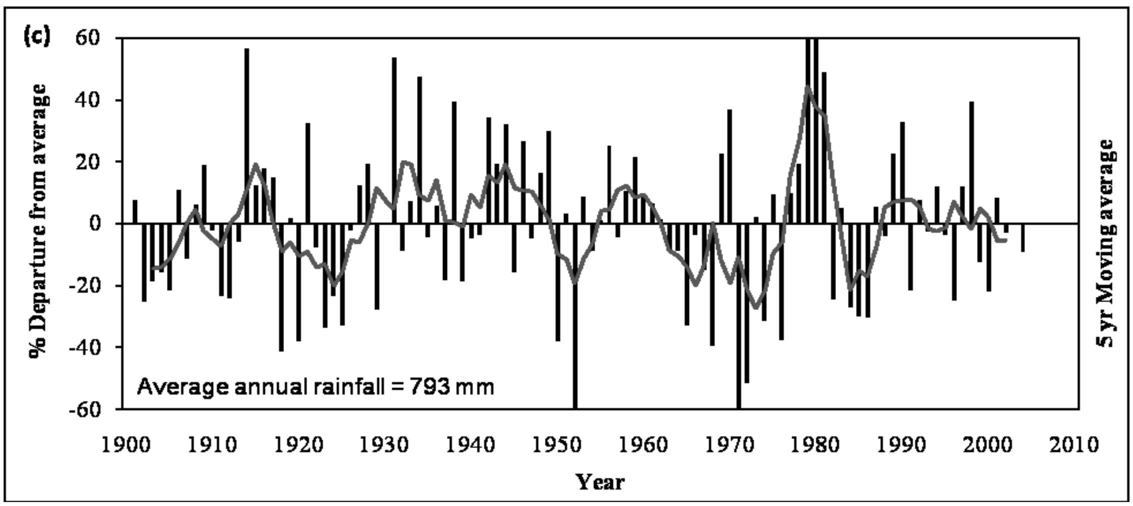


In order to exhibit the variability of rainfall in précised manner, patterns of variations in the annual rainfall of the basin is also depicted by the plot of departure from average annual rainfall, expressed as percentage of mean (Figure 3.5). The figure demonstrates that the rainfall over the basin in general, varies between -30 to +30% from its mean. However, in some instances the maximum departure of rainfall is observed between -40 to +40% from the mean. The diagram, therefore, reveals that the rainfall of the Tapi Basin as a geographical unit is less variable (Figure 3.5). However, it is obvious that the departure of rainfall at different stations in the basin cannot present similar pattern. Therefore, to check the rainfall departure at a station, three stations viz. Chikhaldara, Sakri and Jamner are selected. The rationale to choose these specific stations is that these stations represent different sections of the basin as well as they are having varying annual rainfall amounts. Chikhaldara, located in the eastern hilly tracts is the highest rainfall receiving station and Sakri, the westward situated station is the lowest rainfall receiving station in the basin. Whereas, Jamner, having almost similar rainfall to that of the average rainfall of the basin and located in the middle of the basin. Figure 3.6 (a), (b) and (c) represents the departure of rainfall at Chikhaldara, Sakri and Jamner consequently. In comparison of the Tapi basin as a unit, all these three stations show high inter-annual rainfall variability.

Figure: 3.6 Departure from average annual rainfall
(a) Chikhaldara (b) Sakri and (c) Jamner







These diagrams demonstrate that the rainfall at these stations varies between -60 to +60% from their means which certainly exceeds over the rainfall departure of the whole basin (-40 to +40% from the mean).

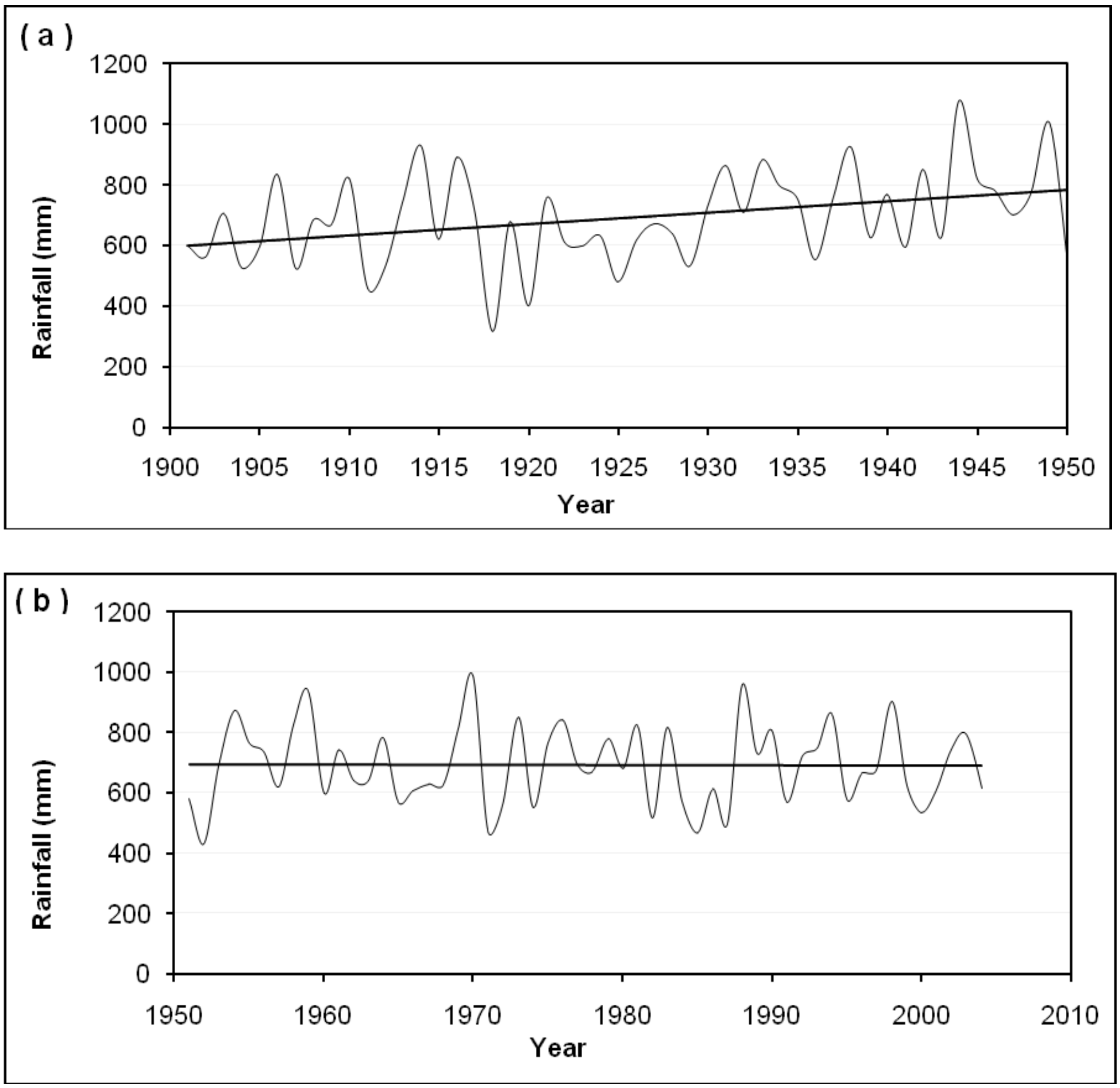
3.6 Variability of seasonal rainfall in climate change period

In recent years climate change emerges an important environmental issue. Many studies are devoted for quantification of climate change and its association with various systems in the environment, especially with the monsoon of Southeast Asia (Loo et al., 2014). Among the various climatic factors rainfall is important to designate climate change (Obot et al., 2010). It is the most sensitive component of the climate and therefore it is widely studied in the view of climate change. The variability in the rainfall becomes crucial in the country due to its consequential socio-economic effects. Therefore, it is important to investigate in context of the climate change whether the characteristics of Indian summer monsoon are also changing (Guhathakurta and Rajeevan, 2008). The present section, therefore, devoted to check the changes occurred if any in the seasonal rainfall of the basin in the second half of the 20th century on the backdrop of climate change. To bring out the relationship of seasonal rainfall with the climate change phenomena, the seasonal rainfall data of two parts of the 20th century have been analyzed and compared.

In general, the post-independence period of India is characterized by industrial development and growing human interference in the environment and therefore usually considered as the period of climate change. Thus, to serve the main objective of the study i.e. to bring out the variability in the seasonal rainfall over the Tapi Basin in the context of climate change, the whole rainfall data have been divided into two sets i.e. 1901 to 1950 and 1951 to 2004. In order to understand the principal characteristics of rainfall, simple statistical technique such as mean is used to summarize the monthly and annual pattern of rainfall as well as rainy days. In addition, to detect the change in the average monthly and seasonal rainfall of the basin, monthly rainfall values are represented in graphical form along with their linear trends. The contribution of monthly rainfall of each month of the monsoon season in the total rainfall of the season in the aforesaid two periods has been reviewed to reveal its variation. The change in number of rainy days with respect to time has been checked by comparing the mean rainy days in both the periods.

Being a part of classic monsoon climatic region, the Tapi Basin exhibit typical properties of the Indian monsoon. Although the Tapi Basin receives rainfall throughout the year, it is exceedingly concentrated in four months of the monsoon season (June to September). Seasonal rainfall contributes about 85% (692 mm) of the average annual rainfall (814 mm) of the basin. The average seasonal rainfall for the period 1901-1950 and 1951-2004 are found just similar (691 mm and 694 mm consecutively). Unlike long-term steady picture of the seasonal rainfall over the period of the century, both parts of it present differential trends of the seasonal rainfall. Figure 3.7 (a) and (b) show the trends of the seasonal rainfall in the first and second half of the 20th century sequentially. The seasonal rainfall for the period 1901-1950 shows an increasing trend, which come down in the period 1951-2004 and does not present any specific trend. The second half of the century is characterized by steady rainfall with no increasing or decreasing trend.

Figure 3.7 Seasonal rainfall trends over the Tapi Basin
(a) from 1901-1950; (b) from 1951-2004



3.7 Variability of monthly rainfall in the monsoon season

It is pertinent to see likewise the behavior of the seasonal rainfall in the aforesaid two periods changed in the monsoonal months also. Therefore, the average monthly rainfall figures of June, July, August and September for the periods 1901-1950 and 1950-2004 are compared with their long-term means (1901-2004) and presented in Table 3.3.

One of the inherent features of the monsoon rainfall is its inter-annual variability. However, these fluctuations from one year to another over a substantial long period of time can point out a direction of behavioral change or trend of rainfall. In view to see the trends of monthly rainfall of the monsoon season in the two parts of the century, monthly rainfall data have been illustrated graphically in Figure 3.8.

Table 3.3 Mean monthly rainfall (mm) of the monsoon season

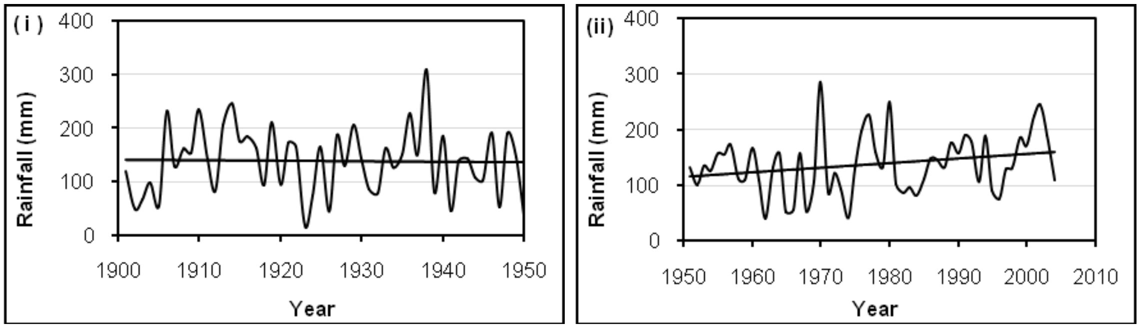
Month / Period	1901-2004	1901-1950	1951-2004
June	140	140	140
July	226	238	216
August	183	160	205
September	143	153	133
Monsoon Season	692	691	694

Data source: IMD, Pune

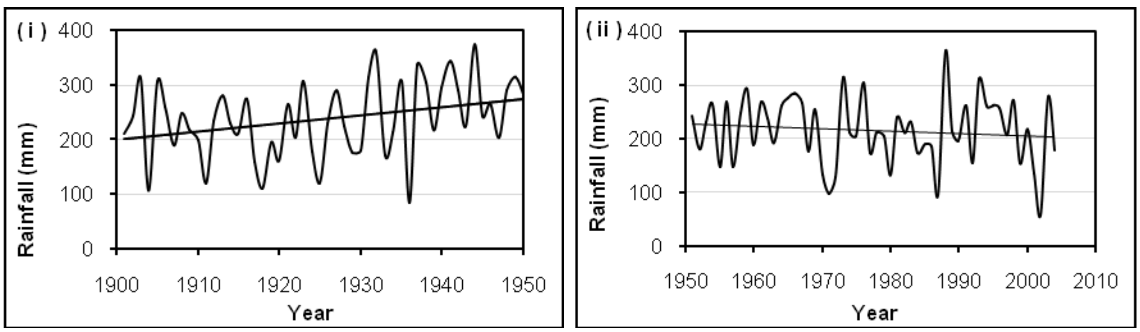
Assessment of mean values of the monthly rainfall of the monsoon season and their trends in first and second half of the 20th century reveal some important facts of the seasonal rainfall of the Tapi Basin. For both the periods (i.e. first and second half of the 20th century), mean monthly average rainfall of June surprisingly remained same to its long-term mean (Table 3.3). However, the consistency of the rainfall in the first period (1901-1950) turns into increasing trend in the second period (1951-2004) (Figure 3.8 (a) (i) and (ii)). July is the rainiest month throughout the period. However, the first half of the century accounts high amount of rainfall than the long-term mean of the month and vice-versa (Table 3.3). Accordingly both these periods present rainfall trends apposite to each other. The rainfall of July in the first period (1901-1950) shows increasing trend while the second period (1951-2004) depicts decreasing trend (Figure 3.8 (b) (i) and (ii)). August is characterized by notable uneven means of rainfall in both the periods under review.

Figure 3.8 Trends of monthly rainfall of the monsoon season

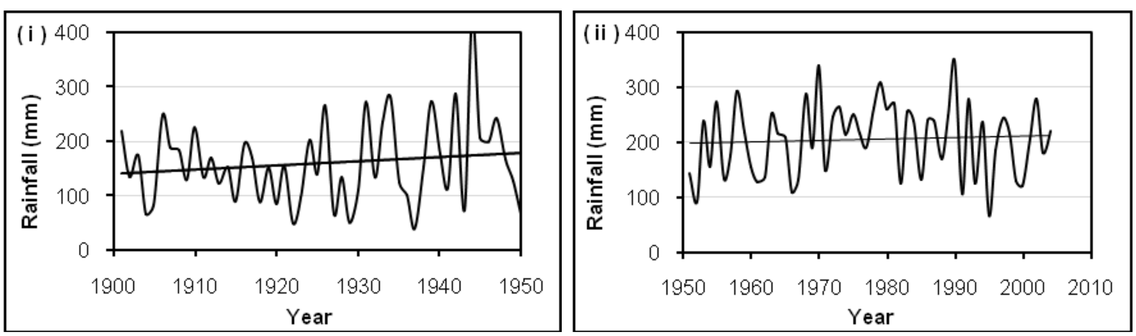
(a) June; (i) 1901-1950; (ii) 1951-2004



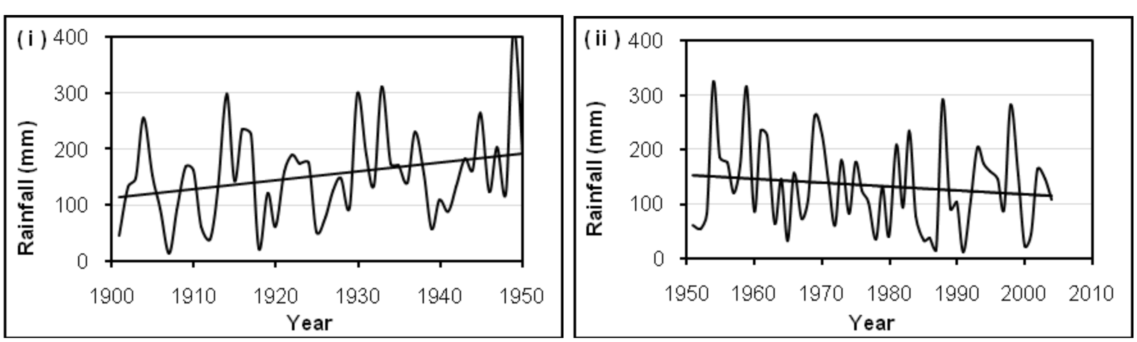
(b) July; (i) 1901-1950; (ii) 1951-2004



(c) August; (i) 1901-1950; (ii) 1951-2004



(d) September; (i) 1901-1950; (ii) 1951-2004



With respect to the long-term mean of the month (183 mm), on an average, the first half of the century received less amount of rainfall (160 mm). Whereas, an increase in the mean rainfall (205 mm) can be noticed in the second half of the century (Table 3.3). However, in both the periods, the rainfall tends to be increasing (Figure 3.8 (c) (i) and (ii)). The mean rainfall of September shows differential characteristics in first and second half of the century. The first half of the century not only receives high amount of mean rainfall (153 mm) but also shows an increasing trend. Whereas, the second half of the century obtained less amount of mean rainfall (133 mm) with decreasing trend (Table 3.3; Figure 3.8 (d) (i) and (ii)).

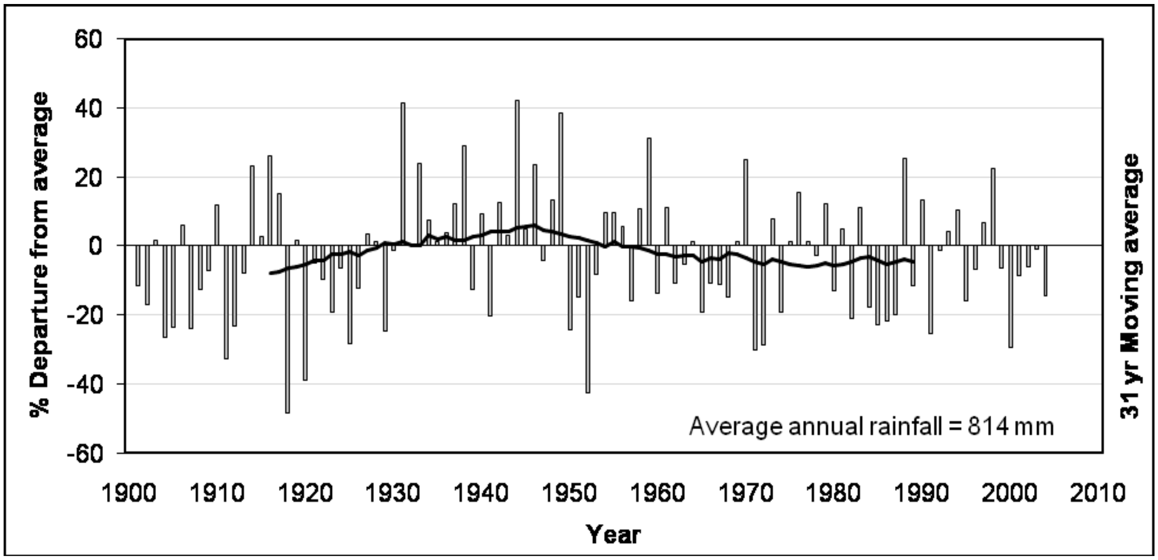
Thus, the present study brings out some important changes in the seasonal rainfall over the Tapi Basin particularly in the second half of the 20th century. The seasonal rainfall of the basin for the period 1901-1950 shows an increasing trend, which come down in the period 1951-2004 and does not present any specific trend. Trend of monthly rainfall of all monsoon months is changed in the second half of the 20th century. The consistency of rainfall in June in the first half of the century turns into an increasing trend in the second half. July and September present clear opposing rainfall trends in two periods of the century. Whereas, an increasing trend of rainfall in August in the first half of the century stabilized in the second half.

3.8 Epochal behavior of rainfall

Variability from one year to another is an integral characteristic of the monsoon rainfall. Therefore, to examine the direction of change of the rainfall moving average method is used as it smoothens the short-term fluctuations to designate the trend. The moving averages illustrate two multi-decadal periods of excess and deficient rainfall which elucidate the period of occurrences of floods and droughts in the study area. This feature characterizes the so-called epochal behavior of monsoon rainfall (Pant and Rupa Kumar, 1997).

Figure 3.9 shows the 31 yr moving averages of the annual rainfall anomalies over the Tapi basin. The figure evidently visualized dry and wet epochs of rainfall of the basin during the 20th century.

Figure: 3.9 Epochal pattern of rainfall of the Tapi Basin



These alternating sequences of multi-decadal periods having excess and deficient rainfall can be summarized as follows:

(i) 1901-1930: Dry epoch

(ii) 1931-1960: Wet epoch

(iii) 1961-1990: Dry epoch

Pant and Rupa Kumar (1997) analyzed the rainfall data of India for the period 1871-1995 to view the variability in rainfall. They observed the same multi-decadal variability of monsoon rainfall over the country. In addition to the above-mentioned dry and wet epochs, they noticed that the last three decades of the 19th century (1871-1900) has been characterized by wet epoch. Therefore, it can be stated that the epochal pattern of the rainfall of the Tapi Basin is quite similar to that found over the country.

3.9 Floods and Droughts

Floods and droughts are two distinct features of rainfall. The deficiency of rainfall causes drought conditions whereas excess rainfall results into flood situations in the region (Kalwar et al, 2005). Both these situations are unfavorable and affect much on the social and environmental conditions of the region. Flood and drought are natural climatological events but are not measured directly by any instrument like any other elements of climate. However, both these aspects can be explained with respect to annual totals of rainfall. Pant and Rupa Kumar (1997) stated that as human activities are adapted to the mean climatic conditions of the region, only the rainfall situations exceeding its average variability turns into drought and flood. Therefore, according to them, a year is classified as a wet year when;

$$Ri \geq AAR + 1\sigma \qquad \text{.... Eq. 3.1}$$

and a dry when,

$$Ri \leq AAR - 1\sigma \qquad \text{.... Eq. 3.2}$$

Where, Ri is the rainfall of year i, AAR is the long-term mean rainfall and σ is the standard deviation. Further, they added that this criterion can be used to any space scale, from all-India to the station rainfall. It is to be noted here that the wet year has been assumed as a flood year and dry year as a drought year.

To recognize the wet (flood) and dry (drought) years in the basin, the annual rainfall data has been analyzed by using Eq.3.1 and 3.2 and the results are given in Table 3.4, 3.5 and 3.6.

Table: 3.4: Tapi basin: flood (wet) years

Year	AAR (mm)	% Departure from AAR
1916	1026	26.0
1931	1151	41.4
1938	1050	29.0
1944	1158	42.3
1949	1128	38.6
1959	1067	31.1
1970	1016	24.8
1988	1020	25.3

AAR= Average Annual rainfall

In the whole data series number of wet years with rainfall exceeding the mean plus one standard deviation (814 mm + 196 mm = 1010 mm) is 8. While the number of dry years receiving deficient rainfall that is the mean minus one standard deviation (814 mm - 196 = 618 mm) is 12 (Table 3.4 and 3.5). Thus, there are nearly 8% wet years while the dry years are about 12%. In comparison of the years showing high rainfall variability, the number of years characterized by invariable (normal) rainfall, is considerably high (84 years) (Table 3.6). Over the period of 104 years on record, 20 years shows striking variability in the annual rainfall, either positive or negative.

Table 3.5: Tapi basin: drought (dry) years

Year	AAR (mm)	% Departure from AAR
1904	600	-26.3
1911	549	-32.6
1918	419	-48.5
1920	498	-38.8
1925	585	-28.1
1929	612	-24.8
1950	615	-24.4
1952	469	-42.4
1971	570	-30.0
1972	581	-28.6
1991	607	-25.4
2000	575	-29.4

AAR= Average Annual rainfall

Thus, nearly $1/5^{th}$ of the total period reveals high variability of rainfall while, $4/5^{th}$ period is featured by normal rainfall. The dry years are associated with drought conditions and wet years with flood situations, and both very often resulted into climatological disasters. In view of this, it has been decided to analyze the annual rainfall data to understand the drought and flood years in the basin. Understanding of frequencies and time interval of incidences of floods and droughts is important in hydrological disaster management and planning. Therefore, to find out the distribution of the drought and flood years in the study period they are plotted against the time and represented in Figure 3.10.

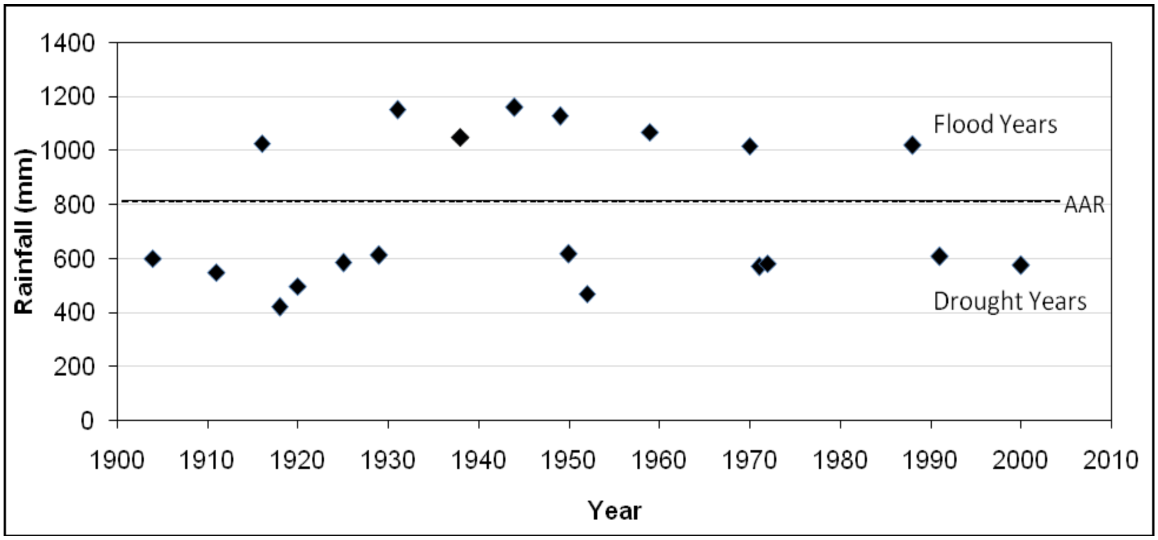
The occurrence of drought and flood in any region depends largely on the meteorological situations which are complex and uncertain. Therefore, the spread of drought and flood years in the Tapi basin does not present any systematic pattern (Figure 3.10).

Table: 3.6: Tapi basin: normal rainfall years

Year	AAR	Year	AAR	Year	AAR
1901	721	1937	913	1974	658
1902	677	1939	711	1975	824
1903	828	1940	889	1976	939
1905	622	1941	650	1977	823
1906	863	1942	917	1978	790
1907	620	1943	839	1979	914
1908	710	1945	854	1980	707
1909	757	1946	1006	1981	853
1910	911	1947	779	1982	643
1912	625	1948	921	1983	904
1913	749	1951	692	1984	669
1914	1001	1953	747	1985	627
1915	837	1954	892	1986	638
1917	937	1955	891	1987	653
1919	826	1956	860	1989	721
1921	773	1957	684	1990	922
1922	736	1958	903	1992	803
1923	656	1960	702	1993	847
1924	761	1961	904	1994	899
1926	714	1962	726	1995	686
1927	843	1963	769	1996	759
1928	823	1964	824	1997	867
1930	802	1965	657	1998	997
1932	818	1966	726	1999	763
1933	1009	1967	724	2001	744
1934	876	1968	695	2002	766
1935	825	1969	824	2003	806
1936	844	1973	879	2004	698

AAR = Average Annual Rainfall

Figure 3.10 Distribution of wet (flood) and dry (drought) years



To quantify and identify the drought and flood incidences over the region several other approaches have also been applied. For example, Kalwar et al. (2005), made five standard categories to demonstrate the drought and flood conditions based on the amount of annual rainfall as mentioned below.

Severe Drought	Less than 50% of average annual rainfall
Moderate Drought	Between (-) 50% and (-) 25% of average annual rainfall
Normal position	Between (-) 25% and (+) 25% of average annual rainfall
Moderate flood	Between (+) 25% and (+) 50% of average annual rainfall
Severe flood	More than 50% of average annual rainfall

Using the criterion mentioned above, the annual rainfall data of the Tapi Basin have been analyzed to identify normal rainfall years as well as drought and flood years and the results are presented in Table 3.7 and 3.8. Analyzing the annual rainfall over the basin, it is observed that in the whole period under study, that is from 1901 to 2004 (104 years), 87 years (90%) received normal rainfall. The number of years that received less rainfall than the normal which resulted into droughts is 10 (Table 3.7). The notable fact about the droughts is that these all are of moderate category and there is no occurrence of severe drought in the basin in the period under study. The lowest rainfall receiving year of widespread drought in the basin is 1918, obtained just 419 mm annual rainfall (Table 3.7).

Table 3.7 Moderate drought years

Year	AAR
1904	600
1911	549
1918	419
1920	498
1925	585
1952	469
1971	570
1972	581
1991	607
2000	575

Table 3.8 Moderate flood years

Year	AAR
1916	1026
1931	1151
1938	1050
1944	1158
1949	1128
1959	1067
1988	1020

As compared to droughts, the number of flood years which received more rainfall than the normal is less. The basin received excess rainfall than the normal for 7 years (Table 3.8). All these are moderate floods and like the severe droughts, no severe flood occurred in the basin. The year 1944, which received maximum annual rainfall (1158 mm) in the basin, was extensive flood year in the basin (Table 3.8). The basin received 42% more annual rainfall than the normal rainfall in 1944.

In summary, it is concluded that in the Tapi basin, 10 moderate drought years have been identified against 7 moderate flood years during 1901 to 2004. Hence, the study reveals that the Tapi Basin neither experienced any widespread severe drought nor a severe flood over the period of a century.

3.10 Rainfall-generating low pressure systems (LPS)

Generally, heavy rain spells are caused by large-scale, extraordinary synoptic situations. In the humid and seasonal tropics heavy, very heavy and extreme rainfalls are mostly associated with synoptic events such as LPS(s). The Tapi Basin lies at the core of the classical monsoon region and falls within one of the two major severe rainstorm zones of India (Dhar and Nandargi, 1995 b). Consequently, the predominant cause of high rainfall in the Tapi Basin is LPS. Low pressure systems (LPS) originating over the Bay of Bengal or land are found resulted into heavy rainfall in short duration of time. Therefore, to understand the association of the heavy rainfall events produced due to low pressure systems (LPS) and cyclonic storms (CS), the data regarding tracks of the cyclones were obtained from the electronic version of the Atlas of Cyclones and Depressions (2008 edition) named as the *Cyclone eAtlas* published by India Meteorological Department (IMD), Chennai. The LPS tracks associated to heavy rainfall in the Tapi Basin are analyzed and interpreted. Earlier studies (Abbi and Jain, 1971; Ramaswamy, 1985) of the synoptic situations associated with the rainstorms indicate that the rainfall-generating systems are associated with;

1. Bay of Bengal depressions moving westwards
2. General active monsoon conditions over Madhya Pradesh and Gujarat
3. Land depressions moving westwards

The orientations of the track of LPS, with respect to the basin, and the rate of movement of the LPS have a profound influence on the rainfall in the river basin.

Characteristics of the rainfall-generating low pressure systems (LPS)

The systems, which include lows, depressions and cyclonic storms (Dhar and Nandargi, 1995 b), cause heavy to very heavy rainfall. Records available for some rain gauge stations in the Tapi Basin indicate that low pressure systems (LPS) can have an immense impact on rainfall. Figure 3.11 (a), (b), (c) and (d) indicate that all the LPS associated with high rainfall in the Tapi Basin occur either in the month of August or September.

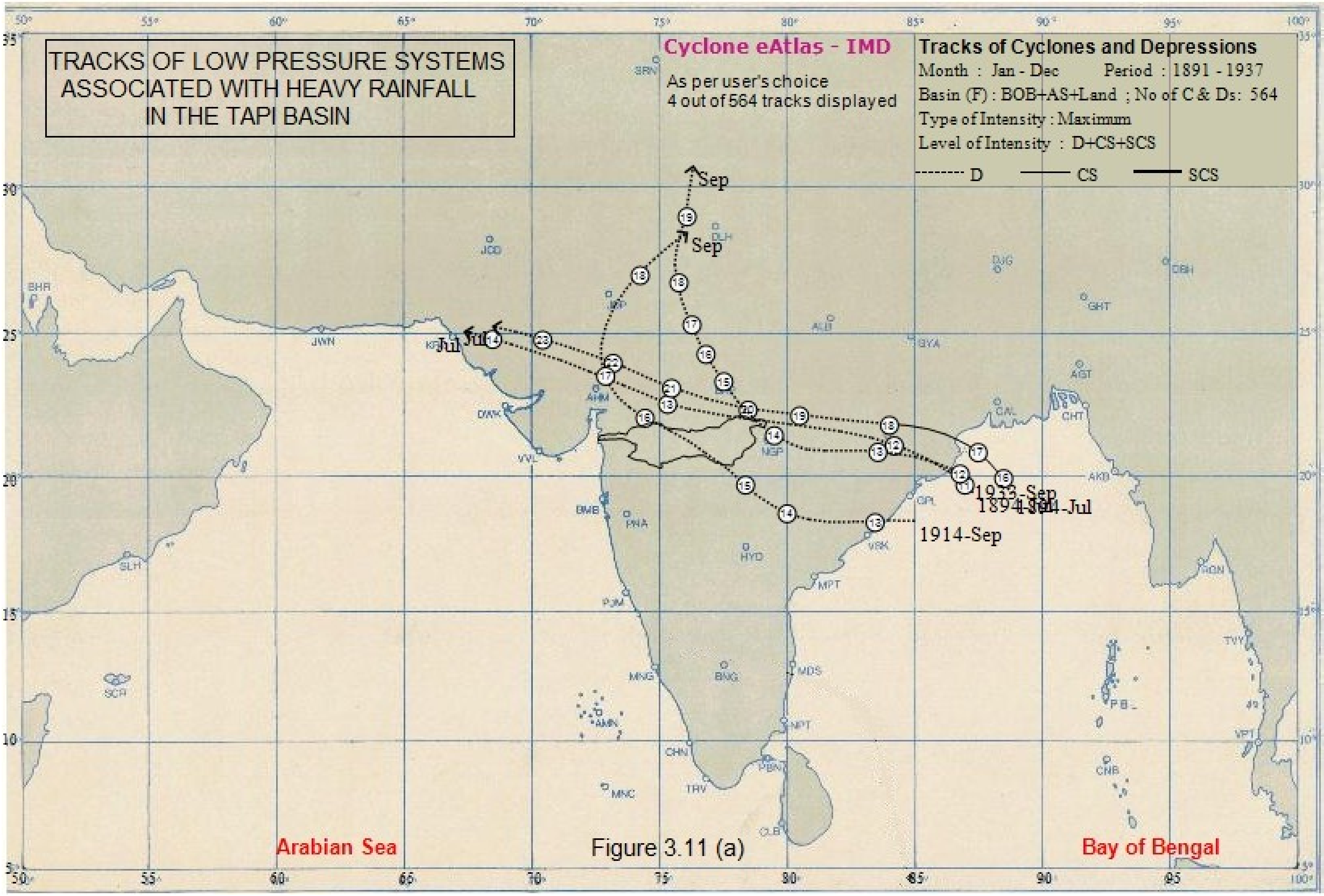
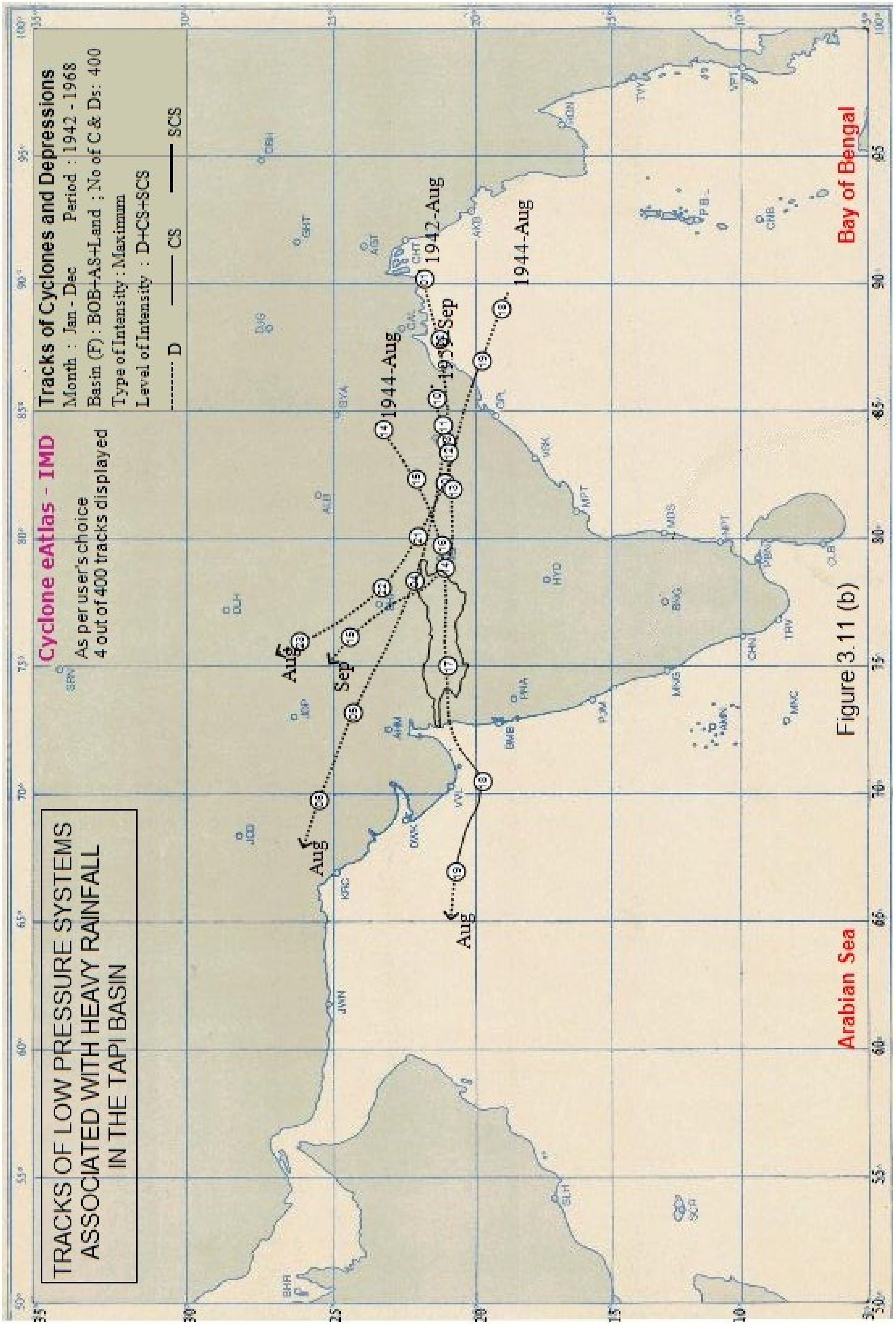

TRACKS OF LOW PRESSURE SYSTEMS
ASSOCIATED WITH HEAVY RAINFALL
IN THE TAPI BASIN
Cyclone eAtlas - IMD
As per user's choice
4 out of 564 tracks displayed
Tracks of Cyclones and Depressions
Month : Jan - Dec Period : 1891 - 1937
Basin (F) : BOB+AS+Land ; No of C & Ds: 564
Type of Intensity : Maximum
Level of Intensity : D+CS+SCS
D
CS
SCS
Sep
Sep
Jul
Jul
1933-Sep
1914-Sep
Arabian Sea
Bay of Bengal

Figure 3.11 (a)



TRACKS OF LOW PRESSURE SYSTEMS ASSOCIATED WITH HEAVY RAINFALL IN THE TAPI BASIN
Cyclone eAtlas - IMD
As per user's choice
4 out of 400 tracks displayed
Tracks of Cyclones and Depressions
Month : Jan - Dec Period : 1942 - 1968
Basin (F) : BOB+AS+Land ; No of C& Ds: 400
Type of Intensity : Maximum
Level of Intensity : D+CS+SCS
D
CS
SCS
1944-Aug
1942-Aug
1944-Aug
Sep
Aug
Sep
Aug
Aug
Arabian Sea
Bay of Bengal

Figure 3.11 (b)

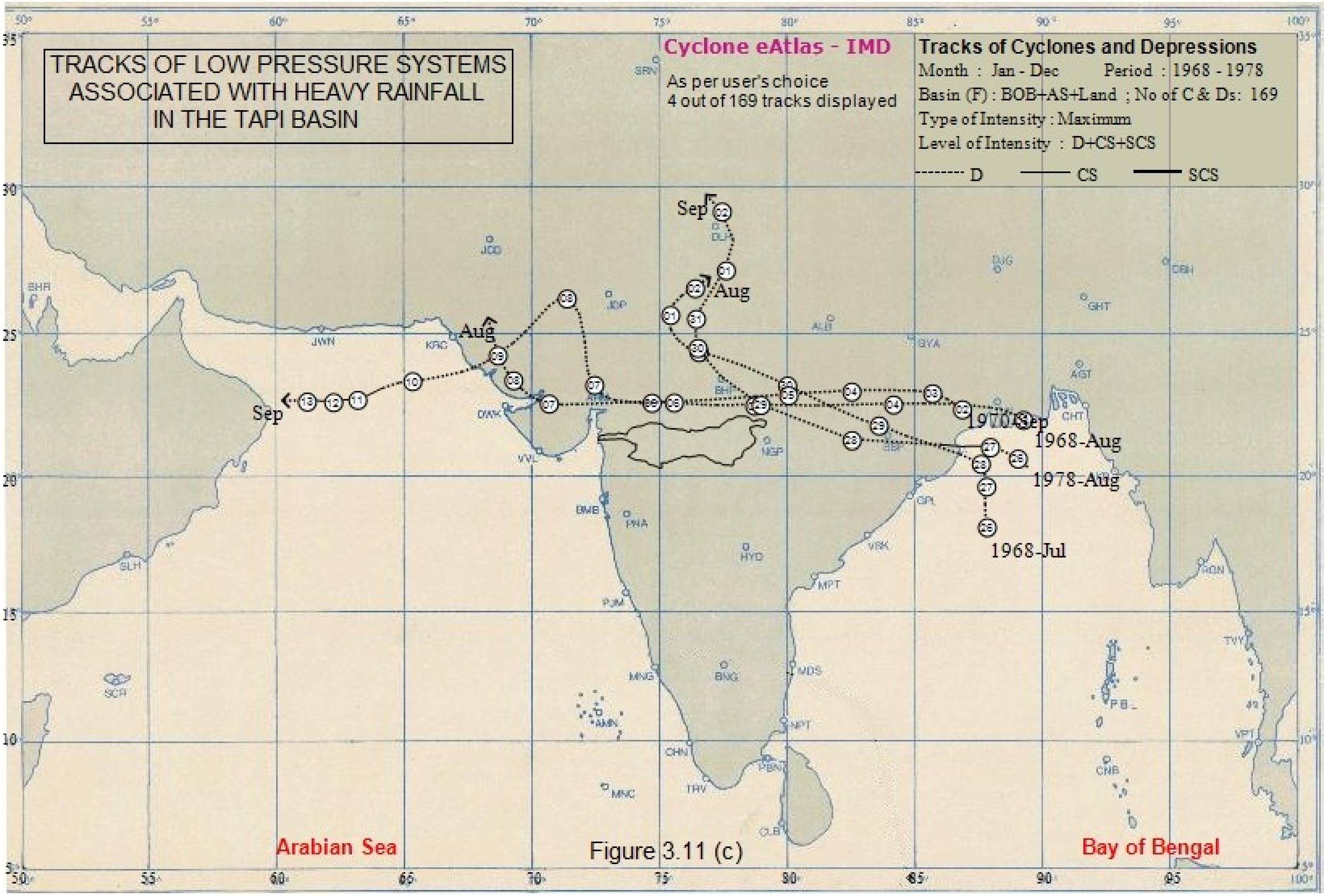
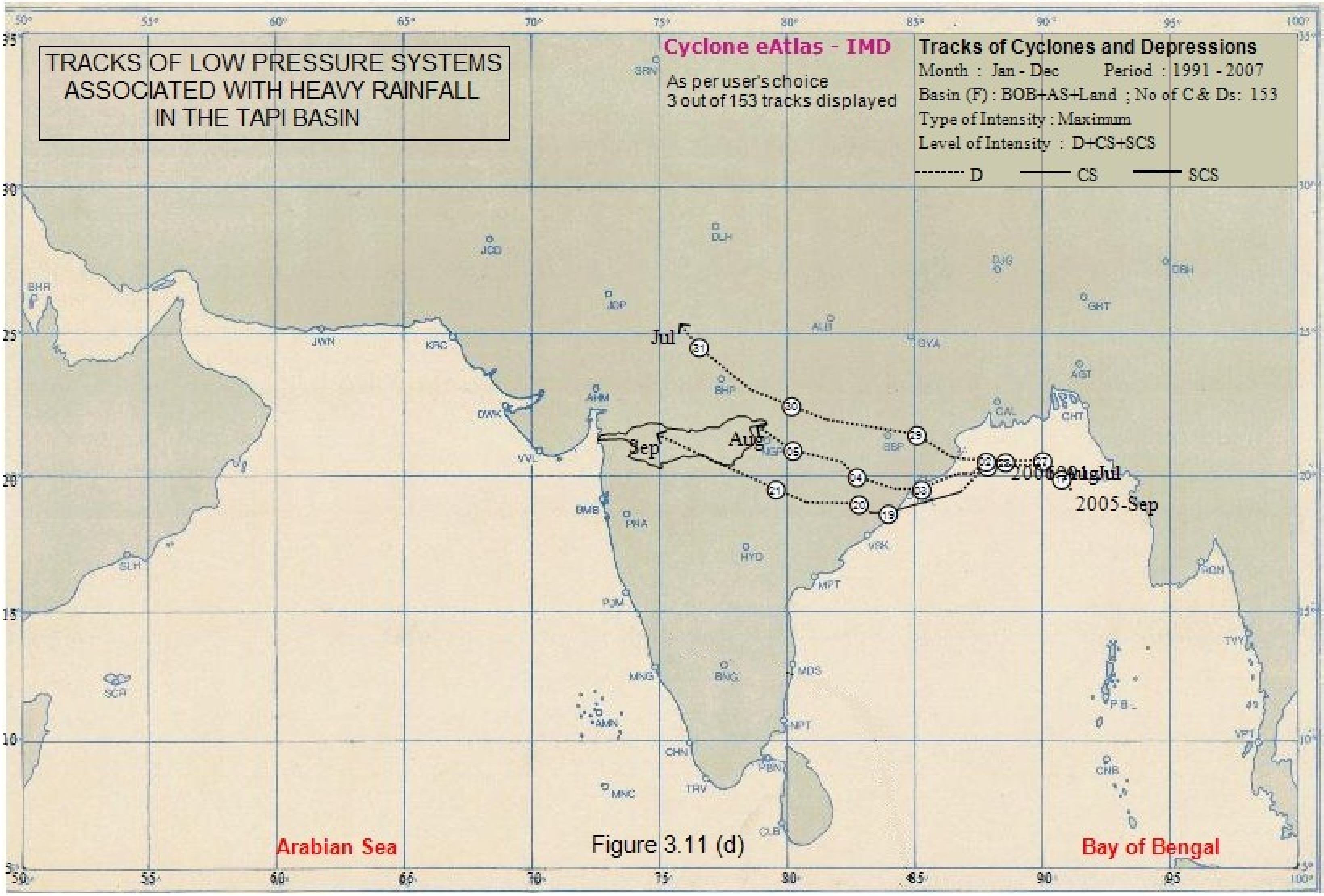

TRACKS OF LOW PRESSURE SYSTEMS
ASSOCIATED WITH HEAVY RAINFALL
IN THE TAPI BASIN
Cyclone eAtlas - IMD
As per user's choice
4 out of 169 tracks displayed
Tracks of Cyclones and Depressions
Month : Jan - Dec
Period : 1968 - 1978
Basin (F) : BOB+AS+Land ; No of C & Ds: 169
Type of Intensity : Maximum
Level of Intensity : D+CS+SCS
D
CS
SCS
Sep
Aug
Aug
Sep
1970-Sep
1968-Aug
1978-Aug
1968-Jul
Arabian Sea
Bay of Bengal

Figure 3.11 (c)


TRACKS OF LOW PRESSURE SYSTEMS
ASSOCIATED WITH HEAVY RAINFALL
IN THE TAPI BASIN
Cyclone eAtlas - IMD
As per user's choice
3 out of 153 tracks displayed
Tracks of Cyclones and Depressions
Month : Jan - Dec
Period : 1991 - 2007
Basin (F) : BOB+AS+Land ; No of C & Ds: 153
Type of Intensity : Maximum
Level of Intensity : D+CS+SCS
D
CS
SCS
Jul
Aug
Sep
2005-Sep
Arabian Sea
Bay of Bengal
Figure 3.11 (d)

According to Abbi and Jain (1971) the low pressure systems (Bay or land depressions), which follow a westward track through the Narmada Basin are more effective in causing heavy rainfall in the Tapi Basin, because the basin is located in the south-western sector which receives heavy rainfall. According to their path, two types of rainfall-producing LPS can be identified.

i. LPS that moved roughly parallel to the basin axis

There are a few LPS that have moved parallel to the basin axis, and have been associated with heavy rain spells. Such type of LPS may require a few days to traverse the basin. The August 1968 and September 1970 LPS are excellent examples of this kind (Figure 3.11(c)). These two cyclones were responsible for heavy rainfall in the Tapi Basin, since the basin remained in the southwest sector of these LPS. In addition to these two LPS, the 1944 cyclone (Figure 3.11(b)), originated as a land depression on August 14 and moved in the most unusual southwest direction (Ramaswamy, 1985). It also traveled in the west direction and passed almost through the center of the basin.

ii. LPS that traversed a part of the basin

Sometime the LPS may traverse only a part of the basin and still produce high-magnitude rainfall in the Tapi Basin. The rainfall magnitude due to such cyclones may vary over the different areas of the Tapi Basin. The best example of this is provided by the 1959 depression, which was responsible for heavy rainfall in the upper and middle Tapi Basin. The 1959 LPS moved westward towards the source area of the river. It further traveled in the north-northwest direction (Figure 3.11(b)). This storm produced torrential rainfall in the upper and middle Tapi Basin and in the Purna Basin and did not severely affect the lower part of the Tapi Basin. Similarly, in 1944, a second LPS in the month of August moved in the northwest direction, causing heavy rainfall in the upper catchment of the Tapi River (Figure 3.11(b)). The July 1991 LPS which resulted dam-failure in the upper Tapi Basin was also the outcomes of a LPS that traversed through the upper Tapi Basin (Figure 3.11(d)).

3.11 Resume

The aim of this chapter was to analyze the annual rainfall data to understand spatio-temporal variability in the Tapi Basin. Therefore, following conclusions have been drawn from the results of the analyses carried out in the above sections.

1. The Tapi Basin illustrates a significant spatially diversified rainfall. Particularly, the eastern and western marginal areas of the basin show strongly non-uniform amount of rainfall than the rest of the area.
2. With reference to the average annual rainfall of the basin and its standard deviation, the whole basin can be divided into three main zones- high rainfall zone, medium rainfall zone and low rainfall zone.
3. The north-eastern part covered by the rugged relief of the Gawilgad Range and the extreme western area of the basin receiving reasonably high rainfall, lie in the first zone. The widespread area in the central and south-eastern part of the basin, formed by the river plains receives rainfall close to the basin's average are categorized into second zone and a small pocket in the south-west of the basin, contiguous to the western high rainfall zone, falls in the third zone.
4. The high rainfall zone of the basin is characterized by great variation in the amount of rainfall in short distance. Whereas, the extensive river plains in the central part of the basin are characterized by almost uniform amount of rainfall. Similarly, the low rainfall zone of the basin in the south-west also obtains uniform amount of rainfall.
5. In general, the spatial pattern of rainfall in the Tapi Basin exhibits a decreasing pattern from east to west with abrupt rise in rainfall to the western edge of the basin.
6. The spatial distribution of rainfall in the basin is orographically controlled. The Western Ghats plays a key role in rainfall diversity in the basin.
7. The continuity and elevation of the Western Ghats and its offshoots acts as a barrier to the south-western monsoon winds and consequentially resulted into heavy rainfall on the windward side and produce a 'rain-shadow' area to the leeward side.
8. A low rainfall zone in the south-west of the basin is in fact the 'rain shadow' area which is an outcome of orographic effect of the Western Ghats. All six stations viz. Malegaon, Nandgaon, Satana, Dhule, Sakri and Shindkheda from this zone receive

remarkablly low rainfall, about 25-35% less than the basin's average rainfall.

9. The lowest rainfall at Sakri is attributed to its specific location. The Galana Range, the east-west trending offshoot of the Western Ghats runs across the path of monsoon winds and is situated in the rain shadow zone of the main rim of the Western Ghats. Therefore, it can be stated that Sakri is located in the *'secondary rain shadow area'* which is the significant reason for very low rainfall in this region.
10. The effect of orography on the rainfall clearly visible in the north-eastern high rainfall zone of the basin. This part of the basin is covered by the Gawilgad Range. With its considerable length and uniformity in elevation, the area vicinities of the Gawilgad Range gets high orographic rainfall which accounts for more than 1000 mm. Chikhaldara, situated on the crest line of the Gawilgad Range, receives highest rainfall (1596 mm) in the basin which is about two times more than the basin's average rainfall.
11. An important and most immediately felt aspect of rainfall of the basin is its inter-annual variability. However, the coefficient of variation (Cv) of the Tapi basin as a unit is 30% suggestung that the rainfall of the basin is less variable.
12. The values of coefficient of skewness (Cs) are positive for all the stations in the basin proposing the occurrence of one or two or a few very wet (high rainfall) years during the gauged period.
13. Two contrasting features of the rainfall can be noticed in two parts of the 20th century. It is observed that in comparison of the rainfall in the second half of the century, rainfall in the first half of the century was more variable. Nevertheless, the first half of the century is characterized by above-average rainfall. Thereafter less variability in the rainfall is observed. The basin received not only average rainfall but also less variable rainfall in the second half of the 20th century
14. The rainfall over the basin, in general, varies between -30 and +30% from its mean. However, in some instances the maximum departure of rainfall is observed between -40 to +40% from the mean. It, therefore, reveals that the rainfall of the Tapi Basin as a geographical unit is less variable.
15. The seasonal rainfall of the basin for the period 1901-1950 shows an increasing trend, which come down in the period 1951-2004 and does not present any specific trend.

16. The consistency of rainfall in June in the first half of the century turns into an increasing trend in the second half. July and September presents clear opposing rainfall trends in two parts of the century. Whereas, an increasing trend of rainfall in August in the first half of the century stabilized in the second half of it.
17. The rainfall over the Tapi Basin demonstrates alternating sequences of multi-decadal periods having excess and deficient rainfall. This epochal behaviour of rainfall of the basin can be summarized in three periods: (i) 1901-1930: dry epoch (ii) 1931-1960: wet epoch and (iii) 1961-1990: dry epoch. The epochal pattern of the rainfall of the Tapi Basin is quite similar to that found over the country.
18. The Tapi Basin neither experienced any widespread severe drought nor a severe flood over the period of a century.
19. The high annual rainfall in the basin shows association with low pressure systems (LPS) that traversed either through or across the basin.

CHAPTER IV

LONG-PERIOD FLUCTUATIONS IN THE MONSOON RAINFALL

4.1 Introduction

A question of prime importance to rainfall studies in India is whether the monsoon rainfall has changed over the last few decades and whether a change is likely to occur in future. Although it is difficult to recognize the likely future trend of rainfall, it is possible to detect the nature of changes that have occurred in the past. Determining the trends or changes in the rainfall are extremely important because studies of hydro-meteorological conditions caused them is useful to detect climatic changes (Kale, 1999). Even though most of the investigations in the last few decades have revealed secular variations in the Indian monsoon rainfall (Mooley and Parthasarathy, 1984; Gregory, 1989b, Parthasarathy et al., 1991; Kripalani and Kulkarni, 1997), the studies of rainfall to determine long-term trends/changes on river basin scale are limited. In the present chapter an attempt has been made to analyze the annual rainfall data of the Tapi Basin to study the long-term fluctuations in the rainfall. The data analyzed in this chapter consists of long-term annual rainfall series available for 56 representative rain gauge stations in the basin. Almost all the stations have long records of rainfall and hence are suitable for identifying long-term trends that might have resulted from long-term changes in the rainfall. The length of data for most of the stations is about over 100 years (see Table 1.1) which is reasonably suitable for long-range studies of rainfall. The objective of this chapter is, therefore, to analyze the annual rainfall records and to detect changes/trends in the annual rainfall of the basin.

There are many studies carried out to detect the rainfall trend on all India or regional scales. According to the type and record length of the rainfall data used for analysis there are varied results regarding the trend of rainfall in the country. Pattanaik (2007) concluded that the monsoon rainfall over the central and northwest

India during 1941–2002 presents decreasing trend. Rupa Kumar et al. (1992) found that, central peninsula, western coastal area present increasing trend of monsoon rainfall but northeast peninsula and northwest peninsula experienced a decreasing trend. The annual rainfall for the first six decades of India has been analyzed by Parthasarthy and Dhar (1974) and noticed an increasing trend over central India and decreasing trend over eastern India. However, Kumar et al. (2010) found that the analysis of fairly long-term rainfall data of India for the period 1871-2005 does not show any visible trend on country level. Although less in number, a few studies examined the rainfall data of some major river basins of India to determine the trend of rainfall on the basin scale. The study of Mirza et al. (1998) revealed that the rainfall over Ganges, Brahmaputra and Meghna Basins does not present any significant trend. The trend analysis of rainfall over the Mahanadi Basin carried out by Rao (1993) also does not show any clear trend. However, the analysis of rainfall after 1960 over major river basins in the central India by Singh et al. (2005) exhibit varying results. They found an increasing trend of rainfall over Indus, Brahmaputra, Ganga, Cauvery and Krishna Basins and decreasing trend over Narmada, Tapi, Sabarmati, Mahi, Godavari and Mahanadi Basins.

4.2 Detection of changes in the annual rainfall

In this section an attempt has been made to evaluate the long-term changes/trends in the annual rainfall records of the Tapi Basin using Mann-Kendall test (Hollander and Wolfe, 1973). Mann-Kendall test is a powerful statistical technique for randomness against trend (Subramanian et al., 1992). Use of Mann-Kendall test in trend analysis of meteorological parameters, particularly of rainfall has been reported by several workers. Srivastava et al. (1998) utilized Mann-Kendall test for finding the trend in rainfall over India for the period 1901-1992 and concluded that more or less all-India rainfall does not show any specific trend. Krishnakumar et al. (2009) determined the long-term changes in seasonal and annual rainfall over Kerala with the help of Mann-Kendall trend test. This non-parametric method has also been used by several workers to quantify the direction and magnitude of trends in the streamflow and rainfall records (Chiew and McMahon, 1993; Kale, 1998; Hire, 2000; Marengo, 1995; Probst and Tardy, 1987). Several other workers (Sahu (2004), Seetharam (2003), Lal et al. (1993) and Suresh et al. (1998)) also applied this test for identification of the nature of changes in the rainfall of the small regions or stations.

The Mann-Kendall's Tau (τ) has been obtained by following equation;

$$\tau = \frac{\text{Actual total of scores}}{\text{Maximum possible total}} \qquad \text{...... Eq. 4.1}$$

The actual total of scores is achieved by procedure outlined in Table 4.1, which is just a demonstration. The scores obtained by this procedure are not used in final results of the study. The annual rainfall data of the Tapi Basin for twelve years have been selected as a representative for calculation of actual total of scores, maximum possible total, and for calculation of τ.

Table: 4.1 Scores for calculating Mann-Kendall's τ for the Tapi Basin (An illustration)

YEAR	**AR**												
1901	721												
1902	677	-1											
1903	828	1	1										
1904	600	-1	-1	-1									
1905	622	-1	-1	-1	1								
1906	863	1	1	1	1	1							
1907	620	-1	-1	-1	1	-1	-1						
1908	710	-1	1	-1	1	1	-1	1					
1909	757	1	1	-1	1	1	-1	1	1				
1910	911	1	1	1	1	1	1	1	1	1			
1911	549	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1		
1912	625	-1	-1	-1	1	1	-1	1	-1	-1	-1	1	**ATS**
	Sum	-3	0	-5	6	3	-4	3	0	-1	-2	1	**-2**

The annual rainfall (AR) of the first year i.e. 1901 is compared with the AR of the subsequent years i.e. 1902, 1903, 1904 and so on. If the values (AR) of the subsequent years (1902, 1903, 1904 and so on) are greater than the value (AR) of the first year (1901) then the scores are +1 and if the values subsequent are smaller than the value of the first year then the scores are –1. For instance, AR of the year 1902 (677 mm) is smaller than AR of the year 1901 (721 mm), therefore, the score is -1; and AR of the year 1903 (828 mm) is greater than AR of the year 1901 (721 mm), thus, the score is +1. In this manner, the AR value of the first year is compared with the AR values of all the years and the scores are obtained. Then sum of scores is calculated, which in this illustration is -3. For the next comparison, the first year's (1901) AR value is dropped and the second year's (1902) value is compared with the rainfall values of the subsequent years (i.e. 1903, 1904, 1905 and so on) and the sum(s) scores are calculated for it. The actual total of scores (ATS) is the total of all sum(s), which in this illustration is -2.

The maximum possible total has been obtained with following equation;

$$\text{Maximum possible total} = N\,(N-1)\,/\,2 \qquad \text{...... Eq. 4. 2}$$

Where; N = Number of observations (for this illustration, N=12).
Therefore, the Mann-Kendall's τ is obtained by putting values in Eq. 4.1;

$$\tau = \frac{-2}{66} = -\,0.030$$

The positive (negative) sign of τ indicates increasing (decreasing) trend. Therefore, the negative value of τ for the given illustration suggests that the rainfall trend for the given period is decreasing. It to be noted that the scores obtained for this example are not used in the study.

4.3 Testing the significance of Tau (τ)

For the large *N*, the method outlined for testing the significance of τ becomes extremely cumbersome. However, Kendall (1955) has shown that when *N* is larger than 8, the theoretical distribution of all possible values of τ approaches the normal distribution. The τ may be transformed into a normal standard deviate as follows;

$$z = \frac{\tau}{\sqrt{2(2N+\ )/9N(N-\ )}} \qquad \text{……. Eq. 4.3}$$

Substituting the calculated value of τ, the value of the *z* can be obtained. For large number of observations ($N > 30$), *z* value has to be greater than 2.32 at 0.01 level and 1.64 at 0.05 level for the sample to be statistically significant.

It is obvious that different stations in the basin cannot present similar trend of rainfall. Therefore, to check the rainfall trend at a station, three representative stations viz. Chikhaldara, Sakri and Jamner are selected. The basis to choose these specific stations is that these stations represent different sections of the basin as well as they are having varying annual rainfall amounts. Chikhaldara, situated in the eastern hilly areas, is the highest rainfall receiving station in the basin. Sakri, located to the west, is the lowest rainfall receiving station whereas, Jamner, having almost similar rainfall to that of the average rainfall of the basin, represents to the central area of the basin. This exercise predominantly intended to observe the change/trend over the basin scale, therefore, Mann-Kendall's τ and *z* scores are obtained for the whole basin besides the above-mentioned three representative stations and the results are given in Table 4.2.

The application of this non-parametric test to the annual rainfall data of the basin designate varied results for different stations. Significant decreasing trend at 0.05 level is observed for Chikhaldara, a highest rainfall receiving station in the basin. Conversely, Sakri, the lowest rainfall receiving station in the basin present significant increasing trend at 0.05 level (Table 4.2). The test, however, does not exhibit any clear trend in the annual rainfall for Jamner, a rainfall station with average annual rainfall close to the basin's average rainfall, located in the central part of the basin (Table 4.2). Moreover, no significant trend of rainfall is observed on the basin scale

(Table 4.2). Therefore, it can be stated that the annual rainfall is decreasing with respect to time at high rainfall stations in the basin. Whereas, apposite to it, low rainfall stations in the basin present an increasing trend of rainfall. However, the stations having similar rainfall amount with the basin does not indicate any considerable trend.

Table: 4.2 Nature of changes/trends in annual rainfall records based on Mann-Kendall test

Station	**Period**	***N***	**Tau (τ)**	***z* score**	**Trend/change**
Chikhaldara	1901 – 2004	104	-0.118	-1.78	Decreasing* trend
Sakri	1901 – 2004	104	0.110	1.66	Increasing* trend
Jamner	1901 – 2004	104	0.022	0.33	No specific trend
Tapi Basin	1901 – 2004	104	0.270	0.27	**No specific trend**

See Figure 1.4 for location of stations; *N* = number of observations; * = statistically significant at 0.05 level

The Tapi Basin is an extensive in area, therefore, before generalizing the results of rainfall trend given in Table 4.2, and to validate these results, trend analysis has been further carried out for three more stations with same procedure. These stations are Multai (high rainfall station), Jalgaon (a station with annual rainfall close to the average annual rainfall of the basin) and Satana (low rainfall station) representing to east, central and west zones of the basin respectively. It is found that no specific rainfall trend has been noticed at Multai. Similarly, Jalgaon also does not designate any specific rainfall trend. However, Satana, a low rainfall station indicate a statistically significant increasing rainfall trend at 0.01 level (z score = 3.80). Therefore, summarizing the rainfall trends obtained at above-mentioned stations in the basin, it is evident that the low rainfall stations in the basin shows a significant increasing rainfall trend. The stations having rainfall close to the average rainfall of the basin does not present increasing or decreasing rainfall trend. Most importantly, the Tapi Basin, as a whole, does not show any significant rainfall trend over the period of a century. It is obvious that the scrutiny of various stations in the basin will underline visible long-term changes/trends in the rainfall at few stations. However, certainly the rainfall over the Tapi Basin not had undergone large variations, which can indicate any specific trend of it. These observations, therefore, provide a weak support to the general view that the rainfall in the basin is progressively decreasing.

Most of the investigations for larger areas (all-India scale) during last few decades have given similar results. These studies clearly specified that the monsoon rainfall, particularly on all-India scale, is trendless and is predominantly random in nature over a long period of time, (Mooley and Parthasarathy, 1984). Gregory (1989) observed that there is no significant linear trend in the monsoon rainfall of any of the ten macro-regions that he recognized. However, though not at particular locations, the presence of some pockets of significant long-term rainfall changes are also reported by some workers (Pant and Rupa Kumar (1997), Raghvendra (1974), Rupa Kumar et al. (1992)).

4.4 Normalized accumulated departure from mean (NADM) method

It is well known that the monsoon rainfall of the same region goes through variations from one year to another. However, departures of rainfall from its long-term mean in any two years are not same (Gadgil, 2002). The year to year fluctuations in rainfall of the region cause complexity in recognition of the direction of change in the rainfall. Therefore, some effective statistical methods are applied to identify the nature of long-term variability in monsoon rainfall. Normalized accumulated departure from mean (NADM) is one of the statistical methods frequently used in the study of rainfall variability.

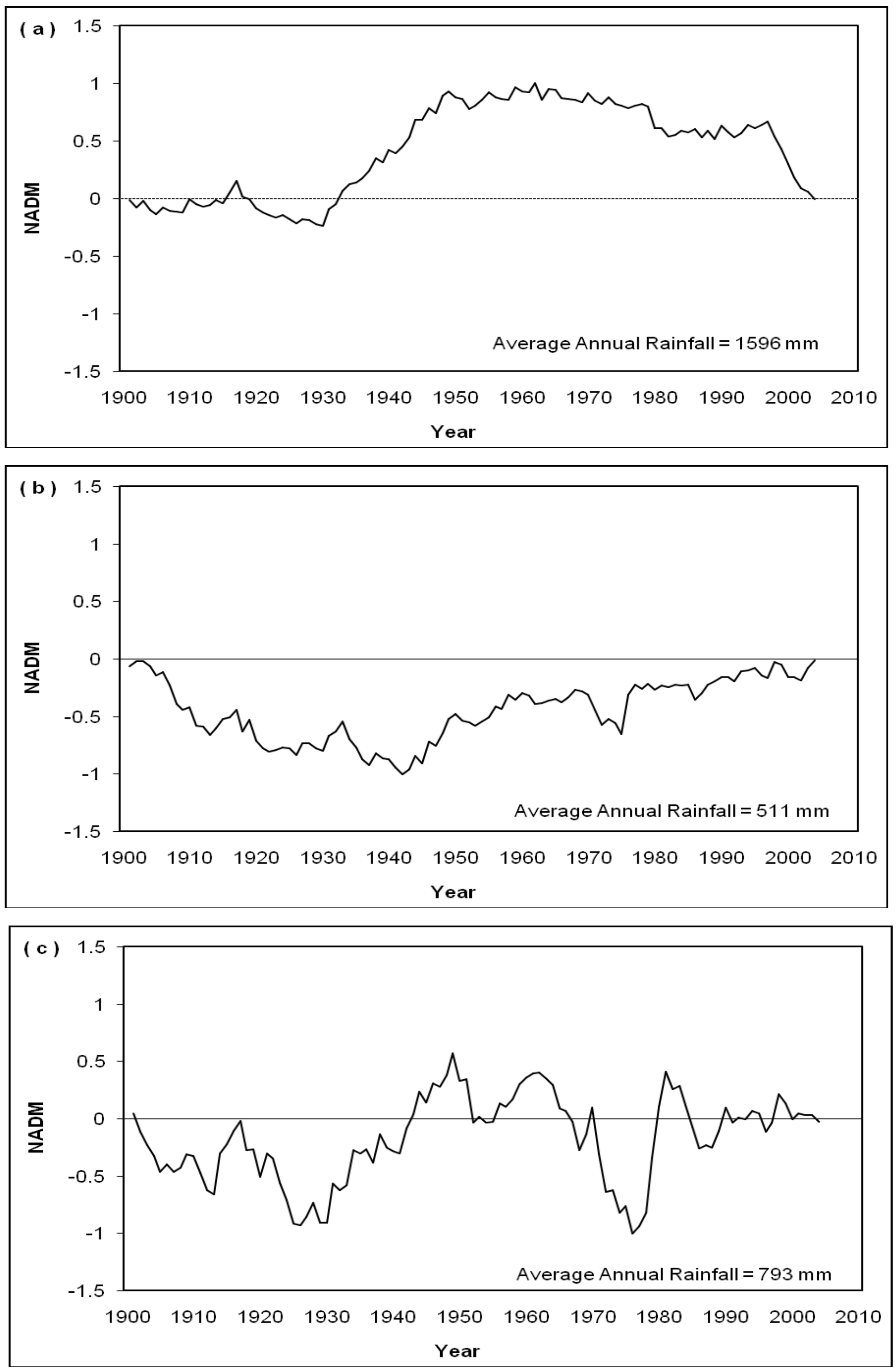
Successive properties within long-term data can be simply resolved by using accumulated departure from mean (ADM) (Riehl et al., 1979; Mooley and Parthasarathy, 1984; Probst and Tardy, 1987; Kale, 1999). Therefore, to emphasize the long-term variability by minimizing short-term fluctuations in the monsoon rainfall, the normalized accumulated departure from mean (NADM) plotting method has been used in the section.

The normalized accumulated departure from mean (NADM) is the accumulated departure from mean (ADM), divided by the largest number (absolute) in order to plot between -1 and +1 (Thomas, 1993). The normalized ADM, therefore, allows apparent as well as statistical association of dissimilar data (Thomas, 1993). Periods featured by above-average state are generally shown by positive slopes of the graph and vice-versa (Gregory, 1989b; Thomas, 1993). In contrast with other methods used for similar purpose, such as running means, the ADM clearly shows the difference between periods of high and low rainfalls (Probst and Tardy, 1987). According to the different workers (Riehl et al. (1979), Thomas (1993) and Kale (1999)) in the field, it is important to evaluate the records of various stations having same time span. Therefore, the length of the plot period has been kept equal while comparing rainfall records of different stations.

The Tapi Basin is widespread and moreover 56 rainguage stations are selected for the study. It is clear that different stations in the basin will present dissimilar patterns of NADM graphs. However, the main purpose of the study is to detect the changes in the rainfall on the basin scale, three representative stations viz. Chikhaldara, Sakri and Jamner are chosen for this exercise. The NADM graphs given in Figure 4.1 (a), (b) and (c) show the long-term trends of rainfall at these representative stations in the basin.

The NADM plots for the above-mentioned stations illustrate unlike patterns (Figure 4.1). The rising natures of NADM graph indicates above-average conditions, whereas, falling nature of the graph correlated with the below-average conditions of rainfall. The NADM graph of Chikhaldara suggests that the rainfall amounts were below-average in the beginning of the 20th century i.e. upto 1930 (Figure 4.1(a)). The middle part of the century i.e. from 1930 to 1960 is featured by sharp rise in the graph which indicates the period of above-average rainfall conditions. The graph shows a regular falling trend after 1960, which is an indicator of the below-average rainfall in this period (Figure 4.1(a)).

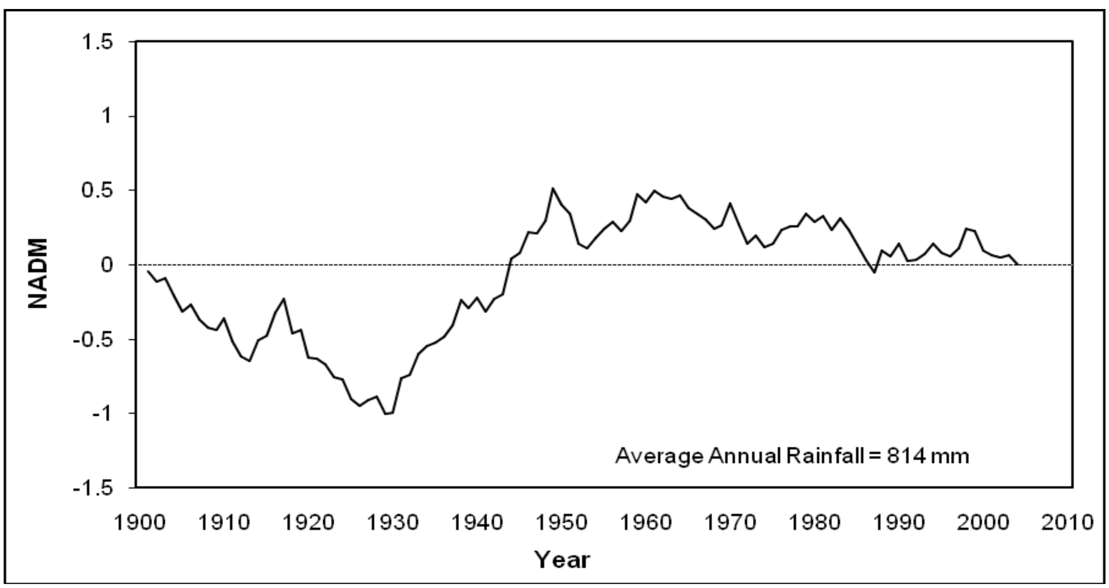
Figure: 4.1 Normalized Accumulated Departure from Mean (NADM) Graphs (a) Chikhaldara (b) Sakri (c) Jamner



The plot for Sakri is open V-shaped with falling slope in the beginning and rising slope in the later part of the century. It shows that the rainfall was below-average in the early stage of the century i.e. upto 1940. However, this period involves two small high rainfall episodes (Figure 4.1(b)). The period after 1940 is characterized by constant rise in rainfall interrupted by marked fall in rainfall between 1970 and 1980 (Figure 4.1(b)).

The NADM plot of Jamner exhibits an asymmetrical pattern and highlights the alternate below and above-average rainfall periods with regular interval (Figure 4.1(c)). The falling nature of the graph in early 1900 indicates below-average rainfall upto 1930, while, the period from 1930 to 1950 is featured by above-average rainfall conditions (Figure 4.1(c)). The period from 1950 to 1980 is attributed with below-average rainfall conditions and again the rainfall conditions are found above-average after 1980 (Figure 4.1(c)).

Figure: 4.2 Normalized Accumulated Departure from Mean (NADM) Graph of the Tapi Basin



An assessment of NADM graphs of the representative stations of the basin does not exhibit similar results. Therefore, in order to have a composite picture of the long-term fluctuations in the rainfall on the basin scale, the NADM graph has been prepared for the basin (Figure 4.2). The falling slope of the graph from 1901 to 1930 is characterized by below-average (low) rainfall. The quick ascend from 1930 continues upto 1950 emphasized the above-average (high) rainfall period (Figure 4.2). The gently sloping nature of the graph in the second half of the century shows the below-average (low) rainfall with short-term episodes of high rainfall (Figure 4.2).

Although from the above illustrations (Figure 4.1 and 4.2) it is difficult to draw general conclusion regarding the rainfall pattern of the Tapi Basin, they point towards some common characteristics of the rainfall over the basin.

(i) The early period of the 20th century i.e. 1901 to 1930 is associated with the below-average (low) rainfall.

(ii) Above-average (high) rainfall period is observed between 1930 and 1960.

(iii) Below-average (low) rainfall period is found in the latter half of the 20th century i.e. after 1960.

Therefore, the analysis of the annual rainfall data of the basin with respect to the deviations in the amount clearly indicates that the major changes in the rainfall occurred around 1930, 1960, and 1990. Mooley and Parthasarathy (1984), Fu and Fletcher (1988), Parthasarathy et al. (1991) and Kripalani and Kulkarni (1997) identified significant changes in the monsoon conditions about the same years in India. The comparison of all-India monsoon rainfall (Parthasarathy et al., 1991) with the rainfall of the Tapi Basin show striking similarity in their long-term fluctuations.

4.5 Teleconnections of the rainfall with ENSO

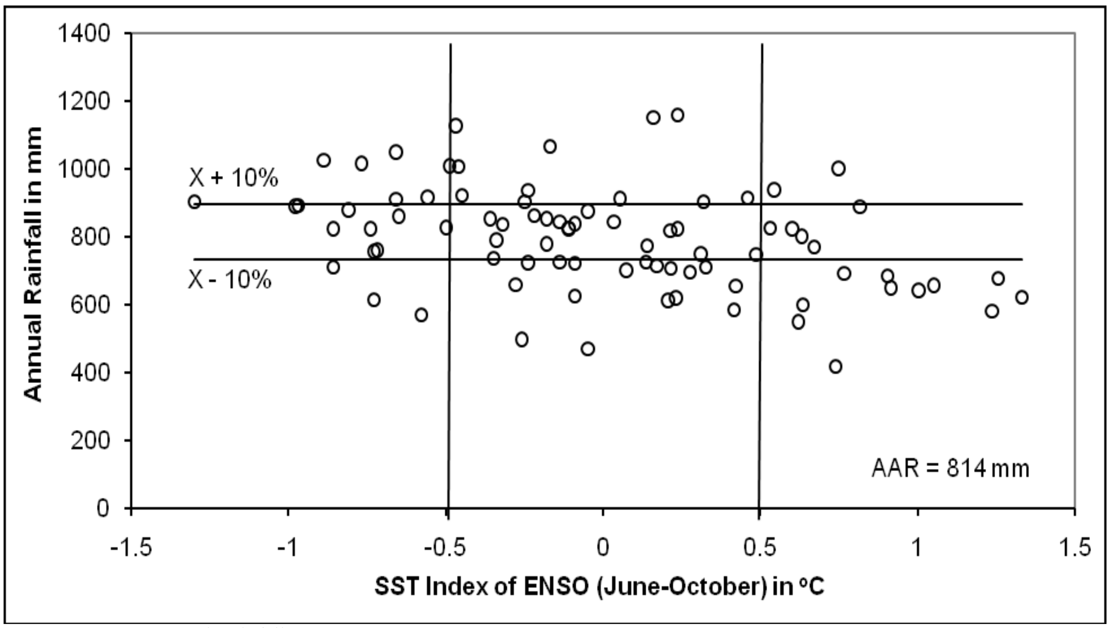
The monsoon teleconnection refer to those situations or developments in the land-ocean-atmosphere system occur several months prior to onset of the monsoon over India and exert a substantial influence on the rainfall of the country (Kelkar, 2009). One of the very important global parameters teleconnected to the Indian summer monsoon rainfall (ISMR) is El Niño and Southern Oscillation (ENSO).

El Niño is the term applied to the periodic warming of the ocean that occurs in the central and eastern Pacific, and Southern Oscillation is the see-saw pattern of atmospheric pressure change that occurs between the eastern and western Pacific (Lutgens and Tarbuck, 2007).

The phenomenon of ENSO was discovered by Gilbert Walker by establishing the fact that Indian monsoon was not an isolated system but had strong teleconnections with the global climate (Kelkar, 2009). After Walker (1924), several studies assessed the possible linkages between the Southern Oscillation (SO) and ISMR and revealed various aspects of the relationship between ISMR and ENSO (Khandekar, 1979; Sikka, 1980, Rasmusson and Carpenter, 1983; Shukla and Paolino, 1983; Ropelewski and Halpert, 1987; Kane, 1989; Simpson et al., 1993; Khole, 2004; Lutgens and Tarbuck, 2007; Ihara et al. 2007). These studies have inferred that in general, ISMR is inversely correlated with Sea Surface Temperature (SST) of the Pacific. Lutgens and Tarbuck (2007) noticed that El Niño is certainly a part of the global circulation and affects the weather at great distances from the Pacific. Moreover, it marked by an abnormal weather patterns. Indian monsoon is more vulnerable to drought situations when El Niño events occur. Conversely, wet monsoons are more likely to prevail, during the La Niña events. (Krishnan and Sugi, 2003). Saha et al. (2007) also recognized the similar association between them.

The rainfall over the Tapi Basin is highly susceptible to the changes in the Indian southwest monsoon which is teleconnected with the ENSO events. Therefore, in the present section an attempt has been made to understand natural variability in the annual rainfall of the basin in relation with the ENSO events. The annual rainfall data for the period of 104 years (1901-2004) of the basin have been used to establish relationship with ENSO events. The method adopted by Eltahir (1996) for the Nile River was used for the analysis. The index of ENSO used in the study is the monthly series of the mean sea surface temperature (SST) anomaly averaged over the central and eastern Pacific Ocean, published by Wright (1989) for the period 1891-1983. The index finally used here is averaged over the monsoon season (June-October). The data on SST were classified into cold, warm and normal conditions on the basis of temperature (-0.5°C and +0.5°C) as suggested by Eltahir (1996). Figure 4.3 shows the categories of the annual rainfall of the Tapi Basin and ENSO index. To investigate the association of the magnitude of the rainfall and the situation of the ENSO in different years, the conditional probabilities of the rainfall have been calculated and presented Table 4.3.

Figure: 4.3 Categories of annual rainfall and ENSO index of the Tapi Basin



AAR = Average Annual Rainfall

Table 4.3 Conditional probabilities of the monsoon rainfall over the Tapi Basin given the SST index of ENSO (N = 83 years)

Region	**AAR**	**SST**		
		Cold	Normal	Warm
Tapi Basin	High	0.44	0.26	0.11
	Average	0.39	0.38	0.28
	Low	0.17	0.36	0.61

Data source: IMD; Low < 10% AAR and High >10% AAR; AAR = Average Annual Rainfall

The analysis shows that the probability of having high rainfall in the Tapi Basin is more (44%) during cold ENSO conditions and very less (11%) during warm

ENSO conditions and vice versa (Table 4.3). Therefore, it is reasonable to infer that during cold ENSO (warm ENSO) events the magnitude of rainfall will be higher (lower). The conclusion of this analysis is matching with the inference drawn by earlier workers mentioned in this section.

4.6 Detection of future changes in the rainfall

A question of prime significance to rainfall studies in India is whether the future is likely to see the situation improved, unchanged or exacerbated. Although, it is difficult to predict the direction and magnitude of change, it is possible to estimate the percentage change required in the future data series before it can be considered to be statistically significant (Kale, 1998). Chiew and McMohan (1993) and Marengo (1995) have used the Student's *t*-test to determine the percentage change required in the mean of the future data series before it can be considered to be significantly different from the historical gauge record.

The percentage change can be estimated as;

$$t = \sigma * t\alpha \sqrt{(1/nh + 1/nf)} \quad \text{....... Eq.4.4}$$

$$\% \text{ Change} = (t \ / \text{AAR}) \times 100 \quad \text{....... Eq.4.5}$$

Where,

t = student *t* value

σ = standard deviation of the historical gauge data

nh = length of historical rainfall series

nf = length of future rainfall data

tα = the critical value of the *t*-statistics at 95% level of significance and

AAR = average annual rainfall

Table 4.4 Percent change required to identify statically significant change in AAR of the Tapi Basin

Region	N	AAR (mm)	σ	Percent change required in the AAR at 95% of confidence level, Years			
				10	20	50	100
Tapi Basin	104	814	196	16	11	8	7

Data source: IMD, Pune; N = No. of observations

Table 4.4 demonstrates the percentage change required in the future rainfall before it can be considered to be significantly different from the historical record. Owing to its inherent nature, the rainfall over the basin shows considerable inter-annual variability in its amount, particularly for the short-period of time. Hence, high variations in the amount of rainfall can be noticed for the short-period of time which ceases with the increase in the time span of the record. It is, therefore, obvious that high percentage change is required in the future rainfall of the short-period of time, before considering it significantly different from historical record. While, for the long-period of time small percentage change is required in the future rainfall to consider it significantly different than the previous data.

The results of application of the *t* test to the statistical parameters of the rainfall data of the Tapi Basin are displayed in Table 4.4. It is observed that on the basin scale 16% change in the annual rainfall is required in the average rainfall of next 10 years to consider it different than the available rainfall record. Similarly, to determine the significant change in the rainfall of the next 20 and 50 years, the average rainfall should vary by 11 and 8 % respectively than the present mean of the rainfall (Table 4.4). Whereas, to declare the average rainfall of the present century (21^{st} century) significantly different than the previous century (20^{th} century), 7% change is required in the long-term mean of the rainfall of the basin (Table 4.4). The analysis of the *t* test as well as other analyses conducted in the previous sections of this and the preceding chapters indicate that the monsoonal rainfall of the Tapi Basin is highly regular and consistent. Therefore, it is likely to be the same in this as well as in the next century.

4.7 Resume

1. Significant decreasing trend of rainfall at 0.05 level is observed for Chikhaldara, a highest rainfall receiving station in the basin. Conversely, Sakri, the lowest rainfall receiving station in the basin present significant increasing trend of rainfall at 0.05 level. Therefore, in general, it is found that the annual rainfall is decreasing with respect to time at high rainfall stations in the basin. Whereas, apposite to it, low rainfall stations in the basin present an increasing trend of rainfall. However, the stations having similar rainfall amount with the basin does not indicate any considerable trend.
2. High rainfall stations (such as Chikhaldara) demonstrate below-average rainfall conditions upto 1930. The middle part of the 20th century i.e. from 1930 to 1960 is featured by above-average rainfall conditions which alter into below-average rainfall conditions after 1960.
3. The low rainfall stations (e.g. Sakri) exhibit below-average rainfall conditions in the early stage of the century, upto 1940. While, the period after 1940 is characterized by continuous above-average rainfall situations.
4. The stations having average rainfall close to the basin's average (for example, Jamner) display an asymmetrical temporal pattern of rainfall. These stations does not signify any specific direction of change in the rainfall amalgamating alternate below and above-average rainfall periods with regular interval.
5. A composite picture of the long-term fluctuations of the rainfall on the basin scale point towards some significant characteristics of the rainfall.
   (i) The early period of the 20th century i.e. 1901 to 1930 is associated with the below-average (low) rainfall.
   (ii) Above-average (high) rainfall period is observed between 1930 and 1960.
   (iii) Below-average (low) rainfall period is observed in the latter half of the 20th century i.e. after 1960.

6. The analysis of the annual rainfall data of the basin with respect to the deviations in the amount clearly indicates that the major changes in the rainfall occurred around 1930, 1960, and 1990.
7. The monsoon rainfall in the Tapi Basin is teleconnected with some global parameters. One of the important parameters is El Niño and Southern Oscillation (ENSO).
8. The probability of having high rainfall in the basin is more (44%) during cold ENSO conditions and very less (11%) during warm ENSO conditions and vice versa. It therefore, indicates that during the cold ENSO (warm ENSO) events the magnitude of rainfall will be higher (lower).
9. It is observed that on the basin scale 16% change in the annual rainfall is required in the average rainfall of next 10 years to consider it different than the available rainfall record. Similarly, to determine the significant change in the rainfall of the next 20 and 50 years, the average rainfall should vary by 11 and 8% respectively than the present mean of the rainfall.
10. To declare the average rainfall of the present century (21st century) significantly different than the previous century (20th century), 7% change is required in the long-term mean of the rainfall of the basin.
11. The application of various techniques to the rainfall data of the basin indicates that the rainfall of the Tapi Basin is highly regular and consistent. Therefore, it is likely to be the same in this as well as in the next century.

CHAPTER V

OVERVIEW AND CONCLUSIONS

5.1 Introduction

Rainfall is considered as the foremost hydrological phenomenon among all other events. It is a climate parameter that shapes the way and manner man lives. Further it controls every aspect of the ecological system, flora and fauna inclusive (Obot et al., 2010). Regime, amount and variability of rainfall are dominant natural factors that affect basically the life and economy of the people (Gadgil, 2002). Therefore, rainfall has always attracted the greatest attention of natural philosophers and meteorologists as it is one of the most important and conspicuous of all atmospheric processes and it has direct relevance to the very survival of all sorts of life (Pant and Rupa Kumar, 1997).

In a variety of climatic patterns of the world, 'monsoon' is very peculiar. Monsoons are observed in different parts of the world, but Indian southwest monsoon stands out amongst all of them. It is an important component of the earth's total climate system and has connections with the global atmospheric circulation (Kelkar, 2009). The monsoon rainfall of India is not uniform in time as well as its amount and distribution is grossly uneven. The variability in monsoon rainfall strongly linked with the society and economy of monsoon countries (Sajani et al., 2007). In view of Kelkar (2009), the Indian monsoon is indeed '*the* monsoon'.

Various studies on Indian monsoon rainfall have been made worldwide including India to understand different facets of Indian monsoon rainfall. These studies mostly are carried out on the administrative areas such as the whole nation, state or at the district level. In comparison of the investigations of the rainfall at nation level, the similar scientific studies at natural regions such as river basins are very limited. A natural region, for instance a river basin can certainly reveal great variations in the distribution of rainfall on spatial and temporal scales. In addition to this, the large variations in the total rainfall from one year to another may also be observed at a basin level. Therefore, the study of rainfall on river basin scale is, indeed, more practical for water resource management within the basin. Kamaraju and Subrahmanyam (1984) stated that a detailed knowledge of the seasonal and annual distribution of precipitation over the basin is highly essential for any analytical work on water balance and utilization.

Forming a part of the tropical monsoonal lands, the Tapi Basin situated in the central-western India displays all the significant characteristics of monsoon rainfall. The regimes of rainfall have strong influence on the natural and cultural environment of an area. Therefore, the preset work is an endeavor to identify characteristics of rainfall over the Tapi Basin. In the study an attempt has been made to reveal the regime characteristics and spatio-temporal aspects of rainfall. In addition, analyses have been carried out to recognize the rainfall trends and properties of the long-term fluctuations in the rainfall over the basin. Summarizing the exercises done in the previous chapters this chapter presents the major results to unveil the rainfall characteristics of the Tapi Basin.

5.2 Regime characteristics of rainfall

Among the dominant natural factors which strongly influence the life and economy of the people, the regime of rainfall is important (Gadgil, 2002). Beckinsale (1969) defined the regime of a rainfall as the variations in its amount. The importance of the study of rainfall regime lies in its significance to recognize the variations in total amount of rainfall at different places of a region and to understand the general pattern of rainfall within it. Regime characteristics of rainfall represent the general picture of the rainfall of a place or a region and can be used for various hydrological purposes.

The rainfall in the Tapi Basin shows significant variations in space and time. The rainfall regime in different parts of the basin is not identical. Specifically, distinct rainfall regime can be observed in the hilly regions and the plains in the basin. Therefore, the Western Ghats to the west, Satpura Ranges to the north, Ajanta Ranges to the south and Gawilgad Range and Betul Plateau to the east present differential rainfall regime than the plains of the Tapi River and its tributaries. Therefore, the principal rainfall regime characteristics of the basin have been investigated in chapter 2 and the major conclusions are summarized below.

The average annual rainfall of the Tapi Basin is 814 mm comprising large spatio-temporal variation. Chikhaldara is the rainiest place in the basin, receives 1596 mm average annual rainfall, which is almost double than the average annual rainfall of the Tapi Basin. Whereas, Sakri is the lowest rainfall receiving station having average annual rainfall just 511 mm. The rainfall in the Tapi Basin shows the supremacy of south-west monsoon season. The basin receives nearly 87% of its total rainfall in monsoon season (June to September) and remaining 13% in non-monsoon season (October to May). July is the rainiest month in the basin, contributes about 29% of the annual rainfall. Whereas, April is the driest month in the basin obtains negligible amount of rainfall. High rainfall stations obtain substantial proportion of annual rainfall in monsoonal months and less in non-monsoon season. For example, Chikhaldara, Dharani, and Surat obtain more than 90% of their annual rainfall in monsoon season and non-monsoon season contributes less than 10% of the annual total. Whereas, at low rainfall stations, such as Malegaon, Satana and Sakri, monsoon season contribute about 80% of annual rainfall and non-monsoon season also receives about 20% of annual rainfall of the station. The average annual rainy days of the basin are 44 per year with high variation from one station to another. The number of rainy days at various stations of the basin varies between 30 and 70. The numbers of rainy days of the various stations in the basin are strongly associated with their annual rainfall totals, showing positive correlations. Moreover, the pattern of rainy days in the basin follows the pattern of annual rainfall that is, high rainfall stations (low rainfall stations) have high number (less number) of rainy days. Chikhaldara, the heaviest rainfall station of the basin has highest number of rainy days (71) in the basin while Sakri, the lowest rainfall station has lowest number of rainy days (31) all over the basin. On the basin scale, July comprises highest number of rainy days (12) in the year followed by August (11 rainy days).

A distinct feature of Indian monsoon rainfall is infrequent heaviness of the fall in short period of time. Considering the average annual rainfall of the Tapi Basin (814 mm) and its average annual rainy days (44), on an average, there is about 20 mm rainfall per rainy day in the basin. However, many heavy to very heavy rainfall spells are on record at various locations in the basin. The 600.6 mm 24 hr rainfall at Amalner on July 30, 1992 is the highest one-day rainfall on record in the basin. The investigation of the highest 24 hr rainfall events in the basin reveals that in general, the heaviness of such events owes to their locations either in the hilly tracts or nearness to sea. Extreme rainfall events, as well as their contribution in the seasonal rainfall (JJAS) over the Tapi Basin are increasing. The study revealed that the average annual rainy days are decreasing, however, average annual rainfall of the basin is neither increasing nor decreasing. The study, therefore, supports the general thought of climate change and subsequently signifies an increase in disaster potential in the basin. Recurrence interval of one-day rainfall up to 200 mm, which is about one-fourth of the basin's average annual rainfall is quiet common in the basin and almost each year experiences 24 hr rainfall events equal to 200 mm. The possibility of 24 hr rainfall over 300 mm (nearly 40% of average annual rainfall of the basin) is in 4 to 5 years. Though a few in number, one-day rainfall about half (400 mm) of the average annual rainfall of the basin is not unusual and shows recurrence interval of 10 to 12 years. The exceptional one-day rainfalls equal or more than 600 mm contributing 70 to 75% of average annual rainfall of the basin are very rare and shows recurrence interval of about 100 years. Therefore, the possibility of such phenomenal rainfall events to happen in the basin is once in a century.

5.3 Sptaio-temporal aspects of rainfall

Although the monsoons are a regular phenomenon, there are fluctuations in their intensity and spatial extent on time scales ranging from days to centuries (Pant and Rupa Kumar, 1997). In addition, it exhibits a wide spectrum of variability on daily, sub-seasonal, inter-annual, decadal and centennial time scales (Rajeevan et al. 2010). The variability in the monsoon rainfall occasionally leads to the extreme hydrological events such as droughts and floods which affects the huge population and national economy (Kripalani et al. 2003). Hence, the variability in the Indian monsoon especially in the global warming scenario is a topic of intense scientific debate. Several studies are carried out on the variable nature of monsoon rainfall of the country on both space and time scales.

Being a part of an inherent monsoonal region, the Tapi Basin reflects all typical features of the monsoon rainfall. The Tapi Basin receives rainfall predominantly during the southwest monsoon period and a small fraction of it is associated with rest period of the year. The rainfall over the region is, therefore, highly seasonal. Nevertheless, there is variability in the rainfall on both space and time scales. Therefore, a comprehensive analysis of rainfall based on the available data can present temporal fluctuations and spatial patterns of the basin rainfall. Variability, both over time and space is an important attribute of rainfall in the Tapi Basin which impinges on its resource value and utilization. Therefore, following the discussion on the regime characteristics of rainfall in the chapter 2, variability in rainfall with respect to space and time has been discussed in chapter 3. The principal aim to analyze the annual rainfall data was to understand spatio-temporal variability in the basin. The major results of the study are as under.

The Tapi Basin illustrates a significant spatially diversified rainfall. Particularly, the eastern and western marginal areas of the basin show strongly non-uniform amount of rainfall than the rest of the area. With reference to the average annual rainfall of the basin and its standard deviation, the whole basin can be divided into three main zones- high rainfall zone, medium rainfall zone and low rainfall zone. The north-eastern part covered by the rugged relief of the Gawilgad Range and the extreme western area of the basin receiving reasonably high rainfall, lie in the first zone. The widespread area in the central and south-eastern part of the basin, formed by the river plains receives rainfall close to the basin's average are categorized into second zone and a small pocket in the south-west of the basin, contiguous to the western high rainfall zone, falls in the third zone. The high rainfall zone of the basin is characterized by great variation in the amount of rainfall in short distance. While, the extensive river plains in the central part of the basin are characterized by almost uniform amount of rainfall. Similarly, the low rainfall zone of the basin in the south-west also obtains uniform amount of rainfall. The high rainfall zone of the basin is characterized by great variation in the amount of rainfall in short distance. Whereas, the extensive river plains in the central part of the basin are characterized by almost uniform amount of rainfall. Similarly, the low rainfall zone of the basin in the south-west also obtains uniform amount of rainfall. In general, the spatial pattern of rainfall in the Tapi Basin exhibits a decreasing pattern from east to west with abrupt rise in rainfall to the western edge of the basin.

The spatial distribution of rainfall in the basin is orographically controlled. The Western Ghats plays a key role in rainfall diversity in the basin. The continuity and elevation of the Western Ghats and its offshoots acts as a barrier to the south-western monsoon winds and consequentially resulted into heavy rainfall on the windward side and produce a 'rain-shadow' area to the leeward side. A low rainfall zone in the south-west of the basin is in fact the 'rain shadow' area which is an outcome of orographic effect of the Western Ghats. All six stations viz. Malegaon, Nandgaon, Satana, Dhule, Sakri and Shindkheda from this zone receive remarkable low rainfall, about 25-35% less than the basin's average rainfall. The lowest rainfall at Sakri is attributed to its specific location. The Galana Range, the east-west trending offshoot of the Western Ghats runs across the path of monsoon winds and is situated in the rain shadow zone of the main rim of the Western Ghats. Therefore, it can be stated that Sakri is located in the *'secondary rain shadow area'* which is the significant reason for very low rainfall in this region. The effect of orography on the rainfall clearly visible in the north-eastern high rainfall zone of the basin. This part of the basin is covered by the Gawilgad Range. With its considerable length and uniformity in elevation, the area environs the Gawilgad Range gets high orographic rainfall which accounts for more than 1000 mm. Chikhaldara, situated on the crest line of the Gawilgad Range, receives highest rainfall (1596 mm) in the basin which is about two times more than the basin's average rainfall. An important and most immediately felt aspect of rainfall of the basin is its inter-annual variability. However, the coefficient of variation (Cv) of the Tapi basin as a unit is 30% suggesting that the rainfall of the basin is less variable. The values of coefficient of skewness (Cs) are positive for all the stations in the basin proposing the occurrence of one or two or a few very wet (high rainfall) years during the gauged period.

Two contrasting features of the rainfall can be noticed in two parts of the 20th

century. It is observed that in comparison of the rainfall in the second half of the century, rainfall in the first half of the century was more variable. Nevertheless, the first half of the century is characterized by above-average rainfall. Thereafter less variability in the rainfall is observed. The basin received not only average rainfall but also less variable rainfall in the second half of the 20^{th} century. The rainfall over the basin, in general, varies between -30 and +30% from its mean. However, in some instances the maximum departure of rainfall is observed between -40 to +40% from the mean. It therefore, reveals that the rainfall of the Tapi Basin as a geographical unit is less variable. The seasonal rainfall of the basin for the period 1901-1950 shows an increasing trend, which come down in the period 1951-2004 and does not present any specific trend. The consistency of rainfall in June in the first half of the century turns into an increasing trend in the second half. July and September presents clear opposing rainfall trends in two parts of the century. Whereas, an increasing trend of rainfall in August in the first half of the century stabilized in the second half of it. The rainfall over the Tapi Basin demonstrates alternating sequences of multi-decadal periods having excess and deficient rainfall. This epochal behaviour of rainfall of the basin can be summarized in three periods:

(i) 1901-1930: dry epoch

(ii) 1931-1960: wet epoch and

(iii) 1961-1990: dry epoch.

The epochal pattern of the rainfall of the Tapi Basin is quite similar to that found over the country. The Tapi Basin neither experienced any widespread severe drought nor a severe flood over the period of a century.

5.4 Long-term fluctuations in the monsoon rainfall

A question of prime importance to rainfall studies in India is whether the monsoon rainfall has changed over the last few decades and whether a change is likely to occur in future. Although it is difficult to recognize the likely future trend of rainfall, it is possible to detect the nature of changes that have occurred in the past. Determining the trends or changes in the rainfall are extremely important because studies of hydro-meteorological conditions caused them is useful to detect climatic changes (Kale, 1999).

There are many studies carried out to detect the rainfall trend on all India or regional scales. However, the studies of rainfall records to determine long-term trends/changes on river basin scale are very limited. In chapter 4, therefore, an attempt has been made to analyze the annual rainfall data of the Tapi Basin in view to obtain the long-term trends/changes over the basin. The principal findings are summarized below.

Significant decreasing trend of rainfall at 0.05 level is observed for Chikhaldara, a highest rainfall receiving station in the basin. Conversely, Sakri, the lowest rainfall receiving station in the basin present significant increasing trend of rainfall at 0.05 level. Therefore, in general it is found that the annual rainfall is decreasing with respect to time at high rainfall stations in the basin. Apposite to it, low rainfall stations in the basin present an increasing trend of rainfall. However, the stations having similar rainfall amount with the basin does not indicate any considerable trend. High rainfall stations (such as Chikhaldara) demonstrate below-average rainfall conditions upto 1930. The middle part of the 20th century i.e. from 1930 to 1960 is featured by above-average rainfall conditions which alter into below-average rainfall conditions after 1960. The low rainfall stations (e.g. Sakri) exhibit below-average rainfall conditions in the early stage of the century, upto 1940. While, the period after 1940 is characterized by continuous above-average rainfall situations. The stations having average rainfall close to the basin's average (for example, Jamner) display an asymmetrical temporal pattern of rainfall. These stations does not signify any specific direction of change in rainfall amalgamating alternate below and above-average rainfall periods with regular interval.

A composite picture of the long-term fluctuations of rainfall on the basin scale point towards some significant characteristics of the rainfall.

(i) The early period of the 20th century i.e. 1901 to 1930 is associated with the below-average (low) rainfall.

(ii) Above-average (high rainfall) period is observed between 1930 and 1960.

(iii) Below-average (low) rainfall period, in the latter half of the 20th century i.e. after 1960.

Therefore, the analysis of the annual rainfall data of the basin with respect to the deviations in the amount clearly indicates that the major changes in the rainfall occurred around 1930, 1960, and 1990.

The monsoon rainfall in the Tapi Basin is teleconnected with some global parameters. One of the important parameters is El Niño and Southern Oscillation (ENSO). The probability of having high rainfall in the basin is more (44%) during cold ENSO conditions and very less (11%) during warm ENSO conditions and vice versa. It therefore, indicates that during the cold ENSO (warm ENSO) events the magnitude of rainfall will be higher (lower). It is observed that on the basin scale 16% change in the annual rainfall is required in the average rainfall of next 10 years to consider it different than the available rainfall record. Similarly, to determine the significant change in the rainfall of the next 20 and 50 years, the average rainfall should vary by 11 and 8 % respectively than the present mean of the rainfall. Whereas, to declare the average rainfall of the present century (21st century) significantly different than the previous century (20th century), 7% change is required in the long-term mean of the rainfall of the basin.

The application of various techniques to the rainfall data of the basin indicates that the rainfall of the Tapi Basin is highly regular and consistent. Therefore, it is likely to be the same in this as well as in the next century.

5.5 Limitations of the study

Although the present study intended to reveal the characteristics of rainfall over the Tapi Basin, the study is not complete in all respects. Some of the major limitations of the present study have been outlined below.

1. Though the present study is based on the rainfall data extended over 100 years (1901-2004), it is comparatively shorter in duration to draw imperative inferences to validate the rainfall aspects of the widespread geographical region of the basin.
2. Moreover, the data that have been used are monthly and annual rainfall figures. Perhaps, the daily rainfall data would have added a new dimension in results.
3. The basin covers an extensive area of 65145 km^2 which is nearly 2% of the total geographical area of India. Rainfall data of 56 raingauge stations were available for the study. Rainfall data of a few more stations would have helped for the comprehensive study.
4. The data of Sea Surface Temperature (SST) were available from 1901 to 1983. The SST data for the corresponding rainfall data (1984-2004) could have been more useful for establishing relationship between ENSO and rainfall of the basin in more improved manner.
5. There is general belief that rainfall is controlled by natural as well as cultural vegetation. The effect of natural vegetation and agriculture on the rainfall has not been covered in the present study.
6. Besides rainfall, the other forms of precipitation have not been studied in the study.
7. The results of the present study could have been supported using some additional statistical techniques.

5.6 Major findings of the study

In spite of a few limitations, the present study attempted to bring out the cohesive characteristics of rainfall of the Tapi Basin with respect to the objectives of the study. The major observations that have emerged from this study are as follows;

1. The average annual rainfall of the Tapi Basin is 814 mm, comprising large spatio-temporal variation. Chikhaldara is the rainiest place in the basin, receives 1596 mm average annual rainfall, which is almost double than the average annual rainfall of the Tapi Basin. Whereas, Sakri is the lowest rainfall receiving station having average annual rainfall just 511 mm. The rainfall in the Tapi Basin shows

the supremacy of south-west monsoon season. The basin receives nearly 87% of its total rainfall in monsoon season (June to September) and remaining 13% in non-monsoon season (October to May). July is the rainiest month in the basin.

2. The average annual rainy days of the basin are 44 per year with high variation from one station to another. The number of rainy days at various stations of the basin varies between 30 and 70.
3. The 600.6 mm 24 hr rainfall at Amalner on July 30, 1992 is the highest one-day rainfall on record in the basin. Extreme rainfall events, as well as their contribution in the seasonal rainfall (JJAS) over the Tapi Basin are increasing. Average annual rainy days are decreasing, however, average annual rainfall of the basin is neither increasing nor decreasing. The study, therefore, supports the general thought of climate change and subsequently signifies an increase in disaster potential in the basin.
4. The Tapi Basin illustrates a significant spatially diversified rainfall. Particularly, the eastern and western marginal areas of the basin show strongly non-uniform amount of rainfall than the rest of the area. The north-eastern part covered by the rugged relief of the Gawilgad Range and the extreme western area of the basin receives reasonably high rainfall. The widespread area in the central and south-eastern part of the basin, formed by the river plains receives rainfall close to the basin's average rainfall and a small pocket in the south-west of the basin, obtains low rainfall. In general, the spatial pattern of rainfall in the Tapi Basin exhibits a decreasing pattern from east to west with abrupt rise in rainfall to the western edge of the basin.
5. The spatial distribution of rainfall in the basin is orographically controlled. The Western Ghats and its offshoots and the Gawilgad Range play a key role in rainfall diversity in the basin.
6. The rainfall over the Tapi Basin demonstrates alternating sequences of multi-decadal periods having excess and deficient rainfall. This epochal behaviour of rainfall of the basin can be summarized in three periods: (i) 1901-1930: dry epoch (ii) 1931-1960: wet epoch and (iii) 1961-1990: dry epoch. The epochal pattern of the rainfall of the Tapi Basin is quite similar to that found over the country. The

Tapi Basin neither experienced any widespread severe drought nor a severe flood over the period of a century.

7. A composite picture of the long-term fluctuations of the rainfall on the basin scale point towards some common characteristics of the rainfall.
   (i) The early period of the 20th century i.e. 1901 to 1930 is associated with the below-average (low) rainfall.
   (ii) Above-average (high) rainfall period is observed between 1930 and 1960.
   (iii) Below-average (low) rainfall period is observed in the latter half of the 20th century i.e. after 1960.

   The deviation in the amount of the rainfall clearly indicates that the major changes in the basin rainfall occurred around 1930, 1960, and 1990.
8. The monsoon rainfall in the Tapi Basin is teleconnected with some global parameters. One of the important parameters is El Niño and Southern Oscillation (ENSO). The probability of having high rainfall in the basin is more (44%) during cold ENSO conditions and very less (11%) during warm ENSO conditions and vice versa. It indicates that during the cold ENSO (warm ENSO) events the magnitude of rainfall will be higher (lower).
9. It is observed that on the basin scale 16% change in the annual rainfall is required in the average rainfall of next 10 years to consider it different than the available rainfall record. Similarly, to determine the significant change in the rainfall of the next 20 and 50 years, the average rainfall should vary by 11 and 8% respectively than the present mean of the rainfall. Whereas, to declare the average rainfall of the present century (21st century) significantly different than the previous century (20th century), 7% change is required in the long-term mean of the rainfall of the basin.
10. The application of various techniques to the rainfall data of the basin indicates that the monsoonal rainfall of the Tapi Basin is highly regular and consistent. Therefore, it is likely to be the same in this as well as in the next century.

The inferences regarding the rainfall characteristics arrived in the present study have been discussed for a medium sized river basin. However, because the topography, climate and geographical location within the monsoonal/tropical region are diverse, the inferences cannot be applied directly to all other natural regions within the monsoonal region. Nevertheless, such studies are beginning to provide a database and discuss the importance of rainfall studies in monsoonal environments. Hence, concluding the discussion it can be stated that in spite of a few limitations, the present study attempted to bring out the cohesive characteristics of rainfall of the Tapi Basin pertaining to the objectives of the study. This work, therefore, certainly opens an avenue to the further research in the rainfall study.

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