Rainfall Trends in India and Their Impact on Soil Erosion and Land Management

A dissertation submitted for the degree of Doctor of Philosophy in the Department of Engineering at the University of Cambridge, UK

by

Indrani Pal

St. John's College **November 2009**

DEDICATION

To My Family

and

Loved Ones

DECLARATION

I hereby declare that, except where reference is made to the work of others, the contents of this dissertation are a result of my own work and include nothing which is the outcome of work done in collaboration. This dissertation has not been submitted in whole or part for consideration for any other degree, diploma or other qualification to this University or any other institution, except where cited specifically.

This dissertation contains no more than 70,000 words, inclusive of appendices, references, footnotes, tables and equations, and has less than 150 figures.

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Indrani Pal

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The secular and objective spirit of scientific philosophy has been the greatest attraction for me and I thank God Almighty to have directed me on this path of scientific research. This journey would have been impossible had I not received the guidance of my supervisor Dr. Abir Al-Tabbaa. Her personality has left an unprecedented impression on me and I am not audacious enough to thank her by words. I am deeply indebted to her for continuous encouragement, generous support and pieces of advice throughout. I thank the CCT, the ORS and St John's College at Cambridge for letting me explore a life time opportunity to pursue research at the University of Cambridge. All my friends and colleagues, at the GRO group and outside, made my academic journey enriching and I thank all of them for every single thing they have done for me. Last, but not least, I would like to express my deep appreciations and affection to my family and loved ones who have played their special role in the most exemplary manner.

ABSTRACT

Under the threat of global warming it is vital to determine the impact that future changes in climate may have on the environment and to what extent any adverse effects can be mitigated. In this research an assessment was carried out on the impact that climate trends may have on soil erosion and contaminant transport in India and examined the potential for top soil management practices to improve or maintain soil quality. Historical rainfall data from 50-135 years and extreme temperature data for 103 years were analysed and long term trends were assessed for various aspects of Indian climates using suitable statistical techniques. Results indicated that intra-region variability for extreme monsoon seasonal rainfall is large and mostly exhibited a negative tendency leading to increasing frequency and magnitude of monsoon rainfall deficit and decreasing frequency and magnitude of monsoon rainfall excess everywhere in India except in the peninsular Indian region. This is further exacerbated by increased and more variable extreme temperatures. Intra-region rainfall variability in India is linked to the pacific Southern Oscillation, where the associations of monsoon drought and El-Niño Southern Oscillation (ENSO) in the regions near to coast are greatest. 50-years high resolution daily gridded rainfall data was analysed to set up certain indices for the extreme daily rainfalls to assess their changes for the six gridded regions of Kerala, the extreme south western state of India where monsoon rainfall initiates every year. This was also done for two study sites, namely Bhoj wetland area of west central India and Sukinda chromite mining site of central north east India. Significant decrease was found in monsoon and spring rainfall extremes and increase in winter and autumn rainfall extremes in Kerala that would affect the tendency of change in seasonal total rainfall as well. Decrease in monsoon rainfall in Kerala also indicate that monsoon rainfall is decreasing in India as a whole, increased occurrence of floods is expected in winter and autumn seasons, together with water scarcity are expected to be felt both in spring and monsoon seasons with a delaying monsoon onset in Kerala. Soil erosion studies were conducted for two northern most gridded regions of Kerala as an extended work of the related MPhil study, and contaminant transport with eroded sediments was looked at for the Bhoj and Sukinda sites using RUSLE2 model software and other

suitable numerical methods. It was found that soil erosion depended on a complex interaction of climate, soil properties, topography, and cover management. An assessment on extreme climate patterns for Bhoj and Sukinda showed an increasing tendency of seasonal and annual rainfall extremes and temperatures leading to an increasing pattern of soil erosion at both the sites. However, a certain consensus was difficult to reach because of the complex interaction of climate and soil carbon that is a very important deciding factor for soil erosion potential. Vegetative cover and plant residue was found providing essential soil nutrients, enhancing soil properties and retarding rainfall impact on bare top soil leading to reduction of soil erosion. Therefore, a soil erosion and contaminant transport prevention plan should take care of the top soil such that it is not kept bare especially when rainfall intensity is high in a given year. This work as a whole has highlighted the importance of regional climatological analysis with the large scale spatial averages especially at local decision making level, which is very useful for the broad scenarios such as climatological and ecological risk management.

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LIST OF ABBREVIATIONS

Δt	Duration of the rain storm over which rainfall intensity is considered to be constant
ΔV	Depth of rain falling during a rain storm over which rainfall intensity is considered to be constant
a	Daily net soil detachment
A	Annual soil detachment
A_a	Average annual soil detachment
c	Daily cover management factor
C	Contaminant concentration in the top soil
CA	Area of a catchment
c_c	Daily canopy subfactor
COV	Coefficient of variation
C_w	Contaminant concentration in surface water
d	Number of storms in a day
e	Kinetic energy of rainfall
E	Total storm kinetic energy
ENSO	El-Niño Southern Oscillation
g_c	Daily ground cover subfactor
I	Rainfall intensity
i	Index of the number of storms in each day
I_{30}	Maximum 30-minutes rainfall intensity
j	Index of the number of years used to produce an average rainfall erosivity/soil loss
k	Daily soil erodibility factor
K_n	Average annual nomograph soil erodibility value in RUSLE2
k_o	Soil organic matter subfactor
k_p	Soil permeability subfactor
k_s	Soil structure subfactor
k_t	Soil texture subfactor
l	Daily slope length factor
L_m	Monthly loss of rainfall through evapotranspiration

m	Slope length exponent
N	Number of observed data series
n	Number of years used to obtain an average rainfall erosivity/soil loss
N_i	Transformed/normalised annual rainfall departure value of monsoon rainfall amount of year i
O_m	Inherent soil organic matter content
OMC/SOM	Organic Matter Content
p	Daily supporting practices factor
P	Annual rainfall
p_c	Partitioning coefficient of a contaminant
P_{cl}	Clay content
P_m	Monthly rainfall
P_r	Permeability class
P_{sl}	Silt content
P_{vfs}	Very fine sand content
q	The number of tied groups while applying MK method
Q	Total runoff discharge
r	Daily rainfall-runoff erosivity factor
R	Annual rainfall-runoff erosivity factor
R_a	Average annual rainfall-runoff erosivity factor
r_h	Daily ridge height subfactor
R_i	Monsoon rainfall amount of year i
R_m	Monthly runoff
R_u	Annual runoff
RUSLE2	Revised Universal Soil Loss Equation – version 2
S	Annual slope steepness factor
s	Soil structure class
s_b	Daily soil biomass subfactor
s_c	Daily soil consolidation subfactor
S_c	Contaminant load reaching catchment outlet
S_d	Standard deviation of monsoon rainfalls.
SDR	Sediment Delivery Ratio

s_m	Daily antecedent soil moisture subfactor
SOI	Southern Oscillation Index
s_p	Slope steepness at gradient θ
s_r	Daily soil surface roughness subfactor
SST	Sea Surface Temperature
S_t	Mann-Kendall test statistic
t	Index of the number of rain days in each year
T	Total number of rain days in each year
T_m	Mean monthly temperature of a catchment
t_p	Number of data values in the p^{th} group while applying MK method
USLE	Universal Soil Loss Equation
$VAR(S_t)$	Variation of Mann-Kendall test statistic
x_a	Rainfall data value in period 'a'
x_b	Rainfall data value in period 'b'
Y	Sediment yield reaching a catchment outlet
Z	Value at standard normal distribution
$Z_{1-\alpha/2}$	Critical value of 'Z' from Standard Normal Table
θ	Slope gradient
λ	Slope length

CHAPTER 1

INTRODUCTION

1.1. The Problem: Climate Change & Soil Erosion

Global atmospheric concentrations of greenhouse gases have increased markedly as a result of human activities since 1750 (Trenberth et al., 2007). Warming of the climate system is now evident from observations of increases in global average air and ocean temperatures (Figure 1.1), widespread melting of snow and ice (Figure 1.2), and rising global average sea levels (Figure 1.3). The understanding of past and recent climate change has been progressing significantly through improvements and extensions of numerous datasets and more sophisticated data analyses across the globe.

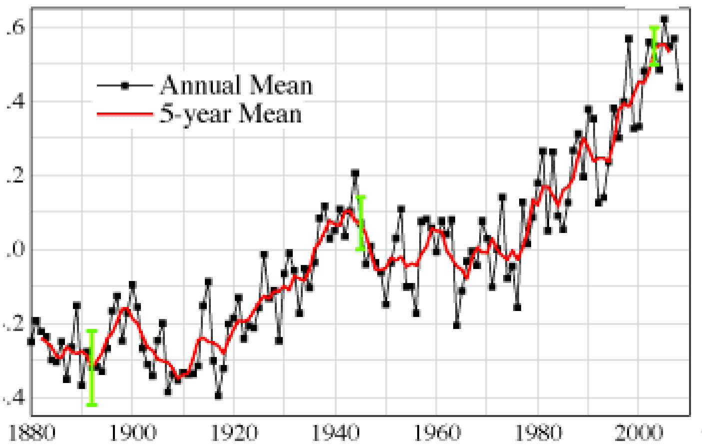


Figure 1.1: Global mean surface temperature anomaly (°C) relative to 1961–1990 (Illustration from NASA).

Climate change is predicted to impact upon the variability and seasonality of temperature and humidity, thereby involving the hydrologic cycle (Figure 1.4). Eleven of the last twelve years (1995-2006) rank among the 12 warmest years in the global instrumental record of surface temperature since 1850 (Trenberth et al., 2007). Changes in global extreme temperatures have been widespread over the last 50 years, the rate of which is almost double that over the last 100 years.

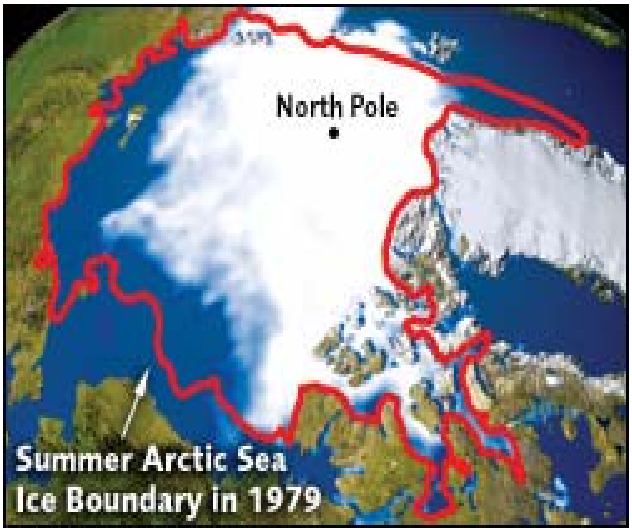


Figure 1.2: The size of the summer polar ice cap since 1979 to 2009 (Illustration from NASA).

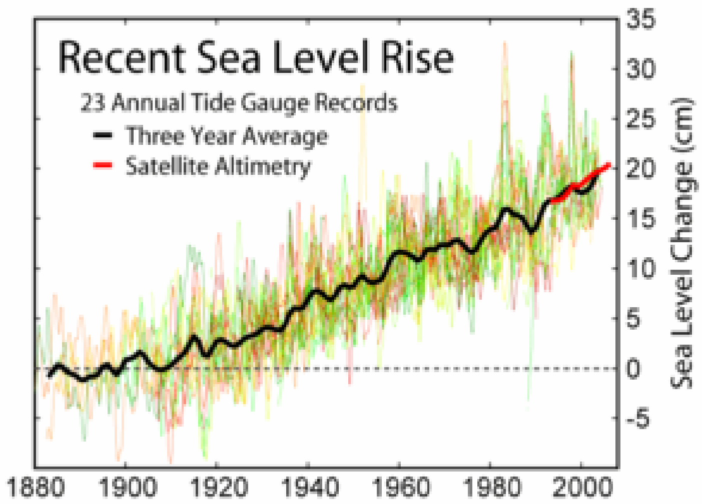


Figure 1.3: Sea level measurements from 23 long tide gauge records in geologically stable environments (http://www.globalwarmingart.com).

At continental, regional and ocean basin scales, numerous long-term changes including widespread changes in rainfall amounts, wind patterns and aspects of extreme weather including droughts, heavy rainfall, heat waves and the intensity of tropical cyclones have also been observed. Change in rainfall affects annual river runoff and water availability. Areas in which runoff is declining are likely to face a reduction in the value of the services provided by water resources. On the other hand, increased rainfall variability and seasonal runoff shifts may also have negative impacts on water supply, water quality and flood risks.

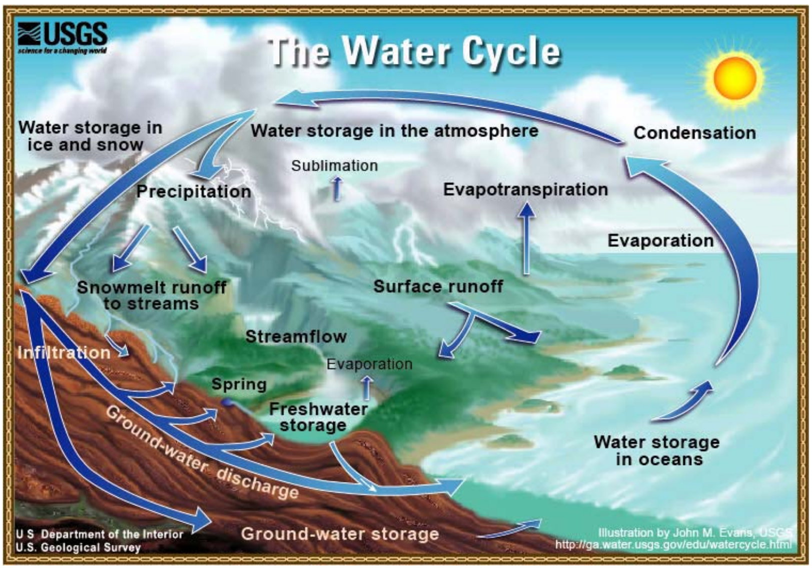


Figure 1.4: The impacts that climate change might have on the regional hydrologic cycle (Evans, 2009).

Although rainfall has increased in many areas of the globe, the areas undergoing drought have also increased. Drought duration and intensity has also increased. More severe droughts have been observed over wider areas since the 1970s, particularly in the tropics and subtropics, and much of Africa (Trenberth et al., 2007). Increased drying due to higher temperature and decreased land rainfall contribute to changes in drought.

The frequency of heavy rainfall events has also increased over most land areas and particularly since about 1950, even in those regions where there has been reduction in total rainfall amount, which is consistent with warming and observed increase in atmospheric water vapour. Increases have also been reported for rarer rainfall events (1 in 50 year return period), augmenting flood risk (Rosenzweig et al., 2007); the very heavy rainfall event in Mumbai, India in July 2005 is a good example (Figure 1.5).

Figure 1.5: Images relating to the 944 mm of rainfall that fell on 26 July 2005 leading to the worst flood in Mumbai region in India (Google Images).

Regionally, such changes are expected to be different from the global average since responses to external forcing in regional rainfall trends depend on atmospheric circulations, interactions of the atmosphere and ocean, and on geographic factors such as orography (Trenberth et al., 2007). Many natural systems are being affected by regional climate changes, which are further complicated by the effects of natural climate variability and non-climate drivers (e.g., land-use change, pollution). For example, scientists in Nepal have embarked on the first field studies of Himalayan glacial lakes, some of which are feared to be swelling dangerously due to global warming (Figure 1.6).

Figure 1.6: The area of Imja glacial lake in Himalaya which has increased (BBC Science and Environment, Tuesday, 23 June 2009).

Effects of climate change on ecosystems, hydrological and terrestrial biological systems are gaining importance, especially in the last three decades (Rosenzweig et al., 2007). The evidences for current impact/vulnerability of altered frequencies and intensities of extreme rainfall are found in soil erosion/landslides, land flooding, transportation systems and infrastructures. Changes in rainfall variability also affect agriculture, forestry and ecosystems, hydrology and water resources, human health, tourism and energy supplies. Changes in drought patterns affect water availability, livelihoods, energy generation and demand, and population migration. Current land and/or water management practices at many places on earth are very unlikely to be adequate to reduce the negative impacts of climate change. Improved incorporation of current climate variability into land and water related management is likely to make adaptation to future climate change easier.

While changes in many different aspects of climate may at least partially drive changes in the surrounding environmental systems, the work presented in this thesis focuses on rainfall changes and their impacts in India at a regional perspective, which is the least studied topic for this region. Rainfall has much larger spatial and temporal variability than temperature, and it is therefore more difficult to identify the impact it has on changes in many systems. Rainfall is a primary source of energy for soil erosion problems in many locations in India, which leads to environmental damage through on- and off-site effects. Erosion by water has been considered as the most serious soil degradation problem in the humid tropical and subtropical India (Bhattacharyya et al., 2007).

The off-site effects of soil erosion arise from the production of sediment which is one of the major pollutants of our environment. While eroded top soil physically leads to unwarranted levels of turbidity in receiving water, the silt and clay fraction (< 63 μm fraction) is, on the other hand, a primary carrier of adsorbed chemicals, especially phosphorous, pesticides and metals. These chemicals are transported by the sediment into the water system. Water bodies undergo large-scale pollution because of siltation, toxic substances, nutrient enrichment, algal blooms and excessive growth of macrophytes, which cause loss of water spread area, water quality degradation and eutrophication. In addition to reduced land productivity of the agricultural soils, accelerated erosion of disturbed, unvegetated ground on construction sites, over ground mines, and refuse dumps also poses significant environmental problems. The magnitude of these effects also changes with the changes in rainfall patterns.

The major problem of agricultural diffuse pollution in India is the heavy silt loads, along with large quantities of dissolved salts, nutrients, organics and even heavy metals and bacterial contaminants washed off during rainy period. Using the example of a lake catchment in west central India, Bhoj wetland, this work brings out the nature of the problems and their changes due to change in rainfall and their possible management options.

Surface mining is a major industry in India. Protection of the environment from the mining sites (operating/abandoned or proposed) is important especially when the site is exposed to runoff and erosion, which can lead to undesirable material leaving the area and contaminating surrounding land and water bodies. For assessing such environmental impacts and long term behaviour of post-mining landforms, scientific methodologies are needed especially where the field data are absent or scarce. Using an example of open cast mining site in central north eastern India, Sukinda valley, this work addresses a detailed study on the nature of the environmental problems the site poses and possible management options.

1.2. Aims and Objectives

The aim of the work presented in this thesis was to study 50-135 years of rainfall data to look at their trends and effects on soil erosion, contaminant transport and land management. This work evaluated past changes of various aspects of Indian climate considering trends and variability of rainfall and temperature at different regional scales. Observational records at various lengths were employed with rainfall record beginning as early as 1871 and temperature from 1901. Changes of extremes of climate were given a particular interest, and observed changes in extreme events were elaborately described. Changes in monsoon rainfall extreme events throughout India, as studied here, were not done before even though extremes of climate are an important expression of climate variability. Therefore, this study provides improved insights into the changes in various types of extreme events including maximum and minimum temperatures, seasonal droughts and heavy rainfalls, and indices of daily rainfall extremes.

A risk of soil erosion and contaminant spreading due to short scale climatic changes were also examined at Kerala as an extension of related MPhil work and the other two case sites in India, which is further followed by a brief discussion on mitigation options through land management practices.

This work mainly focussed on the following objectives,

- To assess the long-term regional mean seasonal and annual rainfalls over the whole country of India at different spatial and temporal scales for the last 135 years of rainfall data (1871-2005)
- To look at the changes in extreme parts of monsoon rainfall in India for different spatial and temporal scales for the last 135 years of rainfall data (1871-2005)
- Since changes in humidity, temperature and rainfall contribute to changes in droughts and floods, a study was also carried out on changes in monsoon seasonal droughts and floods at various severity conditions for different spatial and temporal scales for the 135 years of rainfall data (1871-2005)
- To study the changes in daily extreme seasonal rainfalls in various gridded regions in India using newly available data that permit improved insights into the changes in extreme events such as daily heavy rainfalls in the last 50 years (1954-2003) at shortest possible gridded scales (regions of 50km × 50km grids)
- To examine the changes in monthly, seasonal and annual extreme temperatures in various regions in India for the last 103 years (1901-2003) of temperature data
- To carry out a detailed study to understand the impact of climate change on soil erosion; the mechanism of rainfall induced soil erosion including the effects of rainfall, soil, topography (slope length and steepness), cover management and land practice factors on soil erosion magnitude; and soil erosion impact on soil properties including soil carbon that is also essential for reducing soil erosion

- To investigate the risk of contaminant spreading through sediments and their sensitivity to changes in climate and thus soil erosion patterns in the study sites using both quantitative and qualitative methods
- Finally, possible mitigation options of both the climate change and soil erosion through land management and carbon sequestration was discussed through a qualitative assessment

All of these objectives were met using suitable statistical tools and models and making best use of the existing parameter values from the study sites. The results from this study will provide key information on the regional climatic changes in India and their critical effects on one of the few studied areas that focus for addressing the critical issue of water/land management practices at agricultural and mine sites in wet-dry monsoonal regions in India.

1.3. Structure of the Thesis

This PhD thesis has been divided into two parts. In the first part, a state-of-art knowledge on the regional climatic changes in India and world-wide have been discussed which is followed by an analysis of rainfall and temperature data from India to assess the regional climatic changes. The second part presents the research on the application of the studies carried out in the first part. The implication of climatic changes on soil erosion and land management was considered. This includes a soil erosion study in Kerala, a preliminary study involving contaminant transport with eroded sediments from the two case sites from different parts of India, and possible land management options through top soil management and soil carbon sequestration.

The first part of this work is presented in Chapters 2 and 3 and the second part is presented in Chapters 4 and 5. Chapter 2 covers the existing knowledge relating Indian climate data, global and Indian regional climatic changes and describes the key statistical methodologies utilised to analyse the Indian climate data. Chapter 3 presents, discusses and analyses, in detail, the various results obtained relating long-term Indian climate patterns and rainfall projections.

Chapters 4 and 5 are about preliminary applications of the results and analyses in Chapters 2 and 3. Among various regional implications of climatic change, this study mainly focuses on impacts of observed rainfall trends on soil erosion using the model RUSLE2 and contaminant transport with runoff carried sediments in India using numerical modelling. This study also looks at the adaptation strategies for the rainfall induced soil erosion through various soil cover management options, which are also helpful to control the contaminant transport and soil organic matter depletion.

PART I

INDIAN CLIMATIC PATTERN

CHAPTER 2

LITERATURE REVIEW

This literature review chapter starts with an introduction to Indian monsoon system and discusses the climate data that has been used for this work including daily and monthly time series of rainfall and temperature from India. Then the majority of this chapter presents a detailed review of previous research findings on climatic patterns for the Indian region and world-wide. Finally, the last section of this chapter discusses the methodologies used in this work to look at the long-term climate patterns for India.

2.1. Introduction to Indian Monsoon Season

The word ‘monsoon’ was originally coined from an Arabic word meaning ‘season’. A monsoon is a seasonal wind shift which flows from either hemisphere for a particular interval of time in a year. The main reason behind such wind shifts is the differential response of the land and the ocean to the incident solar radiation during different times of the year. Monsoons are prevalent in the tropics which receive most solar energy, which then creates sufficient temperature and/or pressure gradient to set up a wind current from the colder/high pressure region to the warmer/low pressure region (Das, 1968). The tropics are warmest in the months of June, July and August which form the summer monsoons.

Due to the thermal contrast between the continents and oceans, in the summer a trade wind from the southern hemisphere crosses the equator and penetrates deep into the northern hemisphere and deflects towards the northeast because of the earth’s rotation. Such wind which is saturated with moisture causes maximum rainfall in most parts of India and is termed the south-west monsoon or summer monsoon. In winter, the direction of wind flow changes and it starts blowing from the northern hemisphere to the southern hemisphere and causes rainfall in the south-eastern states of India, Sri

Lanka, Malaysia, Indonesia and north Australia, termed as Asian winter monsoon. In Sri Lanka, Malaysia, Indonesia and north Australia, the heaviest rainfall occurs in the winter months of December and January. This winter monsoon (Oct-Feb) affects only a very limited part of India and especially the peninsular part. Therefore, the summer monsoon is of greater importance and the term 'monsoon' when applied to India generally refers only to be summer monsoon (Das, 1968).

Apart from the differential heating and earth motion, there are various other factors which drive the monsoon wind: mountain barriers, retarding effect of friction as the wind blows over the land. Summer monsoons strike firstly in Kerala, the extreme south-western continental state of India, where monsoon downpours start usually in the first week of June and move upwards at a rate of 1-2 weeks per state. In mid September the monsoon starts withdrawing from the northwest of India. Finally, it withdraws from the extreme south of the Indian peninsula and Sri Lanka by December. Over 75% of India's annual rainfall comes from the summer monsoon.

2.2. Explanation of Various Climatological Data Used in this Study

2.2.1. High Resolution (1°×1° lat/long) Gridded Daily Rainfall Data

Gridded rainfall data sets are useful for regional studies on the hydrological cycle, climate variability and evaluation of regional models. High resolution (1°×1° lat/long) gridded daily rainfall data set for 1951-2003 for the Indian region was utilised here for assessing trends of seasonal and annual rainfall extreme events and estimating rainfall erosivities for the soil erosion estimates from the case study sites. This dataset was developed at the Indian Meteorological Department (IMD) in the National Climate Centre, Pune by interpolating daily rainfall data of 1803 stations around the country (Rajeevan et al., 2005). All those rainfall stations had minimum 90% data availability during the period of 1951-2003. Only 1803 stations' data out of 6329 stations were used for interpolation purposes in order to minimise the risk of generating temporal inhomogenities in the gridded data due to varying station densities (Rajeevan et al., 2005). Figure 2.1 shows the network of rain gauge stations (1803 stations) considered, which illustrates that the density of stations is not uniform throughout the country but is the highest over south peninsula and is very poor over northern plains of India and eastern parts of central India (Rajeevan et al., 2005).

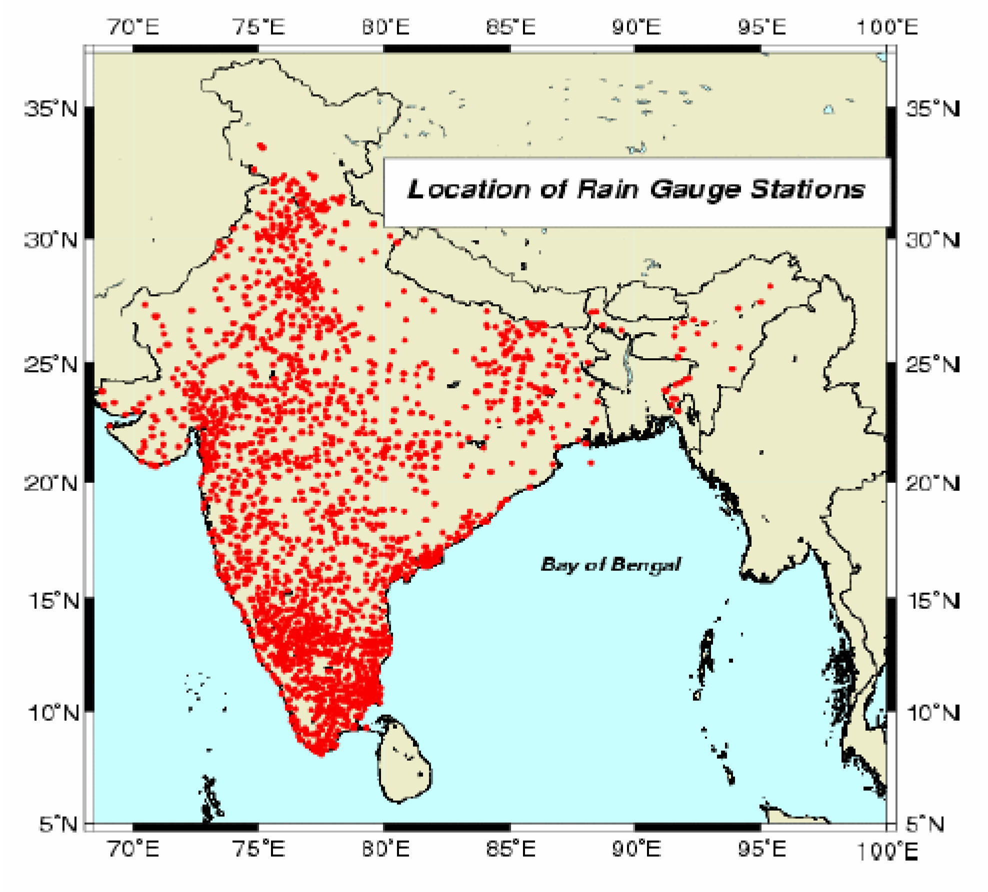


Figure 2.1: Locations of 1803 rain gauge stations (Rajeevan et al., 2005).

Figure 2.2(a) shows the spatial distribution of the seasonal (June-September) mean rainfall averaged for the period 1951-2003 derived from the IMD gridded rainfall data set (Rajeevan et al., 2005). The rainfall pattern suggests that monsoon rainfall is the highest along the west coast of India and north-east India, and lowest is observed over north-west and south-east India.

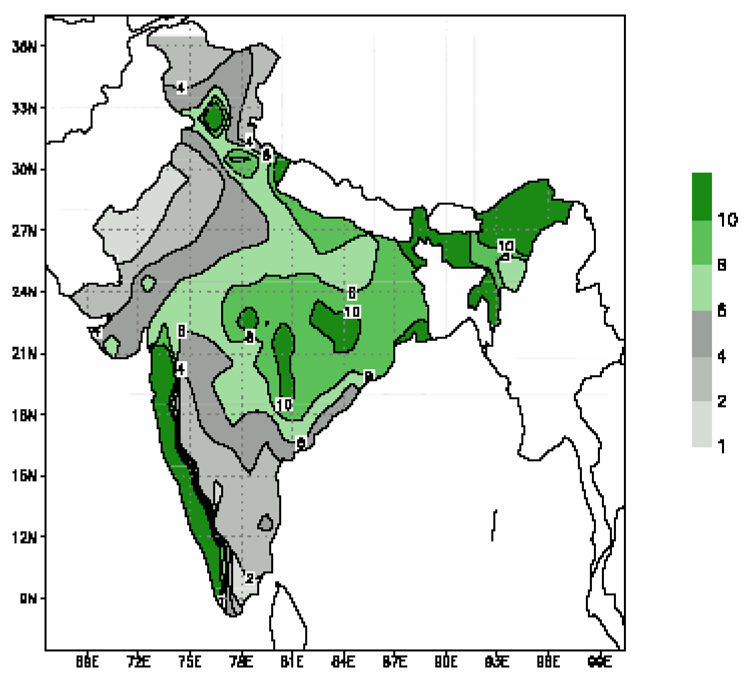


Figure 2.2(a): Spatial pattern of southwest monsoon seasonal (June-September) mean rainfall, 1951-2003 (unit: mm/day) (Rajeevan et al., 2005).

Comparison with global gridded rainfall dataset (VASClimo, Beck et al., 2005) revealed that this Indian rainfall dataset is better in accurate representation of spatial rainfall variation. Although, the inter-annual variability of summer monsoon seasonal (June-September) rainfall was found to be similar in both the datasets, the global dataset underestimates the heavy rainfall along the west-coast and north-east India (Rajeevan et al., 2005). Figure 2.2(b) shows the difference between the IMD gridded rainfall dataset and VASClimo dataset. Over the most parts of India, the differences between the VASClimo data and IMD data are of the order of 50mm only. However, along the west coast, IMD rainfall values are more than the VASClimo values. Figure 2.3 shows the interannual variation of southwest monsoon seasonal rainfall in terms of percentage of long period average (LPA) calculated from both the data sets. It is seen in Figure 2.3 that there is an excellent similarity in the inter-annual rainfall variation with all major drought and excess years were well captured. The correlation coefficient between those data sets was 0.95 for the period 1951-2000 (Rajeevan et al., 2005).

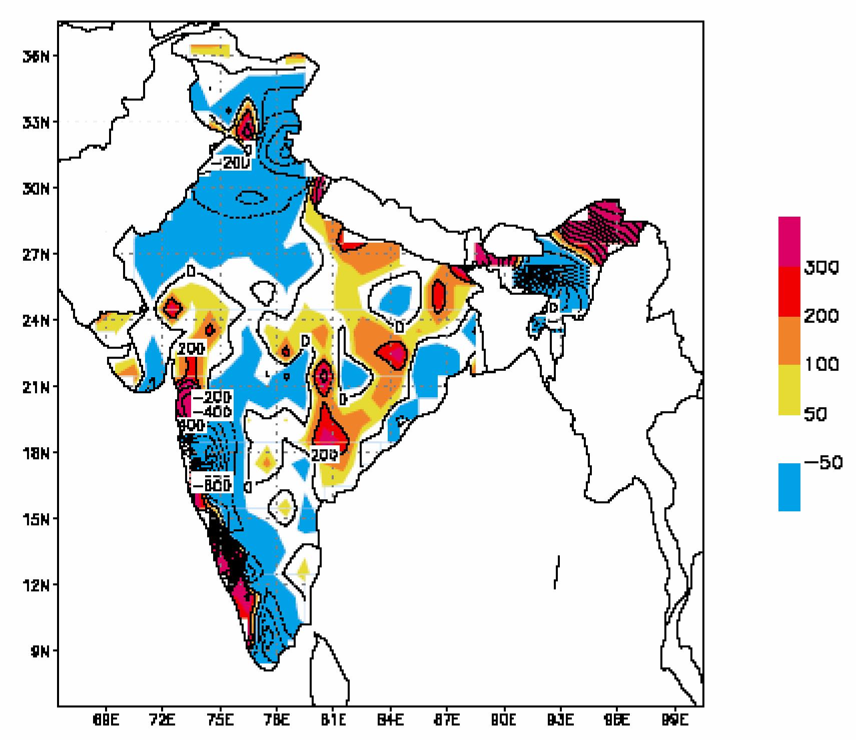


Figure 2.2(b): The difference (in mm) between the IMD gridded rainfall data and VASClimo gridded rainfall data for the southwest monsoon season for the period 1951-2000 (Rajeevan et al., 2005).

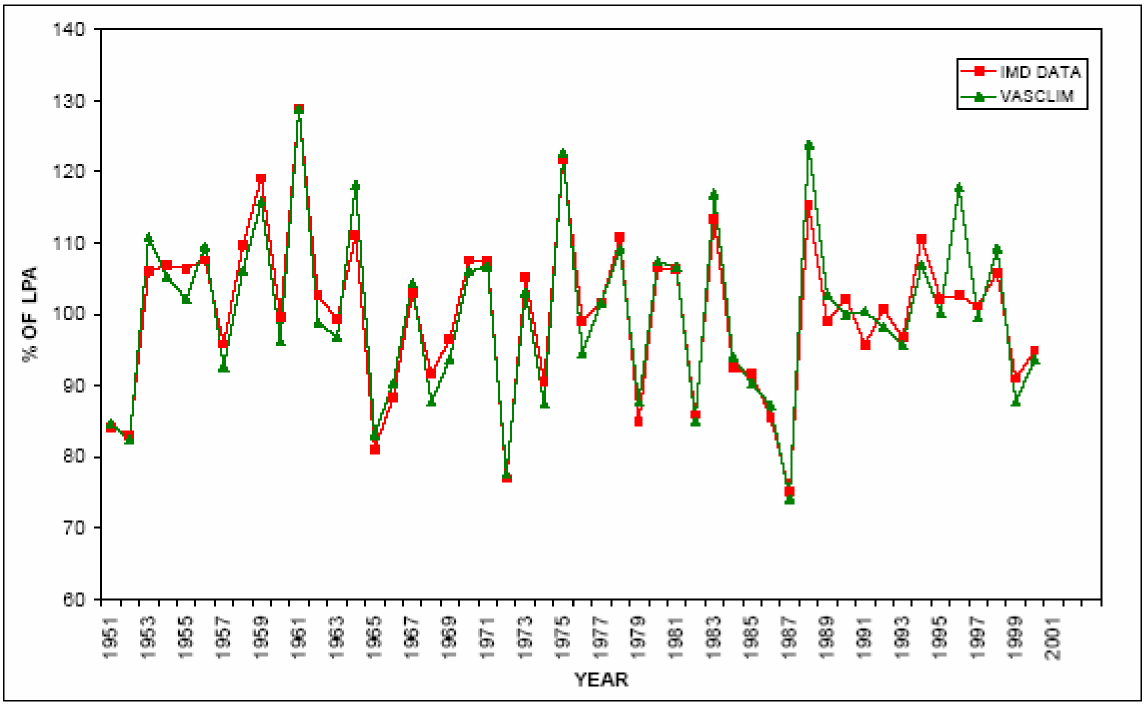


Figure 2.3: Interannual variation of southwest monsoon seasonal (June-September) rainfall from the IMD gridded data set and VASClimo data set for the period 1951-2000 (Rajeevan et al., 2005).

Ever since the introduction of the IMD dataset in 2006, it has been found useful for a range of applications. Rajeevan et al. (2006) wanted to identify the changes in break and active periods during the summer monsoon season over 1951-2003 using this dataset. They found that the summer monsoon break periods identified in India were comparable with the periods identified by earlier studies. Goswami et al. (2006) chose central India to analyse this rainfall data over 1951-2003. They revealed that the instances of very heavy rains have gone up every year from 8 to 18 inches but the spells of moderate rain have been going down while the mean rainfall during the monsoon season has remained unchanged in central India. It is claimed that, this study was the first to observe the evidence of change in monsoon rainfall extremes due to global warming. Later, more and more Indian scientists used this database to study various aspects of Indian rainfall. For example, Ramesh and Goswami (2007) showed that both the temporal length and the spatial coverage of summer monsoon rainfall are decreasing and especially in the continental Indian region. Roy Bhowmik et al. (2008) examined the thermodynamics of the atmosphere in relation to occurrence of convective rainfall over the Indian region from 15 March 2001 to 28 February 2002. They found that a belt of high convective available potential energy occurs along the east coast that extends north up to Gangetic West Bengal and another zone of high along the southwest coast in pre-monsoon and monsoon seasons. Those belts of maximum convective available potential energy again shift over the extreme southern Peninsula during post-monsoon and winter seasons. Chattopadhyay et al. (2008) used this database to validate a new innovative technique known as self-organising map (SOM - a type of artificial neural network that is used to visualise data), which is used to study the monsoon intra-seasonal oscillation.

2.2.2. Monthly Rainfall Data

Observed monthly rainfall data for the period of 1871–2005 was also used in this study, which were downloaded from the website (http://www.tropmet.res.in) of the Indian Institute of Tropical Meteorology (IITM). This time series has been generated by area-weighting the rainfall at 306 rain-gauge stations well distributed across the country. The station rainfall data to form this database were obtained from the Indian Meteorological Department.

India has high spatially variable climate. The amount of rainfall in the monsoon seasons is highly variable, spatially ranging from 160-1800mm/year from the north-west to the north-east and from the far north to the extreme south. Spatially coherent monsoon regions, when aggregated, result in five homogeneous regions covering 90% of the whole of India (except hilly regions in the extreme north of India), which are being considered in some part of this research. The rainfall series used in this work are for North West India (NWIN), West Central India (WCIN), Central North East India (CNEIN), North East India (NEIN) and Peninsular India (PENIN), and also a spatial and temporal average rainfall for the whole of India (ALLIN). These homogeneous study regions are shown in Figure 2.4. The study regions were determined to be distinct with respect to the interannual variability of rainfall.

This data set is one of the most reliable long series going back to 1871. A comparison with Climatic Research Unit (CRU, University of East Anglia) global gridded dataset revealed that both the datasets have a very high correlation (0.9) (Kumar et al., 2007). This long-term monthly Indian rainfall database has also been used in a range of studies outlined here. A trend analysis of monthly rainfall data for the years 1871-1988 revealed a decreasing trend of monsoon rainfall during the late nineteenth century and again in the 1960s in central and western Indian regions (Subbaramayya and Naidu, 1992). This result was very similar to Naidu et al. (1999), who also found decreasing trends during 1880-1905 and 1945-1965 for all sub-divisions in India and only except Tamilnadu region. An analysis of the same data but for 1871-1984 also revealed that the areas in west coast, north Andhra Pradesh and north-west India are undergoing increase in monsoon seasonal rainfall, and decreasing trends were found in east Madhya Pradesh and adjoining areas, north-east India and parts of Gujarat and Kerala (Rupa Kumar et al., 1992). On the other hand, Dash et al. (2007) analysed the all-India rainfall amount for the period of 1871–2003 during different seasons and found a decreasing tendency in the summer monsoon rainfall over Indian landmass and increasing trend in the rainfall during pre and post-monsoon months.

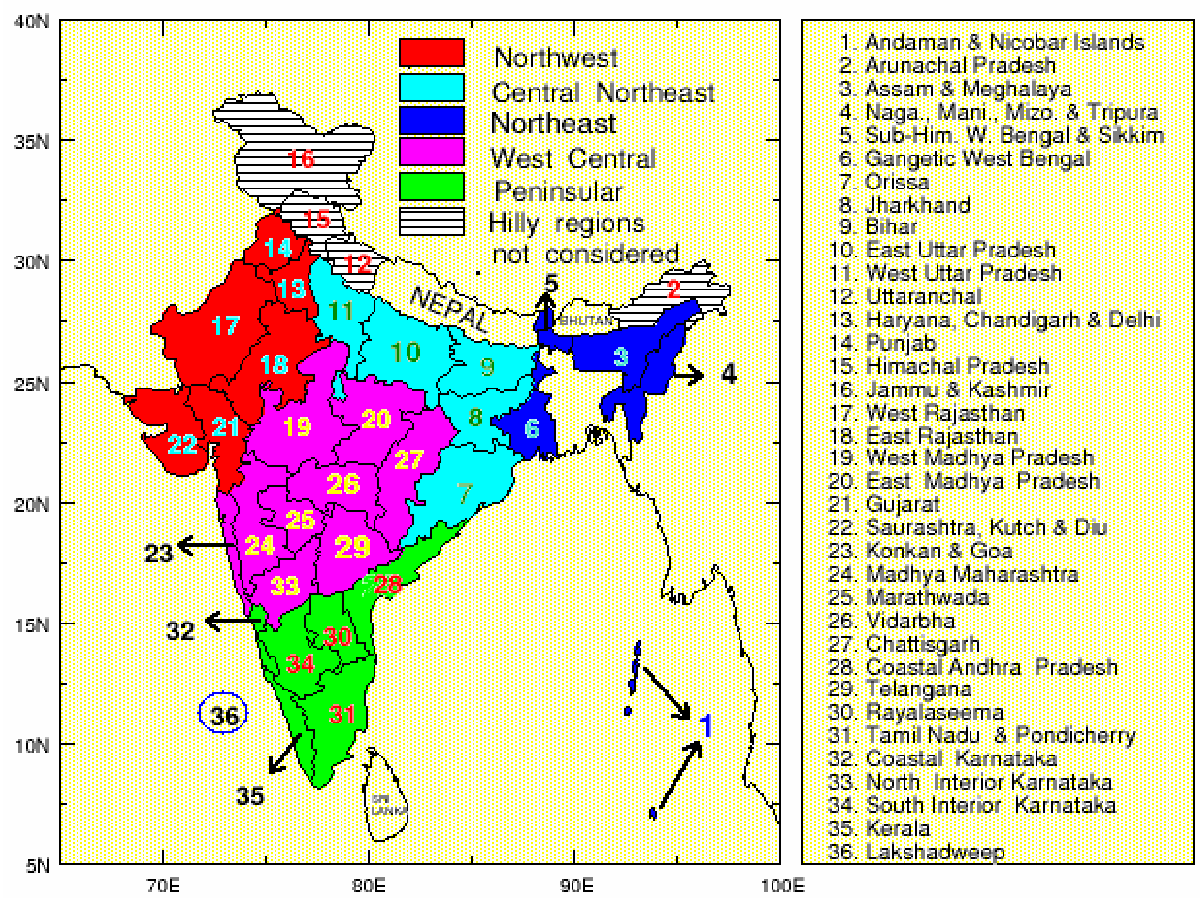


Figure 2.4: Homogeneous study regions in India except the northern-most hilly region, ALLIN, NWIN, WCIN, CNEIN, NEIN and PENIN denotes all-India, north-west India, west-central India, central north-east India, north-east India and peninsular India respectively (http://www.tropmet.res.in).

This dataset was also useful to associate drought and flood with El-Niño and La-Niña in various parts of India (Kane, 1999, 2006). While good associations of El-Niño and monsoon drought, and La-Niña and monsoon flood were observed in north-west, north-central and west-peninsular India, eastern India had normal rainfall or even floods in El-Niño years. On the other hand, Singh (2001), using the same database, observed that the pre-monsoon ENSO conditions have an adverse impact on the seasonal monsoon rainfall over the north-western and extreme south-peninsular Indian region but not in major parts of north-eastern India. A notable failure of Indian drought in 1997-1998 El-Niño year was also a good example (Kane, 1999). Later, using the same database Kane (2006) again confirmed that this association of El-Niño events across pacific and monsoon droughts in India is weakening.

This data was also useful not only to detect a year-to-year random fluctuations of summer monsoon rainfall over India, but also a distinct alternate decadal epoch of above and below normal rainfall (Kripalani et al., 2003). An analysis of this data over southern India and particularly over coastal Andhra Pradesh revealed that values of southern oscillation index and sea surface temperature in September are the key determining factors of winter monsoon rainfall (Bhanu Kumar et al., 2004).

2.2.3. Monthly Maximum and Minimum Temperature Data

This study also used the data set of the regional monthly maximum and minimum temperature time series for 1901-2003, which was compiled by the Indian Institute of Tropical Meteorology (IITM). This dataset was also obtained from http://www.tropmet.res.in, which was created from an all-India network of 121 stations in seven homogeneous land regions across the Indian subcontinent. Regional homogeneity was based on climatological, topographical and geographical characteristics. Seven homogeneous climatological regions namely North East (NE), North Central (NC), West Coast (WC), North West (NW), Interior Peninsula (IP), East Coast (EC) and West Himalaya (WH) were considered as shown in Figure 2.5 (Kothawale and Rupa Kumar, 2005). Also, the data averaged over the whole of India was studied. The data set initially covered the time period from 1901 to 1990 and was later extended to 2003 with data obtained from Indian Daily Weather Reports (IDWRs) published by the Indian Meteorological Department (IMD).

This database was also used previously for different research purposes. For example, linear trend analyses of diurnal and mean temperature over India during the period of 1901-87 and 1901-2003 respectively revealed that the increase in mean temperature over India is solely contributed by the maximum temperature, with the minimum temperatures remaining practically trend less, leading to an increase in the diurnal range of temperatures (Kothawale and Rupa Kumar, 2005; Rupa Kumar et al., 1994). The recent period of 1971-2003 was found to be the period of accelerated warming of 0.22°C/10yr and the mean temperature has been enhanced by about 1 and 1.1°C during winter and post-monsoon months respectively (Dash et al., 2007). Regional changes in minimum temperature are different from all-India changes. In north India, the minimum temperature shows sharp decrease of its magnitude between 1955 and 1972 and then a sharp increase till date; wherein in south India, the minimum temperature has a steady increase (Dash et al., 2007).

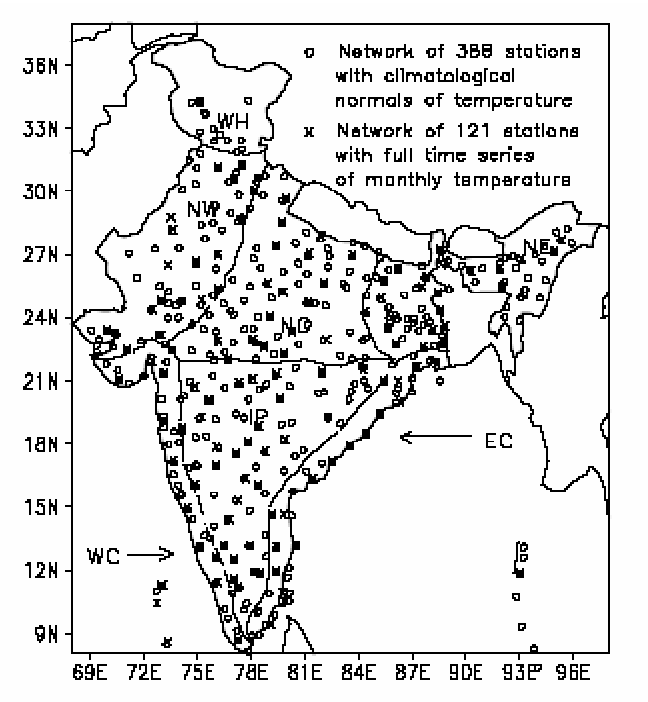


Figure 2.5: Network of temperature stations and homogeneous regions used in this study (Kothawale and Rupa Kumar, 2005).

Krishna Kumar et al. (1997) used this database to reveal that March minimum temperature in east peninsular India and May minimum temperature in west central India could be two good predictors of summer monsoon rainfall in India. On the other hand, Krishnan and Ramanathan (2002) and Sen Roy et al. (2007) used this temperature database partially to determine aerosol and irrigation feedbacks on atmospheric cooling.

Literatures review on the study of seasonal rainfalls in India and worldwide give lots of information on the changes and variability of the same. The following sections summarise some of them.

2.3. Patterns of Annual/Seasonal Rainfall in India and World-Wide

2.3.1. A World-Wide Perspective

Variability is a primary feature of climate. During the last few decades climate change has assumed importance owing to an identified increase in tropospheric temperatures. Associated with the climate change, the spatial and temporal distribution of rainfall is also subject to variations. Rainfall variability and changes are predicted to have a major impact on the water and agricultural sectors in the Asia-Pacific region (Cruz et al., 2007). Any change and/or fluctuations in the hydrological cycle directly affect the availability and quality of fresh water, which is a major environmental issue of the 21st century (Kim et al., 2008).

Global Circulation Models (GCM) predict an increase in global rainfall over the oceans and high latitudes as evaporation is enhanced in the warmer climates (Wentz et al., 2007). To the contrary, drought is projected to rise throughout the 21st century on the tropical land regions that are likely to experience less rainfall (Kruger, 2006; Tebaldi et al., 2006), which is due to the mass continuity that requires that the increased vertical mass transfer and associated increased rainfall at some place should be balanced by declining motion in another place (Bosilovich et al., 2005). Recently, its been reported by NASA that, there has been an increase of 5% rainfall in the tropics; but that increase in total rainfall over the tropics has been mainly concentrated over the oceans but in the land regions it’s been reported to be slightly declined (NASA/Goddard Space Flight Center, 2007). Although no clear evidence on the physical mechanism of this is available yet, the reason for decreasing rainfall in those areas could also be because of the increasing trend of atmospheric residence time of the precipitable water and decreasing cloudiness over the tropical land regions (Bosilovich et al., 2005).

The changes in local regions can be far more dramatic than changes in global averages. Available data suggest that there may be different results even on the land regions. For example, decreasing trends of annual rainfall and seasonal changes were already noticed in Indonesia (WWF, 2007), India (Duan et al., 2006; Wu and Kirtman, 2006), Italy (Cislaghi et al., 2005), Mid-Atlantic regions (NOAA, 2008), South-Eastern Australia (Murphy and Timbal, 2008), Sri Lanka (Zubair et al., 2008), sub-Antarctic Marion Island (Roux and McGeoch, 2008), Turkey (Partal and Kucuk, 2006), UK (Palmer and Raisanen, 2002) and Zimbabwe (Mugabe and Senzanje, 2003). On the other hand increasing trends in summer (Jun-Sept) rainfall has been noticed in Norway (Benestad and Haugen, 2007), Spain (Mosmann et al., 2004), and the United States (Groisman et al., 2001), and increasing trends in winter rainfall total was observed in Canada (Groleau et al., 2007). Following paragraphs demonstrate more findings in patterns of regional climatic changes.

Serrano et al. (1999) studied monthly and annual total rainfall records of the forty meteorological stations in Iberian Peninsula in 1921-1995. No significant trend was detected in the annual total rainfall series; wherein a downward trend was observed in 21 stations only in the month of March. Lopez-Bustins et al. (2007) studied the variation of winter rainfall and its teleconnection in the same region at the end of the 20^{th} century. They observed that the winter rainfall presented a significant decrease in its western and central areas throughout the second half of the 20^{th} century, whereas over the eastern fringe it showed hardly any variation. These variations were related to changes in the frequency of surface circulation patterns over Western Europe.

Yue and Hashino (2003) investigated long term trends in annual and monthly rainfall for Japan choosing three regions including one side of the country adjacent to the Sea of Japan, the other side of Japan adjacent to the Pacific and the southwestern islands of Japan. They observed that large regional variability persists in monthly and annual total rainfall trends. Most of the regions have shown decline in rainfall with greatest decrease in December (38.2-44.7%). Only the part adjacent to the Sea of Japan has been found undergoing significantly increase in rainfall (12.2%) in May.

Xu et al. (2008) analysed climate patterns and trends, spatial and temporal, in the Tibetan Plateau for the period of 1961-2001 based on monthly and annual time series data collected from the National Meteorological Centre, China Meteorological Administration. The results indicated that rainfall in the Tibetan Plateau has increased in most regions of the study area over the past several decades, especially in the eastern and central part, while the western Tibetan Region exhibited a decreasing trend over the same period.

Luo et al. (2008) analysed spatial and temporal trends of rainfall in Beijiang river basin, Guangdong province, China during 1959–2003 using 17 time series (including monthly, annual, wet season, dry season, early flood period and late flood period totals) both on station based and sub-basin based data sets. Their results showed that decreasing trends were mostly detected during the early flood period, especially in May, while upward trends were observed in July and the dry season. In addition, decreasing trends were mostly detected in the southern Beijiang river basin, while upward trends were observed in north of this area.

Domonkos (2003) analysed the time series of monthly rainfall totals from 14 Hungarian observing stations in 1901-1998 to detect the long-term changes in rainfall characteristics in the 20th century. The trends they found didn't follow the trend in European rainfall but the annual rainfall total decreased by 15–20% in Hungary during the 20th century. The decline was substantial in both halves of the century.

Samba et al. (2008) analysed trend and discontinuities in rainfall time series for Congo-Brazzaville over the period 1950-1998. They found significant amount of differences in the results for large towns. Thus, while rainfall series were found showing a stationary evolution in the southern area, an overall negative trend was found in the north.

The following sub-sections summarise an up to date knowledge on the changes in monsoon and other seasonal rainfalls in India, and their possible teleconnections.

2.3.2. Change in Regional Monsoon Rainfall in India

The most important climatological feature of the south Asian region is the occurrence of monsoons, the southwest or summer monsoon being the principal source of water; and the northeast or winter monsoon meets the water needs of the southernmost parts of the Indian peninsula and Sri Lanka. Monsoon rainfall affects millions of lives in India, which is greatly influenced by the shape of the continent, orography, and upper tropospheric conditions etc. that are best addressed by a regional approach (Guhathakurta and Rajeevan, 2008). Rainfall over India is subject to a high degree of variation leading to the occurrence of extreme monsoon rainfall deficit or excess over extensive areas of the country (Dash et al., 2007). Because of large spatial variability of monsoon rainfall, there are occasions when some regions experience floods due to intense rains while at the same time other areas experience severe rainfall deficiency leading to extreme monsoon rainfall deficit. With more concern about climate change, the need to know about and understand the nature and variability of the modern climate and to evaluate possible future changes becomes increasingly important.

As reported by the IPCC in its most recent ‘synthesis report’, the Indian subcontinent will adversely be affected by enhanced variability of climate, rising temperature and substantial reduction of summer rainfall in some parts and water stress by 2020s (Cruz et al., 2007). Population growth makes the stress more unfavourable because this country relies heavily upon rain-fed agriculture and food infrastructures. Since monsoon rainfall (summer monsoon) is a major factor for water resources planning and operation in India, any change or reduction in monsoon rainfall, which contributes to more than 75% of annual rainfall input, may have a great effect on the efficiency and accuracy of such projects affecting the agricultural economy in the country.

Significant number of recent researches reported a statistical evidence of changing tendency of Indian monsoon rainfall; the findings suggest that the monsoon rainfall variability might be remarkably complex (Dash et al., 2007; Kripalani et al., 2003; Naidu et al., 1999). Inter-regional differences put forward a fairly higher degree of local influence on variability. For example, Goswami et al. (2006) examined the distribution and trend of ‘moderate’ daily monsoon rainfall over central India and found a decreasing trend and increasing variability of the same. Soman et al. (1988) noticed a rainfall recession trend in Kerala, south-west peninsular India. Sen Roy and Balling (2004) found decline in annual rainfall in the north-eastern states, parts of the eastern Gangetic plain and Uttaranchal, as shown in Figure 2.6. The standardised regression coefficient in Figure 2.6 is equal to the Pearson product-moment correlation coefficient between the independent and dependent variables, which indicates the strength and sign of any trend. Absolute values of those coefficients above 0.2 indicate statistically significant trends at the 0.05 level. Sometimes, rainfall distribution was expressed in terms of rainfall intensity changes in some areas in India (Goswami et al., 2006).

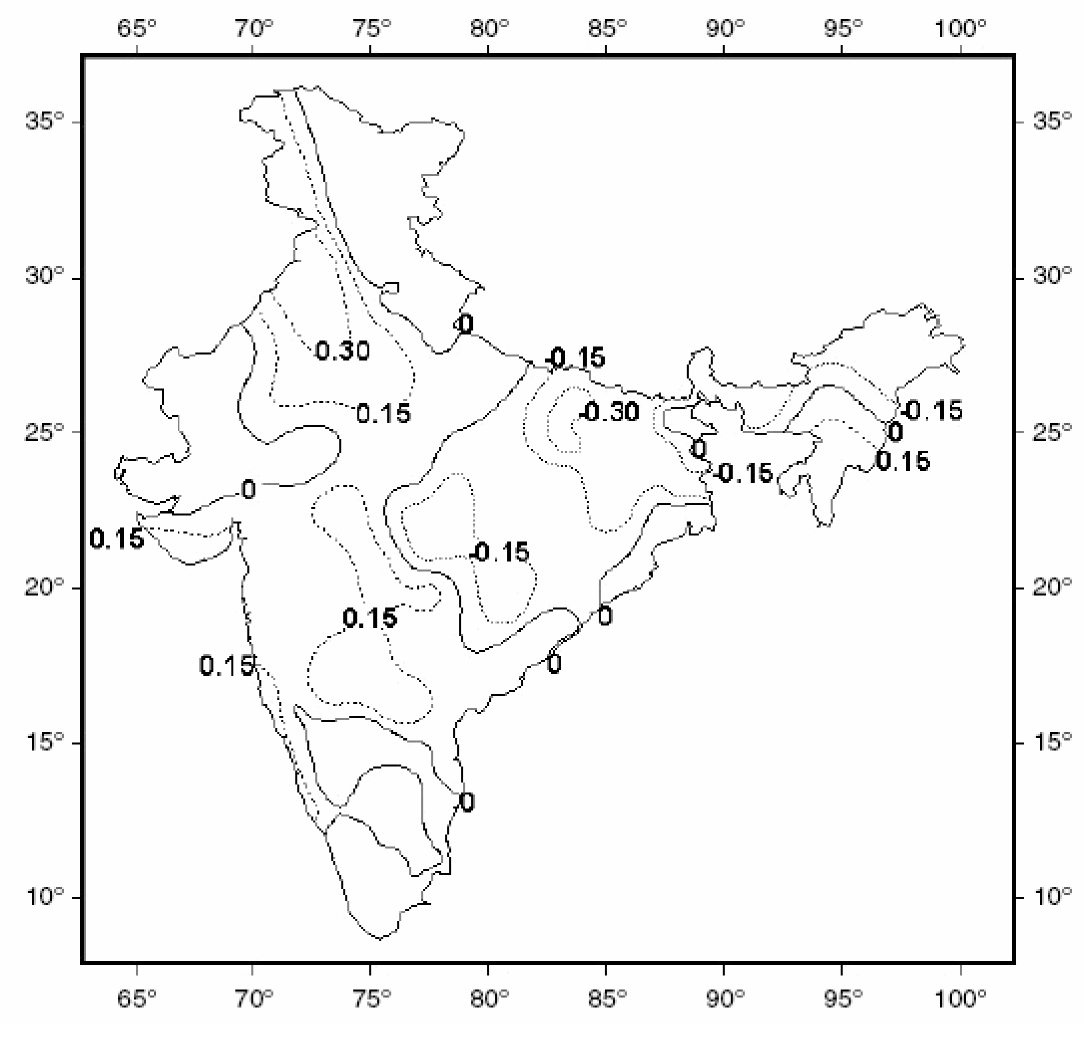


Figure 2.6: Map of standardised regression coefficients showing trends in the total annual precipitation throughout India (Sen Roy and Balling, 2004).

Many other similar studies have been taking place in various other parts of the globe, as mentioned before and the neighbouring countries. Immerzeel (2008) studied the 100 years high resolution data from the Brahmaputra basin area which is located in 4 different countries namely India, Bangladesh, Bhutan and China; however, the author found no specific changes in the monsoon rainfall pattern in that area, which is located in the north eastern Indian region. Ding et al. (2008) observed that the East Asian summer monsoon has greatly weakened in the period of 1888 to 2002, and the Indian summer monsoon underwent weakening process in the last 50 years, which, as they described, was also a cause of summer rainfall changes in China.

2.3.3. Change in Other Seasonal Rainfalls in India

The management of water resources is crucially important for seasonally arid countries, especially those whose rainfall is driven by monsoon like India. Monsoon countries are likely to experience dramatic changes in land use patterns and population rise in the coming decades. There are strong evidences of climate change and its impacts over the last century in India (Dash et al., 2007). Snow accumulation experiment results show that there has been strong variation in the South Asian monsoon in the Indian subcontinent (Duan et al., 2006). Also that there has been observed changes in rainfall intensity (Ramesh and Goswami, 2007; Goswami et al., 2006) and the number of rainy days in various regions in India (Singh et al., 2008) that are highly correlated with the seasonal and annual rainfall amount (Raisanen, 2005; Karl et al., 1995). As a result, inter-annual and decadal-scale fluctuations, as well as long-term changes in the local scale seasonal rainfalls might have important socio-economic consequences for agricultural productivity that is likely to suffer severe losses because of high temperature, severe drought, flood conditions and soil degradation.

The impact of climatic fluctuations and changes on the seasonal hydrological cycle is therefore a key issue for policy makers since India is still strongly dependent on agriculture. Although the summer monsoon (from June to September) is the major rain producing season over India, other seasons also have significant contribution in some specific region. For example, rainfall during winter and spring seasons is mostly predominant by western disturbances or 'Nor'westers' and convective activities over northern parts of India and winter monsoon is prevalent in the southern states. Winter monsoon plays a vital role in the agricultural activities over five meteorological subdivisions in peninsular India comprising coastal Andhra Pradesh, Rayalaseema, South Interior Karnataka, Kerala and Tamilnadu (Figure 2.4). This region receives significant portion of the annual rainfall during October–December and hence this rainfall is crucial especially when the summer-monsoon rainfall fails.

Although, several attempts have been made to study monsoon seasonal and annual rainfall trends in India, as discussed before in sections 2.2.1, 2.2.2 and 2.3.2, there is a lack of other seasonal analyses in the literature. As a result, study of the long-term trends in various seasonal rainfalls in India is an important problem which needs to be investigated. Therefore, in addition to monsoon (June-Sept), the winter (Dec-Feb), spring (Mar-May) and autumn (Oct-Nov) seasons were also analysed in this work and discussed in Chapter 3.

2.3.4. Correlations of Extreme Monsoon Rainfall in India and ENSO (El-Niño and Southern Oscillation)

A monsoon system primarily results from the heat energy difference between the ocean and the land surfaces and resulting atmospheric circulation, as mentioned in section 2.1. Major monsoons of the world occur in and around the Indo-Pacific Ocean. A high air pressure in the Indian Ocean generally corresponds with a low air pressure in the Pacific region and vice versa. Southern Oscillation (SO) is a see-saw in air pressure between the central Pacific and Indian Ocean and is strongly resulted from the difference in sea surface temperature across Pacific. Hence, monsoon across various countries is greatly influenced by SO.

The relationship between monsoon rainfall and the SO has been investigated by many researchers, quoted as 'teleconnection' by the meteorologists, and especially El-Niño and rainfall variability; for example – for India (a number of studies mentioned before in section 2.2.2), Sri Lanka (Suppiah, 1997), Thailand (Singhrattna et al., 2005); South

Korea (Jin et al., 2005), South-East Asia and the Pacific region (Xu et al., 2004), Australia (Power et al., 2006), various parts of Africa (Nash and Endfield, 2008; Balas et al., 2007; Mason, 2001), America (Kim et al., 2008) and also Mexico (Lenart, 2005). El-Niño is used to refer unusually warm water, while La-Niña is the counterpart of El-Niño which is characterised by cooler than normal Sea Surface Temperatures (SSTs) across the equatorial eastern and central Pacific.

It is generally believed that the interannual variability in monsoon activity depends on air-sea interactions which take place during the travel of the monsoon current across the ocean. Therefore, change in Sea Surface Temperature (SST) due to global warming would very likely have an impact on Indian monsoon circulations (Roxy and Tanimoto, 2007). Also, ENSO (El-Niño and Southern Oscillation), which is a function of temperature anomaly across Pacific Ocean, could also have played a significant role in the change of monsoon seasonal rainfall in India and Sri Lanka since it's been regarded as the most important external forcing to Indian monsoon rainfall (Zubair et al., 2008).

It is now a well established fact that there is a link between the Indian monsoon rainfall variability and the SO phenomenon (as also discussed in section 2.2.2). Some studies also revealed the correlation of winter monsoon rainfall in south India and Sri Lanka with SO (Prasanna and Yasunari, 2008; Kumar et al., 2007). Sen Roy (2006) found a negative relationship between winter rainfall (Jan-Feb) in peninsular India and both ENSO indices. Furthermore, Revadekar and Kulkarni (2008) has shown that the winter monsoon rainfall extremes in south peninsular India could be predicted using El-Niño Southern Oscillation Index, 4–6 months in advance.

In the recent years, however, the ENSO-monsoon relationship has been weakening (Kripalani et al., 2007; Krishna Kumar et al., 2006). Wang et al. (2006) found that the correlation between Indian summer rainfall and ENSO was much stronger only before 1980s. A possible explanation for this could be the south-east-ward shift in the Walker circulation anomalies associated with ENSO events, which may lead to a reduced subsidence over the Indian region, thus favouring normal monsoon conditions. Otherwise, increased surface temperatures over Eurasia in winter and spring, which are a part of the mid-latitude continental warming trend, may favour the enhanced land-ocean thermal gradient conducive to a strong monsoon (Krishna Kumar et al., 1999).

2.3.5. Change in Seasonal Rainfalls in Kerala, India

India's population is highly concentrated in Kerala. This state is a major cash crop producing place in the country, where monsoon downpour initiates every year in India before proceeding towards other parts of the country. The rainfall variability is very high in Kerala and this state has been suffering from an extended dry spell for the last 2-3 decades, which is contributing to the decline in agricultural production (Guhathakurta and Rajeevan, 2008). Mean rainfall from 1984 to 2005 has been below average; with only 6 years having more rainfall than 1871-2005 mean (see Chapter 3), resulting in an extended dry period that has led to a number of severe impacts in the region. A very small change in regional circulation pattern, even by a couple of degrees in longitude and latitude, can have a significant impact on seasonal rainfall (Ramesh and Goswami, 2007). Hence, there is an urgent need to understand the variability and possible uncertainty in rainfall over Kerala in order to provide greater certainty in planning and decision making in this state, as presented and discussed in Chapter 3.

2.4. Trends and Variability of Seasonal and Annual Extreme Rainfall Events – An Indicator of Climatic Changes

2.4.1. A World-Wide Perspective

2.4.1.1. Introduction

Climate Change is now a dominating scientific and social issue, which is not only manifested in the hotter and drier summer, and warmer and wetter winters in various world regions. Global warming is also leading to a variable probability of extreme rainfall events, both in the form of intensity and also frequency, as a result of change in energy in the atmosphere and oceans (Roux and McGeoch, 2008). Understanding climate change demands attention to changes in climate extreme events. The principal reason is that extreme weather conditions related to rainfall can cause severe damage and large economic and societal loss (Moberg et al., 2006). Model studies have found an increase in extreme rainfall events almost everywhere on the globe and that the relative change in extreme rainfall is larger than change in total rainfall (Lau and Wu, 2007; Barnett et al., 2006).

Lack of long-term climate data suitable for analysis of extremes is the biggest obstacle to quantifying whether extreme events have changed over the twentieth century, either worldwide or on a more regional basis (Moberg et al., 2006). Figure 2.7 shows the areas of the world where analyses of heavy rainfall have been completed (Easterling et al., 2000). Signs (pluses and minuses) in Figure 2.7 indicate regions where significant changes in heavy rainfall have occurred during the past decades. Four countries (Australia, United States, Norway, and South Africa) were assessed using century-long daily rainfall wherein for other countries data was used since post–World War II period (Easterling et al., 2000).

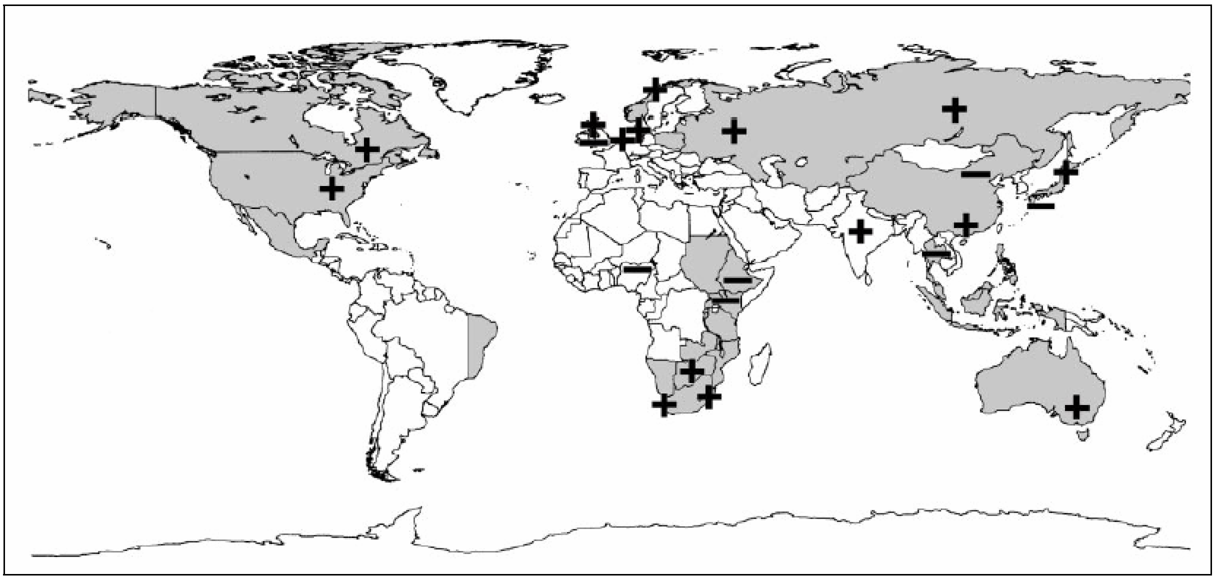


Figure 2.7: Regions for which the large sets of daily rainfall time series are available for analyses of rainfall extremes (Easterling et al., 2000).

Lightly shaded regions in Figure 2.7 are those used in the summary shown in Table 2.1. Usually the season with maximum rainfall totals has been selected in Table 2.1. A single asterisk in Table 2.1 indicates statistically significant linear trend at 95% level. In four regions (marked by **) a statistically significant increase in heavy rainfall was found, while mean rainfall total did not change (or even decreased), and the frequency of rainfall events has decreased during the same period, as in Table 2.1. For the Asian part of Russia this unusual pattern of changes has been attributed to the intensification of summer convective processes (Easterling et al., 2000). Results corresponding to some of the regions in Figure 2.7 are also summarised in Figure 2.8.

Table 2.1: Regions/seasons/periods where the linear trends of the number of days with heavy rainfall are amplified relative to changes in mean rainfall totals and frequency (Easterling et al., 2000).

Country	***Period***	***Threshold used to define heavy rain (mm)***	***Season***	***Average numbers of days with heavy rain***	***Linear trend, % per 10 yr***
Eastern two-thirds of the contiguous United States	1910-96	50.8	JJA	0.6	1.7*
European part of the former USSR	1936-94	20	JJA	1.8	3.9*
Asian part of Russia**	1936-94	20	JJA	2.3	1.9*
Southern Canada	1944-95	20	JJA	2.9	1.9*
Coastal regions of New South Wales and Victoria, Australia	1900-96	50.8	DJF	0.4	4.6*
Norway	1901-96	25.4	JJA	2.0	1.9
Southern Japan	1951-89	100	JJA	1.0	-6.1
Northern Japan**	1951-89	100	JJA	0.3	3.4*
Northern China	1951-97	50	JJA	1.0	-3.1
Southern China	1951-97	100	JJA	0.5	1.3
Ethiopia and Eritrea	1951-87	25.4	JJA	5.5	-11.6*
Equatorial east Africa	1950-97	50.8	MAM	1.1	-11.2*
Southwestern South Africa	1926-97	25.4	JJA	0.7	5.5*
Natal, South Africa**	1901-97	50.8	DJF	0.6	4.1*
Nord-Este, Brazil**	1935-83	50.8 100	MAM MAM	1.0 0.1	3.6 16.1*
Thailand	1951-85	50.8 100	SON SON	2.2 0.4	-8.4* -20.9*

All of the above results together with other and newer studies are discussed in more detail in the following sections.

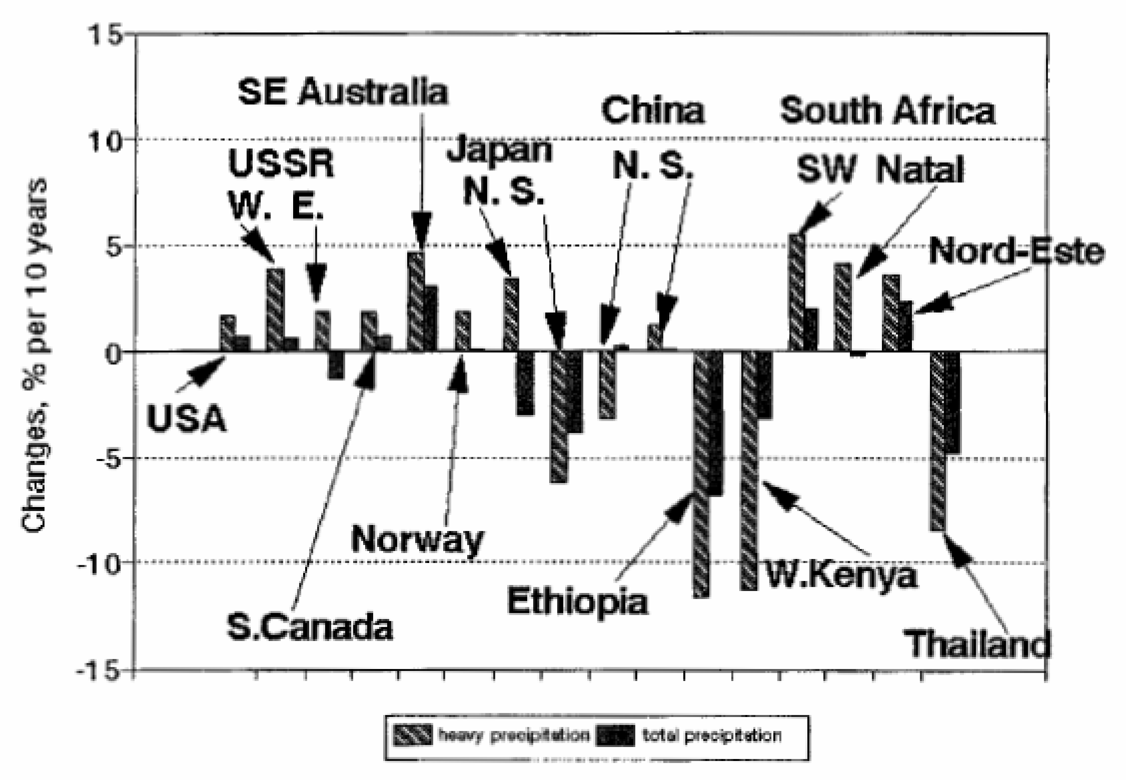


Figure 2.8: Linear trends in total seasonal precipitation and frequency of heavy precipitation events (Easterling et al., 2000).

2.4.1.2. Global Changes

One of the important world-wide assessments of changes in observed daily rainfall extremes have been made by Alexander et al. (2006), who presented a comprehensive global picture of trends in extreme rainfall indices for the period of 1951-2003 using results from a number of workshops held in data-sparse regions and high-quality station data supplied by numerous scientists worldwide. Their results showed widespread rainfall changes with significant increases in extreme rainfall throughout the 20th century, but the changes are much less spatially coherent compared to temperature changes and the change in annual and/or seasonal rainfall (Groisman et al., 2005).

Global rainfall projection data suggest more spatially variable results. For example, Semenov and Bengtsson (2002) analysed data from a coupled atmosphere-ocean general circulation model ECHAM4/OPYC3 for 1900-2099. They found significant positive trends in mean and extreme rainfall over continental areas. Predicted rainfall trend patterns in the period of 2000-2099 followed the tendency obtained for 1900-1999 (observed) but with significantly increased magnitudes. On the other hand, negative trends were found in the number of wet days over most of the land areas except high latitudes in the Northern Hemisphere, which suggests more and more intense rainfall in shorter interval of time. Lau and Wu (2007) did a similar study of analysing global data sets from the Global Precipitation Climatology Project (GPCP) and the Climate Prediction Center Merged Analysis Product (CMAP). Their research revealed that there was a significant shift in the probability distribution functions of tropical rainfall during the period of 1979-2003. This shift featured a positive trend in the occurrence of heavy (top 10% by rain amount) and light (bottom 5%) rain events in the tropics during 1979-2003 and a negative trend in moderate (25-75%) rain events.

Some researchers looked at the frequency and/or severity of global climatic extremes changed during 20th century based on selective indicators derived from daily totals of rainfall. Frich et al. (2002) used such 10 selective indicators during the interval from 1946 to 1999 and reported that extreme rainfall has more mixed patterns of change but significant increases have been seen in the extreme amount derived from wet spells and number of heavy rainfall events. Tebaldi et al. (2006) also examined 10 indicators of extremes derived from an ensemble of 9 GCMs that contributed to the Fourth Assessment Report of the IPCC (IPCC-AR4). They observed that there is a trend towards a world characterized by intensified rainfall, with a greater frequency of heavy-rainfall and high-quantile events, although with substantial geographical variability. Particularly the high latitudes of the northern hemisphere showed the most coherent regional patterns of significant positive changes in the intensity of wet events, as also reported by Sillmann and Roeckner (2008) who calculated the indices for temperature and rainfall extremes on the basis of global climate model ECHAM5/MPI-OM simulations of the twentieth century and SRES A1B and B1 emission scenarios for the twenty-first century. Tebaldi et al. (2006) speculated that the changes in intense rainfall in the northern hemisphere are related to the greater moisture-holding capacity of the warmer air contributing to greater moisture convergence, as well as a pole-ward shift of the storm tracks.

To examine the impact of increasing atmospheric CO_2 on high and low extremes of global monthly-to-annual rainfall, Raisanen (2005) performed twenty model experiments. The author reported that the extremes correlate well with the changes in the long-term mean rainfall. Wet extremes were predicted to be more severe especially where the mean rainfall increased, and dry extremes were predicted to be severe where the mean rainfall decreased. The changes in frequency of extremes were found to be much larger than the changes in their magnitude. Through a similar experiment on equilibrium changes in daily extreme rainfall and temperature events in response to doubled atmospheric CO_2, Barnett et al. (2006) also demonstrated that increase in CO_2 lead to changes in the shape of the daily distributions for both temperature and rainfall, but the effect of these changes on the relative frequency of extreme events is generally larger for rainfall.

While global datasets usually refer to increase in rainfall extremes, regional studies tend to give different results since changes in total and extreme rainfall vary depending upon geographic location (Bell et al., 2004). Extreme events may have major societal, economical and environmental impacts at regional level (Easterling et al., 2000). At the local level and over short periods many of these effects are expected to be more adverse (Cruz et al., 2007). Most analyses of long-term climate observations of rainfall have focused on the change in global annual and seasonal average values. However, extremes at the very local level often cause the biggest impacts and are a medium for alarm about climate change at regional levels because extremes considered in one part of a region might not be quite meaningful across the other part (Manton et al., 2001). The fact that engineering works need to be designed for extreme conditions also requires that special attention is paid to singular values at locals. Regional climate extremes occur when climate variability imposes large anomalies on the average state of the climate system. Hence, a detailed understanding of the spatial and temporal variability of the extremes at the very local level is essential.

Studies related to rainfall extremes are discussed separately for the different continents in the globe, as follows.

2.4.1.3. Changes in Australia

Haylock and Nicholls (2000) analysed daily rainfall from 91 high quality stations over eastern and south-western Australia to determine if extreme rainfall had changes between 1910 and 1998 based on extreme rainfall indices developed. They found that total rainfall in a region is highly correlated with the extreme rainfalls suggesting that the extreme events are more frequent and intense during years with high rainfall. Much of Australia has experienced increases in heavy rainfall events in all parts of the year, except a few stations in south-western Australia where there has been a decrease in both rain days and heavy rainfall events (Manton et al., 2001).

2.4.1.4. Changes in New Zealand

Trends in daily rainfall indices for New Zealand were described by Salinger and Griffiths (2001). This was the first national analysis of trends for this region. The period of analysis considered was 1951-1998. Extreme daily rainfall intensity and frequency above the 95th percentile and the length of consecutive dry day sequences were selected as rainfall indices. Regionally, extreme rainfall patterns were different. The frequency of 1-day 95th percentile extremes was found decreasing in the north and east, and increasing in the west over the study period.

2.4.1.5. Changes in the US

Karl et al. (1995) analysed high-frequency temperature and rainfall data from a number of sites spread over the United States. They found that daily extreme rainfall events increased in the US and the proportion of total rainfall contributed by extreme also increased significantly, as also confirmed by Karl and Knight (1998) and Groisman et al. (2001). An increase in heavy and very heavy rainfall in the US is contributing to high stream flow events both annually and during the months of maximum stream flow. However, from the data of Florida alone, Nadarajah (2005) reported that the pattern of the extreme rainfall variation was that of a decrease in extreme rainfall.

2.4.1.6. Changes in the European Countries and Europe Overall

A number of studies on the rainfall extremes were carried out for the European region and a sample of those results are presented here. Frei et al. (2000) studied past changes and possible future variations in the nature of extreme rainfall and flood events in Central Europe and the Alpine region. Among a detailed overview given on various key contributory physical processes, they studied the potential for more frequent heavy rainfall events in the study region. The results showed that the rarity and natural fluctuation of extreme events largely hampers the detection of systematic variations, which also restricts trend analysis of such events. However, daily rainfall data from Swiss Alps yielded evidence for pronounced trends of intense rainfall events with return period 30 days, which is also true for heavy daily rainfall in the Alpine region of Switzerland (1901–94) in winter and autumn (Frei and Schar, 2001). Furthermore, Frei et al. (2006) analysed the change of rainfall extremes as simulated by six European regional climate models (RCMs) in order to describe/quantify future changes and to examine/interpret differences between models. The model results indicated that winter rainfall extremes tend to increase north of about 45°N, while there is an insignificant change or a decrease to the south. Furthermore, the results revealed that the 20-year return value of future climate in northern Europe corresponds to the 40 to 100-year return value of present climate.

Klein Tank et al. (2002) used the newly constructed daily database from 1946 to 1999 for 195 stations through out Europe and confirmed that the winter extreme rainfall is increasing, as shown in Figure 2.9, although the spatial coherence of the trends was later found low (Klein Tank and Konnen, 2003). For trends significant at the 25% level, but not at the 5% level (Student’s t -test) in Figure 2.9, only the sign of the trend is given and not its magnitude. Yellow colour in Figure 2.9 corresponds to drier conditions and violet to wetter conditions. Green is used for trends that are not significant at the 25% level (Klein Tank et al., 2002). In addition, Moberg and Jones (2005) found that the length of dry spells and summer rainfall in central and western European stations had an increasing tendency over the 20th century. Moberg et al. (2006) analysed century-long (1901-2000) daily rainfall records for stations in Europe west of 60°E. They derived a set of climatic indices mainly focussing on extremes and assessed their trends for both winter (DJF) and summer (JJA) over the study period. Table 2.2 gives a list of indices used in that study. They also found that the winter rainfall totals, averaged over 121 European stations north of 40°N, have increased significantly by ~12% per 100 years wherein no overall long-term trend occurred in summer rainfall totals. Pauling and Paeth (2007) investigated the changes of extreme European winter (December-February) rainfall in the last three centuries. They also found that the winter rainfall generally has become more extreme in Europe, which are due to climate change and no obvious connection of those changes were found to solar, volcanic or anthropogenic forcing.

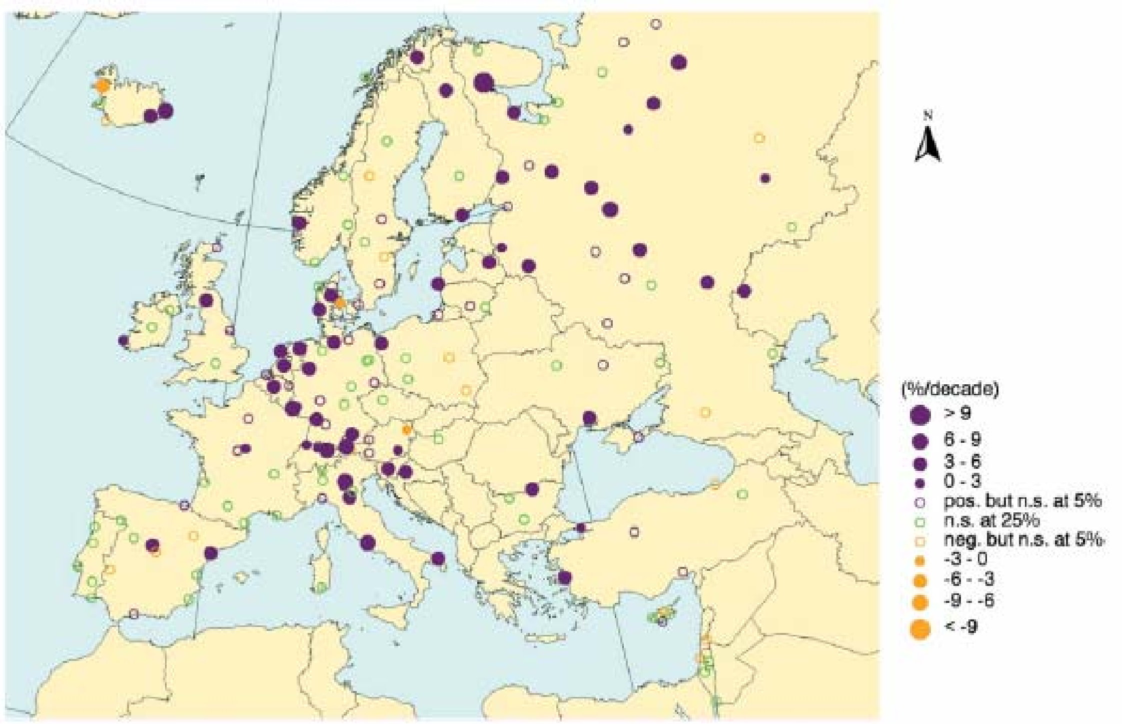


Figure 2.9: Trends in winter (October–March) mean precipitation amount per wet day between 1946 and 1999 (Klein Tank et al., 2002).

Gellens (2000) studied extreme rainfall depths in 165 stations in Belgium in order to detect a possible evolution in the occurrence of extreme rainfall events during the 1951-1995 reference periods. Spearman's rank correlation coefficients showed strong spatial correlation and the Fisher test combined with the individual Mann-Kendall showed significant trends in extreme winter rainfall and no trends were noticed in extreme summer rainfall.

Table 2.2: List of indices of precipitation extremes used in the study by Moberg et al. (2006).

Index	*Description*
PRECTOT, mm	Precipitation (PREC) total
SDII, mm	Simple daily intensity index (average precipitation per wet day, i.e., per day with precipitation > 1mm
PREC90P, mm	90th percentile of daily PREC (percentile defined on the basis of all days in a season)
PREC95P, mm	95th percentile of daily PREC
PREC98P, mm	98th percentile of daily PREC

Brunetti et al. (2001) studied the trends in the daily intensity of rainfall from the 67 sites in Italy from 1951 to 1996. The results showed that the trend for the number of wet days in the year is significantly negative throughout Italy, stronger in the north than in the south, which was mainly concentrated in the winter months. On the other hand, Cislaghi et al. (2005) found that the number and the duration of rainfall episodes are decreasing since 18th century to 2001 in Italy but the average rain rate is significantly increasing especially in northern Italy. The variation of these results is due to the difference in study period.

In the UK, Osborn et al. (2000) observed an increase in heavy wintertime rainfall events and decreases in heavy summertime events. Fowler and Kilsby (2003) analysed multi-day rainfall events in the UK, which are an important cause of severe flooding in this region in addition to increase in river flooding. They studied 1-, 2-, 5- and 10-day annual maxima for 1961-2000 from 204 sites across the UK to do a standard regional frequency analysis for long return-period rainfall events for each of nine defined climatological regions. Their results indicated that little change had occurred for 1- and 2-day annual maxima but significant decadal-level changes was found in 5- and 10-day events in many regions. In south, 5- and 10-day annual maxima have decreased during the 1990s; whereas in north the 10-day annual maxima have risen during the same period, which is already evident in Scotland and northern England where the average recurrence intervals of extreme rainfalls have reduced significantly.

Hundecha and Bardossy (2005) studied the evolution of daily extreme rainfall from 611 stations from 1958 to 2001 within the German side of the Rhine basin. The results indicated that the daily extreme heavy rainfall has shown increasing trends, both in terms of magnitude and frequency in the winter and the transition seasons while summer showed the opposite trend. Annual trends have been found to be going towards more extreme rain days and increased contribution of extreme events to the total amount of rainfall. Therefore, this may explain the frequent wintertime flooding in the Rhine basin in recent years.

Benestad and Haugen (2007) studied shifts in the frequency of complex extremes in Norway based on results from a global climate model. They stated that the general temporal trends predicted by the model were realistic. A slight shift in the joint frequency distributions for spring-time temperature and rainfall was detected in downscaled results.

Martinez et al. (2007) analysed daily amounts of rainfall from 75 rain gauges in Catalonia (NE Spain) for the period 1950-2000. Various indices have been chosen for the analysis. It's been found that complex orography of the country, effects of Mediterranean regime, and remoteness of the Iberian Peninsula to the Atlantic coast are some of the prominent factors that influence the diversity of spatial patterns of the indices. Significant negative trends were observed in the number of rainy days, positive and negative local trends were detected in daily intensity of rainfall and an increasing contribution of light and moderate daily episodes were also observed.

2.4.1.7. Changes in African Countries

Extreme rainfall trends are quite variable in South Africa (Kruger, 2006). While in the largest part of South Africa there has been no evidence of changes in rainfall over the past century, some areas are going through increase in extreme dry seasons and some are experiencing increase in extreme wet seasons and high daily rainfall amounts. While ENSO serves as an important control on rainfall variability in South Africa, a specific pattern of SSTs (Sea Surface Temperature) in the South West Indian Ocean also plays a crucial role in generating extreme conditions in this region (Nash and Endfield, 2008). In the Sahel region of Nigeria, there has been a decrease in the heaviest daily rainfall amounts coinciding with an overall decrease in annual rainfall (Tarhule and Woo, 1998).

2.4.1.8. Changes in South America

Haylock et al. (2006) examined daily rainfall observations through twelve annual indices over the period of 1960 to 2000 to determine changes in both total and extreme rainfall in southern South America. Most of these rainfall indices were also used by Moberg et al. (2006) and Klein Tank et al. (2006), as shown in Tables 2.2 and 2.3. The pattern of trends for the extremes in southern South America was generally the same as that for total annual rainfall, with a change to wetter conditions in Ecuador and northern Peru and the region of southern Brazil, Paraguay, Uruguay, and northern and central Argentina. A decreasing trend was observed for rainfall extremes in southern Peru and southern Chile, with the latter showing significant decreases in many indices.

Table 2.3: Definitions of the indices of wet precipitation extremes used in the study by Klein Tank et al. (2006) (Peterson, 2005).

Index	*Description*	*Definition*
RX1day, mm and RX5day, mm	Highest 1 and 5 day precipitation	Annual maximum precipitation sums for 1day intervals and 5day intervals
R10mm, days and R20mm, days	Heavy and very heavy precipitation days	Number of days per year with precipitation amount ≥ 10 mm and ≥ 20 mm.
R95, mm and R99, mm	Precipitation on very and extremely wet days	Precipitation amount per year above a site-specific threshold value for very and extremely wet days, calculated as the 95th and 99th percentile of the distribution of daily precipitation amounts on days with 1 mm or more precipitation in the 1961–1990 baseline period.

2.4.1.9. Changes in Canada

Groleau et al. (2007) performed a trend analysis on six indices related to winter rainfall (January–February) at 60 weather stations located in southern Québec and New

Brunswick in Canada in order to detect possible trends in the frequency or intensity of winter rainfall events during the twentieth century. Results showed that 19 stations out of 60 present a significant trend - 18 of them being positive at a 5% level for winter (January–February) total rainfall and 9 stations had increasing trends in maximum daily rainfall during January and February. It was hypothesised that the trends in winter rainfall are more likely to be observed for stations located in the southern part of the region under study.

2.4.1.10. Changes in Asian Regions

Manton et al. (2001) analysed trends in extreme daily rainfall from 1961 to 1998 from 91 stations in 15 countries in south-east Asia and the South Pacific, as shown in Figure 2.10. They found that, like global rainfall, extreme rainfall trends are generally less spatially coherent in the study region than are those for extreme temperature. In addition, their results depict that the number of rain days (with at least 2 mm of rain) has decreased significantly throughout south-east Asia and the western and central South Pacific, but increased in the north of French Polynesia and in Fiji, as shown in Figure 2.11. Furthermore, the proportion of annual rainfall from extreme events has increased at a majority of the stations under study, as shown in Figure 2.12.

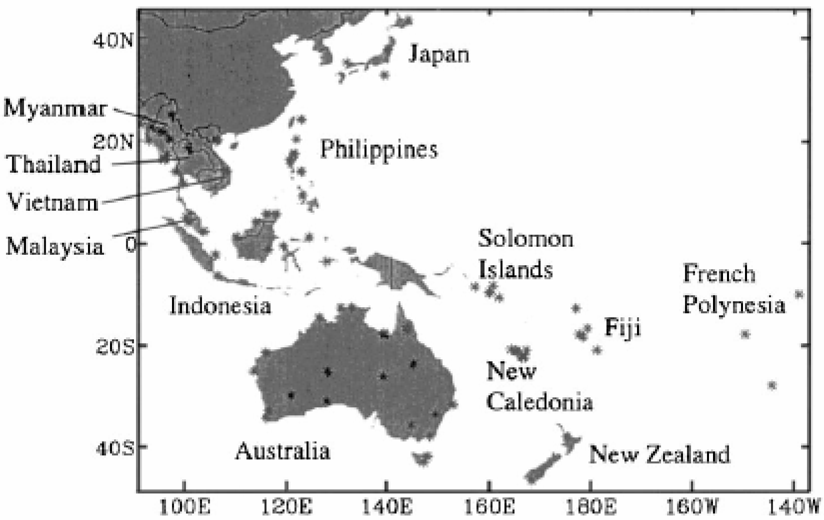


Figure 2.10: Locations of the Southeast Asian and South Pacific considered under study by Manton et al. (2001).

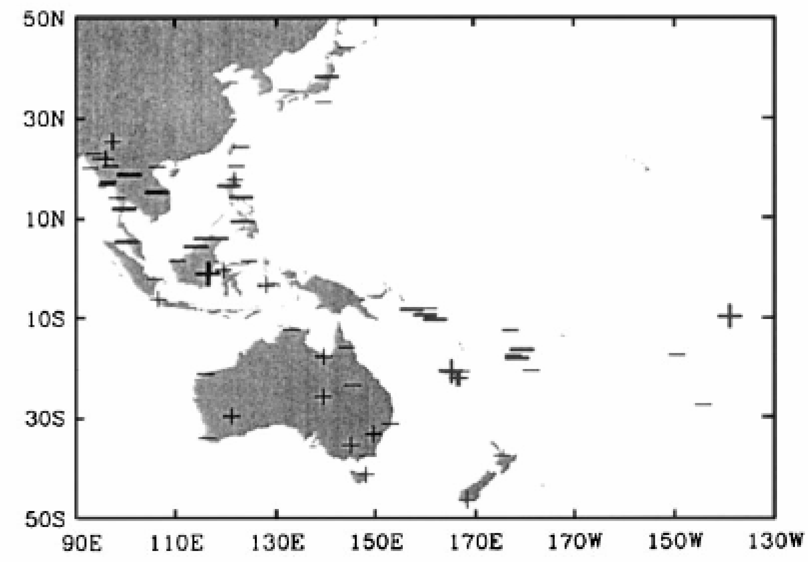


Figure 2.11: Trends in the frequency of days with at least 2 mm of rain (raindays) in the Southeast Asia and South Pacific regions using data from 1961-1998; the sign of the linear trends is indicated by +/- symbols at each site; bold indicates significant trends (95%) (Manton et al., 2001).

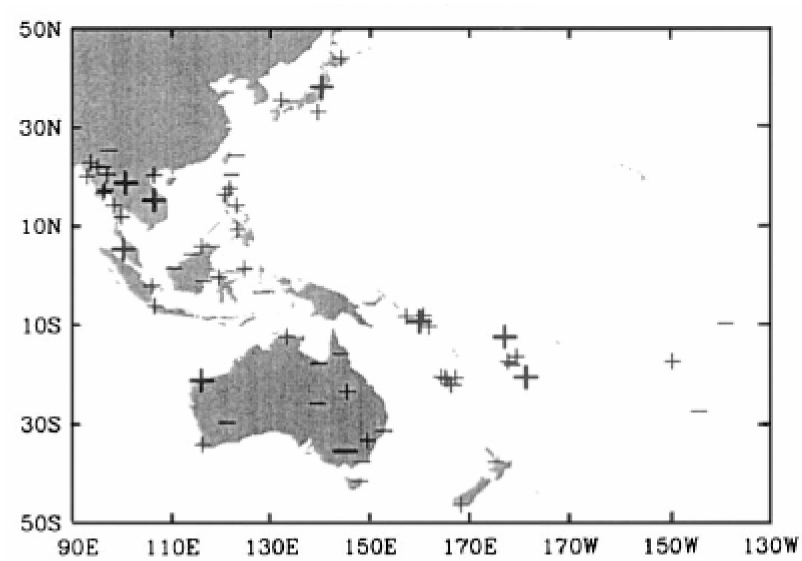


Figure 2.12: Trends in the percentage of annual total rainfall from the events greater than or equal to the 99th percentile (extreme proportion) in the Southeast Asia and South Pacific regions using data from 1961-1998; the sign of the linear trend is indicated by +/- symbols at each site; bold indicates significant trends (95%) (Manton et al., 2001).

Kanae et al. (2004) studied hourly rainfall data since 1890 to 1999 to investigate historical changes in hourly heavy rainfall in Tokyo, Japan. The results indicated that the 1940's and 1990's decades were the periods with considerably strong and frequent hourly heavy rainfall while the former was the strongest. Therefore, it couldn't be concluded that recent hourly heavy rainfall has become stronger or more frequent.

Klein Tank et al. (2006) studied changes in indices of climate extremes on the basis of daily series of rainfall observations from 116 meteorological stations in central and south Asia, as shown in Figure 2.13. This study reported the outcomes of a workshop held in Pune, India (14–19 February 2005) based on a unique daily data set for the whole region of central and south Asia. The extreme indices as used in that work are summarised in Table 2.3 and average trends per decade for the regional indices of rainfall extremes are shown in Table 2.4. Averaged over all the stations in Figure 2.13, most regional rainfall indices of wet extremes showed little change in the study period due to low spatial trend coherence with mixed positive and negative station trends, as in Table 2.4. This gave a slight indication of disproportionate changes in the rainfall extremes, as also shown in Figure 2.14, which is true for the regions in India as well. Figure 2.14 indicates that rainfall extremes have increased in northern and north-eastern India (biggest yellow dots) and decreased in western and south-western Indian regions (biggest green dots) in 1961-2000 (Klein Tank et al., 2006).

Figure 2.13: Stations used for central and south Asia in the study by Klein Tank et al. (2006) for precipitation with data spanning the period 1961-2000 (dots) or 1901-2000 (dots with crosses).

Table 2.4: Trends per decade (with 95% confidence intervals in parentheses) for the regional indices of precipitation extremes (Klein Tank et al., 2006).

Index (units per decade)	*1961-2000*	*1901-2000*
RX1day (mm)	1.02 (-0.20 - 2.24)	0.46 (-0.18 - 1.10)
RX5day (mm)	1.26 (-0.76 - 3.28)	0.97 (-0.21 - 2.15)
R10mm (days)	0.11 (-0.23 - 0.45)	0.08 (-0.10 - 0.26)
R20mm (days)	0.10 (-0.12 - 0.32)	0.08 (-0.04 - 0.20)
R95 (mm)	**6.46** (0.72 - 12.20)	2.85 (-0.59 - 6.29)
R99 (mm)	3.01 (-0.19 - 6.21)	0.43 (-1.75 - 2.61)
RR (mm)	6.87 (-8.41 - 22.15)	**7.81** (0.37 - 15.25)
R95/RR (%)	**0.55** (0.11 - 0.99)	0.11 (-0.21 - 0.43)
R99/RR (%)	0.28 (-0.08 - 0.64)	-0.01 (-0.25 - 0.23)

Note: Values for trends significant at the 95% level (t test) are set bold face.

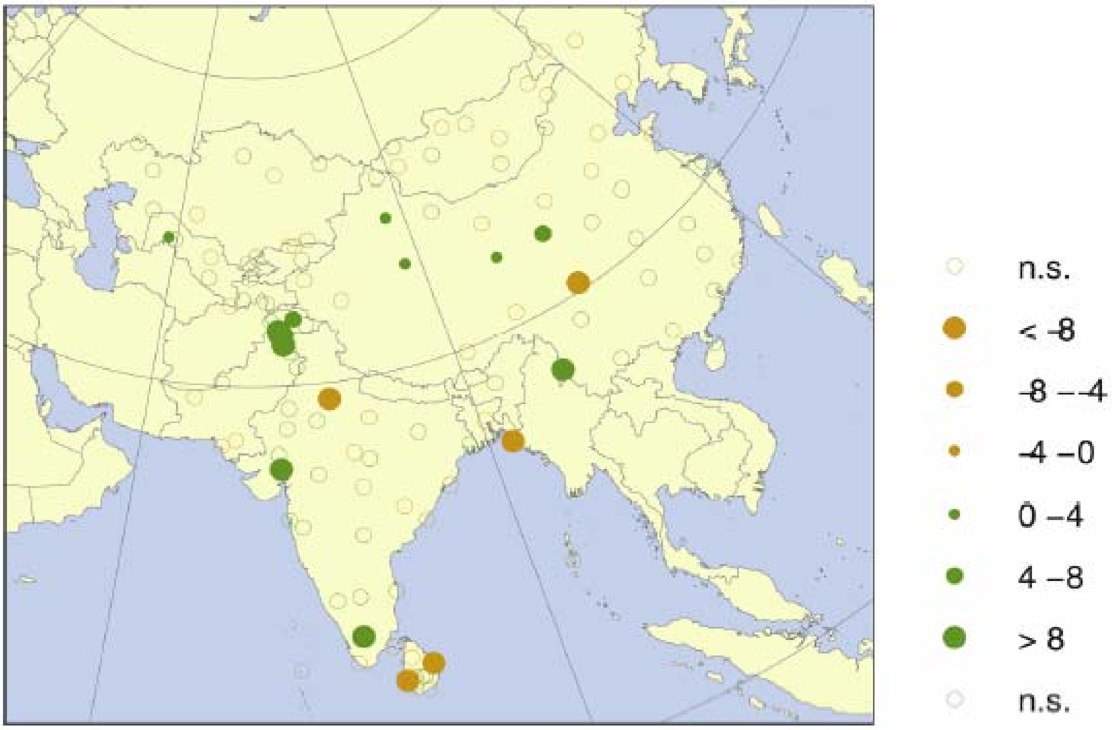


Figure 2.14: Trends per decade for the annual maximum of 5-day precipitation amounts for the period 1961–2000 for central and south Asian region; the dots are scaled according to the magnitude of the trend, green corresponds to increasing trends and yellow corresponds to drying trends (Klein Tank et al., 2006).

Wang et al. (2008) investigated changes in extreme rainfall and stream flow processes in the Dongjiang river basin in southern China using several nonparametric methods. They have shown that significant changes are found in the rainfall processes on a monthly basis indicating that when detecting climate changes, besides annual indices, seasonal variations in extreme events are also important.

2.4.1.11. Summary of Changes

Therefore, it could be concluded that a significant proportion of the global land area has been increasingly affected by a significant change in climatic extremes during the second half of the 20th century. Although model studies have found an increase in extreme rainfall events over the globe, regional studies showed different results. For example, much of Australia (except a few stations in south-west), Norway (west), the US, Swiss Alps, part of India (west and south-west), Ecuador, northern Peru, southern Brazil, Paraguay, Uruguay, northern and central Argentina, north of French Polynesia and Fiji have experienced increases in heavy rainfall events in all parts of the year. Winter rainfall increased in Canada, Europe (north of 40°N) and especially in the northern part of the UK and German side of the Rhine basin. Annual extremes were found decreasing in some parts of Norway (north and east), Southeast Asia and the western and central south Pacific (including north and north-east India), Italy, Spain, Sahel region of Nigeria, southern Peru and southern Chile.

2.4.2. Tendencies of Seasonal Rainfall Extremes in India and Particularly in Kerala

Temporal changes in discrete random extreme events are becoming important in climate change scenario studies because of their socio-economic impacts. The risk of extreme events is difficult to predict but their impacts could be severe. To outline the change in rainfall extremes in a certain region, it is necessary to look at the historical trends of statistical properties of seasonal rainfall extremes.

Losses due to extreme events are increasing steeply in India and especially in the current and recent decades (90s and 00s). Flash flooding that is primarily caused by short-duration, highly intensive rainfall events at the local level, is one of several types of flooding that are likely to be affected strongly by climate change. At the same time emerging shortfall in monsoon rainfall as severe as the unusually dry July of 2002 is a matter of concern (Panda et al., 2007). Rakhecha and Soman (1993) studied annual extreme rainfall series in the time scale of 1 to 3 days duration at 316 stations, well distributed over Indian region, covering 80-years of rainfall data from 1901 to 1980. They reported a significant increase in extreme rainfall series at stations over the North West coast and at some stations to the east of the Western Ghats over the central parts of the peninsula. Stations over the southern peninsula and over the lower Ganga valley have been found to exhibit a decreasing trend at the same level of significance (95%). These findings are also consistent with the results in Figure 2.14.

Sen Roy and Balling (2004) assembled daily rainfall records for 3838 stations in India and identified 129 stations randomly to uniformly distributed across the country with reasonably complete records from 1910 to 2000. They created annual time series of seven different indices of extreme rainfall events, including total rainfall, largest 1, 5, and 30 day totals, and the number of daily events above the amount that marks the 90^{th}, 95^{th}, and 97.5^{th} percentiles of all rainfall at each station. Their studies revealed an increase in frequency of extreme rainfall events over the period 1910 to 2000, which is strongest in an area extending from the north-western Himalayas in Kashmir through most of the Deccan Plateau in the southern peninsular region of India; whereas, decrease in those events were found in the eastern part of the Gangetic Plain and parts of Uttaranchal. The increasing trend of mean 'extreme frequency (90^{th} percentile)' variable for 129 stations is shown in Figure 2.15. Wherein, Figure 2.16 shows a map of standardized regression coefficients (defined in section 2.3.2) showing trends in the largest 5-day rainfall total throughout India. Extreme events have also been reported increasing in the monsoon season over central India (Goswami et al., 2006).

Kerala, the south western Indian state, is a very important region for India since a large part of India's agro-economy is concentrated there. This state is facing an increasing number of flash floods in monsoon seasons in addition to extended number of dry spells, as was discussed in section 2.3.5; and, as a consequence, huge financial and social losses (De et al., 2005). Rare events are making the headlines by reports of natural hazards in various areas in Kerala every year. The inter-annual variations of seasonal rainfall could be driven by the changes in heavy rainfall events, as mentioned before. Historical records show that no statistically significant monotonic trend exists in Kerala rainfall over the record 1871-2005 but strong trends have been identified since 1954 (discussed in next chapter).

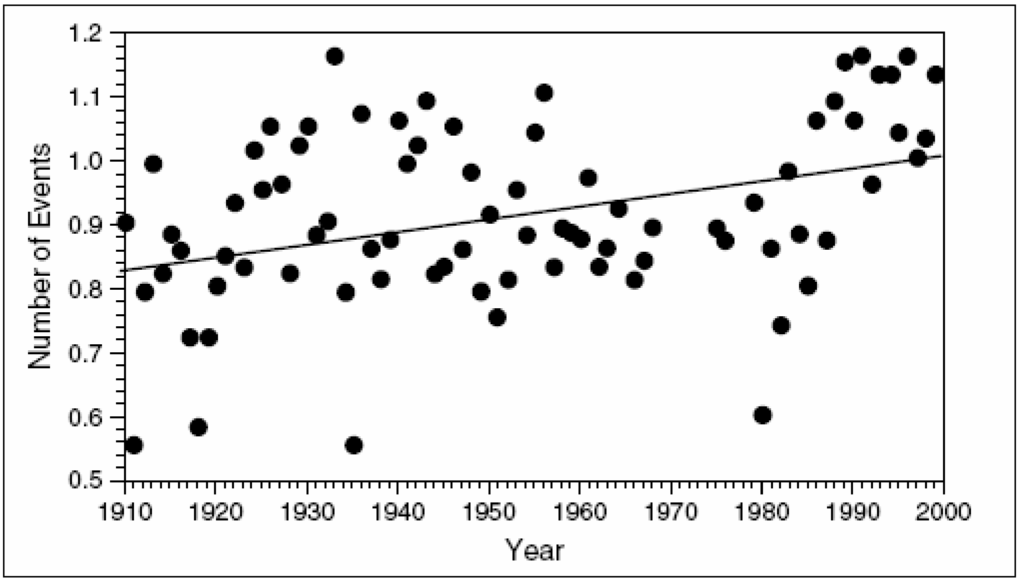


Figure 2.15: Plot of mean 'extreme frequency (90th percentile)' variable for 129 stations (upward trend is significant at 99%) (Sen Roy and Balling, 2004).

Although Kerala is one of the highest monsoon rainfall regions in India, along with the north-eastern Indian states, and receives the first monsoon showers every year, significant amount of rainfall in the other seasons is also important from an agricultural point of view. Assessment of other seasonal extreme rainfall changes in Indian regions is scarce in the literature. Only the recent work by Revadekar and Kulkarni (2008) on winter monsoon extremes and their relation with ENSO in south-east peninsular India in the months of October-December provides some information. However, they did not consider other important seasons such as spring (Mar-May) and autumn (Oct-Nov) in their study. The changes in short-duration extreme events do also have the potential to indicate long-term seasonal and annual climatic changes (Easterling et al., 2000). Increasing off-monsoon seasonal floods and thunderstorms in some parts of Kerala, and also in the neighbouring state of Karnataka in peninsular India (De et al., 2005), make it also important to look at the change in extreme rainfalls in the other seasons in addition to monsoon.

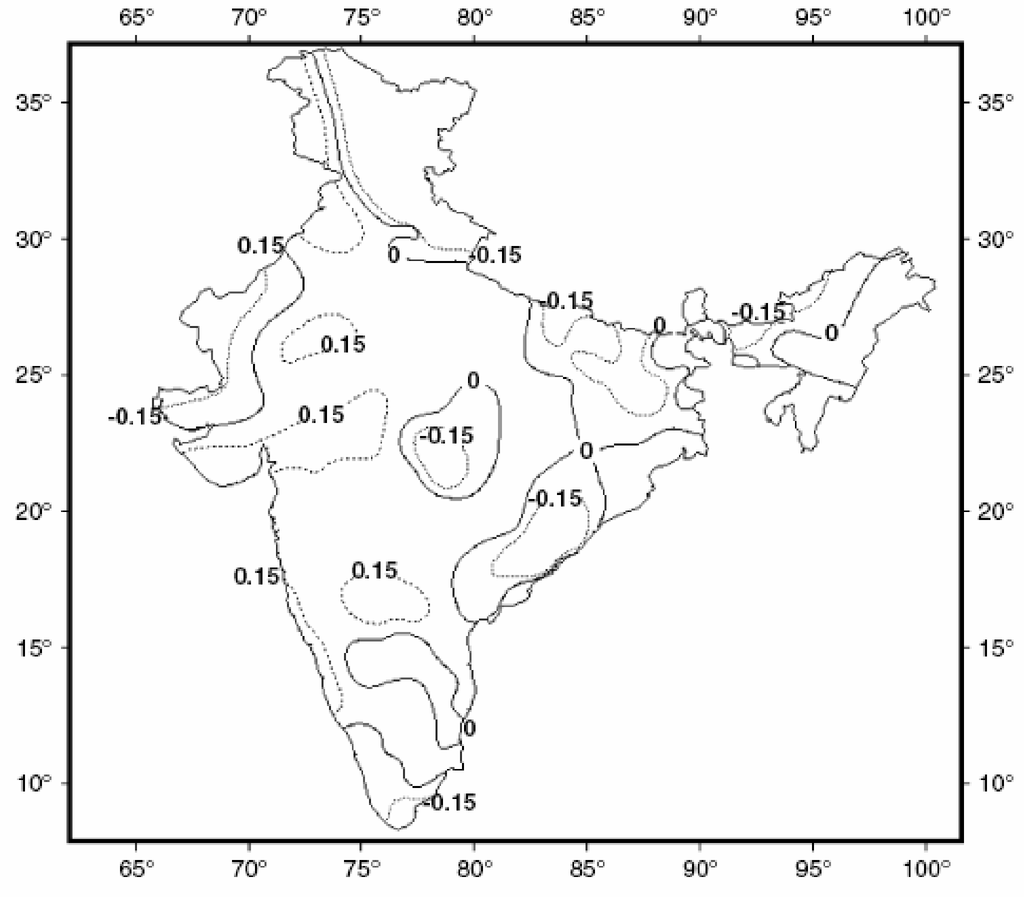


Figure 2.16: Map of standardised regression coefficients showing trends in the largest 5-day precipitation total throughout India (Sen Roy and Balling, 2004).

2.5. Changes/Patterns of Extreme Temperatures in India and Worldwide

Global temperatures are already a few degrees higher than they were in the previous century and it is accepted that the global climate is likely to change in the 21st century, particularly if no mitigation is undertaken to control green house gas emissions (IPCC, 2007). Temperature changes, together with changes in rainfall, are likely to exacerbate the pressure put on water resources, ecosystems and crop yields by the increasing population and increased drought years in various subcontinents. On the basis of the recent IPCC Fourth Assessment Report (2007), eleven of the last twelve years rank amongst the twelve warmest years in the globe since 1850. The last 100-year (1906-2005) linear trend is 0.74°C, which is higher than the corresponding trend in 1901-2000 given in the Third Assessment Report (Bernstein et al., 2007).

Land regions have warmed faster than the oceans. There are also strong human influences, for example irrigation and agricultural impacts, along with land use change, cloud cover and aerosol feedbacks on regional climates (Sen Roy et al., 2007; Sen Roy and Balling, 2005). Moreover, detailed impact assessments require information on changes in climatic variability at a regional and national scale, and the analysis of not only mean changes but also trends in variability of climatic parameters, since variability is also an important part of climate change (Hasanean and Abdel Basset, 2006).

Based on global daily maximum and minimum temperature series during the second half of the 20th century, Frich et al. (2002) found coherent spatial patterns of statistically significant changes, particularly an increase in warm summer nights, a decrease in the number of frost days and a decrease in intra-annual extreme temperature range, which is also consistent with a relatively new study by Brown et al. (2008) based on observed temperature data since 1950. Model projection results also observed the similar results at global scale (Sillmann and Roeckner, 2008; Tebaldi et al., 2006). However, region-wise the results were different, as follows.

Easterling et al. (2000) presented the summary of analyses of temperature extremes around the world, which is shown in Table 2.5. The table shows that warm maximum temperatures have gone up in Australia and New Zealand while down in China and no trend was found in the US. On the other hand, warm minimum temperatures have increased both in China and United States. Based on modelling experiments of future climate change in California State, US, Bell et al. (2004) revealed that daily minimum and maximum temperatures will increase significantly in this region with a doubling of atmospheric carbon dioxide concentration, which will very likely lead to increases in prolonged heat waves and length of the growing season. Salinger and Griffiths (2001) examined various indices of daily extreme temperatures for 1951-1998 to describe significant trends in temperature in New Zealand. They also studied the data for the period of 1930-1998 to ascertain the effects of two main circulation changes that have occurred in this region around 1950 and 1976. It was found that there were no significant trends in maximum temperature extremes (‘hot days’) but a significant increase in minimum temperatures was associated with decreases in the frequency of extreme ‘cold nights’ over the 48-year period. Their results corresponding to maximum temperatures do not agree with Table 2.5 possibly because of the difference in period of analysis.

Table 2.5: Summary of analyses of temperature extremes around the world (Easterling et al., 2000).

Country	***Frost days***	***Warm minimum temperatures***	***Warm maximum temperatures***	***Cold waves***	***Heat waves***
Australia	Fewer		Up		
China	Fewer	Up	Down	Fewer	
Central Europe	Fewer				
Northern Europe	Fewer				
New Zealand	Fewer		Up		
United States	Fewer	Up	No trend	No trend	No trend

Klein Tank and Konnen (2003) studied trends in indices of temperature extremes on the basis of daily series of temperature observations from more than 100 meteorological stations in Europe for a period of 1946-99. They reported a ‘symmetric’ warming of the cold and warm tails of the distributions of European daily minimum and maximum temperatures in this period. In addition, interestingly, an ‘asymmetry’ was noticed in the results when the study period was divided into two sub-periods. For the 1946-75, an episode of slight cooling was noticed because of decrease in annual number of warm extremes. Whereas, for the 1976–99, an episode of pronounced warming i.e. an increase in annual number of warm extremes was noticed, which was two times faster than that expected from the corresponding decrease in the number of cold extremes in the previous sub-period. This implied an increase in temperature variability in 1976-1999, which, according to Klein Tank and Konnen (2003) was mainly due to stagnation in the warming of the cold extremes. Kadioglu (1997) also found a warming trend in mean annual temperature in Turkey over 1939-1989, but a cooling trend from 1955-1989. Hundecha and Bardossy (2005) studied the evolution of daily extreme temperature from 232 temperature stations in 1958-2001 within the German side of the Rhine basin based on certain indices. They found that both the daily minimum and maximum extreme temperatures have increased over the period of investigation with the degree of change showing seasonal variability, which is consistent with previous findings (Klein Tank and Konnen, 2003). Moberg et al. (2006) studied century-long (1901-2000) daily temperature records only for stations in Western Europe (west of 60°E). They found that average trends for 75 stations, which mostly represented Europe west of 20°E, had showed a warming trend in daily temperature extremes while winter warmed more than summer, both in terms of daily maximum and minimum temperatures. Parey et al. (2007) studied observations of high temperatures over 1950-2003 in 47 stations in France. They found a soft periodic oscillation in high temperatures with duration of 20 to 40 years for long observation, and a clear increasing trend and variability during the last decades of the 20th century. Like France and Germany, minimum and maximum temperatures and extreme temperature events have also been found increasing in Italy as well (Bartolini et al., 2008; Toreti and Desiato, 2008).

Kruger and Shongwe (2004) studied 26 station data in South Africa for temporal and spatial trends in temperature for the period of 1960-2003. Majority of the stations exhibited an increase in both annual mean maximum and minimum temperatures while trends in mean maximum were higher in central stations than at coast. Domroes and El-Tantawi (2005) analysed six observed station data for the period 1941-2000 (60 years) and nine station data for the period 1971-2000 (30 years) in order to detect and estimate trends of temperature change in Egypt. They found that mean annual temperature in northern Egypt is decreasing, while that in southern Egypt is increasing. However, seasonally, positive trends prevailed in summer compared with negative trends in winter. Such changes in Egypt could be attributed to not only to human activities but also to atmospheric circulation (Hasanean and Abdel Basset, 2006). Samba et al. (2008) found an irregular variation in temperature over Congo-Brazzaville, central Africa between 1950 and 1998.

Klein Tank et al. (2006) studied changes in indices of climate extremes on the basis of daily series of temperature observations from 116 meteorological stations in central and south Asia. They revealed that the indices of temperature extremes indicated the warming of both the cold tail and the warm tail of the distributions of daily minimum and maximum temperature between 1961 and 2000. While studying the stations with near-complete data for the longer period of 1901-2000, they found that the recent trends in extremes of minimum temperature are consistent with long-term trends but the recent trends in extreme maximum temperatures are part of multi-decadal climate variability. Griffiths et al. (2005) also observed the increases in mean maximum and mean minimum temperature, decreases in cold nights and cool days, and increases in warm nights in Asia-Pacific regions, which is similar to findings by Manton et al. (2001) for south-east Asia and south Pacific. Temperature during the last several decades has also showed a long-term warmer trend in Tibetan Plateau, especially the areas around Dingri and Zogong stations (Xu et al., 2008).

Some studies in India have been carried out on the changes in temperature and their association with climate change, some of which are mentioned in section 2.2.3. Such studies are very important for the Indian agriculture and food security as well (Mall et al., 2006). An overview of spatial and temporal changes of seasonal and annual temperature in India was conducted by Kothawale and Rupa Kumar (2005) who reported substantial recent changes in the nature of trends in surface temperature over a network of 121 stations in India, as also discussed in section 2.2.3. They identified regional patterns of temperature variation within country by constructing annual and four seasonal (winter, pre-monsoon, monsoon and post-monsoon) temperature series for all-India and seven homogeneous regions in Figure 2.5. They quantified the trends by the slope of a simple linear regression line fitted to each of the time series and found a substantial acceleration of the warming trend in the recent period (1971-2003) due to significant warming in both maximum and minimum temperatures. Some studies were also carried out for the individual areas in India and for various time scales.

For example, Bhutiyani et al. (2007) studied long-term trends in maximum, minimum and mean annual air temperatures across the north-western Himalaya during the twentieth century. Their study revealed a significant rise in air temperature in that region, with winters warming at a faster rate. Also, the diurnal temperature range has shown a significantly increasing trend due to increase in both the maximum and minimum temperatures, with the maximum increasing more rapidly. They also found that the real warming started in 1960s, as Kothyari and Singh, (1996) also found for Ganga basin and Shrestha et al. (1999) for Himalayan region in Nepal. Sen Roy and Balling (2005), on the other hand, assembled data at a 1°latitude×1°longitude resolution for 285 cells across India and analyzed the seasonal trends in the maximum and minimum temperature, and diurnal temperature range (DTR). They revealed that maximum and minimum temperatures have increased significantly over the Deccan Plateau, but trends in DTR were not significant except for a decrease in northwest Kashmir in summer. It is not sure whether Bhutiyani et al. (2007)'s study included north-west Kashmir as well since their results didn't match with Sen Roy and Balling (2005). Fowler and Archer (2006) analysed extreme temperature data for the upper Indus basin for the period of 1961-2000. They found that winter mean and maximum temperature had showed significant increases while summer mean and minimum temperatures had consistent decline.

Rupa Kumar et al. (1994) showed that the countrywide mean maximum temperature has risen by 0.6°C. Arora et al. (2005) investigated 125 station data distributed over the whole of India from 1941-1999 to identify monotonic trends in annual average temperature, annual average maximum temperature, annual average minimum temperature and average seasonal temperatures using non-parametric Mann-Kendall (MK) statistical test for every individual station. They found that there is a rising trend in most cases, except for mean pre-monsoon temperature, mean monsoon temperature, pre-monsoon mean minimum temperature and monsoon mean minimum temperature. The south India and west Indian stations showed rise in mean regional temperature but north Indian stations showed a fall in the same.

Although these studies and those reported in section 2.2.3 presented a clear picture of an all-India and region specific analyses, a detailed monthly trends and their impacts on seasonal variations are also important in order to find out whether monthly maximum and minimum temperatures are changing in a particular way. Month-wise studies have already been initiated at different places of the world. For example, intra-annual variability of monthly mean temperatures for the northern hemisphere during the 20th century was reported by Evtimov and Ivanov (2007) while Bartolini et al. (2008) recommended month-wise index trend studies of optimum temperatures for Italy, and Baldi et al. (2006) showed that increasing summer temperature is mainly due to June and August increase in temperature in the Mediterranean region. Since advective processes exerted by atmospheric circulation is also an important factor for the monthly temperature anomalies at regional basis (Hasanean and Abdel Basset, 2006), a month-wise analysis is also vital for India. Furthermore, monthly information could also be used as the predictor of variance of monsoon rainfall; as for example, March and May monthly minimum temperatures were found useful as monsoon predictors in India (Krishna Kumar et al., 1997). Also, a short-term, for example monthly, changes in extreme temperature would be important for inferring how that might affect thermal comforting levels and energy (Holmes and Hacker, 2007).

2.6. Methodologies Used for Detecting Trends

2.6.1. Overview

The purpose of a trend analysis/test is also to determine if the values of a series having a general increase or decrease with increasing time. Confirmatory method of data analysis confirms the presence of suspected trends, presents unknown trends and assesses the detected trends. Several methods of estimating linear trends and their significance have been used in climatological studies. Linear trends in indices for climate variables and extremes have previously been investigated for various regions, as discussed in the previous sections.

In applications of statistics to climatology for analysing trends, both parametric and nonparametric methods are vastly used. However, each statistical test is designed for specific purposes with different assumptions in sampling distribution. Parametric trend tests are regarded to be more powerful than the non-parametric ones when the data is normally distributed, independent and has homogeneous variance (Hamed and Rao, 1998). Also, a parametric method leads to fewer 'type II' errors in hypothesis testing. Probably the most common parametric approach to estimate the trend magnitude is by the Ordinary Least Squares (OLS) linear regression, and the significance being assessed by the t-test. The OLS method is widely used in almost every field, from economics, engineering, physics and climatological applications. OLS method checks only for a linear trend. The main advantage of this method is its simplicity.

The correct application of OLS method requires the variables to be normally distributed and temporally and spatially independent. However, this method has been applied to assessing significance of linear trends for a wide range of variables, frequently without discussing the normality of their distributions and/or their temporal and spatial independence (Huth, 1999). The other main disadvantage of the OLS method is that it can not reject outliers properly (Wilcox, 1998). Also, the impact of time-dependent missing data may bias the parametric rainfall trends if assumed to be zero or at the daily average for the month. Non-parametric Mann-Kendall (MK) method on the other hand is a distribution-free method, more resistant to outliers, can usually be used with gross data errors, and can deal with the missing data values unlike the parametric method (Wilcox, 1998). Mann-Kendall method has widely been used in environmental monitoring for its simplicity and the focus on pair-wise slopes (Gibbons and Coleman, 2001), as also discussed in section 2.6.3. However, non-parametric methods are fraught with more uncertainty in the statistical estimates than the parametric method (Alexander et al., 2006).

Although different methods for trend estimation and significance testing are in use, there is no universally accepted best technique (Moberg et al., 2006). Therefore, considering the advantages and disadvantages, linear trends were estimated using both the methods (OLS and MK), wherever necessary, at each study location for the study period and compared the results. A comparison of parametric and non-parametric methods could also be found in Moberg and Jones (2005), Cohn and Lins (2005) and Huth and Pokorna (2004), for data from Prague and Europe. All of these studies concluded that the trend magnitudes can often be determined by little uncertainty while dealing with different combinations of parametric and non-parametric techniques. The 5% level is chosen to determine if a trend is significantly different from zero.

2.6.2. Parametric OLS Method

Microsoft Excel statistical tool box was utilised to determine linear trends by OLS method. The tool box uses ordinary least-squares trend fitting simply followed by significance assessments based on the standard Student's t-test. Similar methodology was also used in climatological trend estimations in India by Guhathakurta and Rajeevan (2008), Revadekar and Kulkarni, (2008), Singh et al. (2008), Ramesh and Goswami, (2007), Bhutiyani et al. (2007), Goswami et al. (2006), Kothawale and Rupa Kumar (2005), Sen Roy and Balling (2004), Naidu et al. (1999); and world-wide by Moberg et al. (2006), Klein Tank et al. (2006), Moberg and Jones (2005), Osborn et al. (2000), Haylock and Nicholls (2000), and Shrestha et al. (1999).

2.6.3. Non-Parametric Mann-Kendall Method

The Mann-Kendall test is the rank based nonparametric test and is applicable to the detection of a monotonic trend in a time series with no seasonal or other cycle, as described in Kundzewicz and Robson (2004). The test is based on the statistic S_t, which is calculated using the formula –

$$S_t = \sum_{a=1}^{N-1} \sum_{b=a+1}^{N} \mathrm{sgn}(x_b - x_a) \qquad \text{...(2.1)}$$

$$\mathrm{sgn}(x_b - x_a) = \begin{cases} +1 & \text{if } x_b - x_a > 0 \\ 0 & \text{if } x_b - x_a = 0 \\ -1 & \text{if } x_b - x_a < 0 \end{cases} \qquad \text{...(2.2)}$$

where, N is the number of observed data series, x_b and x_a are the values in periods 'a' and 'b' respectively, b > a. For N ≥ 10, the sampling distribution of S_t is as follows. Z follows the standard normal distribution where,

$$Z = \begin{Bmatrix} \dfrac{S_t - 1}{\sqrt{VAR(S_t)}} & \text{if } S_t > 0 \\ 0 & \text{if } S_t = 0 \\ \dfrac{S_t + 1}{\sqrt{VAR(S_t)}} & \text{if } S_t < 0 \end{Bmatrix} \quad \text{(2.3)}$$

$VAR(S_t)$ is determined as,

$$VAR(S_t) = \frac{1}{18}\left[N(N-1)(2N+5) - \sum_{p=1}^{q} t_p (t_p - 1)(2t_p + 5) \right] \quad \text{(2.4)}$$

where q is the number of tied groups and t_p is the number of data values in the p^{th} group. If $|Z| > Z_{1-\alpha/2}$, null hypothesis is rejected and a significant trend exists in the time series. $Z_{1-\alpha/2}$ is the critical value of Z from the Standard Normal Table, for 95% confidence the value of $Z_{1-\alpha/2}$ is 1.96. A positive value of Z indicates an upward trend and a negative value of Z indicates a downward trend.

MK test was used by various researchers around the world. For example – in India by Basistha et al. (2009), Arora et al. (2005), Kothyari and Singh (1996), and Soman et al. (1988), in China by Wang et al. (2008) and Luo et al. (2008), in Tibetan Plateau by Xu et al. (2008), in New Zealand by Salinger and Griffiths (2001) and Griffiths et al. (2005), in Japan by Yue and Hashino (2003), in Germany by Hundecha and Bardossy (2005), in Turkey by Partal and Kucuk (2006) and Kadioglu (1997), in Canada by Groleau et al. (2007), in Hungary by Domonkos (2003), in Britain by Dixon et al. (2006), in Congo-Brazzaville by Samba et al. (2008), in Spain by Martinez et al. (2007) and Mosmann et al. (2004), in Belgium by Gellens (2000), in Italy by Toreti and Desiato (2008), Bartolini et al. (2008), Cislaghi et al. (2005), and Brunetti et al. (2001), and in Egypt by Domroes and El-Tantawi. (2005).

CHAPTER 3

RESULTS AND DISCUSSION

Assessing Climatic Patterns in India

Chapter 3 mainly focuses on presenting the analyses carried out on Indian rainfall data to assess the changes in extreme monsoon climate at various regions in India, the pattern of daily extreme rainfall events in gridded regions of Kerala, and the changes in seasonal and annual rainfall totals in India. The 50-year trends of seasonal and annual rainfalls in various Indian regions were also projected for the next 50 years and illustrated in this chapter. Changes in monthly extreme temperatures at various Indian regions are also discussed here.

3.1. Regional Changes in Extreme Monsoon Rainfall Deficit and Excess in India

Unlike extreme rainfall excess that can result from small scale features such as individual thunderstorm systems, extreme rainfall deficits result from persistence, large scale and organised features of weather and climate which act to suppress rain producing systems that may be expected to occur in monsoon season in Indian region. A study of the behaviour of departures of monsoon rainfall from long-period temporal means and local-scale spatial means is therefore necessary and informative for the regional water resource developments. In view of that, this part of the study examines the trend of frequency and magnitude of extreme monsoon rainfall deficit and excess from 1871 to 2005 (data described earlier in section 2.2.2) for various Indian regions, the regions in Figure 2.4. The 135-year (1871-2005) monthly rainfall data for the whole of India (ALLIN) and all individual regions in India under study are presented in Figure

3.1. It is noted in Figure 3.1 that the North East Indian region (NEIN) receives maximum amount of rainfall, which is followed by the West Central India (WCIN) and Central North East India (CNEIN).

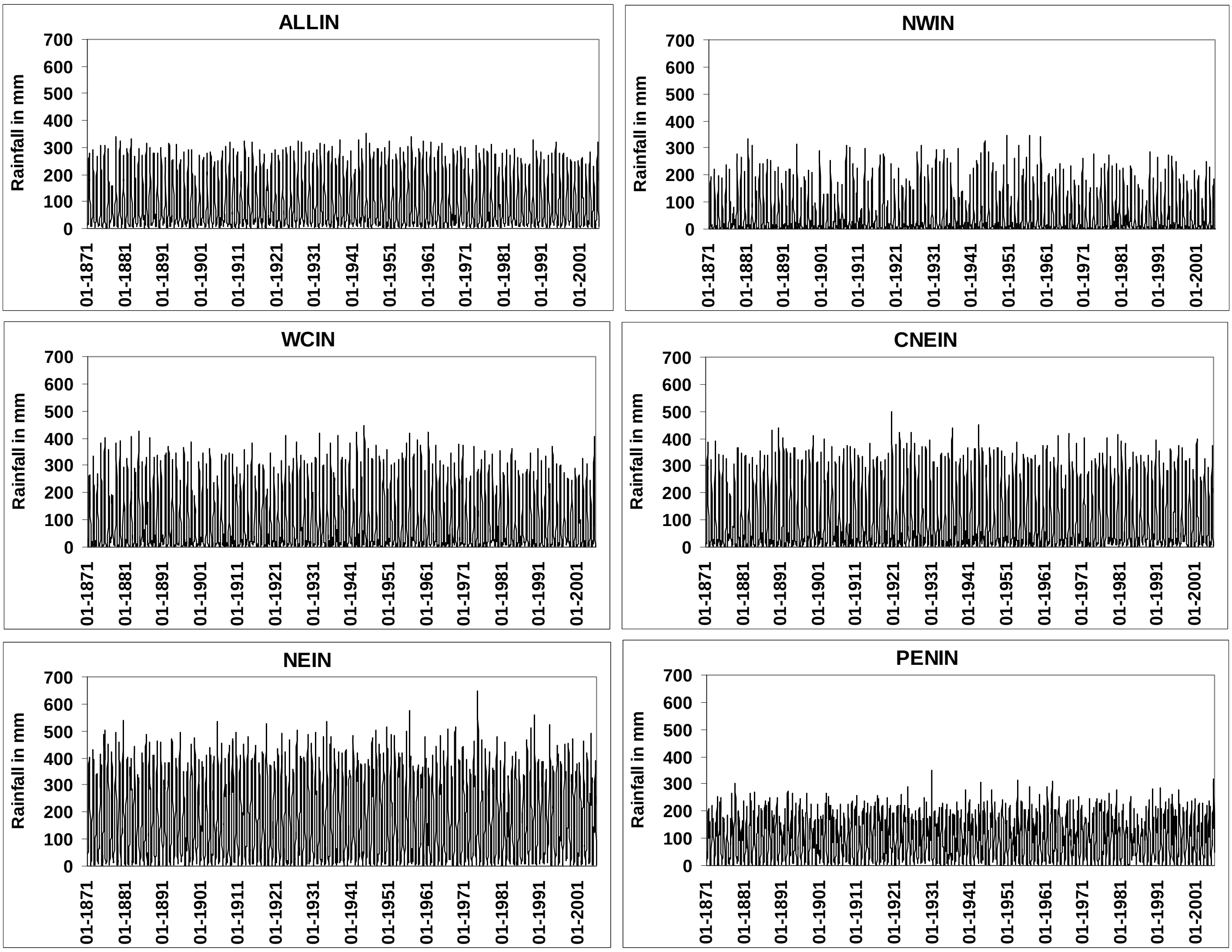
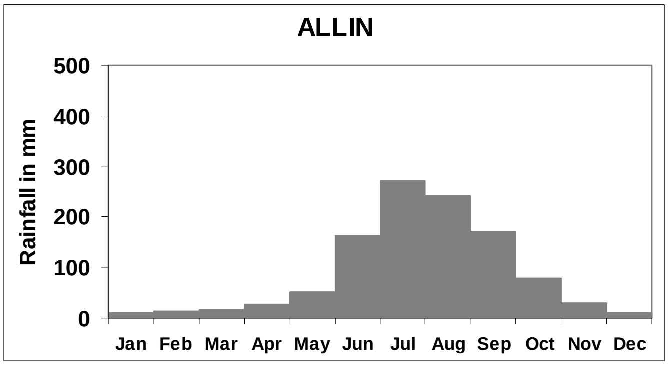


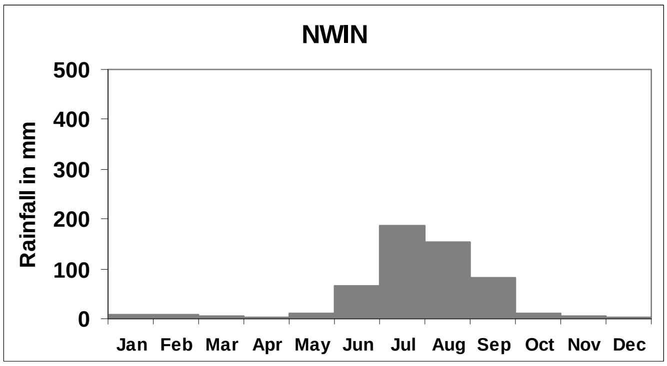
Figure 3.1: The 135-year (1871-2005) monthly time series of rainfall for various regions in India considered of all-India (ALLIN), north-west India (NWIN), west-central India (WCIN), central-north-east India (CNEIN), north-east India (NEIN) and peninsular India (PENIN).

The study regions were determined to be distinct with respect to the interannual variability of rainfall. The seasonal cycle of rainfall in each region is shown in Figure 3.2. The cycles are significantly different, suggesting different mechanisms of variability. The study in this section considers only the south west monsoon rainfall i.e.

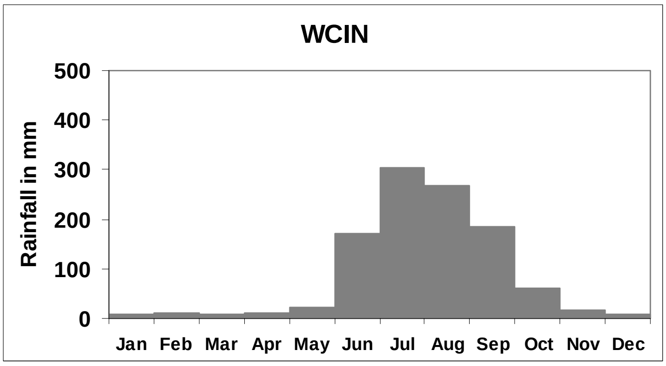
the accumulated rainfall from June to September that contributes to 70-90% of annual rainfall in India.



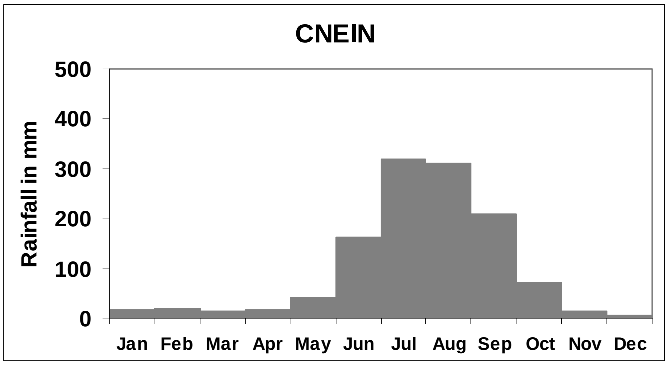
(a)



(b)



(c)



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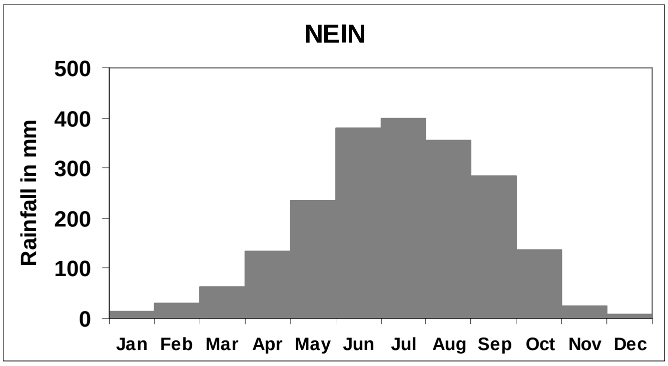
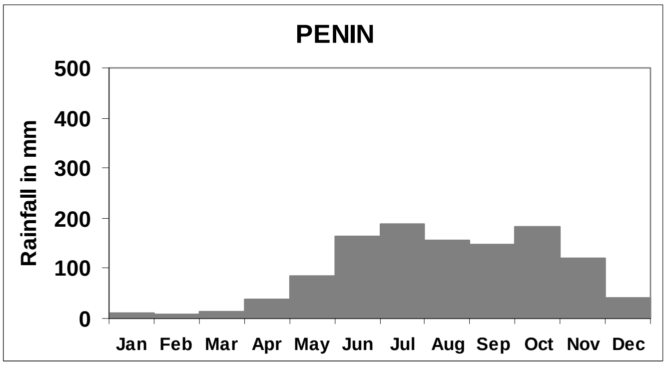


(e)



(f)

Figure 3.2: The seasonal cycle of rainfalls in various study regions in India considered of (a) ALLIN, (b) NWIN, (c) WCIN, (d) CNEIN, (e) NEIN and (f) PENIN.

The trends of climatological variables suggest the tendency of change in spite of intermittent fluctuations. So, long-term trends and their significances were assessed for monsoon excess and deficits over the study period, which would provide an idea of the changing pattern of the same. Extreme monsoon rainfall deficit and excess were based on 135 year (1871-2005) quartiles. Monsoon rainfall which was less than the long-term (135 years) lower quartile was regarded as ‘deficit’ and the same above long-term upper quartile was regarded as ‘excess’. Figure 3.3 shows variation of upper and lower quartiles of monsoon rainfall in different regions in India and including an all-India average. Figure 3.3 depicts a great difference in upper and lower quartiles while WCIN was found to be having the greatest inter quartile range. All the trends and their significances were determined using non-parametric Mann-Kendall (MK) technique (presented earlier in section 2.6.3).

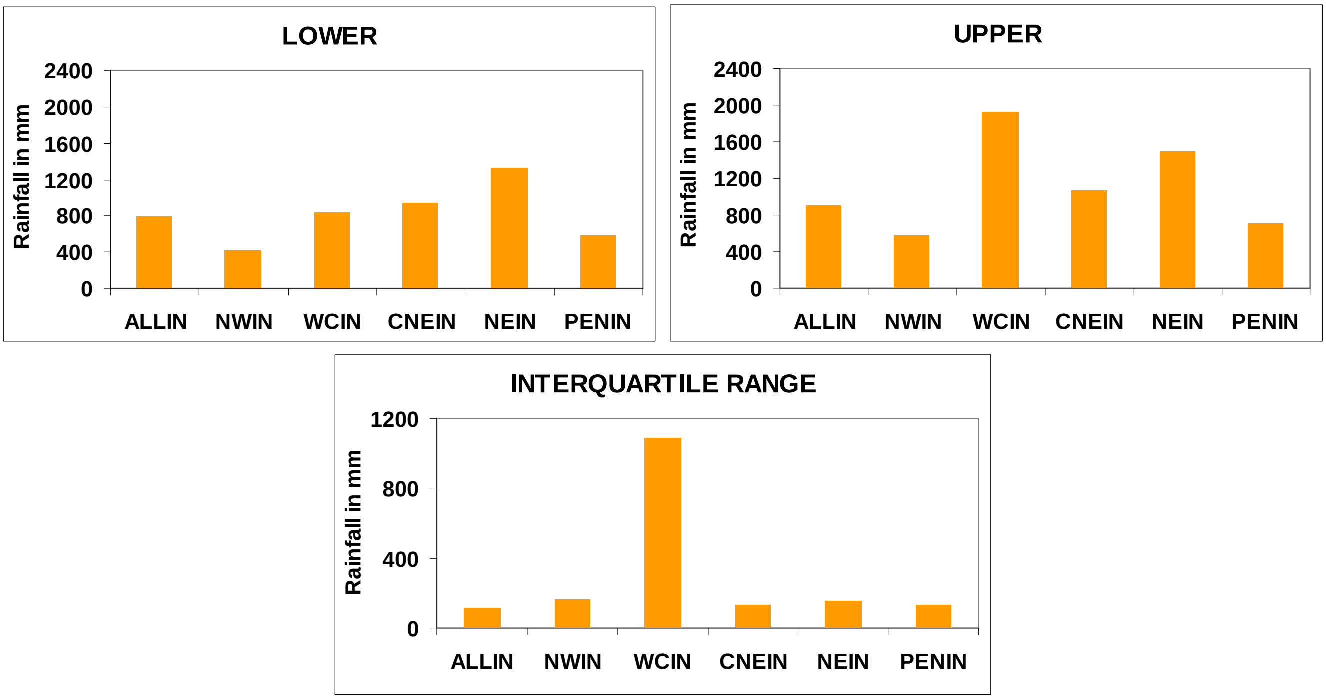


Figure 3.3: Lower and upper quartiles and inter-quartile differences of 135-year (1871-2005) monsoon rainfalls in various study regions in India.

The frequency and magnitudes of extreme monsoon rainfall deficit and excess in India consisted of single sample values per year. Therefore, their changes in distributions and the corresponding graphs would be complicated or even confusing if they were not grouped in a certain interval. Therefore, to eliminate such unnecessary details in trend assessment, the 135 years were subdivided into 9 sub-intervals with a 15-years length each and changes were examined in those intervals.

3.1.1. Changes in Frequency

The first step in the analysis was to determine the frequencies of extreme monsoon rainfall deficit and excess based on lower and upper quartiles of 135-year (1871-2005) monsoon rainfall for every region under study, and thereafter to assess their trends using the MK technique.

Figure 3.4 displays variation of the frequencies of extreme monsoon rainfall deficit and excess which occurred in the 15-year interval starting in 1871, which indicates large regional variations. As noted in Figure 3.4, the frequency of extreme monsoon rainfall deficits has a steady increase in the decades after 1940s in the regions of WCIN and CNEIN, while for NEIN and PENIN, the frequency decreased in the most recent 15-years (1991-2005). ALLIN and WCIN showed a steady decrease in monsoon rainfall excess frequency since 1930s and until the current decade and so did happen in CNEIN and NEIN until 1990, as seen in Figure 3.4. Furthermore, PENIN has been going through a continuous increase in monsoon rainfall excess frequency from 1930s to 1990 and then a sudden drop in the current most 15-years (1991-2005), as in Figure 3.4.

Figure 3.5 shows tendencies in regional frequencies of extreme monsoon rainfall deficits and excesses in Figure 3.4. Figure 3.5 contains 2 maps where all the regional changes are captured and each includes the ALLIN map (small all-India maps inside every panel). Figure 3.5(a) reveals that ALLIN has been undergoing an increasing tendency (in pink) in frequency of monsoon rainfall deficit. All the northern Indian regions show increasing tendencies in the same while PENIN shows no tendency (in grey). Although Figure 3.5(b) indicates tendencies in extreme monsoon rainfall excess frequencies in 1871-2005, it is noted that the tendencies are not simply the opposite of the results corresponding to frequencies of extreme monsoon rainfall deficits in Figure 3.5(a). The figure also shows that extreme monsoon rainfall excess frequency in ALLIN and in all the regions except NWIN is decreasing. Based on Figures 3.5(a) and (b), NWIN is the most vulnerable in terms of both extreme frequencies.

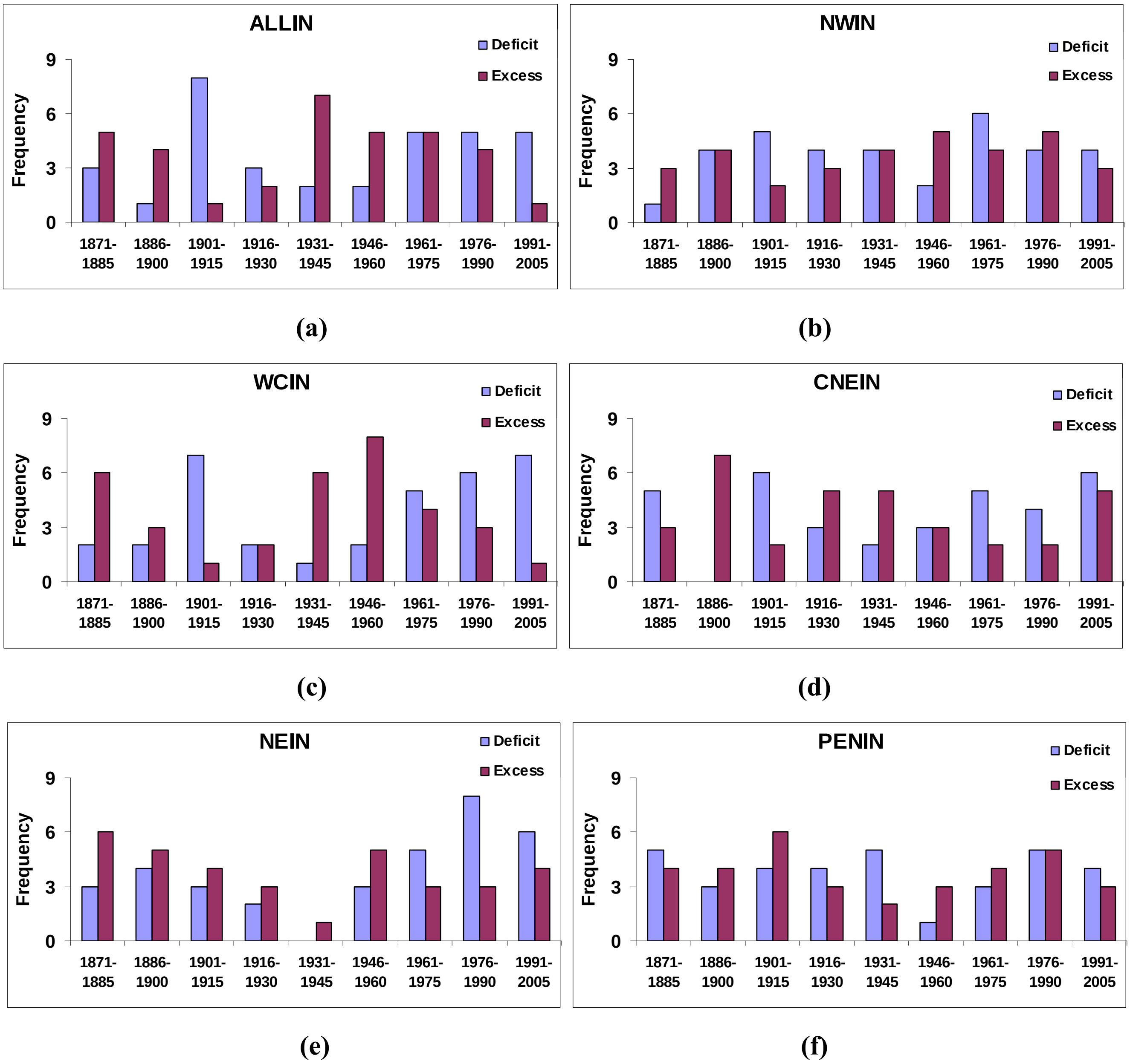


Figure 3.4: Frequencies of extreme monsoon rainfall deficit and excess in 15-year intervals using the 1871 to 2005 data in the different regions in India considered of (a) ALLIN, (b) NWIN, (c) WCIN, (d) CNEIN, (e) NEIN and (f) PENIN.

Table 3.1 shows percentage significance of the trends in Figures 3.5(a) and (b) determined using the MK method. It is noticed in Table 3.1 that the highest significance is seen in NEIN, which experiences the highest monsoon rainfall every year. Therefore, the increase in monsoon deficient years in this region is greatly affecting the ALLIN monsoon rainfall average as well. Table 3.1 also shows that the northern Indian regions have highly significant trends in extreme frequencies in 1871-2005.

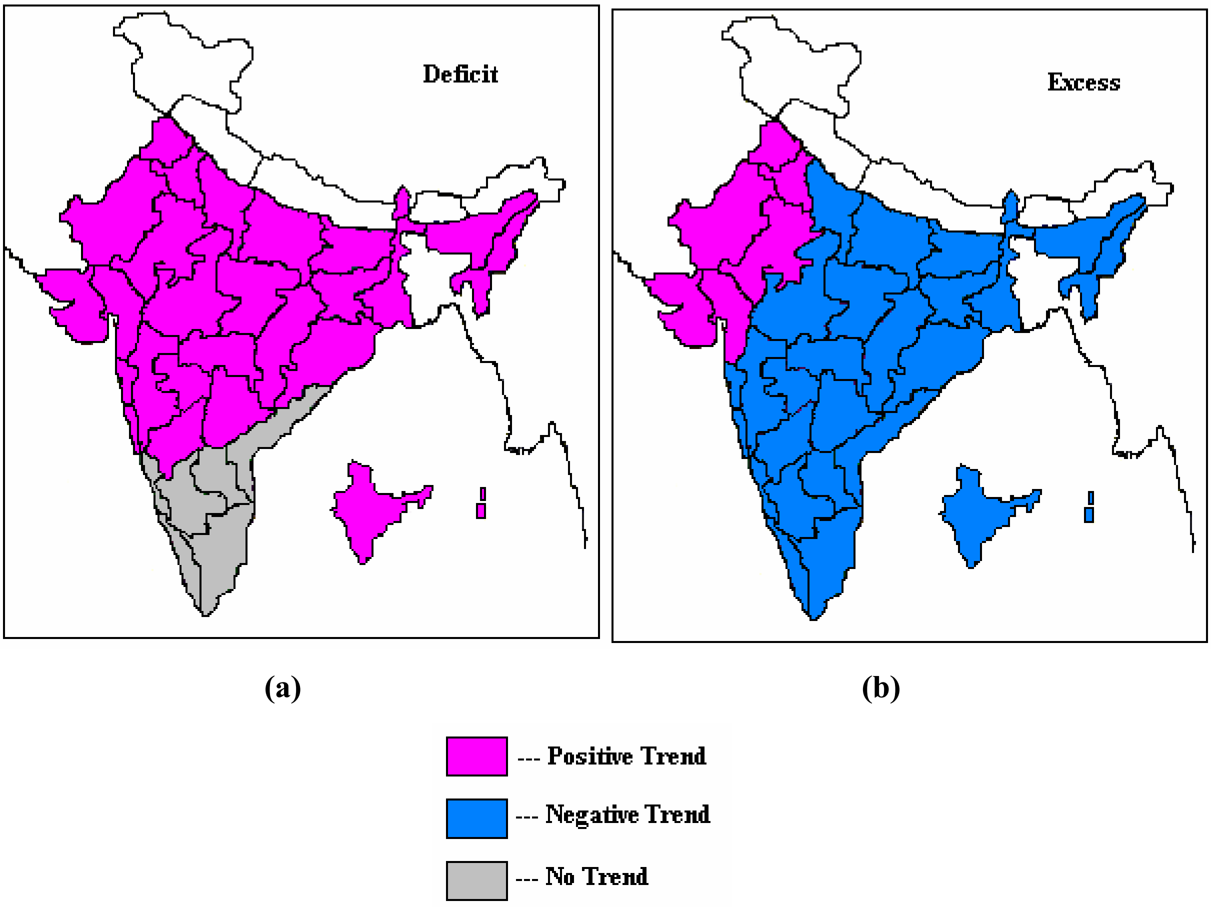


Figure 3.5: Regional trends in frequencies of extreme monsoon rainfall deficit (a) and excess (b) in India in 1871-2005.

Table 3.1: Significance of trends in extreme monsoon rainfall deficit and excess frequency in various regions in India in 1871-2005.

Region	*Percent Significance (based on z-score calculated by MK method)*	
	Extreme monsoon deficit frequency (%)	*Extreme monsoon excess frequency (%)*
ALLIN	59	47
NWIN	40	70
WCIN	79	32
CNEIN	59	46
NEIN	79	79
PENIN	No Trend	24

3.1.2. Changes in Magnitude

Values of the magnitudes of extreme monsoon rainfall deficit and excess with respect to long term lower and upper quartiles of monsoon rainfall were estimated. These are the rainfalls in each year differenced from the lower/upper quartile values and averaged over the 15-year intervals from 1871-2005 in order to look at how the average magnitudes of extreme monsoon rainfall deficits and excesses have changed over the 135 years. Figure 3.6 depicts the variations of those magnitudes over the study period and Figure 3.7 shows the 135-year tendencies.

As noticed in Figure 3.7(a), magnitudes of extreme monsoon rainfall deficiencies have been increasing in every north Indian regions, only except north-west (NWIN). In peninsular India (PENIN), the same is decreasing. Although extreme monsoon deficiency magnitudes in PENIN decreased from the previous decades to mid 1970s, it’s been increasing thereafter, as in Figure 3.6. Increase in magnitude and frequency (section 3.1.1) of extreme monsoon rainfall deficit in NEIN, WCIN and CNEIN make these regions vulnerable to water shortage.

Figure 3.7(b) shows the trends in magnitude of extreme monsoon rainfall excess in various regions in India and including an all-India average. It is noted that the magnitude of extreme monsoon rainfall excess has been decreasing over the last 135 years in northern India (NEIN, NWIN, WCIN, and CNEIN). However, an increase in magnitude of extreme monsoon rainfall excess in NEIN is noticed in the most current 15-years of study (1991-2005), which, along with lesser number of extreme monsoon deficit years from the previous decade (Figure 3.4) and increase in magnitude and frequency of extreme monsoon rainfall excess (Figures 3.4 and 3.6) might have caused some of the severe flood events in the recent times.

Table 3.2 shows percentage significance of the trends in Figures 3.7(a) and (b) determined using the MK method. It is noted in Table 3.2 that the highest significance is found for NEIN region again for the case of magnitude of extreme monsoon deficit. Since this region receives large amount of rainfalls in monsoon season, it could be concluded that the changes in NEIN rainfalls in monsoon season is greatly affecting ALLIN monsoon rainfall average, like frequency in Table 3.1. Table 3.2 also shows that CNEIN has comparatively higher significance both in trends of extreme monsoon rainfall deficit and excess magnitudes in 1871-2005.

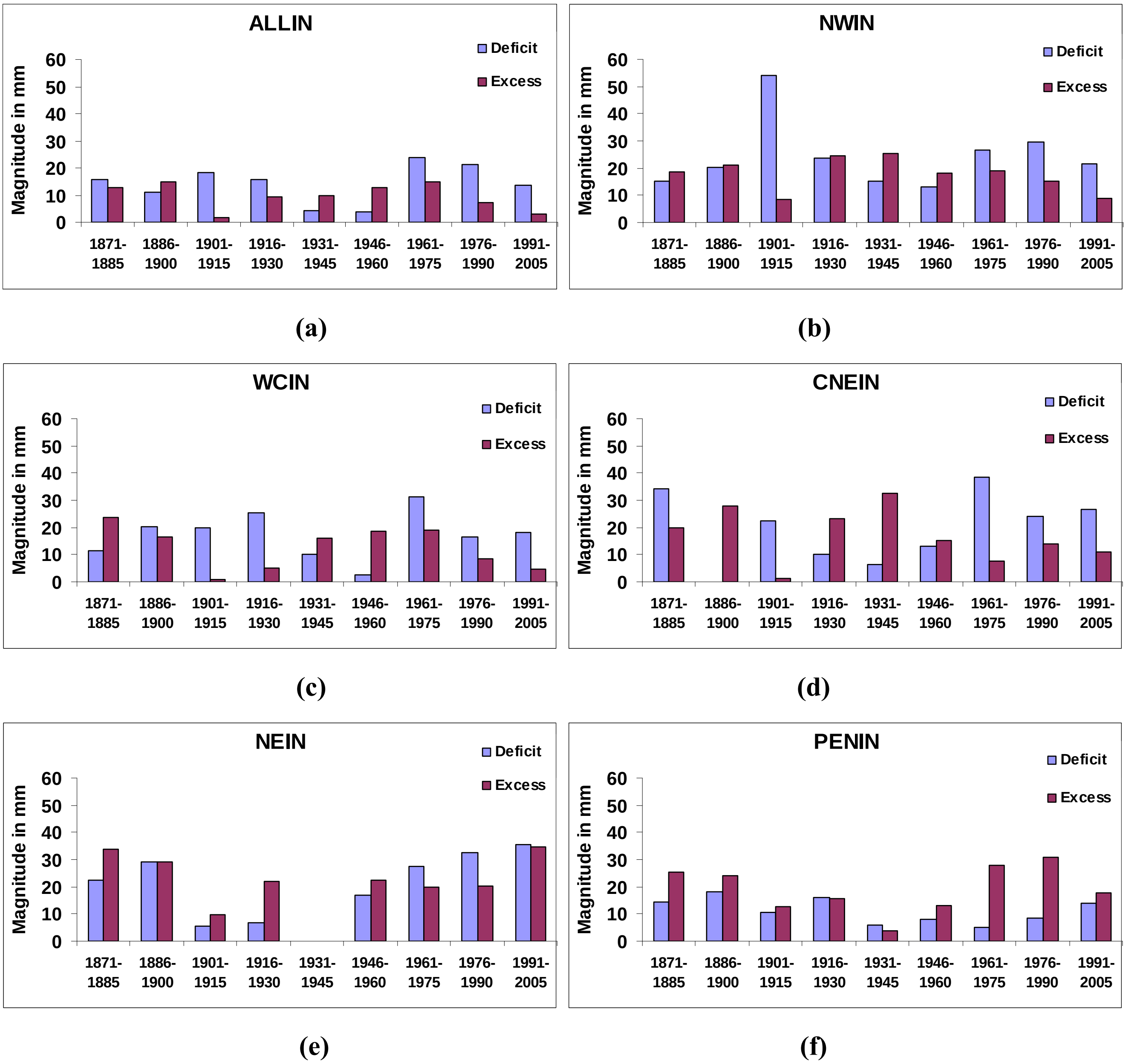


Figure 3.6: Magnitudes of extreme monsoon rainfall deficit and excess in 15-year intervals using the 1871 to 2005 data in the different regions in India considered of (a) ALLIN, (b) NWIN, (c) WCIN, (d) CNEIN, (e) NEIN and (f) PENIN.

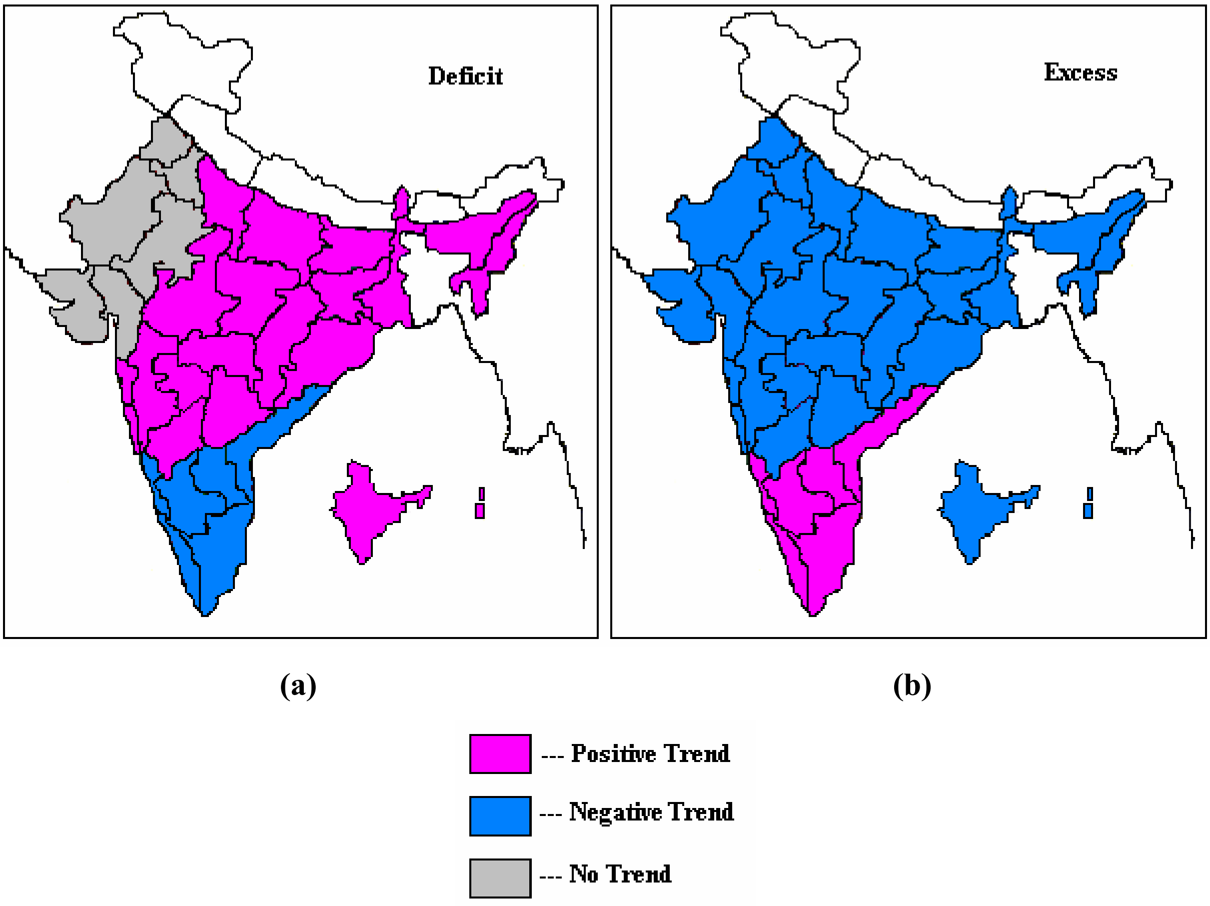


Figure 3.7: Regional trends in magnitudes of extreme monsoon rainfall deficit and excess in India in 1871-2005.

Table 3.2: Significance of trends in extreme monsoon rainfall deficit and excess magnitudes in various regions in India in 1871-2005.

Region	*Percent Significance (based on z-score calculated by MK method)*	
	Extreme monsoon deficient magnitude (%)	*Extreme monsoon excess magnitude (%)*
ALLIN	8	40
NWIN	40	53
WCIN	No Trend	40
CNEIN	65	65
NEIN	82	8
PENIN	75	24

All the results discussed in sections 3.1.1 and 3.1.2 collectively show that, probability of extreme monsoon deficiency is generally increasing in India, which is the highest in northern India while changing tendencies are quite variable in the country and especially north-south wise. Therefore, based on these observations it could be concluded that while extreme monsoonal climate is changing in all the regions in India, the changes are very distinct and as a result, a study based in one particular region may not adequately represent the whole of India.

The results in section 3.1 have been published (Pal and Al-Tabbaa, 2009a).

3.2. Detection of Regional Trends of the Severities of the Meteorological Droughts and Floods in India

This part of the study looks at the changes in monsoon seasonal droughts and floods in terms of their severities in various Indian regions based on the monthly rainfall data discussed in section 2.2.2, unlike section 3.1.1 and 3.1.2 which only discussed the extreme part of it. Extreme monsoon seasonal droughts and floods should validate the findings in section 3.1.1 and 3.1.2 as well. All the trends (and tendencies) here were assessed using parametric OLS technique, as discussed earlier in section 2.6.2.

3.2.1. Methodology

The first step in this analysis was to segregate all the dry and wet years based on their severities and to assess the changes of the severities. Several approaches have been reported in the literature so far to identify and quantify the meteorological drought and flood occurrences over India. Very commonly (Pant and Rupa Kumar, 1997), a year is classified as a wet year when

$R_i \geq R_m + S_d$……………………………………………………………………......(3.1)

and as deficient when

$R_i \leq R_m - S_d$……………………………………………………………………......(3.2) where:

R_i = monsoon rainfall amount of year i,

R_m = long-term mean monsoon rainfall, and

S_d = standard deviation of monsoon rainfalls.

Although the flood and drought years were well separated and documented in those studies, the severity of the droughts and floods across different regions were not specified anywhere. Bhalme and Mooley (1980) developed an index for meteorological droughts and floods based on monthly rainfall data. They defined 'drought area index' and 'flood area index' using the areal extent of the region. Although this procedure seems promising, one has to obtain additional areal coverage information to obtain the indices.

An easier and more systematic component of statistical scientific investigation was utilised here. The regional time series was calculated by first transforming regional rainfall departures that are characterised by long-term mean and standard deviations. For each region the transformed series of rainfall departures were calculated using the following procedure:

$$N_i = \frac{R_i - R_m}{S_d} \quad \ldots\ldots(3.3)$$

where: N_i is the transformed/normalised annual rainfall departure value of R_i.

The resultant series has mean = 0 and standard deviation = 1. The year with below normal monsoon rainfall quantity was assigned a drought year and the excess as a flood year. The standardised values were used as the indices of meteorological drought and flood severity. The value of -0.99 to 0.99 were considered as 'normal' condition, the value of -1.0 (+1.0) to -1.49 (+1.49) as 'moderate' drought (flood) condition, the values of -1.5 (+1.5) to -1.99 (+1.99) were assigned as 'severe' drought (flood) and the value below (above) -2 (+2) is 'extreme' drought (flood).

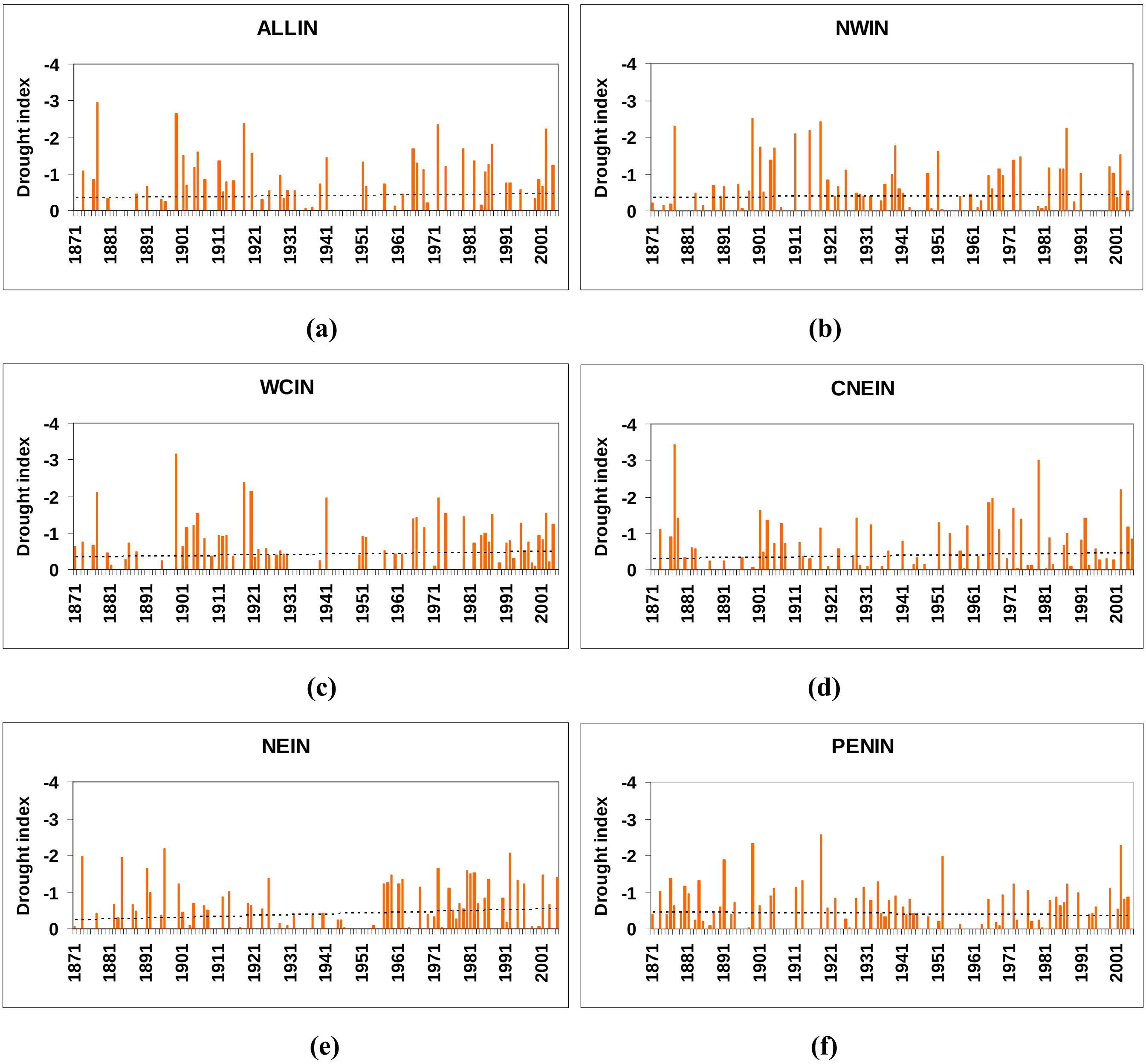
To determine the long-term changes of the flood and drought indices, linear trends that suggest the tendency of change in spite of intermittent fluctuations were examined using the OLS technique.

3.2.2. Results

Figures 3.8 and 3.9 display all the meteorological monsoon droughts and floods respectively which occurred between 1871 and 2005 and their tendencies. The summary of the occurrences of the meteorological monsoon floods and droughts according to their severities are displayed in Tables 3.3 and 3.4. The bold years in Tables 3.3 and 3.4 coincide with the El-Nino and La-Niña occurrences, which will be referred back in section 3.5.2 for a detailed discussion.

Figure 3.8 shows that the meteorological drought has an increasing tendency in NEIN, in which monsoon rainfall is the highest among all the study regions (see Figure 3.2). No statistically significant trends of meteorological droughts can be seen in NWIN, WCIN, CNEIN and PENIN (Figure 3.8) with the former three having slightly increasing tendency and the PENIN region a slightly decreasing tendency. Likewise, the trend of ALLIN drought was not significant but has a slightly increasing tendency. The meteorological flooding, as shown in Figure 3.9, has slightly decreasing trends in ALLIN, CNEIN, and WCIN; whereas, the NEIN, NWIN and PENIN regions have no trend.

Since Figures 3.8 and 3.9 reveal no clear picture of the trends of different types of meteorological droughts and floods, a separate trend assessment was carried out for all types of meteorological droughts and floods. Figures 3.10 and 3.11 display trends of all 'moderate' events that took place in the study time interval at various regions. Figure 3.10 shows that, 'moderate' droughts, which have the highest probability of the occurrences every year, have increasing trends for all the regions except PENIN with the trend in NEIN being the most clear and no trend is found in CNEIN. On the other hand, as Figure 3.11 shows, a decline in 'moderate' flood events is found in NEIN only, an increase is observed in PENIN and NWIN, and CNEIN, WCIN and ALLIN show no trends.



(a) (b)

(c) (d)

(e) (f)

Figure 3.8: Time series of the drought indices and their tendencies based on the rainfall data from 1871 to 2005 in various regions in India considered of (a) ALLIN, (b) NWIN, (c) WCIN, (d) CNEIN, (e) NEIN and (f) PENIN.

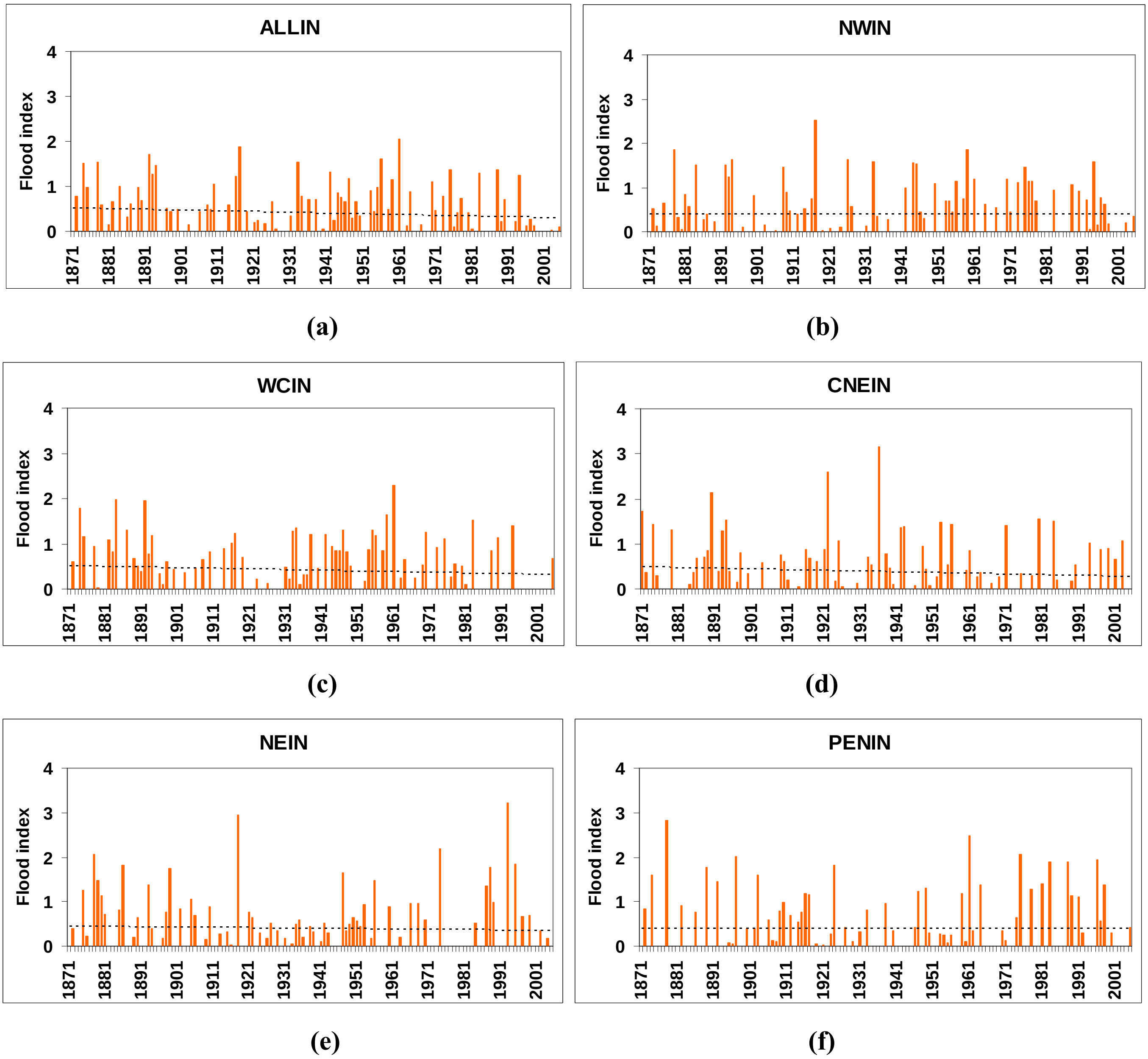


Figure 3.9: Time series of the flood indices and their tendencies based on the rainfall data from 1871 to 2005 in various regions in India considered of (a) ALLIN, (b) NWIN, (c) WCIN, (d) CNEIN, (e) NEIN and (f) PENIN.

Since, very few statistically significant trends were found for the 'severe' and 'extreme' conditions, for the reason that the trend results could be biased by the rarity, the linear trends are not shown for these conditions. However, there are a few exceptions, which are – 'severe' floods for ALLIN which were found to have statistically significant decreasing trend and 'severe' and 'extreme' droughts in WCIN which were found to have statistically significant increasing trends. These increasing meteorological summer droughts in many parts of India could be attributed to the rise in temperature in the drier summer months, reduction of the number of rainy days and increase in ENSO events, as in related work discussed later in section 3.5.2.

Table 3.3: List of meteorological drought years according to their severity indices in various regions in India.

Region	***Droughts***		
	Moderate	***Severe***	***Extreme***
ALLIN	*1904*,**1911**,**1941**,*1951*,1966,1968,1974, **1982**,*1985*, 1986, **2004** (36%-64%)	1901,**1905**,1920,**1965**, *1979*, **1987** (50-67%)	**1877,1899,1918,1972, 2002** (100%)
NWIN	1904,**1925**,1948,1968,**1972**,1974,**1982**, 1985,1986,**1991**,1999,2000 (34%)	1901,**1905**,1939,1951, **2002** (40%)	**1877**,**1899**,**1911**,1915 **1918**, **1987** (83%)
WCIN	**1902**,1904,**1965**,1966,1968,1979,1995, **2004** (38%)	**1905**,**1941**,**1972**,1974 **1987**, **2002** (83%)	**1877**,**1899**,**1918**,1920 (75%)
CNEIN	1878,1903,1907,**1918**,1928,**1932**,1951 1959,1968,1974,1992, **2004** (25%)	1901,**1965**,1966,**1972** (50%)	**1877**,1979,**2002** (67%)
NEIN	1900,**1914**,**1925**,**1957**,1958,1959,1961, 1962,1967,1975,1986,**1994**,1996,2001, 2005 (27%)	1884,**1891**,**1972**,1980, 1981, **1982** (50%)	**1896**, 1992 (50%)
PENIN	1876,1880,1884,**1905**,**1911**,**1913**,1930 1934,**1972**,**1976**,**1987**, 1999 (50%)	**1891**,1952 (50%)	**1899**,**1918**,**2002** (100%)
Note: Bold years coincide with the El-Niño occurrences. Percentages in the brackets refer to the likelihood of the droughts occurring in El-Niño years.			

Table 3.4: List of meteorological flood years according to their severity indices in various regions in India.

Region	***Floods***		
	Moderate	***Severe***	***Extreme***
ALLIN	1884,**1893**,1894,**1910**,**1916**,*1942*,**1947**, 1959, **1970**, **1975**,1983,**1988**,1994 (54-62%)	**1878**,**1892**,**1917**,*1933*, **1956** (80-100%)	*1961* (0%)
NWIN	**1893**,**1908**,**1950**,**1956**,1961,**1970**, **1973**, **1975**, 1976, 1977, **1988** (73%)	**1878**,**1892**,1894,1926 1933,1944,**1945**,1959 1994 (34%)	**1917** (100%)
WCIN	1882,1887,1894,**1916**,**1917**,1933, 1934,**1938**, 1942,**1947**,**1955**,**1956**, **1970**, **1975**,1990,1994 (50%)	1884,**1892**,1959,1983 (25%)	1961 (0%)
CNEIN	**1879**,**1893**,1925,1942,1943,1953,**1956** **1971**, 1994, 2003 (40%)	1894, 1980 (0%)	1890, 1922,1936 (0%)
NEIN	**1879**,**1880**, **1893**, 1905,**1956**,1987 (67%)	**1886**,1899,**1947**,**1988** 1995 (60%)	**1878**,1918,**1974**,1993 (50%)
PENIN	**1892**,**1916**,**1917**,**1947**,1949,1959,**1964**, 1978, **1981**,1989,1991,**1998** (59%)	**1889**,1903,**1924**,1983, **1988**, **1996** (60%)	1878,1897,1961,**1975** (25%)
Note: Bold years coincide with the La-Niña occurrences. Percentages in the brackets refer to the likelihood of the floods occurring in La-Niña years.			

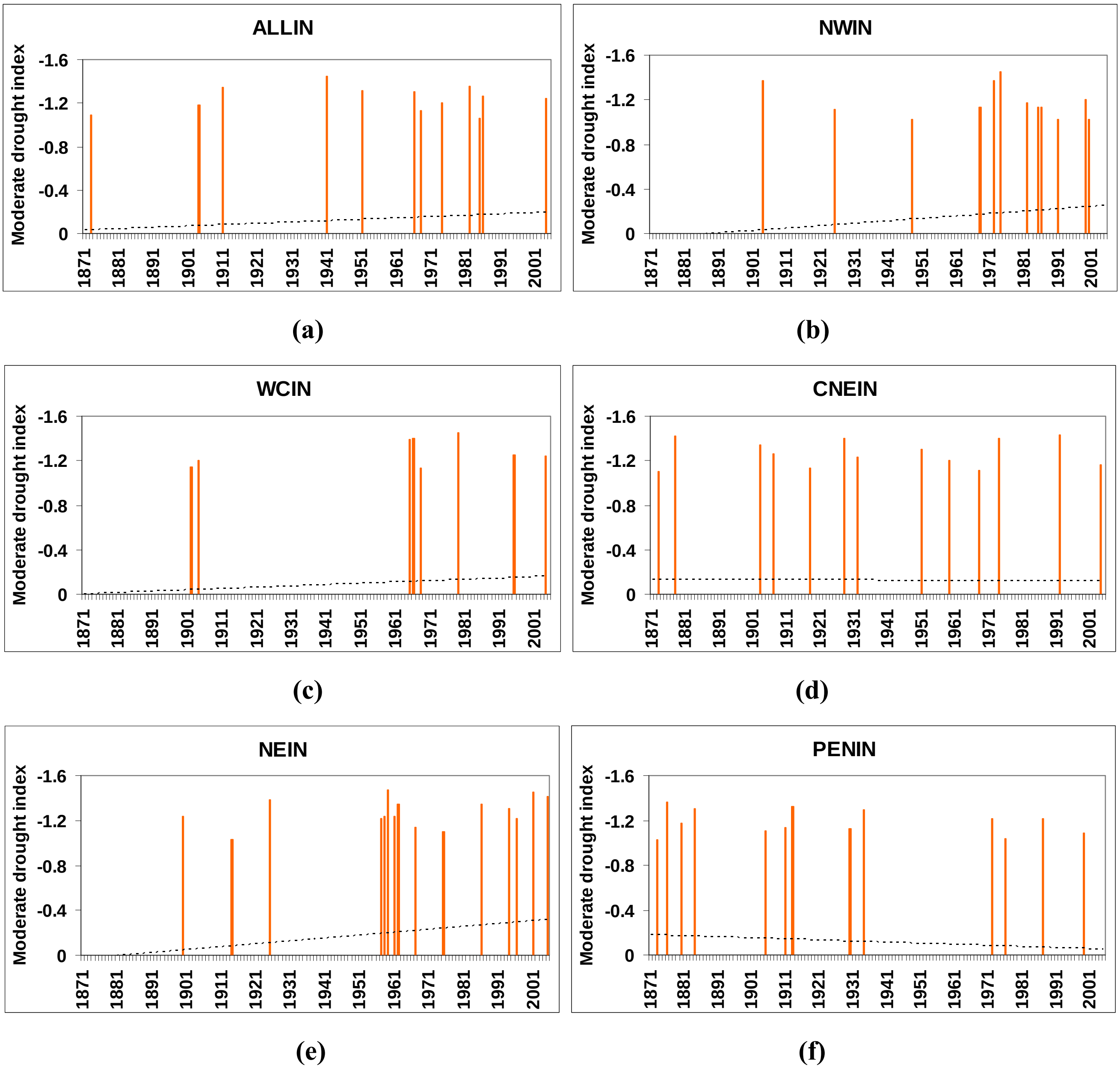


Figure 3.10: Time series of the moderate drought indices and their tendencies based on the rainfall data from 1871 to 2005 in various regions in India considered of (a) ALLIN, (b) NWIN, (c) WCIN, (d) CNEIN, (e) NEIN and (f) PENIN.

All the results discussed in this section and in section 3.1 collectively show that, drought probability is the highest in North East India where the annual average rainfall is the highest and followed by WCIN. Peninsular India has an entirely different trend in all respects and no change is found in moderate drought and floods in Central North East India (CNEIN). However, increasing tendency in extreme monsoon rainfall deficit (section 3.1) makes the region CNEIN vulnerable to monsoon water stress. Therefore, it could be concluded that the average monsoonal climate is definitely changing in all the regions in India but the changes are different, as also discussed in section 3.1.

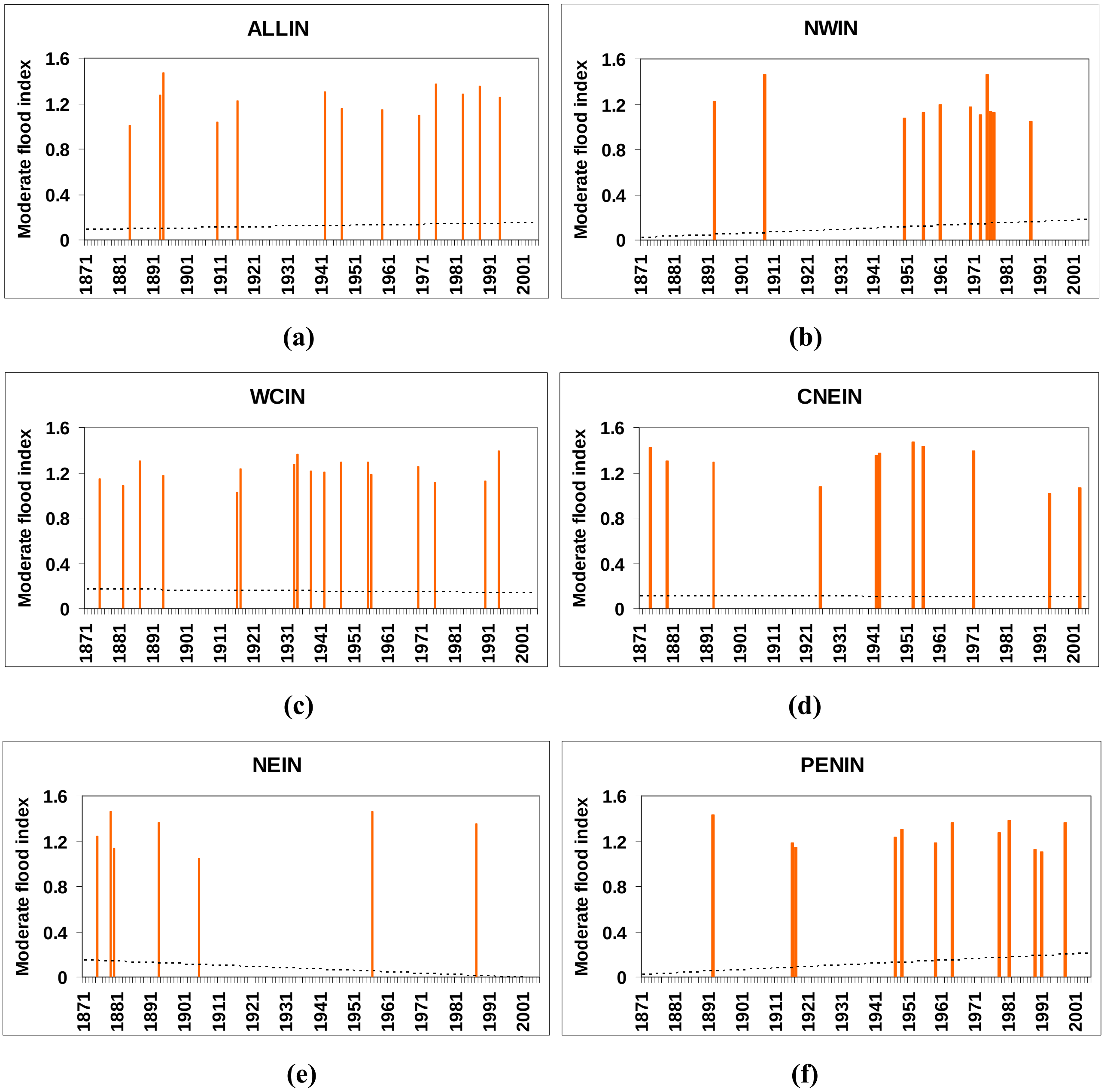


Figure 3.11: Time series of the moderate flood indices and their tendencies based on the rainfall data from 1871 to 2005 in various regions in India considered of (a) ALLIN, (b) NWIN, (c) WCIN, (d) CNEIN, (e) NEIN and (f) PENIN.

3.3. Periodical Cycle of Regional Monsoon Rainfall

This section looks at whether there is any periodical variability of mean monsoon rainfall and its trend based on the monthly rainfall data discussed in section 2.2.2.

3.3.1. Methodology

To analyse the variability of the mean with time, the Moving Average (MA) model is one of the most widely used techniques. MA is very useful to even out any short time fluctuations of a variable. In this section, the so called Nowcasted Moving Average (NMA) model, i.e. the moving average based on previous *n* years of observations was used (Cislaghi et al., 2005). Half decadal (5-year) and decadal (10-year) NMA were computed for all the regional monsoon rainfall data and corresponding long-term trends were also determined. The OLS technique was also utilised here for the trend/tendency detection.

A detailed analysis of the longer term NMA and Standard Deviation (SD) and their percent departures from the long term mean and SD would also give a better idea of the tendency and variability of the data in a longer time scale. Therefore, 25 years NMA and SD were also computed for all the regions and their percent departures were determined, which are further discussed below. These results are useful to arrest any periodical fluctuation at half decadal, decadal or a longer time perspectives.

3.3.2. Results

The decadal and half decadal NMA results are displayed in Figures 3.12 and 3.13 and the trend assessment results are summarised in Table 3.5. Both the figures show that, all the regions have been undergoing periodic monsoon rainfall fluctuations. To display the clear periodicity of monsoon rainfall for all the study regions, same scale wasn’t maintained for the y-axis of the Figures 3.12 and 3.13. Table 3.5 lists all the trend magnitudes and their percent significance.

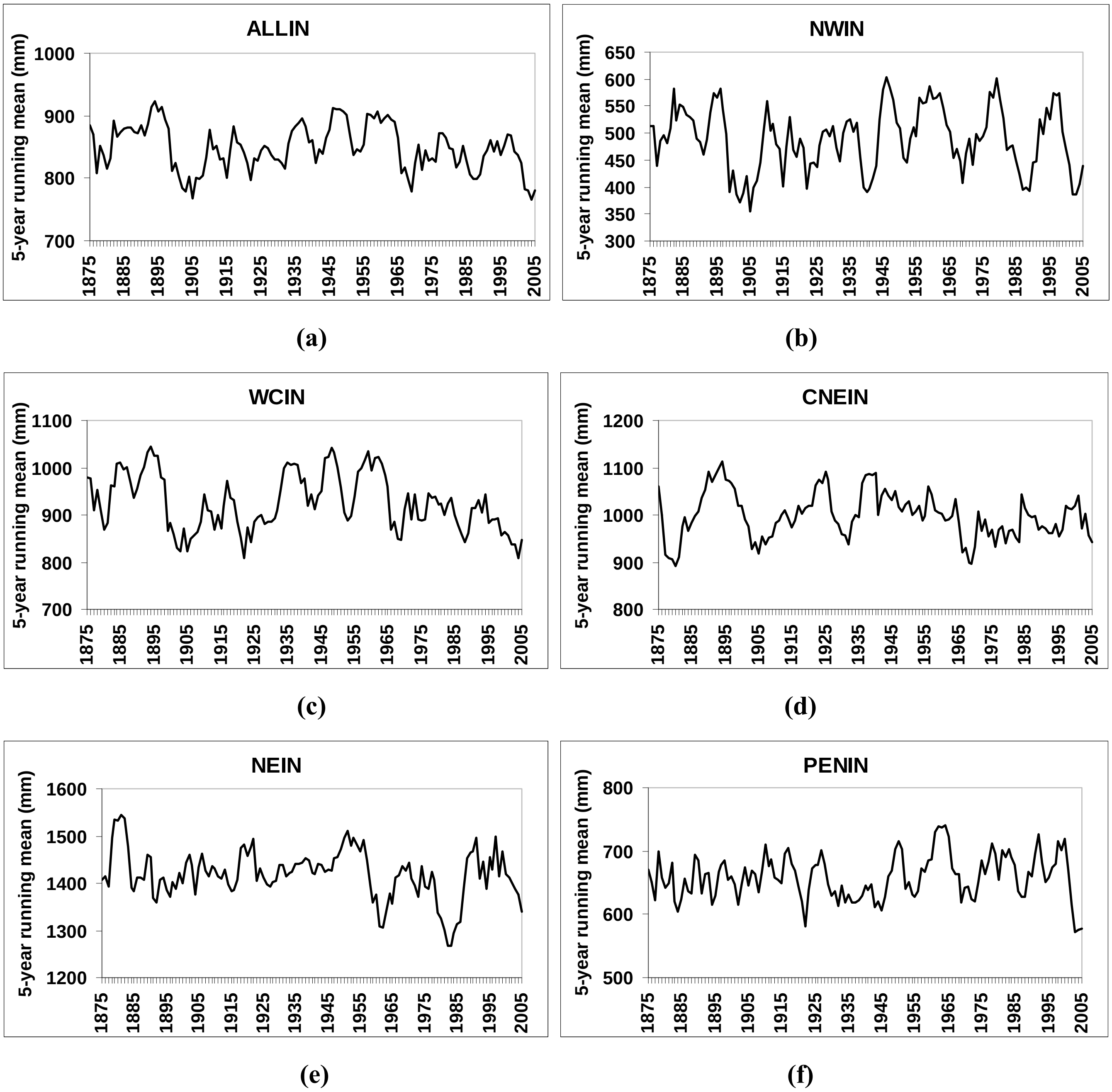


Figure 3.12: Variation of half decadal (5-year) nowcasted moving average of monsoon rainfall based on the rainfall data from 1871 to 2005 in various regions in India considered of (a) ALLIN, (b) NWIN, (c) WCIN, (d) CNEIN, (e) NEIN and (f) PENIN.

It is noted in Table 3.5 that all the trends corresponding to 5- and 10-year moving averages had high significance that determine the certainty of the monsoon rainfall change. The majority of the regions were found to have been undergoing decreasing trends of monsoon rainfall that are 95 to 99% significant, as shown in Table 3.5. On the contrary, only region PENIN shows increasing trends of monsoon rainfall, which are 85 and 99% significant and only region, NWIN has no-trend in both the cases. Table 3.5 also shows that the maximum monsoon rainfall decrease, which is 95 to 99% significant, is in North-Eastern India (NEIN).

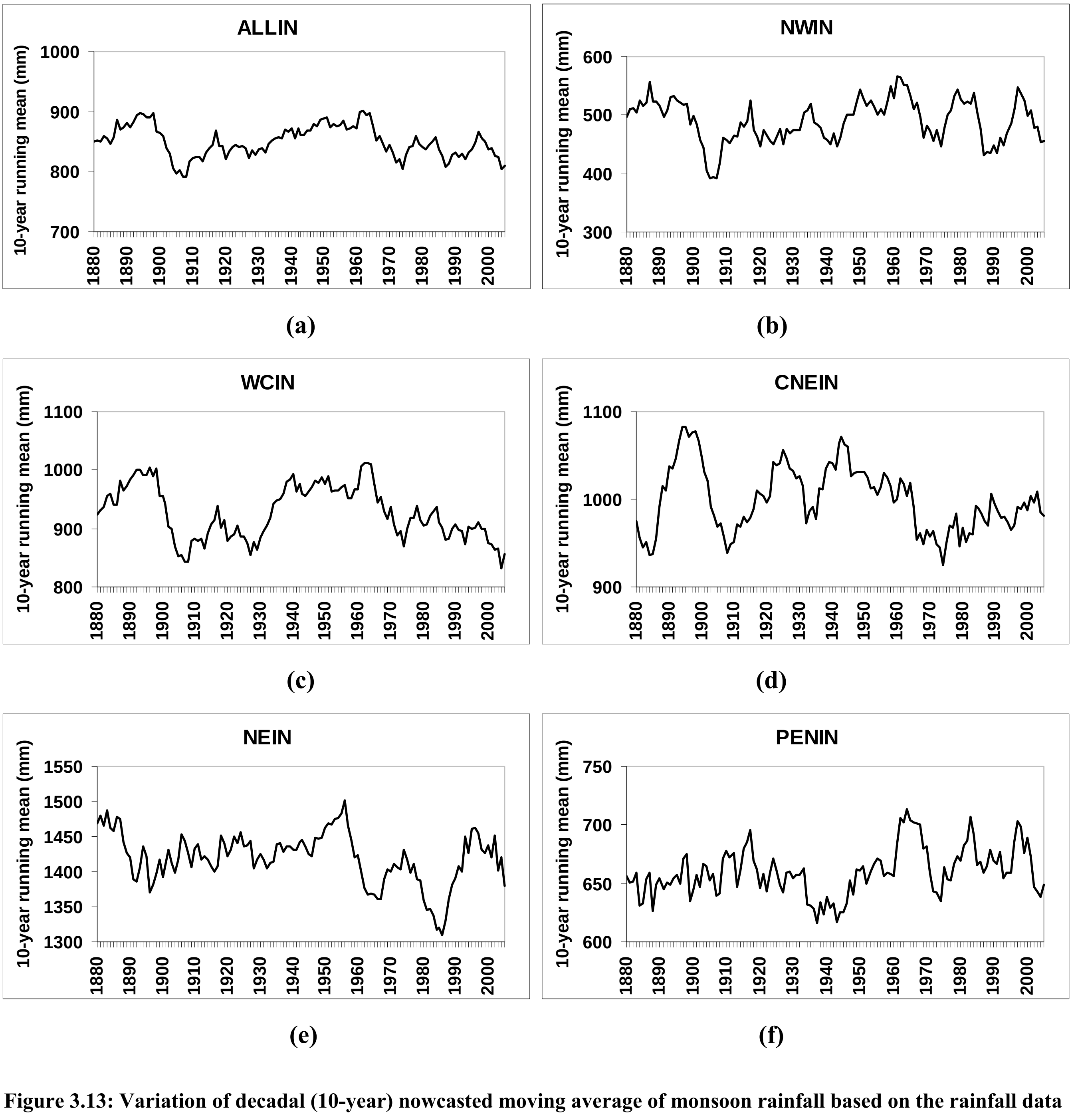


Figure 3.13: Variation of decadal (10-year) nowcasted moving average of monsoon rainfall based on the rainfall data from 1871 to 2005 in various regions in India considered of (a) ALLIN, (b) NWIN, (c) WCIN, (d) CNEIN, (e) NEIN and (f) PENIN.

Taking the previous results into consideration, i.e. increasing trend of meteorological overall droughts and no change in overall floods (see Figures 3.8 and 3.9) it could be concluded that the North East region remains the most vulnerable region to disasters in India during the monsoon season.

Table 3.5: Trends of 5- and 10-year moving mean monsoon rainfalls in India for the period of 1871-2005.

Region	***5-Year***		***10-Year***	
	Trend (mm/100years)	***Significance***	***Trend (mm/100years)***	***Significance***
ALLIN	- 18	95%	- 14	95%
NWIN	No Trend	N/A	No Trend	N/A
WCIN	- 36	99%	- 30	99%
CNEIN	- 20	95%	- 26	99%
NEIN	- 36	99%	- 34	99%
PENIN	+ 12	85%	+ 19	99%
Note: +ve sign = increasing trend; -ve sign = decreasing trend.				

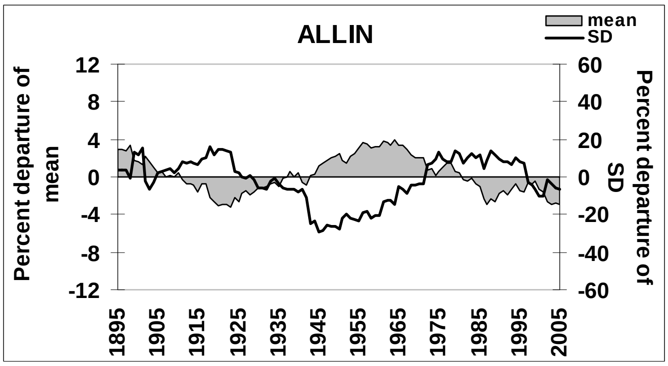
Furthermore, West Central India (WCIN) also falls in the 'disastrous' region category despite its overall drought showing 'no trend' and floods showing decreasing trends (refer Figures 3.8 and 3.9). This is because this region has a similar result to NEIN i.e. decrease in half decadal and decadal mean monsoon rainfall (Table 3.5), and increase in meteorological 'moderate' droughts and no change in 'moderate' floods, as shown and demonstrated previously in Figures 3.10 and 3.11.

Central North East India, on the other hand, shows slightly different results from NEIN and WCIN, with significantly decreasing trend in decadal and half decadal monsoon averages (95-99% significant) and no trend in 'moderate' flood and droughts (Figures 3.10 and 3.11). NWIN shows results that are also unique with both 'moderate' flood and droughts increasing (Figures 3.10 and 3.11), no change in overall flood and droughts (Figures 3.8 and 3.9), and no change in decadal and half decadal monsoon averages (Table 3.5).

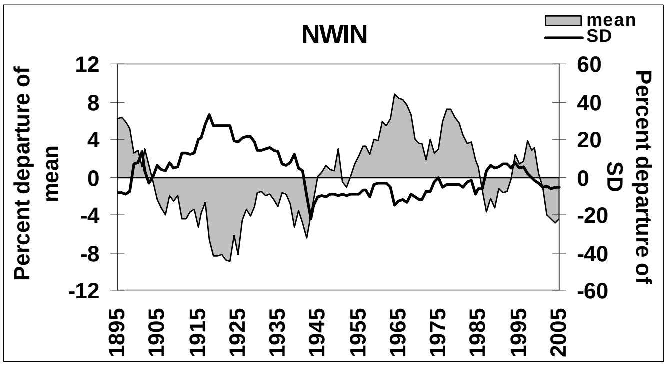
The results above also confirm that, decadal (10-year) changes are much more versatile and statistically significant than the shorter time i.e. half decadal (5-year) changes. So, it is now clear that, although all-India mean-monsoon rainfall shows a statistically significant decreasing trend and virtually provides a comprehensive overall generalisation of Indian monsoon rainfall, it does not at all reflect the regional variability, as seen in the result of ALLIN in Table 3.5 and Figures 3.8, 3.9, 3.10, 3.11, 3.12 and 3.13. Therefore, a region-specific study is always important and essential in order to better understand the locale climate that is vital for various local developments requiring local climatological information.

Figure 3.14 displays the 25-year percent departures of NMA and SD from the long-term mean and SD of monsoon rainfall. The most common and interesting observation for all the cases in the figure is the accompaniment of the highest variability of the monsoon rainfall with the prolonged dry spell. This is consistent with Pant and Rupa Kumar (1997) who also noticed similar outcomes for the all-India monsoon rainfall, where the data ranged from 1871 to 1995. A more region specific study and more up to date time series analysis here reaches a similar conclusion for a regional perspective. Moreover, Figure 3.14 was also helpful to depict that the number of decadal dry/wet cycles do not always occur at every region at a time. However, the results corresponding to WCIN look representative of ALLIN, as seen in Figure 3.14.

The results in section 3.1, 3.2 and 3.3 agree with the earlier analyses (Kumar et al., 2004; Sen Roy and Balling, 2004; Manton et al., 2001) which reported a decline in summer monsoon rainfall over South and Southeast Asian region and specifically in the north-eastern states of India and an increase in rainfall in peninsular India. However, the results disagree with Goswami et al. (2006) in relation to the presence of a trend for all-India monsoon rainfall. This disagreement might be caused by the methods employed to determine the trends or the difference in the data sampling period. This indicates that the selection of the test and methods of analysis significantly affect the underlying conclusions. Since this part of the study tries to detect the long-term trends by incorporating the oscillations present in the database, the methodologies adopted here would show different results to the all-India trend showed in Goswami et al. (2006).



(a)



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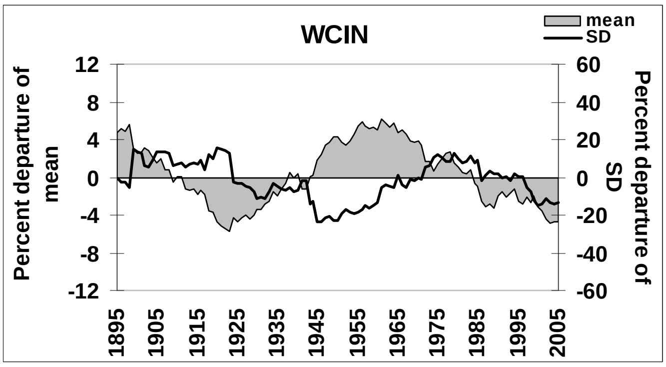

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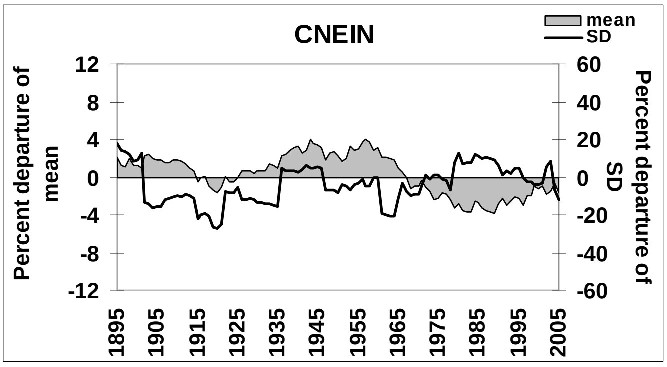

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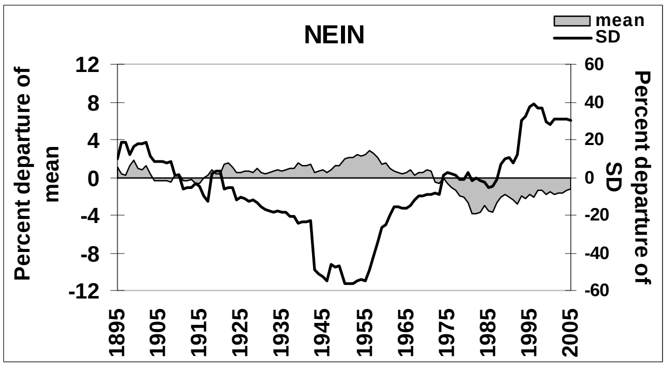

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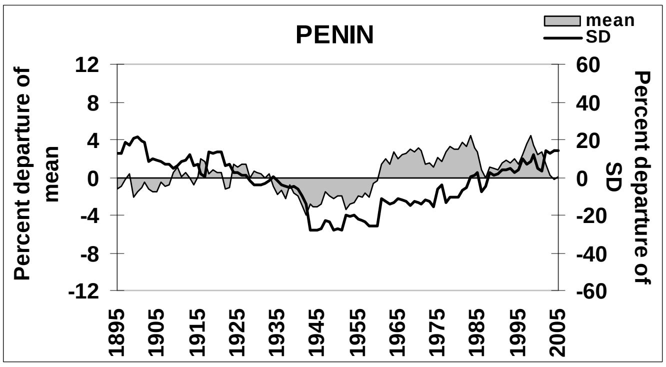


(f)

Figure 3.14: Variation of 25-year-nowcasted-moving-average of percent departure of mean and standard deviation of monsoon rainfall based on the rainfall data from 1871 to 2005 in various regions in India considered of (a) ALLIN, (b) NWIN, (c) WCIN, (d) CNEIN, (e) NEIN and (f) PENIN.

3.4. Sub-Regional Analysis of PENIN

Considering all the results above, it is noted that the results for peninsular India (PENIN) are opposite or exceptional in terms of trends; periodic wet/dry spells etc. Other studies in the later sections (section 3.6.2) will confirm that there is a statistically significant decreasing trend of monsoon rainfall in the region of Kerala - the south western state of peninsular India, marked no. 35 in Figure 2.4. Therefore, a further simple half decadal and decadal NMA analysis was carried out to examine the tendency of monsoon rainfall in the other subdivisions in peninsular India that might help to judge the reasons for the dissimilarity of the results corresponding to PENIN in the above sections. The 135 years (1871-2005) monthly monsoon rainfall data described in section 2.2.2 is also used here. The subdivisions are marked as 28, 30, 31, 32, 34 and 35 in Figure 2.4. The trends and their significance were determined following section 2.6.2.

The half decadal and decadal nowcasted moving average trends are summarised in Table 3.6, which is also displayed in the Figure 3.15. Table 3.6 and Figure 3.15 show that the majority of the regions have been experiencing statistically significant increasing trends with the decadal changes being more than the half decades; the only exception is Kerala where the trend is exactly the opposite. Only Tamilnadu state has no long-term trends and South Interior Karnataka has no significant trend but a positive tendency.

The maximum increase in rainfall is noticed in coastal Karnataka which solely or together with coastal Andhra Pradesh and Rayalaseema are enough to contribute towards distinct results noticed in PENIN. The rainfall changes in coastal Karnataka over the century are very vibrant; as a result incessant rainfall and devastating rare floods are in news for some time. On the other hand, Kerala being exactly the opposite in terms of monsoon rainfall behaviour is important to be analysed separately, which has been performed and presented in the later sections in this chapter.

Table 3.6: Trends of 5- and 10- year moving mean monsoon rainfalls in peninsular India for the period of 1871-2005.

Subdivision		***Trend of monsoon precipitation***	
Number in Figure 2.4	***Location***	***5-year moving average trend (mm/100years)***	***10-year moving average trend (mm/100years)***
28	Coastal Andhra Pradesh	**+ 165**	**+ 178**
30	Rayalaseema	**+ 128**	**+ 158**
31	Tamilnadu	No Trend	No Trend
32	Coastal Karnataka	**+ 625**	**+ 744**
34	South Interior Karnataka	+ 13	+ 18
35	Kerala	**- 123**	**-72**
Note: -ve sign = decreasing, +ve sign = increasing. All bold trends are significant at the 95% level.			

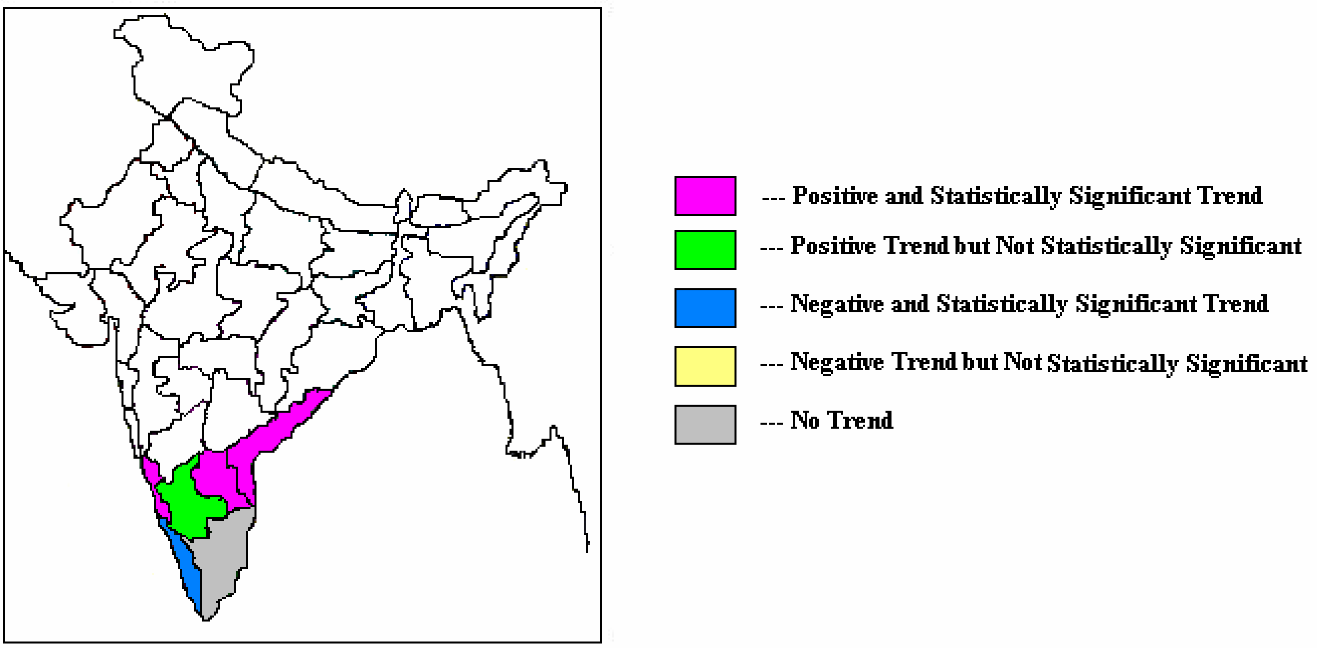


Figure 3.15: Trends in both the 5- and 10-year moving mean monsoon rainfalls in different subdivisions of peninsular India based on the rainfall data from 1871 to 2005.

3.5. 'Teleconnections' of Meteorological Monsoon Droughts/Floods to SO

Many detailed studies have been carried out so far on the teleconnections of Indian monsoon variability and Southern Oscillation (SO), as discussed previously in section 2.3.4. However, no studies except Kane (2000) have focused on a region-specific examination, which could be useful for the regional climate forecast in different parts of India. Kane (2000) performed his analysis only until 1990, which will be extended here until 2005 for the monsoon months only to examine the association of El-Niño and La-Niña with meteorological monsoon droughts and floods at various severity conditions (as illustrated in section 3.2). A study of the relationship between recognised patterns of climate variabilities i.e. El-Niño Southern Oscillation (ENSO) events and La-Niña and monsoon rainfall variability is also presented here.

3.5.1. Methodology

The Southern Oscillation Index (SOI) data for this study was collected from the Bureau of Meteorology, Australia (http://www.bom.gov.au/) covering the period of 1876 to 2007. The dataset consists of monthly averages, the SOIs are expressed as a 'normalised' anomaly and the index scale ranges from about +30 to -30.

When an SOI is strongly positive (i.e. > +5), trade winds blow strongly across Pacific Ocean and the event is called La-Niña. With a strongly negative SOI (i.e. < -5), trade winds are weakened and reversed and the event is called El-Niño (Cruz et al., 2007). This part of the study investigates El-Niño and La-Niña associations with below and above normal monsoon rainfalls (meteorological droughts and floods) in India in 1876 to 2005. The last few decades have seen an increase in both the frequency and intensity of El-Niño events (Cruz et al., 2007). The statistically significant increasing trend of the strong negative SOI i.e. El-Niño in the last 5 decades is shown in Figure 3.16, which is 95% significant. Accordingly, drought conditions in the regions which El-Niño has influence on have been extreme, as also shown and discussed in the following subsection.

3.5.2. Results

Figure 3.17 displays all-India average monsoon rainfall and the SOI that is averaged over monsoon months (June-September) from 1876 to 2005. It is clearly noticed in Figure 3.17 that, there have been an influence of SOI on Indian monsoon since, usually rainfall is greater in the years when the SOI is large and positive (La-Niña events) and the opposite occurs when SOI is strongly negative (El-Niño events). All the strong El-Niño and La-Niña years are listed in Table 3.7; the bold drought/flood years in Tables 3.3 and 3.4 merge with these years respectively.

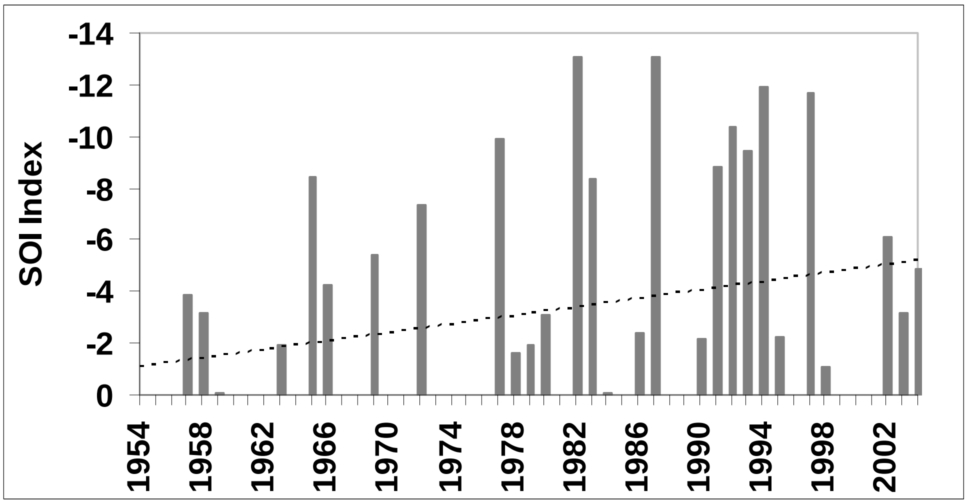


Figure 3.16: Sharply increasing linear trend of negative SOI (El-Niño) from 1954 to 2004.

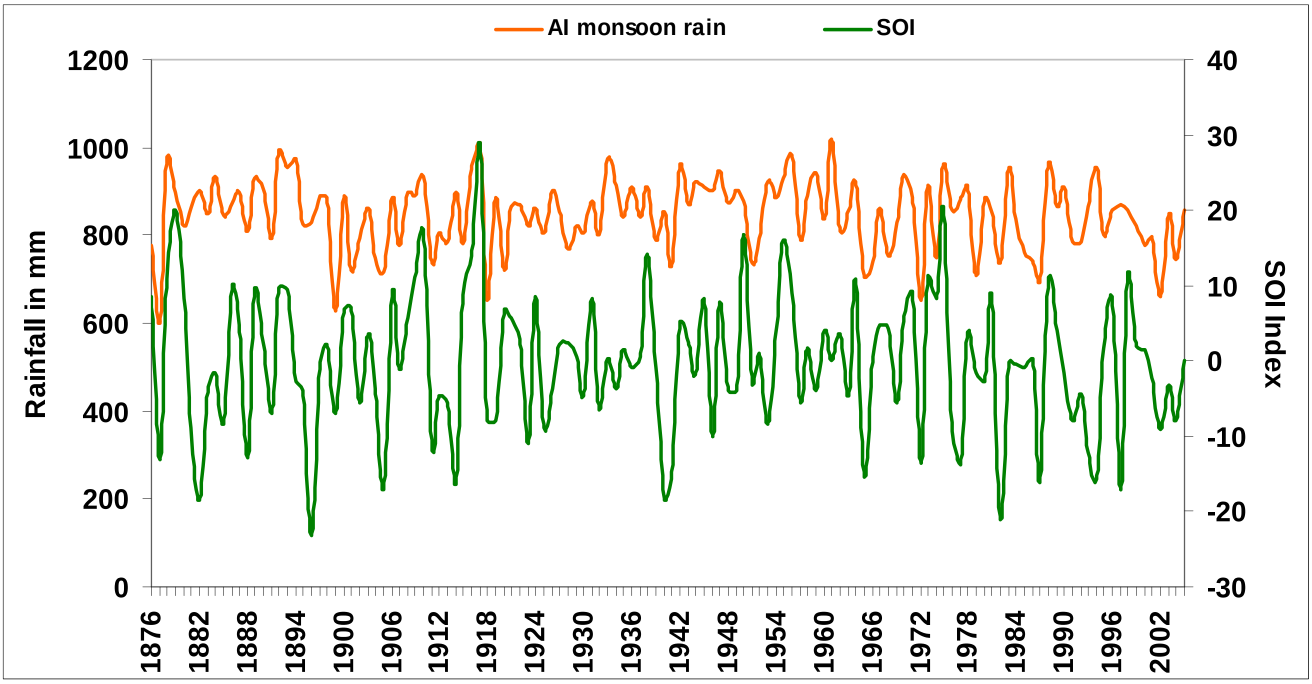


Figure 3.17: The variation of average all-India monsoon rainfall and SOI from 1876 to 2005.

Table 3.3 demonstrates that all the major monsoon droughts in India were observed occurring in the El-Niño years and many but not all the major floods occurred in La-Niña years. Figure 3.18 shows all strong El-Niño and La-Niña events occurred between 1876 and 2005 for a better reference. The most notorious drought in India occurred in 1877 that was followed by 1899, 1918, 1972 and 2002 according to their severities (De et al., 2005), which all happened in the El-Niño years, as also noticed in Figures 3.17 and 3.18. Likewise, many more moderate to severe droughts in India were also found well coinciding with El-Niño years, which are listed in Table 3.3. On the other hand, only 'severe' floods agree well with La-Niña events, and also the 'moderate' floods to a certain extent, as noticed in Table 3.4. However, the most extreme monsoon flood year, 1961, doesn't coincide with La-Niña occurrence. Italics in Tables 3.3 and 3.4 refer to drought/flood events in weak to moderate El-Niño (La-Niña) years that are not listed in Table 3.7 or shown in Figure 3.18.

Table 3.7: List of severe El-Niño and La-Niña years.

El-Niño	1877,1881,1882,1885,1888,1891,1896,1899,1902,1905,1911,1913,1914,1918, 1919,1923,1925,1932,1940,1941,1946,1953,1957,1965,1969,1972,1976,1977, 1982,1987,1991,1993,1994,1997,2002,2004
La-Niña	1876,1878,1879,1880,1886,1889,1892,1893,1900,1901,1906,1908,1909,1910, 1915,1916,1917,1920,1921,1924,1931,1938,1945,1947,1950,1955,1956,1964, 1970,1971,1973,1974,1975,1981,1988,1996,1998

Tables 3.3 and 3.4 also list the years of various types of droughts and floods occurred in different regions in the study time interval highlighting the years that coincide with El-Niño and La-Niña events, as also mentioned previously in section 3.2.2. It is noticed that 'extreme' droughts in every region very likely occur in the El-Niño years with 50 to 100% likelihood that is consistent with the IPCC report, which revealed that at least 50% droughts in South Asia are associated with El-Niño (Cruz et al., 2007). This probability decreases from the south to the north and from the north-west to the north-east, as seen in Table 3.3. The possibility of the occurrence of 'severe' droughts with El-Niño is also significantly high with 50 to 83% likelihood. However, there is very low probability of 'moderate' meteorological droughts occurring in the El-Niño years. This is because the local impacts play a major role. Since, coastal Sea Surface Temperatures are probably a response to the pacific ENSO that can modulate monsoon rainfall

directly or indirectly (Balas et al., 2007); coastal parts of India (PENIN and NWIN) at the side of Arabian sea/Indian Ocean may undergo maximum impacts. On the other hand, 'moderate' and 'severe' monsoon flood occurrences better agree with 'La-Niña' years than the 'extremes'. Also, the results above show that the influence of SO is not symmetric and varies among the regions, for example, the 1997-1998 'El-Niño of the century' had no impact on monsoon rainfall whereas the relatively weak 2002 event was the worst monsoon drought in Indian recorded history since rainfall was a record low. Similar results could be found for Australia (Power et al., 2006).

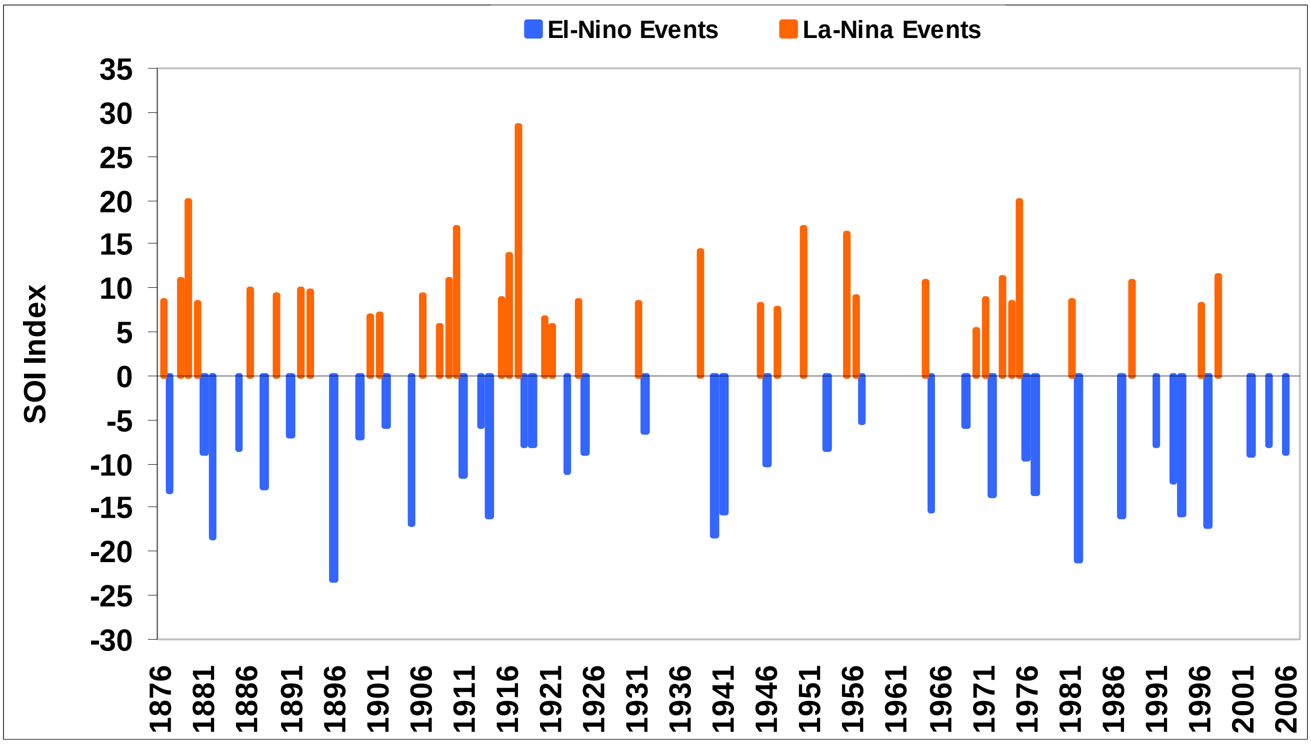


Figure 3.18: Strong positive and negative SOI anomalies (El-Niño and La-Niña) occurred in 1876-2005.

Overall, although not very clear, SOI could be a potential entity to improve the estimates of probabilities of 'extreme' monsoon rainfall over the Indian region significantly. Hence, high quality prediction results of SOI from various climatological organisations around the world could very well be used as an alarm bell for 'extreme' meteorological droughts during monsoon seasons, which could be very useful for water resources planning and management in India. However, since monsoon rainfall is expected to be more variable during the dry periods, as in section 3.3.2, the quantitative prediction of monsoon rainfall may become tougher during El-Niño in a changing climate.

The results in sections 3.2-3.5 have been submitted for publication (Pal and Al-Tabbaa, 2009b).

3.6. Changes in Seasonal Rainfall in India Using OLS and MK

3.6.1. Overview

This section details the work performed to detect the natural climate change in terms of changes in various seasonal rainfalls in the areas of Kerala, the peninsular India, various climatological regions in India and India as a whole using the data discussed in sections 2.2.1 and 2.2.2.

The daily time series for the six grids of Kerala was extracted from the database discussed in section 2.2.1 for the 50 years (1954-2003) of analysis. The location of Kerala state and its gridded areas are shown in Figure 3.19 and the daily rainfall time series for all those regions are shown in Figure 3.20. As noted in Figure 3.20, region 2 (11.5N, 76.5E) experienced most intense rainfall in a day in the last 53 years (1951-2003), which is followed by the region 1 (11.5N, 75.5E). However, as Figure 3.20 shows, there is a decreasing tendency of extreme daily rainfall intensity at region 2 from the 1970s; wherein, at region 1, an increasing tendency is noticed and particularly since the 1990s. All these data will be discussed in more detail in the later sections (3.6.2, 3.7, 3.8 and 3.9).

Since the period 1961-1990 is referred to as 'baseline' according to the WMO standard and a significant shift of tropical rainfall is found in the period 1979-2003 (Lau and Wu, 2007), only the second half of the 20th century is considered in many planning decisions. Also, two great changes in Indian monsoon circulation were observed in the

1960s and 1970s (Ding et al., 2008). Hence, trends in seasonal rainfalls were determined here and later in this chapter for the period of 1954-2003.

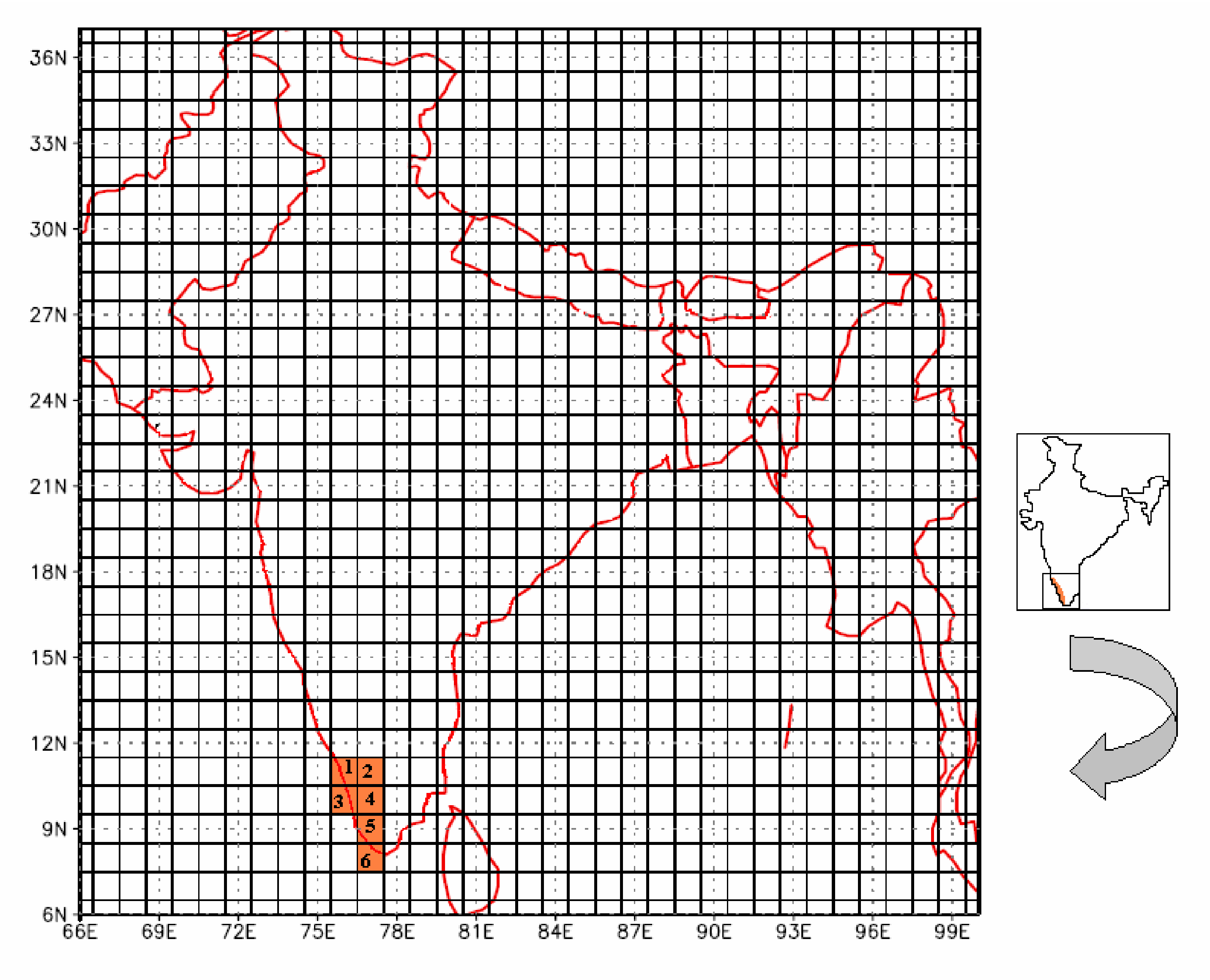


Figure 3.19: Location of Kerala state in India (orange colour grids mark the study regions considered). The numerical numbers in the grid points represent 1°×1° grids as follows, 1 = 11.5N, 75.5E; 2 = 11.5N, 76.5E; 3 = 10.5N, 75.5E; 4 = 10.5N, 76.5E; 5 = 9.5N, 76.5E; 6 = 8.5N, 76.5E (Rajeevan et al., 2006).

A comparison of Ordinary Least Squares (OLS) linear regression and Mann-Kendall (MK) methods (presented in sections 2.6.2 and 2.6.3) is also carried out here, which will be helpful to find out whether normality assumptions for the trend detection by parametric method is reasonable for the analysis of seasonal rainfall totals from various regions in India. For this comparison, regions of different spatial scales were considered. For additional investigation, apart from the six short-scaled areas making up the whole of Kerala (as in Figure 3.19), other larger geographical regions in India were also considered (Figure 2.4), for which the monthly rainfall data described in section 2.2.2 was used. These include: (i) whole Kerala state and other states making up the whole of peninsular India (green colour region in Figure 2.4), (ii) various climatological regions in India making up most of the whole of India (except the northern most hilly region) and (iii) the largest spatial average, spatially averaged all-India rainfall. Response of monsoon rainfall to climate change in the northern-most hilly region, i.e. Himalayan region, could be found in Duan et al. (2006).

The average seasonal and annual trends in rainfall indices were first estimated considering the shortest possible spatial scales using both the techniques. Only the region of Kerala state was chosen for that purpose with a total of six gridded regions covering the whole of Kerala (Figure 3.19). The trend estimates are all listed in Table 3.8, where data explained in section 2.2.1 was used.

Figure 3.21(a) and (b) show an example of the variation of total annual rainfall in the whole of Kerala for the period of 1871-2005 and 1954-2005. The rainfall data discussed in section 2.2.2 was used in Figure 3.21. No significant trend was noticed in the long-term but several decadal variations were observed (thick line) in Figure 3.21(a). However, since 1954, the changes were more apparent, as shown in Figure 3.21(b), where a sharp decrease in annual rainfall is noticed in Kerala. Similar phenomena were also noted for the case of larger-scaled climatological divisions in India. Parametric trends corresponding to annual rainfall for the periods of 1871-2005 and 1954-2005 for the regions in Figure 2.4 are shown in Figures 3.22 and 3.23. No significant trends were noticed in the period of 1871-2005 in annual rainfall that were shown in Figure 3.22. However, significant trends were observed for annual rainfall particularly in WCIN, NEIN and PNEIN in the period of 1954-2005, as shown in Figure 3.23. These results are discussed in more detail in the subsequent sections.

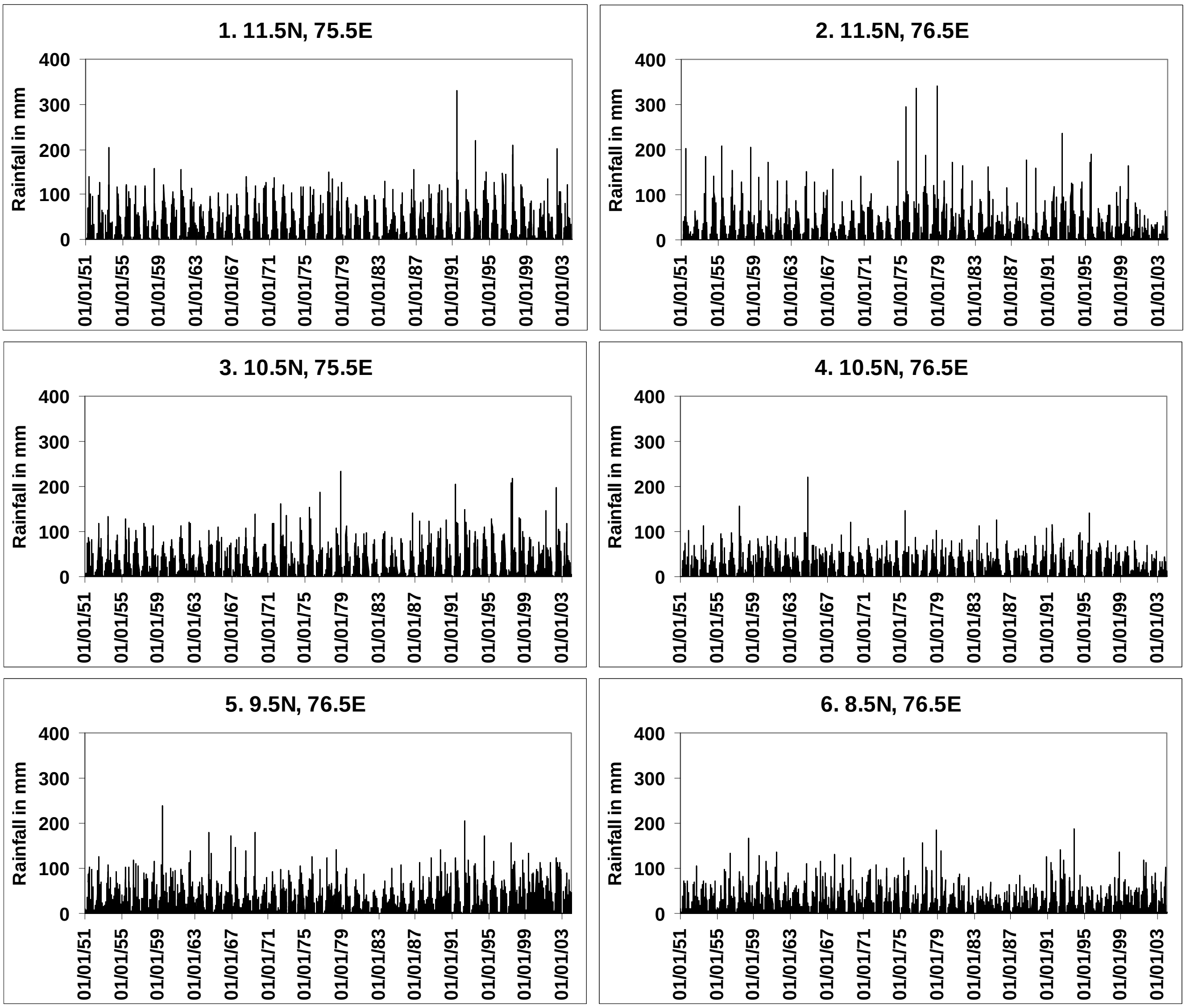


Figure 3.20: The 53-year (1951-2003) daily time series of rainfall in various gridded regions of Kerala.

3.6.2. Trends in Various Seasonal Rainfalls in Gridded Regions of Kerala

The magnitudes and the directions of the decadal trends as estimated by the parametric (P) and non-parametric (NP) methods (presented in sections 2.6.2 and 2.6.3), for the case of the Kerala grids, are summarised in Table 3.8. The results are presented for the six regions in Kerala and for the individual seasons as well as annual rainfall. It is noted in Table 3.8 that, except for a few cases, parametric and non-parametric estimates of the trends in seasonal and annual rainfall amounts are very close to each other. Table 3.8 depicts that the rainfall has an increasing tendency in autumn season; winter has different trends in different regions but a significant increasing trend in region 2, and decreasing trends in spring and monsoon seasons and annually.

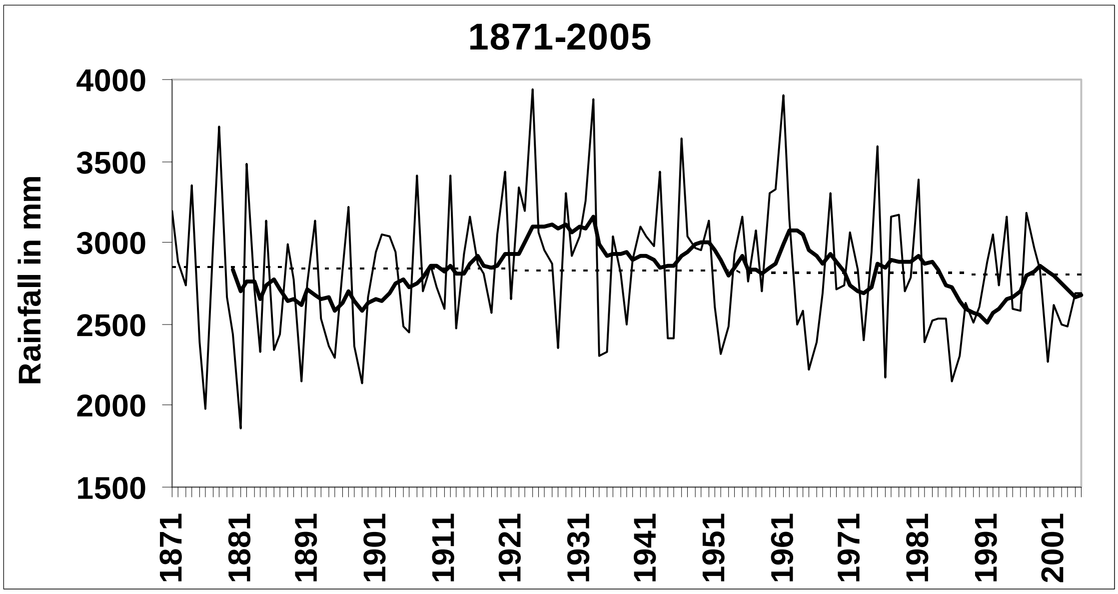
Table 3.8: Magnitudes and directions of trends (mm/10years) in seasonal and annual rainfall in various regions in Kerala using parametric (P) and non-parametric (NP) techniques.

Region	***Winter***		***Spring***		***Monsoon***		***Autumn***		***Annual***	
	P	***NP***	***P***	***NP***	***P***	***NP***	***P***	***NP***	***P***	***NP***
1.11.5N,75.5E	+ 3.7	+ 3.0	**- 45.8**	**- 39.9**	**- 175.4**	**- 144.3**	+ 13.3	+ 20.4	**- 205.4**	**- 163.1**
2.11.5N,76.5E	**+ 8.9**	**+ 5.2**	**- 27.2**	**- 20.9**	-58.3	- 65.4	+ 23.9	+ 18.5	- 53.2	- 85.1
3.10.5N,75.5E	- 2.0	- 0.3	**- 55.3**	**- 63.6**	-29.6	- 37.5	+ 6.5	+ 10.3	- 81.6	- 82.0
4.10.5N,76.5E	- 0.4	- 0.6	**- 48.0**	**- 47.4**	**- 193.2**	**- 194.3**	- 8.8	- 3.8	**- 251.0**	**- 232.2**
5.9.5N,76.5E	+ 1.5	- 2.8	**- 49.9**	**- 46.2**	- 64.7	- 60.8	+ 17.1	+ 15.6	- 96.5	- 86.4
6.8.5N,76.5E	+ 1.6	- 2.8	**- 50.7**	**- 44.1**	- 59.2	- 62.3	+ 24.0	+ 20.4	- 86.7	- 88.5

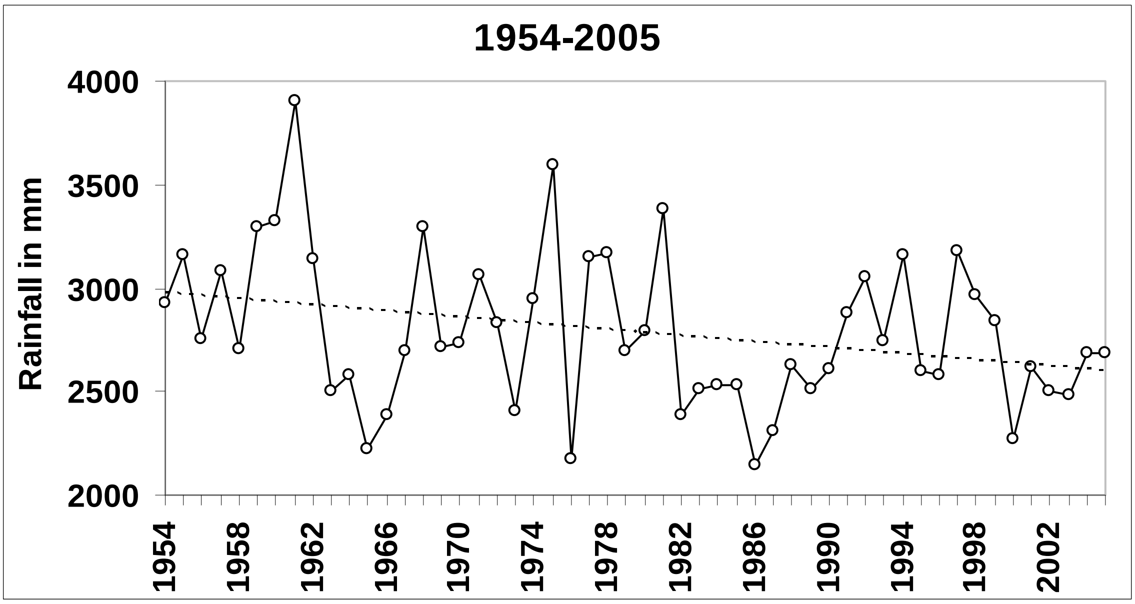
Note: P = parametric method estimates; NP = non-parametric method estimates; + ve sign = increasing trend; – ve sign = decreasing trend; bold numbers indicate significant trends at the 95% level.

The total amount of seasonal or annual rainfall is usually correlated both with the number of rainy days and rainfall intensity (Karl et al., 1995). Therefore, decrease in the spring and monsoon seasonal rainfall, which were highly significant, could be attributed to the increase in the number of dry days and decrease in extreme rainfalls in those seasons, which will be discussed in sections 3.7 and 3.9. A temporal shrinkage of the monsoon period in India because of the decrease in number of rainy days in the pre-onset (May 15-May 31) of the monsoons was also observed by Ramesh and Goswami (2007). Wherever in Kerala monsoon rainfalls have highly significant decreasing trends, as in Table 3.8, annual rainfall was noticed to have statistically significant decreasing trends as well. This is because more than 70% of rain falls in the monsoon season alone, as shown previously in Figure 3.2 for the large scale regions in India and here again in Figure 3.24 for the gridded regions of Kerala.

Table 3.8 also demonstrates that, only one region in Kerala namely 11.5N,76.5E, exhibits a statistically significant increase in winter rainfall. This is because there was a significant decrease in the number of dry days and significant increase in the contribution from extreme rainfall only in this particular area in Kerala. However, although there was no significant trend in the autumn total rainfall in Table 3.8; the increasing tendency was because of the significant decrease in the number of dry days and increase in extreme rainfall intensity, which were significant in some of the gridded regions, as also discussed in detail in sections 3.7 and 3.9.

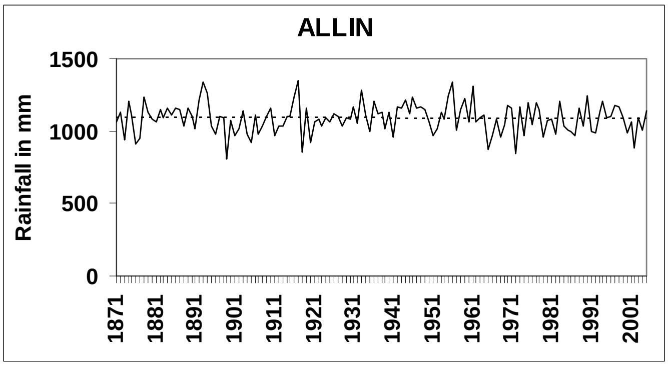


(a)

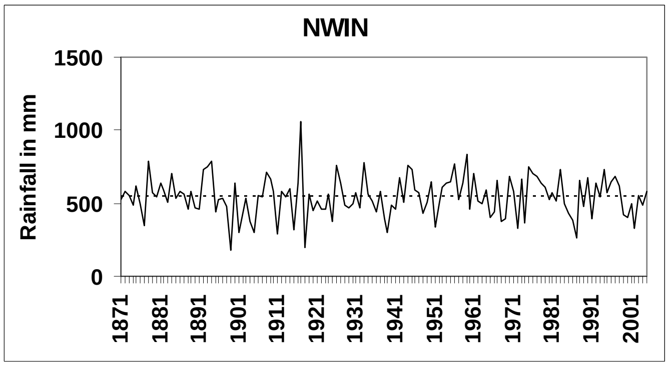


(b)

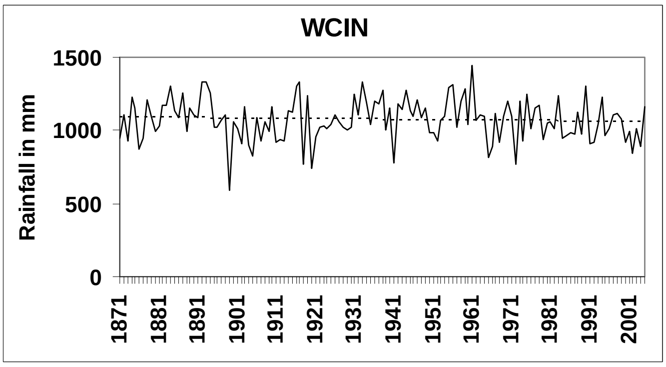
Figure 3.21: Variation of total annual rainfall and its trend in Kerala for (a) 1871-2005 and (b) 1954-2005.



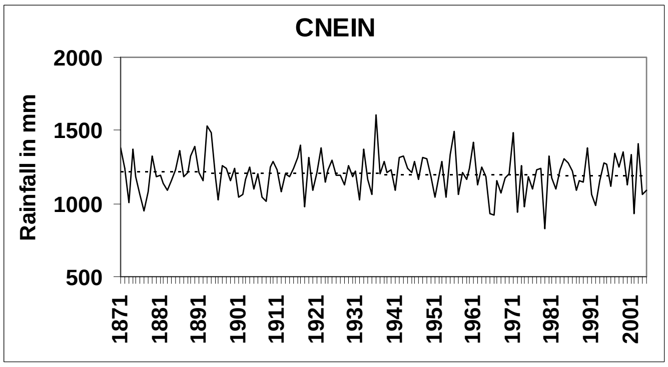
(a)



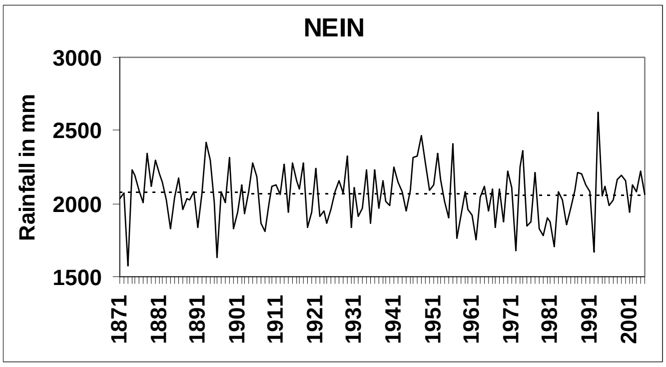
(b)



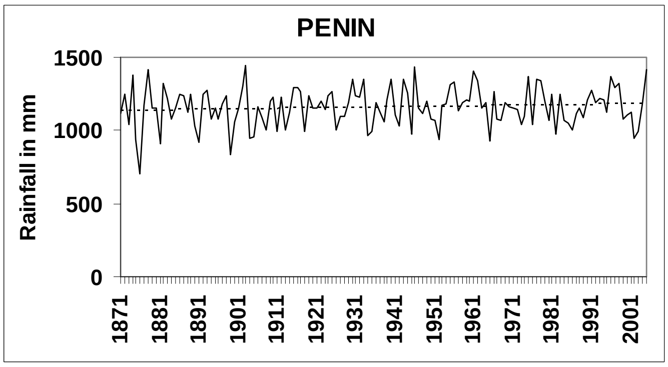
(c)



(d)

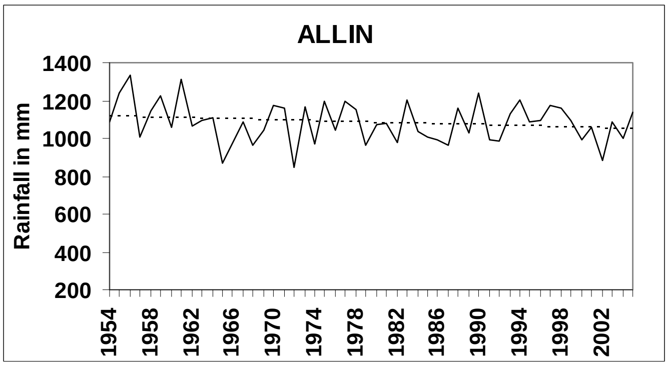


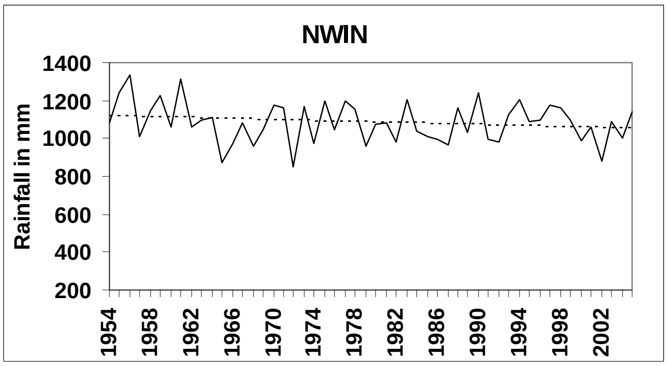
(e)



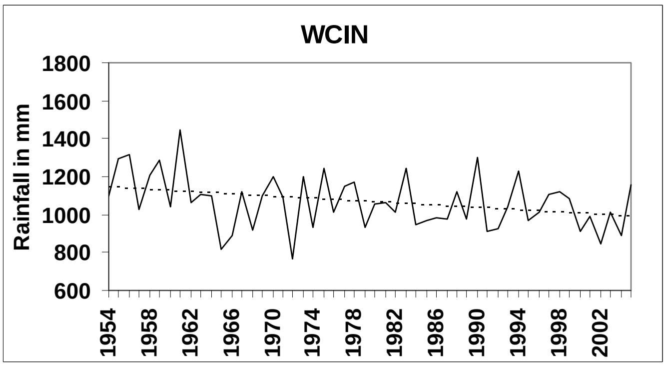
(f)

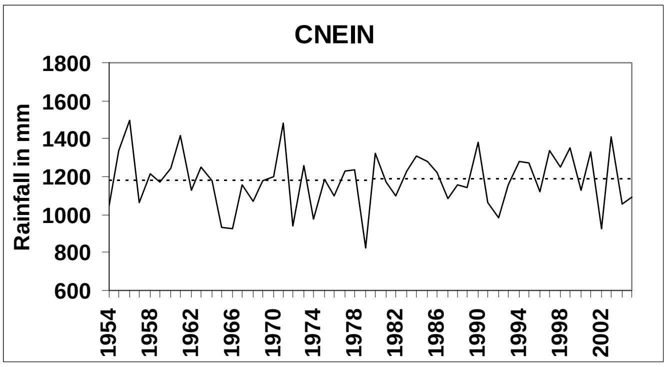
Figure 3.22: Variation of annual rainfall and its trend based on the rainfall data from 1871 to 2005 in various regions in India considered of (a) ALLIN, (b) NWIN, (c) WCIN, (d) CNEIN, (e) NEIN and (f) PENIN.



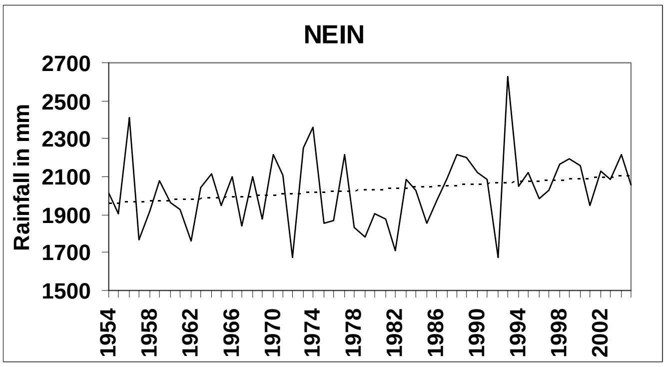


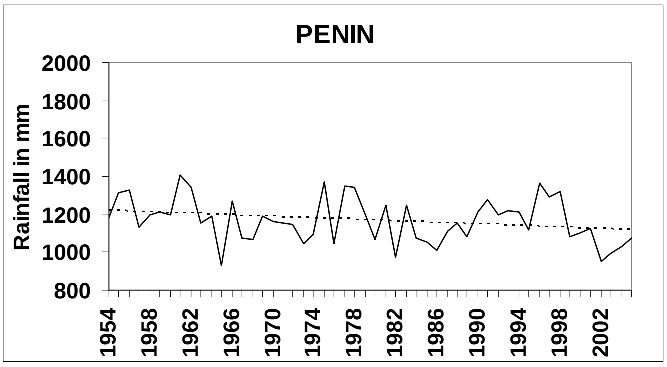
(a) **(b)**





(c) **(d)**





(e) **(f)**

Figure 3.23: Variation of annual rainfall and its trend based on the rainfall data from 1954 to 2005 in various regions in India considered of (a) ALLIN, (b) NWIN, (c) WCIN, (d) CNEIN, (e) NEIN and (f) PENIN.

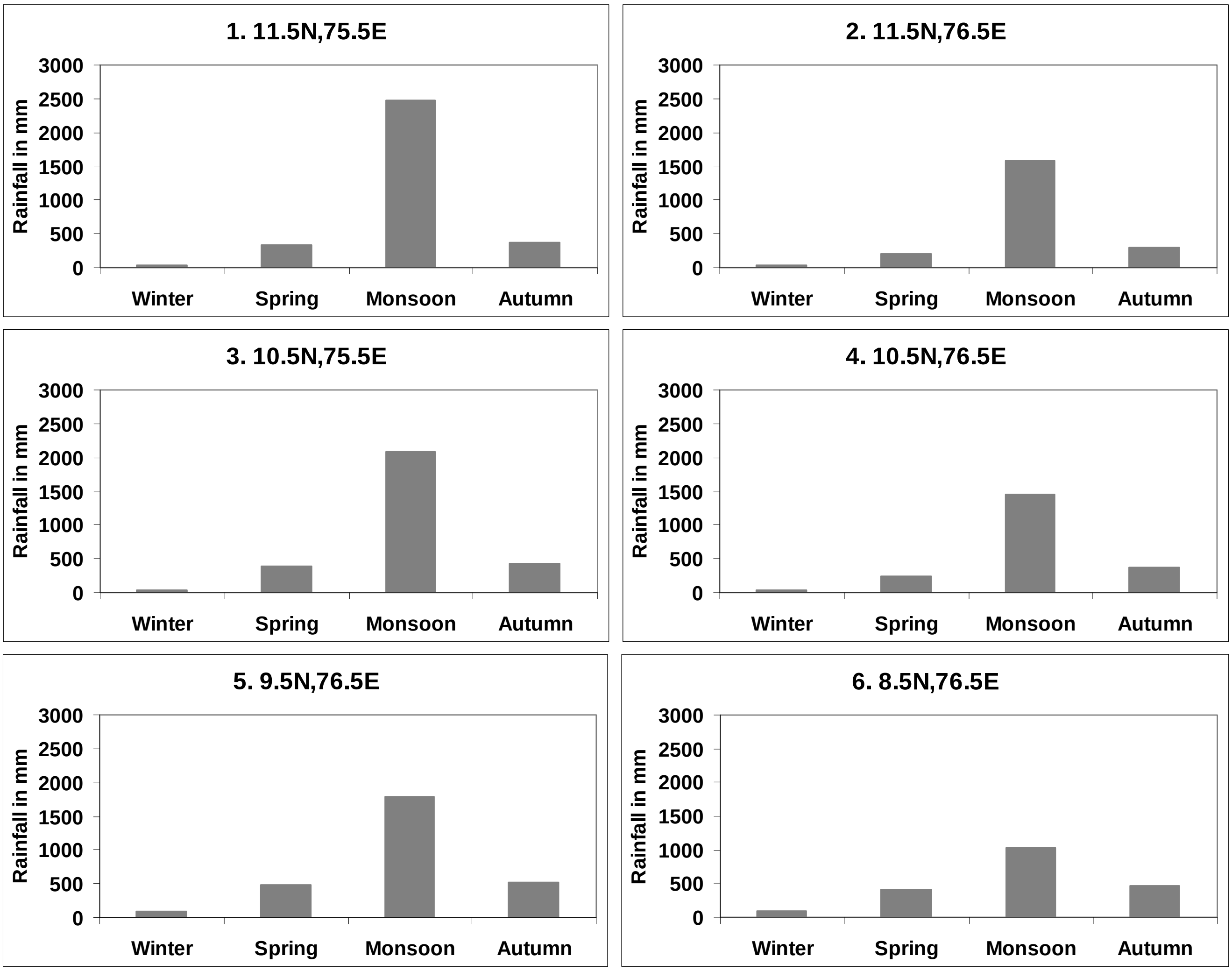


Figure 3.24: Seasonal distribution of rainfall in various gridded regions of Kerala based on daily rainfall data for 1954-2003.

3.6.3. Trends in Various Seasonal Rainfalls in the States of Peninsular India

Figure 3.25 shows trends in seasonal and annual rainfall in various regions in peninsular India based on the parametric OLS method and daily rainfall data from 1954-2003. Table 3.9 shows the comparison between the magnitudes and the directions of the trends corresponding to various regions in peninsular India. The table shows the results of both parametric study (relating to the trends shown in Figure 3.25) as well as those based on the non-parametric (NP) method estimates. As seen in Table 3.8 before and also noted in Table 3.9 that the differences between the parametric and non-parametric trend estimates are very consistent, with a few exceptions which are not significant.

Figure 3.25, and the corresponding results in Table 3.9, shows that the winter rainfall (winter monsoon) has statistically significant increasing trend (pink colour) in coastal Andhra Pradesh and increasing tendencies (green colour) in Rayalaseema, Tamilnadu, South Interior Karnataka and Kerala covering most of peninsular India. This indicates an increase in north-eastern monsoon rainfall activity in this region. Since no specific studies have been reported so far on the cause of winter rainfall increase in these regions, there have been some speculations reported that change in ENSO phenomena could be a probable reason; since Zubair et al. (2008) found some positive correlations of October to December rainfall increase in southern India and Sri Lanka, and El-Niño events.

The spring seasonal rainfall has statistically significant negative trends (blue colour) in most of the regions in peninsular India, which include Tamilnadu, Coastal Karnataka, South Interior Karnataka and Kerala. The pattern of rainfall decline in the spring season (March-May) in peninsular India is consistent with the autumn (March-May) in Australia (Murphy and Timbal, 2008). No region shows statistically significant trends in the monsoon and autumn rainfall in the period of 1954-2003 but there are decreasing and increasing tendencies in various regions (yellow and green colours). Although a significant decreasing trend in monsoon rainfall has been reported in Kerala and significant increase in coastal Andhra Pradesh and Rayalaseema in 1901-2003 (Guhathakurta and Rajeevan, 2008), Figure 3.25 shows only decreasing tendencies in monsoon rainfall everywhere in peninsular India. Kerala and South Interior Karnataka are hence undergoing significant decreases in annual rainfall, as seen in Figure 3.25 with the linear trends in annual rainfall in these regions being within -62.3 to -78.3mm and -27.6 to -30.7mm/decade respectively (in Table 3.9).

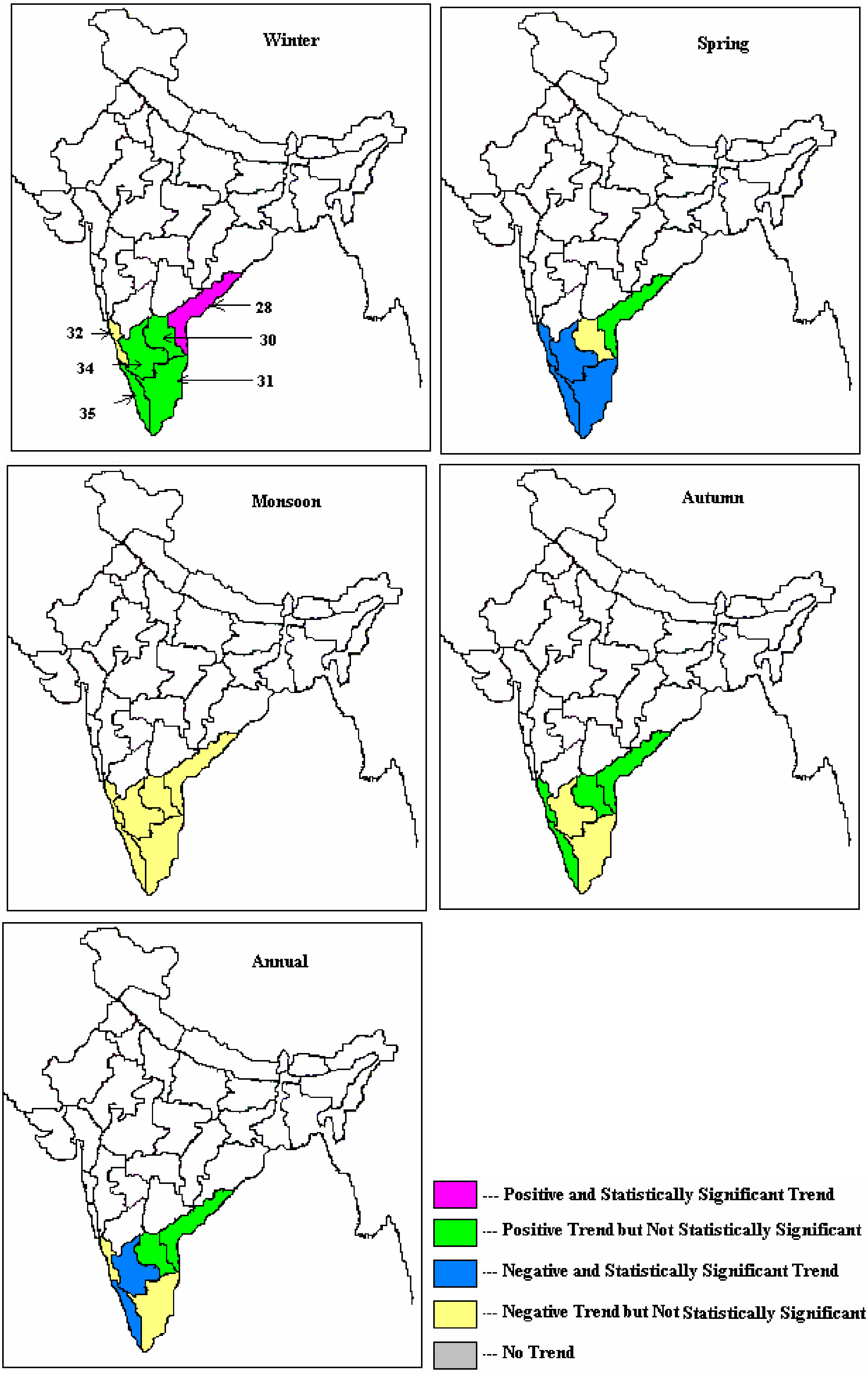


Figure 3.25: Trends in seasonal and annual rainfall using OLS technique based on rainfall data from 1954-2003 in various regions in peninsular India.

Table 3.9: Magnitudes and directions of trends (mm/10years) in seasonal and annual rainfall in various regions in peninsular India using parametric (P) and non-parametric (NP) techniques.

Region		***Winter***		***Spring***		***Monsoon***		***Autumn***		***Annual***	
		P	***NP***	***P***	***NP***	***P***	***NP***	***P***	***NP***	***P***	***NP***
28	Coastal Andhra Pradesh	**+ 9.2**	**+ 5.6**	+ 4.4	+ 2.1	- 13.5	- 17.5	+ 5.6	+ 7.1	+ 7.4	+ 10.9
30	Rayalaseema	+ 1.8	+ 0.1	- 2.4	- 0.8	- 2.7	- 9.6	+ 11.2	+ 10.8	+ 7.5	+ 6.7
31	Tamilnadu	+ 5.6	+ 0.9	**- 7.5**	**- 5.9**	- 2.8	- 4.6	- 7.7	- 8.0	- 15.8	- 20
32	Coastal Karnataka	- 4.7	No Trend	**- 35.8**	**- 26.1**	- 1.3	+ 27.5	+ 8.0	+ 5.4	- 33.9	+ 1.4
34	South Interior Karnataka	+ 0.7	+ 0.2	**- 14.3**	**- 12.8**	- 11.9	- 9.5	- 5.0	- 1.9	**- 30.7**	**- 27.6***
35	Kerala	+ 0.8	+ 0.09	**- 48.5**	**- 45.5**	- 47.1	- 42.5	+ 17.0	+ 21.2	**- 78.3**	**- 62.3***

Note: numbers in first column = subdivision number in Figure 2.4; P = parametric method estimates; NP = non-parametric method estimates; + ve sign = increasing trend; – ve sign = decreasing trend; bold numbers indicate significant trends at the 95% level and bold * indicates significant trends at 90%.

3.6.4. Trends in Various Seasonal Rainfalls in Different Climatological Regions in and All Over India

Table 3.10, similar to Table 3.9, shows a comparison between the magnitudes and the directions of the trends in seasonal and annual rainfall in the five different regions in India and all India, using the symbols as defined in Figure 2.4 using both the parametric and non-parametric analyses. Figure 3.26, similar to Figure 3.25, displays the 5 panelled diagram of the trends corresponding to the parametric OLS method only. Table 3.10 reveals that the trend estimates corresponding to both parametric and non-parametric methods are consistent except for a few non-significant trends, as was also noticed in Tables 3.8 and 3.9. Figure 3.26 shows that west-central Indian (WCIN) monsoon rainfall has statistically significant decreasing trends, which agrees well with the recent snow accumulation experiment results that revealed the decreasing trend in monsoon rainfall (Duan et al., 2006). The same authors also observed a negative correlation of Indian monsoon rainfall with the northern hemisphere temperature changes. Also, significant decreasing trends corresponding to the west central Indian monsoon rainfall agree with Ramesh and Goswami (2007), who found a decreasing trend of temporal length and spatial coverage of the Indian summer monsoon over the period of 1951-2003 affecting the monsoon rainfall changes in the same period.

Table 3.10: Magnitudes and directions of trends (mm/10years) in seasonal and annual precipitation in various regions of India using parametric (P) and non-parametric (NP) techniques.

Region	Winter		Spring		Monsoon		Autumn		Annual	
	P	NP	P	NP	P	NP	P	NP	P	NP
ALLIN	+ 1.8	+ 0.9	+ 1.3	+ 1.3	- 14.1	- 13.8	- 1.8	- 0.25	- 13.1	- 13.0
NWIN	+ 1.5	**+ 1.5**	+ 2.7	**+ 2.3**	- 17.6	- 18.7	- 3.2	- 1.4	- 17.2	- 19.0
WCIN	+ 1.3	+ 0.3	**- 3.4**	**- 3.8**	**- 30.0**	**- 31.9**	+ 0.6	+ 0.5	**- 31.4**	**- 31.1**
CNEIN	+ 0.9	+ 0.2	**+ 9.7**	**+ 9.6**	+ 3.9	+ 3.1	- 8.0	- 6.5	+ 6.5	+ 13.4
NEIN	+ 2.5	+ 1.3	**+ 16.3**	**+ 18.2**	+ 7.3	+ 1.8	N/T	+ 2.5	+ 26.0	+ 28.7
PENIN	+ 3.9	+ 0.5	**- 10.4**	**- 11.0**	- 10.7	- 13.7	+ 1.4	+ 2.2	- 16.7	- 19.8

Note: P = parametric method estimates; NP = non-parametric method estimates; + ve sign = increasing trend; – ve sign = decreasing trend; bold numbers indicate significant trends at the 95% level and bold * indicates significant trends at 90%.

Goswami et al. (2006), on the other hand, used the daily rainfall data (discussed in section 2.2.1) for central India (parts of WCIN and CNEIN) to show that there was an increase in the frequency and intensity of heavy rain events, and a decrease in the frequency of light to moderate rain events in the monsoon seasons from 1951 to 2000. Therefore, the decrease in light to moderate showers in WCIN could also have offset the increasing contribution from heavy events and donated to the decreasing monsoon rainfall in this region. On the other hand, an increasing tendency of monsoon rainfall in central north east India (CNEIN), as in Figure 3.26, could be because of an increase in heavy rainfall intensities in that region, as per Goswami et al. (2006), and regional warming of Sea Surface Temperature (SST) over the Indian Ocean, which seems to have enhanced the monsoon rainfall mainly over the Indian Ocean and reduced the rainfall over northeast India (Singh and Oh, 2007).

Figure 3.26 shows disagreement with Goswami et al. (2006) and Dash et al. (2007)'s findings that ALLIN monsoon rainfall in the period of 1871-2005 has no trend, and that in CNEIN and NEIN has decreasing monsoon rainfall trends. It also has disagreement with the results of change in monsoon droughts and floods in sections 3.1 and 3.2. The possible explanation of such disagreements could be the variation of the study time interval. These mismatches due to the usage of different study time intervals are due to a brief increase of monsoon rainfall which occurred in 1880-1920 that might have been compensated for by the decrease in the same in the period 1920-1995, which made different trend results for 1871-2005 (Duan et al., 2006).

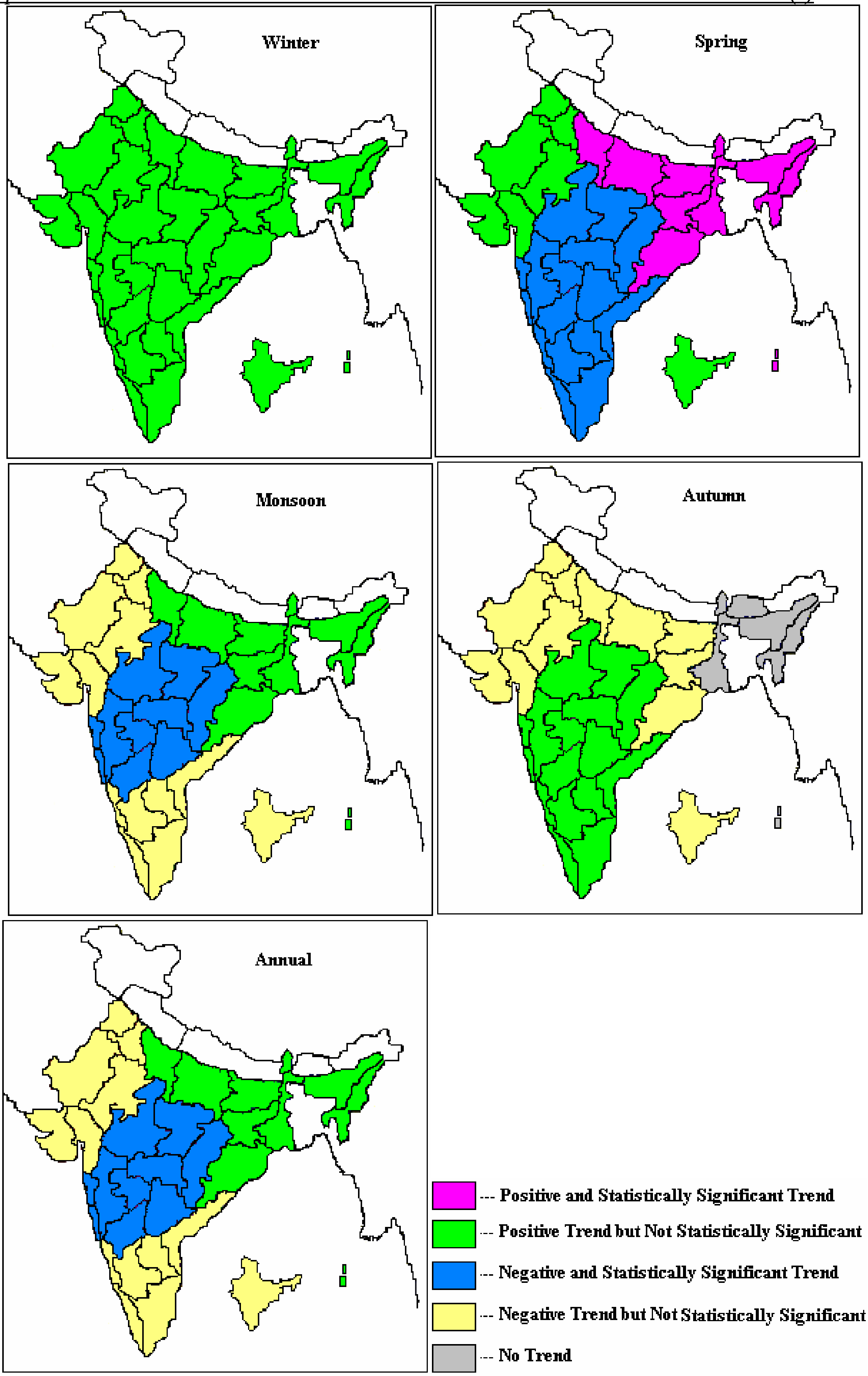


Figure 3.26: Trends in seasonal and annual rainfall in various regions in India using parametric OLS technique based on rainfall data from 1954 to 2003 (small India maps inside every block indicate average all-India change).

Spring rainfall shows uneven results with statistically significant decreasing trend in WCIN and PENIN suggesting decreasing convective activities which is the main cause of spring rainfall over these regions; whereas, in CNEIN and NEIN, increasing trends in spring rainfall were noticed, as in Figure 3.26, which suggest that the convective activities are increasing in these regions. Since most of the regions in peninsular India showed statistically significant decrease in spring rainfall, as demonstrated in Figure 3.25, overall average of spring seasonal rainfall amount in peninsular India exhibits significant decrease in this season, as shown in Figure 3.26.

Winter rainfall is seen to have an increasing tendency everywhere in India. This increase in winter rainfall is possibly due to increase in extreme rainfall in this season through out the country (Revadekar and Kulkarni, 2008). Autumn rainfall has increasing tendency mainly in WCIN and PENIN but decreasing tendency in the other regions except for NEIN which has no trend. Singh et al. (2008) found maximum increasing trend in post-monsoon or autumn rainfall over central India, which agrees with this study.

In WCIN, a statistically significant negative trend in annual rainfall was noticed. The reasons behind the decrease in annual rainfall in WCIN could be the shrink in the monsoon period (Ramesh and Goswami, 2007), the increase in dry days or the significant decrease in the July rainfall (Guhathakurta and Rajeevan, 2008) in this region.

The results in section 3.6 have been submitted for publication (Pal and Al-Tabbaa, 2009c).

3.7. Analysing Monsoon Daily Rainfall Extremes in Kerala Using Parametric OLS

3.7.1. Introduction

Climate change has the potential ability to alter the occurrence and severity of daily extreme events. Although predicting changes of such extreme events is difficult, understanding them is important to determine the impacts of climate change in various sectors. Given the present global interest and importance of probable trends in daily extreme rainfall events, this part of the study detects the changes in long-term daily extreme monsoon rainfall using existing data, based on the premise that the trend in magnitude of rainfall extremes is likely to be more sensitive to climate change. This study would also provide an idea on whether the tendency of change in monsoon rainfall in Kerala is affected by the extremes.

Previous studies that assessed statistically significant tendencies of rainfall extremes in India were very limited in numbers (those mentioned in section 2.2.1) and were based on spatially averaged conditions for a significantly large part of the country (Goswami et al., 2006). However, spatial averages may bias area-specific studies. Therefore, this part of the study concentrates on the Kerala region. The six separate gridded regions comprising the whole state of Kerala, presented earlier in Figure 3.19, are also used here. Although Soman et al. (1988) studied station-based data for all over Kerala region; their study does not go beyond 1980s.

Only the second half of the 20th century (1954-2003) is again considered here. The high resolution daily gridded data that was discussed in section 2.2.1 and showed previously in Figure 3.20 was used for this part of study. A range of rainfall extreme indices were utilised here that would give a clear picture of the changing extremes in Kerala. The trends of monsoon rainfall extreme indices, which could be considered as an indicator of climate change at local scales, were assessed using the parametric OLS method. The significance of all the trends was tested for the 95% level. Trends that are not significant are marked in the tables.

This study takes a further step towards a detailed comprehensive knowledge on the statistics of extreme monsoon rainfall, which would also help in the prediction of future risks of extreme events of any given severity and provide an evidence-based scientific advice for the integrated risk assessment of extremes in the Kerala state, which could further be applied to other locations. Among the various types of generally used or region-specific indices found in the literature and discussed in the last chapter (section 2.4.1.6 and 2.4.1.10 and Tables 2.2 and 2.3), three types of indices were considered in this study, as follows:

Percentile-based indices: the amount of rainfall falling above the 95th and 99th percentile, absolute indices: maximum 1-day and 5-day rainfall amounts, and threshold-based indices: rainfall frequencies, based on fixed thresholds, and a range of extreme indices, based on variable thresholds that vary from location to location depending on the time series used. All the indices were estimated for the monsoon seasons.

3.7.2. Percentile-Based and Absolute Indices

The total annual quantities of rainfall above the long-term average 95th and 99th percentiles of daily monsoon rainfall for each of the six regions in Kerala were computed over the 50 year period of 1954 to 2003 and their variation and tendencies are shown in Figures 3.27 and 3.28 respectively. The figures show that there are decreasing tendencies of the total quantity of extreme rainfall at 7 out of the 12 cases presented. However, in some cases the results showed increasing (although not significant) trends as well i.e. regions 3 and 5 in both figures, where very high amount of rainfalls contributed from the extremes were observed in the 1990s.

A sharp decrease is noticeable at regions 1 and 4 (Figures 3.27 and 3.28) which is of the order of 40-80 mm/decade for the former region and 91 mm/decade for the latter region; both trends were found to be statistically significant at the 95% level. A significance test only for the most recent decades i.e. 1979-2003 however revealed a statistically significant (93% significant) increasing trend in total rainfall of the extremes in region 5; the magnitude being 147 mm/decade, as shown in Figure 3.29(a). Also, the magnitude of statistically significant (97% significant) negative trend in region 4 in 1979-2003 was four times the value for 1954-2003 (163 mm/decade), as shown in Figure 3.29(b). Therefore, strong change in climate since the late 70's is observable.

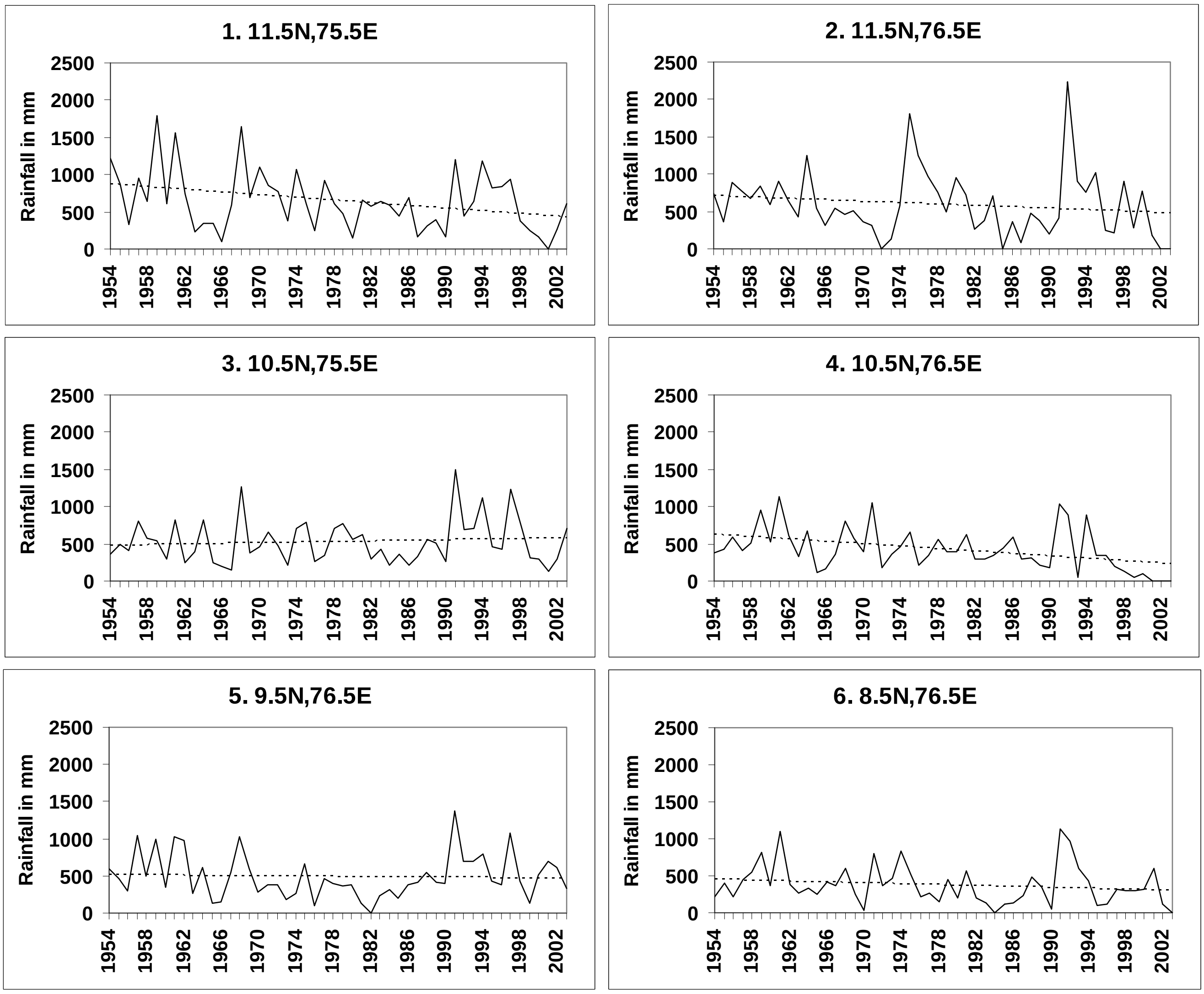


Figure 3.27: Variation of total amount of extreme rainfall above 95 percentile and their trends in the study regions of Kerala in 1954-2003.

The variation of maximum 1-day and 5-day monsoon rainfalls and their tendencies in the six study regions of Kerala are shown in Figures 3.30 and 3.31 respectively. The trends exhibit a similar pattern of negative tendencies, as noticed in Figures 3.27 and 3.28. Only region 1 shows exception for the case of 1-day maximum but the trend is not significant (Figure 3.30). As Figure 3.30 shows, region 1 has been experiencing exceptionally high rainfalls in a day since the 1990s as compared to the previous records. Statistically significant sharp decreasing trends in the 5-day maximum rainfall were noticed for regions 2 and 4, as in Figure 3.31, and negative but not significant and no trends were observed for the other four regions.

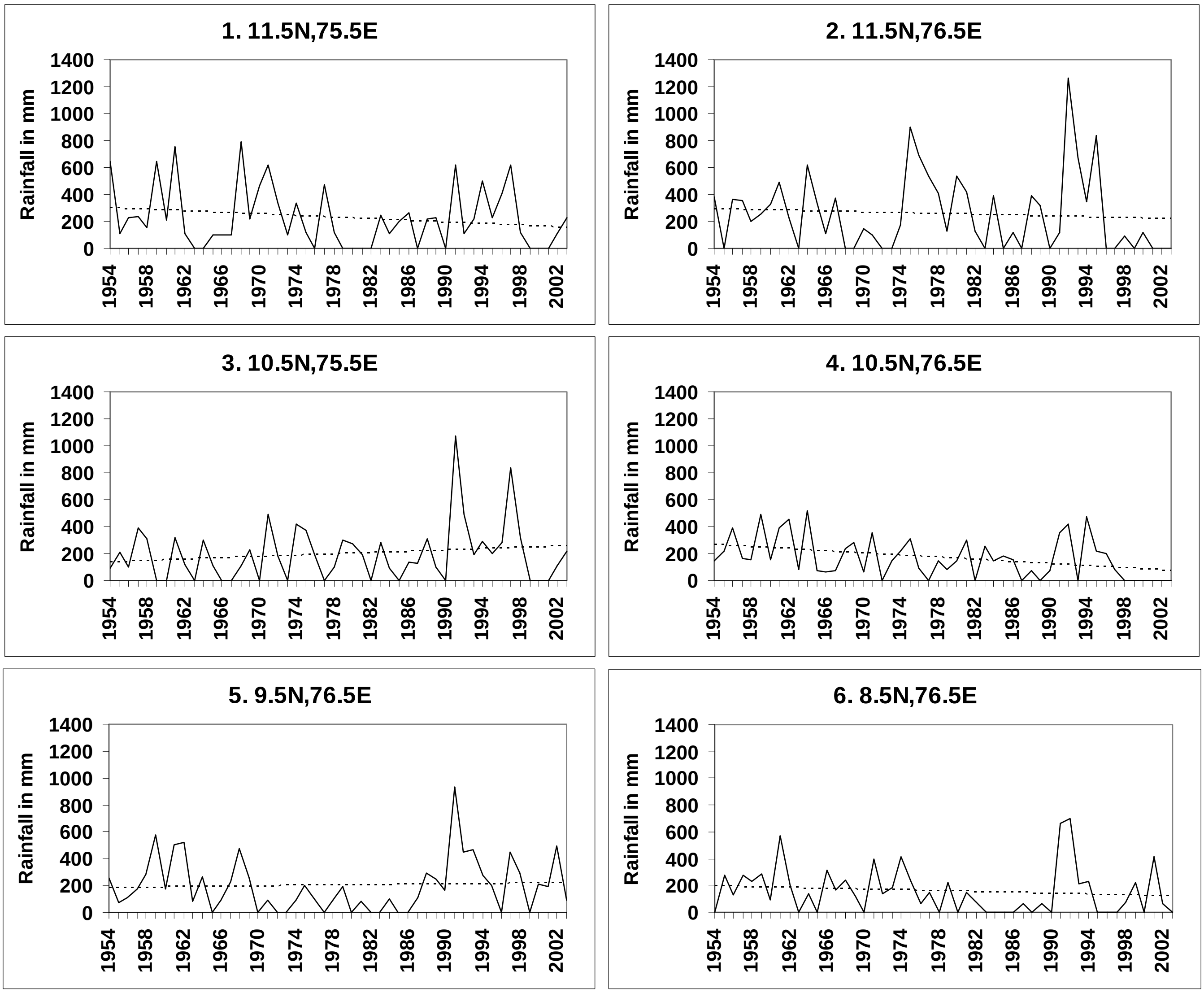
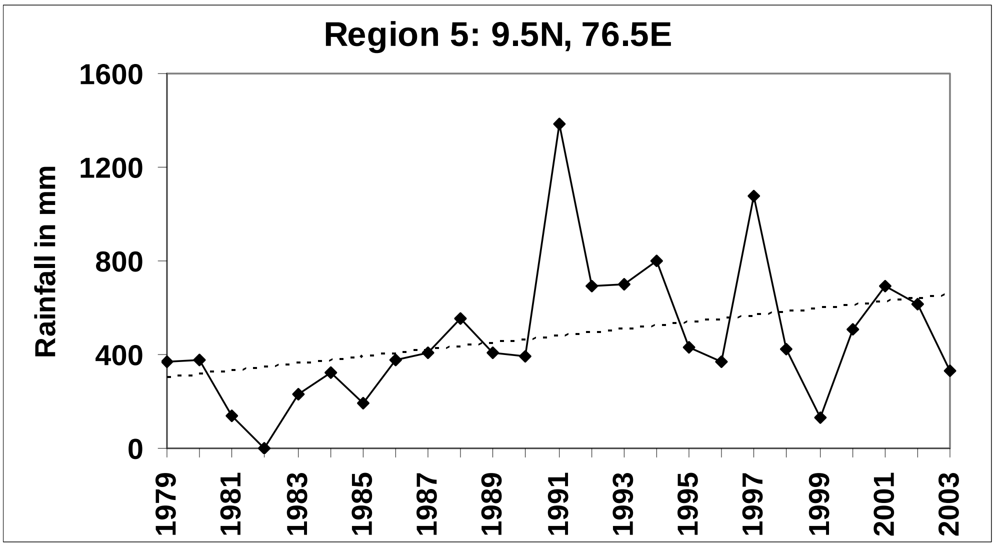
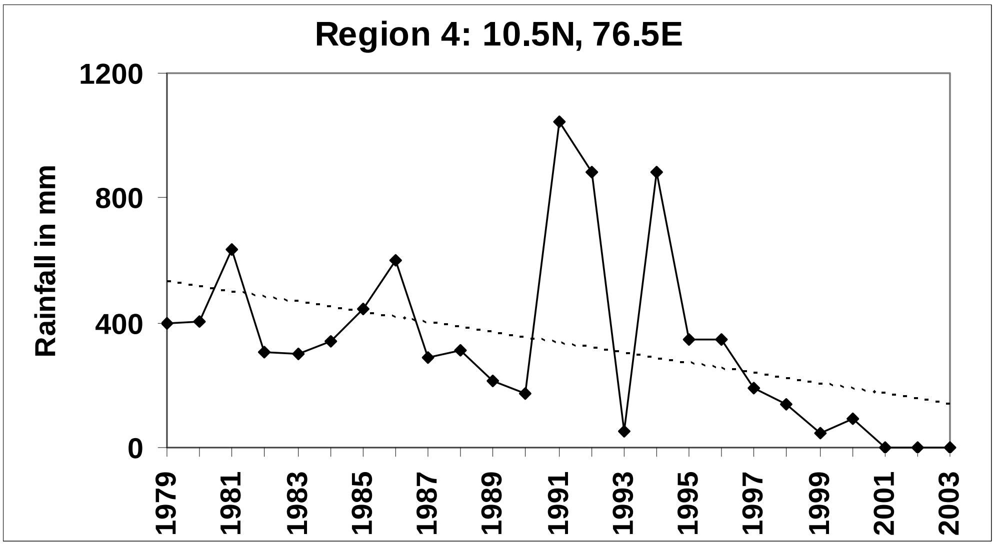


Figure 3.28: Variation of total amount of extreme rainfall above 99 percentile and their trends in the study regions of Kerala in 1954-2003.

The results in this section indicate that rainfall extremes are indeed changing in Kerala. However, the changes are irregular and location specific. The results corresponding to most changes apparent in the current decades and after 1979 are also coherent with the World Meteorological Organisation (WMO) report (Lau and Wu, 2007). Statistically significant differing trends of extremes at two neighbouring places conclude that while one area goes through sudden flash flooding, water shortage could be expected in the other area at the same time. Therefore, before any engineering projects commence in any area in Kerala, a location-specific regional analysis and study for a step change is important. Further studies in the following sections (3.7.3-3.9) confirm these findings.



(a)



(b)

Figure 3.29: Variation of total amount of extreme rainfall above 95 percentile and their trends in (a) 9.5N, 76.5E and (b) 10.5N, 76.5E in Kerala in 1979-2003.

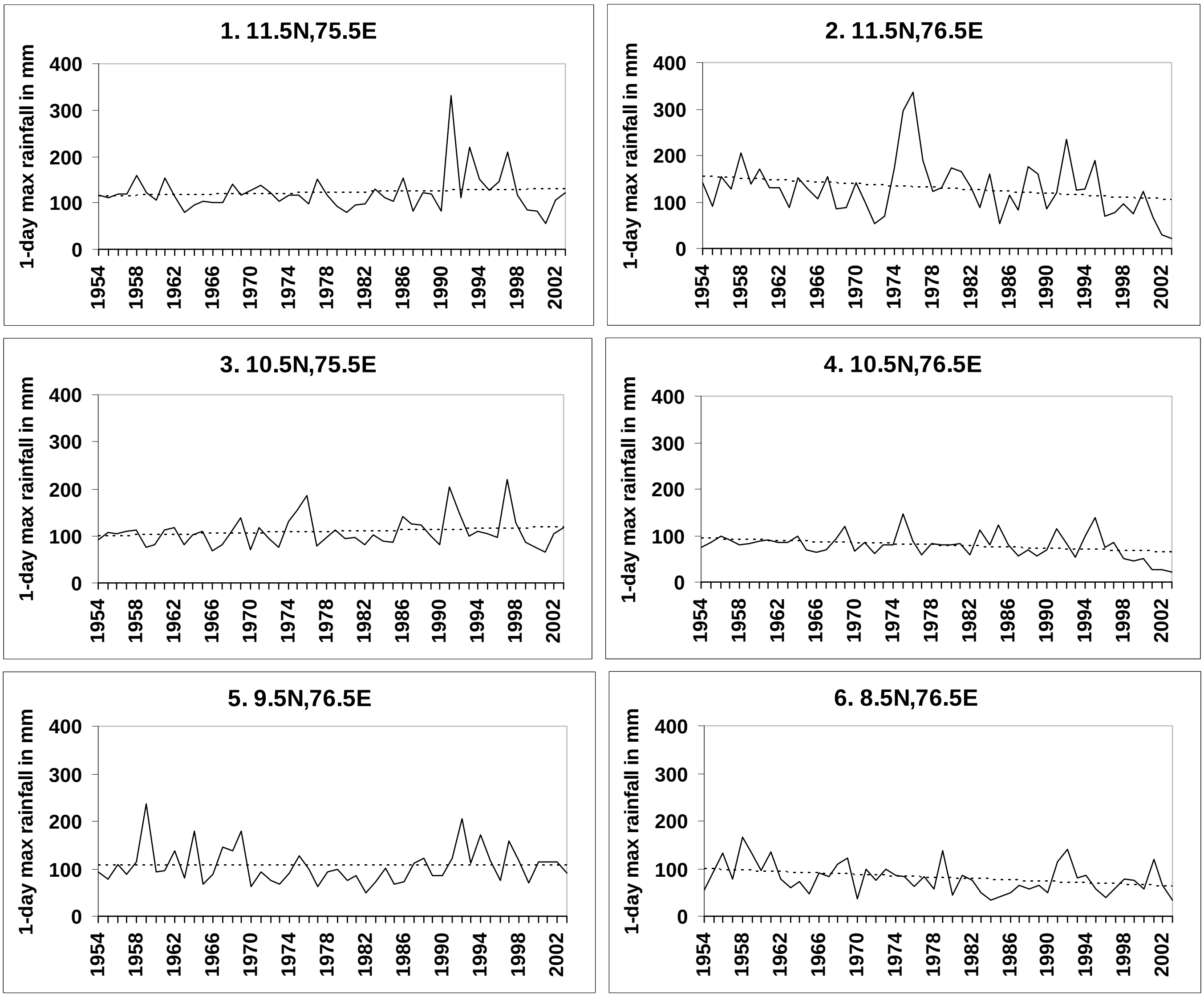


Figure 3.30: Variation of maximum 1-day monsoon rainfall and their tendencies in the study regions of Kerala in 1954-2003.

3.7.3. Threshold-Based Indices

3.7.3.1. Definitions

Threshold-based indices are categorised based on spatially fixed and spatially variable thresholds. Spatially fixed thresholds are used to classify the daily rainfalls in monsoon seasons for all the grid points in Kerala. These are typically defined as: ‘low-moderate’ daily rainfall events that have magnitudes of 5-100mm, ‘heavy’ rainfall events that have magnitudes ≥100mm/day and 'extreme' rainfall events that have magnitudes ≥150 mm/day (Goswami et al., 2006).

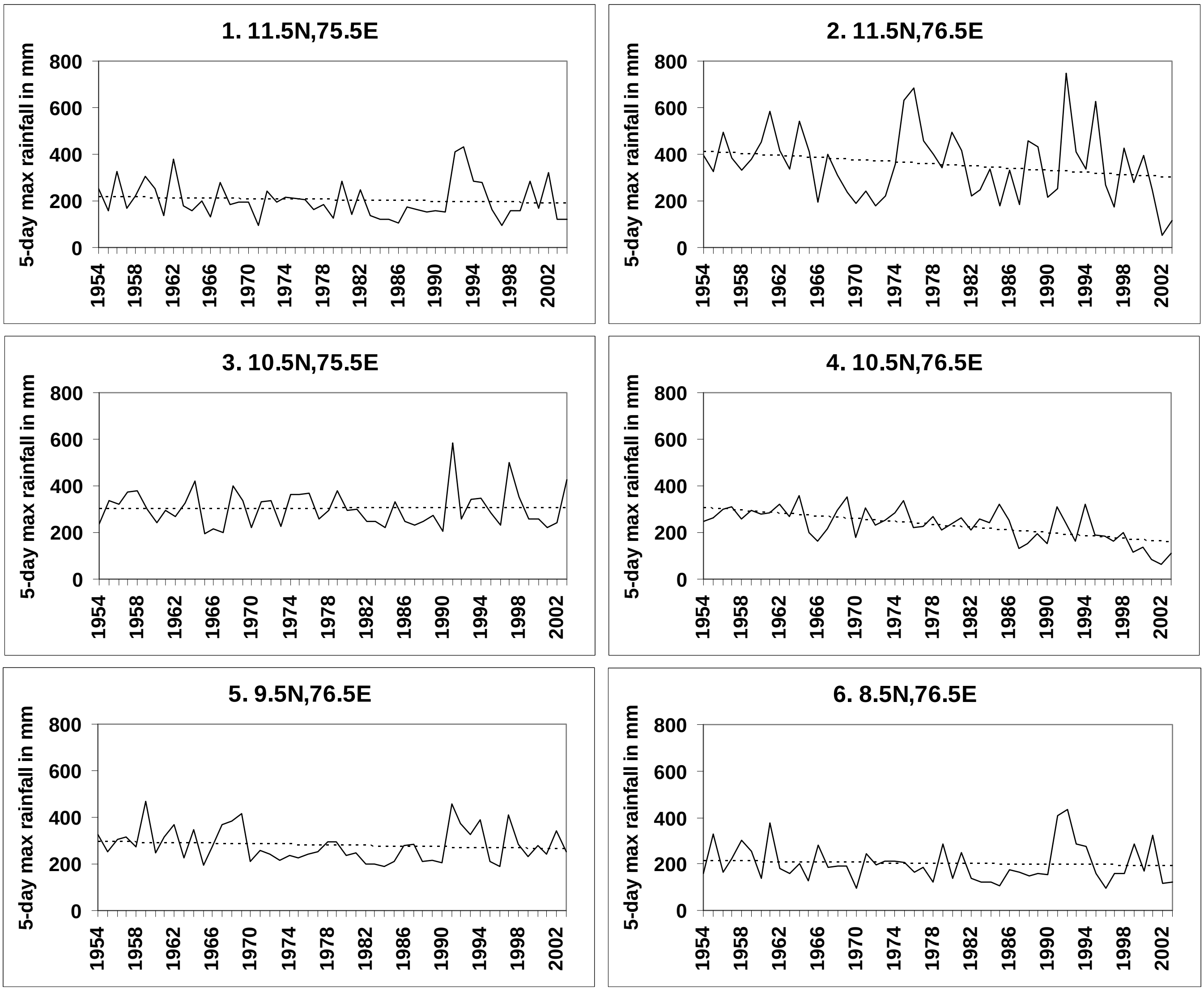


Figure 3.31: Variation of maximum 5-day monsoon rainfall and their tendencies in the study regions of Kerala in 1954-2003.

These definitions of the fixed threshold-based indices however may not be meaningful for the spatially variable monsoon rainfall characteristics in Kerala. Therefore, extreme rainfall indices based on spatially variable thresholds are also considered in this study, namely extreme rainfall frequency, extreme rainfall intensity and extreme rainfall percent (to be defined in section 3.7.3.3). The spatially variable thresholds vary in absolute magnitude from site to site but are the lower bound of the extreme event magnitudes in corresponding regions. For these variable threshold-based extreme indices, only the typical time series of the days with ≥1mm rainfall are considered in order to avoid any artificial trends.

3.7.3.2. Extreme Rainfall Indices Based on ‘Fixed’ Thresholds and their Trends

Frequencies of various category rainfalls, as defined above, were computed for the monsoon season in the six regions of Kerala in order to detect changes that do not reflect in the seasonal means. Table 3.11 summarises the total number of various category rainfall events which occurred within 1954-2003. The table illustrates that, not all the grids experienced a similar number of rainfall events in the 50 years considered. The maximum number of ‘extreme’ rainfall events occurred in location 2 which was much higher, almost three times, that of the next highest which was region 1.

Table 3.11: Number of rainfall events in the monsoon months in the study regions of Kerala in 1954-2003.

Region		*‘low-moderate’*	*‘heavy’*			*‘extreme’*
			Total no. in 1954-2003	*Total no. in 1954-1978*	*Total no. in 1979-2003*	
1	11.5N,75.5E	3865	90	60	30	8
2	11.5N,76.5E	2881	84	46	38	22
3	10.5N,75.5E	3826	46	21	25	5
4	10.5N,76.5E	3199	6	2	4	0
5	9.5N,76.5E	3552	29	10	19	6
6	8.5N,76.5E	2398	17	9	8	1

The total amount of ‘extreme’ rainfalls based on fixed threshold and their tendencies in all six grids are shown in Figure 3.32. The figure shows that the total amount of extreme rainfall (≥150 mm/day) at both regions 2 and 1 show positive trends (not statistically significant). The figure also shows that frequencies were highest since 1979. No ‘extreme’ events occurred in the immediate south neighbourhood grid 4 and very few occurred in other regions. The analysis shows that, among the total of 42 ‘extreme’ events which occurred in the whole of the Kerala region in 1954-2003, 17, i.e. ~ 40% of the total number occurred in the 90's. That means that rare extreme events have had a greater tendency to occur in recent years.

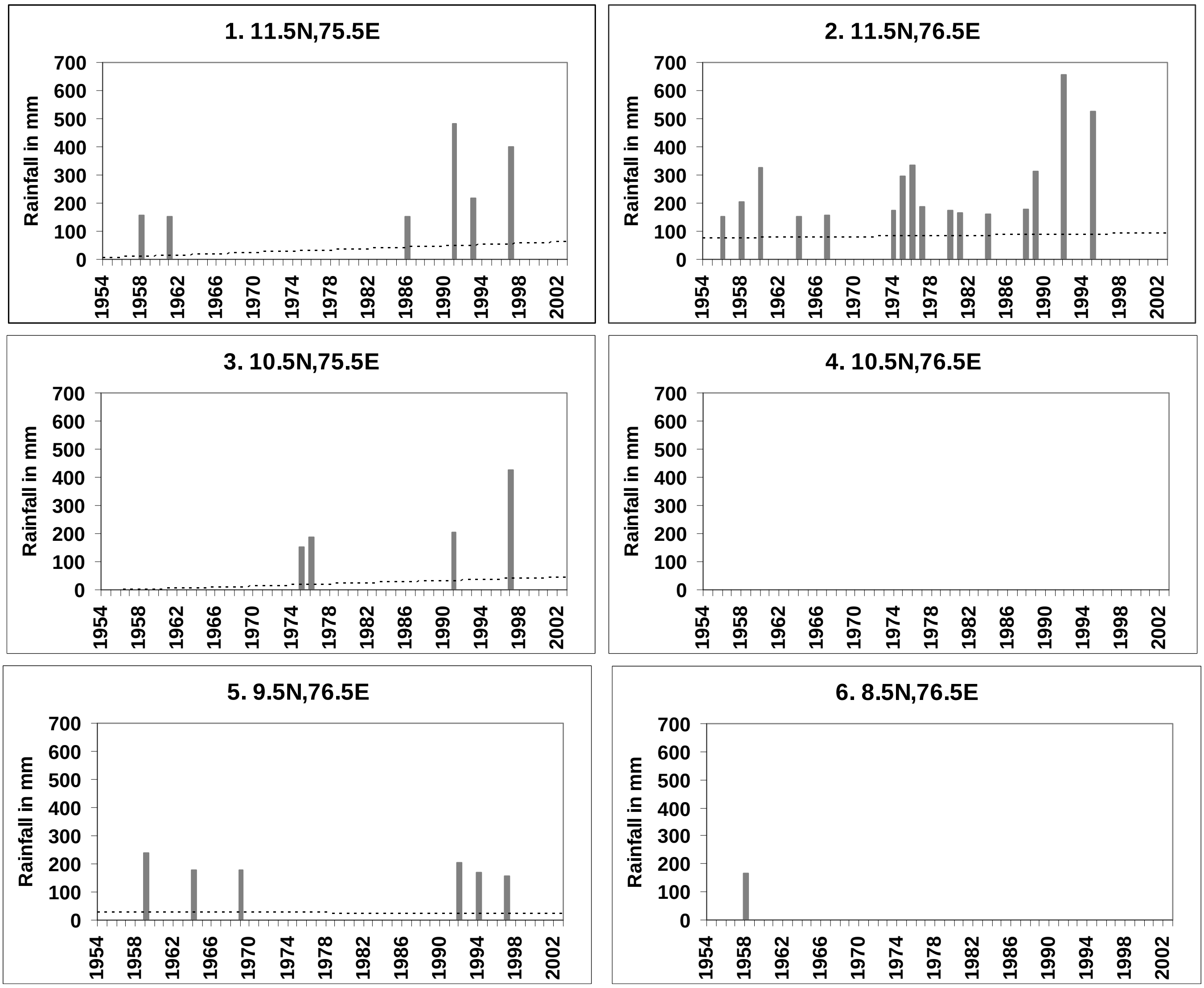
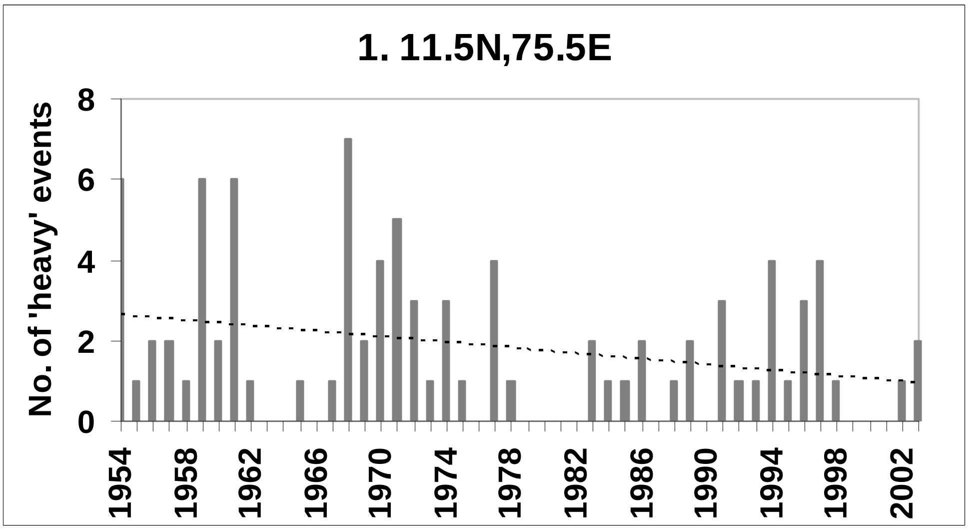


Figure 3.32: Total amount of 'extreme' rainfalls (≥150 mm/day) and their tendencies in the study regions of Kerala in 1954-2003.

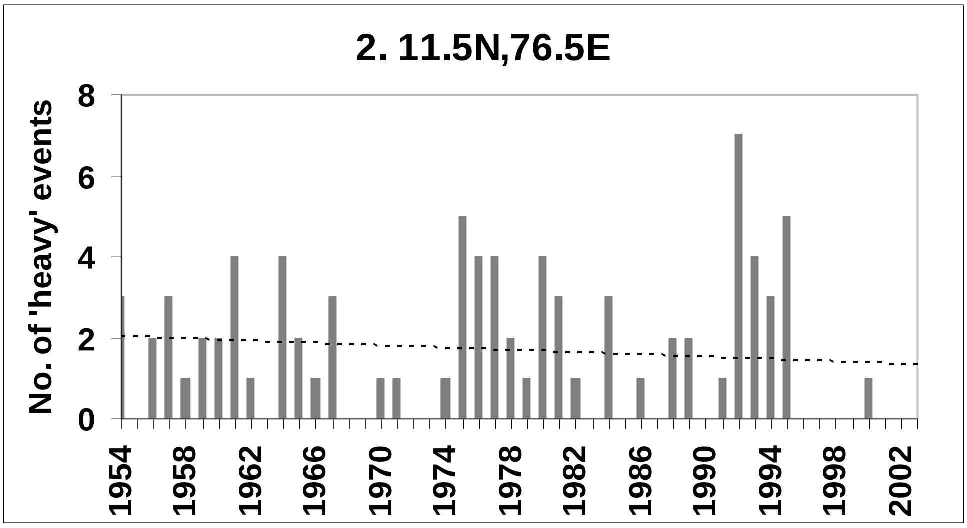
Table 3.11 and corresponding results in Figure 3.32 also shows that no. 4 grid which had zero 'extreme' rainfall events in the 50 years considered, experienced very few 'heavy' rainfalls as well but that the number of 'low-moderate' rainfall events was relatively high and comparable with its neighbourhood regions. This means that 'heavy' to 'extreme' rainfalls, as characterised here, are 'rare' in this region. It is also noticed that region 1 (11.5N,75.5E) is the grid that experienced the most ‘heavy’ and ‘moderate’ rainfall events in the studied 50 years; followed by region 2 (11.5N,76.5E), whereas ‘low-moderate’ rainfall events in grid 2 were lesser in number compared to grid 4 that had the least number of ‘heavy’ events. Trend estimates corresponding to the number of ‘heavy’ and ‘extreme’ events might be biased because most are significantly less in numbers i.e. ‘rare’ and therefore it is very difficult to quantify their risk (Palmer and Raisanen, 2002). Therefore, trend assessment was carried out for the grids that had at least, on average, one ‘heavy’ event per year; whereas trends of frequency of ‘extreme’ events were not considered. It was found that only gridded regions 1 and 2 fell in this criterion, as noted in Table 3.11.

Figure 3.33 displays the trends of ‘heavy’ rainfall frequencies in regions 1 and 2. It is noted from the figure that a negative trend is seen in both regions 1 and 2, indicating that in both regions the number of ‘heavy’ rainfall events are reducing. The significance test confirms that the decreasing trend in gridded region 1 was significant but not in 2 probably because a sudden high number of ‘heavy’ rainfall events occurred in region 2 in the early 1990s. However, interestingly, trends of total rainfall corresponding to ‘heavy’ events are becoming variable and different from their frequencies, as shown in Figure 3.34. The figure shows that grid 5 exhibits statistically significant positive trend and grid 1 exhibits statistically significant negative trend. However, for the case of grid 1, the trend is exactly the opposite in 1979-2003 and the magnitude of the trend value for grid 5 is greater (~ 3 times) than that for 1954-2003, as shown in Figure 3.35.

Since the above results indicate that the major change in rainfall pattern happened in Kerala during 1979-2003, a study was also carried out to find out whether there was any step change in ‘heavy’ rainfall frequencies in all the study areas. Figure 3.36 and Table 3.11 (column 5 and 6) show the results. It is found in Figure 3.36 and Table 3.11 that the frequency of the ‘heavy’ events has reduced in 1979-2003 in 50% of the areas in Kerala, in a range of 17-50% reduction in the number of events as compared to the number of ‘heavy’ events in 1954-1979. In grids 1 and 2, 60 and 46 events occurred in 1954-1978 whereas only 30 and 38 events in 1979-2003 indicating more possibility of the reduction of the number of ‘heavy’ rainfall events in the current decades; therefore the same could be stated for Kerala as well since these two areas contribute to most 'heavy' rainfall events in Kerala. Considering the above results, with more 'rare' events occurring since the 90's and increasing 'heavy' rainfall amounts in some regions, it can be concluded that, although 'heavy' rainfall frequencies are decreasing, some areas in Kerala are still at risk of flash floods and droughts. Increased risk of droughts is further proved in the paragraph below.



(a)



(b)

Figure 3.33: Trends of 'heavy' rainfall (≥ 100mm/day) frequencies in (a) 11.5N,75.5E and (b) 11.5N,76.5E in Kerala in 1954-2003.

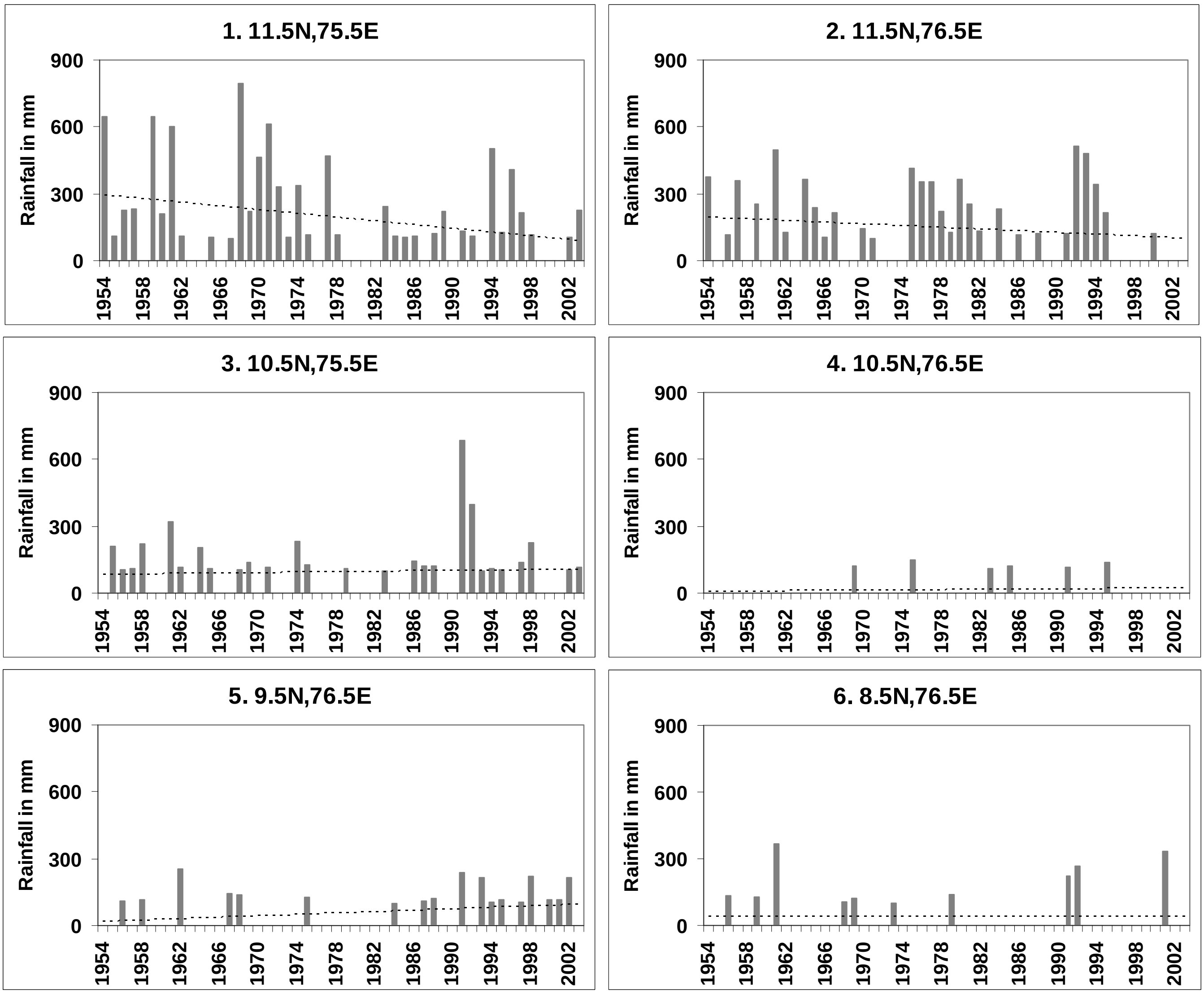


Figure 3.34: Total amount of 'heavy' rainfalls based on fixed threshold and their tendencies in the study regions of Kerala in 1954-2003.

As was seen in Table 3.11, 'low-moderate' rainfalls form a considerable part of the total monsoon rainfall in Kerala. Therefore this is a very important quantitative factor for monsoon water requirement in Kerala. A trend assessment study of the change in the number of 'low-moderate' raindays would provide an insight into the reasons for negative monsoon rainfall trends in the Kerala regions. Figure 3.37 shows the variability in the number of 'low-moderate' raindays in the six regions of Kerala over the period of 1954-2003 in which it can be noticed that all the areas have been undergoing decreasing trends. The trend estimates are summarised in Table 3.12, where in the period of 1954-2003, all areas are significant up to 95% level except grid 2. The range of decrease in 'low-moderate' rainfall event frequencies is 2-7days/decade. The maximum decrease is happening in region 4 with as much as 7days/decade. These decreasing numbers of rain days in Kerala are a symbol of a higher number of meteorological and agricultural droughts.

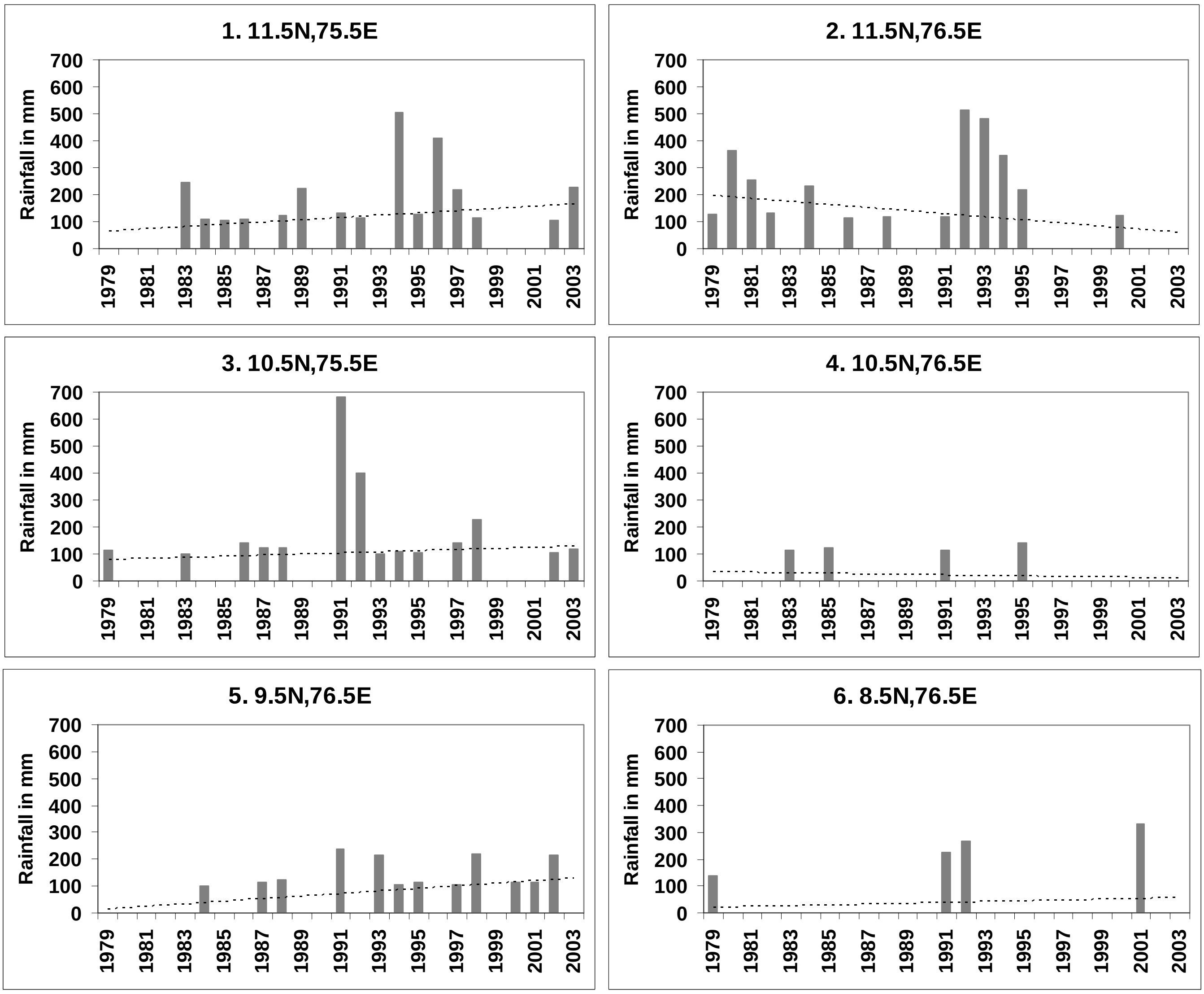


Figure 3.35: Total amount of 'heavy' rainfalls based on fixed threshold and their tendencies in the study regions of Kerala in 1979-2003.

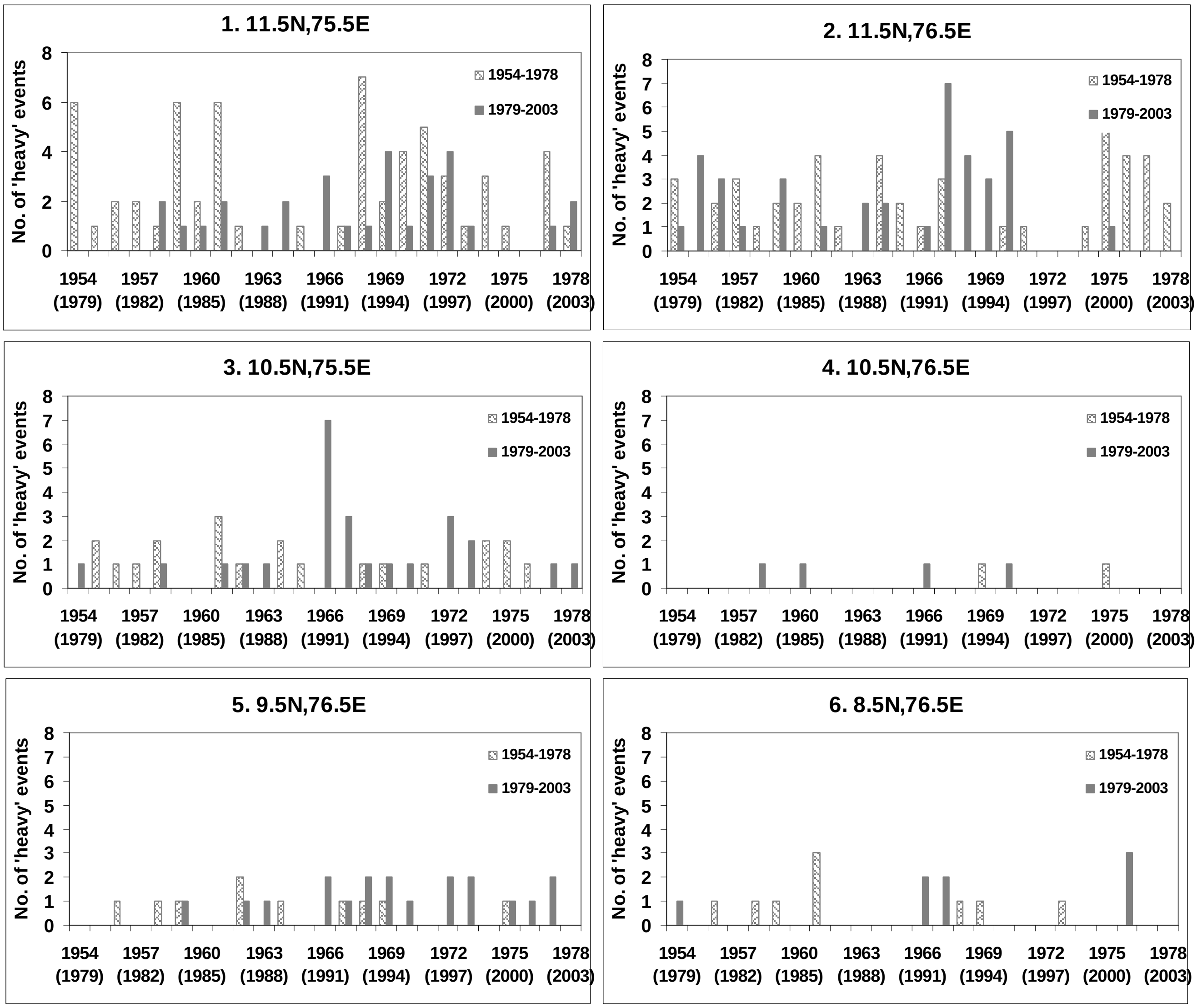


Figure 3.36: Frequencies of 'heavy' rainfall events based on fixed threshold in the study regions of Kerala in 1954-1978 and 1979-2003.

Table 3.12: Trends in rainfall frequencies for 'low-moderate' monsoon seasonal rainfall events at the study regions of Kerala in 1954-2003.

Region		*Raindays (days/decade)*		
		1954-2003	*1954-1978*	*1979-2003*
1	11.5N,75.5E	**- 2**	- 1	**- 7**
2	11.5N,76.5E	- 2	+ 5	- 5
3	10.5N,75.5E	**- 3**	+ 1	**- 5**
4	10.5N,76.5E	**- 7**	- 1	**- 17**
5	9.5N,76.5E	**- 4**	- 2	**- 6**
6	8.5N,76.5E	**- 3**	- 2	- 2

Note: + ve sign = increasing trend; – ve sign = decreasing trend; bold numbers indicate significant trends at the 95% level.

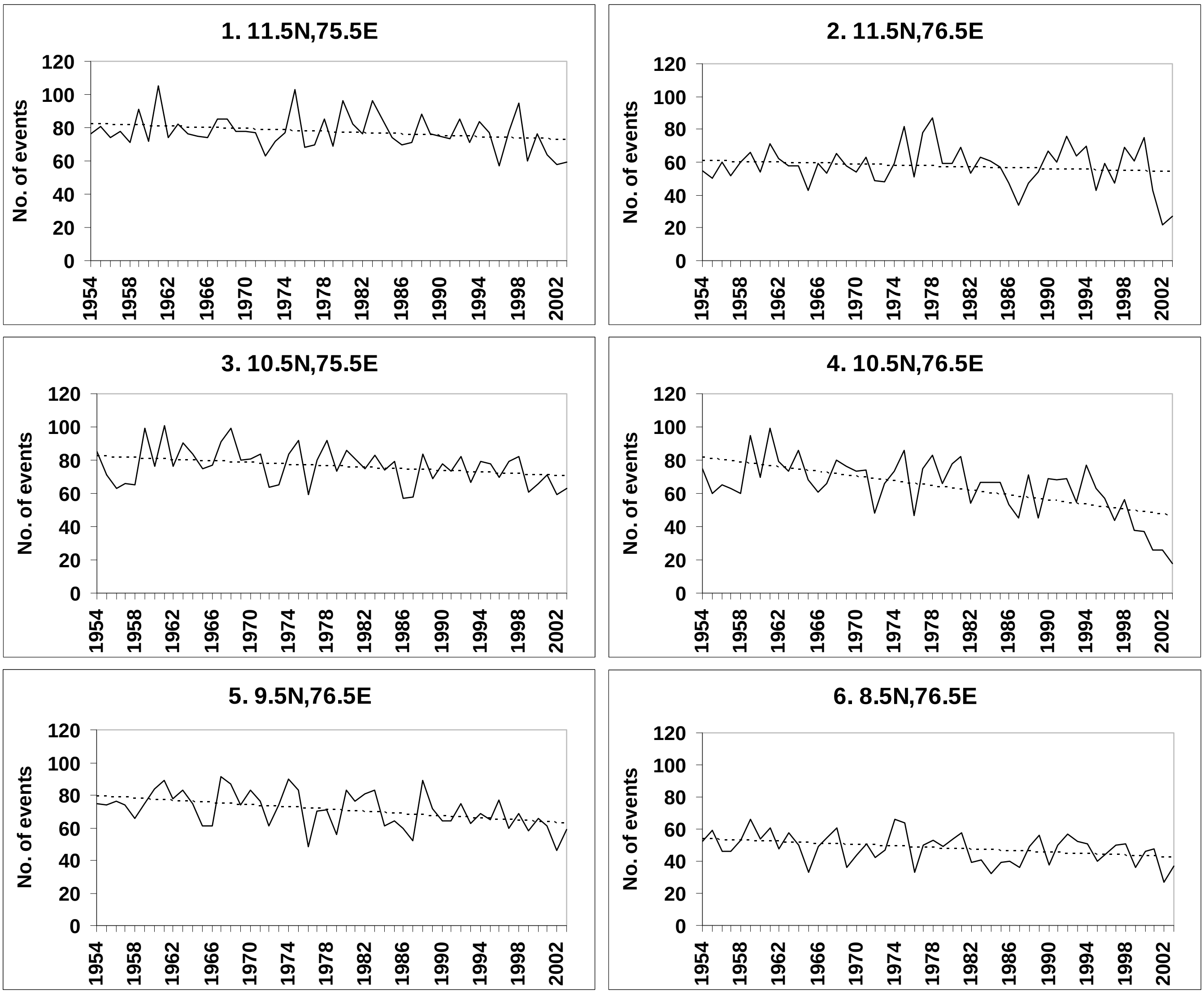


Figure 3.37: Variability and the trends in number of raindays corresponding to 'low-moderate' events in the study regions of Kerala in 1954-2003.

Although most of the trends in the period 1954-2003 in Table 3.12 are statistically significant, it is possible that a linear trend is imposed on a time series by the existence of a step change in the records. WMO warned about the possibility of this kind of misuse of trend techniques that could lead to an insignificant result, even though there is no trend (Kundzewicz and Robson, 2000). To check whether this is the case for Kerala, the time series was again split into the two periods 1954-1978 and 1979-2003 for all the regions, and the trends were estimated for them all. The results for periods 1954-1978 and 1979-2003 are displayed in Table 3.12. Interestingly, for most of the cases, statistically significant changes are observed in the most recent decades; which is also the main deciding factor of the 50-year trend estimated before. In 1954-1978, on the other hand, although tendencies are visible, none are statistically significant. The decrease in 'low-moderate' rainfall frequency is the highest in region 4 in the period 1979-2003.

The quantities of rainfall in the 'low-moderate' categories are shown in Figure 3.38 together with their tendencies which are decreasing in all the regions. All the trends are statistically significant except for regions 2 and 3. In conclusion, 'low-moderate' rainfall is indeed decreasing and this is true for every region in Kerala, which is also consistent with the decreasing trend of 'low-moderate' rainfall in the central Indian region (Goswami et al., 2006).

The above results depict that the Kerala region is very much diversified in terms of the occurrences of the different categories of rainfall events. Hence a particular statistically significant trend found in the rainfall series in one period in one region would not be expected in the rainfall series in its neighbourhoods because of the fundamental statistical limitations and spatial variation which also constitute critical factors for trend detection (Frei and Schar, 2001). So, it is now clear that the local factors play a significant role when studying changes in rainfall.

3.7.3.3. Extreme Rainfall Indices based on 'Spatially Variable' Thresholds and their Trends

3.7.3.3.1. Extreme Rainfall Frequency

Extreme rainfall frequency is defined as the number of events above a spatially variable extreme threshold. The extreme rainfall frequency index examines changes in the number of extreme events and was calculated by counting the number of events in a year with intensities above a threshold. A long-term 95th percentile of the daily rainfall intensity in the monsoon months could be used as a potential threshold to separate extreme events, which varies significantly from year to year and also spatially and therefore a fixed threshold might be impractical for different regions in Kerala. The long-term mean 95th percentiles over the 50 monsoon seasons were estimated for all the study regions considering only the raindays, which are summarised in Table 3.13. It is noted that the 95th percentiles are very much diverse ranging from 43 to 74mm/day at various locations with the region 1 having the maximum magnitude and followed by the regions 2 and 3. These values were taken separately as potential thresholds to identify the extreme events in every region in Kerala.

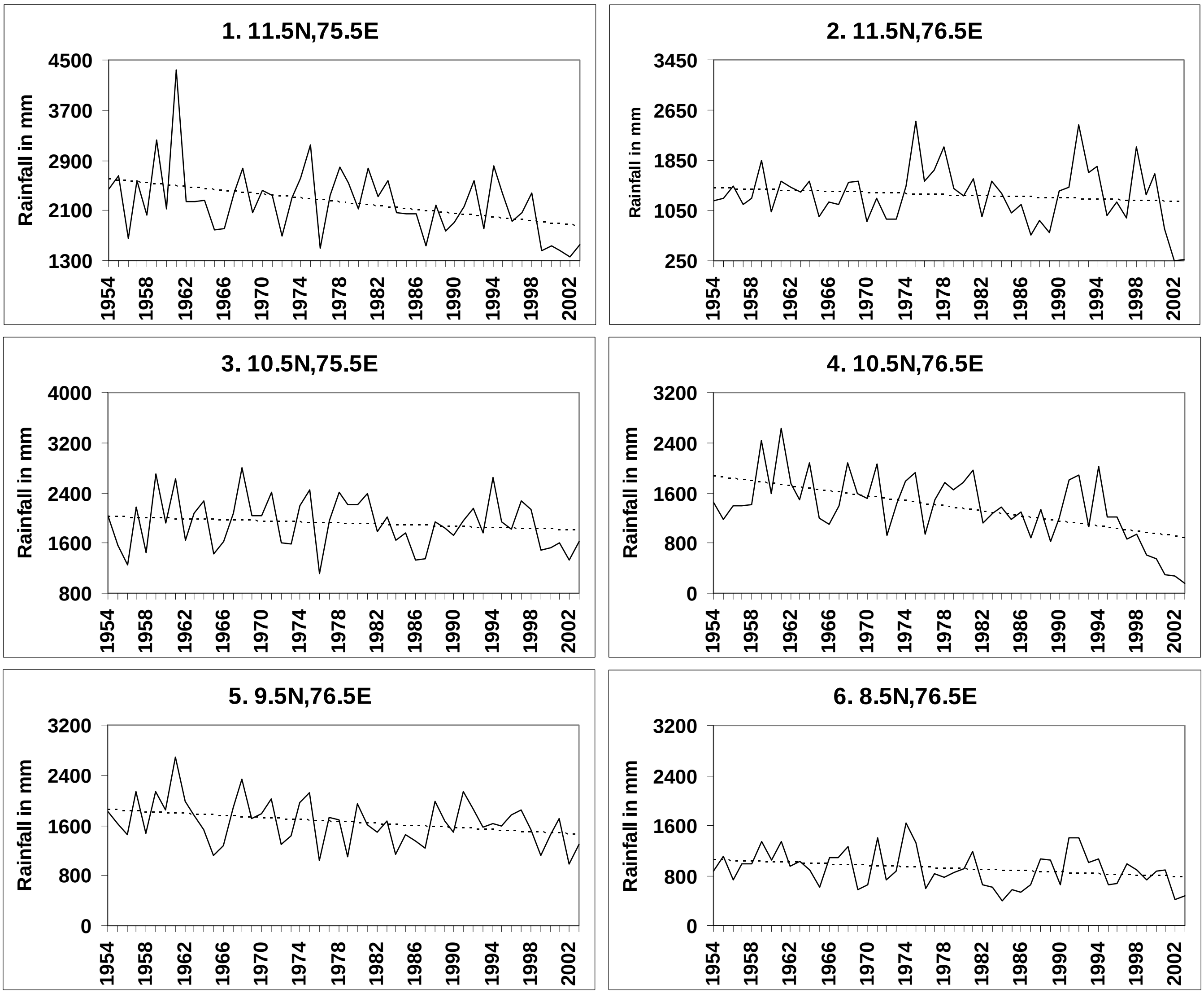


Figure 3.38: Variability and the trends in amount of rainfall corresponding to 'low-moderate' events in the study regions of Kerala in 1954-2003.

Table 3.13: Average 95th percentiles of monsoon rainfall at the study regions of Kerala in 1954-2003.

Region		Average 95th percentile (mm/day)
1	11.5N,75.5E	74
2	11.5N,76.5E	66
3	10.5N,75.5E	61
4	10.5N,76.5E	47
5	9.5N,76.5E	57
6	8.5N,76.5E	43

Since only the days corresponding to at least 1mm rainfall were considered in this case, a study was also carried out to examine the change in the number of raindays and total rainfall in those days. The corresponding trends are summarised in Table 3.14. It can be noted that the total monsoon rainfalls (in the raindays) are decreasing in an order of 30 to 194 mm/10 years; and also noted was a reduction of over 1-6 raindays/10years in the monsoon months in various regions. The maximum reduction of rainfall quantity and the number of raindays merge at grid 4 while it is not the case for grid 1, being the second in terms of negative trend magnitude of monsoon rainfall. For the case of region 1 the reducing trend of monsoon rainfall quantity might be attributed to reduction of the statistically significant trend of 'heavy' and 'low-moderate' raindays, especially in the latest decades (refer to Tables 3.12 and 3.14 and Figures 3.33 to 3.37). Therefore, the reduction of raindays in the Kerala region plays a major role in the total rainfall reduction in the monsoon months.

Table 3.14: Trends in total rainfall in the raindays and number of raindays at the study regions of Kerala in 1954-2003.

Region		Total rainfall (mm/10 years)	Raindays (days/10-years)
1	11.5N,75.5E	**- 176**	- 1
2	11.5N,76.5E	- 59	- 1
3	10.5N,75.5E	- 30	**- 2**
4	10.5N,76.5E	**-194**	**- 6**
5	9.5N,76.5E	**- 65**	**- 5**
6	8.5N,76.5E	**- 60**	**- 2**
Note: + ve sign = increasing trend; – ve sign = decreasing trend; bold numbers indicate significant trends at the 95% level.			

Figure 3.39 illustrates the trends of extreme frequencies corresponding to different regions in Kerala whereas Table 3.15 summarises the magnitudes of those trends and indicates whether they are statistically significant. Table 3.15 also shows the range of number of extreme rainfall events in a year in each of the study regions in Kerala. All

the regions experienced 0 to 17 extreme rainfall events in the 50-years of study. The figure and the table show that the regions 1 and 4 have statistically significant decreasing trends in frequencies of extreme events. Therefore, it can now be well established that the reduction of extreme rainfall frequencies plays one of the most important roles in the principal reduction of monsoon rainfall in this state (Figures 3.38 and 3.39).

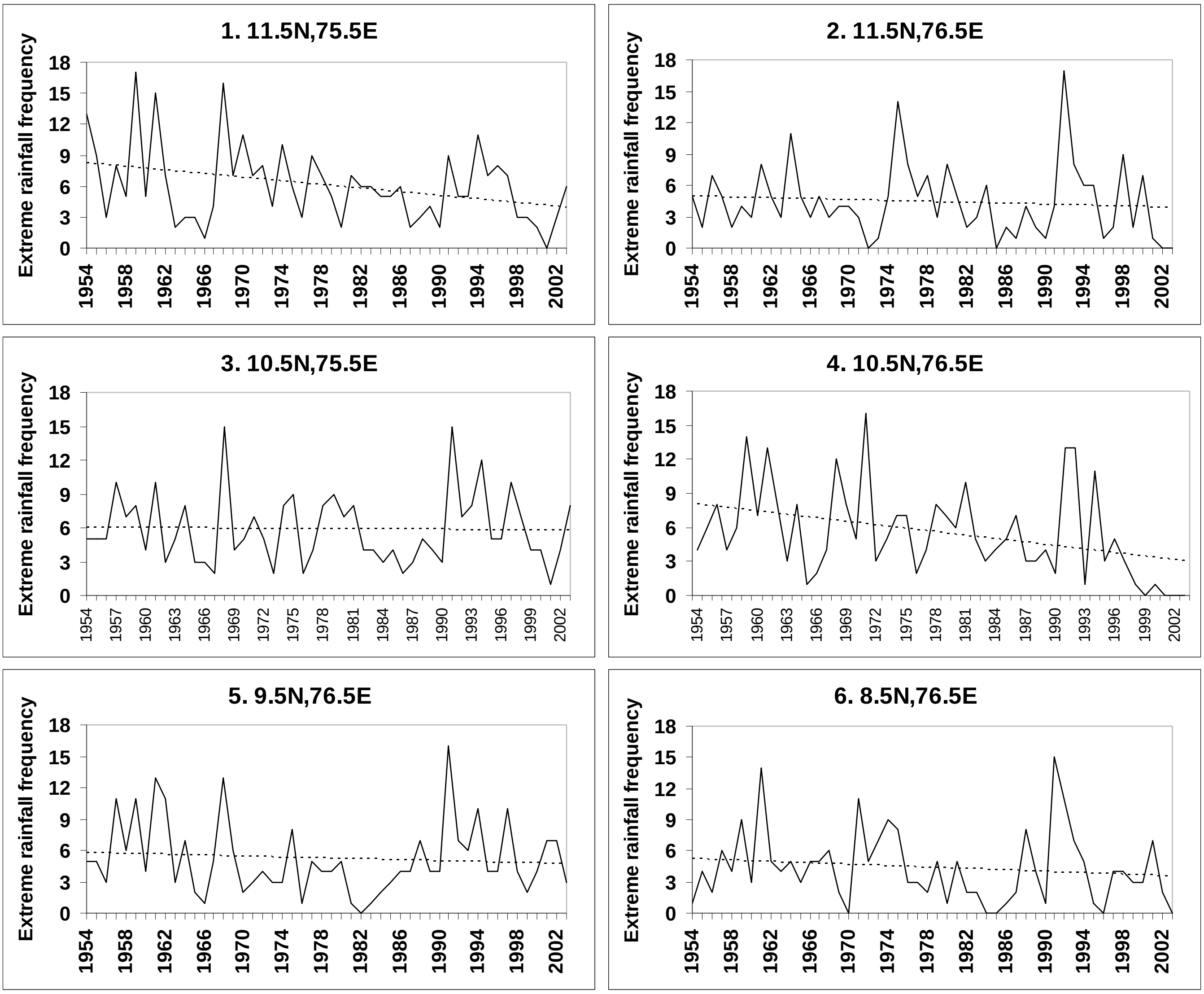


Figure 3.39: Variation of extreme rainfall frequencies based on spatially variable thresholds and their trends for the study regions of Kerala in 1954-2003.

Table 3.15: Trends in extreme rainfall frequency calculated based on 95 percentile at the study regions of Kerala in 1954-2003.

Region		***Range of no. of extreme events in a year***	***days/10 years***
1	11.5N,75.5E	0-17	**- 1**
2	11.5N,76.5E	0-17	No trend
3	10.5N,75.5E	1-15	No trend
4	10.5N,76.5E	0-16	**- 1**
5	9.5N,76.5E	0-16	No trend
6	8.5N,76.5E	0-15	No trend
Note: + ve sign = increasing trend; – ve sign = decreasing trend; bold numbers indicate significant trends at the 95% level.			

These results agree well with the report that the frequency of extreme rainfall in south and south-east Asian region has exhibited a decreasing tendency (Manton et al., 2001). However they do not agree with the studies conducted for the central Indian region (Goawami et al., 2006) and the West Indian coast (Sen Roy and Balling, 2004). The differences between the findings presented here and those of Goswami et al. (2006) are likely to be due to both different spatial areas under study and to the different periods of analysis. Therefore, collectively it could be concluded that, there are significant changes in frequencies of extreme rainfall events in Kerala but the magnitudes and the tendencies of the changes vary with time and region.

3.7.3.3.2. Extreme Rainfall Intensity

Extreme rainfall intensity is defined as the average intensity of rainfall from extreme events. It actually describes the changes in the upper percentiles. These indices were calculated using the following two different methods:

Method 1: Averaging the highest four events for each year
Method 2: Averaging all events above the long-term 95^{th} percentile

Figures 3.40 and 3.41 display the variation of extreme rainfall intensities and their trends corresponding to both methods 1 and 2 respectively; whereas, Table 3.16 summarises the quantitative values of the trends. In all the cases, the trends are very similar between the two methods employed to estimate the extreme intensity whereas the magnitudes are different. The trend is stronger for the case of method 2. The long-term trends of the indices, as shown in Figures 3.40 and 3.41 and Table 3.16 are negative for the four cases of regions 1, 2, 4 and 6 and positive for the two cases of 3 and 5. Except for grid 1, the three other negative trends are statistically significant. However, the positive trends, as seen in Table 3.16, are not significant.

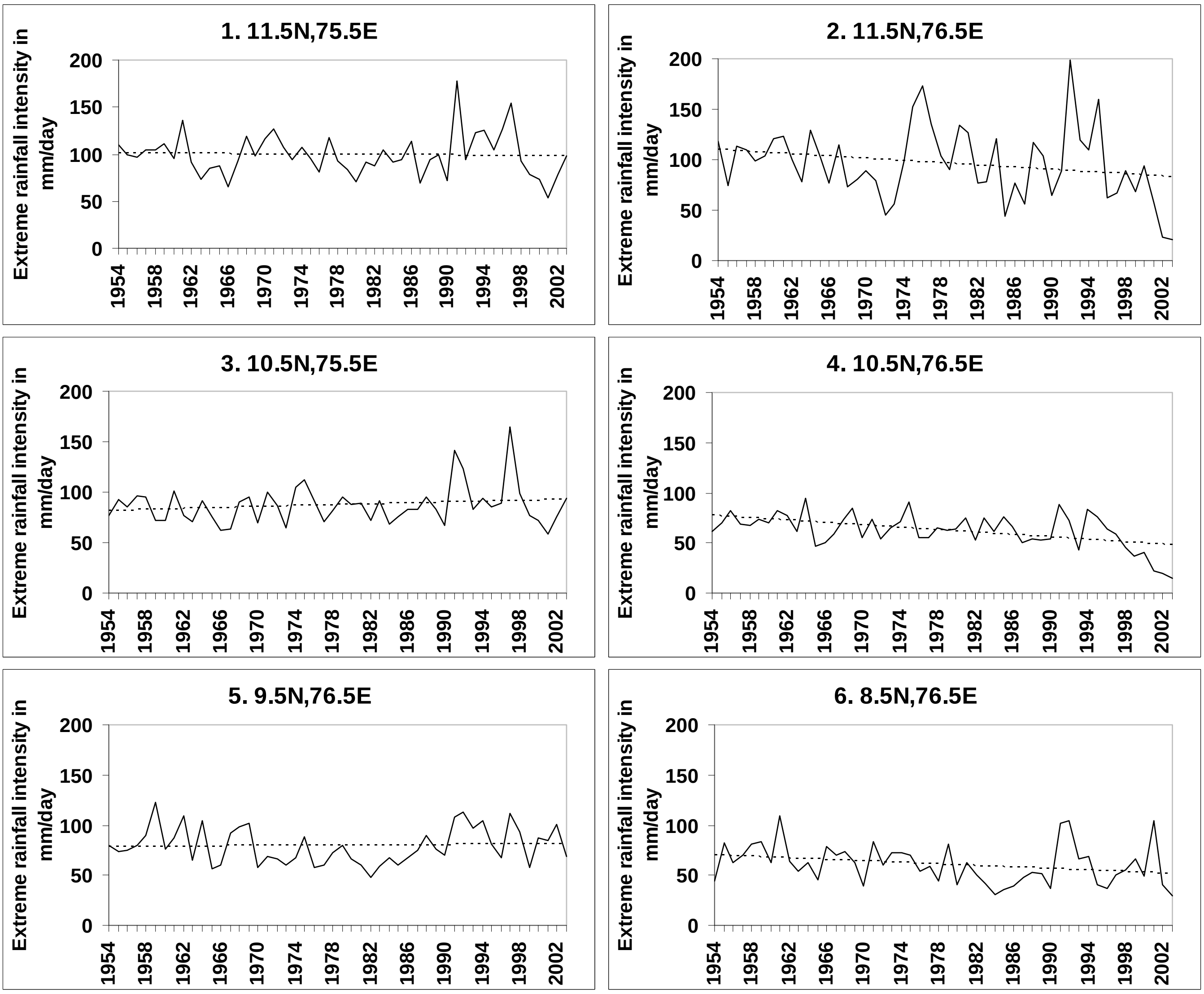


Figure 3.40: Variation of extreme rainfall intensities based on spatially variable thresholds ('method 1') for the study regions of Kerala in 1954-2003.

Table 3.16 also shows that the decreasing trends of extreme intensity vary from 0.5 to 6.7 mm/day/10 years. In addition, the positive trends of extreme intensities over region

3 and 5 vary from 0.5 to 2.2 mm/day/10 years. Collectively again it is seen that there is a strong possibility of Kerala experiencing a decrease in extreme rainfall intensities in the coming decades. However, the occurrence of sudden flash floods at some locations in Kerala is also expected.

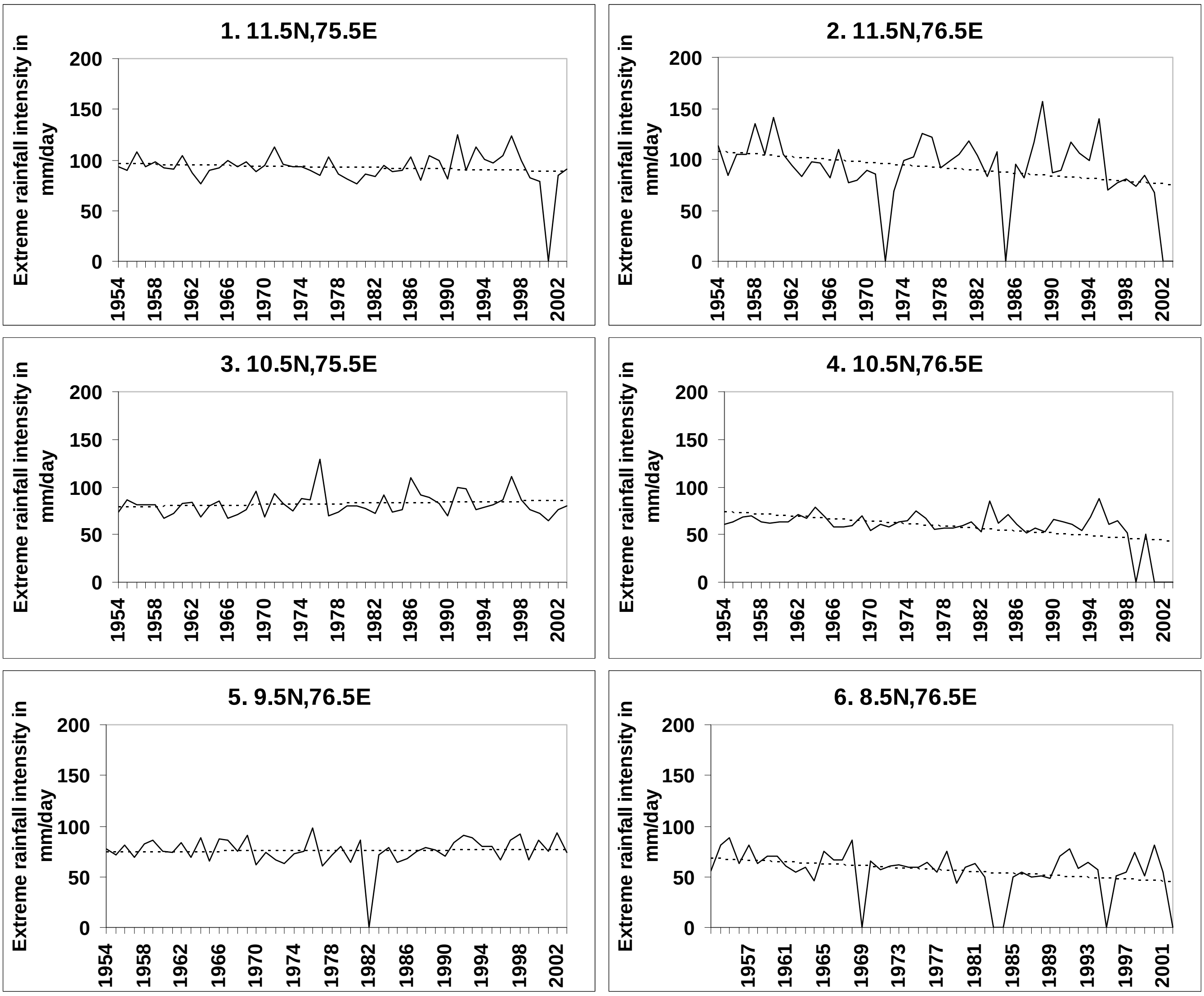


Figure 3.41: Variation of extreme rainfall intensities based on spatially variable thresholds ('method 2') for the study regions of Kerala in 1954-2003.

Table 3.16: Trends of extreme rainfall intensity at the study regions of Kerala in 1954-2003.

Region		***Method 1*** ***In mm/day/10 years***	***Method 2*** ***In mm/day/10 years***
1	11.5N, 75.5E	- 0.5	- 1.6
2	11.5N, 76.5E	**- 5.6**	**- 6.7**
3	10.5N, 75.5E	+ 2.2	+ 1.1
4	10.5N, 76.5E	**- 6.0**	**- 6.4**
5	9.5N, 76.5E	+ 0.5	+ 0.5
6	8.5N, 76.5E	**- 3.6**	**- 4.8**
Note: + ve sign = increasing trend; – ve sign = decreasing trend; bold numbers indicate significant trends at the 95% level.			

3.7.3.3.3. Extreme Rainfall Percent

This index is defined as the proportion of total rainfall from the extreme events and is estimated using the following two methods:

Method 1: Proportion of total monsoon rainfall in the highest four events
Method 2: Proportion of total monsoon rainfall from all events above the average long-term 95th percentile

This index reflects changes in the upper portion of the daily rainfall distribution. The percentage of the total rainfall from the highest events is an indicator of changes in the shape of the rainfall distribution. This index is calculated for each year by dividing the total rainfall from the extreme intensity by the year's total monsoon rainfall. Figures 3.42 and 3.43 display the variation of extreme rainfall percents and their trends corresponding to both methods 1 and 2 respectively; whereas, Table 3.17 summarises the trends in the extreme percent calculated using the above two methods for the six study regions of Kerala.

The figures and the table show that the results corresponding to both the methods are not consistent. From Table 3.17 and Figure 3.42, it can be seen that the results corresponding to method 1 show statistically significant positive trends at four locations, exceptions are regions 2 and 6, which means that the percentage contribution from the highest rainfall events towards the total seasonal rainfall is increasing at 60% of the area in Kerala. However, results corresponding to method 2 in Table 3.17 and

Figure 3.43 are completely different from those of method 1 in terms of their sign and magnitudes. Hence the results strongly depend on the type of index being used for trend assessment.

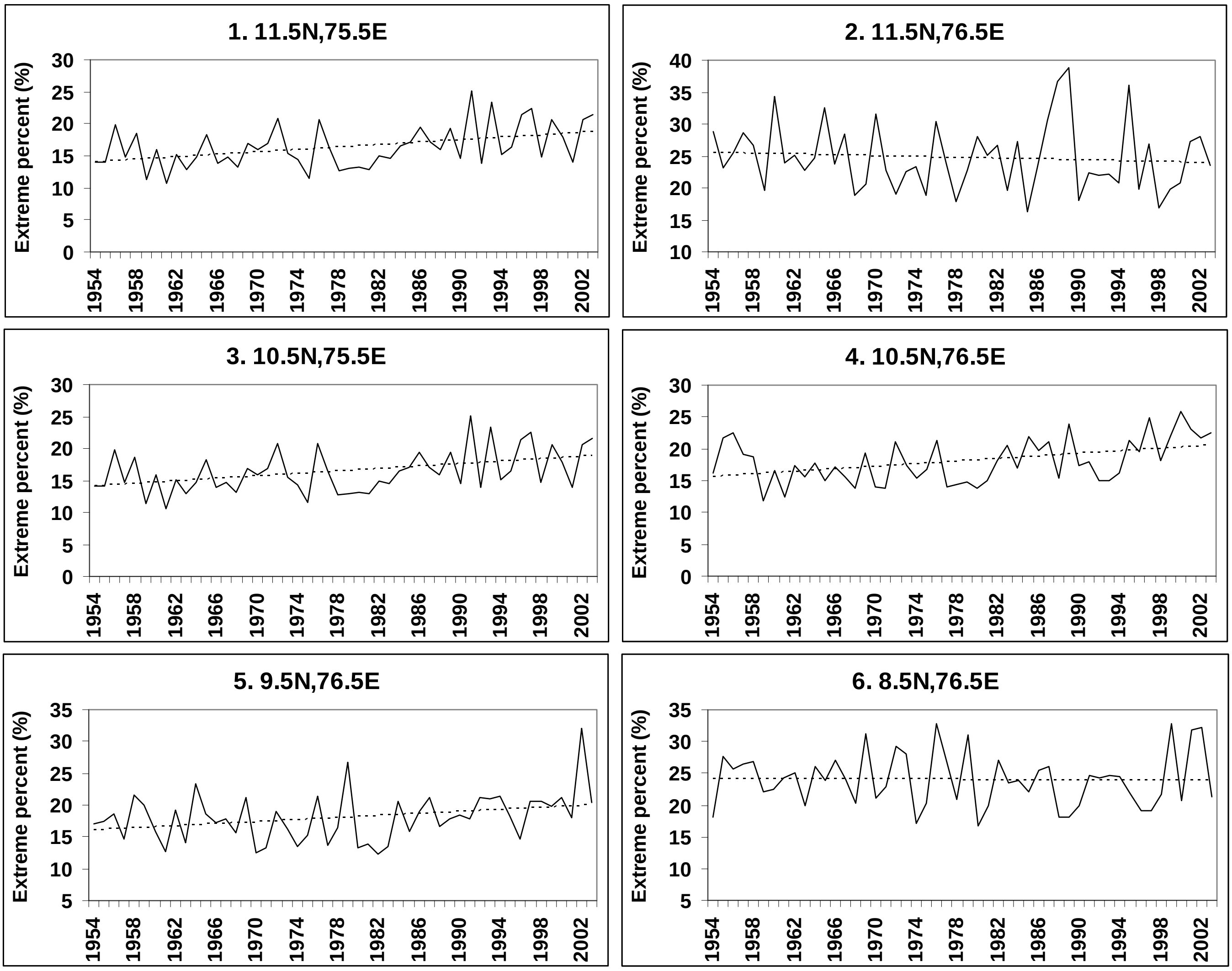


Figure 3.42: Variation of extreme rainfall percents based on spatially variable thresholds ('method 1') for the study regions of Kerala in 1954-2003.

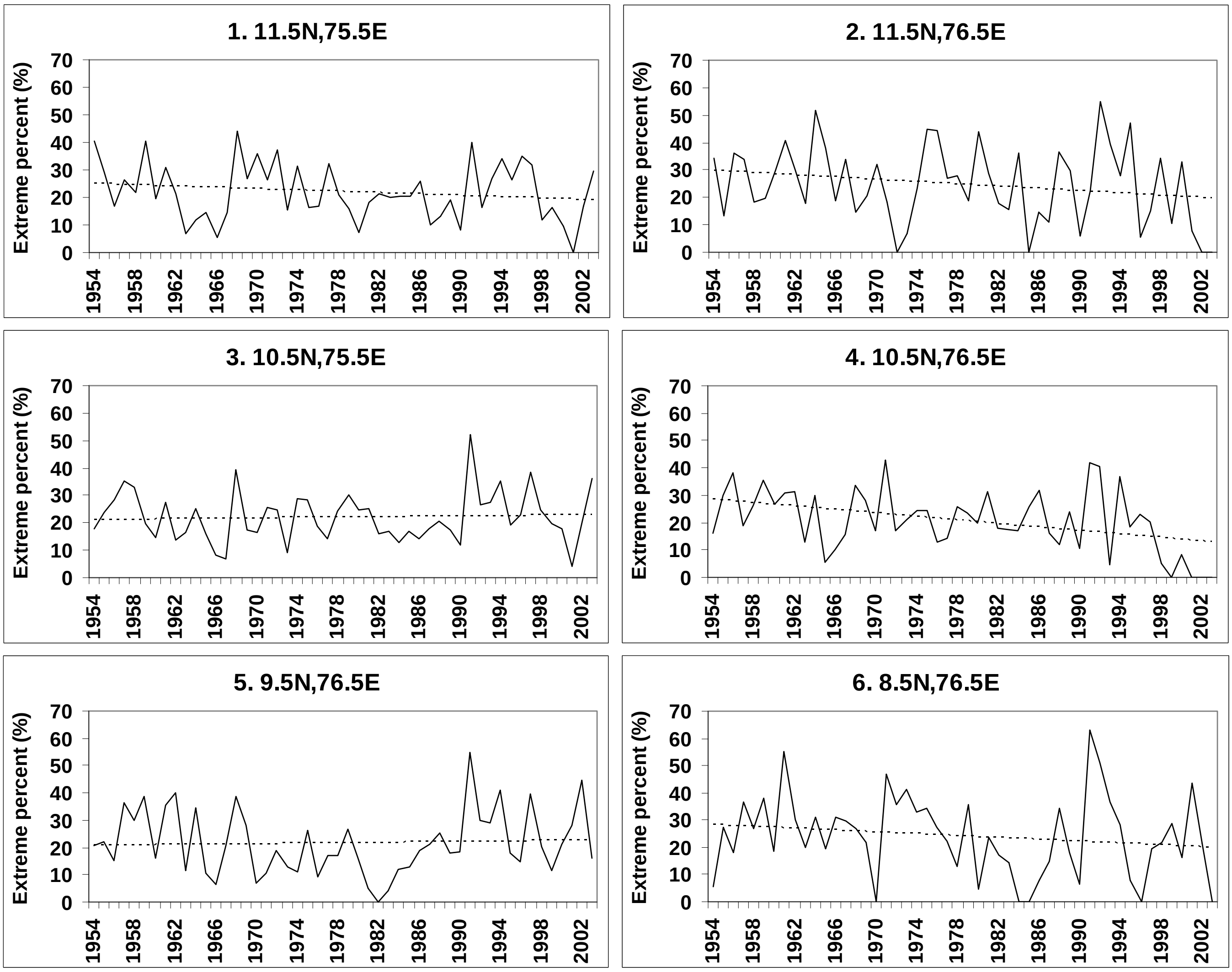


Figure 3.43: Variation of extreme rainfall percents based on spatially variable thresholds ('method 2') for the study regions of Kerala in 1954-2003.

Table 3.17: Trends of extreme rainfall percent at the study regions of Kerala in 1954-2003.

Region		***Method 1 In % per 10 years***	***Method 2 In % per 10 years***
1	11.5N, 75.5E	**+ 1**	- 1
2	11.5N, 76.5E	- 0.3	- 2.1
3	10.5N, 75.5E	**+ 1**	+ 0.4
4	10.5N, 76.5E	**+ 1**	**- 3.1**
5	9.5N, 76.5E	**+ 0.8**	+ 0.3
6	8.5N, 76.5E	- 0.05	- 0.2
Note: + ve sign = increasing trend; – ve sign = decreasing trend; bold numbers indicate significant trends at the 95% level.			

3.8. Correlations between Total Monsoon Rainfall and Various Monsoon Extreme Indices

In the previous sections (3.7.3.3.2 and 3.7.3.3.3), it was noted that the total rainfall quantities in the extreme raindays have decreasing tendencies (Tables 3.16 and 3.17). Also, the total number of raindays, frequencies of low-moderate rainfall and extreme rainfall frequencies in the monsoon months has long-term decreasing trends. Therefore, a further study was carried out to find whether the decrease in total monsoon rainfall is correlated with the other attributes at every region in Kerala and to suggest which one has the most effect on total monsoon rainfall. The results are summarised in Table 3.18.

Table 3.18 shows that the total rainfall in the raindays is positively correlated (0.49-0.87) with the total number of raindays in the monsoon months. However, the positive correlations are stronger (0.66-0.95) with the frequency of low-moderate raindays in the season. The spread of correlation values among regions is notably large. Therefore, it could be concluded that, the higher the number of raindays, especially the days with low-moderate rainfall, the higher the total rainfall in the monsoon months, which should generally be true. However, very high correlations between extreme rainfall frequencies and extreme rainfall intensities in columns 4 and 5 in Table 3.18 conclude that the expectations of the extreme precipitations are higher in the major monsoon years. Since the positive correlations with extreme rainfall intensities derived by method 2 (column 6) were not as good as method 1, the first four highest precipitation events in any monsoon season (method 1) would be very important and prime decisive factors of the total rainfall. Therefore, collectively, low-moderate rainy days, number of days having above 95^{th} percentile rainfall quantity (extreme rainfall frequency) and the average of the highest four events in each monsoon season (extreme rainfall intensity) are very important decisive factors for total monsoon rainfall in the Kerala region.

The results in sections 3.7 and 3.8 have been submitted for publication (Pal and Al-Tabbaa, 2009d).

Table 3.18: Correlation coefficients between total rainfall in the raindays and various other attributes in the monsoon months at the study regions in Kerala.

Region		*Correlation Coefficients*				
		Number of raindays	*Low-moderate rainfall frequency*	*Extreme rainfall frequency*	*Extreme rainfall intensity (method 1)*	*Extreme rainfall intensity (method 2)*
1	11.5N,75.5E	0.49	0.66	0.83	0.59	0.36
2	11.5N,76.5E	0.69	0.79	0.90	0.84	0.52
3	10.5N,75.5E	0.60	0.76	0.81	0.60	0.08
4	10.5N,76.5E	0.87	0.95	0.86	0.85	0.64
5	9.5N,76.5E	0.55	0.68	0.76	0.60	0.12
6	8.5N,76.5E	0.57	0.83	0.88	0.85	0.52

3.9. Analysing Other Seasonal Extremes in Kerala Using Non-Parametric MK Method

3.9.1. Introduction

Recent news on the occurrence of off-seasonal natural disasters (refer to websites 1 and 2), such as pre-monsoon drought and post-monsoon flooding in India and particularly in the peninsular region, highlight the urgent need to look at the patterns of change in seasonal rainfall extremes at the local level. Therefore, winter (Dec-Feb), spring (Mar-May) and autumn (Oct-Nov) seasonal rainfall extremes are also analysed here in this section to investigate whether there have been any significant changes in the daily extreme rainfalls in various seasons in Kerala over the second half of the 20th century. Previous analyses (section 3.6.2) found that the average autumn and winter total rainfall in Kerala does not seem to show any significant trends but that the spring rainfall does.

Six separate gridded regions, as discussed in section 3.7 previously, comprising of the whole state of Kerala are studied, as shown in Figure 3.19. Gridded regional analyses help in identifying spatial changes at very small scales, which provide local information on the changing climate that is not usually extracted from the aggregated spatial mean (Bardossy and Hundecha, 2003). Collectively, this work was aimed at characterising the singular events that have the potential to help in defining and assessing the associated risks, and developing mitigation and adaptation strategies in the state of Kerala.

In this section, the analysis of the rainfall extremes was based on the indices developed under the World Climate Research Programme on Climate Variability and Predictability Working Group on Climate Change Detection (Peterson, 2005), which also coincide with the indices mentioned in Tables 2.2 and 2.3 and used in section 3.7. Some of these indices have been previously used in the analyses of the trends in global and regional climates (Bardossy and Hundecha, 2003; Alexander et al., 2006). Selective indices used here for the seasonal analyses are demonstrated in Table 3.19. Seasonal extreme indices were calculated on a yearly basis for the entire 50 years (1954-2003) of study for all the areas under investigation in Kerala. The base period considered here was 1961-1990. Before moving onto the extremes, changes in seasonal total rainfall in the wet days and changes in the frequency of the dry days are also examined and discussed in the first two sub-sections below.

Table 3.19: Extreme rainfall indices (DP = daily precipitation amount) used for seasonal rainfall extremes in Kerala (Peterson, 2005).

Index	*Description*	*Units*
PREP_ST	Seasonal total precipitation from wet days (DP ≥ 1 mm)	mm
TDD	Seasonal total number of dry days (DP < 1 mm)	Days
R95p	Seasonal total precipitation from DP > 95th percentile of the wet days (based on the period 1961 – 1990)	mm
R99p	Seasonal total precipitation from DP > 99th percentile of the wet days (based on the period 1961 – 1990)	mm
RX1day	Seasonal maximum precipitation in 1day	mm
RX5day	Seasonal maximum precipitation in 5 consecutive days	mm
RXF	Extreme frequency i.e. number of days with rainfall > 95 percentile in the season	days
RXP	Extreme percent i.e. proportion of total seasonal rainfall from all events above the average long-term 95th percentile	%

All the trends for each index were determined using non-parametric Mann-Kendall method (as described in section 2.6.3). The results of the trend assessments are summarised in the following headings. The figures discussed in the sections below show three-panel map of trends in various gridded regions in Kerala for the three seasons analysed. Only the grids under study are shown in those figures. Symbolic colours are used to indicate the trends, which are mentioned in the respective captions.

3.9.2. Long-Term Changes of Seasonal Total Precipitation (Index PREP_ST)

The trends in total precipitation from the wet days (the days with precipitation ≥1mm) show seasonal variabilities, as seen in Figure 3.44 and the spatially averaged trends in different seasons over the whole of Kerala are shown in Figure 3.45. The most apparent feature of the results in Figure 3.44 is that trends in seasonal rainfalls over the study period are not consistent throughout the state (except for the spring season) even though the mean and standard deviation of daily rainfall over these regions is more or less consistent (see Table 3.20). This intraregional variability for the rainfall indices is possibly because of small spatial correlations for rainfall because of topographical differences (Figure 3.46).

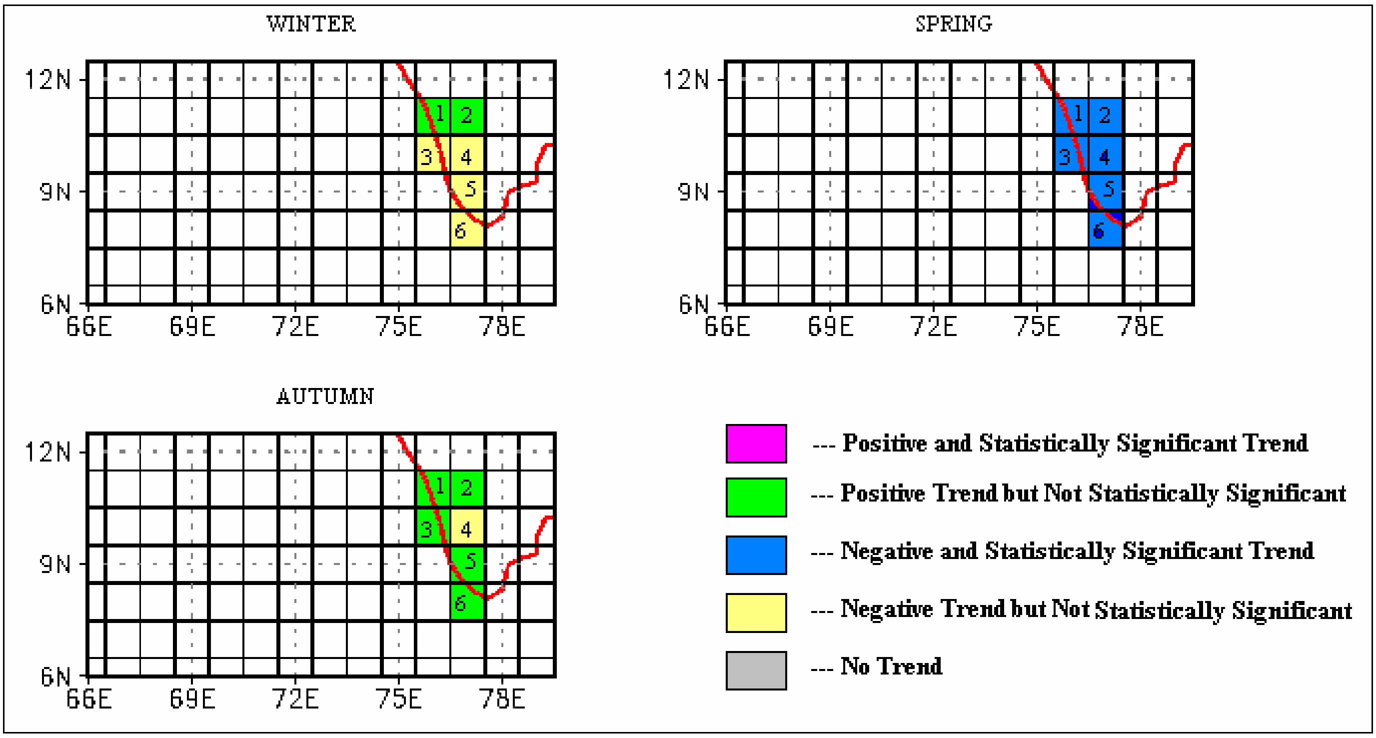


Figure 3.44: Trends of seasonal total precipitations from the wet days (PREP_ST) in various regions in Kerala in 1954-2003.

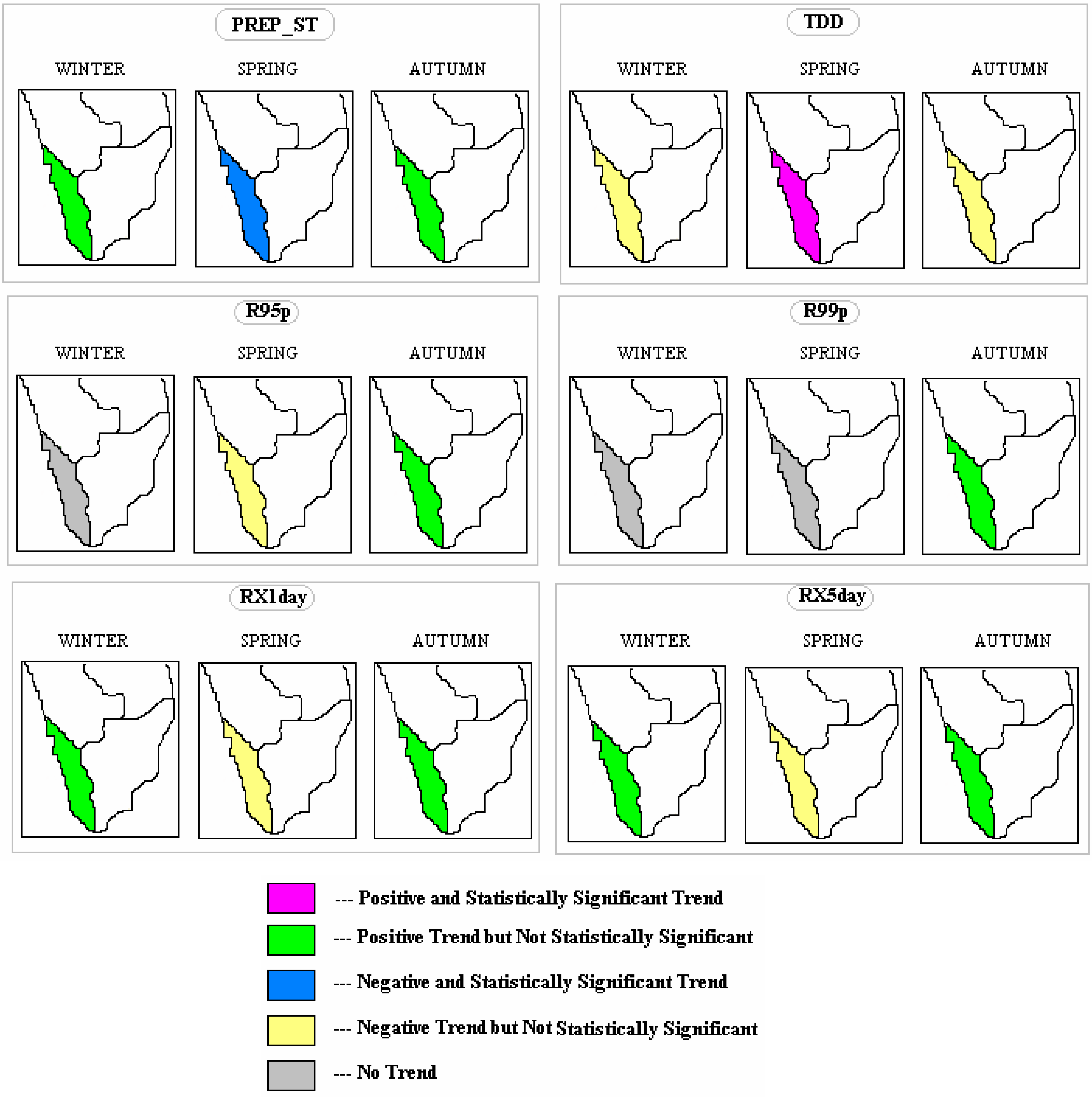


Figure 3.45: Trends of spatially averaged extreme indices in various seasons in Kerala in 1954-2003.

Figure 3.44 shows that two extreme northern regions of Kerala show positive tendencies in winter seasonal rainfall and, four locations show negative tendencies, while none are significant. On the other hand, spatially averaged winter seasonal rainfall show positive tendency in Kerala, spring rainfall has statistically significant decreasing trends throughout the state, as in Figure 3.45. Furthermore, although positive tendencies were noticed everywhere in Kerala (except grid no. 4), no region has statistically significant trend for the autumn rainfall (Figure 3.44). The spatially averaged trends in index PREP_ST in autumn season in Kerala also show positive tendencies (Figure 3.45). Hence the above results indicate that the trends corresponding to large scaled spatial averages are not representative of the local regional changes, and therefore are not recommended to use in local projects.

Table 3.20: Mean and standard deviation of seasonal rainfalls in Kerala (1954-2003).

Region		Mean			SD		
		Winter	Spring	Autumn	Winter	Spring	Autumn
1	11.5N,75.5E	0.4	3.8	6.0	2.2	5.0	5.2
2	11.5N,76.5E	0.4	2.3	4.8	2.3	4.0	6.8
3	10.5N,75.5E	0.5	4.3	7.1	2.9	5.7	5.2
4	10.5N,76.5E	0.4	2.7	6.1	2.1	2.9	4.5
5	9.5N,76.5E	1	5.27	8.4	2.5	4.8	5.6
6	8.5N,76.5E	1	4.5	7.6	2.5	4.1	5.9

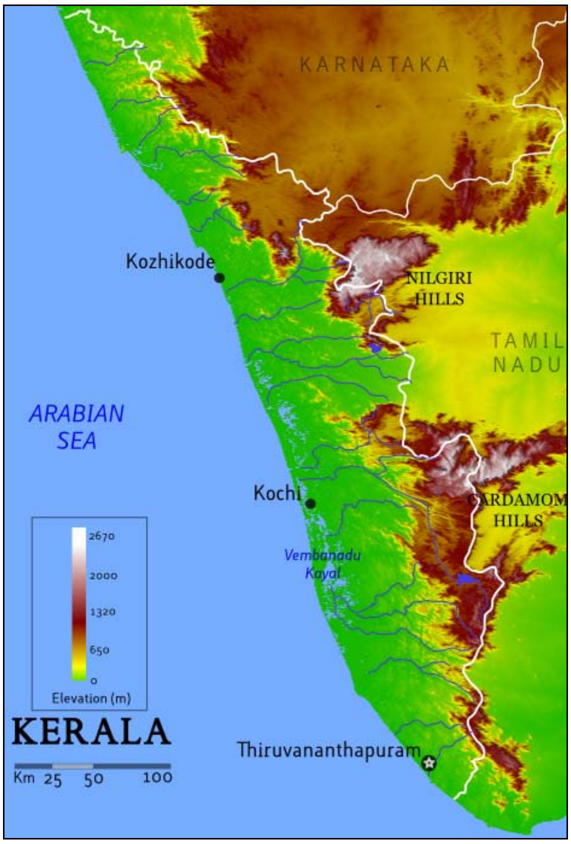


Figure 3.46: Topographical map of Kerala.

3.9.3. Long-Term Changes of Seasonal Total Number of Dry Days (Index TDD)

The winter season has the maximum number of dry days in Kerala. Spatially averaged trends of TDD in various seasons are shown in Figure 3.45. The figure indicates whether possible increase or decrease in water stress is experienced in different seasons in Kerala, which is important for natural vegetation and crop growth. It could be noticed in Figure 3.45 that the number of dry days are significantly increasing in spring season, which is a clear indication of severe water stress in this season. The increasing frequency of dry days in spring season could be another indication of delayed monsoon onset in Kerala. Spatially averaged trends of total number of dry days in winter and autumn seasons have decreasing tendency, which are possibly contributing to increase in total rainfall from the wet days (index PREP_ST), as in Figures 3.44 and 3.45.

Results corresponding to every individual grid in Kerala are different from the spatial average results above. The trends for every individual region are displayed in Figure 3.47. The figure shows that the number of winter dry days has no significant trend in most places except only the region at the highest elevation (grid 2) that exhibits significantly decreasing number of dry days in Kerala. Also that, the other north most region (grid 1) shows decreasing tendency in the number of dry days. This could be one of several reasons for the increase in winter rainfall in these two northern regions, as discussed in the previous section. The spatial distribution of the regions indicates that the famous port and agricultural district Kozhikode/Calicut, is situated in grid 1 (see Figure 3.46). In spring, most of the areas have been undergoing water stresses since they have statistically significant increasing trends of the number of dry days; whereas, interestingly, no significant trends are noticed in the north most regions (grid 1 and 2) in Kerala. In the autumn, around 33% of the total area under investigation shows a significant decrease in the number of dry days, the areas are located at the highest elevation (grid 2) and at the southern coastal part of Kerala (grid 6). Grid 1, the other northern part of Kerala also shows decreasing tendency of TDD in autumn, like winter. Exactly opposite results were noticed for the total number of wet days in the various seasons (not shown) meaning that there is an increasing tendency of rainfall occurring more frequently in the winter and autumn seasons and less frequently in spring in Kerala.

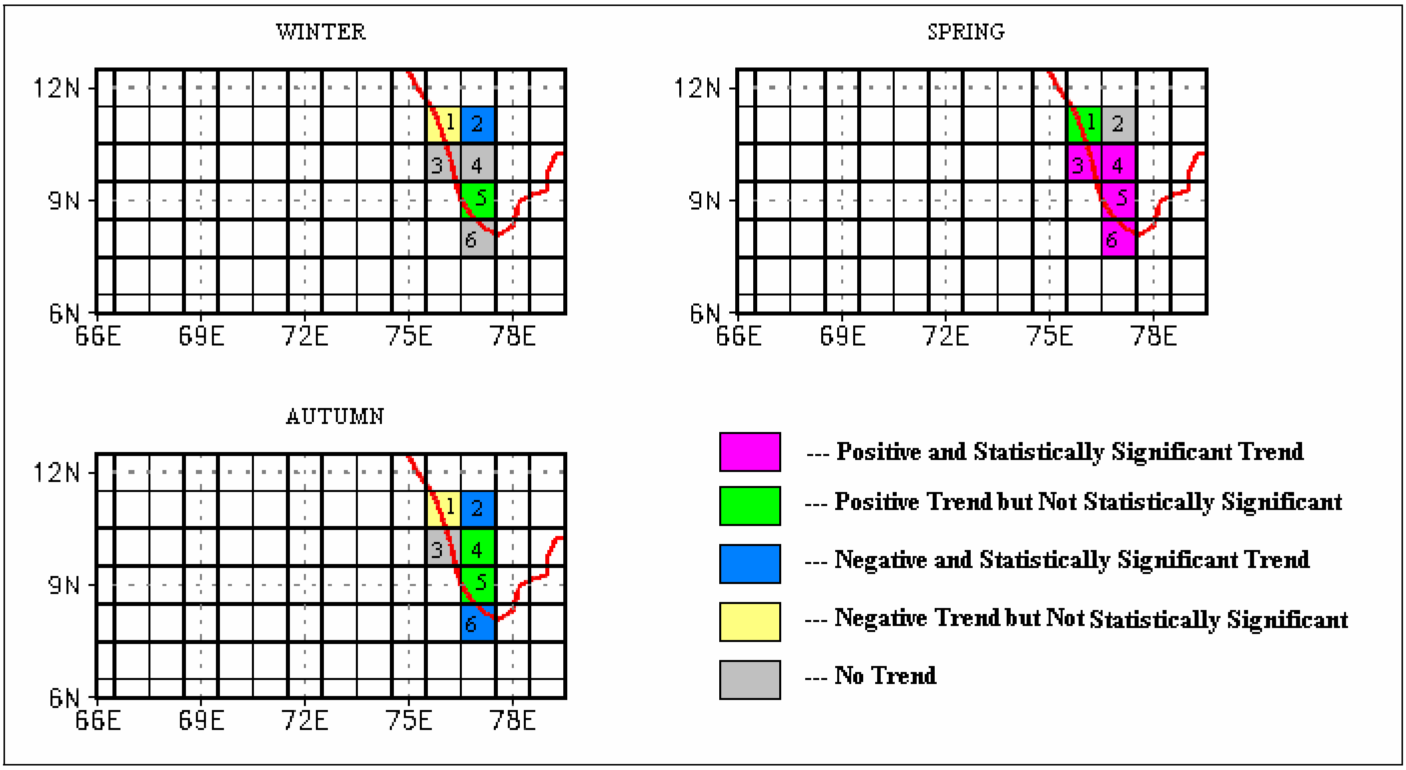


Figure 3.47: Trends of total number of dry days (TDD) in various seasons in different regions in Kerala in 1954-2003.

3.9.4. Trends of Extreme Rainfalls

The remaining six indices in Table 3.19 give a direct measure of extreme rainfall in the various seasons.

3.9.4.1. Indices R95p and R99p

Figures 3.48 and 3.49 show the trends corresponding to the total rainfall above 95th and 99th percentile. The percentile rainfall values were averaged over 1961-1990 i.e. the base line set by WMO to separate 24-hour daily rainfall extremes in every year of the 50 years of study. All the extreme rainfall amounts in a year are then summed up to get R95p and R99p for every year.

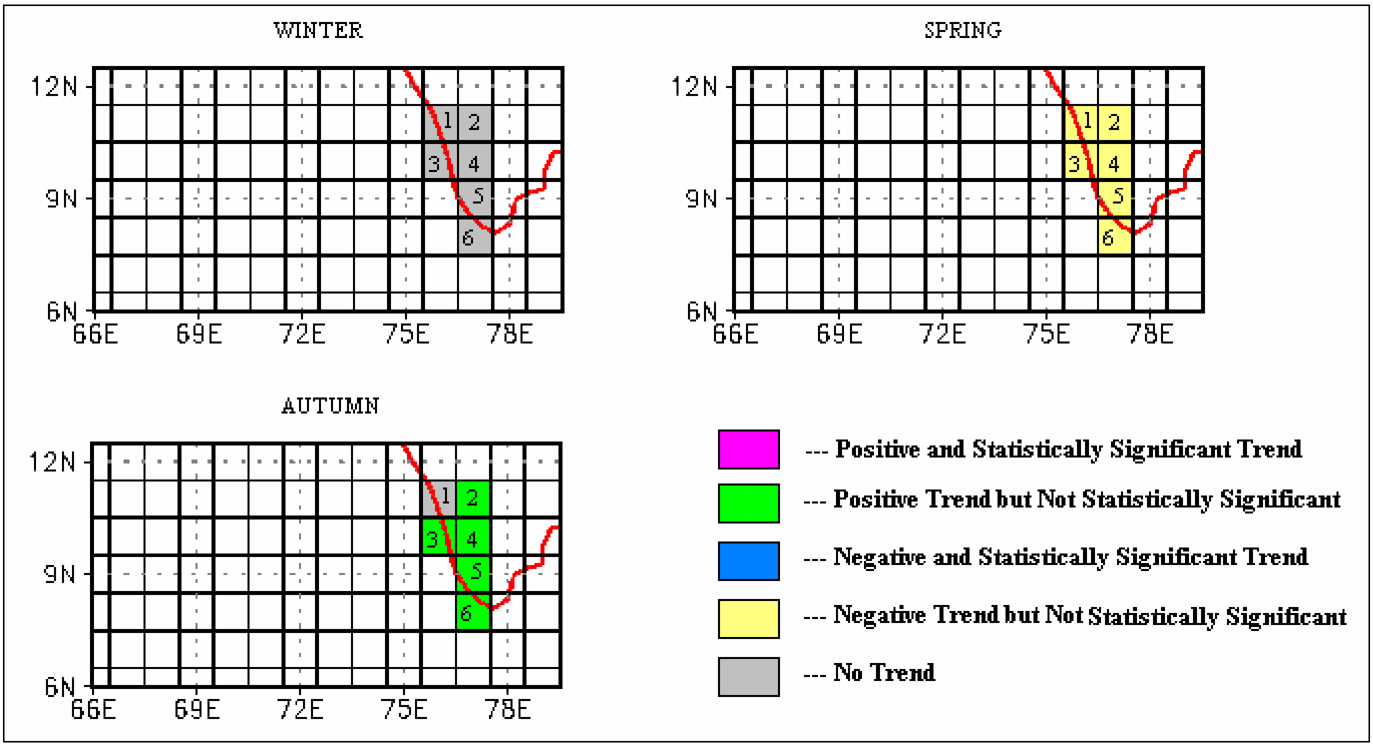


Figure 3.48: Trends of seasonal total rainfall from daily rainfall > 95th percentile from the wet days (based on the period 1961–1990) in different regions in Kerala in 1954-2003.

Figure 3.45 displays the spatially averaged trends and variabilities of the various seasonal R95p and R99p in Kerala. It is noted in the figure that, both the cases exhibit no trends in the winter season. A decreasing tendency of R95p index in spring season is noticed while no trends were found in R99p index. In autumn season, however, total amount of extreme rainfall above 95th percentile shows increasing tendency for both the cases although none was statistically significant.

The results corresponding to the gridded regions were variable and sometimes different from those of spatial average. While in winter, trends corresponding to both the indices show no tendencies, decreasing tendencies in R95p index are observed in spring but no trend in R99p index was found in spring season. Therefore, it is noted that, together with statistically significant increases in the number of dry days and decrease in extreme rainfalls, the spring season tends to go through severe water stresses, which is a familiar phenomenon these days in Kerala. Furthermore, while increasing tendency in R95p in autumn season is almost everywhere in Kerala, only a single region (grid 5) shows an increasing tendency and other grids have no trends for the case of R99p index. Hence, increase in extreme rainfall tends to exhibit a higher number of flash floods in the autumn season, which is also an emerging scenario in some parts of Kerala (De et al., 2005); for example, Kochi (see Figure 3.46) and its nearby regions, which fall within grid 5.

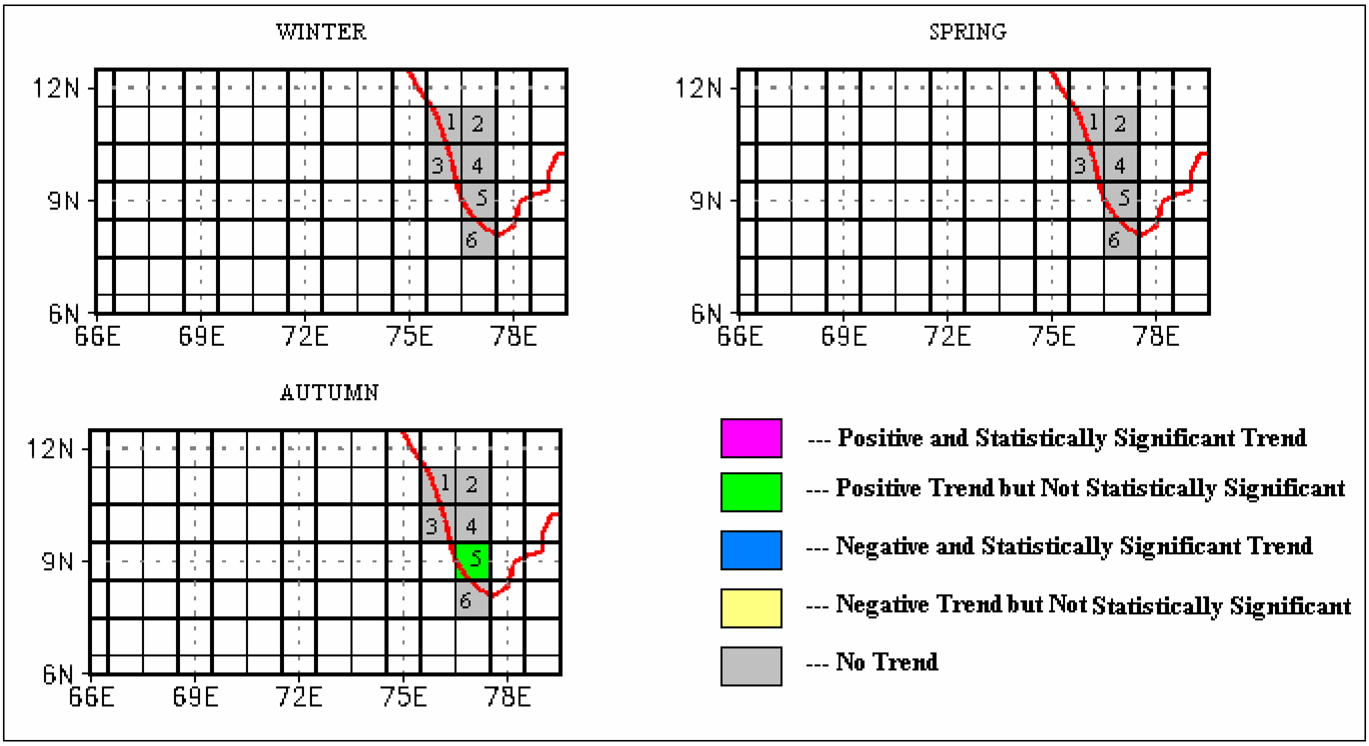


Figure 3.49: Trends of seasonal total rainfall from daily rainfall > 99th percentile from the wet days (based on the period 1961–1990) in different regions in Kerala in 1954-2003.

3.9.4.2. Indices RX1day and RX5day

These indices indicate whether there are changes in the amount of rainfall received in the day with the highest rainfall and the amount of rainfall received in a 5-day scenario per year with the highest rainfall respectively. These indices give an indication of the trends in rainfall amounts usually coming from extreme weather occurrences. Trends in spatially averaged RX1day and RX5day indices for various seasons are shown in Figure 3.45. Figure 3.45 displays that winter and autumn extremes are increasing in Kerala and spring extremes are decreasing, which are affecting the seasonal totals, as also mentioned before.

Figure 3.50 depicts the trends corresponding to these two indices in various seasons and a number of gridded regions in Kerala. Trends in both indices showed coherent tendencies; therefore the results corresponding to both are displayed in a single figure (Figure 3.50). Winter extremes have increasing trends in the northern most regions in Kerala (grids 1 and 2), which must have affected the seasonal total, as was discussed in section 3.9.2. For the spring, the extreme rainfall is decreasing everywhere while the trend corresponding to grid 4 is statistically significant. In addition, the autumn extremes show increasing trends except a decrease in southern coastal tip of Kerala.

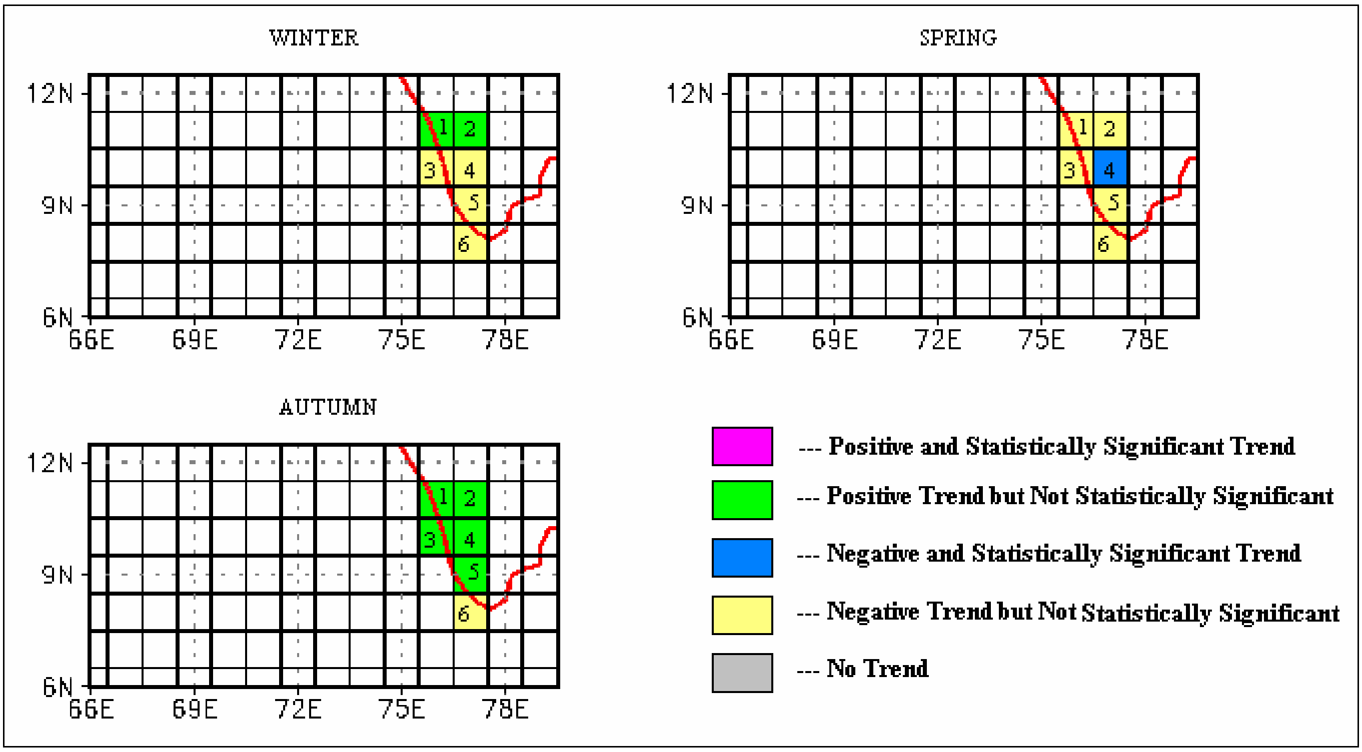


Figure 3.50: Trends of seasonal maximum rainfall in 1 and 5-days in different regions in Kerala in 1954-2003.

3.9.4.3. Indices RXF and RXP

The extreme frequency index (RXF) examines changes in the number of extreme events and was calculated by counting the number of events in a year with intensities above a threshold. The extreme percent (RXP), on the other hand, is the proportion of total seasonal rainfall from all events above the same threshold. A long-term (1961-1990) 95th percentile of the daily rainfall intensity in the months corresponding to various seasons was used as the threshold to separate the extreme events, which varies significantly from year to year and also spatially in Kerala. The trends of extreme rainfall frequencies corresponding to different regions in Kerala in all the seasons showed no significant trends but only one region (grid 3) in spring season that showed significantly negative trend in extreme rainfall frequency, as shown in Figure 3.51; whereas, trends corresponding to extreme rainfall percent (RXP) are different from that of RXF, as shown in Figure 3.52.

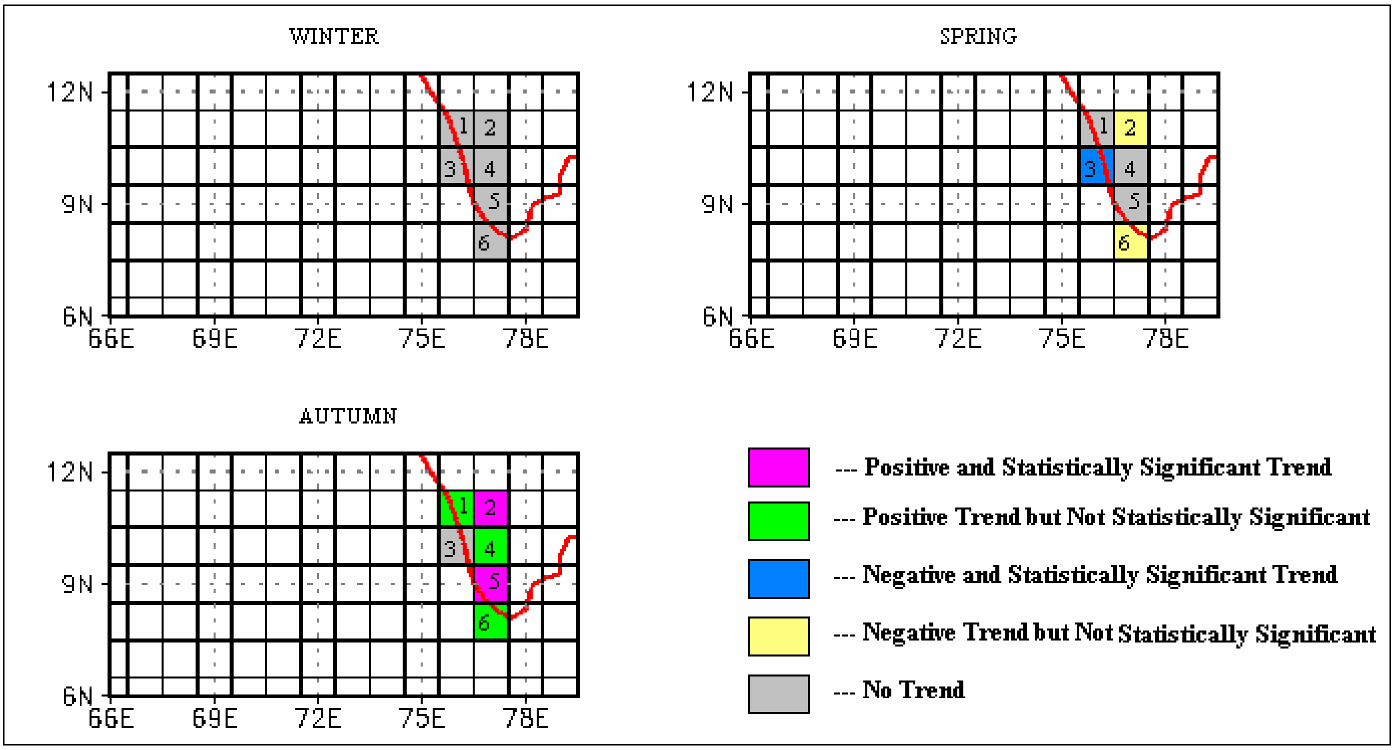


Figure 3.51: Trends of extreme rainfall frequency (RXF) i.e. number of all the rainfall events with magnitude above the average long-term 95th percentile in different regions in Kerala in 1954-2003.

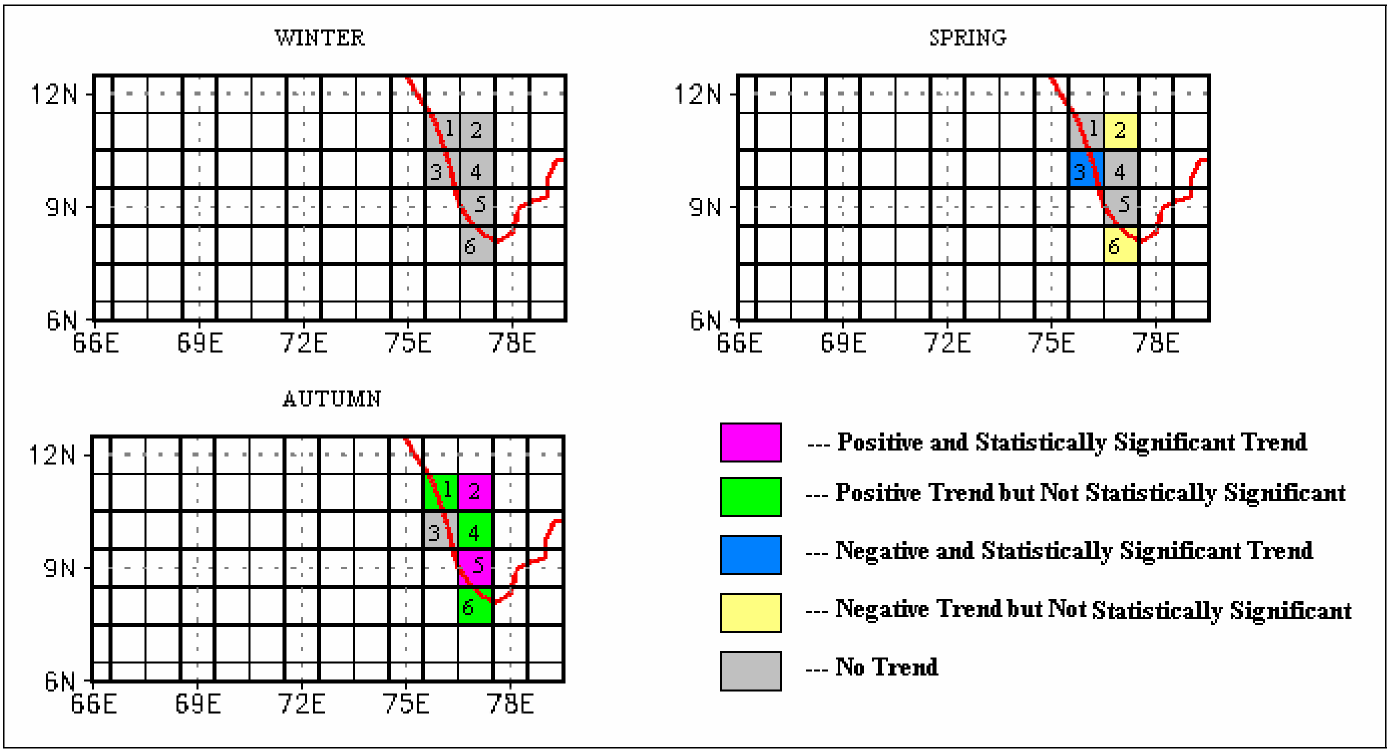


Figure 3.52: Trends of extreme percent (RXP) i.e. proportion of total seasonal rainfall from all events above the average long-term 95th percentile in different regions in Kerala in 1954-2003.

Figure 3.52 shows that, while winter extreme rainfall proportion has no trend like RXF, around 50% of the spatial area of Kerala is undergoing decreasing trends in RXP in the spring season. Furthermore, autumn extreme rainfall proportion has increasing trends and they are statistically significant in two gridded regions in eastern Kerala (grid 2 and 5), which are at the proximity of western ghat mountains. Therefore, in addition to grid 5, as discussed previously, significant increasing trend in total contribution from the extreme autumn rainfall in some parts of Kerala is an indication of more flooding in the autumn season.

Collectively, although not always statistically significant, winter and autumn rainfall extremes are always showing increasing tendencies of floods and spring showing increasing tendencies of water stress. In addition, it can now be seen that extremes play one of the most important roles in the seasonal rainfall changes wherein tendencies of the changes have high local variabilities in Kerala, which implies that the regional assessment of climatological variables is needed for the local developments.

The results discussed in section 3.9 have been published (Pal and Al-Tabbaa, 2009e).

3.10. Long-Term Trends and Variability of Monthly and Seasonal Extreme Temperatures in India

3.10.1. Introduction

Maximum and minimum temperatures are changing worldwide together with changes in the mean temperatures. Examining regional fluctuation of the extreme temperatures at short time scales is important for there are strong human influences on regional climates. This part of the work investigates the trends and changes of variation of the monthly maximum and minimum temperatures and their effects on seasonal fluctuations in various climatological regions in India based on the data described in section 2.2.3. A study of local variabilities in climate change is essential for knowing which areas of the Indian region could be more affected by the changes and therefore more at risk for societal health and activities. The magnitude of the trends and their significance were determined by parametric OLS (section 2.6.2) and the variations were determined by the coefficient of variations (COV). A coefficient of variation for each individual month and season and for each region was determined as COV = 100 × standard deviation/mean. The slopes of the OLS linear fits estimate the rates of equivalent linear warming.

Analysis of 103 years (1901-2003) of temperature data was carried out for seven individual regions (Figure 2.5) covering the whole of India, as well of an all-India average. The study was conducted for all the months and seasons covering the whole year; the seasons being: winter (Dec-Feb), spring (Mar-May), monsoon (Jun-Sept) and autumn (Oct-Nov). The average highest temperatures over India occur during the spring season, and the surface temperatures drop dramatically with the onset of the monsoon season due to extensive cloudiness and rainfall associated with the monsoon circulation. The trend results are discussed below.

3.10.2. Interannual Variabilities of 'Monthly' Extreme Temperatures

3.10.2.1. Coefficient of Variation

The monthly differences in coefficient of variations (COV) of maximum and minimum temperatures are shown in Figures 3.53 and 3.54 respectively. Figure 3.53 demonstrates that the maximum monthly temperatures significantly vary from month to month and from region to region. The highest variation is usually seen in the month of February; with the only except of Interior Peninsula and Western Himalaya where the maximum variation were observed in the months of June and January respectively. From January to October the variation profiles were found quite similar in All-India, North East, North Central and West Coast; but there were differences in the magnitudes, as in Figure 3.53. The highest magnitude of variation was in West Himalaya and followed by North West and the least variation was found in the West Coast region. Although the January to May variation profile for the North-West is similar to other northern Indian regions, other monthly variations were found to be different. The lowest variations of the maximum monthly temperature, on average, were observed in the month of August in all the regions, with except of North East where September, on average, was found to be the least variable month in terms of maximum temperature. In Western Himalaya, however, all the months from June to September are less variable compared to the other months.

Figure 3.54 shows unique profiles of variation of the minimum monthly temperatures from January to December for all the regions, which were found similar to the profile noticed in Western Himalaya maximum temperature (U shaped). A small difference was observed in the Interior Peninsula from regions other than Western Himalaya, with a sudden small rise in June. The large difference in Western Himalayan regional variabilities in extreme temperature profiles and magnitudes is because of the contrast in physiographic characteristics of the area (Bhutiyani et al., 2007; Hasanean and Abdel Basset, 2006). Western Himalaya minimum temperature variation is unique in that the highest variation of the minimum temperature was found to take place in November while other monthly fluctuations were relatively very low.

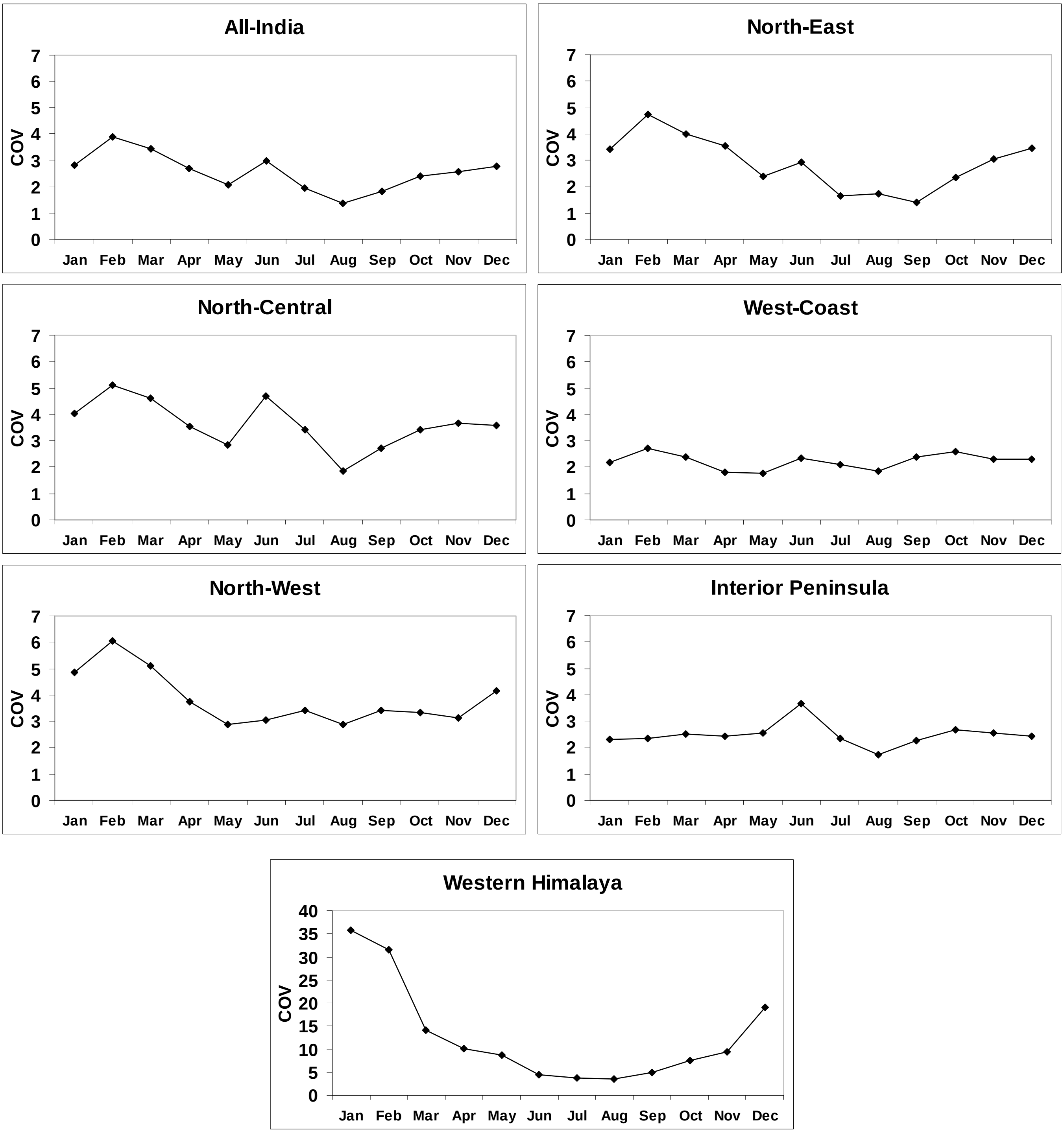


Figure 3.53: Month-wise coefficient of variations of maximum temperatures in various regions in India over 1901-2003.

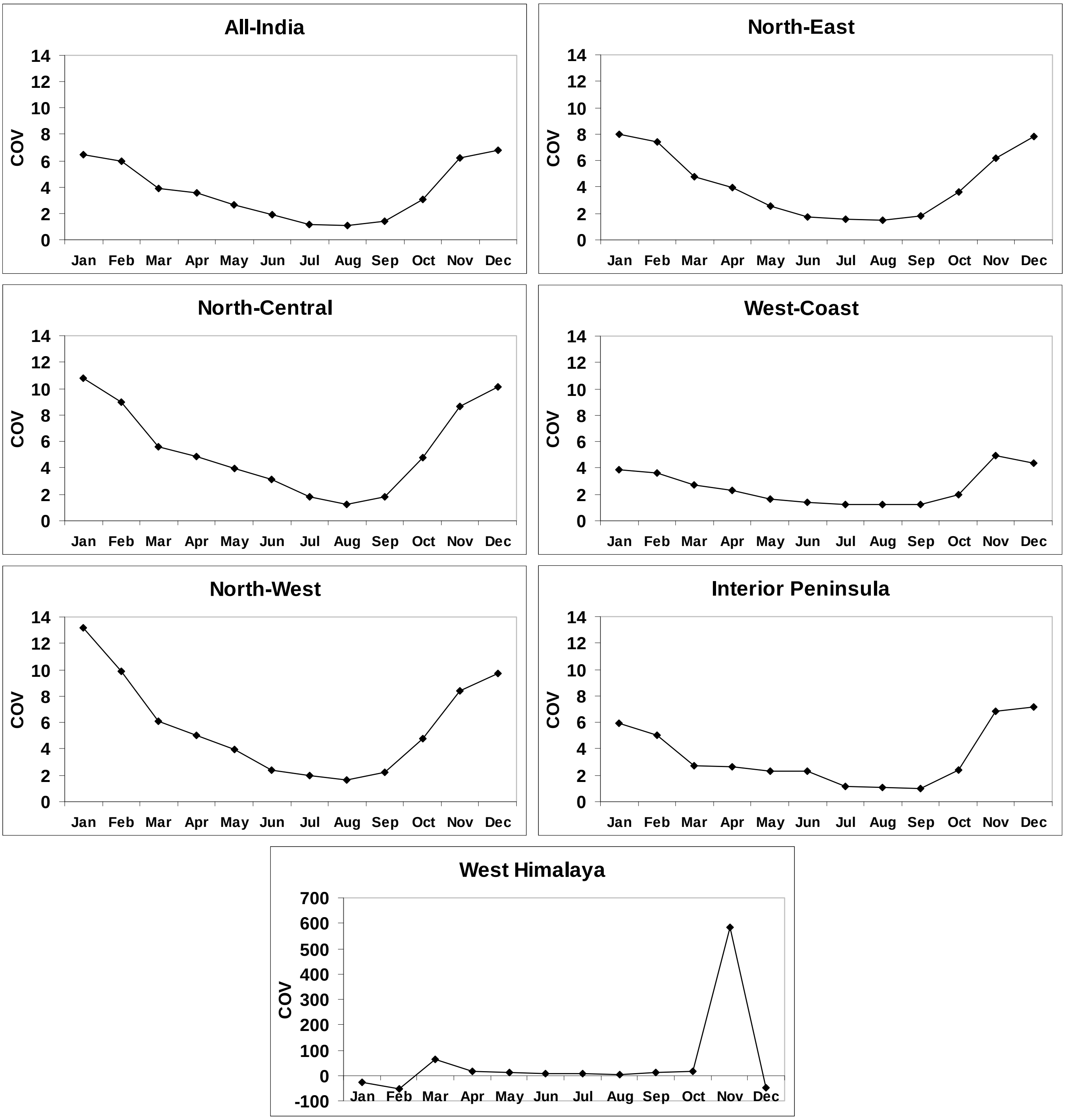


Figure 3.54: Month-wise coefficient of variations of minimum temperatures in various regions in India over 1901-2003.

Amongst the remaining regions, the most variability in terms of the magnitude of COV was found highest in North West followed by North Central India and least in West Coast, similar to maximum temperature as previously described. Also, August was found to be the lowest variability month for the minimum temperature, similar to the maximum temperature variations. This leads to the conclusion that the summer monsoon extreme temperatures are more stable than the winter temperatures over India.

3.10.2.2. Trend Analysis of 'Monthly' Extreme Temperatures

Figures 3.55 and 3.56 illustrate monthly analyses of maximum and minimum temperatures from 1901 to 2003. In the figures, as before, a range of colours in various regions in India (Figure 2.5) signify various degrees of changes. The average trend for the whole of India is shown in the small India map inside every block.

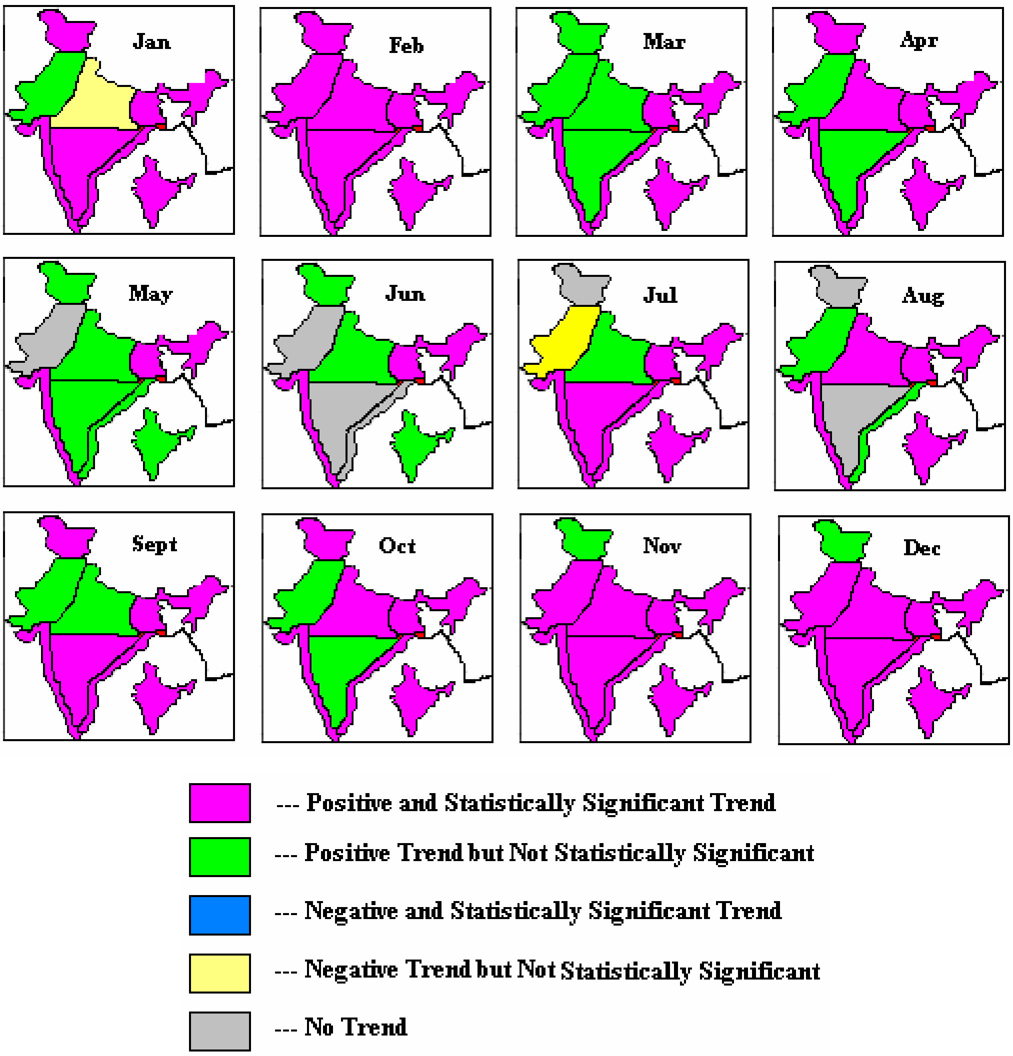


Figure 3.55: Monthly trends in maximum temperatures in various regions in India over 1901-2003.

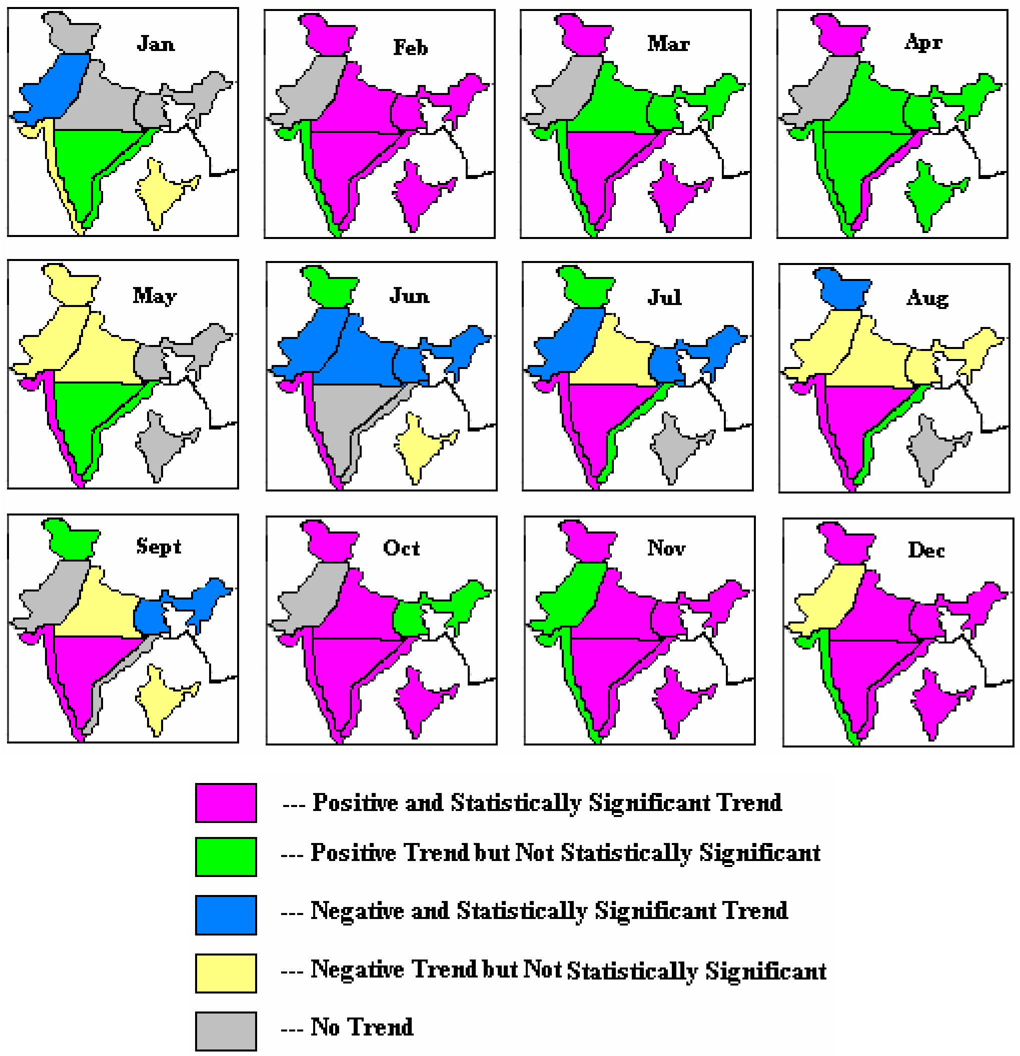


Figure 3.56: Monthly trends in minimum temperatures in various regions in India over 1901-2003.

As seen in Figure 3.55, the maximum temperatures in all the months have increased (pink and green) in India except for a decreasing tendency (yellow) in North-Central (NC) India in January and in North-West (NW) India in July. In the North-West (NW) of India, significant changes took place only in November, December and February while in the West Himalayan (WH) region it was in September, October, January, February and April. Interestingly, the West Himalayan region was found having the highest increase in maximum temperature in February compared to all the regions and all the seasons. Clear and significant increases in all the months took place in North-East (NE) India and the West Coast (WC) where maximum temperature increased as much as 19.0°C/100years in November and 17.9°C/100years in February (as shown in

Table 3.21). This could be due to the locations of these regions, their proximity to the ocean and interactions between the atmosphere and the ocean. The area of significant increase in maximum temperature over the North-East (NE) is in conformity with Sen Roy and Balling (2005).

Table 3.21: Monthly trends in extreme temperatures (in °C/100 years) in various regions in India over 1901-2003.

Maximum								
Region / Months	***All India***	***North East***	***North Central***	***West Coast***	***North West***	***Interior Peninsula***	***East Coast***	***West Himalaya***
Jan	**+5**	**+5.3**	-1.3	**+13.6**	+3.3	**+5.3**	**+8.5**	**+1.6**
Feb	**+13.6**	**+16.4**	**+12.3**	**+17.9**	**+11.2**	**+10.5**	**+10**	**+25**
Mar	**+7.3**	**+8.5**	+7.0	**+12.6**	+6.0	+5.3	**+7.1**	+10
Apr	**+8.3**	**+10**	**+9.6**	**+9.3**	+8.1	+4.4	**+4.6**	**+17.7**
May	+3.2	**+5.5**	+3.4	**+7.7**	No Trend	+1.6	+3.1	+1.4
Jun	+2.3	**+7.8**	+1.1	**+7.9**	No Trend	No Trend	No Trend	+4.5
Jul	**+4.1**	**+4.8**	+6.4	**+9.0**	-1.4	**+5.7**	**+4.6**	No Trend
Aug	**+5.3**	**+11.1**	**+7.1**	**+8.2**	+5.4	No Trend	+2.8	No Trend
Sept	**+6.8**	**+6.5**	+4.9	**+12.8**	+6.6	**+6.6**	**+9.0**	**+9.4**
Oct	**+7.7**	**+12.3**	**+7.4**	**+12.7**	+5.1	+2.7	**+5.3**	**+13.2**
Nov	**+12.9**	**+19**	**+16.5**	**+14.7**	**+8.4**	**+10.3**	**+11.7**	+3.5
Dec	**+12.5**	**+17.0**	**+11.4**	**+17.7**	**+10.6**	**+10.6**	**+12.7**	+6.0
Minimum								
Region / Months	***All India***	***North East***	***North Central***	***West Coast***	***North West***	***Interior Peninsula***	***East Coast***	***West Himalaya***
Jan	-0.11	No Trend	No Trend	-0.25	**-0.8**	+0.28	+0.3	No Trend
Feb	**+0.6**	**+0.8**	**+0.6**	+0.2	No Trend	**+0.8**	**+0.7**	**+1.2**
Mar	**+0.4**	+0.2	+0.4	+0.2	No Trend	**+0.7**	**+0.6**	**+0.67**
Apr	+0.2	+0.1	+0.2	+0.2	No Trend	+0.3	**+0.3**	**+0.5**
May	No Trend	No Trend	-0.2	**+0.2**	-0.2	+0.1	+0.2	-0.3
Jun	-0.2	**-0.2**	**-0.5**	**+0.2**	**-0.45**	No Trend	No Trend	+0.24
Jul	No Trend	**-0.34**	+0.2	**+0.2**	**-0.3**	**+0.3**	+0.1	+0.2
Aug	No Trend	-0.1	-0.1	**+0.2**	-0.1	**+0.2**	+0.1	**-0.5**
Sept	-0.1	**-0.6**	-0.2	**+0.3**	No Trend	**+0.2**	No Trend	+0.3
Oct	**+0.3**	+0.2	**+0.6**	**+0.2**	No Trend	**+0.4**	**+0.2**	**+0.6**
Nov	**+1.0**	**+0.1**	**+0.2**	+0.5	+0.5	**+0.9**	**+0.6**	**+1.4**
Dec	**+0.7**	**+1.0**	**+1.0**	+0.4	-0.1	**+0.8**	**+0.7**	**+1.2**
Note: + ve sign = increasing trend; – ve sign = decreasing trend; bold numbers indicate significant trends at the 95% level.								

Generally, maximum changes in maximum temperatures were observed in February followed by November and December, as in Figure 3.55 and Table 3.21. October and January also had significant increasing trends in most cases. All of these months belong to the winter and autumn seasons, which were also reported to have increases in mean and extreme rainfall events (refer to sections 3.6.2-3.6.4). Within the spring season, April had increasing trends in the maximum temperature in all the regions with two regions showing insignificant trends, as in Figure 3.55 and Table 3.21. May, on the other hand, had no significant trends anywhere except for the North-East (NE) and West Coast (WC), the highest spring rainfall regions in India. Like May, the June maximum temperature only increased significantly in the North-East (NE) and West Coast (WC) regions. Also, May and June are the only months when the all-India average maximum temperatures did not change significantly. July and August went through increases in maximum monthly temperatures, but not significant in many of the regions. September trends, on the other hand were found significantly positive in most of the regions except for the North-Central (NC) and North-West (NW) regions, as shown in Figure 3.55. No trends (grey colour) were observed in North-West (NW) in May and June, in Western Himalaya (WH) in July and August, in Interior Peninsula (IP) in June and August, and in East Coast (EC) in June.

Changes in minimum monthly temperatures were a little different from and less significant than maximum temperature changes, as in Figure 3.56 and Table 3.21. As illustrated in Figure 3.56 and Table 3.21, January almost had no significant trends except for a statistically significant decrease in the North-West (NW) region. Like the maximum temperatures, November, December and February had the maximum increase in minimum temperatures with the West Coast (WC) and North-West (NW) regions showing no significant trends. In March many regions in India went through significant minimum temperature increases with the exception of the North-East (NE), North-Central (NC), North-West (NW) and West-Coast (WC) regions. April and May had no significant trends in most places. The monsoon months usually showed a decrease (cooling) in minimum temperatures (blue and yellow colours) in the northern regions (NE, NC and NW) and an increase (warming) in the southern India regions (IP and WC). The August temperature also decreased significantly (blue colour) in the West Himalaya (WH) region of India. WH had a minimum temperature rise from Oct-Dec and again from February to April. October minimum temperatures increased in all the regions with a few exceptions of insignificant changes in NE and NW regions.

3.10.3. Interannual Variabilities of 'Seasonal' Extreme Temperatures

3.10.3.1. Coefficient of Variation

The coefficient of variation (COV) of seasonal maximum and minimum temperatures is shown in Figures 3.57 and 3.58 respectively. Like the monthly variations, seasonal maximum temperatures vary significantly from year to year and from region to region. Figures 3.57 and 3.58 illustrate that the maximum variation in both cases is found in the Western Himalayan (WH) region in all the seasons because of its unique pattern of variability in the corresponding months. This is because this region is very different in terms of topography, geography and climatology than the other regions. Since February is the most variable month and August the least, as discussed in section 3.10.2.1, winter is the most and monsoon is the least variable season.

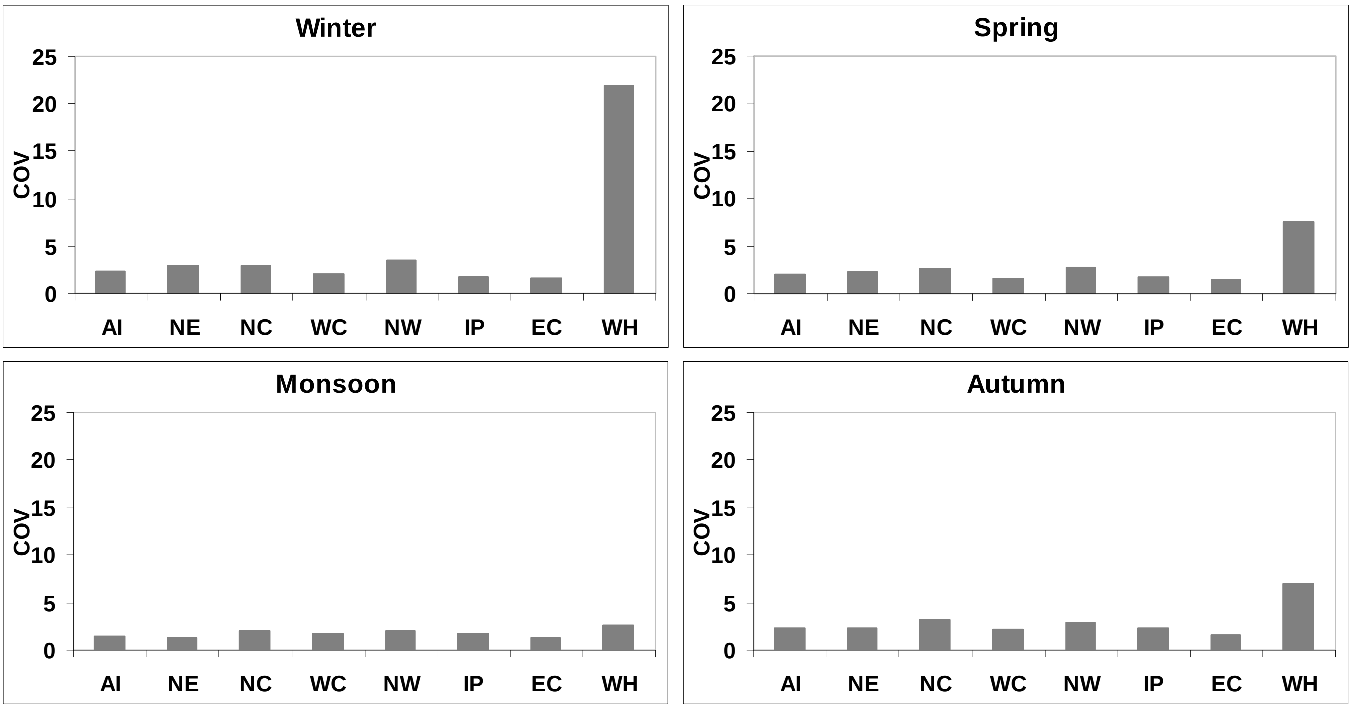


Figure 3.57: Seasonal coefficient of variations of 'maximum' temperatures in various regions in India over 1901-2003.

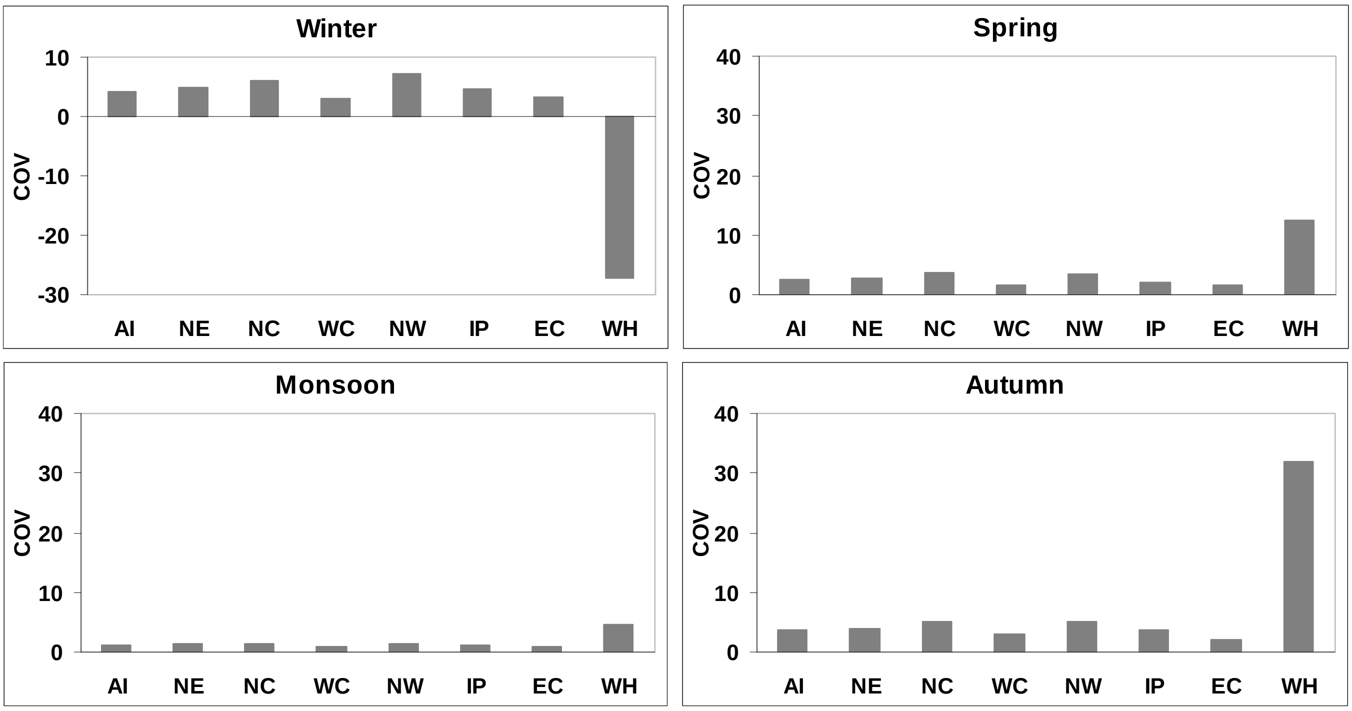


Figure 3.58: Seasonal coefficient of variations of 'minimum' temperatures in various regions in India over 1901-2003.

A further analysis was carried out on the trends of coefficient of variation in various seasonal and annual average maximum and minimum temperatures as shown in Figures 3.59, 3.60 and 3.61. Interestingly, while the annual maximum temperature showed negative significant trends (blue) over the whole of India (Figure 3.59), winter had positive tendencies to variability in many regions, with only a statistically significant trend in the NE region, as in Figure 3.60. On the other hand, the WH region, which had the highest winter variability, as discussed before, was found to have a significantly decreasing trend in the winter maximum temperature variability (Figure 3.60). Although the spring, monsoon and autumn variabilities had negative trends, only the autumn season exhibited significance in all but the western regions (WC, NW and WH), as in Figure 3.60.

Figures 3.59 and 3.61 show that the changes in the minimum seasonal temperature variabilities were different but the annual changes were found significantly negative in most of the regions, and so were the autumn and spring seasonal minimum temperatures; whereas, only the NE monsoon seasonal variability had a significantly positive trend. Winter had mostly positive tendencies, like the maximum temperature variability, but a significant trend was found only in the West Coast region, wherein a negative significant trend was again found in the WH region, as in Figure 3.61.

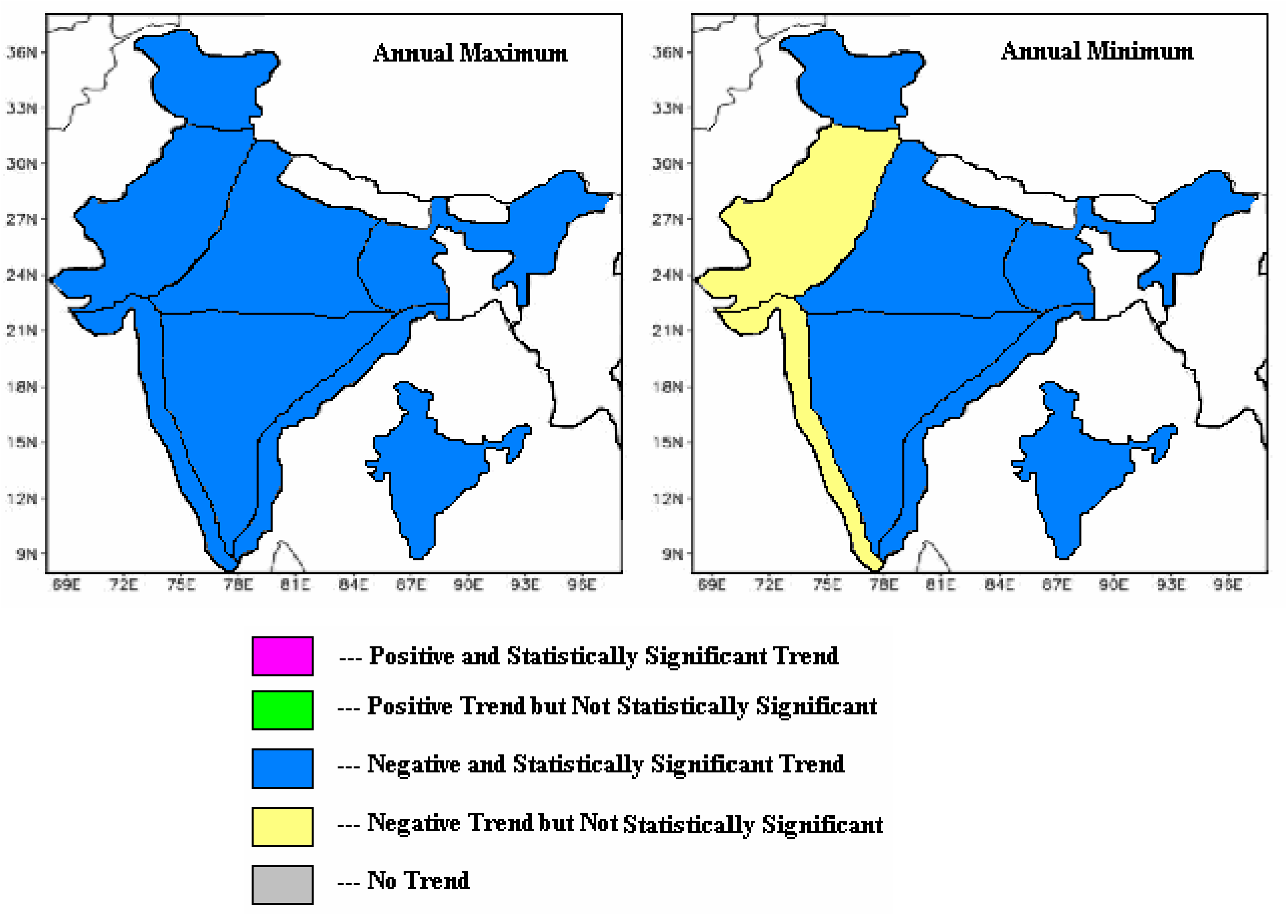


Figure 3.59: Trends of annual coefficient of variations of maximum and minimum temperatures in different climatological regions in India over 1901-2003.

3.10.3.2. Trend Analysis of Maximum 'Seasonal' Temperature

Figure 3.62(A) and Table 3.22 show trends of maximum seasonal temperatures from 1901-2003. The figure illustrates that the maximum temperatures increased significantly (pink and green) over the entire region, while the greatest changes were observed in the winter and autumn seasons with magnitudes as much as 1.6°C/100years on an average (Table 3.22), as consistent with Kothawale and Rupa Kumar (2005). This result is also consistent with Hingane et al. (1985) who examined mean temperature changes in various Indian regions from 1901-1982.

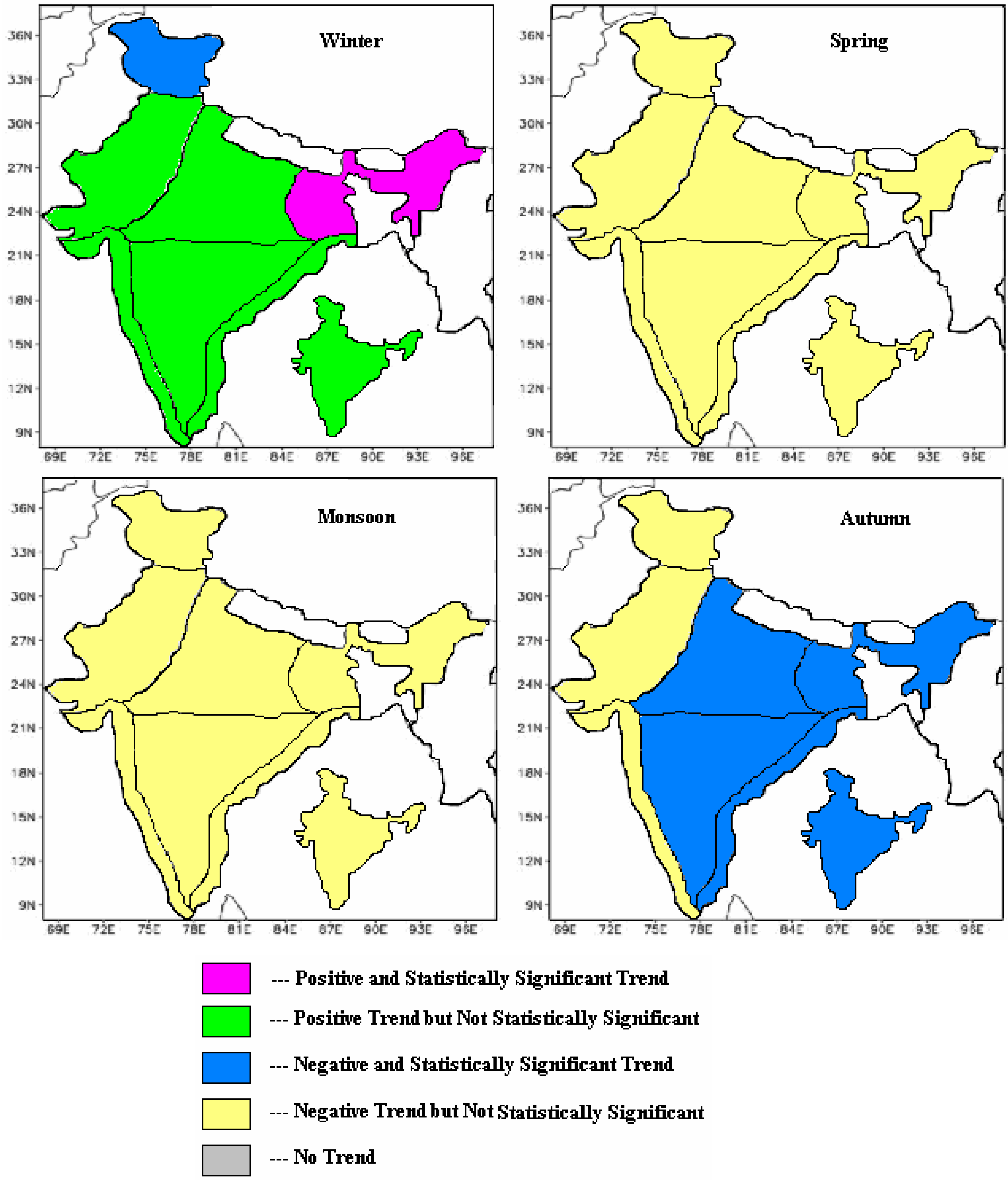


Figure 3.60: Trends of seasonal coefficient of variations of maximum temperatures in different climatological regions in India over 1901-2003.

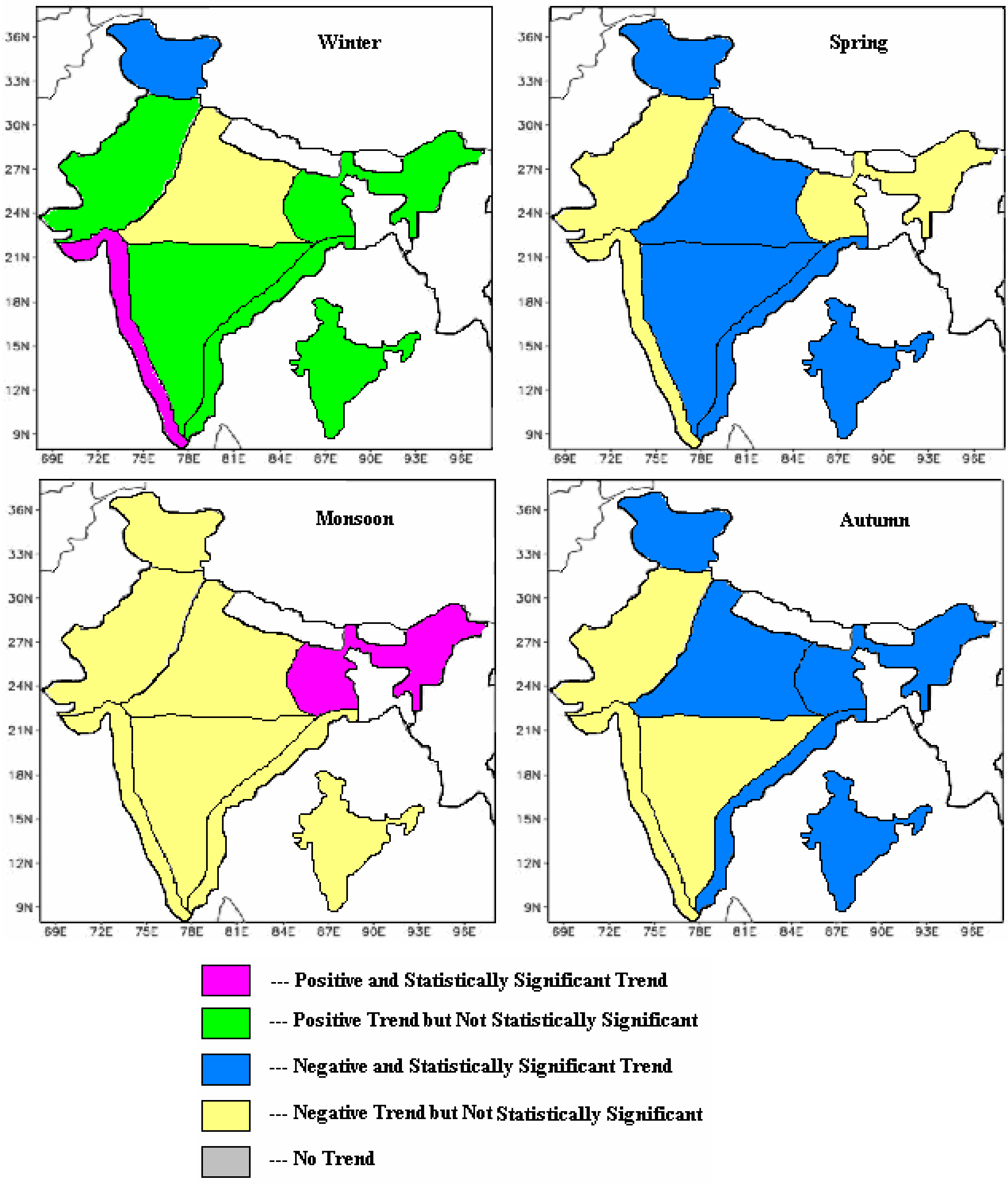


Figure 3.61: Trends of seasonal coefficient of variations of minimum temperatures in different climatological regions in India over 1901-2003.

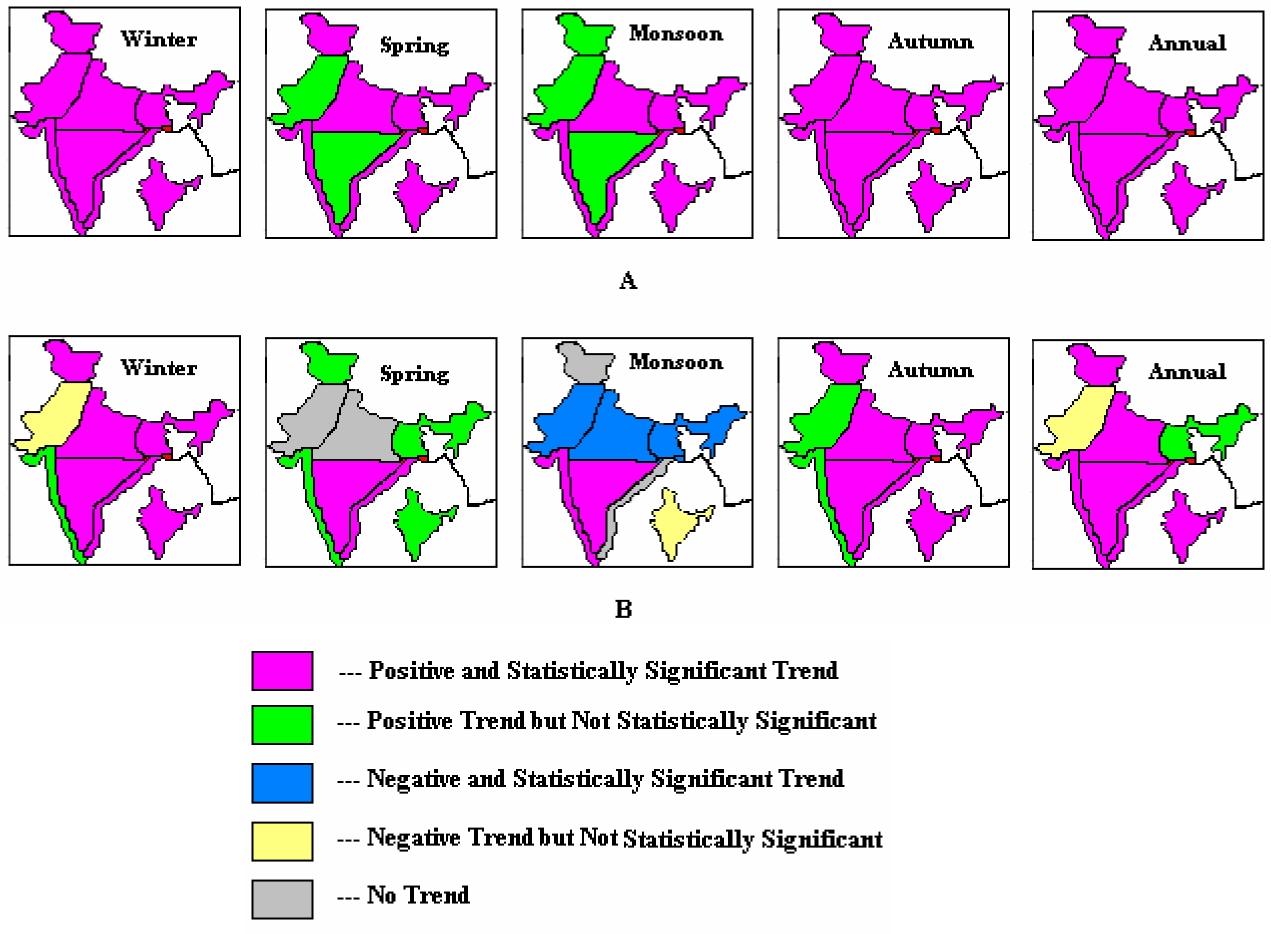


Figure 3.62: Annual and seasonal trends in different climatological regions in India over 1901-2003 in terms of (A) maximum temperatures and (B) minimum temperatures.

Table 3.23 summarises the months which had significant trends in extreme temperatures in the corresponding seasons demonstrating the month(s) that contributed the most to the significant seasonal trends. While December-January-February had significant contributions in winter seasonal maximum temperature changes, February was the only month that was active in each individual region of India, as shown in Table 3.23. Because February and December had the greatest magnitude of trends, these months could be considered to have contributed the most to winter seasonal changes. Wherein, February was the most important on an all-India basis. In winter, the greatest increase in maximum seasonal temperature occurred in West Himalaya and West Coast regions followed by the North East India (Table 3.22). The conclusion on West Himalaya is highly analogous to those of Bhutiyani et al. (2007) and Shrestha et al. (1999) who studied the maximum and mean annual temperature changes in the same region only in the winter and monsoon seasons in the 20th century using a different data source. Interestingly, they arrived at the same temperature increase in winter in Western Himalaya.

Table 3.22: Seasonal trends in extreme temperatures (in °C/100 years) in various regions in India over 1901-2003.

Maximum					
Region	***Winter***	***Spring***	***Monsoon***	***Autumn***	***Average Annual***
All India	**+1**	**+0.6**	**+0.4**	**+1**	**+0.74**
North East	**+1.3**	**+0.8**	**+0.76**	**+1.6**	**+1.0**
North Central	**+0.77**	**+0.66**	**+0.49**	**+1.2**	**+0.71**
West Coast	**+1.6**	**+0.98**	**+0.95**	**+1.4**	**+1.2**
North West	**+0.87**	+0.50	+0.25	**+0.67**	**+0.53**
Interior Peninsula	**+0.84**	+0.37	+0.26	**+0.65**	**+0.51**
East Coast	**+1.0**	**+0.49**	**+0.37**	**+0.85**	**+0.65**
West Himalaya	**+1.6**	**+0.96**	+0.36	**+0.83**	**+0.89**
Minimum					
Region	***Winter***	***Spring***	***Monsoon***	***Autumn***	***Average Annual***
All India	**+0.38**	+0.17	-0.10	**+0.66**	**+0.22**
North East	**+0.58**	+0.10	**-0.33**	**+0.64**	+0.18
North Central	**+0.48**	No Trend	**-0.26**	**+1.1**	**+0.25**
West Coast	+0.13	+0.23	**+0.22**	+0.37	**+0.23**
North West	-0.32	No Trend	**-0.25**	+0.21	-0.14
Interior Peninsula	**+0.60**	**+0.37**	**+0.21**	**+0.69**	**+0.44**
East Coast	**+0.55**	**+0.39**	No Trend	**+0.43**	**+0.34**
West Himalaya	**+0.81**	+0.32	No Trend	**+1**	**+0.47**
Note: + ve sign = increasing trend; – ve sign = decreasing trend; bold numbers indicate significant trends at the 95% level.					

Spring seasonal maximum temperatures also showed increasing trends everywhere except North West and Interior Peninsula regions because of no significant trends in March-April-May months, as seen in Figure 3.55 and Table 3.23 (marked by a cross). Most interestingly, North-Central and West Himalaya regions, where only April had significant changes in maximum temperature, had significantly high trends in the spring season as well. Therefore, April could be considered as the most important contributor to the spring season for the majority of the regions and including all-India while only West and East Coast had March trends more important than April. In the spring, the maximum changes occurred in the West Coast region (0.98°C/100years) and followed by WH (0.96°C/100years) and NE India (0.80°C/100years), as shown in Table 3.22.

Table 3.23: List of the months those contributed to various seasonal changes of extreme temperatures.

Maximum				
Region	***Winter***	***Spring***	***Monsoon***	***Autumn***
All India	D,J,**F**	Ma,**A**	Jl,Au,**S**	O,**N**
North East	**D**,J,**F**	Ma,**A**,M	Ju,Jl,**Au**,S	O,**N**
North Central	D,**F**	**A**	**Au**	O,**N**
West Coast	D,J,**F**	**Ma**,**A**,M	Ju,Jl,Au,**S**	O,**N**
North West	D,**F**	×	×	**N**
Interior Peninsula	D,J,**F**	×	*Jl,S*	**N**
East Coast	**D**,J,**F**	**Ma**,**A**	Jl,**S**	O,**N**
West Himalaya	J,**F**	**A**	S	**O**
Minimum				
Region	***Winter***	***Spring***	***Monsoon***	***Autumn***
All India	**D**,F	*Ma*	×	O,**N**
North East	**D**,F	*Ma*	Ju,Jl,**S**	**N**
North Central	**D**,F	×	**Ju**	O,**N**
West Coast	×	*Ma,M*	Ju,Jl,Au,S	*O*
North West	*J*	×	**Ju**,Jl	×
Interior peninsula	**D,F**	**Ma**	Jl,Au,S	O,**N**
East Coast	**D,F**	**Ma**,A	×	O,**N**
West Himalaya	**D,F**	*Ma,A*	*Au*	O,**N**

Note: D = December, J = January, F = February, Ma = March, A = April, M = May, Ju = June, Jl = July, Au = August, S = September, O = October, N = November; bold = important months in the respective season; italic and underlined = significant months but insignificant seasonal trends.

Like spring, monsoon also had a significantly increasing trend of maximum temperature in most regions except for North-West, Interior Peninsula and West Himalaya. For the North-West region, none of June-July-August-September months had significant trends (Figure 3.55 and Table 3.21), which was the cause for the insignificant trend in this season (Figure 3.62(A)). However, interestingly, Interior Peninsula had significant trends in July and September, and West Himalaya had a significant trend in September month, as in Figure 3.55 and Tables 3.21 and 3.23. These had no effects on significant changes but a positive tendency in the monsoon season, as in Figure 3.62(A). Therefore, it could be stated that, even though monthly contributions are important for the significant trends in a season, monthly significant changes do not always reflect significant seasonal changes. Among all the four months in the monsoon season, September provides the most important contribution to seasonal maximum temperature changes on an all-India basis and for the West and East coasts; while August is important for North-East and North-Central India regions. In the monsoon season, the maximum increase was in the North-East India region (0.95°C/100years) and followed by the WC region (0.76°C/100years), as in Table 3.22.

The autumn and winter season show the highest rise in maximum temperature over the whole time period of study. As seen in Figures 3.55 and 3.62(A), and Tables 3.21, 3.22 and 3.23, November is the most important month contributing to the autumn temperature increase, for most regions and on an all-India basis, while October is the corresponding month for West Himalaya. In the autumn, the maximum temperature increase took place in North-East India (1.6°C/100years) followed by WC (1.4°C/100 years), as in Table 3.22.

3.10.3.3. Trend Analysis of Minimum 'Seasonal' Temperature

Figure 3.62(B) and Table 3.22 show the changes in minimum temperatures in the different seasons for the seven regions in India from 1901 to 2003. It is noted in Figure 3.62(B) and Table 3.22 that the trends in the autumn seasonal minimum temperatures have the greatest changes followed by the winter season. In winter, most of the regions were found to go through a minimum temperature rise, while the West-Coast and North-West regions had no significant changes. Although in the West-Coast region none of the winter months (December-January-February) had significant changes (cross-marked in Table 3.23 and Figure 3.56), the December and February monthly tendencies still produced a positive tendency in the winter season (Table 3.21 and Figure 3.56). On the other hand, in the North West region, a significant positive trend in January had no effect on the negative, but insignificant, tendency in winter, but a negative tendency in December might be the reason (Tables 3.21 and 3.23 and Figure 3.56). In the rest of the regions and India as a whole, December played a prime role in the winter minimum seasonal temperature rise; wherein February was also important in Interior Peninsula and West Himalaya as marked in Table 3.23.

In the spring, interesting effects of monthly changes were observed. Significant increasing trends in the spring season were only found in Interior Peninsula (IP) and East Coast (EC). In IP, only the March minimum temperature increased significantly;

whereas in EC, March and April had a minimum temperature increase (Figure 3.56 and Table 3.21). This pre-monsoonal temperature increases could be connected to the mean monsoonal rainfall increase in these regions, as discussed in section 3.6. In India as a whole and the North-East (NE) region, even though March showed significant increase in minimum temperature, no significant trend in April and no tendency in May resulted in an insignificant trend in the spring season (Figures 3.56 and 3.62(B) and Tables 3.21, 3.22 and 3.23). In the West Coast (WC) region, even though March and May had significantly increasing trends, they only affected a positive tendency in the spring season. In the NW and NC India, no changes were found in the minimum temperature because of no changes in the corresponding months (Tables 3.21 and 3.23 and Figure 3.62(B)). In WH, there was a positive tendency but non-significant spring minimum temperature even at a significant increase in March and April – which might be due to a negative tendency in May.

In the monsoon season, minimum temperature trends were found to be most variable spatially and monthly, as shown in Figure 3.62(B). Negative significant trends were noted in the North Indian regions (NE, NC and NW), as in Figure 3.62(B), where most of the monsoon months had negative tendencies with mainly significant trends. It was difficult to generalise which month played the most important role for this case. However, according to the magnitude of the trends, September in the NE region and June in the NC and NW regions appear to be the key months (see Tables 3.21 and 3.23). These regional coolings could be attributed to the impact of land-use changes associated with the Green Revolution in the NW and NC India regions (Sen Roy et al., 2007). The decreasing trends in the monsoon minimum temperature in NC, NE and NW regions agree with Sen Roy and Balling (2005). In the WC and IP regions the minimum temperature increased in the monsoon season because most of the months had significant positive changes. The EC and WH regions had no trends for they had insignificant changes in most of the monsoon months; the only significant change in August in WH did not have any effect on the seasonal change.

In the autumn, as illustrated before, the minimum temperature trends were found greatest and most positive everywhere. November temperature changes played the most important role in this season (Table 3.23, Figures 3.56 and 3.62(B)) with a maximum seasonal increase in minimum temperature in the NC region (1.1°C/100years) followed by the WH region (1°C/100years), as in Table 3.22. In the NW, the autumn seasonal trend was not significant but had a positive tendency for there were no months with significant changes; wherein, despite having a significant increase in October, no significant trend but a positive tendency was observed in the WC region.

Figure 3.62(B) also shows that, the average annual minimum temperature increased in all the regions except for the NW, regardless of how non-significant. Bhutiyani et al. (2007) observed that deficient annual rainfall could be associated with high maximum and low minimum temperatures because of the increase in daytime direct radiation and release of night-time outgoing long wave radiation. Therefore, significantly decreasing annual rainfall in the West Central Indian region, as discussed before (Table 3.10), could be associated with the maximum and minimum temperature changes. Over all, the trend in maximum temperatures is so variable in India that an all-India average is not helpful to arrive at a general conclusion.

Therefore, from section 3.10 overall, it can be concluded at this point that a seasonal significant change might mean at least one month in that season having significant change but the opposite is not always true.

The results discussed in section 3.10 have been published (Pal and Al-Tabbaa, 2009f).

3.11. Projection of Long-Term Seasonal Rainfalls Based on 50-Year Trends for Indian Regions

Based on the 50-year trend (1954-2003) results discussed previously for various Indian regions in section 3.6.4, linear projections were made for the next 50-years (2004-2053) for all the study regions in India. The slopes and intercepts of the linear trends corresponding to OLS method were chosen for the projection purpose. As was noticed from Table 3.10 and Figure 3.26, four regions namely WCIN, CNEIN, NEIN and

PENIN went through significant changes in spring rainfall, and WCIN went through significant decrease in monsoon rainfall and annual rainfall. However, this section discusses the future projections of all those significant changes and also the non-significant trends corresponding to OLS method in Table 3.10. If the changing trends from 1954 to 2003 continue for all the study regions, the projected rainfall trends would look like Figures 3.63, 3.64, 3.65, 3.66 and 3.67 for winter, spring, monsoon, autumn and annual respectively.

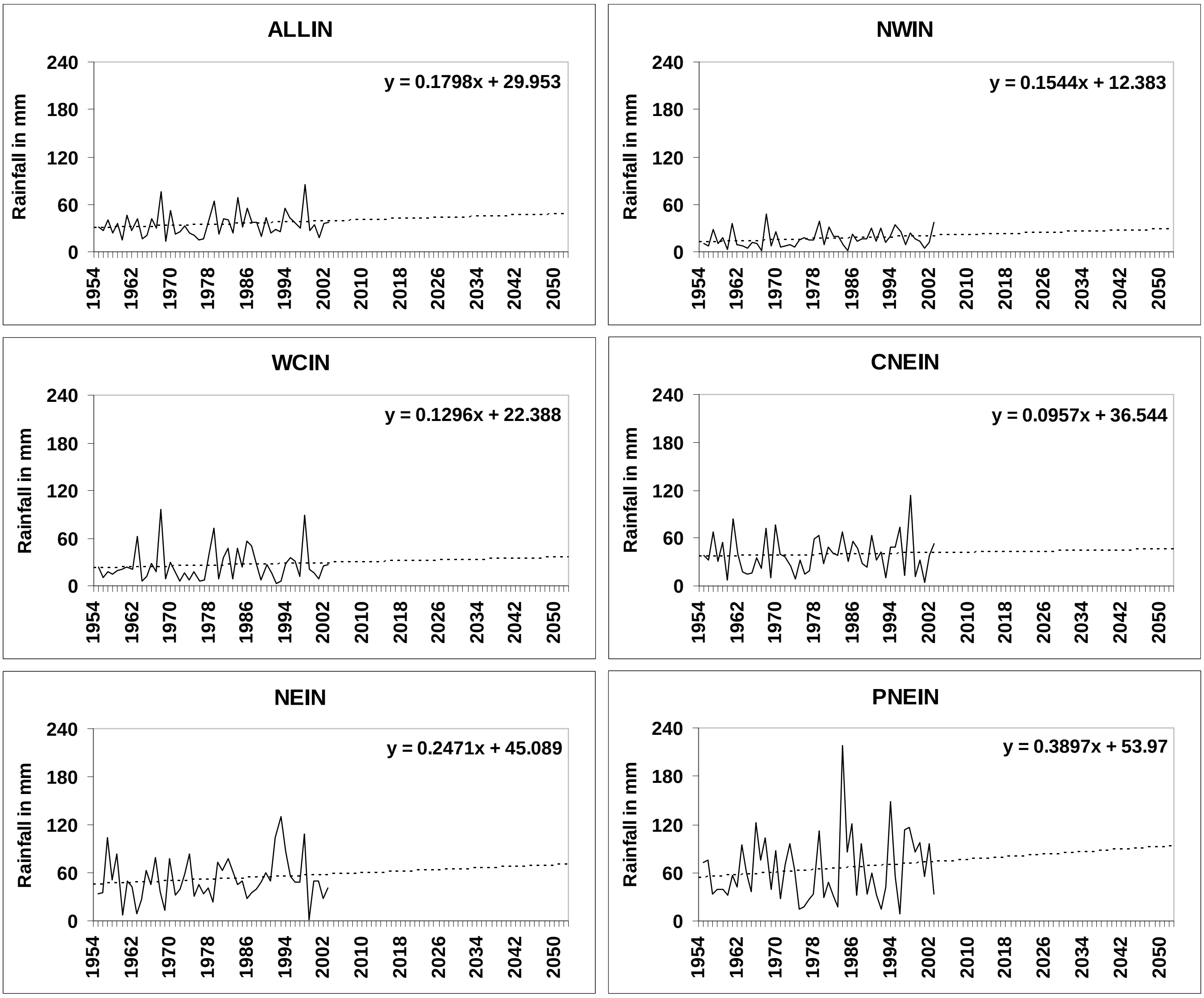


Figure 3.63: 50-year projections of winter rainfall in the study regions of India.

Figure 3.63 shows the 50-year projection of winter rainfall changes in ALLIN, NWIN, WCIN, CNEIN, NEIN and PENIN respectively. All the regions follow an increasing tendency but the magnitudes of the changes are variable. Table 3.24 shows probable percentage changes of average seasonal and annual rainfalls in the next 50 years. As noted in Table 3.24 that there will be a maximum increase in winter average rainfall in NWIN (46%), which will be followed by PENIN (30%). A 25% increase in the whole of India, 24% increase in WCIN and 23% increase in NEIN in winter average rainfall will be expected to occur in the next 50-years from the 1954-2003 average. While an increase in average winter rainfall could be good for the deserted region of NWIN, an increase in the same in other places may bring more number of off-monsoon floods.

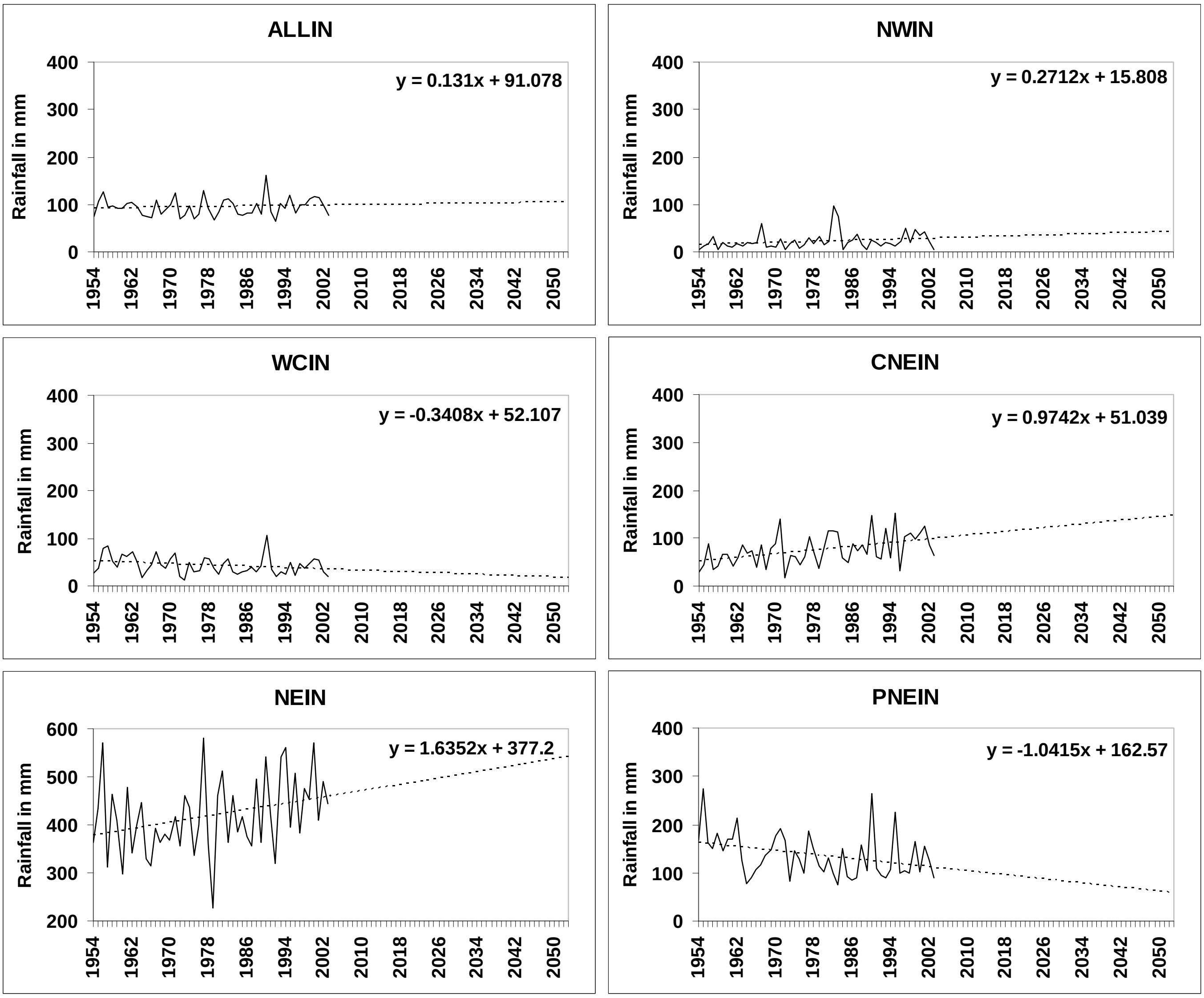


Figure 3.64: 50-year projections of spring rainfall in the study regions of India.

Figure 3.64 shows the 50-year projection of spring rainfall changes in ALLIN, NWIN, WCIN, CNEIN, NEIN and PENIN respectively. It is seen in Figure 3.64 that all the north Indian regions (NWIN, CNEIN, and NEIN) show increasing trends while all the south Indian regions (WCIN and PENIN) have decreasing trends. In north-India, a 19-63% increase, and in south-India, a 38-39% decrease in average spring seasonal rainfall will be expected in 2004-2053 from 1954-2003 average. CNEIN and NEIN regions are prone to convective activities in the pre-monsoon season. Therefore, an increase in average spring seasonal rainfall in these regions may mean that the pre-monsoon disasters will very likely increase.

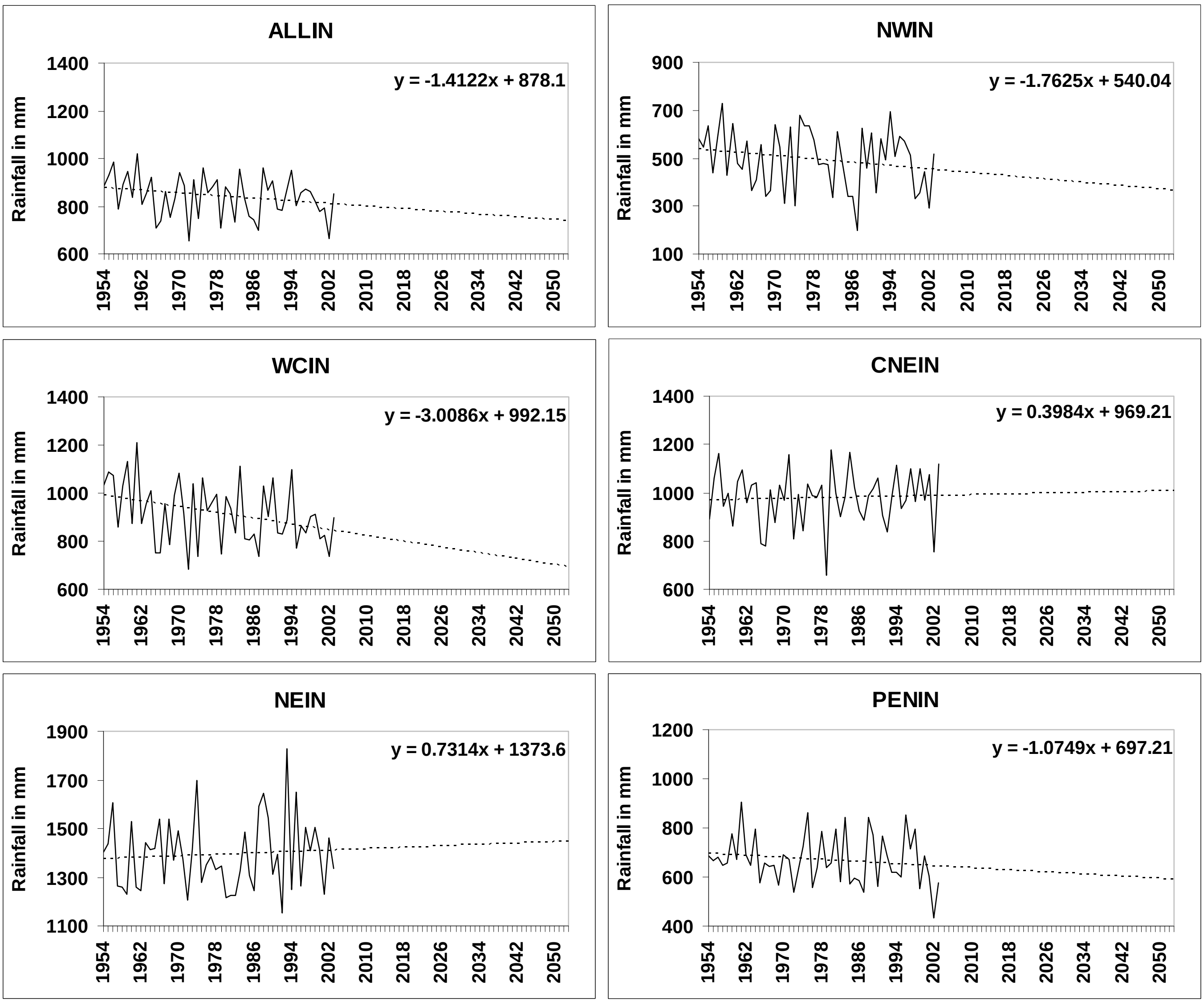


Figure 3.65: 50-year projections of monsoon rainfall in the study regions of India.

Figure 3.65 shows the 50-year projection of monsoon rainfall changes in all the study regions of India. A decrease (from 8% to 18%) has been noted in average monsoon rainfall amount every where in India except central north east (CNEIN) and north eastern parts (NEIN), as in Table 3.24. The maximum decrease in average monsoon rainfall will be occurring in NWIN (18%) and followed by WCIN (16%), which could be dangerous for the agriculture in WCIN since it is very dependable on the monsoon seasonal rainfall.

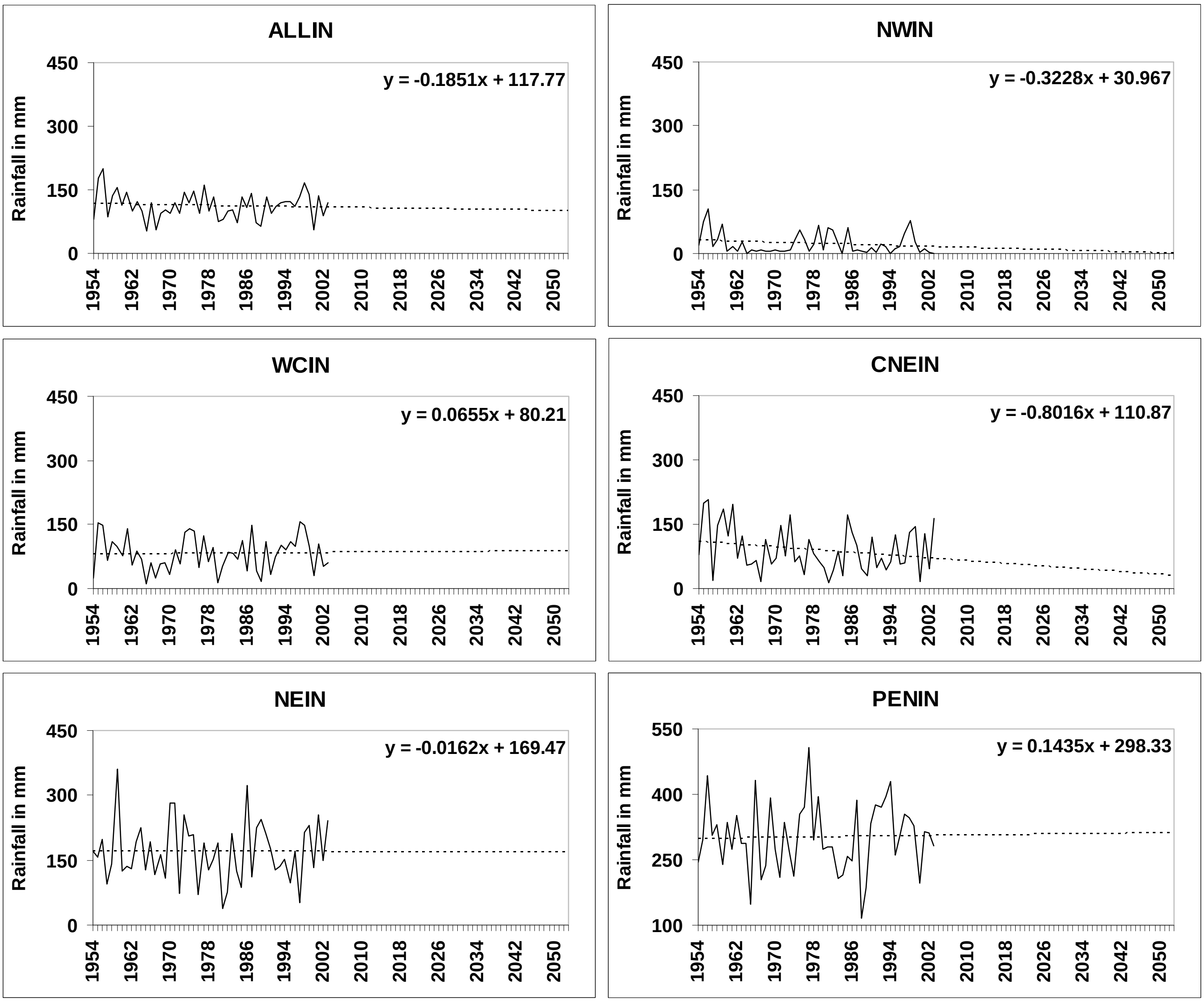


Figure 3.66: 50-year projections of autumn rainfall in the study regions of India.

Figure 3.66 and Table 3.24 show the 50-year projection of autumn rainfall changes in all the study regions of India. The most interesting point to be noted in Table 3.24 is that a large decrease (70%) in average autumn rainfall will be expected in 2004-2053 in NWIN but an increase (44%) in the same will be expected in its immediate neighbouring region of CNEIN. A slight increase in average autumn rainfall will be expected in WCIN and PENIN (4% and 2%) in 2004-2053 and in NEIN the same will be expected to be more or less the same as 1954-2003.

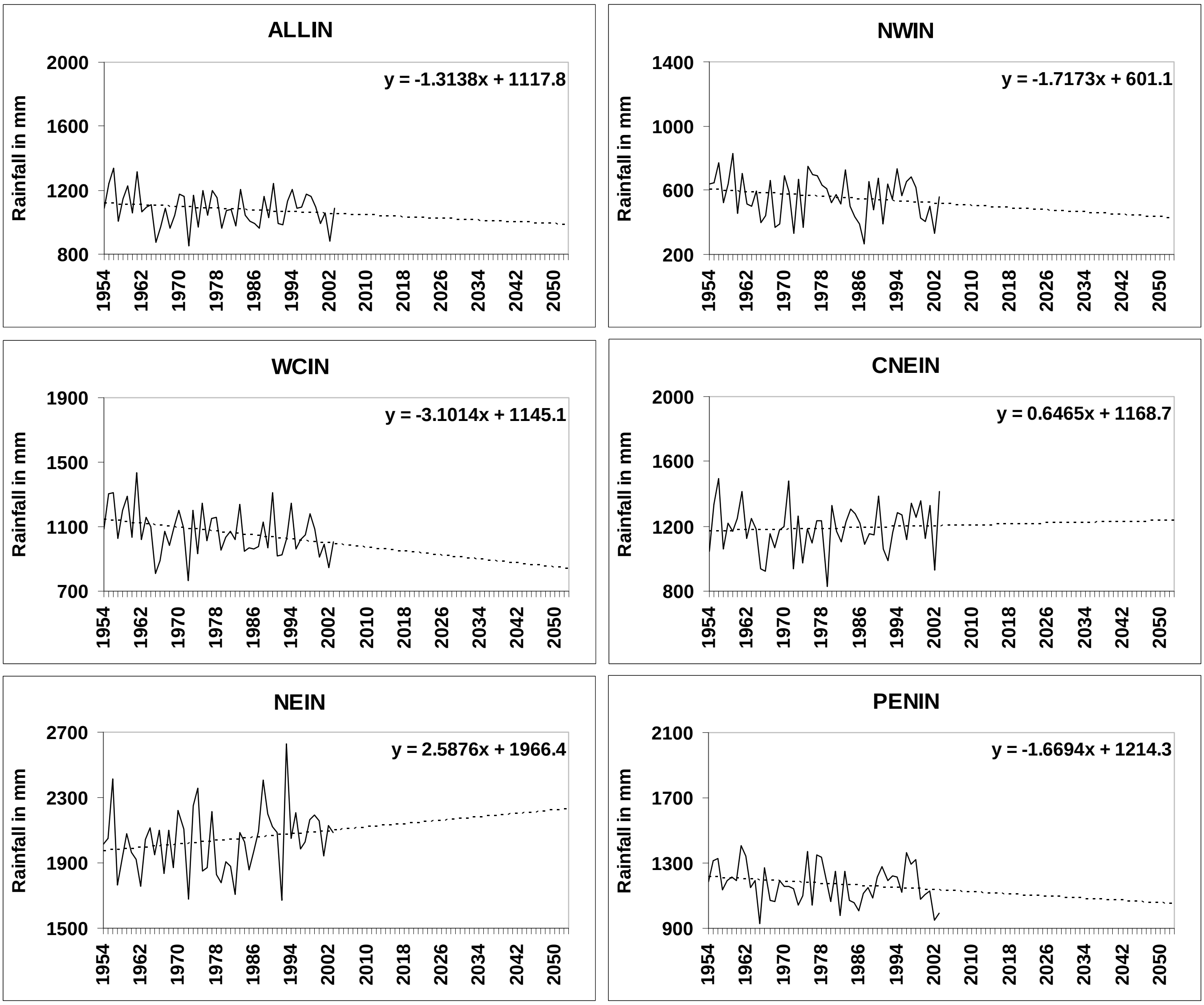


Figure 3.67: 50-year projections of annual rainfall in the study regions of India.

Table 3.24: Changes in average seasonal rainfalls in the next 50 years (2004-2053) based on estimated trend values in 1954-2003.

Winter			
Region	***Average rainfall in mm in 1954-2003***	***Average rainfall in mm in 2004-2053***	***Change***
ALLIN	34.6	43.4	25%
NWIN	16.4	24	46%
WCIN	25.8	32.1	24%
CNEIN	39	43.7	12%
NEIN	51.5	63.6	23%
PENIN	64.1	83.2	30%
Spring			
Region	***Average rainfall in mm in 1954-2003***	***Average rainfall in mm in 2004-2053***	***Change***
ALLIN	94.4	101	7%
NWIN	22.7	36.1	59%
WCIN	43.4	26.5	-39%
CNEIN	76	124.1	63%
NEIN	419	500	19%
PENIN	136	84.5	-38%
Monsoon			
Region	***Average rainfall in mm in 1954-2003***	***Average rainfall in mm in 2004-2053***	***Change***
ALLIN	842	772.2	-8%
NWIN	495.1	407.8	-18%
WCIN	915.4	766.5	-16%
CNEIN	979.3	999	2%
NEIN	1392.3	1428.5	3%
PENIN	669.8	616.6	-8%
Autumn			
Region	***Average rainfall in mm in 1954-2003***	***Average rainfall in mm in 2004-2053***	***Change***
ALLIN	113	104	-8%
NWIN	22.7	6.8	-70%
WCIN	82	85.1	4%
CNEIN	90.4	50.75	44%
NEIN	169.1	168.3	-1%
PENIN	302	309.1	2%
Annual			
Region	***Average rainfall in mm in 1954-2003***	***Average rainfall in mm in 2004-2053***	***Change***
ALLIN	1084.3	1019.3	-6%
NWIN	557.3	472.3	-15%
WCIN	1066	912.5	-14%
CNEIN	1185.2	1218	3%
NEIN	2032.4	2160.5	6%
PENIN	1171.7	1089.1	7%
Note: + ve sign = increasing change; – ve sign = decreasing change.			

Figure 3.67 and Table 3.24 show the 50-year projection of annual rainfall changes in all the study regions of India. The patterns of the changes in average annual rainfall are consistent with monsoon rainfall changes in Figure 3.65. Maximum decrease in average annual rainfall (15%) will be found in NWIN in 2004-2053, which will be followed by WCIN (14%), as in Table 3.24. Increases in average annual rainfall (3-7%) will be expected in CNEIN, NEIN and PENIN (Table 3.24).

It is also noticed in Table 3.24 that the changes are least for annual average rainfall. As rainfall amount decreases, deviations increase. Therefore, NWIN shows maximum changes in all the seasonal rainfalls among all the regions.

PART II

IMPACTS OF AND ADAPTATION STRATEGIES FOR OBSERVED REGIONAL CLIMATIC PATTERNS IN INDIA

CHAPTER 4

LITERATURE REVIEW

This chapter reviews relevant topics from the literature including climate change impact on soil erosion and soil carbon, rainfall-induced soil erosion and its effects on top soil properties, contaminant transport with eroded sediments, and management options to control soil erosion. The detailed description of rainfall-induced erosion, model RUSLE2 and its application to soil erosion problems and the availability and suitability of the rainfall data from different parts of the world were documented in detail in the related MPhil study (Pal, 2007). Hence, only a very brief description of rainfall-induced soil erosion and its estimation using RUSLE2 is presented here where appropriate in terms of the results presented in Chapter 5.

4.1. Climate Change and Soil Erosion

The predicted climate change is expected to increase risks of soil erosion, which can exacerbate soil degradation and desertification (O'Neal et al., 2005). A relationship between rainfall change and water erosion processes in terrestrial ecosystems is shown in Figure 4.1 (Wei et al., 2009) which shows that change in rainfall affects soil erosion processes by altering soil features, vegetation, cultivation systems, plant litter and landform. Figure 4.1 also indicates that rainfall-induced soil erosion affects soil properties and soil carbon dynamics (as is also discussed later in section 4.3). The magnitude of the expected change in soil erosion risks with climate change will most likely depend on local and regional conditions, as shown in Table 4.1 as an example (Blanco and Lal, 2008). As the model studies indicate in Table 4.1, an increase in annual rainfall amount from 1-20% may increase soil erosion by 1.7-241% in the 21st century.

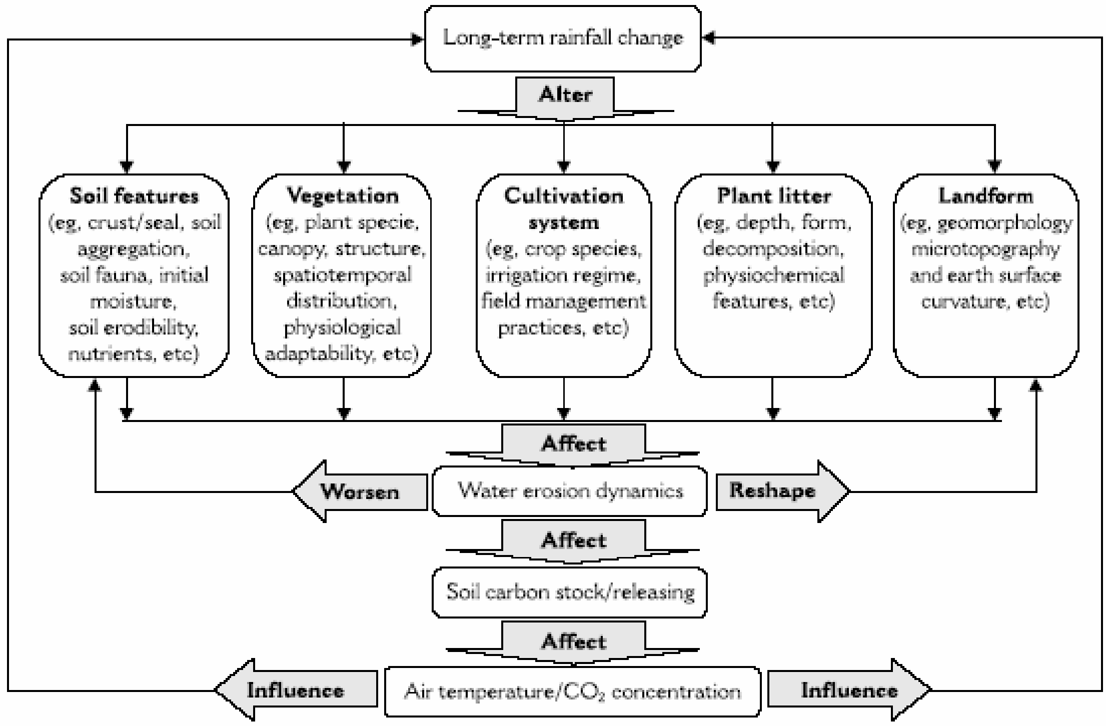


Figure 4.1: Relationship between rainfall change and water erosion processes in terrestrial ecosystems (Wei et al., 2009).

Table 4.1: Effect of the predicted increases in annual rainfall amount on soil erosion in the 21st century (Blanco and Lal, 2008).

Location	***Scenario***	***Model***	***Rainfall increase (%)***	***Soil erosion increase (%)***
UK South Downs	High levels of CO_2 emissions	EPIC	5 10 15	10 26 33
U.S. Corn Belt region	Corn/soybean rotations	EPIC	20	37
Eastern U.S. Corn Belt region	A range of cropping systems, soil types, and climate conditions	WEPP- CO_2, Hadley Centre ($HadCM_3$-GGal), and Decision Support System for Agrotechnology Transfer (DSSAT)	10-20	241
Eight locations in the USA	A wide range of soils and rainfall intensities	WEPP and RUSLE	1	2.4
USA	Review of modelled results across USA	WEPP and $HadCM_3$-GGal	1	1.7

Effects of climate change on erosion are expected to be more severe in soils managed by resource-poor farmers in developing countries (Blanco and Lal, 2008). Such high risks in developing countries may be attributed to large areas of degraded ecosystems and the fact that erosion control strategies are either limited or nonexistent. In the humid tropics, heavy rainfall would increase runoff and cause flooding of lowlands. While the amount of rainfall may decrease in arid and semiarid regions, the erosivity of rains may increase (Blanco and Lal, 2008). Thus, decrease in precipitation rates may not always result in lower soil erosion rates. Indeed, predicted decreases in rainfall in arid and semiarid regions are just as likely to increase water erosion as in humid regions (Pruski and Nearing, 2002).

Sedimentation of downstream water bodies with runoff sediment is a concern under the new climate. Figure 4.2 shows non-linear responses of sediment yield with respect to storm patterns, soil water deficit and vegetation cover in Mediterranean watersheds (Nunes et al., 2009). These variables are bound to change due to climate change, as discussed previously in Chapters 2 and 3 in case of storm patterns, and later in section 4.6.2.2 for soil water and soil cover. The non-linearity of sediment yield is different for different watersheds, as noticed in Figure 4.2. This result can be explained by changes in runoff and its transport capacity and changes to the SDR (sediment delivery ratio).

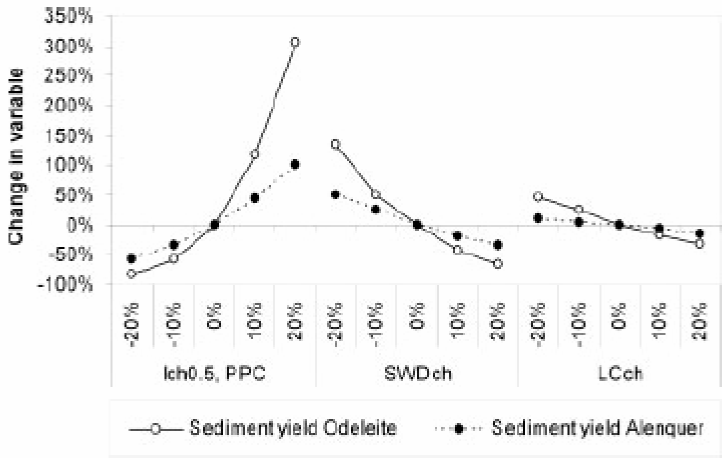


Figure 4.2: Averaged changes to sediment yield in two study areas for changes to rainfall intensity (Ich0.5,PPch at left), soil water deficit (SWDch at centre) and land cover (LCch at right) (Nunes et al., 2009).

The projected increases in soil erosion by climate change can cause pollution of water resources with dissolved and suspended loads. A detailed study on nutrient losses through eroded sediments is also done and discussed later in section 4.4.2. Because soil warming stimulates decomposition and mineralisation of soil organic matter (discussed later in detail in section 4.6.2.2), more soluble nutrients and soil-borne chemicals may be released in water runoff. Thus, there is a greater chance for the soluble compounds to be delivered to surface and subsurface water bodies through leaching and runoff. For example, on a forest catchment in Norway, runoff from artificially warmed field plots had greater concentration of nitrates and ammonia than that from control plots without warming (Lukewille and Wright, 1997).

4.2. Rainfall-Induced Soil Erosion

4.2.1. Overview

Soil erosion, by water or wind, represents the most important soil degradation process and affects more than 1 billion hectares globally (Foster, 2003). The global soil loss by erosion would be in the range of 150-1500 million tonne per year, which is about one third of all soil degradation (Robert, 2001). Projected changes in climate are expected to affect the hydrologic cycle, increasing the intensity, amount, and seasonality of precipitation in many parts of the world (as discussed previously in Chapters 2 and 3), and thus affecting soil erosion.

Two principal, sequential events are associated with soil erosion: firstly, the soil particles are detached by erosive agents such as rainwater and made available for transport; and secondly, detached soil materials are transported. The rate of erosion and the soil formation from or at a given site results from a combination of various physical and management variables, which can be considered under three group headings: energy, resistance, and protection (Morgan, 2006). The energy group includes the potential ability of rainfall/runoff to cause erosion, termed erosivity. Fundamental to the resistance group is the erodibility of the soil, which depends on its mechanical and chemical properties. The protection group refers to plant cover by intercepting rainfall and reducing the velocity of runoff.

Field measurements and laboratory experiments of soil erosion allow rates of erosion to be determined at different positions in a landscape over various spatial and temporal scales. However, it is not always possible to take measurements at every point in a landscape. It also takes a long time to build an adequate database in order not to be biased by an extreme event or a few years of extreme rainfall or to take changes in landuse, climate and topography into consideration. To overcome these deficiencies models are useful to predict erosion under a wide range of conditions, as also noted in Table 4.1.

Most of the models used in soil erosion studies are based on defining the most important factors and, through the use of observation, measurement, and experiment and statistical techniques, relating them to soil loss. It is generally recognised that a good model should satisfy the requirements of reliability, universal applicability, ease of use with a minimum number of data, comprehensiveness in terms of the factors and erosion processes included and the ability to take account of changes in climate, landuse and topography. Figure 4.3 shows a flow chart of a model of the processes of soil erosion by water (Meyer and Wischmeier, 1969).

The most widely accepted and commonly used method for predicting large-scale rate of soil loss resulting from raindrop splash and runoff at particular field conditions remains the empirical Universal Soil Loss Equation or USLE (Wischmeier and Smith, 1978) and its modifications including most recent Revised USLE-version2 or RUSLE2 (Foster, 2003). While USLE and its immediate successors RUSLE/RUSLE1.06c (Table 4.1) could only predict the rate of soil erosion treating landscapes as homogeneous surfaces, RUSLE2 can as well estimate soil deposition for concave soil profiles. RUSLE2 can also be applied on cropland, pastureland, rangeland, disturbed forestland, construction sites, mined land, reclaimed land, landfills, military lands, and other areas (Hancock et al., 2006; De Munck et al., 2006; Evans, 2000; Foster, 2003) wherever mineral soil is exposed to the erosive forces of impacting raindrops and runoff. The RUSLE2 model and its factors were elaborately described in Pal (2007) but a brief description of how the model works is again found below.

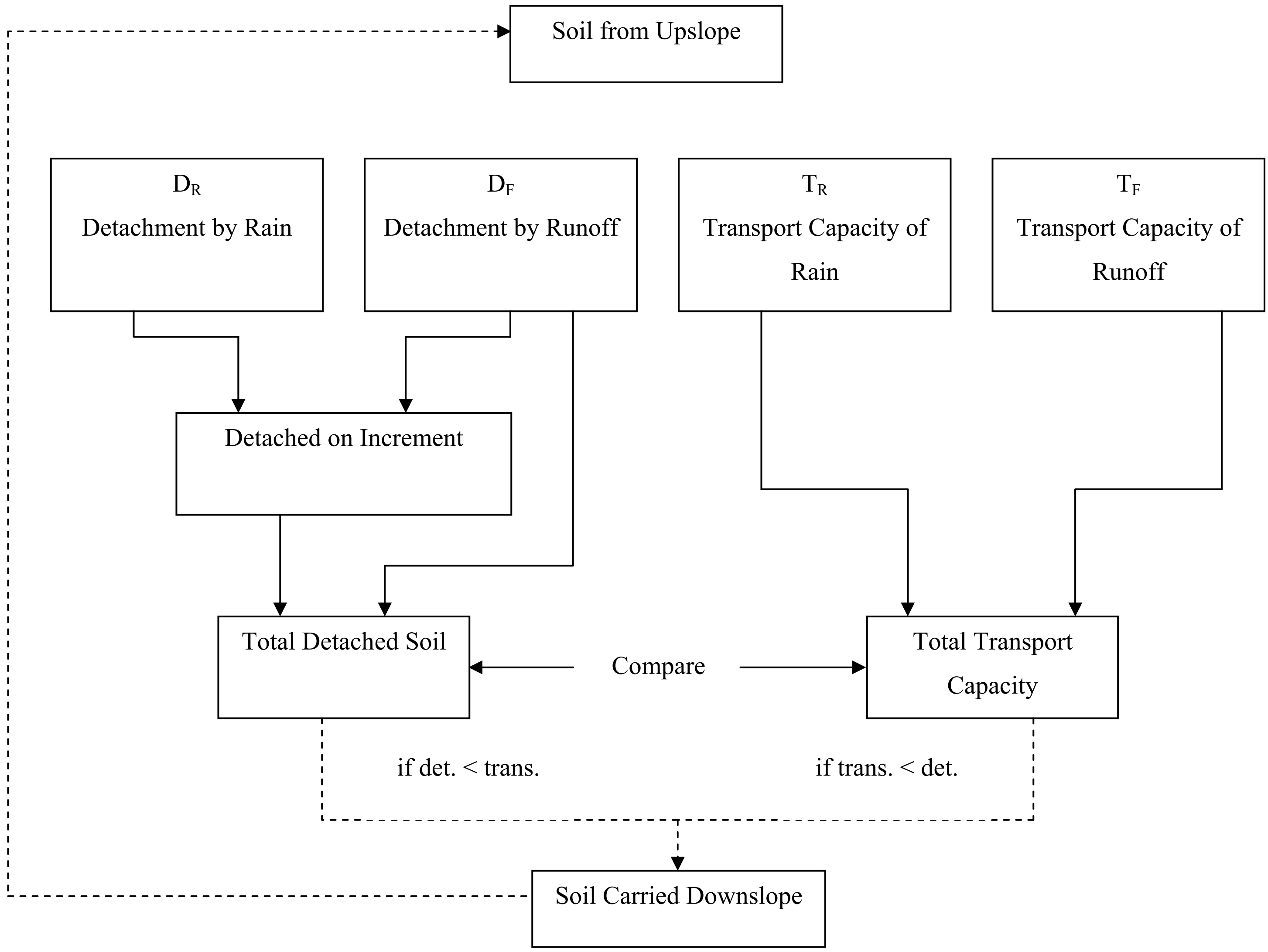


Figure 4.3: Flow chart of a model of the processes of soil erosion by water (Meyer & Wischmeier, 1969).

4.2.2. Rainfall-Induced Soil Loss Prediction Model: RUSLE2

4.2.2.1. Introduction

RUSLE2 estimates rill and interrill erosion along a single overland flow path integrating a number of factors that can be determined from available meteorological, soil, topographical or landuse data for a given location. It quantifies soil erosion as the product of six factors representing rainfall-runoff erosiveness, soil erodibility, slope length, slope steepness, cover management and support conservation practices, as follows.

$$a = r\ k\ l\ S\ c\ p \quad (4.1)$$

where:

a = daily net detachment expressed in tonne/ha; when summed up gives the annual soil detachment 'A' which when averaged over a number of years gives the average annual detachment 'A_a';

r = daily rainfall-runoff erosivity factor expressed in MJ-mm/ha-hr; when summed up for a year gives the annual value 'R' which when averaged over a number of years gives the average annual erosivity 'R_a';

k = daily soil erodibility factor expressed in tonne/ha/(MJ-mm/ha-hr);

l = daily slope length factor;

S = annual slope steepness factor (slope steepness is assumed to be unchanged in RUSLE2 for all conditions throughout a year except for variations in slope steepness at different places);

c = daily cover management factor;

p = daily supporting practices factor. l, S, c and p have no units.

4.2.2.2. Rainfall Runoff Erosivity Factor

Rainfall erosivity is defined as the potential ability of rainfall to cause erosion from an unprotected field. The main concept behind quantifying rainfall erosivity is the computation of the kinetic energy (e) of an erosive rainstorm, which is related to the intensity (I). The expression that was proposed by Brown and Foster (1987) is the expression recommended in RUSLE2, and the corresponding expression is:

$$e = 0.29\ [1 - 0.72 \exp(-\ 0.05\ I)] \quad (4.2)$$

where: e = kinetic energy in MJ/ha-mm of rainfall and I = rainfall intensity in mm/hr. 'I' for a particular increment of a rainfall event can be calculated using the relationship:

$$I = \Delta V / \Delta t \quad \text{……(4.3)}$$

where: ΔV = depth of rain falling during that increment (mm) and Δt = duration of the increment (hours) over which rainfall intensity is considered to be constant.

The total storm kinetic energy (E) in MJ/ha is calculated using the relationship:

$$E = e.\ \Delta V \quad \text{……(4.4)}$$

In order to calculate 'r' (MJ-mm/ha-hr), the storm kinetic energies (E) in a day are multiplied by the corresponding maximum 30-minutes rainfall intensity, which hence ideally requires 30-minutes storm rainfall data. The expression for 'r' is as follows:

$$r = \sum_{i=1}^{d} (E)_i (I_{30})_i \quad \text{……(4.5)}$$

where: I_{30} = maximum 30-minutes rainfall intensity (mm/hr); i = index of the number of storms in each day; d = number of storms in a day.

Annual rainfall-runoff erosivity factor (R) (MJ-mm/ha-hr) and average annual rainfall-runoff erosivity factor (R_a) (MJ-mm/ha-hr-yr), are defined as:

$$R = \left[\sum_{t=1}^{T} r_t\right] \quad \text{……(4.6)}$$

$$R_a = \frac{1}{n}\sum_{j=1}^{n} [R]_j \quad \text{……(4.7)}$$

where: t = index of the number of rain days in each year; T = total number of rain days in each year; j = index of the number of years used to produce the average; n = number of years used to obtain the average.

From expressions 4.2-4.7 it is clear that rainfall erosivity mainly changes with the change in rainfall amount and intensity.

4.2.2.3. Soil Erodibility Factor

The average daily soil erodibility factor ‘k’ is the major soil variable in RUSLE2, which is defined as the ease with which soil is detached by splash during rainfall or by surface flow or both. Various physical, chemical and mineralogical soil properties and their interactions affect ‘k’ values. Generally, soils with faster infiltration rates, higher levels of organic matter and improved soil structure have a greater resistance to erosion (Morgan, 2006) whereas soils with higher content of intermediate particle size fractions such as very fine sand and silt are easily eroded (Mukhopadhyay et al., 2006).

‘k’ in the RUSLE2 is mainly determined using modified soil erodibility nomograph. Soil erodibility nomograph is a set of empirically determined soil erodibility values based on various soil properties, which is mainly determined as follows,

$$K_n = (k_t\, k_o + k_s + k_p)/100 \qquad \text{(4.8)}$$

where: K_n = average annual nomograph soil erodibility value, k_t = soil texture subfactor, k_o = soil organic matter subfactor, k_s = soil structure subfactor and k_p = soil permeability subfactor, 100 = a conversion factor from percentage to fraction.

$$k_t = k_{tb} = 2.1\times10^{-4}\,[(P_{sl} + P_{vfs})(100-P_{cl})]^{1.14} \qquad \text{for } (P_{sl} + P_{vfs}) \leq 68\% \qquad \text{(4.9)}$$

$$k_t = k_{tb} - [0.67(k_{tb} - k_{t68})] \qquad \text{for } (P_{sl} + P_{vfs}) > 68\% \qquad \text{(4.10)}$$

where: $k_{tb} = k_t$ at $(P_{sl} + P_{vfs}) \leq 68\%$, P_{sl} = silt content (%), P_{vfs} = very fine sand content (%) and P_{cl} = clay content (%), $k_{t68} = k_t$ at $(P_{sl} + P_{vfs}) = 68\%$. Values for sand, silt, and clay content are for the upper soil layer susceptible to erosion, usually assumed to be 100 mm thick.

$k_o = (12\text{-}O_m)$……………………………………………………………………….(4.11)

where: O_m = 'inherent' soil organic matter content (%).

$k_s = 3.25\ (2\text{-}s)$……………………………………………………………………...(4.12)

where: s = soil structure class (very fine granular = 1; fine granular = 2; medium or coarse granular = 3; blocky, platy or massive = 4).

$k_p = 2.5\ (P_r\ \text{-}3)$……………………………………………………………………..(4.13)

where: P_r = permeability class.

Expressions 4.8-4.13 indicate that any change in soil texture, organic matter content and permeability will change in soil erosion. Effects of various soil properties on soil erosion in Kerala, in terms of different texture, organic matter and permeability classes were discussed in the results presented in MPhil thesis (Pal, 2007). A summary of those results will be presented in Chapter 5.

4.2.2.4. Topographical Factors

Slope length and steepness represent how topography affects soil erosion. Soil loss increases with increase in slope length and steepness. Slope length is considered by the slope length factor (l) in RUSLE2. Experimental data have shown that average erosion for the slope length λ (ft) varies as:

$l = (\lambda/72.6)^{m}$……………………………………………………………………..(4.14) where: 72.6 = unit plot length in ft (22.1m), and m = slope length exponent which is related to the ratio of rill to interrill erosion and a function of rill to interrill soil erodibility ratios (function of soil texture), ground cover, and slope steepness.

The slope steepness factor (S) reflects the influence of slope gradient (θ) on erosion. Soil loss increases more rapidly with slope steepness than it does with slope length. The slope steepness factor is evaluated as follows:

$$S = 10.8\sin\theta + 0.03 \quad \text{for } s_p < 9\% \qquad (4.15)$$

$$S = 16.8\sin\theta - 0.50 \quad \text{for } s_p \geq 9\% \qquad (4.16)$$

where: s_p = slope steepness at gradient θ (i.e. 100tan θ); The upper limit for s_p has only been mentioned for the disturbed lands as 84% in Renard et al. (1997).

4.2.2.5. Cover Management Factor

The cover management factor 'c' in RUSLE2 represents how landuse and management affect soil loss. The parameters which are universally important in the impact of cover management systems on erosion are: above ground vegetative material, ground cover directly in contact with the soil surface, soil-surface roughness and ridge height created randomly by mechanical disturbance, soil biomass and consolidation introduced by the mechanical disturbance or roots grown there, and in some cases impact of antecedent soil moisture on reduction of runoff. These parameters are combined to compute 'c' values as following:

$$c = c_c\, g_c\, s_r\, r_h\, s_b\, s_c\, s_m \qquad (4.17)$$

where: c_c = daily canopy subfactor; g_c = daily ground cover subfactor; s_r = daily soil surface roughness subfactor; r_h = daily ridge height subfactor; s_b = daily soil biomass subfactor; s_c = daily soil consolidation subfactor; and s_m = daily antecedent soil moisture subfactor. These sub-factors were discussed in detail in Pal (2007).

Cover management factor takes into account the upper ground vegetation, biomass, and antecedent soil moistures which are also important part of the land management options that will be discussed in section 4.6.1 on the adaptation strategies of soil erosion and contaminant mobilisation. While a parametric study on how the upper ground vegetation helps to reduce soil erosion was presented previously (Pal, 2007), it is considered again here in section 4.6.1.2 as it relates to land management options. This chapter and Chapter 5 both elaborates the research further on climate change impact on soil erosion, contaminant transport and land management.

4.2.2.6. Support Practice Factor

The support practice factor (p) in RUSLE2 is employed to take the erosion control practices, if any, into account in the erosion computation. The support practices affect erosion by modifying flow pattern, direction of surface runoff and reducing its transport capacity resulting in deposition and reduced erosion (Renard et al., 1997). Support practices include contouring/ridging, porous barrier, interceptor barriers, sub-surface drainage, and irrigation. The 'p' value in RUSLE2 will be equal to 1 for the purpose of this research as also considered for the Kerala region in the MPhil study (Pal, 2007) meaning no erosion control 'practice' available for the land representing the worst case scenario.

4.3. Effect of Soil Erosion on Soil Properties

Soil erosion affects the properties of the eroded soil. With the reduction of the top soil depth, the quality and productivity of the top soil also reduces due to soil redistribution and modification of the soil properties by soil erosion (Lal 1999(a)). As more and more of the subsoil becomes mixed into the top soil by tillage operations, it may become more prone to soil erosion if the subsoil has more silt, less organic matter and less water holding capacity (Heckrath et al., 2005). A number of soil properties are affected by soil erosion. For example, soil texture is changed and organic matter, available water holding capacity and soil fertility are usually reduced. In addition, the spatial variability of soil properties also increases (Heckrath et al., 2005).

4.3.1. Effect on Soil Texture

Top soil texture changes because of erosion and there has been sufficient evidence from the literature on different soil types that the clay fractions of eroded soil horizons increased and silt fractions decreased with soil erosion (Lal, 1999(a)). Moderate erosion of the soil in western Kentucky, USA was found to have increased clay content from 20 to 25% in the top soil (Murdock and Frye, 1983). Studies on Lithuanian soil (loamy sand and clay loam) and soil in Jutland, Denmark also revealed that the percentage of clay fractions of arable soil horizons increased with soil erosion (Jankauskas et al., 2008; Heckrath et al., 2005). Table 4.2 shows the changes in soil texture due to different magnitude of soil erosion from Miamian soil, USA (Ebeid et al., 1995).

Table 4.2: Changes in soil texture for Miamian soil in the USA for different erosion classes, and at deposition and un-eroded sites (Ebeid et al., 1995).

Erosion class	*Sand (%)*	*Clay (%)*	*Silt (%)*
A. 0-10 cm depth			
Slight	34.5	18.4	47.1
Moderate	36.5	26.3	37.2
Severe	38.5	33.3	28.2
Deposition	33.5	19.9	46.6
Un-eroded site	37.2	13.5	49.3
B. 10-20 cm depth			
Slight	30.2	19.3	50.5
Moderate	32.4	28.2	39.4
Severe	35.8	37.6	26.6
Deposition	31.2	21.3	47.5
Un-eroded site	34.9	15.9	49.2

The data in Table 4.2 indicate that the degree of soil erosion had a significant effect on sand, silt and clay contents for both 0-10cm and 10-20cm depths. While sand and clay contents increased, the silt content decreased with increasing degree of soil erosion for slight to moderate to severe. The least clay content for both depths was observed in the un-eroded site. The decrease in silt content with increasing degree of erosion appears to be due to the susceptibility of silt to detachment and transport by agents of erosion, as was mentioned in section 4.2.2.3.

4.3.2. Effect on Soil Organic Matter and Soil Nutrients

Since soil erosion removes the lighter and more easily dislodged particles, organic matter is one of the more easily erodible constituents (Lal, 1999(a)). A vast proportion of the carbon of the soil in a farmland becomes lost from the topsoil often as a direct result of the loss of the soil itself resulting in decline in quality. Such reduction in the carbon content of agro-ecosystems is of concern to the UN Framework Convention on Climate Change (UNFCC) since depletion of the soil organic carbon pool exacerbates emission of CO_2 into the atmosphere, reduces soil stability and aggravates soil water retention.

Organic matter (OM) measurements by acid digestion generally quantify organic carbon content (OC). The ratio of OC:OM is normally accepted to be 1:1.72 (Jones, 2006). Figure 4.4 illustrates a positive correlation between soil loss and loss of soil carbon from the Ohio soil in the USA (Starr et al., 2008). The reduction of soil organic carbon content with different degrees of soil erosion from various types of soils in the USA was also studied by Kimble et al. (2001). They reported that the range of soil organic carbon lost by erosion in the top 25 cm of moderately and severely eroded soils was between 15-65%. Organic matter is the major source of nutrients and hence reduction in organic matter/carbon content due to soil erosion will also affect soil nutrient content in the top soil (Clark, 1996), as is discussed later in section 4.4.2.

Although much of the historic carbon loss from soil is attributed to erosion and degradation, the net effect of erosion and deposition in the carbon cycle is the subject of debate. Soil erosion and terrestrial sedimentation, as speculated by some researchers; also play a significant role in modifying the dynamics of soil organic matter and fluxes associated with it in a watershed level. According to Berhe et al. (2007) most carbon transported by erosion never leaves the watershed. There could also be a possibility that eroded carbon can be partially replaced by new organic carbon produced by photosynthesis in the eroded site and/or preservation from decomposition of at least some eroded soil organic carbon arriving in some depositional areas in a watershed, which may constitute an important terrestrial carbon sink (Berhe et al., 2008). Therefore, many researchers today strongly feel that there is a clear need to assemble larger databases and a spatially explicit approach with which to evaluate critically the effect of soil erosion and deposition on soil carbon dynamics in a variety of conditions of land-use, topography, climate, and soil data (Shi et al., 2009; Quine and van Oost, 2007). In addition to the effect of soil erosion on top soil organic matter content, climate change also has an adverse impact on the same, which is discussed later in section 4.6.2.2.

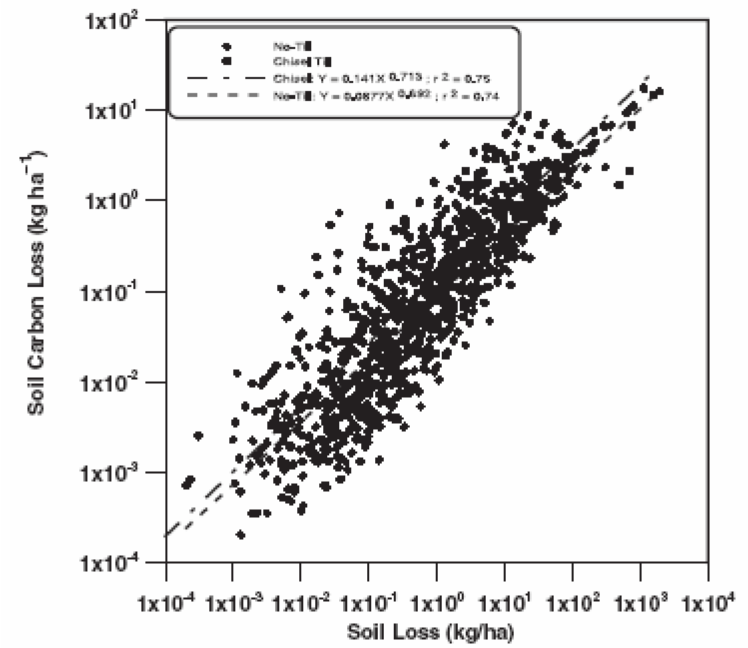


Figure 4.4: Carbon loss versus soil loss in runoff events in Ohio soil in USA (Starr et al., 2008).

Erosion in soils which are highly fertile, naturally or by fertiliser addition, will result in greater fertility losses. All nutrients are lost during erosion but the most economically significant losses will probably be those of nitrogen, phosphorus and potassium (Clark, 1996). Erosion removes nutrients from the soil not only in forms available to plants but also from soil reserves of nutrients in ‘fixed’ forms that are unavailable to plants. Artificial fertilisers supply nutrients only in available form failing to replenish soil reserves of fixed nutrients. A study by Pimentel et al. (1995) on a loamy soil in the US with 4% organic matter, 5% slope and 700mm rainfall, found a soil erosion rate of 17 tonne/ha/year. They also looked at the long-term impacts of soil erosion (approximated by a time period of 20 years) on soil nutrients and organic matter content and reported that there was a loss of organic matter up to 2 tonne/ha/year, which had reduced the crop yield (up to 4% in 20years). In addition, a 2 kg/ha/year loss of potassium was found to have reduced the crop yield up to 8% over the same time period.

Murdock and Frye (1983), Ebeid et al. (1995), and very recently Papiernik et al. (2009) studied the effects of erosion on nutrient loss from various types of soils. They all revealed that erosion caused significant reduction in the nutrient status of the soil, as also shown in Table 4.3. Effect of soil erosion on soil properties also varies spatially and with different erosion classes. As seen in Table 4.3, the loss of exchangeable K, Ca, Mg and cation exchange capacity (CEC) were found to be increased with increasing degree of erosion for various depths (Ebeid et al., 1995). While the soil organic carbon content was not different among the three erosion phases and ranged from 1-1.06% for the 0-10cm depth and from 0.86-0.99% for the 10-20cm depth, a higher soil organic carbon content (1.83% for the 0-10cm and 1.42% for the 10-20cm) was observed for the depositional phase confirming that the organic matter got eroded and carried away from the study site. The maximum soil organic carbon contents for both the soil depths were observed for the un-eroded sites. The increase in CEC with increasing degree of soil erosion might be attributed to the increase in clay content in eroded sites (Table 4.2).

Heckrath et al. (2005), while studying the tillage erosion and its effects on soil properties in Northern Jutland, Denmark, also observed that the soil organic carbon and phosphorous (P) contents in soil profiles increased from the shoulder toward the toe of the slopes because of deposition. Lal (1999(a)) found up to 2.6% decrease in organic carbon content in the top soil because of erosion. Nutrient transport through soil erosion and sediments is presented in detail later in section 4.4.2.

Table 4.3: Soil chemical analysis for 0-10cm and 10-20cm depths for Miamian soil in the USA for different erosion classes and deposition and un-eroded sites (Ebeid et al., 1995).

Erosion class	*Organic Carbon (%)*	*P (ppm)*	*K (cmol/kg)*	*Ca (cmol/kg)*	*Mg (cmol/kg)*	*CEC (cmol/kg)*
A. 0-10 cm depth						
Slight	1.04	16.3	0.17	2.29	0.27	9.2
Moderate	1.00	17.0	0.31	3.28	0.62	13.6
Severe	1.06	14.3	0.33	3.44	0.73	17.0
Deposition	1.83	21.3	0.24	3.23	0.47	13.7
Un-eroded site	2.93	24.0	0.26	2.88	0.52	16.8
B. 10-20 cm depth						
Slight	0.99	13.0	0.17	2.49	0.29	10.1
Moderate	0.86	15.5	0.31	3.52	0.66	14.6
Severe	0.97	11.3	0.30	3.84	0.84	17.0
Deposition	1.42	16.0	0.19	3.35	0.47	13.9
Un-eroded site	1.51	10.3	0.21	2.31	0.41	11.1
Note: cmol = centimols, P = phosphorous, K = potassium, Ca = calcium, Mg = magnesium, CEC = cation exchange capacity.						

4.3.3. Effect on Soil Bulk Density

Soil density generally increases with soil erosion (Lal, 1999(a)). Table 4.4 shows the change in soil bulk density and particle density for different erosion classes for Miamian soil in the USA (Ebeid et al., 1995). The data in Table 4.4 indicate that the bulk density of un-eroded Miamian soil in central Ohio at 0-10cm depth was significantly low (1.20 Mg/m^3) but high bulk density of 1.45-1.49 Mg/m^3 was observed in moderately and severely eroded phases. Although the sand content increased with increasing severity of erosion by 4-5% (Table 4.2), increase in bulk density with increasing degree of erosion was mostly due to high compactability of the eroded phases (Ebeid et al., 1995). Particle density of 0-10cm depth was also the least for the un-eroded site and there were no differences in particle density for 10-20cm depth. The long term research data from Lithuanian loamy sand and clay loam and loamy soil in the USA under different land use systems on slopes of varying steepness also showed that top soil management leads to decrease in soil bulk density for it reduces the soil erosion (Jankauskas et al., 2008; Lal, 1999(a)).

Table 4.4: Changes in soil bulk density and particle density for Miamian soil in the USA for different erosion classes, and deposition and un-eroded sites (Ebeid et al., 1995).

Erosion class	*Bulk density (Mg/m^3)*	*Particle density (Mg/m^3)*
A. 0-10 cm depth		
Slight	1.41	2.66
Moderate	1.49	2.61
Severe	1.45	2.64
Deposition	1.44	2.65
Uneroded site	1.20	2.46
B. 10-20 cm depth		
Slight	1.45	2.67
Moderate	1.59	2.67
Severe	1.55	2.66
Deposition	1.50	2.67
Uneroded site	1.34	2.66

4.3.4. Effect on Porosity and Available Soil Moisture Content

Erosion usually reduces the total soil porosity and plant available water holding capacity of any types of soil, which is a primary effect contributing to productivity loss (Lal, 1999(a)). A study of two different types of soils in Kentucky (Maury and Crider) revealed that the plant available water holding capacity decreased from 29 to 24% in the Maury soil and from 24% to 20% in the Crider soil because of erosion. 20-years research data by Pimentel et al. (1995) on a loamy soil in the US revealed that there could be 0.1mm loss of water holding capacity of the top soil per annum due to soil erosion, which could cause at least 2% loss of crop yield in 20 years. Murdock and Frye (1983) explained that as the clay increases and organic matter decreases because of erosion, the amount of water a soil can make available to the plant decreases. Heckrath et al. (2005) observed that the lowest available water holding capacity was accompanied by the highest clay content of top soil in Denmark. Ebeid et al. (1995) also revealed that the highest porosity and therefore available water capacity was found to be in the un-eroded soil.

4.4. Contaminant Transport with Eroded Sediment

4.4.1. Introduction

As a result of the application of chemical fertilisers and/or pesticides (fungicides, herbicides, and insecticides), manufacture of metal based compounds, smelting or metal-containing ores, and combustion of fossil fuels, organic or inorganic contamination released can affect soils, water, and atmosphere. Such elements are environmentally liable through normal biogeochemical pathways to sinks such as sediments, soils or biomass. The fate of contaminants in agricultural and/or industrial site soils is often less well studied compared to their fate in groundwater and biomass (Gooddy et al., 2007). The possible mobilisation of hazardous substances in soils to the groundwater or surface water will always be considered as serious problem, especially in areas where rainfall characteristics are changing, as also discussed in section 4.1. Detailed studies are therefore necessary to estimate the total concentrations of those hazardous chemicals in soils in the affected areas, to identify the interactions between the pollutant and the soil components, and their potential sorption and/or solubility to adequately understand the mechanisms by which a pollutant is spread into the environment.

Heavy metals and nutrients have an affinity for the fine (silt, clay and organic matter) fractions of soil particles most probably because of larger surface area (Rahimi et al., 2005). Therefore, soil is the ultimate and most important sink of trace elements. Top soil (0-15cm) may possess maximum levels of contaminants than in the soil underneath (Saha and Ali, 2007). Since erosion specifically detaches finer-sized soil particles (mainly silt) and organic matter (Tables 4.2 and 4.3 and Figures 4.1 and 4.4), presence of the nutrient/contaminant content in eroded soil materials is usually greater than the source soil. Also, sediments which arrive at catchment outlet also tend to contain more contaminant concentrations than the eroded soil at the source (Ongley, 2005), because sand-size fractions are usually lost during down-field transport. Sediments generated via soil erosion and their associating pollutants, sorbed or structurally incorporated into eroded soil particles as they are transported through overland flow to surrounding land or water, could be a major problem for the ecosystem.

The transport of contaminants by runoff could be of two forms – dissolved and suspended. In a humid zone, the majority of contaminants reach most water bodies with sediments in particulate phase depending on the physical and chemical environment (Kleeberg et al., 2008; Miller, 1997), geomorphology of the site, and the concentration of the contaminants in soil (Ferrier et al., 2008). These sediments become deposited in river channels or flood plains and contaminate 100s of km distances from the source (Macklin et al., 2003). Contaminants are also transported in dissolved form that is initiated by the release of contaminants from soil and suspended sediments. This process takes place when rainfall interacts with a thin layer of surface soil (1-5mm) before leaving the field as surface runoff. When agricultural sediments accumulate in a water body, they do not only enrich the water with organic or inorganic nutrients but also make it shallow (Bloomfield et al., 2006). The concentration of a pollutant in the receiving water will also depend on the relative travel times of water from the treated or untreated fields to the water body of concern (Schiedek et al., 2007). Hence, improved understanding of organic and inorganic contaminant chemistry in the soil system will lead to improved management of contaminated areas.

This research has considered as case studies the impact of climate change on soil erosion and nutrient/contaminant transport and land management at an agricultural site (Bhoj wetland in west-central India) and a chromite mining site (Sukinda valley in central north east India), and hence the following sub-sections discuss available literature from India and elsewhere on the properties of various agricultural and mining contaminants, and summarise the evidence available for such contaminant transport with sediments. Emphasis was placed on the transport of nutrients (phosphorous, nitrogen and potassium), and chromium (Cr) since these were available specifically at the study sites.

4.4.2. Transport of Agricultural Pollutants with Sediments

Chemical fertilisers and pesticides applied on fields may be applied to bare soils, intercepted by the crop or lost as spray drift. Pesticide remaining in the soil will partition between the soil and the soil water. Organochlorine pesticides (OCPs) have extensively been used in India due to their low cost. However, their resistance to degradation results in the contamination of water, soil and food (Singh et al., 2007). In agricultural fields, about two thirds of the chemical fertilisers applied may remain in the soil in both free and intact form (Misra, 2006). Free chemical nutrients in soil leach down or flush away with the runoff water and pollute groundwater and surface water respectively.

Sorption of pesticides onto soil is as a result of the equilibrium between the concentration attached onto the soil and in the soil water. Thus, when rainfall replaces pre-event soil water, presumed to be in equilibrium with the soil, there is the potential for desorption of some of the pesticides from the soil into the event water. Runoff events can also promote erosion of soil particles and the transport of sorbed pesticides. The magnitude of this loss route is generally small compared to that transported in the water phase because of the relative amounts of water moved compared to eroded soil. However, for some highly sorbed pesticides, this erosion becomes the dominant transport path from the field to surface waters (Ray et al., 2008).

Tables 4.5 and 4.6 summarise the factors affecting pesticide concentration and transport in runoff, categorised into climatic, soil properties, pesticide properties, and erosion management (Ray et al., 2008). All the factors presented are equally important for pesticide transport with runoff. Climate factors include rainfall intensity, rainfall duration, time for runoff after inception of rainfall, temperature and rainfall/runoff timing. Soil factors include soil texture and organic matter content, soil surface crusting and compaction, soil water content, slope and degree of aggregation and stability Pesticide related factors include water solubility, adsorption and polarity characteristics with soil organic matter, persistence to remain at the soil surface, formation (liquid or otherwise), application rate and degree of exposure to climate after application.

Table 4.5: Climate and soil factors affecting pesticide concentration and transport in runoff (Ray et al., 2008).

Climatic Factors	***Comment***	***Soil Factors***	***Comment***
(i)Rainfall/runoff timing with respect to pesticide application	Highest concentration of pesticide in runoff occurs in the first significant runoff event after application. Pesticide concentration and availability at the soil or leafy surfaces dissipate with time thereafter.	(i)Soil texture and organic matter content	Affects infiltration rates; runoff is usually higher in finer-textured soil. Time to runoff is greater on sandy soil, reducing initial runoff concentrations of soluble pesticides. Organic matter content affects pesticide adsorption and mobility. Soil texture also affects soil erodibility, particle transport potential and chemical enrichment factors.
(ii)Rainfall intensity	Surface runoff occurs when rainfall rate exceeds infiltration rate. Increasing intensity increases runoff rate and energy available for pesticide extraction and transport. It may also affect depth of surface interaction.	(ii)Surface crusting and compaction	Crusting and compaction decreases infiltration rates, reduces time to runoff, and increases initial concentrations of soluble pesticides.
(iii)Rainfall duration/amount	Affects total runoff volume; pesticide wash off from foliage related to total rainfall amount; leaching below soil surface also affected.	(iii)Water content	Initial soil water content of a rainstorm may increase runoff potential, reduce time to runoff, and reduce leaching of soluble chemicals below soil surface before runoff inception.
(iv)Time for runoff after inception of rainfall	Runoff concentration increases as time to runoff decreases**.** Pesticide concentrations and availability are greater in first part of the event before significant reduction occurs as a result of leaching and incorporation by precipitation.	(iv)Slope	Increasing slope may increase runoff rate, soil detachment and transport, and increase effective surface depth for chemical extraction.
(v)Temperature	Little data available, but increasing temperature normally increases pesticide solubility and decreases physical adsorption. In tropical soil, pesticides often decompose more quickly because of high temperature.	(v)Degree of aggregation and stability	Soil particle aggregation and stability affect infiltration rates, crusting potential, effective depth for chemical entrainment, sediment transport potential, and adsorbed chemical enrichment in sediment.

Table 4.6: Pesticide and management factors affecting pesticide concentration and transport in runoff (Ray et al., 2008).

Pesticide Factors	***Comment***
(i)Solubility	Soluble pesticides may be more readily removed from crop residues and foliage during the initial rainfall or be leached into the soil. However, when time for runoff is short, increasing solubility may enhance runoff concentration.
(ii)Sorption properties	Pesticides strongly adsorbed in soil will be retained near application site, i.e., possibly at soil surface and be more susceptible to runoff. Amounts of runoff depend on amount of soil erosion and sediment transport.
(iii)Polarity/ionic nature	Adsorption of non polar compounds determined by soil organic matter; ionised compounds, and weak acids/bases is affected more by mineral surface and soil pH. Lyophilic compounds are retained on foliage surfaces and waxes, whereas polar compounds are more easily removed from foliage by rainfall.
(iv)Persistence	Pesticides that remain at the soil surface for longer periods of time because of their resistance to volatilisation, and chemical, photochemical, and biological degradation have higher probability of runoff.
(v)Formulation	Wettable powders are particularly susceptible to entrainment and transport. Liquid forms may be more readily transported than granular. Esters that are less soluble than salts produced higher runoff concentrations under conditions where initial leaching into soil surface is important.
(vi)Application rate	Runoff concentrations are proportional to amount of pesticide present in runoff zone. At usual rates of application for pest control, pathways and processes (e.g., sorption and degradation rates) are not affected by initial amounts present, therefore, runoff potential is in proportion to amounts applied.
(vii)Placement	Pesticide incorporation or any placement below the soil surface reduces concentrations exposed to runoff process.
Management Factors	***Comment***
(i)Erosion control practices	Reduces transport of adsorbed/insoluble compounds. Also reduces transport of soluble compounds if runoff volumes are also reduced during critical times after pesticide application.
(ii)Residue management	Crop residues can reduce pesticide runoff by increasing time to runoff, decreasing runoff volumes, and decreasing erosion and sediment transport. However, pesticide runoff may be increased under conditions where pesticides are washed from the crop residue directly into runoff water (high initial soil water, clay soil, intense rainfall immediately after pesticide application).

Pesticide transport can be managed by decreasing time to runoff, runoff volumes, erosion and sediment transport using erosion control practices and residue management, as summarised in Table 4.6. Various soil erosion (and therefore contaminant transport) management practices are discussed later in section 4.6.1. Most of the climate factors, soil factors and management factors that are discussed in this section will also be incorporated into the methodology to qualitatively determine the contaminant transport from polluted soil, as is described in detail in section 4.5.2.

Apart from pesticides, when nutrients, such as phosphorous, nitrogen, potassium etc, become transported with the sediments and runoff, they become potential pollutants of surface water. Assessment of phosphorous concentrations in sediments has been carried out by several researchers in India and elsewhere (Kronvang et al., 2005; Balchand and Nair, 1994). Phosphorous and nitrogen are the nutrients in agricultural soils that cause freshwater eutrophication (Ulen et al., 2007). Mihara and Ueno (2000) found that there is ‘roughly’ a proportional relationship between the amount of nitrogen and phosphorous transfer and soil losses (the correlation coefficient was 0.78-0.97). In addition, since soil carbon loss is proportional to soil loss, Figure 4.4, nutrient losses are also proportional to soil carbon loss due to soil erosion, as shown in Figure 4.5 (Starr et al., 2008). Measurement of phosphorous transport in North America and Europe indicate that as much as 90% of the total phosphorous flux in rivers can be associated with suspended sediment (Kronvang et al., 2005; Sharpley et al., 2001).

Figure 4.6 presents the major pathways by which phosphorus is transported from deposition as fertiliser on cropland to the surface and ground water supply (Johnes and Hodgkinson, 1998). Among all the pathways shown in Figure 4.6, phosphorous (P) becomes transported in particulate form by means of soil erosion and runoff vastly from agricultural lands or post mining sites (Edwards and Withers, 2007), and also, to a certain extent, from suburban lawns, construction sites and golf courses (Sharpley et al., 2001). The importance of soil erosion for the loss of P from agricultural catchments can be seen from the increasing loss of both dissolved phosphorus (DP) and particulate phosphorus (PP) with increasing soil erosion risk, as shown in Table 4.7 and Figure 4.7 (Kronvang et al., 2005; Havlin, 2004). The results in Table 4.7 also illustrates that there could be an enrichment of total phosphorous in suspended solids even when the erosion risk is very low. However, as Figure 4.7 suggests, P-enrichment ratio decrease with increasing erosion rate. According to Havlin (2004), as erosion rate increases, particle size separation decreases that result in decreased enrichment. The P-enrichment ratio was also considered in the determination of contaminant transport (section 4.5.1).

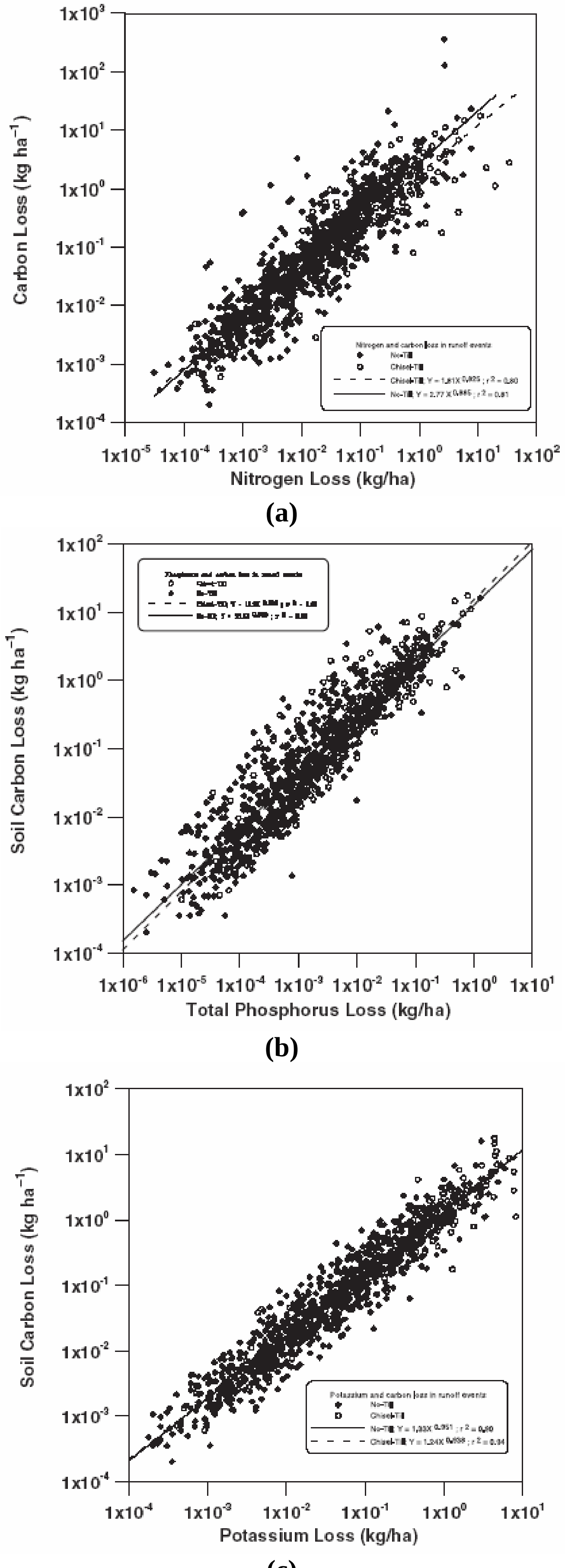


Figure 4.5: Losses of (a) nitrogen, (b) phosphorous and (c) potassium with soil carbon in runoff events (Starr et al., 2008).

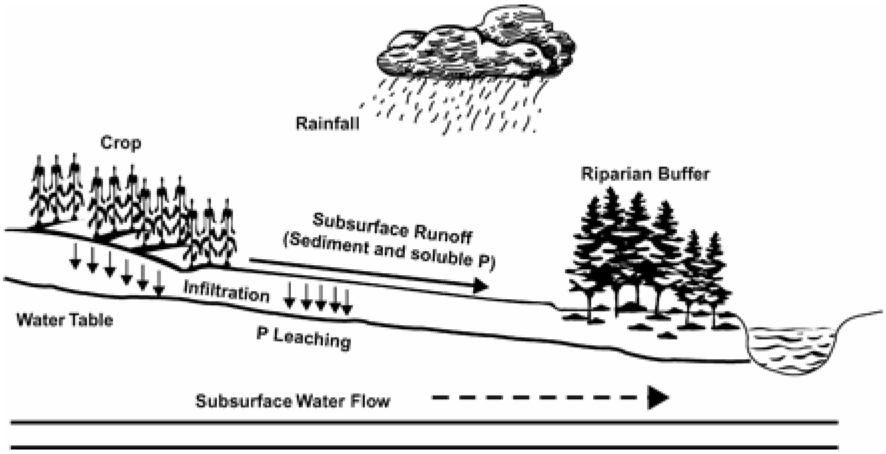


Figure 4.6: Diagram of major pathways contributing to P transport to surface and groundwater (Johnes and Hodgkinson, 1998).

Table 4.7: Average soil erosion risk and average annual losses of suspended solids (SS), total phosphorous (TP), particulate phosphorous (PP), and dissolved reactive phosphorous (DRP) from agricultural areas in three catchments in Norway; Mordre and Kolstad were monitored during the period 1991-2002, whereas Skuterud was monitored during the period 1993-2002 (Kronvang et al., 2005).

Catchment	*Size in ha*	*Soil erosion risk in Mg/ha/yr*	*Loss in kg P/ha/yr*			
			SS	*TP*	*PP*	*DRP*
Skuterud	450	0.9	1.5	2.4	2.1	0.4
Mordre	680	0.6	1.1	1.5	1.3	0.2
Kolstad	310	0.07	0.2	0.5	0.4	0.2

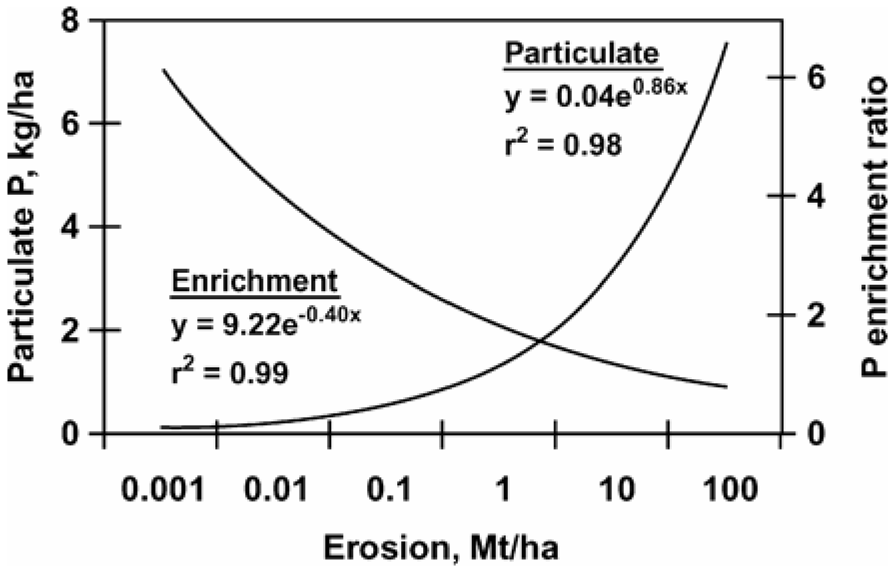


Figure 4.7: Effect of soil erosion rate on particulate P loss and P enrichment ratio (Havlin, 2004).

Since the transfer of P in particulate form is generally associated with a lack of crop cover exposing the soil to the energy of raindrops and subsequent mobilisation of fine-grained particles which are enriched with P, the quantity and bioavailability of the P enriched sediments delivered to and beyond a field is not only a function of soil erosion rate, and soil organic matter content, it also depends on the quantity of P selectively adsorbed onto the eroding soil particles or aggregates (Withers et al., 2007). Figure 4.8 presents a diagram showing extracted phosphorus contents in runoff sediments and sediment size distribution, on South American soils (Bertol et al., 2007). The figure shows that extracted P losses in runoff sediments decrease exponentially with the increase in sediment size. Most of the factors mentioned here are also taken into account to determine the qualitative and quantitative P-loss from the Bhoj study site, as discussed in sections 4.5.1 and 4.5.2.

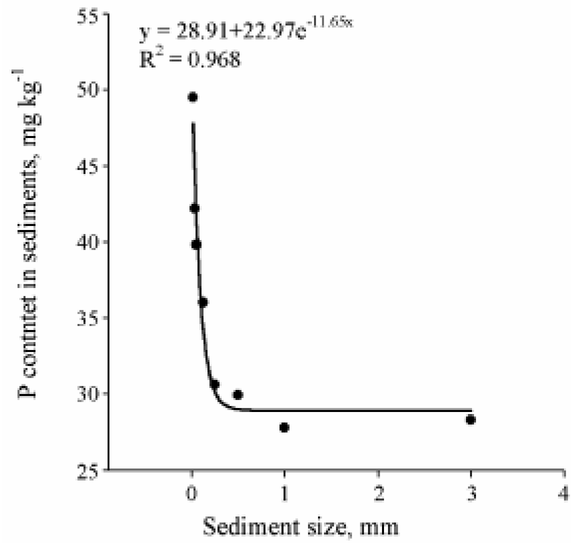


Figure 4.8: Extracted phosphorus contents in runoff sediments and respective sediment size distribution (Bertol et al., 2007).

Apart from P, of all the major plant nutrients, N provides the greatest responses in crop yield from fertiliser addition and is also most readily lost from the agro-ecosystem (Merrington, 2002). The amount of nitrogen available in the soil at any one time to meet the demands of a growing crop is the product of the complex network of physical, biological and chemical pathways through which the various forms of N move (N cycle). Changes in the global nitrogen cycle due to anthropogenic input have also generated large environmental concerns. For example, additional or excess nitrogen (that is not consumed or tied up in plants and micro-organisms in the soil) is an important contributor to the widespread problem of aquatic eutrophication and elevated concentrations of nitrate in groundwater (Carpenter et al., 1998). Several studies have demonstrated that the changes in agricultural practices in the last 50 years have significantly contributed to increased N concentrations in surface and groundwater (Mulla and Strock, 2008; Merrington, 2002).

The net impact of N on the ecosystem depends on the relative importance of processes in the soil such as transport and storage. Transport processes include leaching, preferential flow, seepage, interflow, runoff, erosion, and gaseous movement (Mulla and Strock, 2008). Nitrogen occurs in many chemical forms. The most common in the soil system are nitrate, ammonium, and various gaseous forms, including nitrous oxide and nitrogen gas. Nitrate is an anion, which is soluble in water. Ammonium is a cation, which is strongly sorbed to soil particles through cation exchange processes, and it can also be incorporated into soil organic matter (Mulla and Strock, 2008).

The amount of N lost through runoff and soil erosion being affected by the timing, frequency, intensity, duration and amount of precipitation, the slope gradient, residue cover, tillage, soil physical and chemical properties, organic matter content, and soil surface roughness, and the crop or N management (Mulla and Strock, 2008), as also mentioned for the case of pesticide and P transport in the previous paragraphs and in Figure 4.5. The leading loss pathway for N depends on the N form. N in both nitrate and ammonium forms are lost in dissolved form with runoff water while nitrate-N being the dominant among both. However, nitrate-N lost through runoff water is several degrees lesser (as much as 30 times) than that gets lost through leaching (Mulla and Strock, 2008). On the other hand, nitrogen is susceptible to transport by soil erosion predominantly in the ammonium-N form, because it is adsorbed to the negatively charged surface soil clay particles or is associated with soil organic matter. Follett et al. (1987) studied organic N loss on sloping land in Minnesota, USA from soils from some of the major land resource areas. Using USLE (predecessor of RUSLE2) they compared organic N in eroded sediment as a function of tillage, slope gradient, soil organic matter level, and soil series. They found that the loss of organic-N from eroded sediment was reduced by nearly 50% under conservation tillage compared to conventional tillage.

N and P are the main nutrients that restore soil fertility, and together with K are subject to losses by water erosion, as mentioned several times in this chapter already. However, unlike the nutrients P and N, little attention has been given to potassium (K) because this element loss is lesser as compared to P and N and especially in presence of N since N fertilizer increase plant uptake of K, sometimes as much as 90% (Alfaro et al., 2004). However, there have been many previous agronomic studies that have shown that, because K is a mobile ion in soils, significant amounts can be lost by leaching (Quemener, 1986) thereby affecting the efficiency of the fertilizers applied. Potassium loss can be expressed as concentration in the water or in the sediment and as amounts lost, like P and N. These losses are influenced by the amount of K applied as fertilizer, the crop, the type of soil, and the amount of drainage. The content of available potassium is always higher in uppermost soil layer than that in lower soil layers and it is closely related to the organic matter content of the soil like P, N and pesticide (Alfaro et al., 2004). Figure 4.5(c) shows a strong correlation (0.94) of K-loss with soil organic carbon loss in runoff events (Starr et al., 2008). The concentration of potassium in runoff carried sediment from a fertilised field could be as high as 13 times as that of its level in the original soil, as mentioned in Troeh and Thompson (2005). Rainfall is the factor that most strongly affects K transport (Alfaro et al., 2004; Wang et al., 2002). Therefore, to reduce K losses through leaching and surface runoff, applications of manures or mineral fertilizers should be avoided before heavy rainfall.

In addition to the nutrients discussed in the previous paragraphs, chemical fertilisers and pesticides are also heavy metal (As, Mn, Cd, Cu, Zn, Pb, Cr, Ni) contributors to the environment (Eapaea et al., 2007), which could be added on to soil by irrigation water, sewage sludge application or transport from nearby contaminated sites (Borujen et al., 2005). In India (mainly West Bengal state) and Bangladesh, Arsenic contamination, from natural or anthropogenic sources, is very well known among other types of heavy metal contaminants in the agricultural regions (Saha and Ali, 2007; Roychowdhury et al., 2005). Arsenic is also found in the central Gangetic plains of Uttar Pradesh, Bihar, Jharkhand and the Brahmaputra valley in Assam, and several regions of Madhya Pradesh and Chattisgarh in India. Arsenic (As) has a great affinity to metal oxides or hydroxides and the fine particles in soil (Voigt et al., 1996; Ducatoir and Lamy, 1995) and therefore, accumulation of As in contaminated irrigation water would be expected in the top agricultural soils. Following rain/flood water inundation of a field in the rainy season, the concentration of As in the top agricultural soil reduces back to the concentration monitored before the irrigation period (Saha and Ali, 2007). The reason could be remobilisation of As due to reductive dissolution of iron oxy-hydroxides or leaching into deeper soil layers and/or transportation away with flood/rain water.

Diffuse pollution control is nowadays an important concern, since it has been clearly identified as the cause of water quality degradation. In India, with the introduction of intensive agriculture and adoption of modern farming techniques involving the application of agricultural chemicals, the problems caused by diffuse agricultural pollution are bound to grow. The highest nitrogen surplus in India is found in Uttar Pradesh, followed by Madhya Pradesh and Andhra Pradesh (Krishna Prasad et al., 2004). Amongst different type of sites, the agriculturally polluted area of Bhoj wetland in Madhya Pradesh is of research interest here and the nutrient transport (P, N and K) results are presented later in Chapter 5. In addition to this, a study relating how this nutrient transport is affected by rainfall changes in Bhoj region was carried out and presented in Chapter 5. Climate change impact on nutrient transport is important to look at because any changes in rainfall patterns will also affect the pattern of nutrient transport as well, which is important from environmental management point of view.

4.4.3. Transport of Mining Site Pollutants with Sediments

Large quantities of contaminants are released through industrial mining activities, which can be dispersed widely and contaminate soils, water and air. Although large quantities of contaminants might be restricted to the vicinity of the mining area; this could still be a source of significant environmental concerns. The mining sites themselves, which sometimes remain abandoned for rehabilitation, or the rehabilitated sites, or mining sites which are still operating, could lead to contamination of the surrounding land, watercourses and sediments introducing a significant number of pollutants into the environment (Ferrier et al., 2008; Frostick et al., 2008; Garcia et al., 2008; Kleeberg et al., 2008).

Trace metals such as Al, Fe, Mn, Ni, Co, Cu, Pb, As, Th and U, which could be found in the very fine non-cohesive mine waste, become loosened by intense rainsplash and as a result become transported locally by sheet/rill/gullies (Evans et al., 2000). On the other hand, topsoil in mining areas typically undergo considerable physical disturbance that can lead to high level of soil erosion (Loch and Orange, 1997). There could be some areas in a post-mining site or rehabilitated mining site with a high erosion rate contributing to contamination of the surrounding land and water bodies by contaminants sorbed or structurally incorporated into eroded soil particles sourced from the mine site (Hancock et al., 2008). For example, in Australia, Pb, with other trace metals, have deposited in sediments downstream of a former uranium mining site where the top section of the soil was rich in clay and organic matter (Frostick et al., 2008).

Several researchers have studied the spatial distribution of chemical elements in the top soils from the territory of mining areas, their concentration in soil, relationship with soil properties, and behaviour in soil and subsoil (Frostick et al., 2008; O'Shea et al., 2007). The study by Frostick et al. (2008) found that the adjacent areas to an abandoned uranium mining site in Australia had elevated levels of trace metals and radio nuclides. Lead (Pb) isotope ratios were highly radiogenic in some samples, indicating the presence of U-rich material. In addition, there was some indication that the erosion products with more radiogenic Pb isotope ratios had deposited in sediments downstream of the former mining site. O'Shea et al. (2007) studied arsenic content in a sandy coastal aquifer that was used extensively for human consumption. They developed an aquifer specific geomorphic model and found that arsenic was regionally derived from erosion of arsenic-rich stibnite (Sb_2S_3) mineralisation present in the vicinity. Fluvial processes transported the eroded material over time to deposit on an aquifer elevated in arsenic. They also found an association of arsenic with pyrite in the aquifer, which was likely to influence arsenic distribution in the aquifer as a function of the adsorptive capacity.

The surrounding areas of former arsenic and gold mining sites could be highly enriched in arsenic and accompanied by several other heavy metals such as copper, zinc and lead (Matera et al., 2003). Under oxidizing conditions and in an aerobic environment, arsenates (Ar^{V}) are stable and become strongly adsorbed onto clays, heavy metals, manganese (Mn), calcium carbonates and organic matter (Eapaea et al., 2007; Matera et al., 2003; Cai et al., 2002). Arsenic speciation in soils differs based on soil properties and composition. Arsenic sorption on oxides, clay minerals (kaolinite and montmorillionite) and humic substances is mainly pH dependent, like Cr, as is discussed later in this section of paragraph below.

As discussed in section 4.4.2 in relation to pesticides and nutrients studies worldwide have indicated that soils with higher clay and organic matter contents usually exhibit higher metal concentrations (Baize et al., 1999). Also, iron (and Al) rich clays have been found to be a predominant carrier of metals and phosphorous, which is also applicable for Indian soils (Bose and Sharma, 2002). A part of this research also looks at the chromium transport with runoff carried sediments from lateritic soil (rich in iron) in Sukinda valley in Orissa, India. The specific information relating association of Cr with iron rich soil will be discussed in a later paragraph in this section.

Soil contaminant transport studies in and around mining sites are very few in India. Those available in the literature include Godgul and Sahu (1995) for the chromite mining site in Sukinda in Orissa, India and Manjunatha et al. (2001) for a manganese ore mining site in Karwar, Karnataka district in south-west India, which provided some information. Godgul and Sahu (1995) carried out a laboratory leaching study on Sukinda valley chromite mine overburden samples. A chemical analysis of stream water, and sediments taken from nearby Brahmani river beds indicated the possibility of chromium mobilisation from the chromite ores into water bodies.

Amongst the range of heavy metal pollutants in mining sites in India, mobilisation of hexavalent chromium (Cr^{VI}) from the Sukinda chromite mining site through runoff and sediments has not been looked at before in India and will hence be considered in detail in this study. In addition, the study of rainfall changes and their effects on soil erosion and contaminant transport is also important from an environmental management point of view especially because the Sukinda region falls in central north east India, which is experiencing rainfall changing patterns (refer Chapter 3). Therefore, a study relating climate change impact on Cr transport was also performed as a part of this work as presented in Chapter 5.

Environmental chromium exists primarily in two valence states, trivalent (Cr^{III}) and hexavalent chromate (Cr^{VI}). Chromium species at different oxidation states show substantially different physical and chemical properties. Cr^{VI} is an oxidant with high solubility and mobility in soils and aquifers, as well as high toxicity to human and ecosystems even at low concentrations; whereas Cr^{III} has lower mobility, mostly precipitated as hydroxides or adsorbed onto mineral surfaces. Cr^{VI} is known to be up to 1000 times more toxic than the Cr^{III} (Godgul and Sahu, 1995).

Chromate mobility in soils depends on soil type, soil pH, soil sorption capacity, soil organic matter and temperature (Aide and Cummings, 1997). The adsorbed amount of Cr^{VI} onto the soil is controlled by the pH values of the medium and the electrostatic charge of the mineral particles present, with low adsorption occurring at high pH (> 8.5) values and high adsorption occurring at low pH values (Rodriguez and Candela, 2005). In addition to increasing pH, Cr^{VI} sorption could also be depressed by the presence of other anions, notably SO_4^{2-} and $H_2PO_4^-$ (Gemmell, 1973). Chromate adsorption could also get affected in the presence of copper, organic matter (both soluble and insoluble), Fe^{II} and sulphides (Khaodhiar et al., 2000; Echeverria et al., 1999; Fendorf, 1995). Application of an organic amendment to reduce and bind Cr^{VI} on to the soil appeared feasible as a technique to immobilize Cr^{VI} in contaminated soils (Cifuentes et al., 1996). Whereas, in natural systems, manganese oxides have proven to be the only compound capable of oxidizing Cr^{III} back to Cr^{VI}. Hence, chromate sorption by soils is a very complex phenomenon because of the many soil components, their individual surface configuration, the multi component nature of solute and soil interactions, and possible reduction of Cr^{VI} to Cr^{III}, with subsequent precipitation or sorption of trivalent species.

Due to its anionic nature, Cr^{VI} is not retained appreciably on negatively charged colloids of soils or sediments. Hydrous oxides of Al and Fe often are present at significant levels in surface environments; they commonly have a net positive charge and a potential chemical affinity for Cr^{VI}. $Chromium^{VI}$ is also sorbed by kaolinite and to a lesser extent by montmorillionite (Gemmell, 1973). Cr moves from terrestrial to water systems mainly by surface run-off and/or transport through the soil to groundwater. Since Sukinda valley region has lateritic soil that is rich in iron content (oxide), hexavalent chromium has a great tendency to be transported with the sediment.

4.5. Determination of Sediment Production and Contaminant Transport

4.5.1. Quantitative Estimation of Contaminants Transported Downstream

As discussed earlier in section 4.4.1, there are two major pathways through which pollutants are delivered to surface water from a contaminated soil ground: (1) sediment and sediment-adsorbed pollutants can be transported through erosion, and (2) soluble pollutants can be transported to surface water dissolved in runoff water. This section presents the methodology used for quantitative determination of contaminants transported downstream.

Approaches to the estimation of annual contaminant load with sediments from a contaminated site involve three stages. The first stage involves determination of site erosion. At the second stage, the mass of eroded sediment delivered to the catchment outlet is determined which is performed by modifying the gross soil loss estimates from the study sites by a Sediment Delivery Ratio (SDR). Sediment yield from a watershed is the output of erosion process, and is difficult to estimate as it arises from the complex interaction of a range of hydro-geological processes. Vegetation dissipates rainfall energy, binds the soil, increases porosity by its root system, and reduces soil moisture by evapotranspiration to affect the sediment yield. Hence SDR takes into account the sediment transport and deposition processes from the site to downstream. At the third and final stage, a determination of the agro/mine-derived contaminant flux to downstream receiving waters is carried out.

At catchment scale, predicting the quantity of sediment transferred in a given time interval from the eroding sources to the basin outlet (sediment yield) can be carried out by coupling a soil erosion model with a mathematical expression describing the sediment transport efficiency of the hill slopes. The existing limitations in field applicability of physically based modelling involve numerous input parameters, differences between the scale of measurement of the input parameters and the scale of basin, uncertainties of the selected model equations, etc, which increases the attractiveness of a parametric soil erosion model, like USLE (Tyagi et al., 2008; Singh et al., 2008). But USLE was developed for the estimation of the annual soil loss from small plots of an average length of 22.1m (also mentioned in section 4.2.2.4 for RUSLE2), which is of less use for this project since the project deals with large watersheds (>5500ha). On the other hand, RUSLE2, which is the most recent revised version of USLE, is not only well known for its usage for both agricultural and mining areas but is also less complex and can universally be used for estimating gross erosion taking place at the large study sites (Hancock et al., 2006; Evans, 2000). Hence this study follows 'Estimating Soil Loss for Large Areas' in RUSLE2, as demonstrated in Foster (2003).

When the soil particle is eroded, it is detached by rainfall. However, it goes through various processes (detachment, transport and deposition) before reaching the catchment outlet and not all the materials eroded at a time would reach the outlet point. The Sediment Delivery Ratio (SDR) is used to capture those phenomena. SDR is the percentage of the annual gross erosion from within a catchment that arrives at the catchment outlet each year. SDR is a value between 0.0 and 1.0, generally decreasing with the basin size. The magnitude of SDR depends on the nature, extent and location of sediment sources, land slope and cover conditions and soil texture. In spite of extensive studies on the erosion process and sediment transport modelling, no universally accepted SDR model is available to date. However, certain region-specific hypotheses and models are available in the literature. The hypothesis following Mishra et al. (2006) incorporating significant effect of infiltration and other hydrologic losses for the Indian watersheds and USA is used here. This hypothesis correlates SDR and runoff coefficient, since both are affected by the rainfall impact, overland flow energy, vegetation, infiltration, depression and ponding storage, change of slope of overland flow and drainage. The sediment yield varies with time because these factors vary with time throughout the year. This hypothesis is well validated for the watershed data from India and the USA. SDR is estimated as follows:

$$SDR = \text{runoff coefficient} = R_u/P \qquad (4.18)$$

where: R_u = annual runoff in mm and P = annual rainfall in mm.

The soil texture determines both permeability and erodibility of soils (section 4.2.2.3). Permeability describes infiltration, which, in turn, determines hydrologic activeness of the soil surface in terms of both runoff generation and soil erosion (expression 4.13). Thus, the processes of runoff generation and soil erosion are closely interrelated.

The annual runoff amount for all the years are calculated using Khosla's empirical expression (Subramanya, 2002), which was derived based on the rainfall, runoff and temperature data from various catchments in India and the USA, which is as follows,

$$R_m = P_m - L_m \qquad (4.19)$$

$$L_m = 0.48\ T_m \text{ for } T_m > 4.5°C \qquad (4.20)$$

where: R_m = monthly runoff in cm and $R_m \geq 0$; P_m = monthly rainfall in cm; L_m = monthly loss in cm; T_m = mean monthly temperature of the catchment in °C; for $T_m \leq$ 4.5°C, the loss L_m may provisionally be assumed as:

T°C	4.5	-1	-6.5
L_m (cm)	2.17	1.78	1.52

Annual runoff $R_u = \sum R_m$ ……………………………………………..…………...(4.21)

Khosla's formula is indirectly based on the water-balance concept and the mean monthly catchment temperature is used to reflect the losses due to evapotranspiration. The formula has been tested on a number of catchments in India and was found to give reasonably good results for the annual yield for use in preliminary studies (Subramanya, 2002). This formula can also be used to generate runoff data from historical rainfall and temperature data.

The sediment yield (Y) reaching the catchment outlet is calculated using the following equation (Evans, 2000):

$Y = SDR \times A \times CA$…………………………………………………………..(4.22)

where: A = soil loss calculated from RUSLE2 (tonne/ha) based on field data (section 4.2.2); and CA = area (ha) of the catchment.

Contaminant concentration data collected from the study sites when multiplied with the estimates for delivery of eroded soil to the water bodies, gives an estimate for the contaminant flux passing with the transported sediment from the site to downstream waterways from each catchment, following Hancock et al. (2006), De Munck et al. (2006) and Evans et al. (2000), which is as follows:

$S_c = Y \times C \times 10^{-3}$ ……………………………………………………….....(4.23)

S_c = contaminant load reaching catchment outlet in kg, Y = sediment load in tonne, C = contaminant concentration in the top soil in mg/kg or ppm and 10^{-3} = a conversion factor.

This methodology assumes that there is no grain size fractionation effect. Selectivity in deposition gives rise to different specific activities in eroded soil particles relative to the specific activities for total soil and, secondly, mobilisation of the pollutants by solution in runoff waters will be small in comparison with the flux attached to eroded particles. The first assumption is reasonable given that the higher-activity surface soils consist largely of eroded waste rock material (Hancock et al., 2006). Hence, the contaminant flux estimates discussed in this work relate only to the contaminants sorbed onto or structurally incorporated into eroded soil particles. Therefore, this methodology enables a comparison of the relative importance of the different contaminated sites from a contaminant impact assessment perspective.

The results will be validated with the data available for contaminant concentration in surface water as well. Total runoff generated in the watershed is,

$$Q = R_u \times CA \times 10^4 \quad \text{……………………………………………………..(4.24)}$$

where: Q = total runoff volume in litre; R_u = runoff depth in mm; CA = catchment area in ha.

Contaminant reaching surface water body is given by,

$$C_w = S_c \times 10^6/Q \quad \text{……………………………………………………..(4.25)}$$

where: C_w = contaminant concentration in surface water in mg/litre; S_c is in kg and Q is in litre and 10^6 = conversion factor.

4.5.2. Qualitative Assessment of Risk for Contaminant Loss from a Polluted Site

4.5.2.1. Introduction

A knowledge survey is important to conduct as a qualitative substitute when extensive quantitative data are not available. A qualitative assessment gives some idea on the risk of contaminant transport from surface soils. Although the concept of soil erosion and sediment transport is not new, less attention has been directed to transport of sediment-associated contaminants. Water quality concerns have forced many nations to consider developing recommendations for watershed/land management based on the potential for contaminant transport (Gilliom et al., 1995). However, soil testing data do not explicitly provide the information needed for the assessment of the potential for contaminant loss from a site because such data do not account for the processes controlling the transport of contaminants in overland flow and subsurface flow. Therefore, soil testing data can not directly be used for estimates of environmental risk (Sharpley et al., 2001). For example, two adjacent fields having similar contaminant levels but different topography and management practices have differing susceptibilities to surface erosion and runoff, and as a result, have substantially different contaminant loss potential. Table 4.8 shows the primary factors influencing contaminant loss from any site and its impact on nearby surface water quality, which are categorised into transport factors and management factors. These factors were also mentioned in Tables 4.5 and 4.6 for pesticides but these are those factors which would particularly be used in this methodology to determine contaminant transport qualitatively, and therefore summarised in Table 4.8 again.

4.5.2.2. Transport Factors

Transport factors are critical for site assessment because they demonstrate potential processes that are involved in contaminant transport from a site. The main controlling elements are erosion, surface runoff, subsurface flow/leaching potential, and distance or connectivity of the site to the water body, as also discussed in the earlier sections. It has also been mentioned earlier that erosion particularly removes finer sized soil particles; as a result, contaminants have a great affinity to stick to those final fractions and that surface runoff can carry the contaminants either in dissolved form or with suspended soil particles. Subsurface flow of water is also very important for some of the contaminants leach down with infiltrating water. This again is affected by the soil texture, structure, presence of organic matter, adsorption affinity to the soil particles, and water solubility of the contaminant. Because of the variable paths and time of water flow through a soil, contaminant loss through subsurface flow is more complex than for surface runoff. In order to find out whether the contaminants transport from a given site reaches a nearby water body, it is necessary to account for whether water leaving a site is actually reaching there. Therefore, location of a study site with respect to a water body may determine whether runoff from the field actually leaves the site and reaches the channel. To simplify this, a site can be categorised as whether it is connected to the stream or not.

Table 4.8: Factors influencing contaminant loss from a site and its impact on nearby surface water quality (Sharpley et al., 2001).

Factors	***Description***
Transport	
Erosion	Total contaminant loss is strongly related to erosion
Surface runoff	Water has to move off or through the soil for the contaminant to move
Subsurface flow	Contaminants can leach through the soil depending on its texture
Soil texture	Influences relative amounts of surface and subsurface flow occurring
Irrigation runoff (agricultural sites)	Improper irrigation management can induce surface runoff and erosion of contaminants
Connectivity to surface water	The closer the field to the stream, the greater the chance of contaminants reaching it
Stream channel effects	Eroded material and associated contaminants can be deposited or resuspended with a change in stream flow. Dissolved contaminants can be sorbed or desorbed by stream channel sediments and bank material
Sensitivity to nutrient input (agricultural sites)	Shallow lakes with large surface area tend to be more vulnerable to eutrophication
Site Management	
Contaminant concentration	As soil contaminant concentration increases, the loss of the same in surface runoff and subsurface flow increases
Applied nutrient (agricultural sites)	The more mineral fertilizer or manure applied, the greater the risk of nutrient loss
Application timing (agricultural sites)	The sooner it rains after agro fertilizer or manure is applied, the greater the risk for contaminant loss

4.5.2.3. Site Management Factors

A number of site management factors affect contaminant loss from a site. These include soil test contaminant concentration, and rate, type and method of fertilizer/manure application. These are basically applicable to agricultural farms. Therefore, while these factors reflect day-to-day farm operations, transport factors tend to represent inherent soil, topographic and climatic properties. The loss of contaminant with runoff highly depends on the contaminant concentration of surface soil. However, regression relationships between soil contaminant and the quantity in surface water vary with soil type and management (Pote et al., 1999).

4.5.2.4. Methodology

The contaminant loss index is usually designed as a tool to rank the vulnerability of sites to contaminant loss in surface runoff. It is not a quantitative predictor of contaminant loss but a qualitative assessment. US Natural Resource Conservation Service (NRCS), in cooperation with research scientists in the US developed a site assessment tool for Phosphorus (P) loss potential to overcome the limitations of using a soil P threshold as the only measure of the site P loss potential (Sharpley et al., 2001). Those indices were developed based mainly on the general assessment of the site conditions. They found that there is a strong association of the phosphorous loss index (P-index) rating and dissolved phosphorous in surface runoff. Therefore, the P-index can accurately account for and describe a site's vulnerability for P-loss if surface runoff to occur. A similar methodology was employed in this study.

The contaminant loss index takes into account and ranks the transport and site management factors (as summarised in Table 4.8) controlling contaminant loss in surface runoff and in the sites where the risk of contaminant movement is expected to be high. Such site vulnerabilities are assessed by selecting the rating values for the transport and site management factors in Table 4.8, as shown in Tables 4.9 and 4.10 respectively.

Table 4.9: Contaminant loss potential due to transport characteristics in the contaminant index (Sharpley et al., 2001).

Transport Characteristics	***Relative Ranking***					***Field Value***
Soil Erosion	Soil loss (tonnes/ha/year)					
Soil Runoff Class	Very low **0**	Low **1**	Medium **2**	High **4**	Very High **8**	
Subsurface Drainage	Very low **0**	Low **1**	Medium **2**	High **4**	Very High **8**	
Leaching potential	Low **0**		Medium **2**		High **4**	
Connectivity	Not Connected [a] **0**	**1**	Partially Connected [b] **2**	**4**	Connected [c] **8**	
	Total site value (sum of erosion, surface runoff, leaching, and connectivity values): T_1 **Transport potential for the site (total value/23) [d]:**					

[a] Field is far away from water body. Surface runoff from field does not enter water body
[b] Field is near but not next to water body. Surface runoff sometimes enters water body, *e.g.*, during large intense storms.
[c] Field is next to a body of water. Surface runoff from field always enters water body.
[d] The total site value is divided by a high value (23)

To determine the contaminant loss potential due to the transport characteristics of a site, the relative ranking values of soil erosion, surface runoff, leaching potential and connectivity are first summed up, and then divided by 23, the value corresponding to 'high' transport potential as of NRCS (erosion is 7, surface runoff is 8, leaching potential is 0 and connectivity is 8). The normalisation with respect to maximum transport values for a site depicts that if the transport potential is < 1, a fraction of maximum potential occurred, as shown in Table 4.9.

To determine contaminant loss potential based on site management factors, contaminant concentration in sample soil, and rate and timing of application of the chemicals (agro only) are mainly considered (Sharpley et al., 2001), as shown in Table 4.10. The correction factor of 'p_c' indicates the fraction of soil contaminant value in runoff water or partitioning coefficient of the contaminant.

A phosphorous loss index value, representing cumulative site vulnerability to phosphorous loss is then obtained by multiplying summed transport and site management factors ($T_1 \times T_2$), as shown in Table 4.11.

Table 4.10: Contaminant loss potential due to site management characteristics in the contaminant index (Sharpley et al., 2001).

Site Characteristics	***Relative Ranking***					***Field Value***
	Very low	Low	Medium	High	Very High	
Soil test contaminant	Soil test contaminant in mg/kg					
Loss rating value	Soil test contaminant in mg/kg × p_c *					
Fertilizer P rate (agro only)	Fertilizer rate in kg P/ha					
Fertilizer application method and timing (agro only)	Placed with planter or injected more then 2” deep **0.2**	Incorporated < 1 week after application **0.4**	Incorporated > 1 week or not incorporated > 1 following application in spring-summer **0.6**	Incorporated > 1 week or not incorporated following application in autumn-winter **0.8**	Surface applied on frozen or snow covered soil **1.0**	
Loss rating value (agro only)	Fertilizer P application rate × loss rating for fertilizer P application method and timing					
Manure P rate (agro only)	Manure application (kg P/ha)					
Manure application method and timing (agro only)	Placed with planter or injected more then 2” deep **0.2**	Incorporated < 1 week after application **0.4**	Incorporated > 1 week or not incorporated > 1 following application in spring-summer **0.6**	Incorporated > 1 week or not incorporated following application in autumn-winter **0.8**	Surface applied on frozen or snow covered soil **1.0**	
Loss rating value (agro only)	Manure P application rate × loss rating for manure P application method and timing					
Total Site Management Value (sum of soil, fertilizer, and manure P loss rating values) for agro sites: T_2						
Total Site Management Value (sum of soil rating values) for other sites: T_2						
* p_c = fraction of soil contaminant value in runoff water, for P it is 0.2						

Table 4.11: Worksheet and generalised interpretation of the Phosphorous index (Sharpley et al., 2001).

P index	*Generalized interpretation of the P index*
Low < 30	LOW potential for P loss. If current land practice is maintained, there is a low probability of adverse impacts on surface waters
Medium 30-70	MEDIUM potential for P loss. The chance for adverse impacts on surface waters exists, and some remediation should be taken to minimize the probability of P loss
High 70-100	HIGH potential for P loss and adverse impacts on surface waters. Soil and water conservation measures and a P management plan are needed to minimize the probability of P loss
Very high >100	VERY HIGH potential for P loss and adverse impacts on surface waters. All necessary soil and water conservation measures and a P management plan must be implemented to minimize the P loss
P index rating for a site = transport potential value × Site management value /145; 145 is the value to normalize the break between high and very high to 100. The following is used: *Transport Value (23/23; i.e. 1.0)* Erosion is 7 tonnes/ha per year, 7 Surface runoff class is very high, 8 Field is connected, 8 *Site Management (145)* Soil test maximum P (in the US) is 200, 200 × 0.2 = 40 Fertilizer P application (in the US) is 30 kg P/ha, 30 Manure P application (in the US) is 75 kg P/ha, 75	

4.6. Land Management for Soil Erosion

This concluding section discusses various land management options to reduce soil erosion, which in turn will reduce contaminant transport and depletion of soil organic matter. Since soil organic matter is an important ingredient in the reduction of soil erodibility (section 4.2.2.3) and contaminant transport (sections 4.4.2 and 4.4.3), top soil management through soil carbon sequestration is also a way to manage this problem. However, as recent climatic changes are affecting the presence of soil carbon to a great extent, a research relating this aspect is also covered here (section 4.6.2.2).

4.6.1. Land Management Practices to Reduce Soil Erosion

4.6.1.1. Introduction

As discussed previously in sections 4.1-4.5 rainfall-induced soil erosion is one of the main reasons that influence topsoil degradation, which, together with overland flow are the main source of contaminant spreading with sediments and loss of soil organic matter. Therefore, to control soil erosion, proper top soil management is necessary. Soil erosion is mainly prevented by protecting the soil from the impact of rainwater, by preventing water from moving down slopes and by slowing down water when it flows along slopes. Thus, retarding the cause and enhancing the protection of top soil are the main keys to controlling soil erosion problems. The following subsections summarise some of the natural and artificial erosion and sediment control practices that provide onsite soil and land resource protection.

4.6.1.2. Planting and Maintaining Vegetation Cover

One of the most effective methods of preventing erosion problems is the planting of vegetation. Dense, deep-rooted vegetation is the best protection possible for any slope (Figure 4.9(a) and (b)). Plants act as protective shields to the soil lessening the impact of rainfall, wind and excessive watering. The plants will also help stabilise the soil and prevent it from becoming prone to soil erosion (Morgan, 2006). Plants which crawl up and spread instead of growing upwards are also great soil erosion prevention plants.

Foliage also absorbs the destructive energy of rainfall preventing the detachment of soil particles whilst the root systems can bind and restrain soil particles (Morgan, 2006; Toy et al., 2002). Vegetation can also filter out sediment from rainwater run-off. A grassed waterway slows down the speed of running water and does not let the water pick up soil particles. Grass also protects the soil under it from being washed away. Water in a grassed waterway is clearer than water on the cultivated part of the field. Contour farming is another method that is useful in preventing and controlling soil erosion by water runoff. It is done by planting along the slope of a hill, following the natural contours of the land, instead of straight up and down or across (Morgan, 2006; Toy et al., 2002). The relationship of soil erosion and above ground vegetative cover has been incorporated in RUSLE2 in cover management factor, as was discussed previously in section 4.2.2.5.

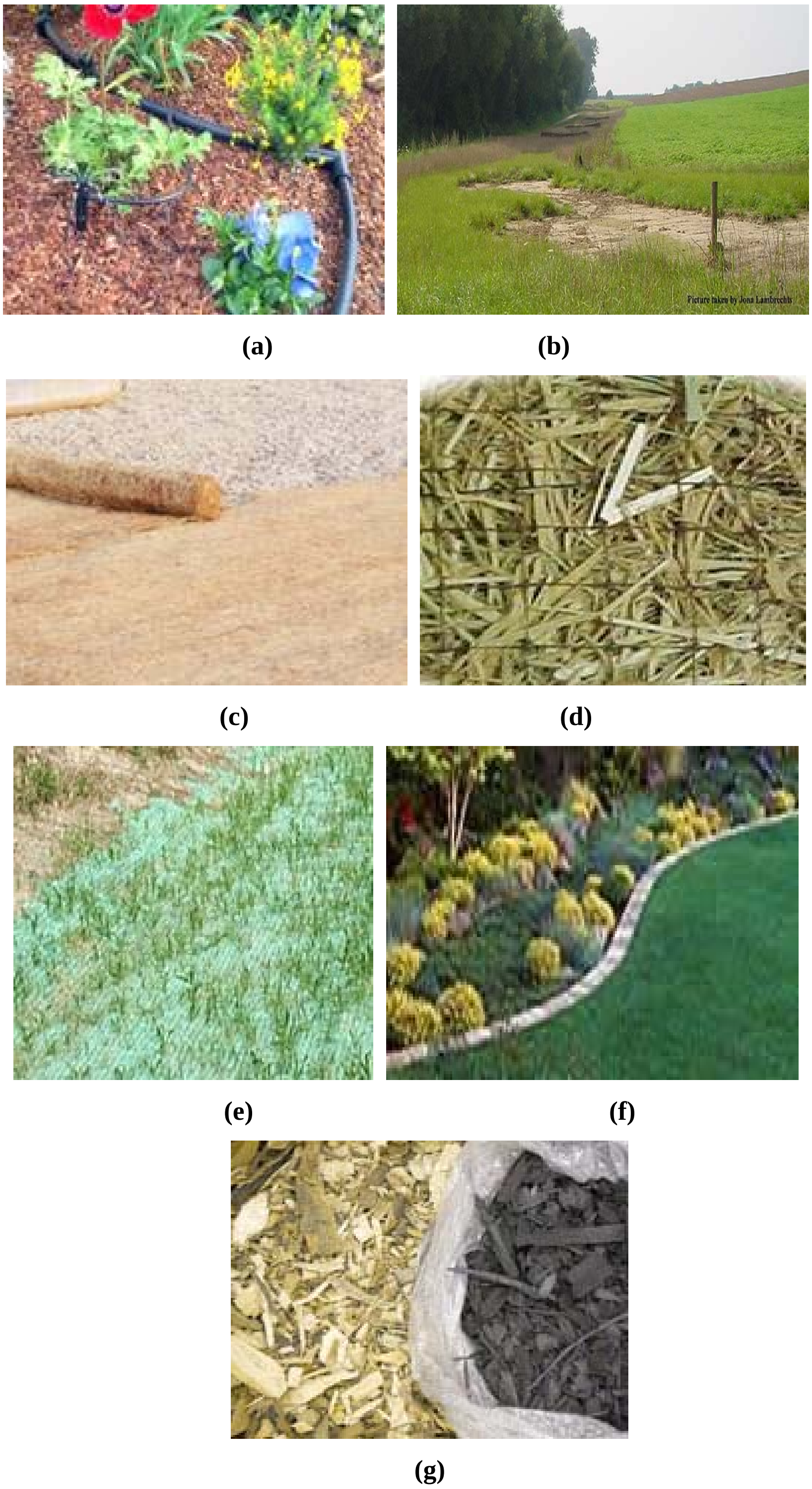


Figure 4.9: Various management options to prevent top soil erosion (a) planting vegetation, (b) grassed water way, (c) matting, (d) and (e) fibre mulch mat, (f) retaining wall/edging, (g) biochar (source: Google image).

4.6.1.3. Matting

Artificial soil erosion prevention products are available in many styles. One of the most common products which are used on residential properties, vegetation crops and vacant land is matting (Figure 4.9(c), (d) and (e)). Matting is available in natural wood fibres or synthetic material. The matting is placed on the soils surface to prevent erosion from occurring. The matting allows plants, crops and trees to grow through it and the soil generally remain healthy and stabilized. Erosion control mats may remain in place for several months, or even years, and serve as composite erosion control solutions. Matting can be cut to size to suit the area (Morgan, 2006). Despite synthetic geo-textiles are dominating the commercial market, the matting constructed from organic materials are highly effective in erosion control and vegetation establishment. Erosion control matting is available in loads of different designs and sizes which include:

- Conserving soil moisture.
- Offering a realistic natural look to the landscape.
- Increasing water infiltration.
- Moderating soils temperature.
- Absorbing and breaking down the harsh impact of rainfall.

4.6.1.4. Mulch/Fertiliser

Another soil erosion prevention method which is beneficial to the soil and plants, is applying a layer of mulch and fertiliser over the soil. The mulch and fertiliser layer will assist the soil to soak in water slowly and it will also lessen the impact of rainfall as it penetrates through to the soil. The mulch and fertiliser layer will also stabilise the degraded soil by regaining its pH levels to be healthy and neutralised. Any type of mulch or fertiliser can be used to prevent soil erosion (Morgan, 2006).

4.6.1.5. Retaining Walls/Edging

Transport of sediments and therefore carried chemicals can be prevented by building a small retaining wall around the affected land (Figure 4.9(f)). The retaining wall will act as a shield for the soil and prevent soil erosion from occurring. The wall will also keep water retained in the area so that the soil will slowly soak it in. This method can be very rewarding if used in conjunction with other soil erosion prevention methods (Morgan, 2006; Toy et al., 2002).

4.6.1.6. Biochar

Biochar, Figure 4.9(g), is the carbon-rich solid product resulting from the heating of biomass in an oxygen-limited environment and can be used as a fuel or as a soil amendment. Due to its highly aromatic structure, biochar is chemically and biologically more stable compared with the organic matter from which it was made (Lehmann and Joseph, 2009). When used as a soil amendment, biochar can boost soil fertility, prevent soil erosion, and improve soil quality by raising soil pH, trapping moisture, attracting more beneficial fungi and microbes, improving cation exchange capacity, and helping the soil hold nutrient (Lal, 2007, 2008). Moreover, biochar is a more stable nutrient source than compost and manure. Therefore, biochar as a soil amendment can increase crop yields, reduce the need for chemical fertilisers, and minimise the adverse environmental effects of agrochemicals on the environment (Lal, 2007, 2008). Another potentially enormous environmental benefit associated with biochar use in soil is that it can sequester atmospheric carbon. Using Biochar can reclaim land that was once lost to soil erosion and turn it back into productive land (Lal, 2007, 2008). Biochar is rapidly gaining attention in the agricultural community where its dual function of increased soil health and crop yield makes its appeal undeniable.

4.6.1.7. Other Measures

In addition to the above soil protection and management measures, the following points summarise some of the other ways to prevent soil erosion from any type of land (Morgan, 2006; Toy et al., 2002):

- Reduce run off onto fields from contaminated areas by provision of adequate drains or ditches.

- Incorporate biomass into the soil. Adding to and incorporating organic matter such as manure, sewage sludge (bio solids), or paper mill waste in the soil can reduce erosion significantly (carbon sequestration).
- Minimise soil disturbance, but if the soil must be disturbed mechanically, leave the soil rough, with large clods.
- Add soil amendments such as PAMs (polyacrylamides) that reduce the erodibility of the soil and increase infiltration.
- Take care when irrigating to avoid run off.
- Divert water away from vulnerable areas.

4.6.2. Land Management and Soil Carbon Sequestration

4.6.2.1. Introduction

The process of storing carbon dioxide (usually captured from the atmosphere) in soils, ocean, vegetation (especially forests), and geologic formations is known as carbon sequestration. Although oceans store most of the earth's carbon, 75% of carbon in the terrestrial biosphere is in the soil (Sanginov and Akramov, 2007), which is three times more than the amount stored in living plants and animals (Robert, 2001). Therefore, soils play an important part of the carbon cycle.

The primary route through which carbon is stored in the soil is as soil organic matter (SOM). SOM is a complex mixture of carbon compounds, consisting of decomposing plant and animal tissue, microbes, and carbon associated with soil minerals. Carbon compounds added to soil, provide important benefits for the soil, crop and environmental quality, in the prevention of erosion and desertification and for the enhancement of bio-diversity. A conceptual framework outlining how organic matter inputs influence soil quality is illustrated in Figure 4.10. As Figure 4.10 shows, soil organic matter influences a wide range of physical, chemical and biological properties including supplying nutrients and trace metals to soil, developing strength of soil aggregates and stabilising the soil structure, which increases permeability, reduces soil erodibility (expressions 4.8-4.13 in section 4.2.2.3). Toxicity of pollutants in a soil (both organic, such as pesticides, and mineral, such as heavy metals or aluminium) may also decrease through fixation with the organic matter (Robert, 2001; Tordoff et al., 2000). Water quality is also improved by the decrease of erosion and runoff of water and pollutants.

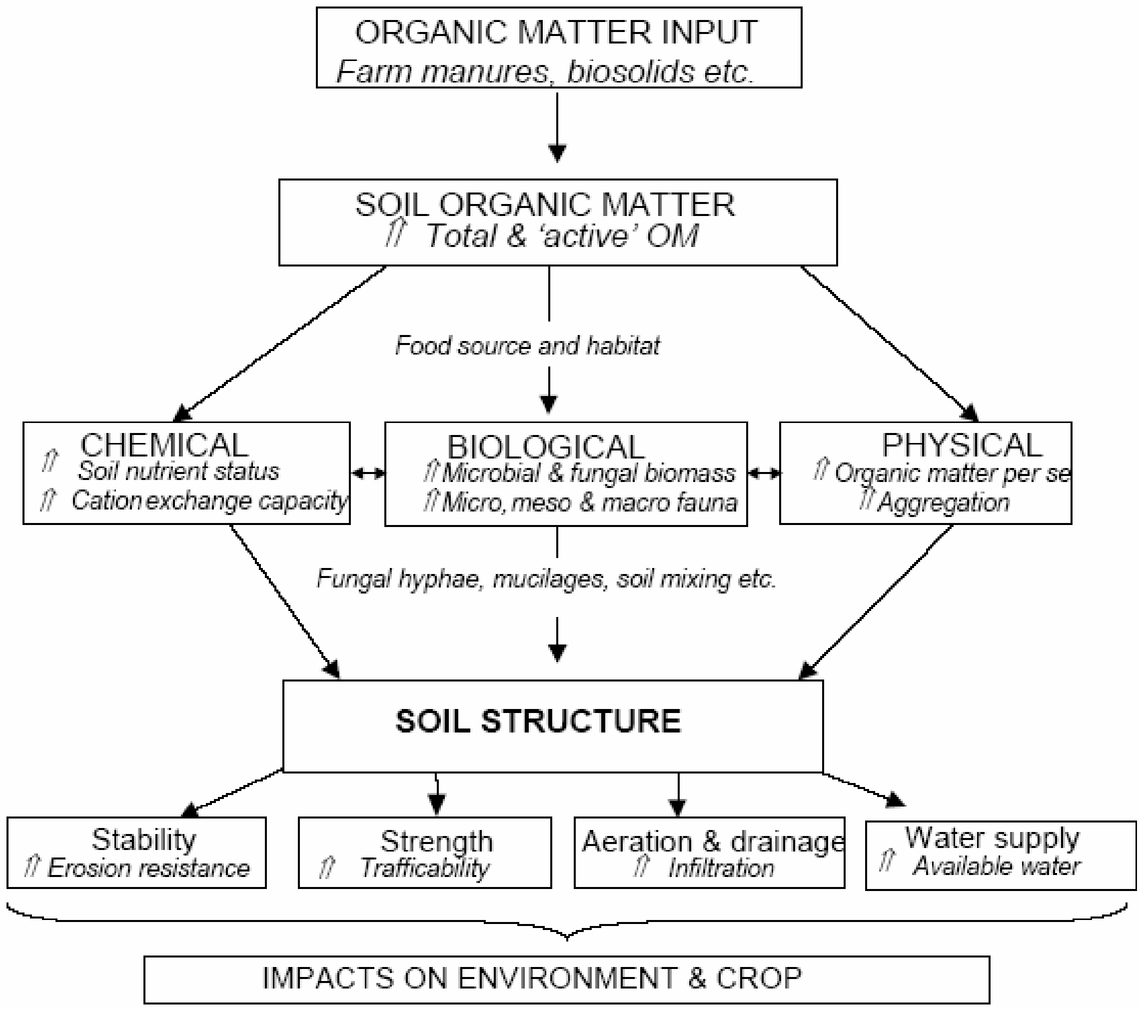


Figure 4.10: Effects of soil organic matter additions – a conceptual framework (http://www.sorp.org/media_files/general/sorp_technical_note_website_section_3.pdf).

The principal benefits of sustainable soil carbon management at various spatial scales are summarised in Figure 4.11 (Robert, 2001) and three principal strategies of carbon sequestration in soils are outlined in Table 4.12 (Lal, 1999(b)). With the exception of some specific erosion control methods mentioned in Table 4.12, such as terraces or contour ridges, most of the methods used to prevent soil erosion aim to increase soil stability (of which organic matter is one of the main factors) or to protect the soil surface with a cover of vegetation, plant residues, etc. Such methods for preventing erosion will also be appropriate for carbon sequestration and land management (and vice versa).

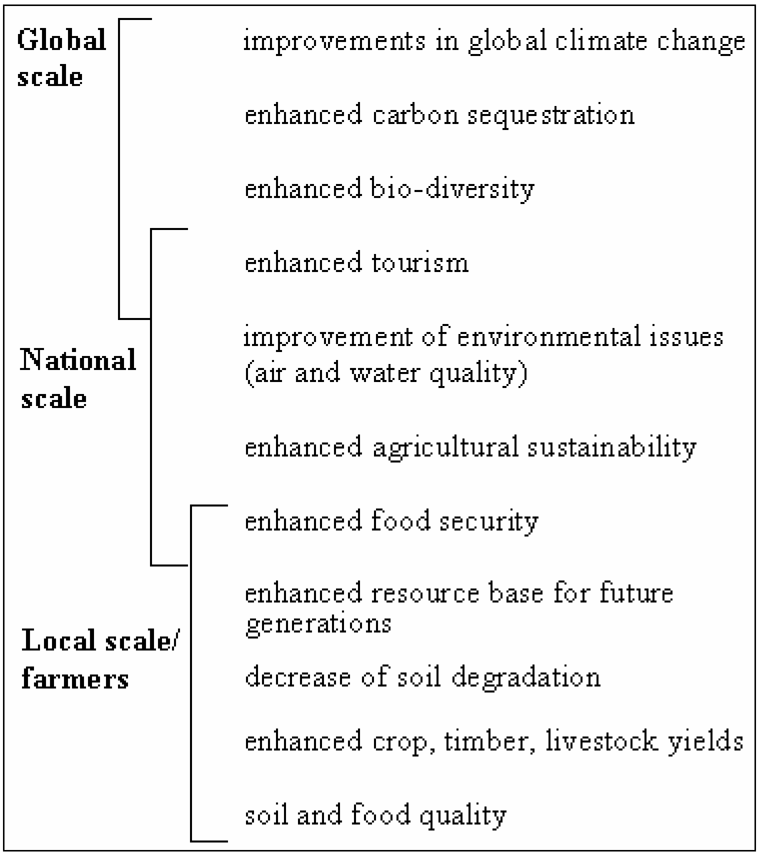


Figure 4.11: Principal benefits of sustainable soil carbon management at various spatial scales (Robert, 2001).

4.6.2.2. Effect of Climate Change on Soil Carbon Sequestration

4.6.2.2.1. Overview

As discussed in detail in Chapters 2 and 3, anthropogenic climate change is projected to include increasingly extreme and variable precipitation regimes, as well as atmospheric warming. Since most aspects of terrestrial ecosystem functions are vulnerable to these hydrological changes (as discussed in section 4.1 for soil erosion), important interactions of elevated temperatures and soil carbon can also be expected (Heimann and Reichstein, 2008). Since 90% of all terrestrial vegetation types worldwide have > 50% of their roots in the upper 0.3 m of the soil profile, most biomes are at risk of being affected by projected climatic changes and more extreme soil moisture dynamics (Froberg et al., 2008).

Table 4.12: Strategies of carbon sequestration in soil (Lal, 1999(b)).

Strategy	***Practices***
Reduce losses from soil due to: (i) Accelerated erosion (ii) Mineralization (iii) Decomposition	Mulch farming, conservation tillage cover crops, terraces, contour ridges, low stocking rate, improved pasture Enhancing aggregation, deep placement of biomass, providing N, P and S for humification Increasing lignin content in plant
Increase carbon concentration in soil by (i) Returning biomass to soil (ii) Enhance water use efficiency (iii) Improving nutrient use efficiency	Mulch farming, conservation tillage use of biosolids on land, compost etc Soil-water conservation, water harvesting, supplemental irrigation through appropriate techniques Integrated nutrient management, new formulations, judicious rate and timing of application, precision farming
Improvement in crop yield and biomass production (i) Improved cropping/farming system (ii) Cultivars with high lignin content and deep root system (iii) High yield and biomass	Improved varieties, proper crop rotations and crop combinations Biotechnology, soil management, P placement, liming

The components of the climate that are most important for soil processes are temperature and rainfall (Heimann and Reichstein, 2008) since soil organic carbon storage decreases with increase in temperature and increases with increase in soil water content (Blanco and Lal, 2008), as shown in Figure 4.12. However, there are large uncertainties regarding the impact of climate change on global carbon stocks and dynamics. The effects are likely to vary regionally and depend on several factors because of the interaction between soil moisture and temperature effects on microbial activity (Bekku et al., 2003; Smith, 2003).

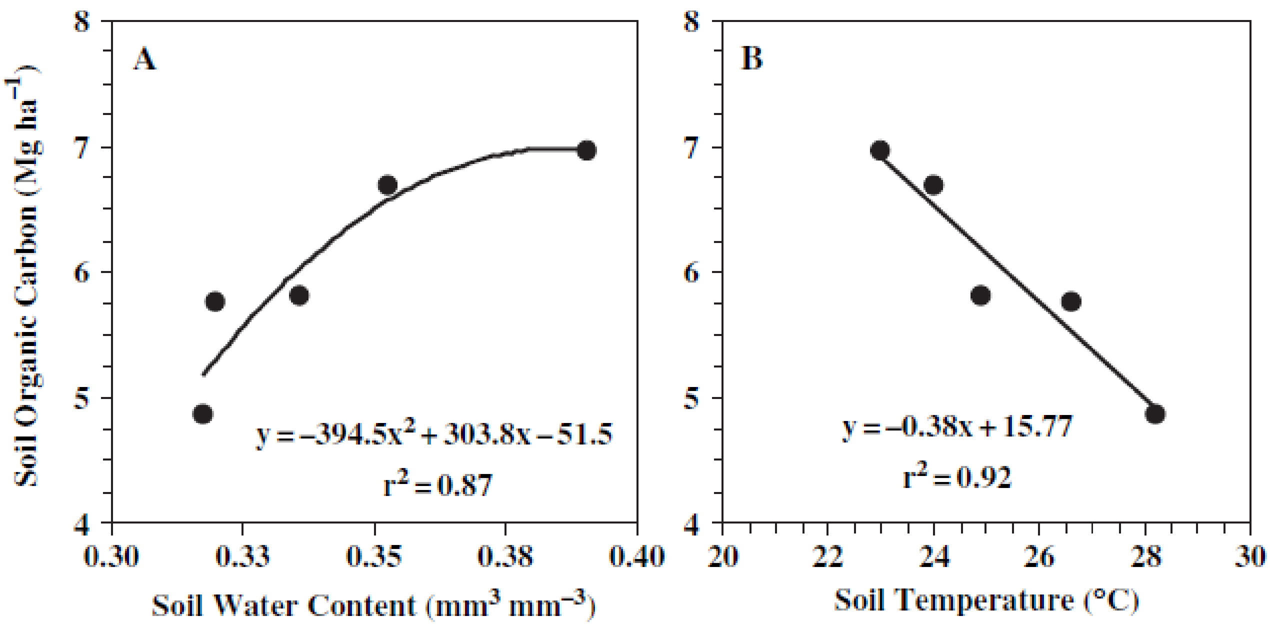


Figure 4.12: Organic C pool increases with increase in water storage capacity and decrease with soil temperature in the 0-2cm depth of no-till soils (Blanco and Lal, 2008).

4.6.2.2.2. Effects of Rainfall and Temperature Changes

Projected increases in rainfall variability (both frequency and timing) and changes in seasonal distribution can rapidly alter key water-carbon-cycle interaction processes, as these factors determine whether the water will be used by plants and transpired, or will just run off or evaporate (Li et al., 2006). It is also widely believed that increases in ambient temperature due to global climatic change will decrease the organic matter content of soils and increase the emission of greenhouse gases from them leading to a positive feedback between climate change and the carbon cycle (Jones et al., 2005; Parton et al., 1995).

Soil moisture, which is primarily affected by both precipitation and temperature changes, is an important control on carbon storage (Figure 4.12). The rate of soil organic matter decomposition due to microbial activity, which depends to a large extent on soil moisture availability and climate change, could either increase or decrease depending on available soil water. Optimal microbial activity occurs at or near field capacity – the maximum amount of water that soil can hold against gravity, when the macro pore spaces are mostly air-filled, thus facilitating O_2 diffusion, and the micro pore spaces are mostly water-filled, thus facilitating the diffusion of soluble substrates (Luo and Zhou, 2006). Soil moisture could affect microbial activity negatively both during dry conditions by limiting the availability of water, and during wet conditions by limiting diffusion of O_2 through the soil (Froberg et al., 2008). The amount and timing of precipitation, therefore, has the potential to impact the decomposition of soil organic carbon and thereby the carbon stocks (Nemani et al., 2002).

An increase in precipitation would increase soil moisture. However, higher air temperatures will increase the rate of evaporation and, in some areas, remove moisture from the soil faster than it can be added by precipitation. Under these conditions, some regions are likely to become drier even though their rainfall increases. Figure 4.13 shows the model projections of global averaged time series of monthly mean soil moisture for the three future climate scenarios for the years of 1900-2100 (Sheffield and Wood, 2008). The figure indicates that, globally, soil moisture decreases under all scenarios leading to soil organic carbon decrease (Figure 4.12), which is also consistent with Smith et al. (2009). The local effects of climate change on soil moisture, however, will vary with the degree of climate change (IPCC, 2001). For example, Laporte et al. (2002) investigated the effect of rainfall patterns on soil surface CO_2 efflux and soil moisture in a grassland ecosystem of northern Ontario, Canada, where climatic change is predicted to introduce new precipitation regimes. They found that the soil surface CO_2 efflux decreased by 80% while soil moisture content decreased by 42% for a more intense and less frequent rainfall and total monthly rainfall remained unchanged. This again suggests that inter-rainfall intervals are by themselves critical in controlling soil carbon sequestration.

Precipitation also has a direct role regionally and globally in the amount of soil organic carbon (SOC) stored in soil at various depths. Organic carbon migrates in the soil as a result of leaching and soil organisms can mix large amounts of soil. Leaching and mixing tend to increase with precipitation. Therefore, if leaching and mixing by organisms were dominant factors in the vertical distribution of SOC, then SOC should be deeper as precipitation increases. However, Jobbágy and Jackson (2000) found the opposite to be true. This information is important for the global carbon budgets and carbon sequestration strategies.

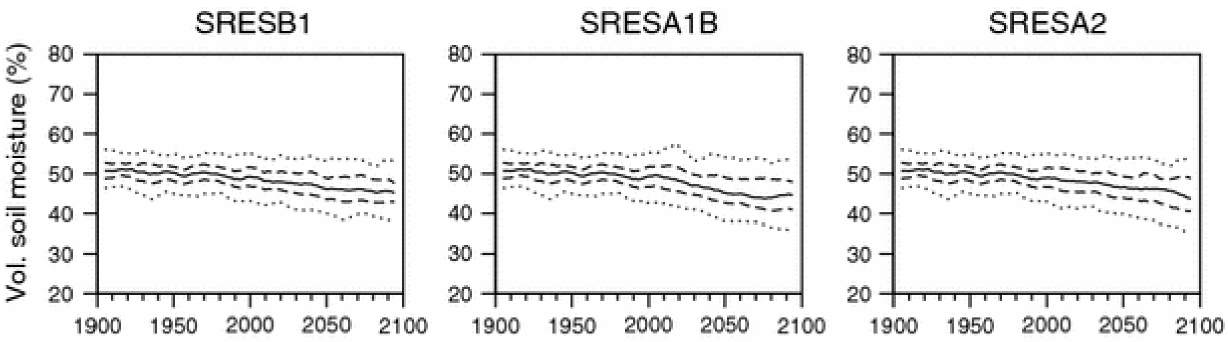


Figure 4.13: Global average time series of soil moisture for the twenty-first century for the SRESB1, SRESA1B and SRESA2 scenarios (Sheffield and Wood, 2008).

A number of studies looked at the direct effect of temperature on CO_2 efflux (Fang and Moncrieff, 2001; Davidson et al., 1998). Fang and Moncrieff (2001) studied the effect of temperature on CO_2 efflux from two types of soils (farmland and forest) in Scotland and found that soil respiration rate increases exponentially with temperature, as shown in Figure 4.14, which is also consistent with the findings of Davidson et al. (1998) who found a 80% variation of soil respiration with increase in temperature. Figure 4.14 illustrates that two types of soils had an exponential increase in respiration rate with respect to temperature (scatter plots), with a minimum efflux of 0.035 and 0.057 mg CO_2 m^{-2} s^{-1} for forest soil and farmland soil at about 10°C, respectively. The efflux from forest soil was more responsive to temperature, although with a considerable scatter among different samples.

Another example of past and projected climate change for 1850-2100 and its impact on soil carbon sequestration is shown in Figure 4.15 (Friedlingstein et al., 2006). The figure shows that the efficiency of the earth system to absorb the anthropogenic carbon perturbation from atmosphere is also reducing due to climate change and leading to a larger fraction of anthropogenic CO_2 staying airborne. The data in Figure 4.15 and that by Jones et al. (2005) in Figure 4.16 suggest an accumulation of soil carbon during the 20th century followed by a more rapid release of soil carbon during the 21st century. It is this rapid release of carbon that causes the transition of the terrestrial biosphere from carbon sink to source and is responsible for the positive feedback between climate and the carbon cycle (Jones et al., 2005).

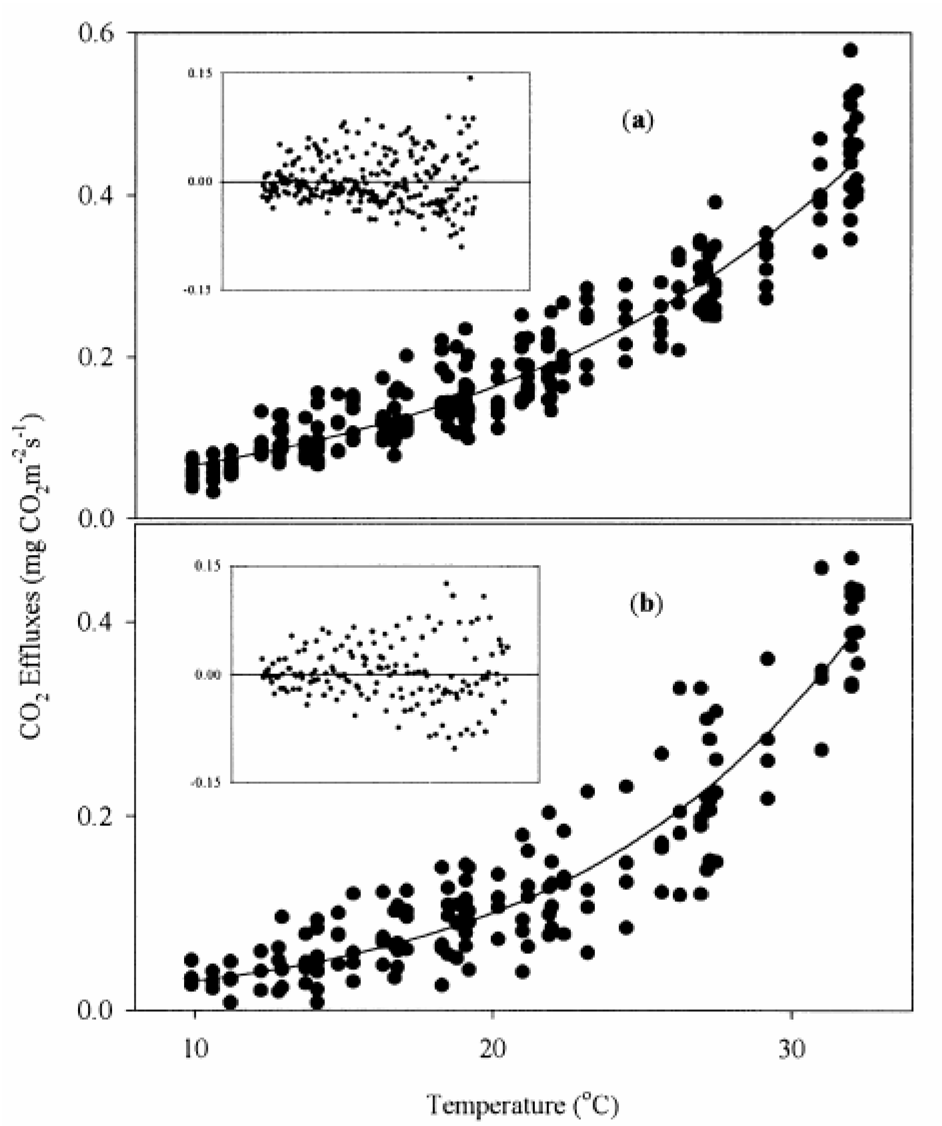
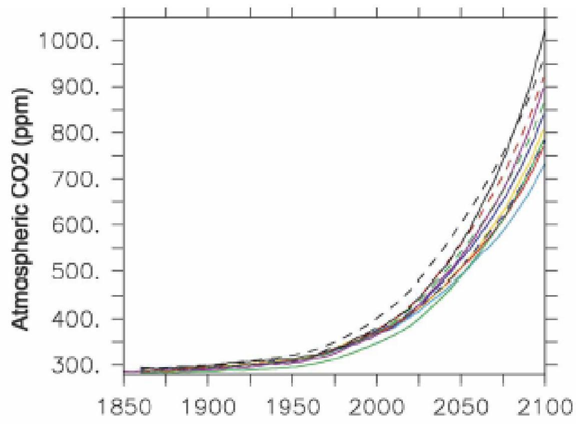
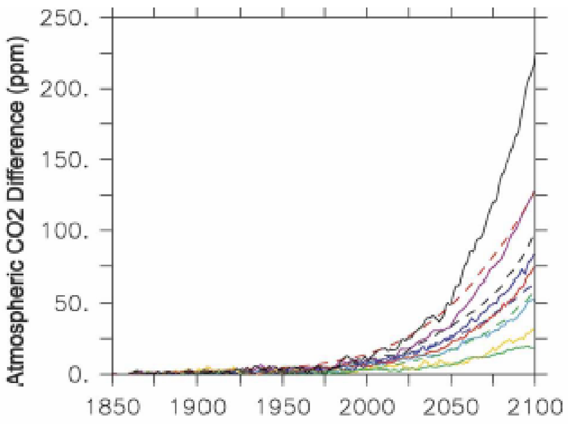


Figure 4.14: Fitted Arrhenius relationships for both soils. Scattered points stand for the soil respiration rate measured in different incubation periods from (a) six soil samples for farmland and (b) four soil samples for forest, the small inset graph shows residuals between measured and simulated effluxes (Fang and Moncrieff, 2001).

The majority of the models also located the reduction of soil carbon sequestration in the tropics due to temperature increases (Friedlingstein et al., 2006). However, the attribution of the land sensitivity to changes in net primary productivity versus changes in respiration is still subject to debate and no consensus emerged among the models (Friedlingstein et al., 2006). Furthermore, some models also indicated that carbon-sink of different ecosystems may increase with increase in temperature for soil respiration decreases (Cao et al., 2002). Therefore, despite much research, an agreement has not yet emerged on the temperature sensitivity of soil carbon. This is because the diverse soil organic compounds exhibit a wide range of kinetic properties, which determine the intrinsic temperature sensitivity of soil carbon (Davidson and Janssens, 2006).



(a)



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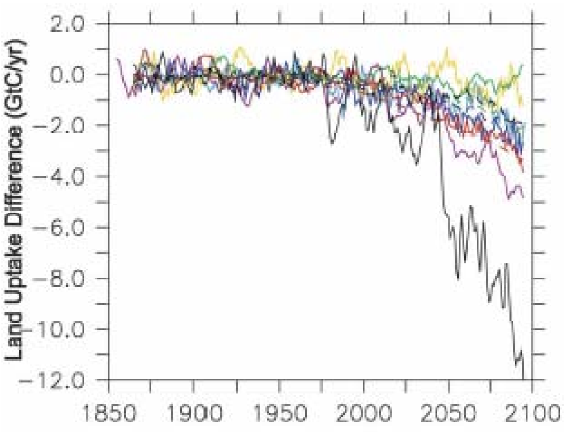

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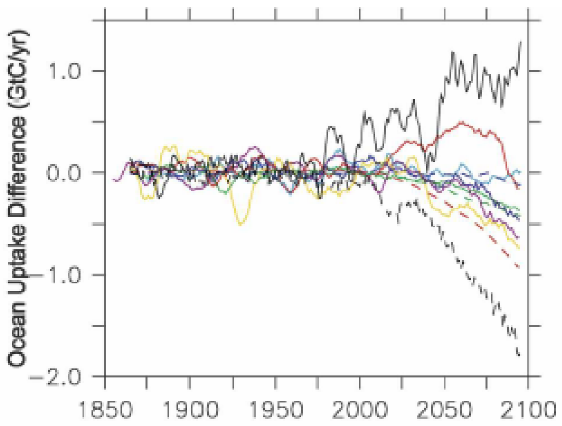


(d)

Figure 4.15: (a) Atmospheric CO_2 for the coupled simulations (ppm) as simulated by the HadCM3LC (solid black), IPSL-CM2C (solid red), IPSL-CM4-LOOP (solid yellow), CSM-1 (solid green), MPI (solid dark blue), LLNL (solid light blue), FRCGC (solid purple), UMD (dash black), UVic-2.7 (dash red), CLIMBER (dash green), and BERN-CC (dash blue); (b) atmospheric CO_2 difference between the coupled and uncoupled simulations (ppm), (c) land carbon flux differences between coupled and uncoupled land carbon fluxes and (d) same as (c) for the ocean carbon fluxes (Friedlingstein et al., 2006).

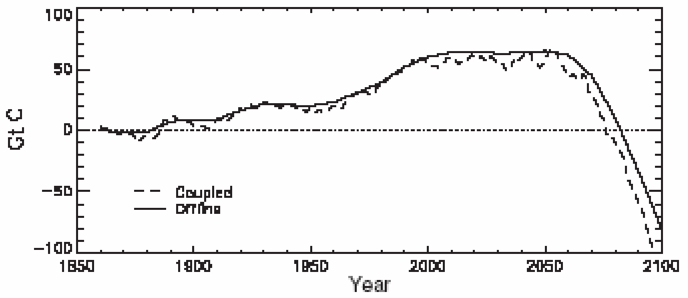


Figure 4.16: Global total soil carbon changes (in Giga tonne C) for the fully coupled HadCM3LC experiment (Jones et al., 2005).

4.6.2.2.3. Regional Differences of Effect of Rainfall and Temperature Changes

Because the mechanisms through which climatic changes affect CO_2 sources and sinks are diverse, it is very difficult to formulate simple rules or patterns that apply across diverse ecosystems and timescales (Zhang et al., 2009).

In the humid tropics and monsoon climates, increased intensities of rainfall events and increased rainfall totals would not only increase leaching rates in well-drained soils with high infiltration rates, but also cause temporary flooding or water-saturation, hence reduced organic matter decomposition, in many soils in level or depressional sites. Peat soils are also a common result. Decomposition also slows as soils dry irrespective of the temperature changes (Froberg et al., 2008).

In subtropical and other sub-humid or semi-arid areas, less rainfall and increasing intra- and inter-annual variability could lead to less dry-matter production and hence, in due course, lower soil organic matter contents (Diaz et al., 1997). In Mediterranean ecosystems, soil respiration may have a pulsed response to precipitation events, especially during prolonged dry periods. Almagro et al. (2009) hypothesised that soil moisture content, rather than soil temperature is the major factor controlling CO_2 efflux rates in the Mediterranean ecosystem during the summer dry season.

In arctic climates, the gradual disappearance of large extents of permafrost and the reduction of frost periods in extensive belts adjoining former permafrost are expected to improve the internal drainage of soils in vast areas, with probable increases in leaching rates. The appreciable increase in period when the soil temperature is high enough for microbial activity would lead to lower organic matter contents and release enough heat to facilitate further soil melting, probably not fully compensated by increased primary production through somewhat higher net photosynthesis (Heimann and Reichstein, 2008).

Figure 4.17 (Heimann and Reichstein, 2008) provides an overview of the feedback loops that could be induced by climate change in below-ground eco-system carbon balances. Pink arrows in Figure 4.17 denote effects of terrestrial ecosystems on climate, orange arrows denote effects of climate change on terrestrial ecosystems, and black arrows denote interactions within ecosystems. The background image in Figure 4.17 is a world map of soil organic carbon.

Figure 4.17(a) shows potential interactions between microbial metabolism and the physics of permafrost thawing and carbon release. Figure 4.17(b) shows ‘microbial priming effect’ which is a phenomenon by which addition of substrates with readily available energy (for example – glucose, cellulose etc) to the soil stimulates decomposition of soil carbon material that has been deemed stable. Increasing CO_2 concentrations can lead to enhanced below-ground allocation of labile carbon (open to change; adaptable) through roots and root exudates, which can enhance microbial activity and foster decomposition of carbon. The response of ecosystem to prevailing trend in climate change could also be altered by the interaction of carbon and nitrogen cycles, as shown in Figure 4.17(c). Those loops could alter expected ecosystem carbon responses to the prevailing trend of climate change.

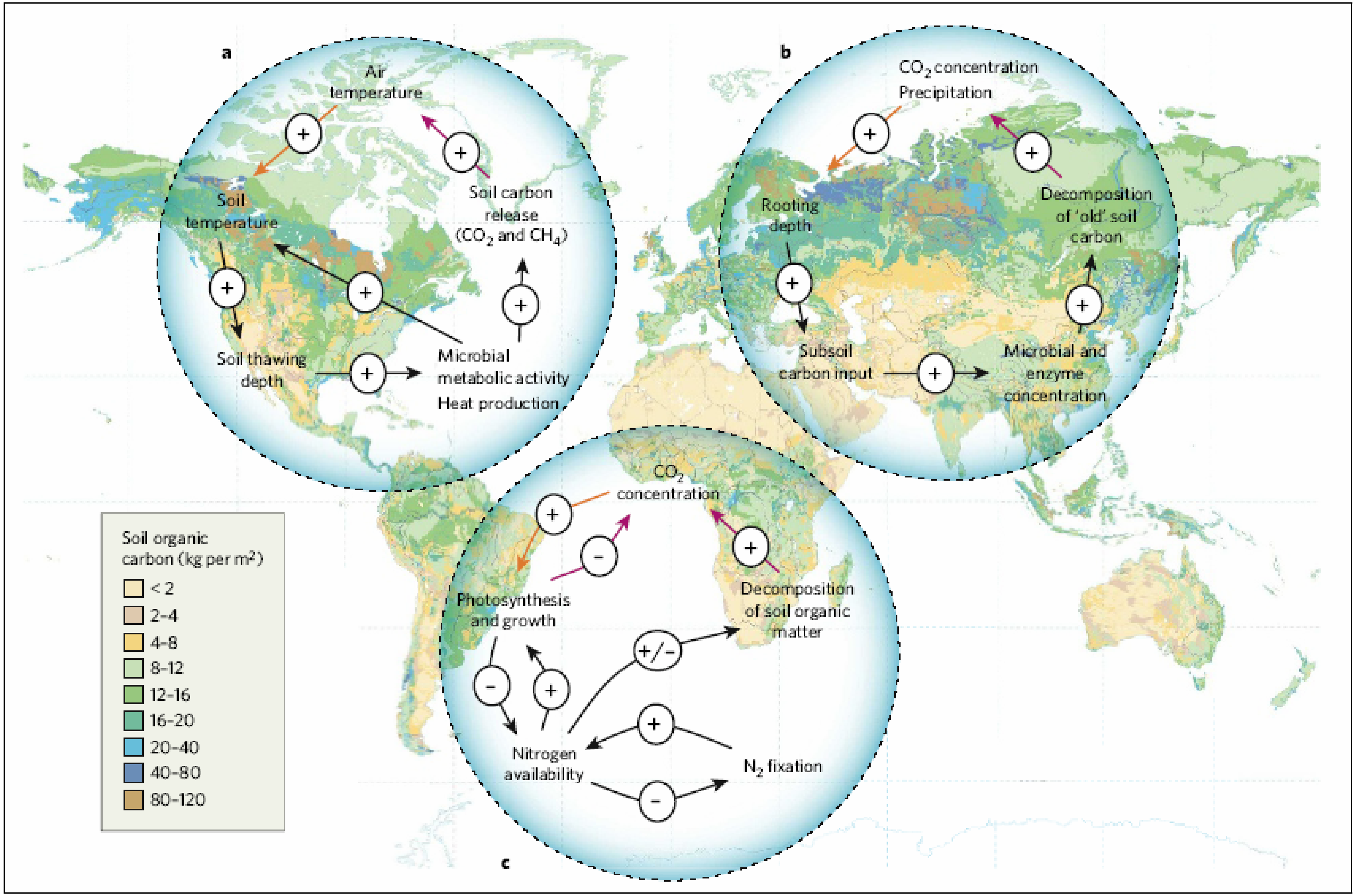


Figure 4.17: An overview of the feedback loops that could be induced by climate change in below-ground eco-system carbon balances (Heimann and Reichstein, 2008).

4.6.2.2.4. Soil Carbon Sequestration Potential in India

With a large land area and diverse eco-regions, there is a considerable potential for soil carbon sequestration in India at 39-49 teragram/10^{12}gC/year (Lal, 2004). Diverse ranges of soils of varying characteristics are characterised by wide range of SOC concentrations, which is related to their clay content and climate. Lal (2004) presented data on soil organic carbon content in soils at various locations in India, shown in Table 4.13, indicating an average value of ~ 5g/kg. Table 4.14 shows that SOC concentrations of soils of India increase with increasing rainfall.

Table 4.13: Soil organic carbon concentration of some soils in India (Lal, 2004).

Location	*Soil Texture*	*SOC content (g/kg)*
Bangalore, Karnataka	Sandy loam	5.5
Barrackpore, West Bengal	Sandy loam	7.1
Bhubaneswar, Orissa	Sandy	2.7
Coimbatore, Tamilnadu	Clay loam	3.0
Delhi	Sandy loam	4.4
Hyderabad, Andhra Pradesh	Sandy clay loam	5.1
Jabalpur, Madhya Pradesh	Clayey	5.7
Ludhiana, Punjab	Loamy sand	2.1
Palampur, Himachal Pradesh	Silty clay loam	7.9
Pantnagar, Uttar Pradesh	Silty clay loam	14.8
Rauchi, Bihar	Silty clay	4.5

Table 4.14: Soil organic carbon concentration of soils of India in relation to the rainfall regime and temperature (Lal, 2004).

Rainfall (mm/year)	*Mean annual temperature (°C)*	*SOC content (g/kg)*	
		Surface	*Sub-soil*
< 500	25.9-26.7	1.2-8.0	1.2-4.0
500-1000	23.6-27.9	1.8-12.5	0.7-11.7
> 1000	24.4-27.2	2.6-9.0	2.3-8.4

As discussed previously, soil degradation, decline in soil quality with an attendant reduction in biomass productivity and environment moderating capacity, have severe adverse impacts on the soil organic carbon pool. A comparison of soil organic carbon concentration in cultivated and undisturbed soils in various regions in India is shown in Table 4.15 which shows that accelerated soil erosion depletes the SOC pool severely and rapidly up to ~ 60%. The SOC loss by erosion and runoff can be high even on gentle slopes. Although the fate of SOC displaced along with eroded sediments is governed by a series of complex and interacting processes, a considerable part of it is mineralised leading to the release of CO_2 under aerobic conditions. It has been evaluated that, soil erosion by water leads to emission of 6 teragram C/year in India (Lal, 2004).

Table 4.15: Depletion of soil organic carbon concentration of cultivated compared with that in undisturbed soils (Lal, 2004).

Region	***SOC content***		***Percent reduction***
	Cultivated (g/kg)	***Native (g/kg)***	
1. Northwest India			
Indo-Gangetic Plains	4.2 ± 0.9	104 ± 3.6	59.6
Northwest Himalaya	24.3 ± 8.7	34.5 ± 11.6	29.6
2. Northeast India	23.2 ± 10.4	38.3 ± 23.3	39.4
3. Southeast India	29.6 ± 30.1	43.7 ± 23.4	32.3
4. West Coast	13.2 ± 8.1	18.6 ± 2.1	29.1
5. Deccan Plateau	7.7 ± 4.1	17.9 ± 7.6	57.0

Important strategies to increase the soil carbon pool include soil restoration of degraded soils, and adoption of recommended management practices of agricultural and forestry soils including woodland regeneration, no-till farming, cover crops, nutrient management, manuring and sludge application, improved grazing, water conservation and harvesting, efficient irrigation, agro-forestry practices, and growing energy crops on spare lands (Lal, 2004). An example from India of how SOC degradation decreases with the top soil management through top soil cover and increases the soil carbon sequestration are shown in Figures 4.18 and 4.19 (Mandal et al., 2006). C depletion in Figure 4.18 had a negative correlation of -92% with the amount of crop residue C inputs to the soil. Figure 4.19 also revealed that in order to maintain a SOC level (zero change) in a soil, the critical amount of C input to the soil should be 2.9 $MgCha^{-1}yr^{-1}$; which is similar to the value (3.3 $MgCha^{-1}year^{-1}$) found by Majumder et al. (2008) for a different soil in West Bengal, India.

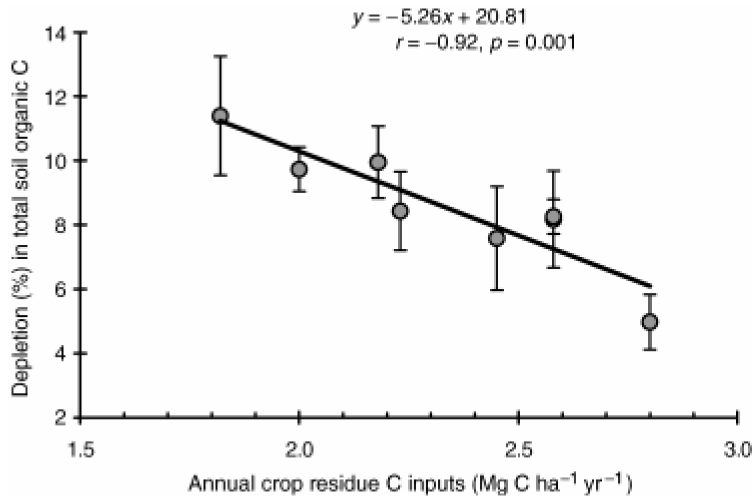


Figure 4.18: Inverse relationship of depletion in soil organic carbon with crop residue C inputs (error bars represent the standard error of mean) in Orissa and West Bengal, India (Mandal et al., 2006).

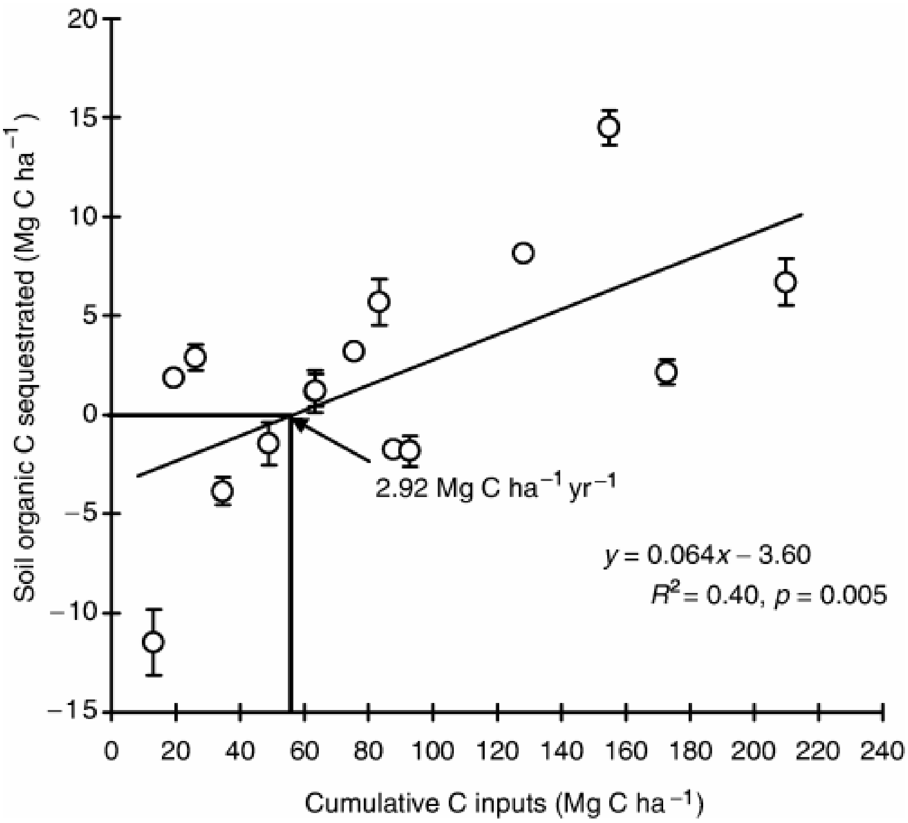


Figure 4.19: Critical C input value and its influence on C sequestration (error bars represent the standard error of mean for sequestrated C) in Orissa and West Bengal, India (Mandal et al., 2006).

CHAPTER 5

RESULTS AND DISCUSSION

This chapter presents the results of a study performed on the impact of observed past and projected future climate trends (Chapter 3) on soil erosion (section 5.1), the impact of soil erosion trends on contaminant transport (section 5.2), a qualitative determination of the risk of contaminant loss (section 5.3), and the effects of regional rainfall and temperature patterns on soil carbon sequestration at two case study sites (section 5.4). A summary of the results and findings of the MPhil work (Pal, 2007) is presented at the start of section 5.1 and linked to the rest of the work as appropriate. The chapter concludes with recommendations for controlling soil erosion and related contaminant transport through effective land management options (section 5.5). Contaminant transport and land management related studies as presented in this chapter formed a small part of the overall research and hence the coverage here is preliminary and limited. More time and data would be needed for a more extensive study.

5.1. Impact of Past and Projected Climate Trends on Soil Erosion

Chapter 4 reviewed the existing literature on the impacts of climatic changes on soil erosion, which was also seen to be having several effects on soil properties including soil organic matter that is vital for soil stability to reduce soil erosion (sections 4.1-4.4). While Chapter 3 analysed the Indian climate data and looked at their trends and projections, section 5.1 looks at the effects of those rainfall changes on soil erosion. Sub-section 5.1.1 concentrates on the regions in Kerala while sub-section 5.1.2 on two study sites which are elsewhere in India. Because land degradation from water-induced soil erosion is a serious problem in India (Pal, 2007) and only fragmentary information on the same is available, among various impacts of rainfall changes on the environment, the rainfall induced top soil erosion in India is an important area to look at.

5.1.1. Kerala Regions

5.1.1.1. Region 1

Kerala state is a part of the Western Ghat range in peninsular India. The annual soil erosion rates in coastal Western Ghats is very high and vary from 30-40 tonne/ha/yr, as marked in orange colour in the iso-erosion map of India shown in Figure 5.1 (Singh et al., 1992). A study of soil erosion problems using the 50-years (1954-2003) daily rainfall data for one gridded region in Kerala (region 1, 11.5N,75.5E in the north of Kerala, Figures 5.2 and 5.3) was conducted for rainfall-runoff erosivity as well as a parametric study for the parameters that affect soil erosion (expression 4.1 in section 4.2.2.1) as included in RUSLE2 model, which was documented in detail in the MPhil thesis (Pal, 2007). The findings and conclusions from that work are summarised below.

5.1.1.1.1. Rainfall Runoff Erosivity Factor

Rainfall erosivity is the rainfall parameter in RUSLE2 (section 4.2.2.2). The annual erosivities, R, were computed using 50-years daily rainfall data for region 1 in Figure 5.3. Very high temporal variability of total and monsoon seasonal rainfall was observed in this gridded region. 24-hour maximum rainfall in a given year also varied significantly, magnitudes of 100mm of the same returned every year during monsoon seasons whereas return periods of 100-160mm varied between 1-10 years, which and together with the same in gridded region 2 in Kerala will be discussed in section 5.1.1.2. Very rare and high magnitude rainfalls were noticed returning several times but only since the 1990’s (4 times in 1991-2003), as noted in Figure 5.3. Therefore, intense and high frequent storms could be expected in the near future giving rise to increased erosion and more frequent flooding in this area.

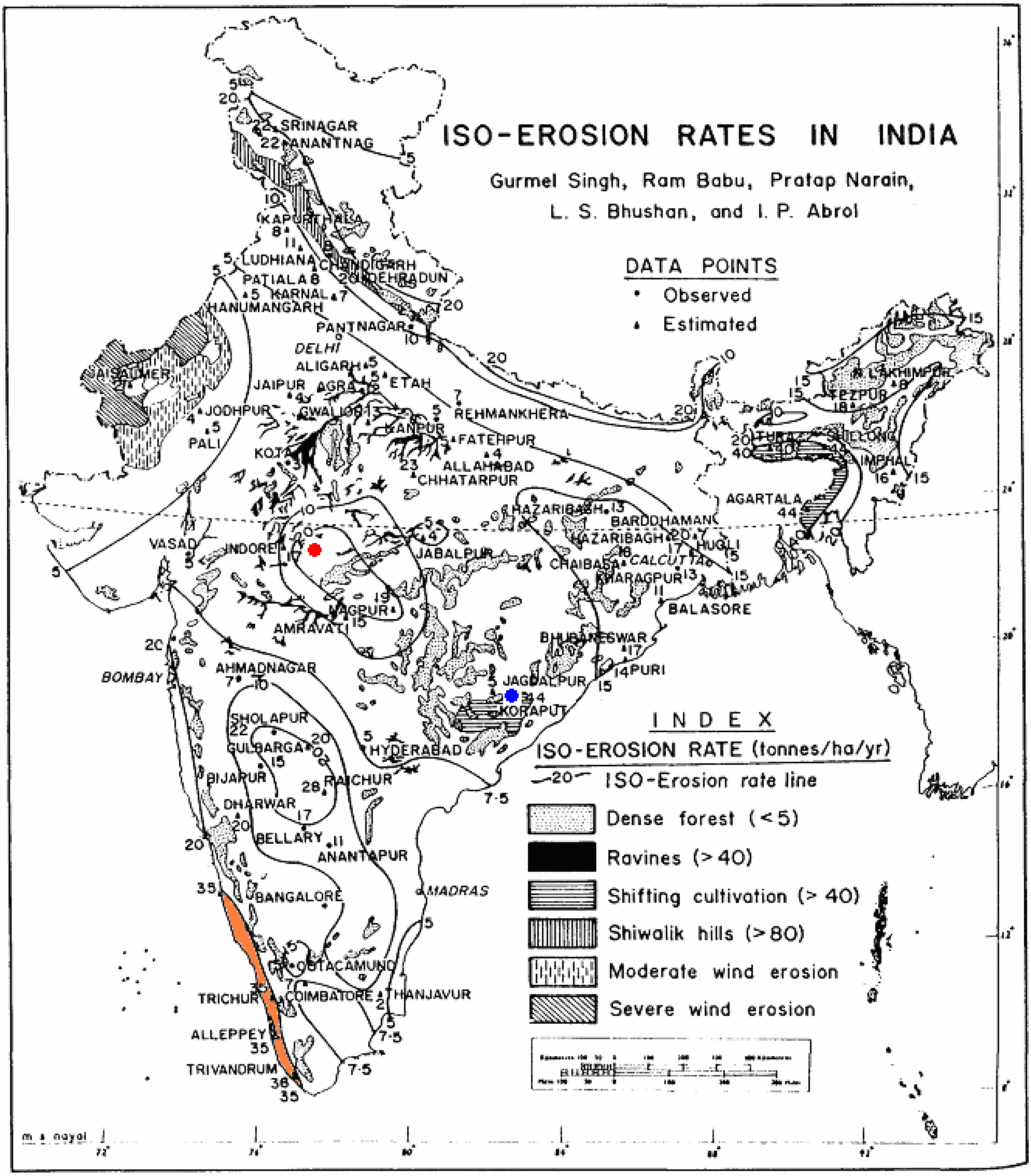


Figure 5.1: Iso-erosion rates in India (Singh et al., 1992), red and blue circles indicate two case study sites in west central India and central north east India respectively, and orange colour region is Kerala.

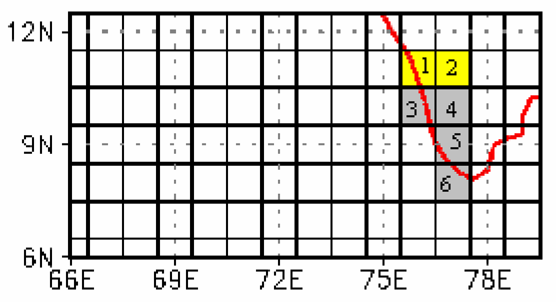


Figure 5.2: Gridded regions in Kerala, India; the numerical numbers in the grid points represent 1°×1° grids as follows, 1 = 11.5N,75.5E; 2 = 11.5N,76.5E; 3 = 10.5N,75.5E; 4 = 10.5N,76.5E; 5 = 9.5N,76.5E; 6 = 8.5N,76.5E; yellow colour grids mark the gridded study sites considered (Rajeevan et al., 2006).

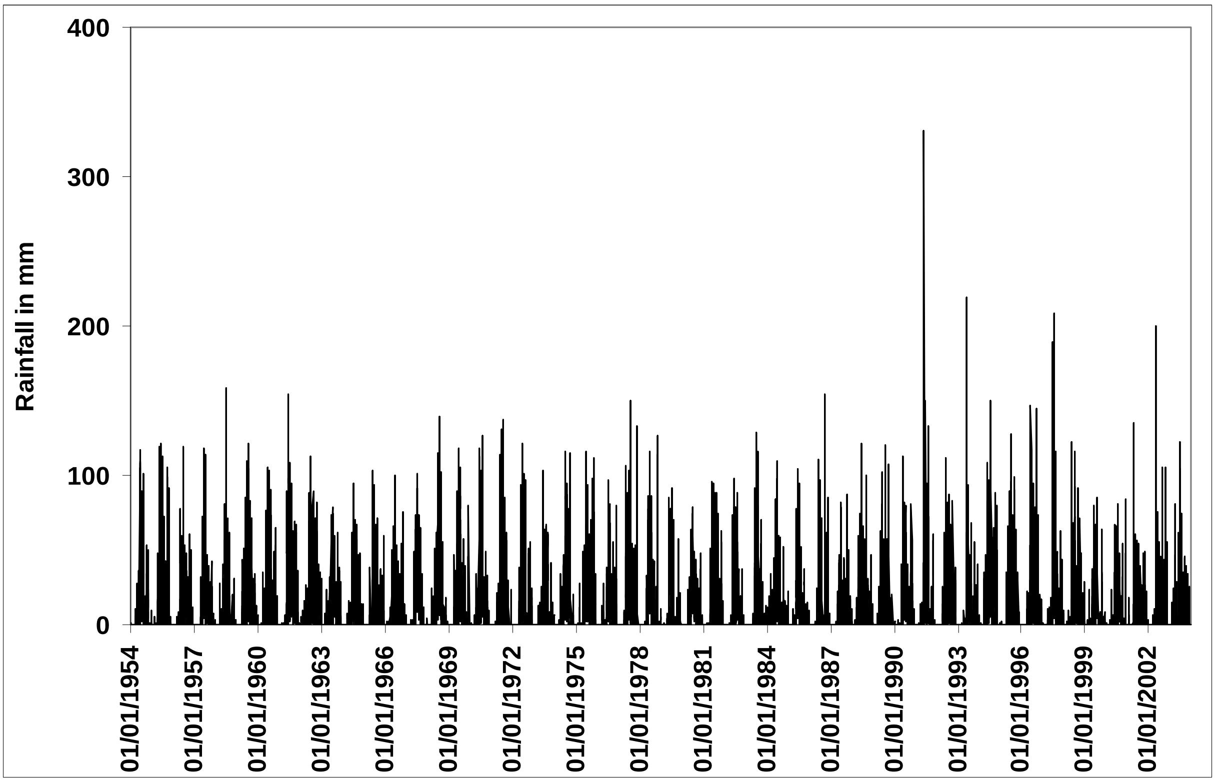


Figure 5.3: The 50-year daily time series of rainfall in grid 11.5N,75.5E (region 1) in Kerala.

Around 77% of rainfall contribution in this area (11.5N,75.5E) in Kerala came from the summer monsoons alone and most of the erosive rainstorms occurred in this season, erosion in other seasons were seen to be insignificant since the highest rain intensities and cumulative amounts were observed in the months of June/July and therefore the highest erosivities (around 70%) in a given year are also expected in these months, as shown in Figure 5.4. An analysis of 50-year annual rainfall erosivities showed that rainfall erosivity varies from year to year depending largely on rainfall intensity and amount, as shown in Figure 5.5. The trend analysis of 50-year erosivity values was performed later and is discussed in section 5.1.1.2. Soil loss increased with increase in erosivity, was maximum when erosivity was maximum, and, like erosivity, depends both on rainfall amount and intensity, as shown in Figure 5.6.

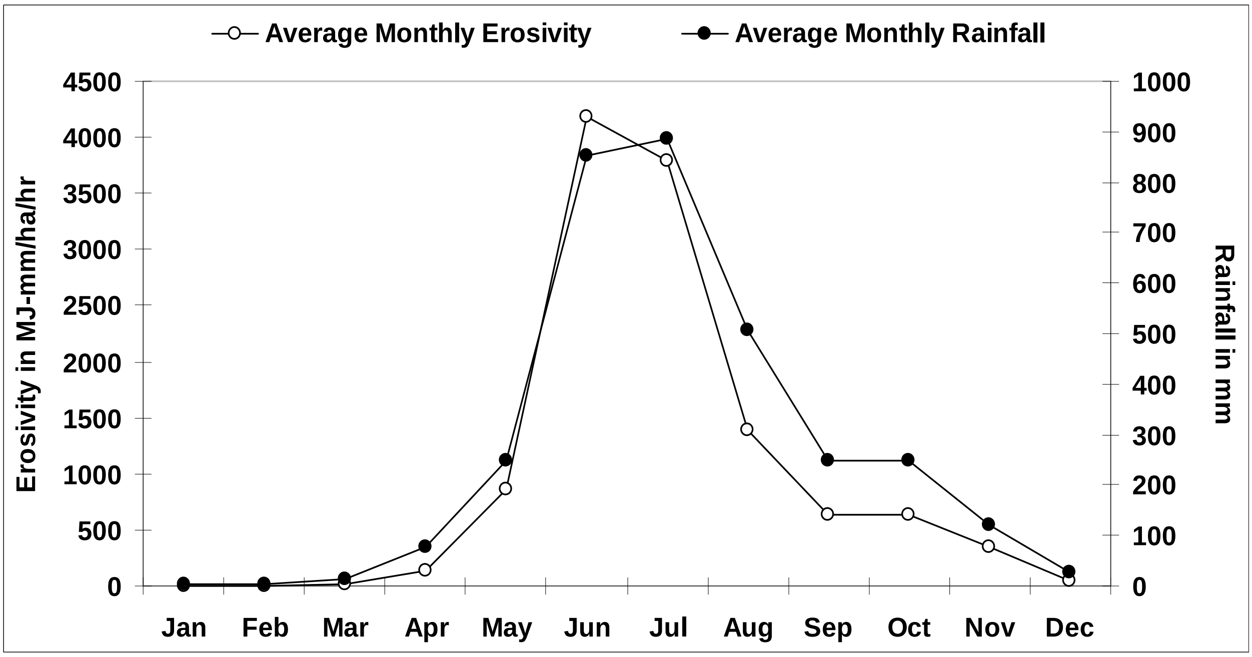


Figure 5.4: Mean monthly erosivity and rainfall values for 11.5N,75.5E in Kerala (Pal, 2007).

5.1.1.1.2. Soil Erodibility Factor

The major RUSLE2 soil variable is the soil erodibility factor, as discussed in Chapter 4 (section 4.2.2.3) and documented in more detail in related MPhil work (Pal, 2007). To study the effects of soil parameters on soil erosion, various types of soils available in different parts of Kerala were considered. It was discussed that among various properties of soil, silt content, organic matter content (OMC) and permeability are very important factors that would affect soil erosion. The effects of change in silt content, OMC and permeability on soil erodibility factor in RUSLE2 were looked at in MPhil (using expressions 4.8-4.12).

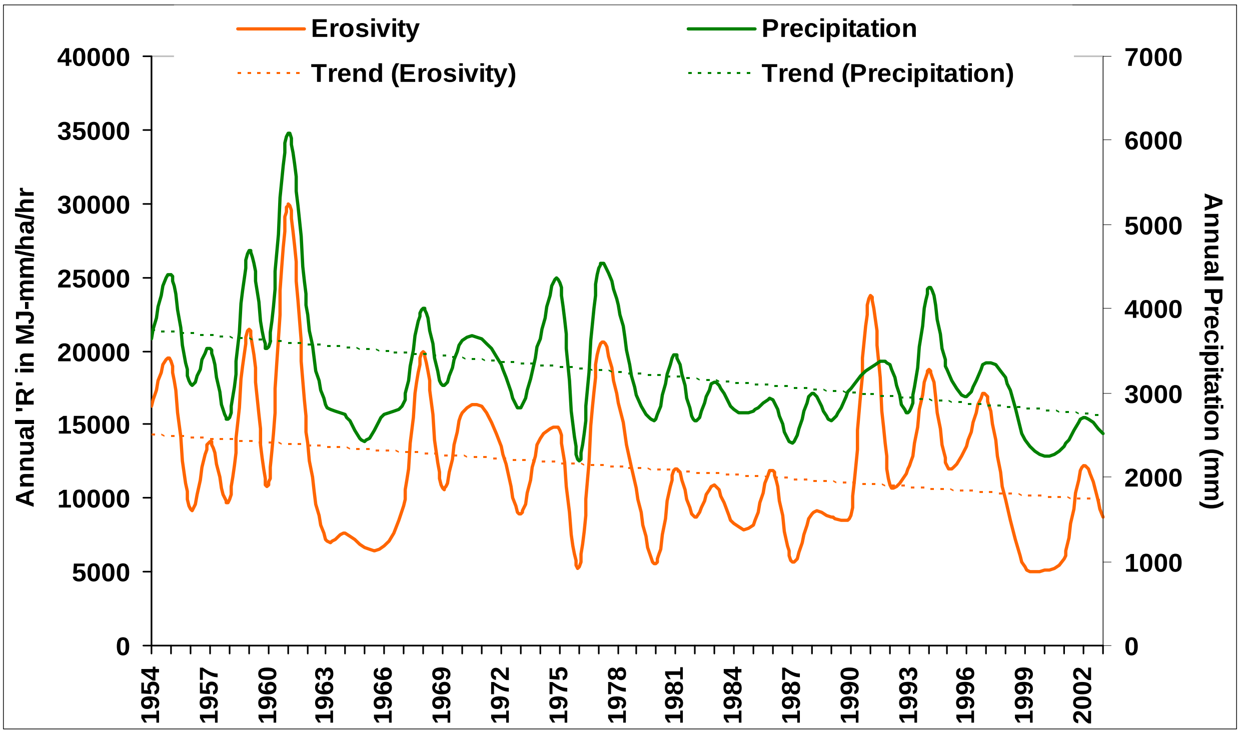


Figure 5.5: Inter-year variation of annual rainfall erosivity and rainfall and their 50-year trends in grid 11.5N,75.5E in Kerala (Pal, 2007).

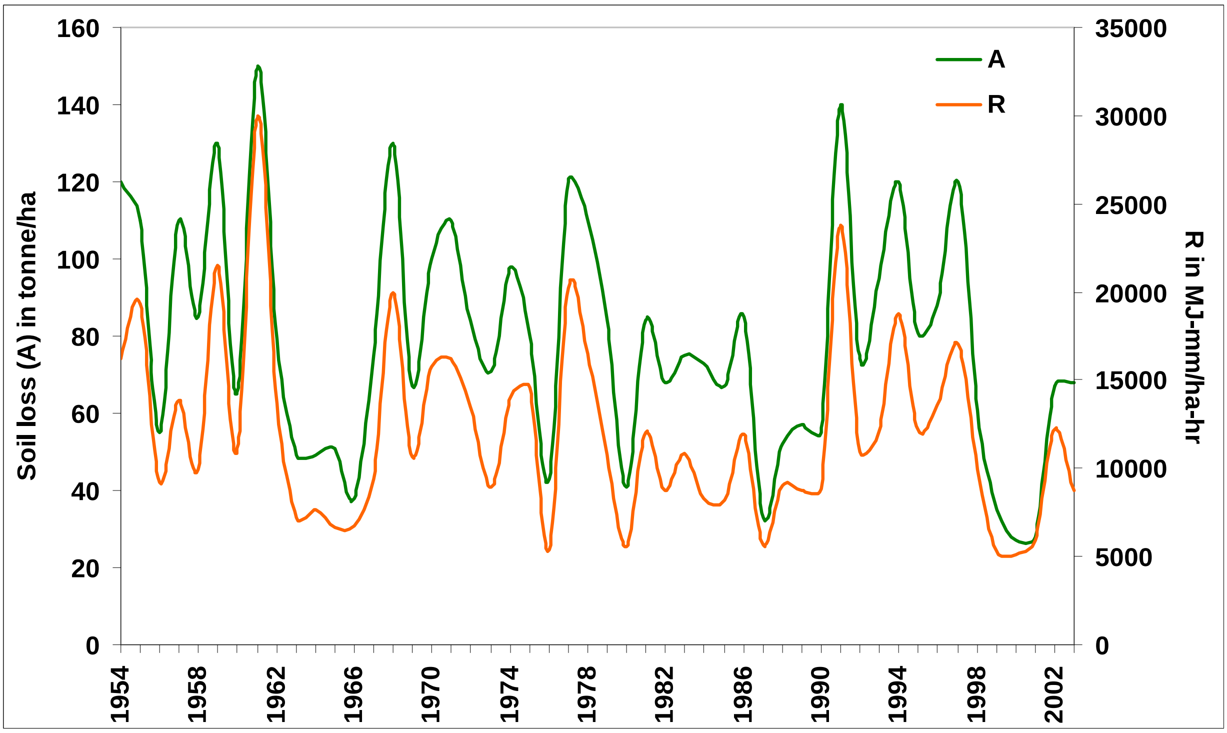


Figure 5.6: Inter-year variation of soil loss and rainfall erosivity in grid 11.5N,75.5E in Kerala (Pal, 2007).

The study showed that the same soil can behave differently in different climatological conditions resulting in different soil erodibility values and in turn soil loss computations. The variation of the average annual soil loss estimates with average annual soil erodibility values as computed by RUSLE2 for different soils in Kerala are linear, as shown in Figure 5.7, which is also true from expression 4.1 if the other five factors are kept constant.

Soil texture, SOM/OMC and permeability together affect soil erosion potential. High silt content, low organic matter and low permeability tend to cause more erosion, as shown in Figure 5.8(a), (b) and (c). However, it is also possible that at the same silt content the erodibility and thus the soil erosion remains the same (Figure 5.8(a)) due to the influence of clay content/OMC(SOM)/permeability combinations present in the soil. Therefore, the combination of soil parameters is also an important deciding factor on how much they will be affecting the soil erosion.

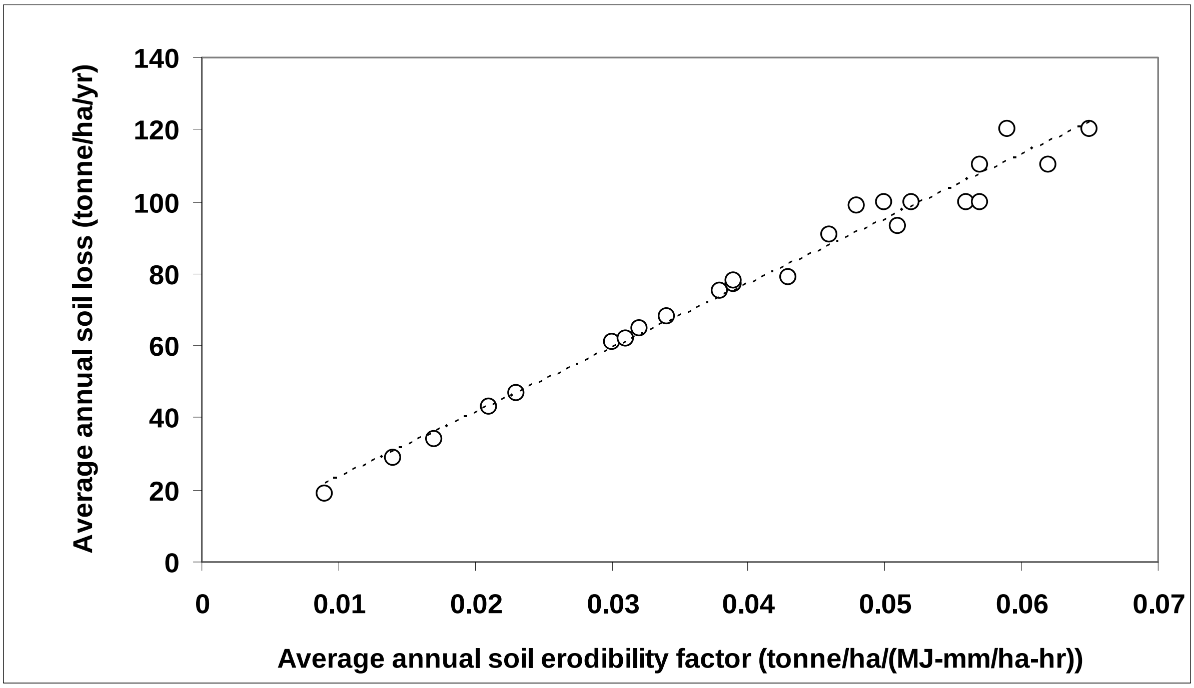
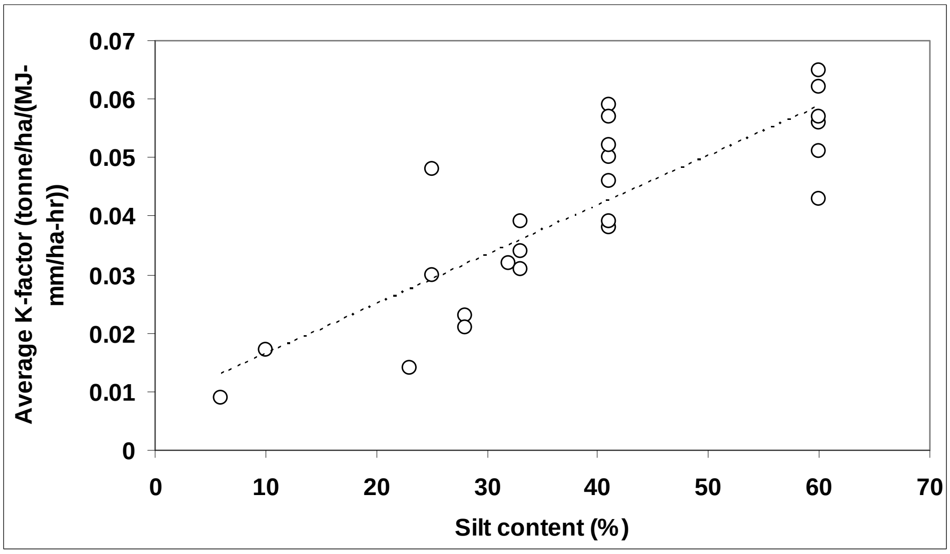
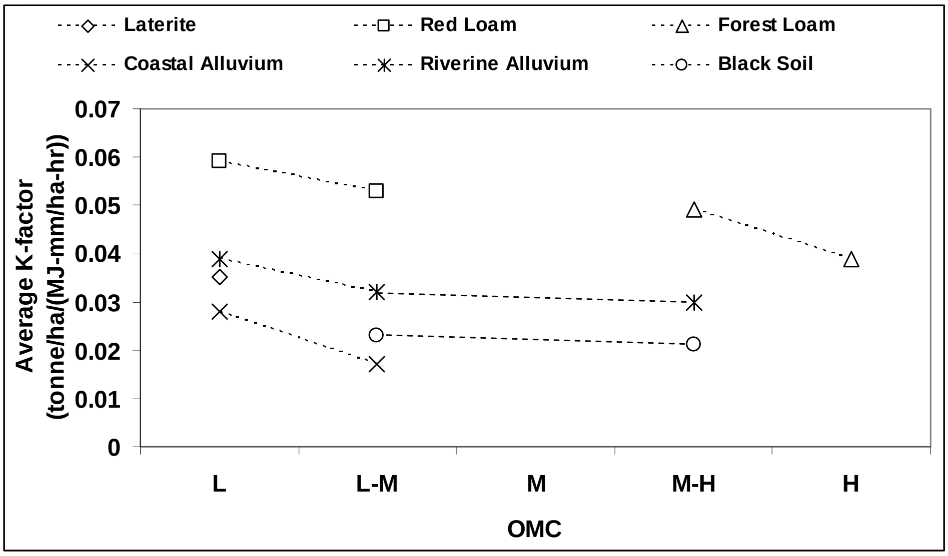


Figure 5.7: Variation of average annual soil loss (A_a) with the average annual soil erodibility (K_n) based on rainfall data for grid 11.5N,75.5E in Kerala (data extracted from Table 3.2 in Pal (2007)).



(a)



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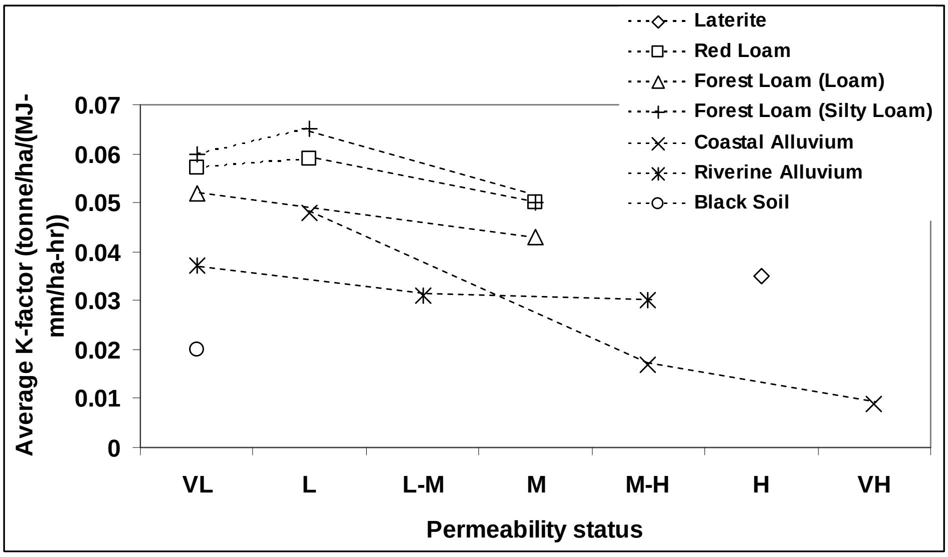


(c)

Figure 5.8: Variation of K-factor values with changes in (a) silt content (b) OMC and (c) permeability status based on data for grid 11.5N,75.5E, Kerala (VL = very low, L = low, L-M = low-moderate, M = moderate, M-H = moderate-high, H = high, VH = very high) (data extracted from Table 3.2 in Pal (2007)).

5.1.1.1.3. Topographical Factors

Soil erosion increases with increase in slope length and steepness; the loss increases gradually with slope length – for a 50-times increase in slope length, soil erosion is 2 times higher, as shown in Figure 5.9. Slope steepness has more effect than slope length on soil loss that increases linearly with increase in slope steepness. The loss is gradual for mild slopes (< 9%) and increases more rapidly further, as shown in Figure 5.10.

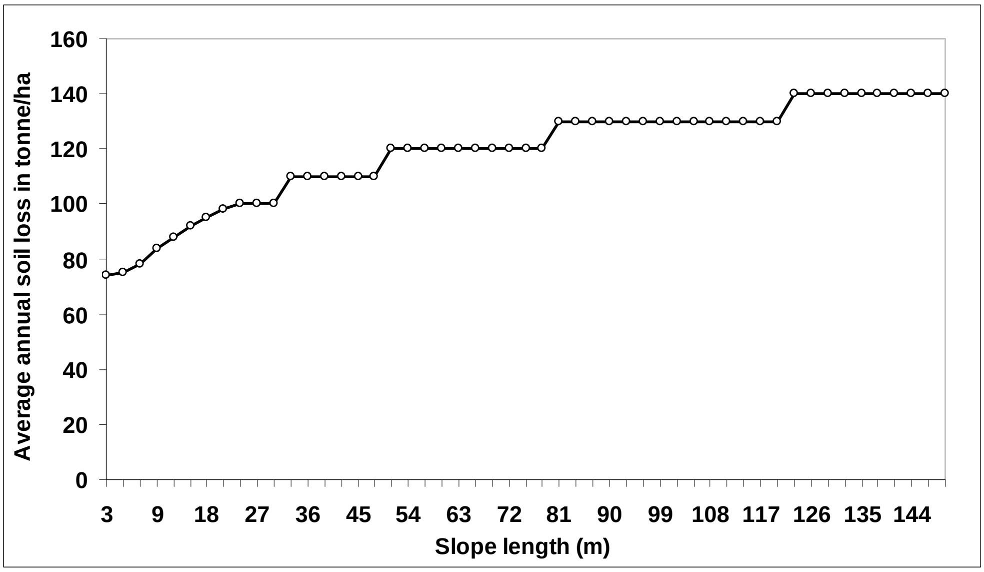


Figure 5.9: Effect of slope length on average annual soil loss for grid 11.5N,75.5E in Kerala (Pal, 2007).

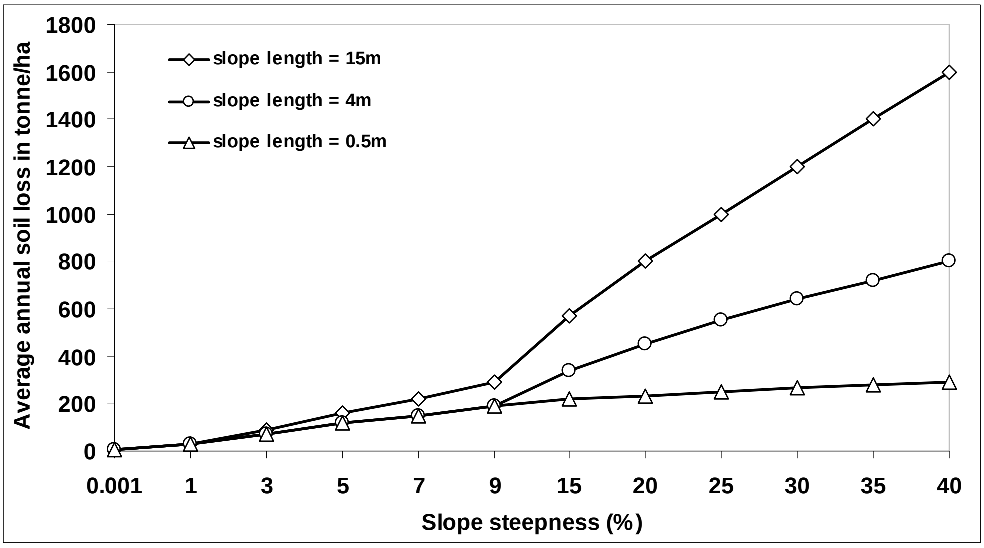


Figure 5.10: Effect of slope steepness on average annual soil loss for grid 11.5N,75.5E in Kerala (Pal, 2007).

5.1.1.1.4. Cover Management Factor

Bare soil was found to be the most vulnerable to soil erosion. However, it is worst if the same soil is mechanically disturbed, as in Figure 5.11. It was also found that there was a substantial reduction in soil loss due to vegetation establishment because of the effect of vegetation retarding erosion, i.e. reduction in 'c_c' and 'g_c' values in equation 4.17 in section 4.2.2.5, as noted in Figure 5.12. A 92% reduction of soil loss was observed due to the imposition of additional external residue (condition 4 compared to condition 3 in Figure 5.12). The data shown in Chapter 4, Figure 4.2 also indicated that with increase in land cover, significant soil erosion was decreased for both watersheds studied by Nunes et al. (2009). Therefore, maintaining ground vegetative cover especially when rainfall erosivity is the highest in a given year is important in order to reduce the impact of rain drops and overland flow.

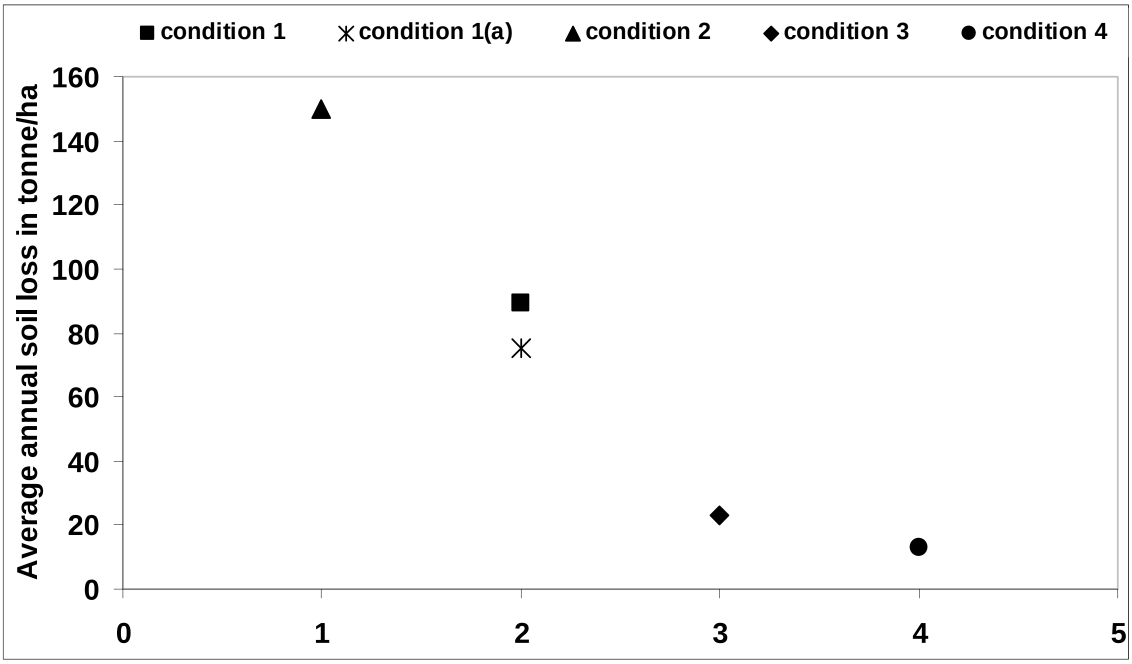


Figure 5.11: Effect of land operations on average annual soil loss in grid 11.5N,75.5E in Kerala where condition 1 and 1(a) = undisturbed bare soil conditions with long term natural land roughness 6mm and 15mm respectively; condition 2 = disturbance operation that always loosens the soil and makes it more erodible; condition 3 = vegetation growing with no external residue is added; condition 4 = external residue added with condition 3 (Pal, 2007).

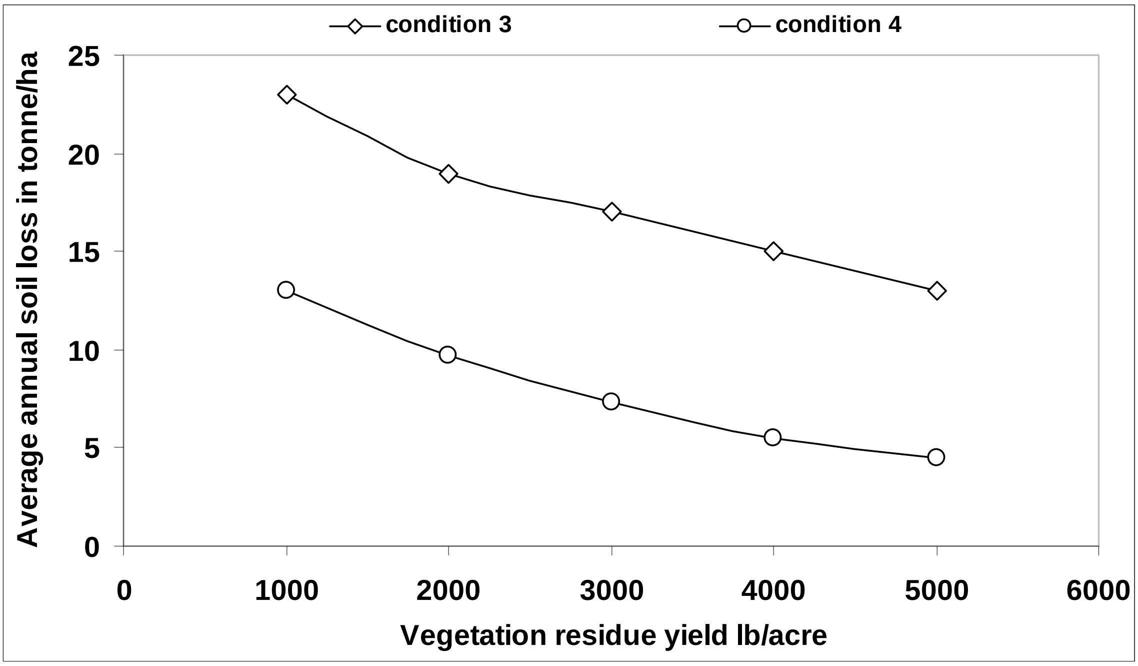


Figure 5.12: Effect of vegetation residue yield on average annual soil loss in grid 11.5N,75.5E in Kerala, India where condition 3 = vegetation growing but no external residue is added; and condition 4 = additional external residue is added with condition 3 (Pal, 2007).

As a result of having conducted the research detailed in Chapters 2 and 3 after the conclusion of the MPhil work mentioned above (Pal, 2007), the analysis performed in the MPhil study was hence extended to include a second gridded region in Kerala state (region 2, 11.5N,76.5E in Figure 5.2). The reason why this area was selected will be discussed in section 5.1.1.2.

5.1.1.2. Comparison between Regions 1 and 2

5.1.1.2.1. Introduction

Regions 1 and 2 are the north most areas in Kerala and the most important gridded regions in terms of rainfall characteristics affecting soil erosion. While region 1 experiences the highest average rainfall in monsoon season, as seen in Chapter 3 (Figure 3.24), region 2 experiences the highest daily rainfall extremes and region 1 has the second highest daily rainfall extremes, as illustrated previously in Chapter 3 (Figure

3.20). Both of these rainfall characteristics are important for soil erosion point of view, as found in the conclusions above from the MPhil study.

Although the 50-year trends corresponding to extreme rainfalls in region 2 (11.5N,76.5E) of Kerala showed decreasing trends (Chapter 3, Figures 3.27 and 3.28), the 1990's decade had the largest spikes in extreme rainfall amounts in this region among all the 6 regions (also in Figures 3.31 and 3.32), and that this area (and region 1) experienced increasing trends in 'extreme' rainfalls corresponding to a fixed threshold i.e. > 150mm/day, as in Figure 3.32. If the same trend continues, increase in 'extreme' rainfalls (> 150mm/day) in future will increase the soil erosion problems in regions 1 and 2 in Kerala (refer section 4.3), if all other factors (expression 4.1 in Chapter 4) be unchanged. Therefore these two gridded regions in Kerala could be considered as the worst affected places in terms of rainfall induced soil erosion.

Furthermore, an analysis of other seasonal rainfalls in all the 6 grids in Kerala in Chapter 3 (section 3.9) indicated that there is an increase in total rainfalls and extreme events in winter and autumn seasons in regions 1 and 2 as well. Although soil erosion in the seasons other than monsoon were seen insignificant, as mentioned in the conclusions in section 5.1.1.1.1, increasing trends of winter and autumn extreme rainfalls are important for if the same trends continue in future, would increase soil erosion in these seasons as well. Therefore, 50-year annual rainfall-runoff erosivities were determined and illustrated here for region 2 and compared with region 1, which will indicate how the rainfall changes would affect soil erosion in region 2 since rainfall erosivity is directly proportional to soil erosion estimates (refer to expression 4.1 in Chapter 4).

5.1.1.2.2. Rainfall Runoff Erosivity Factor

The rainfall-runoff erosivity factor is the prime rainfall factor in RUSLE2 and defined as the potential of the rainfall to cause soil erosion (section 4.2.2.2). The quantitative estimation of rainfall-runoff erosivity factor, which mainly changes with the rainfall changes, was determined here using daily gridded rainfall data for 11.5N,76.5E in

Kerala. The 50-year (1954-2003) daily rainfall data for this region was presented earlier in Figure 3.20 and is again shown here in Figure 5.13. A marked feature of the climate in this region is the high temporal variability of rainfall. Significant variations in maximum daily peak rainfalls per year are noticeable in the figure, in particular in 1975-1979 and again in the 1990's.

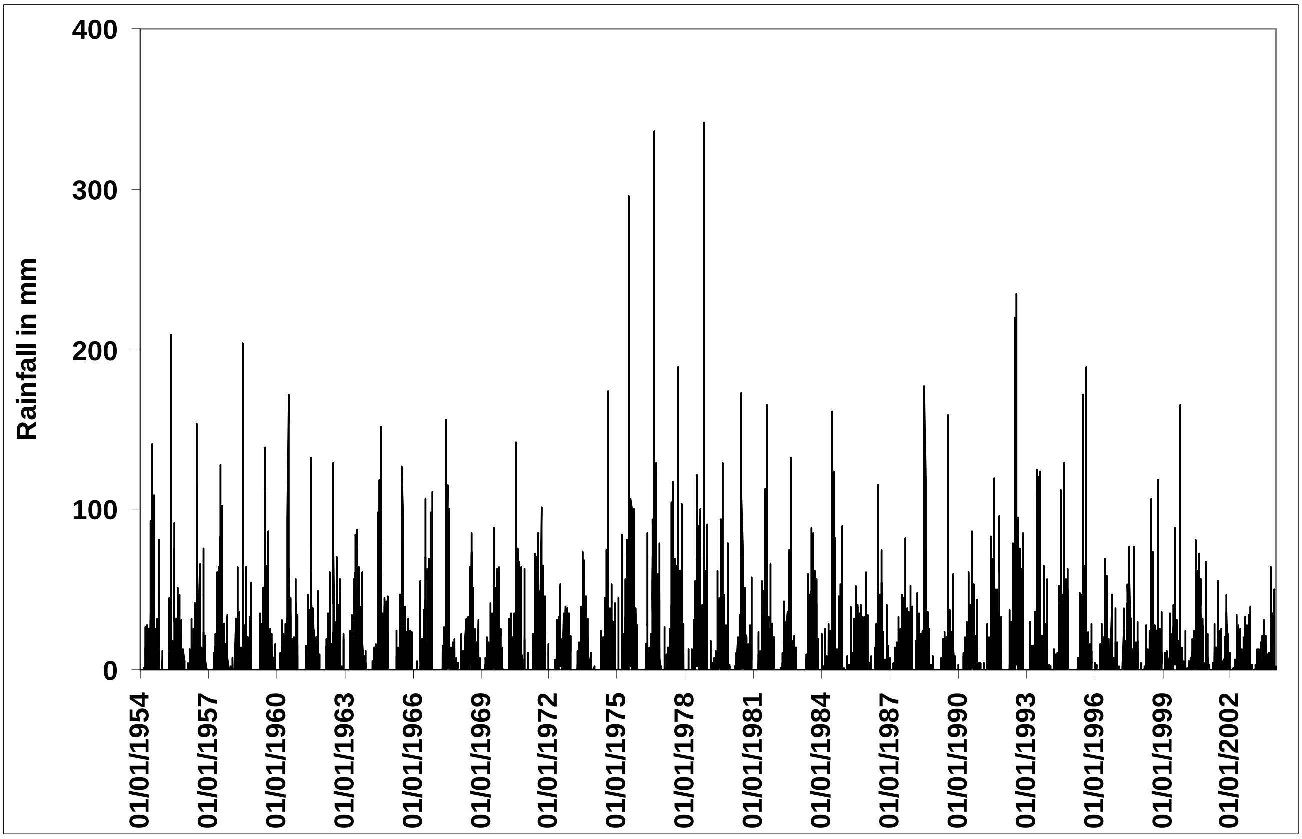
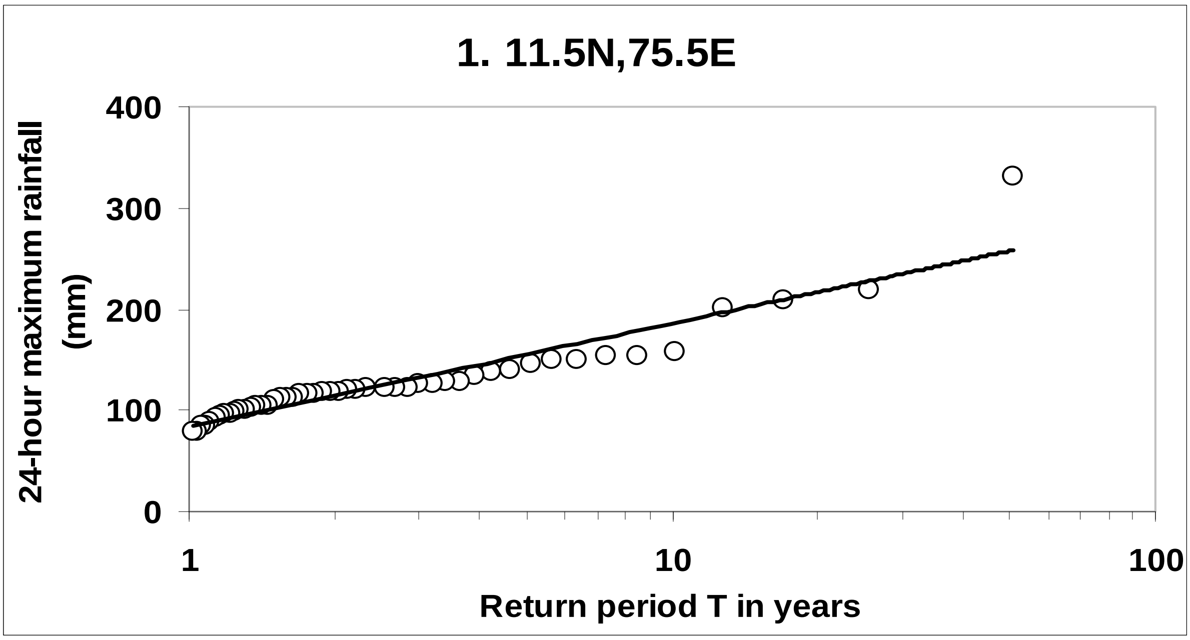


Figure 5.13: The 50-year daily time series of rainfall in grid 11.5N,76.5E (region 2) in Kerala.

Figure 5.14 shows the frequency distributions of the 24-hour maximum rainfalls, which occurred in each of the 50 years in the study sites of Kerala. Wherein, Figure 5.15 shows a clear picture of the list of 24-hour maximum rainfalls in the descending order of magnitudes. As Figure 5.14 indicates, the 24-hour maximum rainfalls with an average magnitude of 100-200mm are seen to have had a return period between 1 and 10 years in region 2. Since the only daily rainfall events with more than 300mm magnitudes and a return period of 50-51 years occurred back in 1976 and 1975, as in Figures 5.13 and 5.15, unlike region 1 it can not be concluded for region 2 that there is significant possibility of such highly intense rainfall (>300mm) to occur in the coming decades as well. However, generally higher rainfall intensities in region 2 than all the other grids in Kerala (Figure 3.20) makes gridded region 2 the most vulnerable to soil erosion.



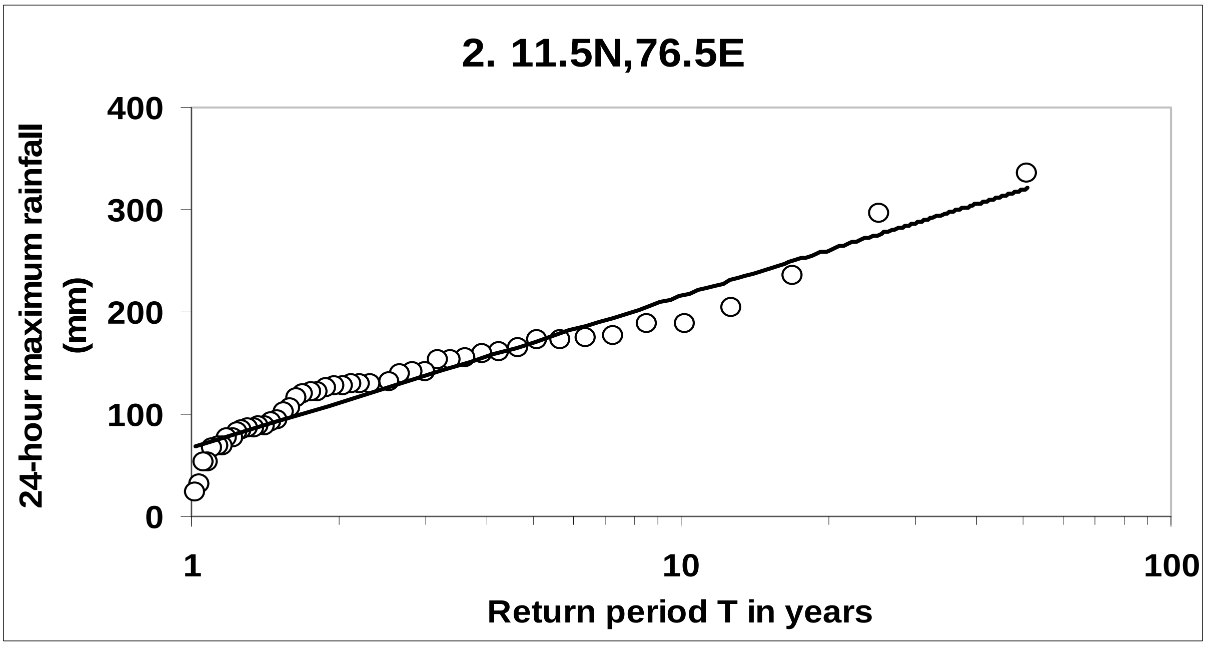


Figure 5.14: The 50-year 24-hour maximum rainfall frequency distributions in gridded study regions in Kerala.

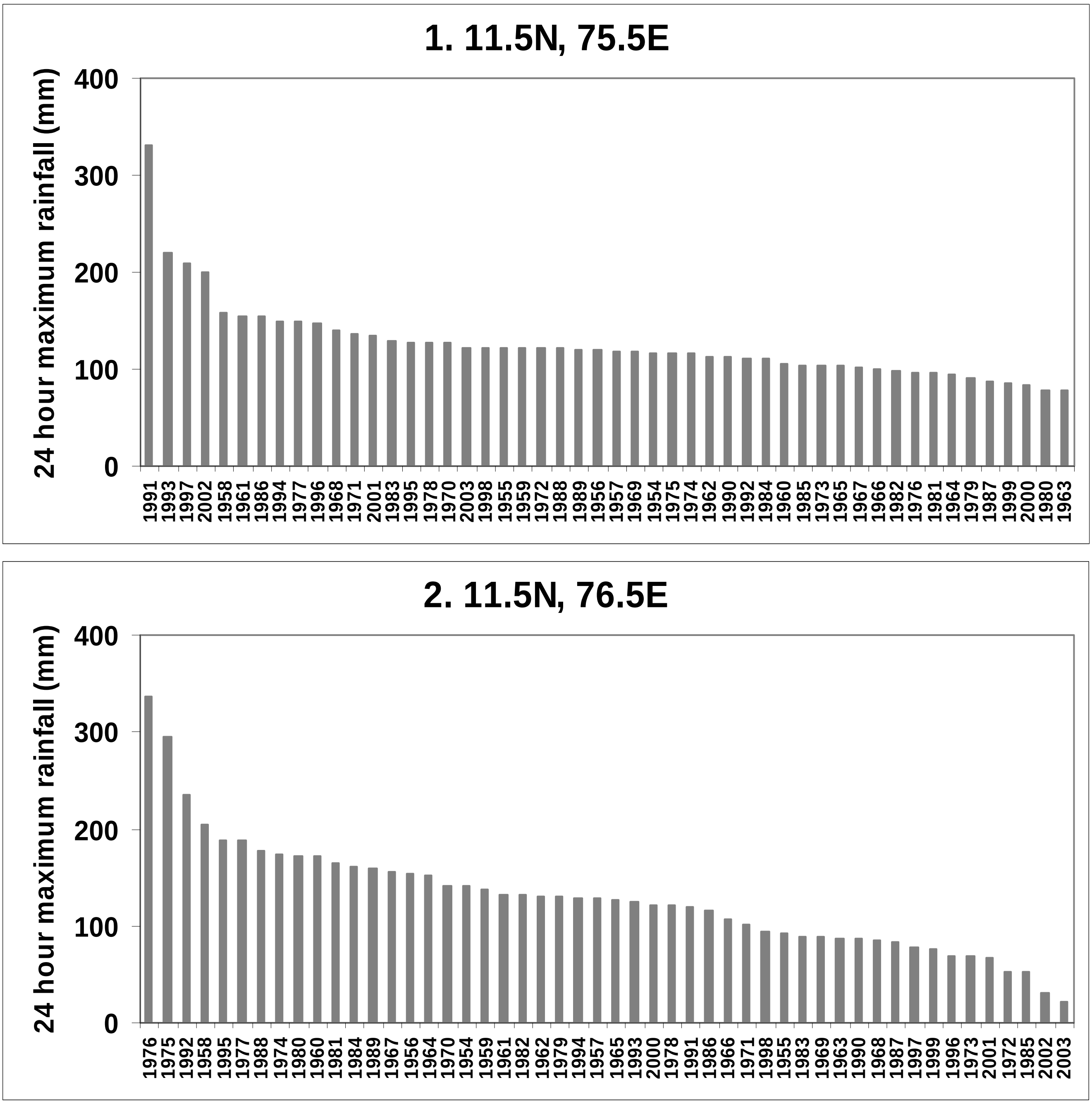


Figure 5.15: The 50-year 24-hour maximum rainfalls in descending order of magnitudes in the gridded study regions of Kerala.

Figure 5.16 shows the 50-year variation of annual and monsoon rainfalls in gridded region 2 (grid 11.5N,76.5E) in Kerala. Those values show that an average of 2120mm of rainfall has precipitated every year in this region, and out of that around 75% comes from the summer monsoon. The 50-year annual rainfall-runoff erosivity factors as determined using daily rainfall data in Figure 5.13 are shown in Figure 5.17. The computation of rainfall-runoff erosivity factor using unit energy-rainfall intensity models (e-I) was presented and described in brief in the previous chapter (section 4.2.2.2) and in detail as part of the MPhil work (Pal, 2007).

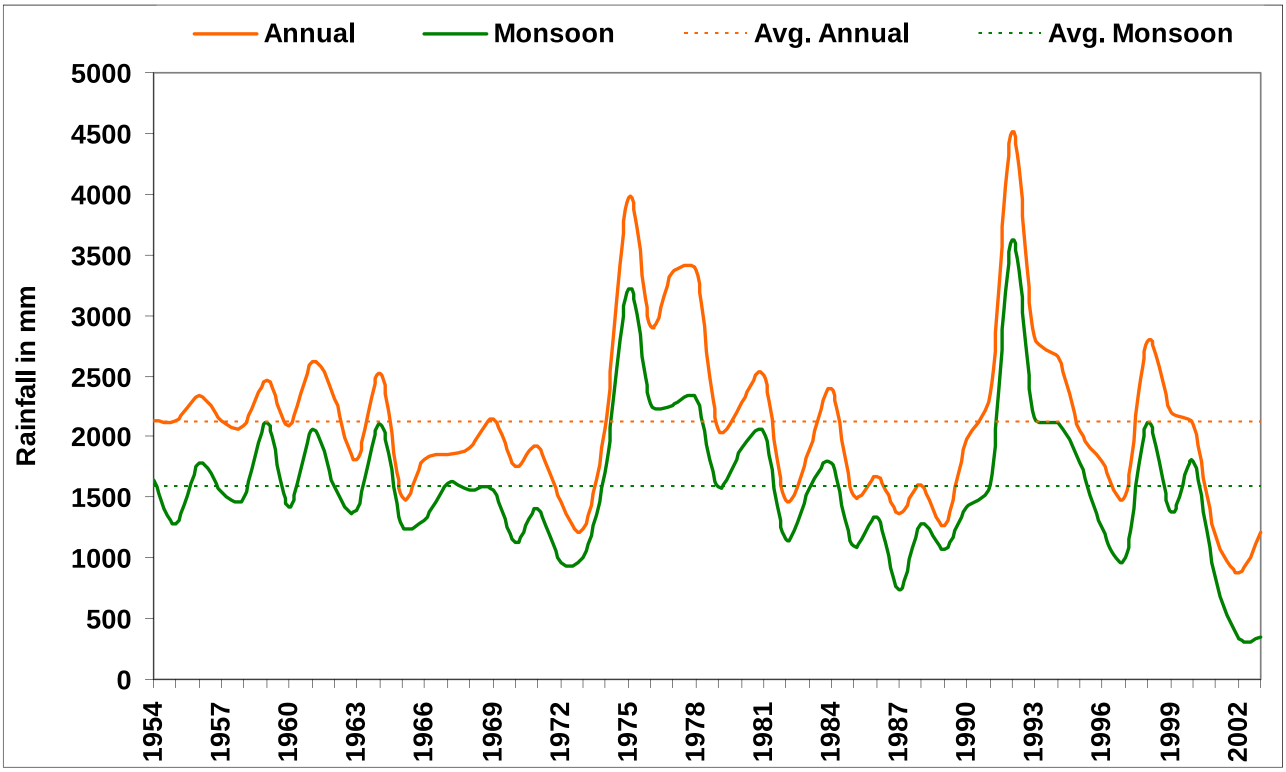


Figure 5.16: The 50-year time series showing the monsoon and annual rainfalls in gridded region 2 in Kerala.

The annual rainfall/precipitation data for the gridded region 2 in Kerala was also plotted on the same graph as the annual erosivities, calculated for all the 50 years, in Figure 5.17. The two sets of data suggest that the lower the annual rainfall, the lower the corresponding erosivity, as also concluded previously in section 5.1.1.1.1 for region 1 and shown in Figures 5.4 and 5.5. The data in Figure 5.17 indicate that maximum erosivity occurred in 1992 in region 2, the year when maximum rainfall occurred. Even though 1976 had the highest rainfall intensity, it had lower rainfall erosivity than 1992 and 1975 because 1976 had much lesser annual rainfall than those occurred in 1992 and 1975. In 1978, the erosivity was higher than 1976 again because of the same reason. However, this was not true for some of the years for the gridded region 1 in Figure 5.5

and also in Figure 5.17 for 1955-56, 1967-68, 1978-79, and 1994-95 for region 2. The best example for gridded region 1 is the year 1991 in which the rainfall erosivity increased dramatically from the previous year (2.7 times) in Figure 5.5, wherein the increase in the amount of total rainfall from the previous year was only 8%. This was because the rainfall erosivity is a function of both the quantity of rainfall and its intensity. Since the year 1991 experienced highly intense rainfall, the erosivity was very high. Same explanation is also applicable for Figure 5.17 for the years 1955-56, 1967-68, 1978-79 and 1994-95.

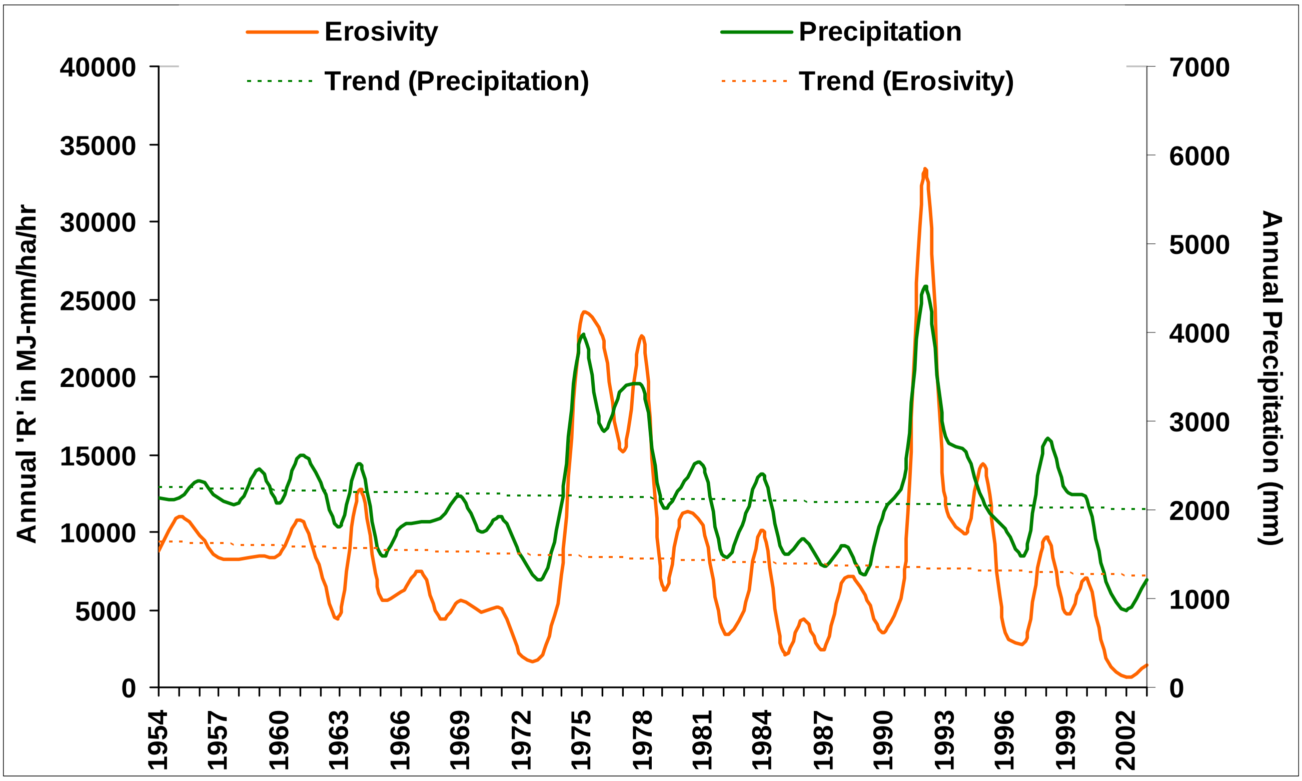


Figure 5.17: Inter-year variation of annual rainfall erosivity and rainfall and their 50-year trends in gridded region 2 in Kerala.

5.1.1.3. Trend of Soil Erosion in Region 1

As seen in Figures 5.5 and 5.17 previously, 50-year annual rainfall totals and erosivities in gridded regions 1 and 2 in Kerala are showing decreasing trends, which are also expected to affect the soil erosion in the same way since rainfall erosivity is proportional to soil erosion (if all other factors are kept constant) (Chapter 4, expression 4.1). Therefore, 50-year trend of soil erosion is only shown and discussed for the region 1, which is illustrated in Figure 5.18.

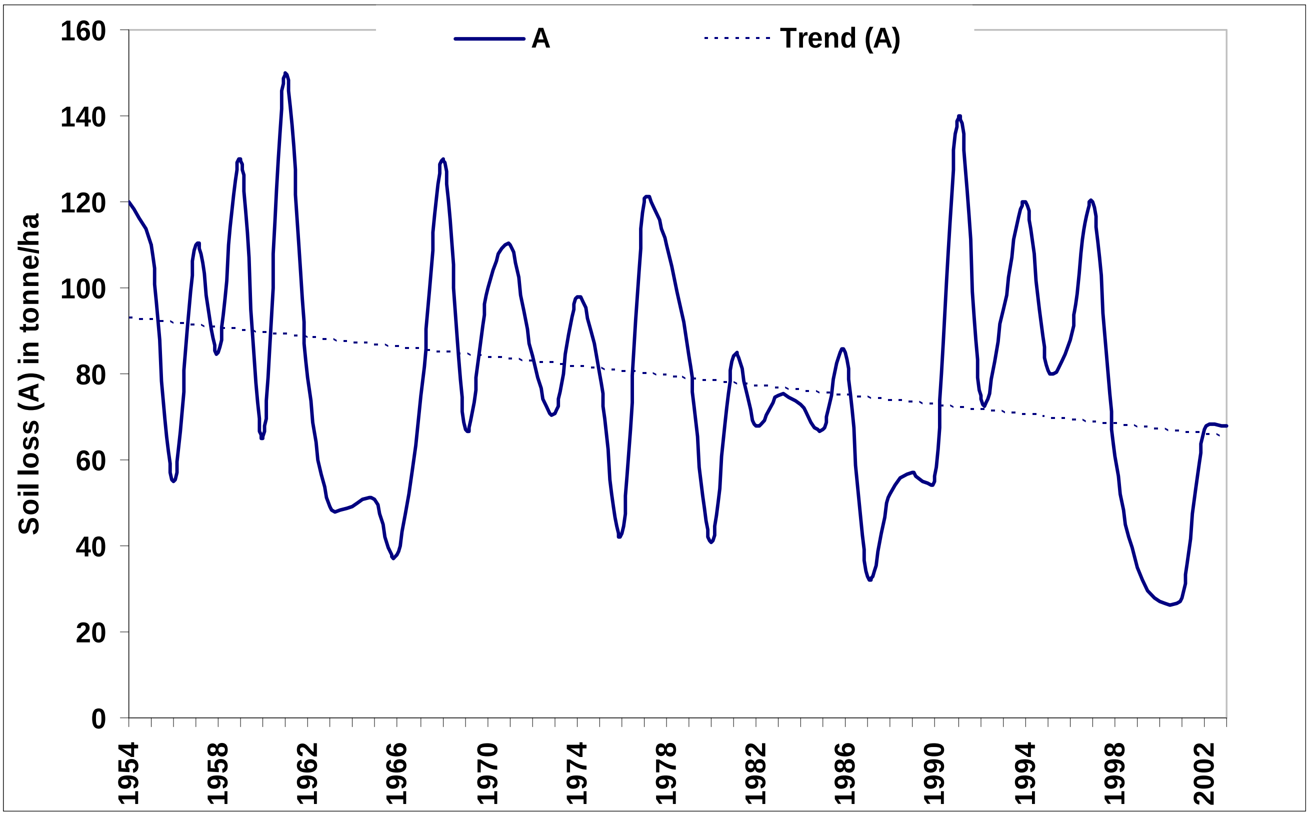


Figure 5.18: Inter-year variation of annual soil erosion and its 50-year trend in region 1 in Kerala.

Figure 5.18 shows that average 50-year soil loss in gridded region 1 in Kerala is 79 tonne/ha, which is almost double the range (35-40 tonne/ha) given in the iso-erosion map of India in Figure 5.1. The soil loss estimates in Figure 5.18 showed high over estimation because this study considered the worst site specific conditions only as relating to soil factor, slope factors, cover management and support practice factors in RUSLE2 (sections 4.2.2.3-4.2.2.6). Also that iso-erosion map of India (Figure 5.1) was built using USLE (predecessor of RUSLE2) and using a different set of rainfall data.

Figure 5.18 also shows a decreasing trend of soil loss in gridded region 1 in Kerala. But, it could be possible that soil erosion increases even when the rainfall is decreased, as discussed previously in Chapter 4, section 4.1 (Pruski and Nearing, 2002). Since the other five factors were kept constant while computing soil erosion in Figure 5.18 to look at the effect of rainfall variation only, it is difficult to say whether soil erosion is indeed decreasing in this region since there are other climate actors (both soil water content and temperature) in play to change soil organic matter and soil cover, which are some of the main players to change soil erosion problems as well, as in section 4.6.2, Figure 4.12 (Blanco and Lal, 2008). Since temperature has been increasing in all over peninsular India (including Kerala) (Chapter 3, Table 3.22), it could also be possible that the top soil organic matter has been decreasing due to increase in temperature and decrease in soil water content due to decreasing rainfall, as in Figures 5.5 and 5.17 (refer to Chapter 4, Figure 4.13; Sheffield and Wood, 2008), which increase soil erosion problem in turn (Figures 4.2-4.4 and 4.10). However, this effect was difficult to capture using RUSLE2 in Figure 5.18.

5.1.2. Study Sites

5.1.2.1. Introduction

An important aspect of this research was to look at contaminant transport associated with soil erosion. However, no appropriate site with contaminant data was found for Kerala state. Therefore, two areas namely Bhoj wetland in West Central India (WCIN) and Sukinda valley in Central North East India (CNEIN) (refer Figure 2.4) were chosen for this purpose. Required site specific data for Bhoj and Sukinda sites were found from the Indian Institute of Soil Science (IISS) and published literature, which will be cited later in relevant sections.

Bhoj wetland is an agriculturally polluted site in Madhya Pradesh state in WCIN and Sukinda valley is an open cast chromite mining site in Orissa state in CNEIN. Rainfall patterns and their projections were studied both for WCIN and CNEIN regions in Chapter 3 (section 3.11) and the relevant information will again be referred back in later sections whenever necessary. In addition to studying the impact of climate change on soil erosion (like Kerala), Bhoj and Sukinda site specific data were also used to assess the effects of soil erosion patterns on contaminant transport (section 5.2), the qualitative risk of contaminant transport (section 5.3), and climate change impact on soil carbon (sections 5.4).

The iso-erosion map that is shown in Figure 5.1 and the information from the literature indicates that the erosion potential for the North-Eastern states of India (NEIN in Figure 2.4) and the Orissa state (region 7 in CNEIN in Figure 2.4) is the highest and exceeds 40 tonne/ha/yr (Bhattacharyya et al., 2007; Singh et al., 1992). West-Central India (WCIN) is also vulnerable to soil erosion (~ 20 tonne/ha/yr) for it faces high intensity rainfall and its rainfall pattern represents the average all-India (ALLIN) rainfall pattern (see Figure 3.2). Therefore WCIN and CNEIN are also important regions in terms of both the rainfall changes (discussed earlier in sections 3.1, 3.2, 3.3, 3.6.4) and soil erosion. Bhoj and Sukinda sites are marked in Figure 5.1 in red and blue circles respectively. Although rainfall trends and their 50-year projections were explored for CNEIN and WCIN in Chapter 3 (sections 3.1, 3.2, 3.3, 3.6.4, 3.11), short scaled (gridded) rainfall trend assessments hadn't been done for these two case sites, which were again done and presented in this chapter later in sections 5.1.2.2.2 and 5.1.2.3.2. A more detailed discussion on these two case study sites and the results involving impact of past and projected climatic changes on soil erosion and contaminant transport are found later in the sub-sections below.

5.1.2.2. Bhoj Wetland

5.1.2.2.1. Description of the Study Site

In the last half of the century, lakes were the first victims in nature which underwent large scale pollution problems because of various activities and especially agricultural activities which caused environmental degradation. Bhopal lakes in India are not an exception: the upper and lower lakes and their catchments in Bhopal are together known as Bhoj wetland. Figure 5.19 shows the Bhoj wetland basin with the location of the lakes where the lower lake is situated towards the east end of the upper lake and is almost fully surrounded by human settlements from all sides.

The essential details of both the lakes are summarised in Table 5.1 (Kodarkar, 2005; Verma et al., 2001). As Table 5.1 mentions, both the lakes are man made, open drainage freshwater lake. Upper lake is 24 times bigger than the lower lake. The catchment area of the upper lake is 361 km^2 while that for the lower lake is 9.6 km^2. Since the water in the upper lake is mainly used for potable water supply (as in Table 5.1), pollution of this lake due to sediment and nutrients carried away from the agriculturally polluted areas in Bhoj catchment makes it vulnerable for the 0.5 million people in the region.

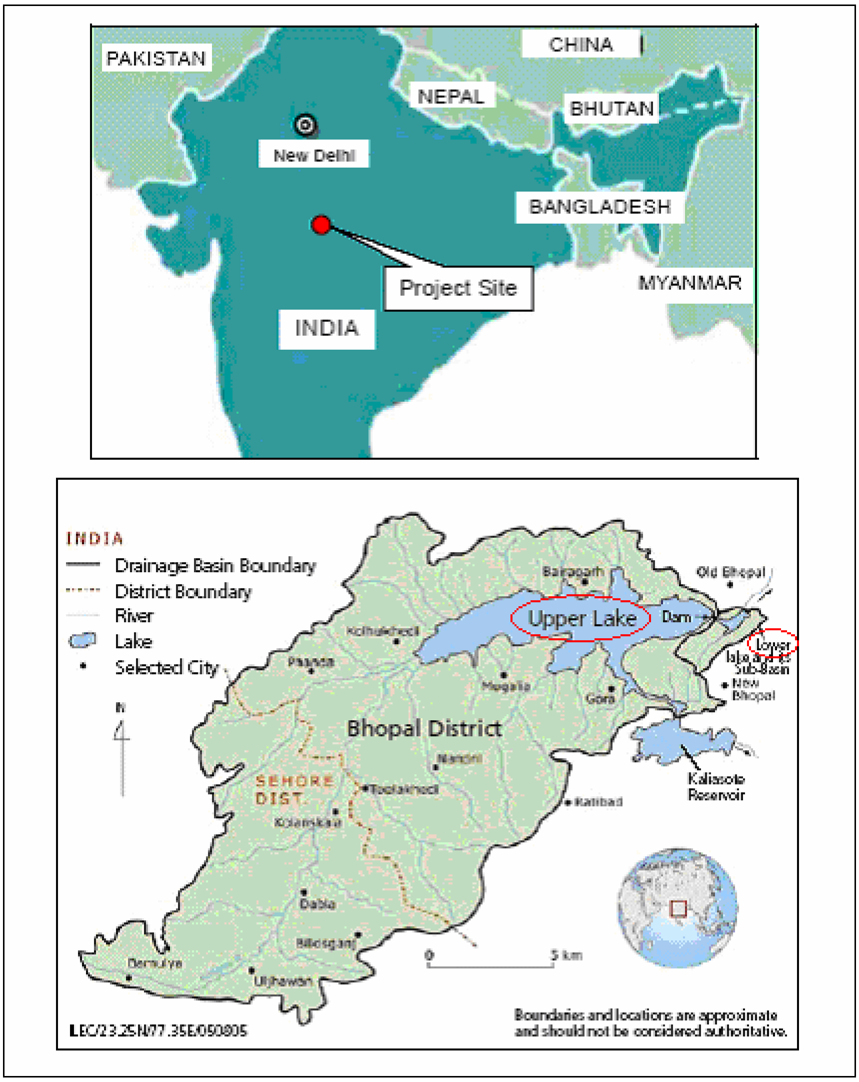


Figure 5.19: Project site – Bhoj wetland basin, upper and lower lakes of Bhopal (circled in red) in Madhya Pradesh, India.

The negative manifestations exhibited in Bhopal lakes were loss of water-spread area because of siltation, continuous algal blooms because of nutrient enrichment and eutrophication, and water quality degradation. Agricultural practices are undertaken in most (around 70%) of the lake catchment areas. During the rainy season, eroded sediments and associating nutrient-rich organic materials from the surrounding agricultural areas of the catchment become transported by monsoon runoff, which is one of the causes of the sedimentation at the shallow side of the lakes and also eutrophication. Therefore, management of lakes and reservoirs directly link to their catchments.

Table 5.1: Basic features of upper and lower lakes of Bhoj wetland (Kodarkar, 2005; Verma et al., 2001).

	Upper Lake	***Lower Lake***
Country	India	
Lake origin	Man-made (11th Century)	Man-made (Late 18th Century)
Type of Dam	Earthen	
Latitude	23°12´ – 23°16´N	23°14´ – 23°16´N
Longitude	77°18´ – 77°23´E	77°24´ – 77°25´E
Climatic region	Warmer humid (humid sub-tropical)	
Drainage basin type	Open	
Salinity type	Fresh	
Altitude	503.5 m	500 m
Surface area	31 km^2	1.29 km^2
Catchment area	**361 km^2 Catchment/surface area ratio: 11:1**	**9.6 km^2**
Volume	0.117 km^3	0.004 km^3
Maximum depth	11.7 m	9.5 m
Average depth	6 m	No information
Source of water	Rain water and sewage	Rain water, seepage from upper lake and domestic sewage
Main use of water	Potable water supply	Washing and boating
Population	0.5 million	
Population density	1350 persons/km^2	

Exposure of catchment, devoid of any vegetation due to housing and excessive construction activities on the higher slopes, particularly in the urban areas on the northern bank, has increased the rate of soil erosion in these areas. As a result the shoreline has shrunk and large land masses of silt deposits are formed within the lake thus reducing the storage capacity and water spread area of the lake. Natural phenomena such as soil erosion and siltation are changing the lake environment, which, together with anthropogenic disturbances, has posed a serious threat to the quality of water (Wanganeo, 2000).

Although few researchers have addressed the siltation and eutrophication problems in those lakes (Kodarkar, 2005; Verma et al., 2001; Wanganeo, 2000), no one has looked at the source of where the problem is generated. Personal communication with Dr. Kodarkar, a leading scientist at the Indian Association of Aquatic Biologists (IAAB), Hyderabad, revealed that ‘lake management depends on understanding the catchment first; however, unfortunately our understanding of catchment and its characteristics is very poor’. Therefore, this study tries to reveal the impact of rainfall to cause soil erosion and nutrient transport in Bhoj catchment. While section 5.1.2.2.3 will look at soil erosion, nutrient transport will be discussed later in section 5.2.2.

5.1.2.2.2. Changes in Rainfall Extremes

As mentioned in section 5.1.1.1.1 and 5.1.1.2.2, rainfall characteristics including rainfall amount and intensity are very important determinants of soil erosion. Since short scaled rainfall changes could be different from the changes in larger scaled regions, as noticed for gridded regions in Kerala in section 3.9.2 (Figures 3.44 and 3.45), an additional study was carried out here to look at whether changes in rainfall characteristics in Bhoj site are different than that noticed for WCIN in Chapter 3 (section 3.6.4).

High resolution daily gridded rainfall data, as described in Chapter 2 (section 2.2.1) was used for the analysis of the average and extreme rainfalls in Bhoj. The rainfall data extracted for this study region (23.5N,77.5E) from 1951-2003 is shown in Figure 5.20. As apparent from Figure 5.20, the extreme maximum daily rainfalls have decreased in late 1990s and early 2000s from the 1970s and 1980s in Bhoj. However, a season specific analysis of daily rainfalls will make it clear whether extreme rainfalls in various seasons have been changing, which will be discussed in the following paragraphs.

Parameters PREP_ST (total rainfall in the days with > 1mm rain), TDD (total number of dry days), R95p (amount of rainfall above long-term 95th percentile), R99p (amount of rainfall above long-term 99th percentile), RX1day (maximum 1-day rainfall), RX5day (maximum 5-days rainfall), RXF (rainfall frequencies for rainfalls above long-term 95th percentile) and RXP (percent contribution to total rainfall from the extreme rainfalls above long-term 95th percentile) from Table 3.19 (Chapter 3) are also presented here to assess the changes in rainfall in Bhoj.

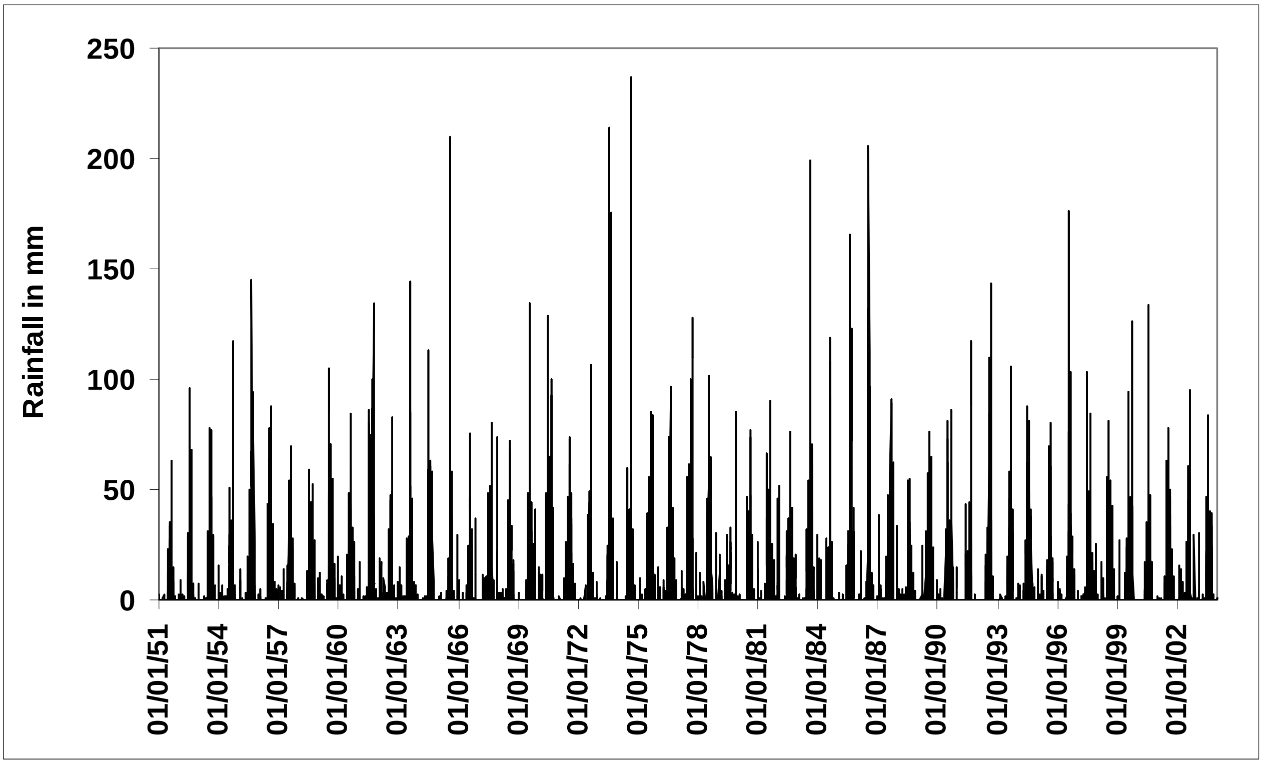


Figure 5.20: The 53-year daily time series of rainfall in Bhoj wetland.

Table 5.2 displays the trends of annual and seasonal extreme rainfall indices, determined both by the parametric OLS and non-parametric Mann-Kendal methods, as described in sections 2.6.2 and 2.6.3. The table reveals that the annual rainfall (PREP_ST) is increasing in Bhoj wherein seasonal variabilities are quite strong. This result doesn't match with the rainfall patterns noticed for WCIN in section 3.6.4 (Figure 3.26). Therefore, rainfall patterns for WCIN will not be followed here to assess soil erosion changes in Bhoj but the gridded rainfall, which was shown in Figure 5.20, will be used.

Table 5.2: Trends of extreme rainfall indices (PREP_ST, TDD, R95p, R99p, RX1day, RX5day, RFX and RXP) for Bhoj by OLS and MK methods for 1951-2003.

	PREP_ST (mm/10years)		***TDD (days/10years)***		***R95p (mm/10years)***		***R99p (mm/10years)***	
	OLS	***MK***	***OLS***	***MK***	***OLS***	***MK***	***OLS***	***MK***
Annual	+11.6	+8.8	+0.42	+0.71	+6.2	+8.2	+6.2	+8.2
Winter	+1.4	No Trend	No Trend	No Trend	+1.5	No Trend	+1.5	No Trend
Spring	+1.8	+1.5	No Trend	No Trend	+2.1	No Trend	+2.1	No Trend
Monsoon	+8.1	+7.0	+0.7	+0.7	+3.8	+2.6	+3.8	+2.6
Autumn	No Trend	No Trend	No Trend	No Trend	-1.3	No Trend	-1.3	No Trend
	RX1day (mm/10years)		***RX5day (mm/10years)***		***RXF (days/10years)***		***RXP (%/10years)***	
	OLS	***MK***	***OLS***	***MK***	***OLS***	***MK***	***OLS***	***MK***
Winter	+0.33	+0.21	+1.0	+0.1	No Trend	No Trend	+5.5	No Trend
Spring	+0.42	+0.71	-1.0	No Trend	***+0.2***	No Trend	***+0.7***	No Trend
Monsoon	-0.7	-0.2	+0.9	-0.5	No Trend	No Trend	+2.8	+2.5
Autumn	-0.8	+0.2	-2.0	-0.5	No Trend	No Trend	No Trend	No Trend

Note: -ve = decreasing, +ve = increasing. All bold trends are significant at the 95% level and all the bold italic trends are significant at the 90% level.

Results corresponding to OLS and MK estimates in Table 5.2 are quite similar in all cases with some of the exceptions of winter, spring and autumn seasons, i.e. the times of least rainfall. However, none of the trends were found to be statistically significant at 95% level, as in Table 5.2.

Winter usually has positive trends in RX1day and RX5day but none are significant. Absolutely no trends were found in TDD and RXF in winter and an increasing tendency was found in annual and monsoon TDD, as in Table 5.2. Soil under a rainfall regime of greater dry days but more intense rainfall events may or may not produce soil erosion and runoff, depending on the soil moisture status of the soil (section 4.6.2.2).

It is also noted in Table 5.2 that total rainfall contributed by seasonal extremes (R95p and R99p) show increasing tendencies and only except autumn season in Bhoj. Spring is the season which is particularly vulnerable for the agricultural soils because of the lack of crop residues and/or the fact that fertilizers and pesticides are usually applied to agricultural fields before monsoon rainfall starts. The monsoon rainfall extreme intensities (RX1day) are usually decreasing, as also visually seen in Figure 5.20 since 1-day maximum rainfalls in a year usually occur in monsoon seasons.

Changes are also observed for the extreme rainfall frequencies (RXF) and percent contribution of the same to total seasonal rainfalls (RXP), as shown in Table 5.2. As Table 5.2 indicates, spring extreme rainfall frequencies are increasing in Bhoj while those for winter, monsoon and autumn have no trends. The same trend results are also noticed for the percent contribution from the extreme rainfalls (RXP) in spring and positive trends for monsoon seasons. For winter RXP, the results corresponding to OLS and MK don’t match for Bhoj.

5.1.2.2.3. Effect of Climate Change on Soil Erosion

Like Kerala, in section 5.1.1.3, a study was carried out to examine the effect of observed rainfall changes (section 5.1.2.2.2) on soil erosion problems in the Bhoj area. The annual erosivities were estimated using the rainfall data in Figure 5.20 and Figure 5.21 shows the variation of annual erosivities and annual rainfalls in Bhoj.

The data in Figure 5.21 suggest that the lower the annual rainfall, the lower the corresponding erosivity. However, this is not true for all years. One exception is the year 1986, in which the rainfall erosivity increased from the previous year (1.2 times), wherein the amount of the total rainfall decreased from the previous year. This is because the rainfall erosivity is a function of both the quantity of rainfall and its intensity, as was also found for Kerala (sections 5.1.1.1.1 and 5.1.1.2.2). Since the year 1986 experienced highly intense rainfall (Figure 5.20), the erosivity was very high.

Apart from the annual erosivities discussed above, Table 5.3 shows other data required for determining annual soil erosion at the Bhoj site. As Table 5.3 indicates, the soil in the Bhoj site is clayey black cotton soil with ‘very low’ permeability and very high runoff potential. The black colour comes from the presence of humus i.e. the organic matter, which is found to be moderate-high in the soil, as in Table 5.3. Table 5.3 also indicates that the slope steepness is variable in Bhoj. Therefore the worst case i.e. 20% slope was considered for this study. Soil cover condition is highly disturbed and there is no soil management practice (c=1 and p=1 in expression 4.1), as in Table 5.3.

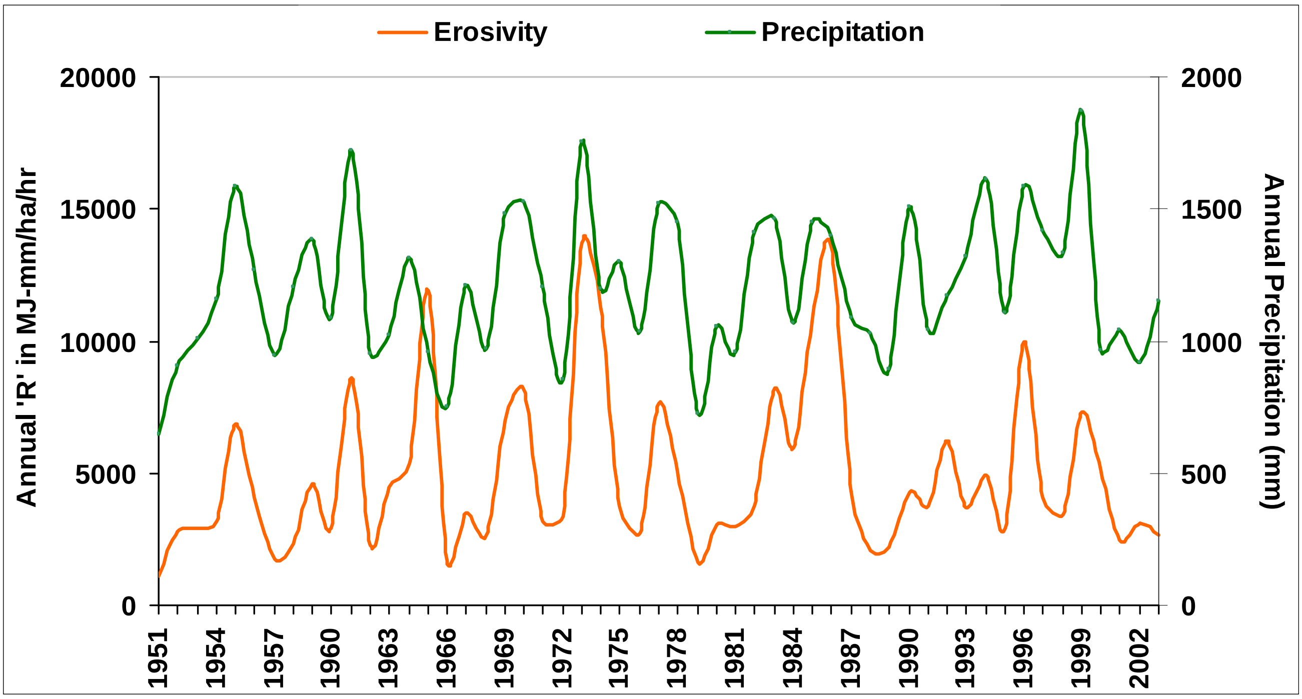


Figure 5.21: Inter-year variation of annual rainfall erosivity and rainfall in Bhoj.

Table 5.3: Data used for soil erosion estimates by RUSLE2 for Bhoj region (Rao et al., 1999).

Soil physical properties	Black Cotton soil clay = 51%; silt = 29% and sand = 20%
Permeability	Very Low
Group D soil = highest runoff	
Field slope length	Variable; therefore taken as 3m i.e. point soil loss as recommended by RUSLE2
Field slope steepness	Variable from 8-20%; taken the worst case i.e. 20% slope
Organic matter	Moderate-high in RUSLE2
Soil cover situation	Highly disturbed, continuous bare i.e. worst case
Erosion protection Practices	Not yet followed

The computation of annual runoff from the monthly rainfall amounts and monthly average temperatures were discussed in Chapter 4 in section 4.5.1 (expressions 4.18-4.21). The annual runoff values so estimated and along with annual rainfalls and their trends are shown in Figure 5.22. The figure shows that runoff increases with increase in rainfall and therefore both rainfall and runoff had similar patterns (increasing) in Bhoj (Figure 5.22). Since there were large annual fluctuations in both the rainfall and runoff, a study was also done to check the decadal variation as well to examine which decade had the maximum rainfall and runoff in the 53 years of study, decadal variation of those results were also plotted and shown in Figure 5.23. As seen in Figure 5.23, the current most years of 1990-2003 had the highest average rainfall and surface runoff, which would cause more soil erosion in the recent years. But this could not always be true, as discussed in the following paragraphs.

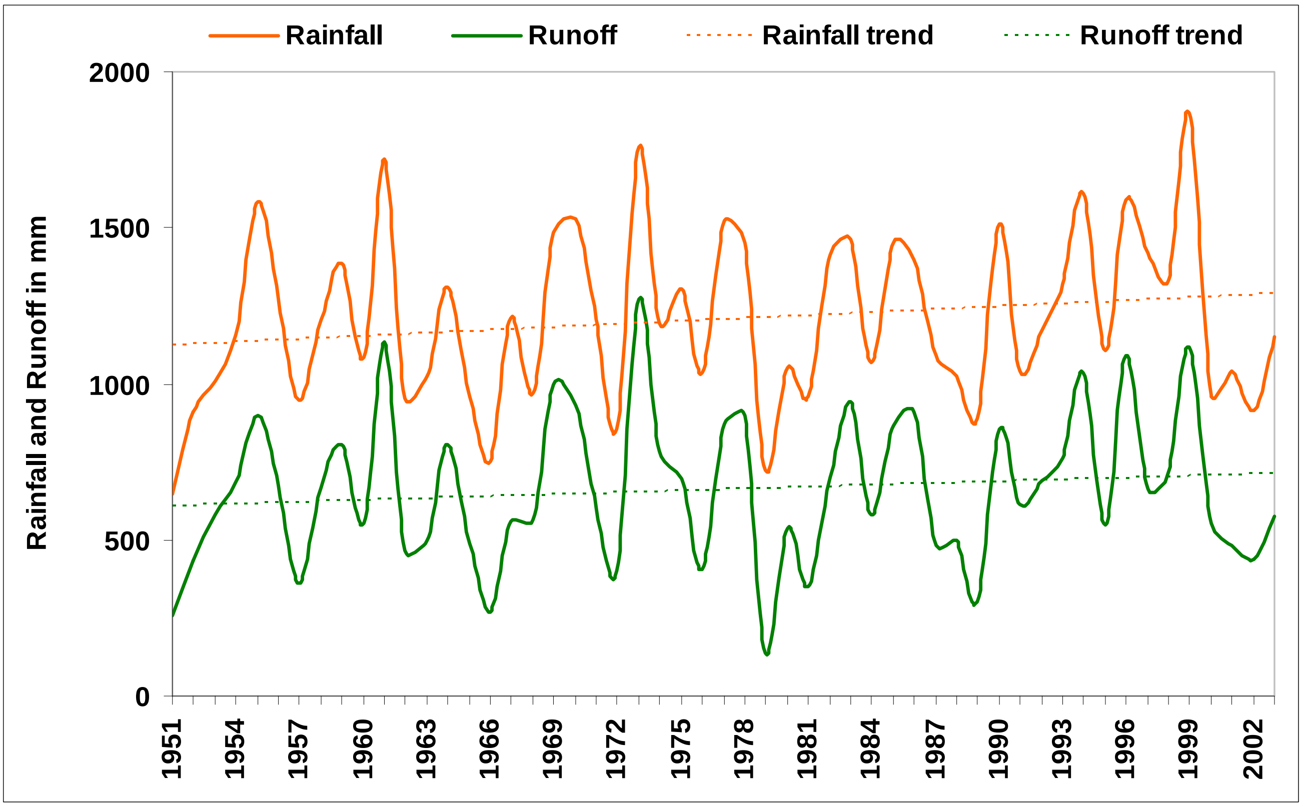


Figure 5.22: Annual variation of rainfall and runoff amounts and their linear trends in Bhoj site in 1951-2003.

Average soil erosion from the Bhoj wetland was computed based on the rainfall erosivities in Figure 5.21 and the soil and site specific data given in Table 5.3 using RUSLE2. The annual and decadal variation of soil erosion in Bhoj region is shown in Figures 5.24 and 5.25. Figure 5.24 shows that the annual soil erosion has been increasing in Bhoj, which could be attributed to the increase in annual rainfall, as discussed previously in section 5.1.2.2.2 (Table 5.2) and also shown in Figure 5.22. However, the decadal changes of soil erosion quantity in Figure 5.25 were different from the rainfall-runoff fluctuations in Figure 5.23. Since soil erosion is dependent on rainfall intensity, as mentioned earlier in the conclusions from previous study in section 5.1.1.1.1, in spite of the maximum rainfall amount occurrence in 1999, the 1980s experienced maximum soil erosion. Therefore, from the work performed in section 5.1.2.2.2 (Table 5.2), it could also be concluded that there could be a tendency that the monsoon seasonal soil erosion will increase in Bhoj region since PREP_ST, R95p and R99p in monsoon season showed increasing trends in the last 53 years even though RX1day, which is also seen in Figure 5.20 have decreasing tendencies.

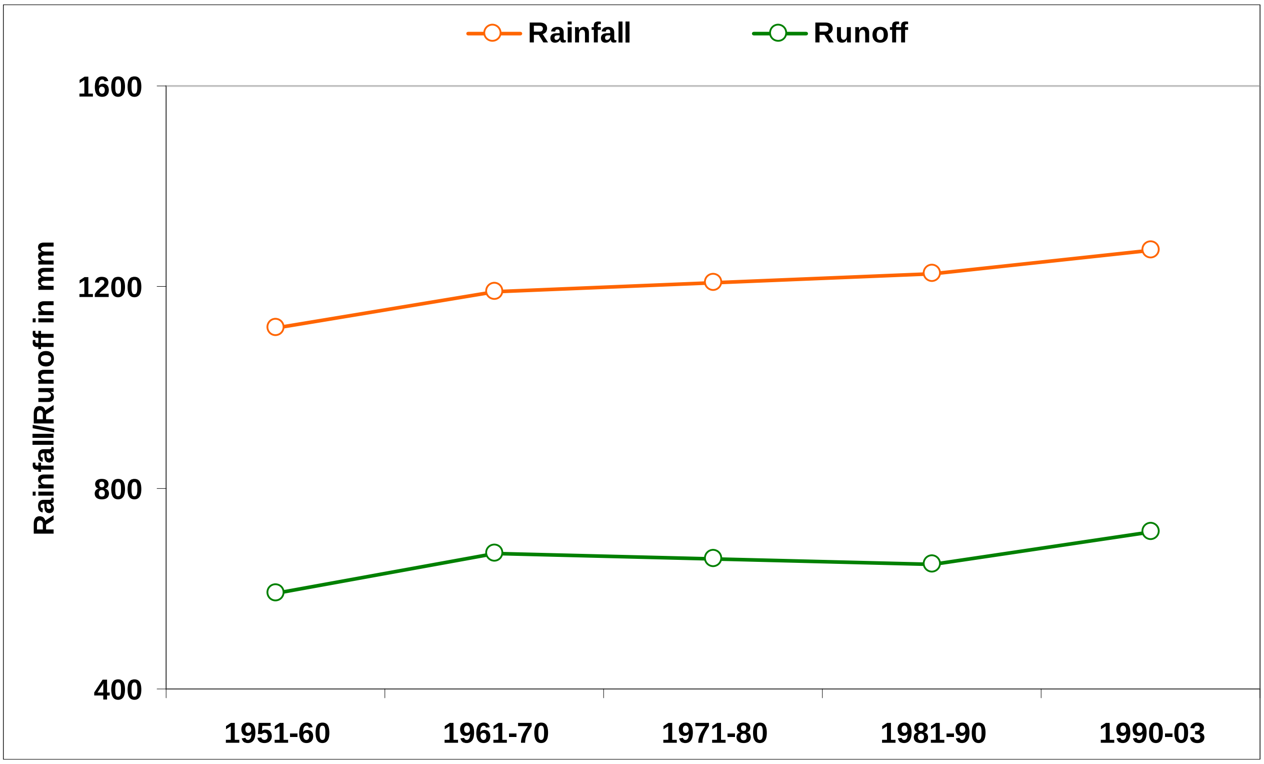


Figure 5.23: Decadal variation of rainfall and runoff amounts in Bhoj site in 1951-2003.

Referring back to Chapter 3, sections 3.10.3.2 and 3.10.3.3 (Table 3.22), it was found that temperature is increasing in north central temperature region of India (Figure 2.5), where Bhoj region is located. This could be another reason for increase in soil erosion since soil organic carbon tends to deplete as a result of increase in temperature, which makes the soil structure unstable, as discussed in Chapter 4 in section 4.6.2.2 (Blanco and Lal, 2008).

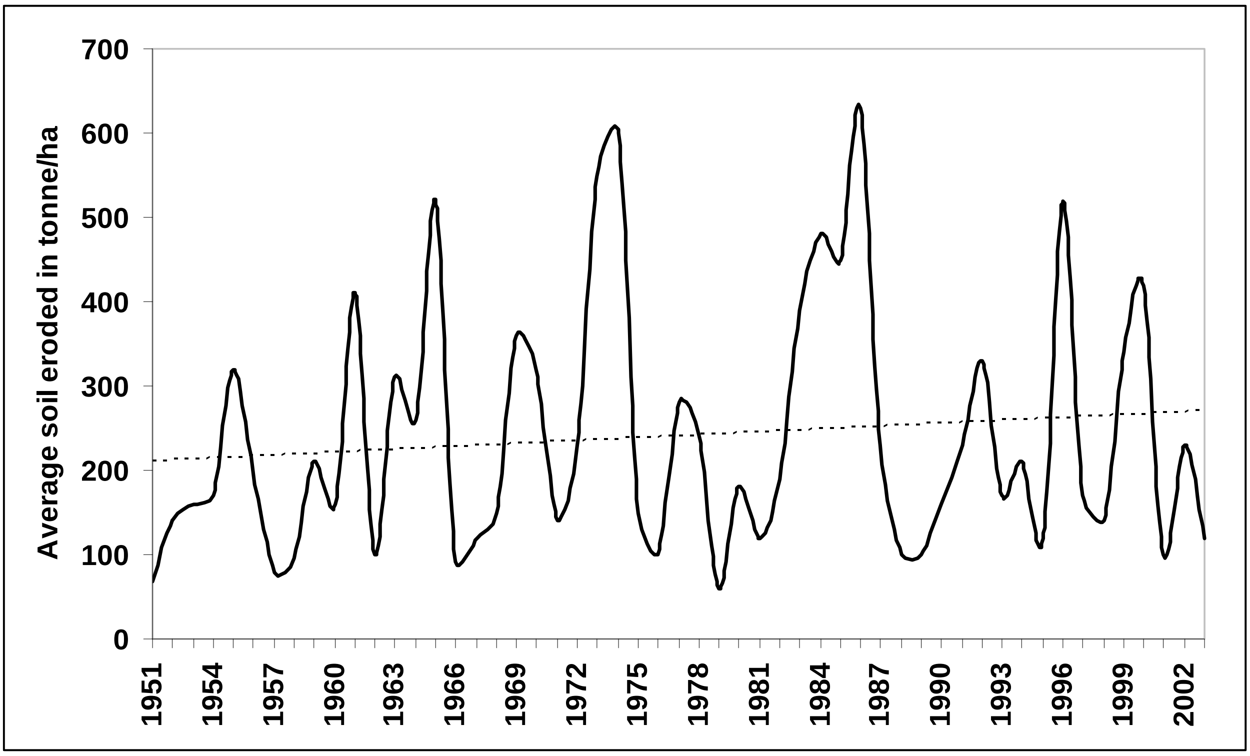


Figure 5.24: Annual variation of soil eroded in Bhoj area in 1951-2003.

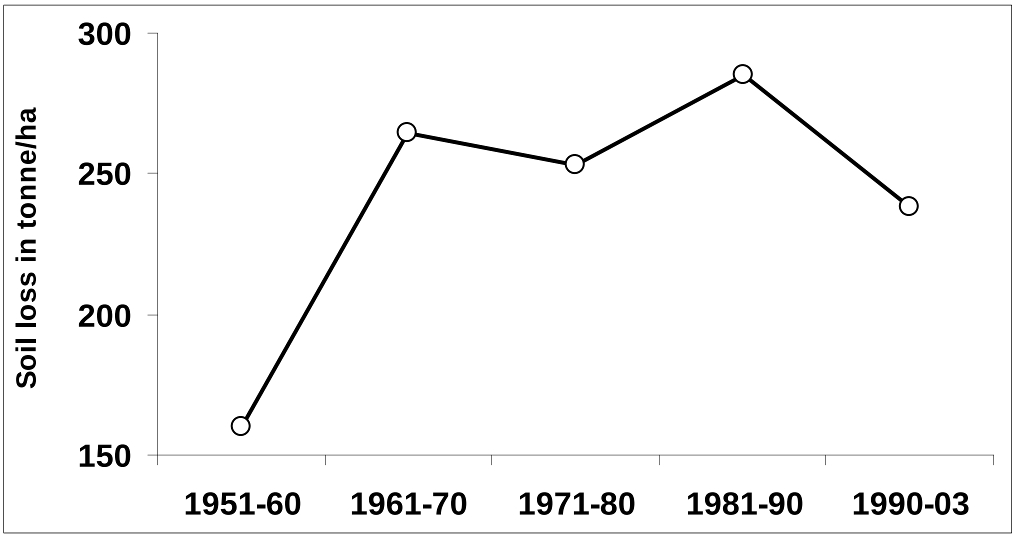


Figure 5.25: Decadal variation of soil erosion amounts in Bhoj area in 1951-2003.

If it is assumed that the 53-year annual rainfall trend (increasing) in Figure 5.22 will continue in the same pattern for the next 50-years, the trend would be as shown in Figure 5.26. The 50-year soil erosion projection from that shown in Figure 5.24 is also shown in Figure 5.26, which indicates that a 13% increase in average annual rainfall will lead to a 8% increase in average annual soil erosion in the next 50-years if all other variables remain unchanged, which is consistent with the model studies discussed in the previous chapter in section 4.3 in Table 4.4 (Ebeid et al., 1995), which indicated an increase in soil erosion from 1.7-241% with a 1-20% increase in rainfall amount.

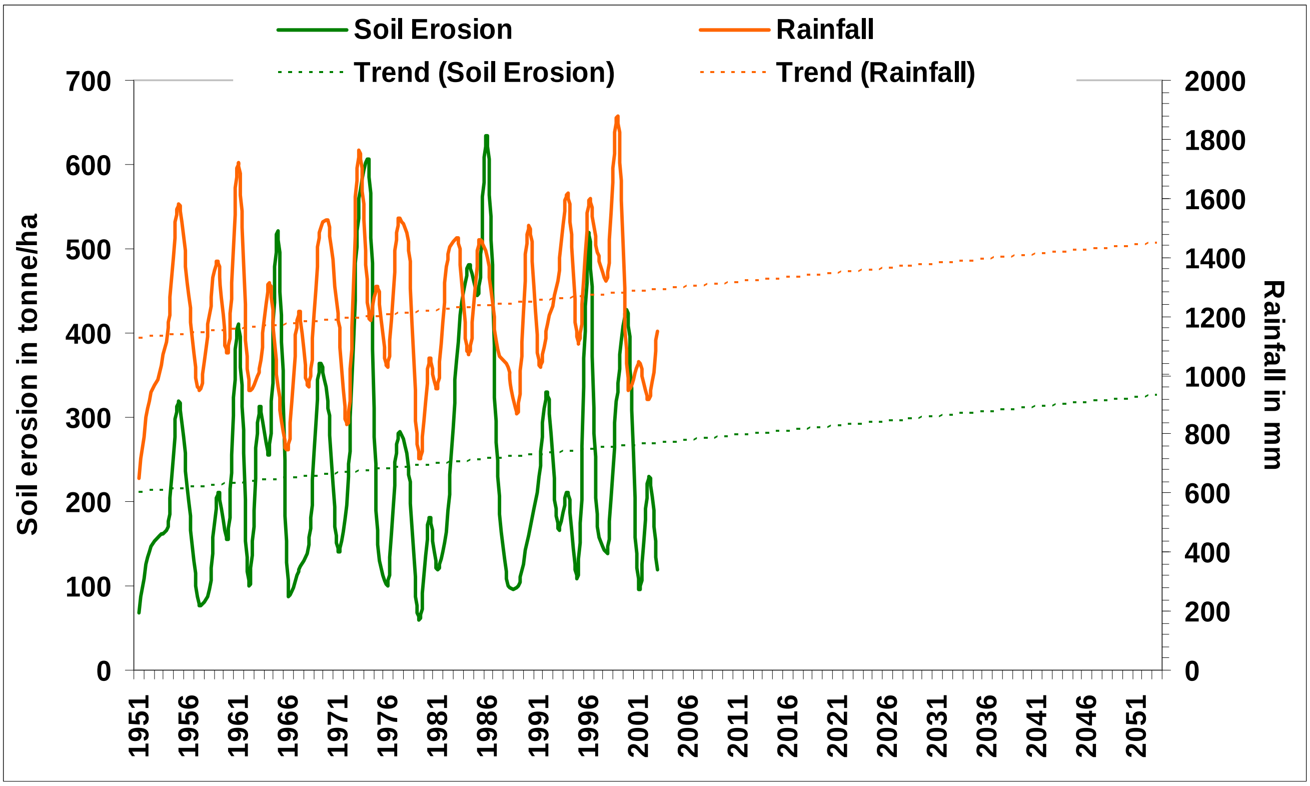


Figure 5.26: 50-year (2004-2054) rainfall and soil erosion projections using 53-year (1951-2003) data for Bhoj.

5.1.2.3. Sukinda Valley

5.1.2.3.1. Description of the Study Site

From the various mining districts identified in India for their significant impacts on the local environment and ecosystems, the area located in the chromite belt of the Sukinda watershed in the state of Orissa, shown in Figure 5.27, comprising of 12 mines, was selected for this project. In terms of geographical distribution of mineral resources of India, about 10-14% of mineral production comes from the state of Orissa. Orissa stands out as one of the major producer of Chromite, Nickel, Iron, Manganese, Tin, Graphite, Bauxite, Lead and Zinc in India.

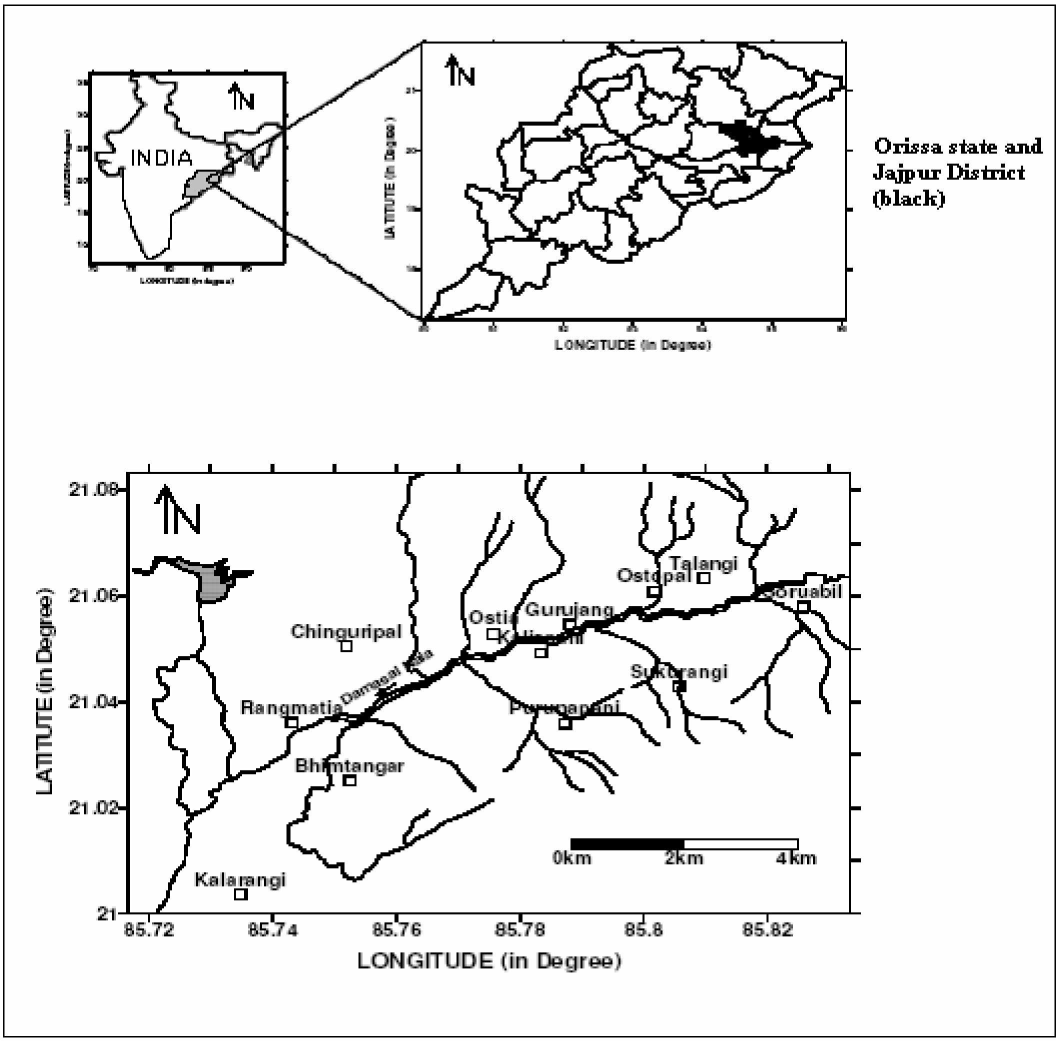


Figure 5.27: The location and key map of Sukinda showing drainage system (Dhakate and Singh, 2008).

Chromite is the only economic source of chromium. In Orissa, chromites are confined to three areas namely Boula-Nuasahi in Keonjhar district, Sukinda valley in Jajpur district, and Bhalukasuni in Balasore district. Out of those, Sukinda valley in Orissa was labelled as one of the top 10 of the world's 30 most polluted places in a report published in 2007 by the Black Smith Institute, NY (http://www.worstpolluted.org/). Seventy years of rigorous open-cast chromite mining have caused massive cavities in the ground, mountains of waste rock and soil, a blemished landscape, poisonous water and soil, damaged agricultural fields, degraded forestland, water scarcity affecting agricultural production and the people have been slowly poisoned over the years like in many mining areas around the country (Ericson et al., 2007). Orissa Remote Sensing Applications Centre highlighted a net increase of degraded forest land from 731.88ha in 1974 to 1828.98ha in 1994. Large territory of once fertile agricultural land in nearer villages is covered with mine overburden.

Sukinda Valley is reported to contain 97% of India's chromite ore deposits and is one of the largest open cast chromite ore mines in the world (Ericson et al., 2007). Twelve mines continue to operate without any environmental management plans. The chromite ores and waste rock material are dumped in the open ground without considering their impact on the environment. There is also an acute dust problem in the area. Given water scarcity, many villagers are forced to bathe in the water that accumulates in the abandoned chromite mine pits.

In the untreated or partially treated water while discharged by the mines, after washing the ore into the open fields of surrounding areas, the carcinogens make their way into Brahmani River through runoff. The Brahmani River is the only perennial water source for 2.6 million residents in the district. The toxic elements finally end up onto the Bay of Bengal where Brahmani River empties out, as shown in Figure 5.28.

In Sukinda, approximately 70% of the surface water and 60% of the drinking water contain hexavalent chromium at more than double the national and international standards (Dubey et al., 2001). The Orissa Voluntary Health Association (OVHA) reported, based on up to 1995 survey data that ~ 85% of deaths in the mining areas and 86% of deaths in the nearby industrial villages occurred due to chromite-mine related diseases. The survey report also revealed that villages within 1 km of the sites were the worst affected, with ~ 25% of the inhabitants suffering from pollution-induced diseases. However, there has been virtually no attempt to clean up this contamination.

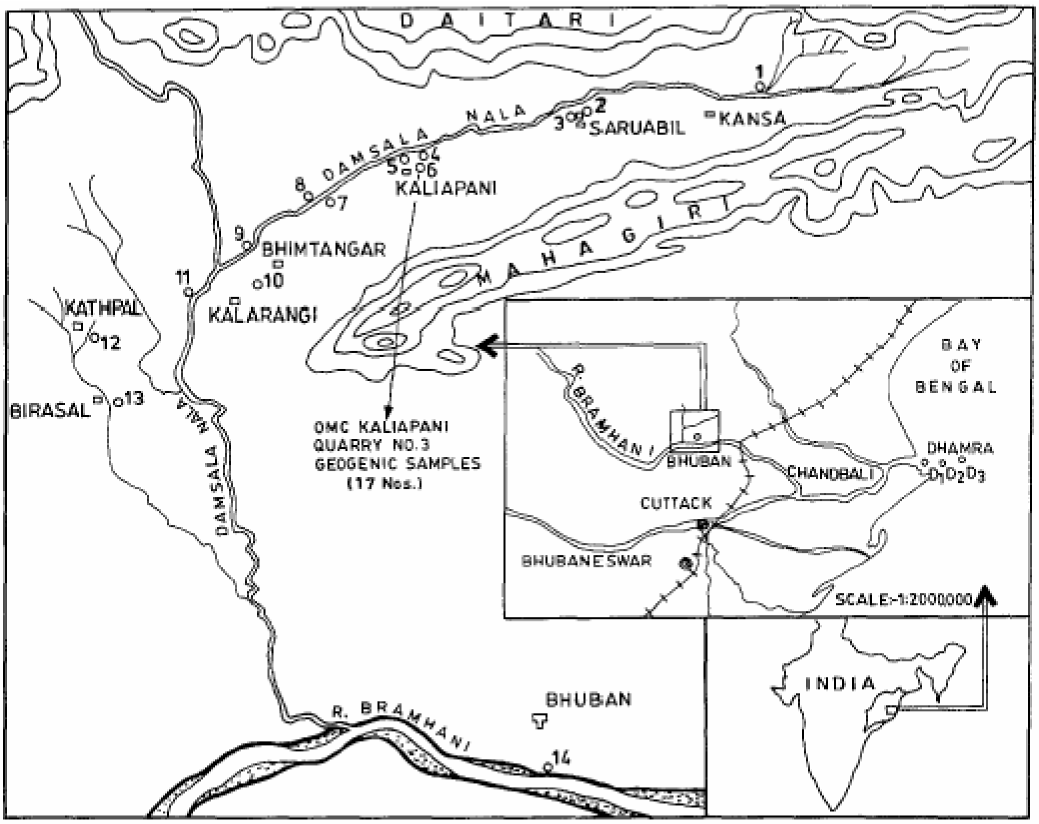


Figure 5.28: The location showing Damsala nala – the principal tributary of Bramhani River in Jajpur district that empties out in Bay of Bengal (Godgul and Sahu, 1995).

Sukinda valley is situated in northern Orissa's Jajpur district which is located in between 20°01´–21°04´N latitude and 85°40´–86°53´E longitude covering an area of 55km^2 (Dubey et al., 2001). Figure 5.27 shows the location and the key map of Sukinda valley showing drainage system as well. In the southeast and northwest, there situates Mahagiri and Daitari hill ranges respectively, as also in Figure 5.28. Chromite mines are located at the northern hill slopes of Mahagiri range and in the valley area. The area with the chromite deposits has an elevation ranging between 166-208m above sea level. This area is flood-prone, resulting in further contamination of the waterways (Ericson et al., 2007). An abandoned open pit chromite mine in the upstream part of the Sukinda watershed is shown in Figure 5.29 and view of one of the open-pit chromite mines operating in the Sukinda watershed is shown in Figure 5.30.

Figure 5.29: Abandoned open pit chromite mine in the upstream part of the Sukinda watershed.

Figure 5.30: View of one of the open-pit chromite mines operating in the Sukinda watershed.

5.1.2.3.2. Changes in Rainfall Extremes

High resolution gridded daily rainfall data, as described in section 2.2.1 was also used here for the analysis of the extreme rainfalls, like Bhoj. This section will also check whether average rainfall pattern in Sukinda is similar to that found for CNEIN in section 3.6.4 (Figure 3.26). The rainfall data collected for Sukinda Valley (averages of daily rainfalls from 4 grids – 20.5N,85.5E; 20.5N,86.5E; 21.5N,85.5E; 21.5N,86.5E) for

1951-2003 is shown in Figure 5.31. It is noted in the figure that, the highest two extreme rainfall events since mid 1970s occurred in the late 1990s.

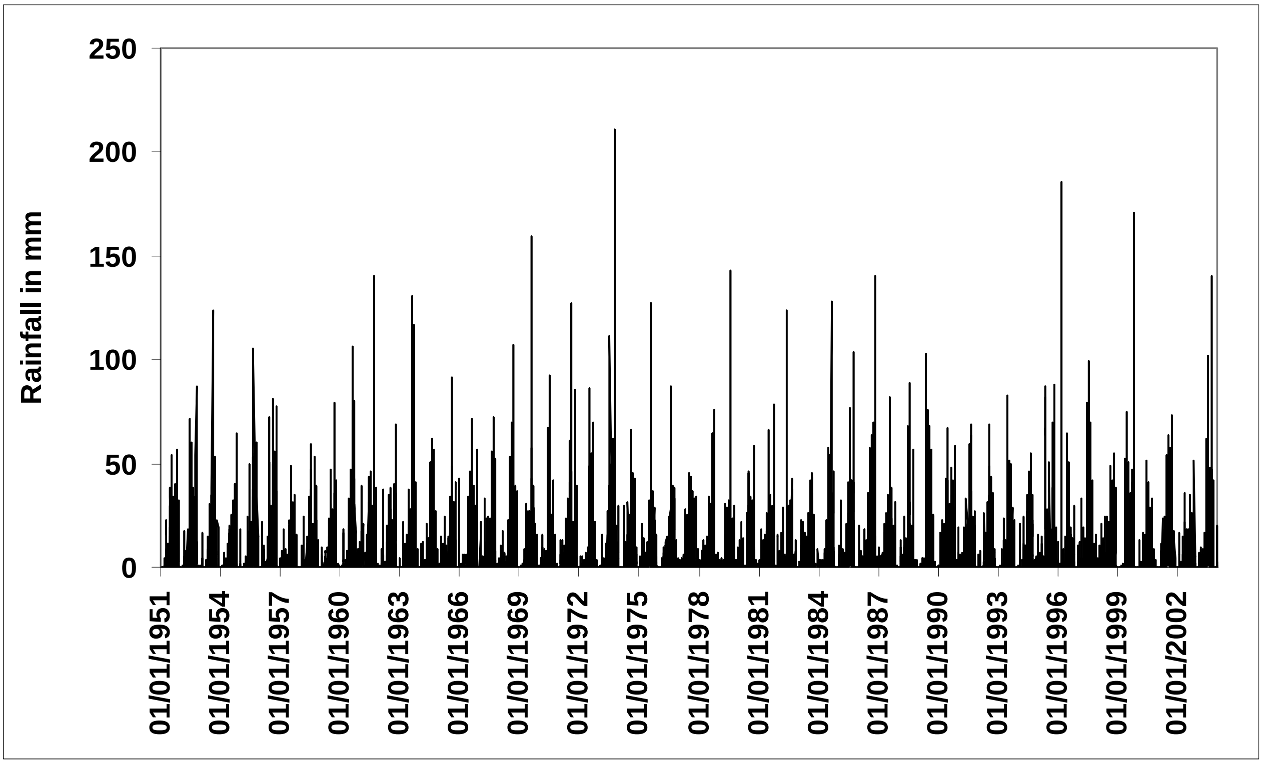


Figure 5.31: The 50-year daily time series of rainfall in Sukinda.

Parameters PREP_ST, TDD, R95p, R99p, RX1day, RX5day, RXF and RXP from Table 3.19 are also presented here to assess the changes in rainfall extremes in Sukinda, like Bhoj in section 5.1.2.2.2. Table 5.4 shows the trends of all those indices determined both by the parametric OLS and non-parametric Mann-Kendal methods, as described in sections 2.6.2 and 2.6.3. The table reveals that the annual rainfall (PREP_ST) is increasing in Sukinda wherein seasonal variabilities are noticed. This annual rainfall pattern in Sukinda is similar to that observed for CNEIN (Figure 3.26) annually and in all the seasons except monsoon. Therefore, like Bhoj, the rainfall data shown in Figure 5.31 was used for rainfall erosivity estimation for Sukinda region.

Table 5.4 also shows that the results corresponding to OLS and MK estimates are quite similar in all the cases with some of the exceptions of winter and autumn seasons, i.e.

the times of least rainfall (Table 5.4), like Bhoj in Table 5.2. Spring seasonal rainfall (PREP_ST) has a positive significant trend in Sukinda; whereas, monsoon rainfall has decreasing tendency. Considering that the parametric OLS method assumes normality, which is not true for the seasonal rainfalls into consideration, results corresponding to MK could be considered to be hold true, which show increasing tendency in winter and decreasing tendency in autumn in Sukinda region (Table 5.4).

Table 5.4: Trends of extreme rainfall indices (PREP_ST, TDD, R95p, R99p, RX1day, RX5day, RFX and RXP) for Sukinda by OLS and MK methods for 1951-2003.

	PREP_ST (mm/10years)		***TDD (days/10years)***		***R95p (mm/10years)***		***R99p (mm/10years)***	
	OLS	***MK***	***OLS***	***MK***	***OLS***	***MK***	***OLS***	***MK***
Annual	+18	+27.7	-1.9	-1.7	+17	+10.1	+13.9	+10.1
Winter	-1.3	0.4	-0.41	-0.5	-2.9	No Trend	-2.8	No Trend
Spring	**+22.8**	**+18.6**	***-1.3***	***-1.1***	**+16.1**	**+7.4**	**+13.7**	**+0.1**
Monsoon	-8.0	-2.8	-0.19	-0.28	-2.7	-1.8	-7.2	-3.3
Autumn	+4.6	-7.5	No Trend	No Trend	+6.5	No Trend	+10.2	No Trend
	RX1day (mm/10years)		***RX5day (mm/10years)***		***RXF (days/10years)***		***RXP (%/10years)***	
	OLS	***MK***	***OLS***	***MK***	***OLS***	***MK***	***OLS***	***MK***
Winter	-1.3	-0.8	**-3.7**	**-2.6**	No Trend	No Trend	No Trend	No Trend
Spring	**+6.3**	**+2.2**	***+7.7***	***+2.4***	No Trend	No Trend	+5.4	+1.9
Monsoon	+4.3	+4.2	-3.7	-3.3	No Trend	No Trend	+1.7	+1.2
Autumn	+3.3	+1.1	+3.2	-3.2	No Trend	No Trend	No Trend	No Trend

Note: -ve = decreasing, +ve = increasing. All bold trends are significant at the 95% level and all the bold italic trends are significant at the 90% level.

Furthermore, Table 5.4 indicates that there is a decreasing tendency of TDD in Sukinda in all the seasons except autumn while spring TDD has 90% significant trends (bold/italic). Soils under a rainfall regime of decreased number of dry days will more likely be wetter and therefore, more apt to produce soil erosion and runoff, which is the case for Sukinda for all the seasons except autumn. A decrease in the number of dry days with no increase in rainfall intensity tends to emphasise subsurface flow to surface water and ground water, which is the case for monsoon season in Sukinda, as noticed in Table 5.4.

The changes in seasonal total rainfalls above 95^{th} and 99^{th} percentiles (R95p and R99p) are also shown in Table 5.4. It is noticed in this table that the largest and significant increase in rainfall extremes occurs in the spring season in Sukinda. There is an increasing tendency in R95p and R99p annually even though the decreasing tendencies are noted for the monsoon season, as in Table 5.4.

Changes in 1-day and 5-day extreme rainfalls are also noted in Table 5.4. It is seen in the table that winter rainfall extreme intensities are usually decreasing, spring rainfall extreme intensities have statistically significant positive trends (90-95%) for both the indices, and monsoon rainfall extreme intensities had different results for RX1day and RX5day. No changes were observed for the extreme rainfall frequencies (RXF) in Sukinda and positive changes were noted for the percent contribution of the extreme rainfall to seasonal total rainfalls (RXP), as shown in Table 5.4. For winter and autumn, there were no trends for RXP in Sukinda.

From the results above it could be deduced that since the rainfall extremes are increasing in autumn and spring seasons in Sukinda, there is a positive tendency to higher erosion in these seasons as well. These seasonal changes might be contributing to annual increase in total rainfall and the extremes in Sukinda even though monsoon seasonal rainfall shows a decreasing tendency. Such increase in annual rainfall total and extremes will lead to more soil erosion annually, as will be shown later in the following section.

5.1.2.3.3. Effect of Climate Change on Soil Erosion

Like Bhoj region a study was carried out to investigate soil erosion patterns due to rainfall changes in the Sukinda region. The annual erosivities were estimated using the data in Figure 5.31 and are shown in Figure 5.32 together with the variation of annual rainfalls. The highest annual erosivity occurred in 1973 and followed by 1999 and 2003. Figure 5.32 suggests that the higher the annual rainfall, the higher the corresponding erosivity. However, this is not true for all the years. 1973 had the highest intensity of rainfall, as noted in Figure 5.31, and therefore had the highest erosivity in the 53 years of study. 1999 and 2003 years, which had second and third highest rainfall erosivities, didn’t have the second and third highest intense rains but experienced higher annual rainfalls, as shown in Figure 5.32. Although 1996 had the second highest intense rainfall, as in Figure 5.31, because it had very less annual rainfall, as in Figure 5.32, the rainfall erosivity was lesser in 1996. This again shows that the rainfall erosivity is a function of both the quantity of rainfall and its intensity.

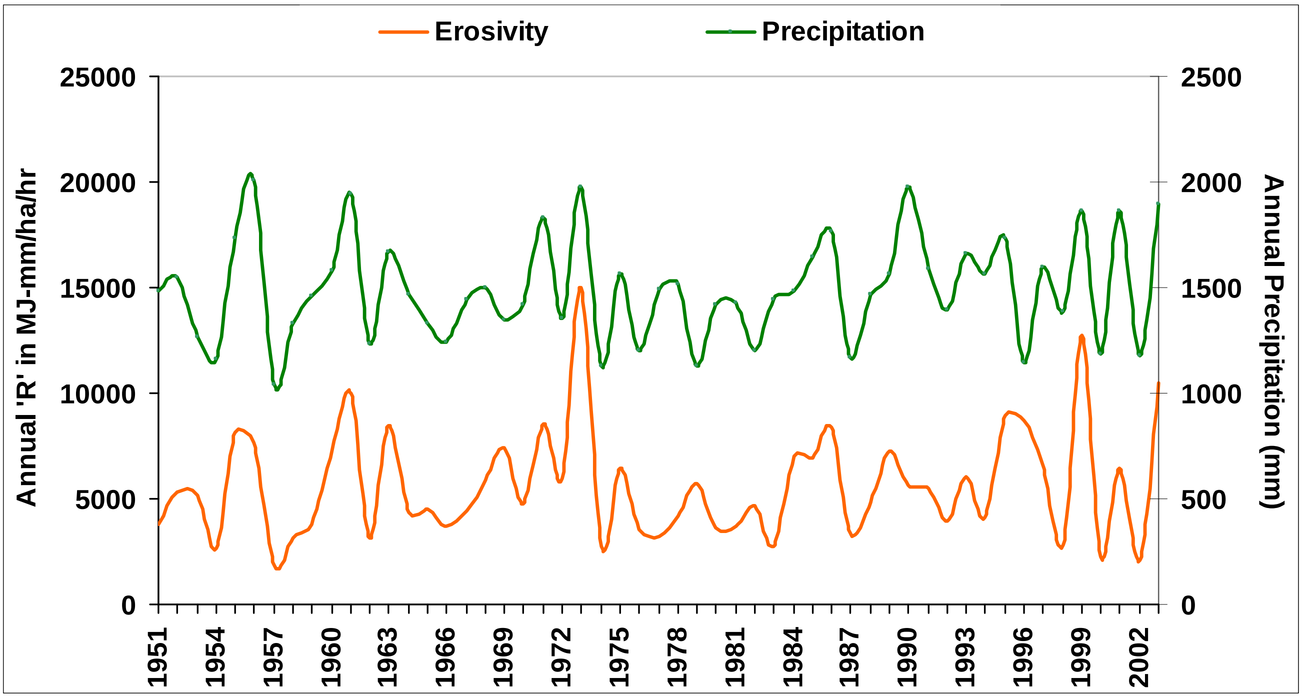


Figure 5.32: Inter-year variation of annual rainfall erosivity and rainfall in Sukinda.

Apart from the annual erosivities in Figure 5.32, Table 5.5 shows other data required for determining annual soil erosion at the Sukinda region. This data was provided by the Indian Institute of Soil Science (ISSR - http://www.iiss.nic.in/). As Table 5.5 indicates, the soil in Sukinda region is lateritic soil, as also found for Kerala but with different texture (Pal, 2007). The soils in Sukinda region is of sandy loam and clay loam types with ‘moderate’ permeability and moderate runoff potential. Moderate permeability causes moderate soil erodibility, as noted in Figure 5.8. Although slope steepness is variable in Sukinda, the worst case i.e. 10% slope was considered for this study. Soil cover condition is highly disturbed and there is no soil management practice (c=1 and p=1 in expression 4.1).

Table 5.5: Data used for soil erosion estimates by RUSLE2 for the Sukinda chromite mining site.

Soil physical properties	<u>Lateritic Soil</u> Sandy loam; clay = 10%; silt = 25% and sand = 65% Clay loam; clay = 34%; silt = 33% and sand = 33%
Soil structural class	Coarse and fine
Permeability	Moderate (2-4 cm/hr)
Group B soil (in RUSLE2) = moderate infiltration rate when thoroughly wetted	
Field slope length	Variable; therefore taken as 3m i.e. point soil loss as recommended by RUSLE2
Field slope steepness	Variable; therefore taken the worst case i.e. 10% slope
Organic matter	low-moderate in RUSLE2
Soil cover situation	Highly disturbed, Barren and very rough i.e. worst case
Erosion protection Practices	Not yet followed

The computation of annual runoff from the monthly rainfall amounts in Sukinda and monthly average temperatures were discussed in Chapter 4 in section 4.5.1 (using expressions 4.18-4.21). The annual runoff values so estimated and along with annual rainfalls and their trends are shown in Figure 5.33.

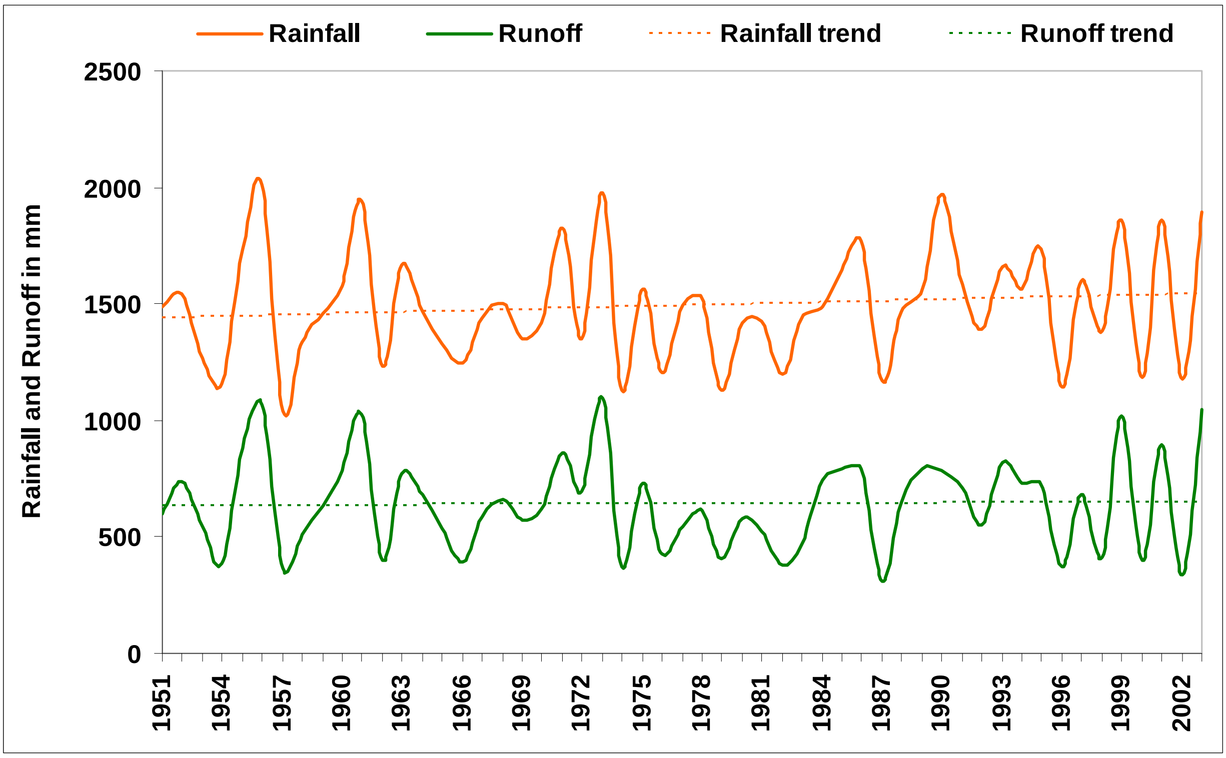


Figure 5.33: Annual variation of rainfall and runoff amounts in Sukinda in 1951-2003.

Figure 5.33 shows that runoff increases with increase in annual rainfall total in Sukinda. Since there were large annual fluctuations in both the rainfall and runoff, a study was also done to check the decadal variation as well to examine which decade had the maximum rainfall and runoffs in the 53 year study period. Decadal variation of those results were also plotted and shown in Figure 5.34. As seen in Figure 5.34, the current most years 1990-2003 had the highest average rainfall and surface runoff, which would cause more soil erosion in the current most years like as found for Bhoj wetland before. But this case is not true always, as found for Bhoj wetland in section 5.1.2.2.3.

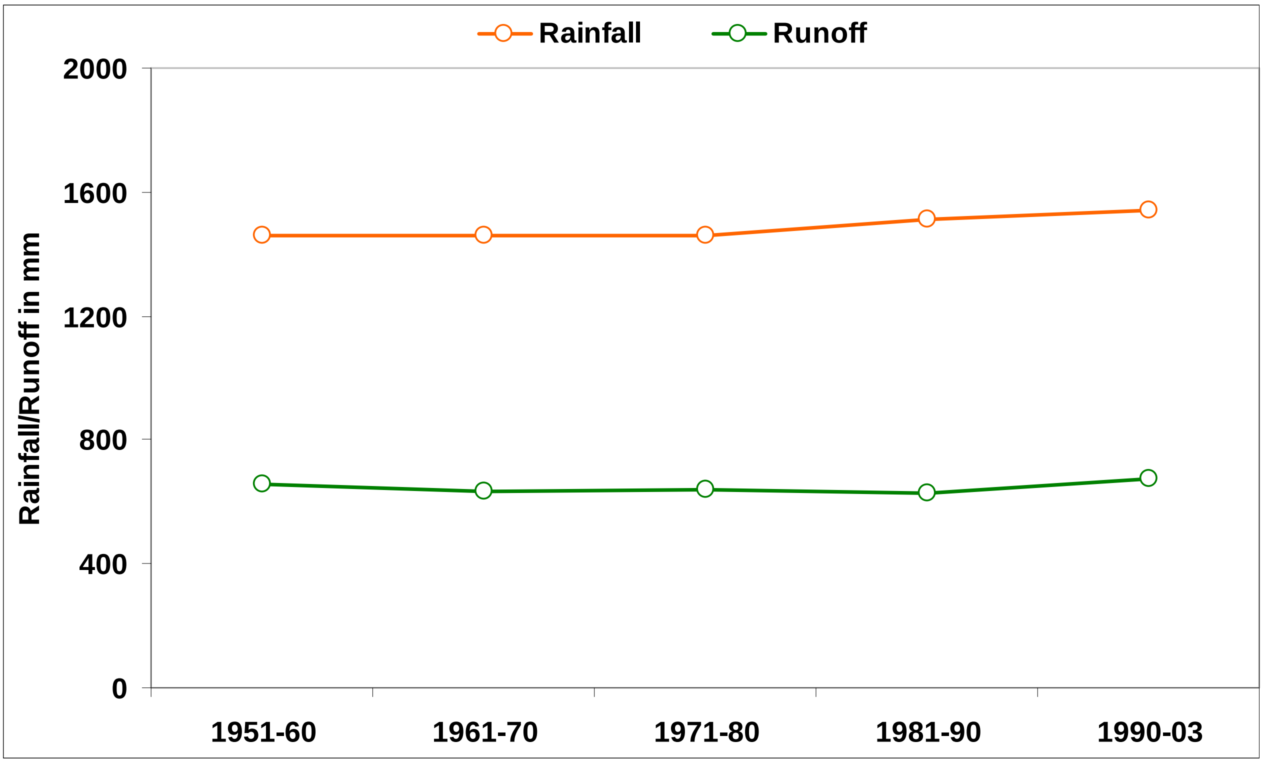


Figure 5.34: Decadal variation of rainfall and runoff amounts in Sukinda in 1951-2003.

Average soil erosion from the Sukinda valley was computed using RUSLE2 based on the rainfall erosivities in Figure 5.32 and the soil and site specific data given in Table 5.5. The annual and decadal variation of soil erosion in Sukinda valley is shown in Figures 5.35 and 5.36. Although there was an average increase in soil erosion profile as in Figure 5.35, due to increase in rainfall and runoff (Figure 5.33), and increase in extremes (Table 5.4), the decadal change of soil erosion quantity was different in Figure

5.36 from the rainfall-runoff fluctuations in Figure 5.34. Since soil erosion is dependent on rainfall intensity, as mentioned earlier in section 5.1.1.1.1 and for Bhoj in section 5.1.2.2.3, 1973 experienced maximum soil erosion.

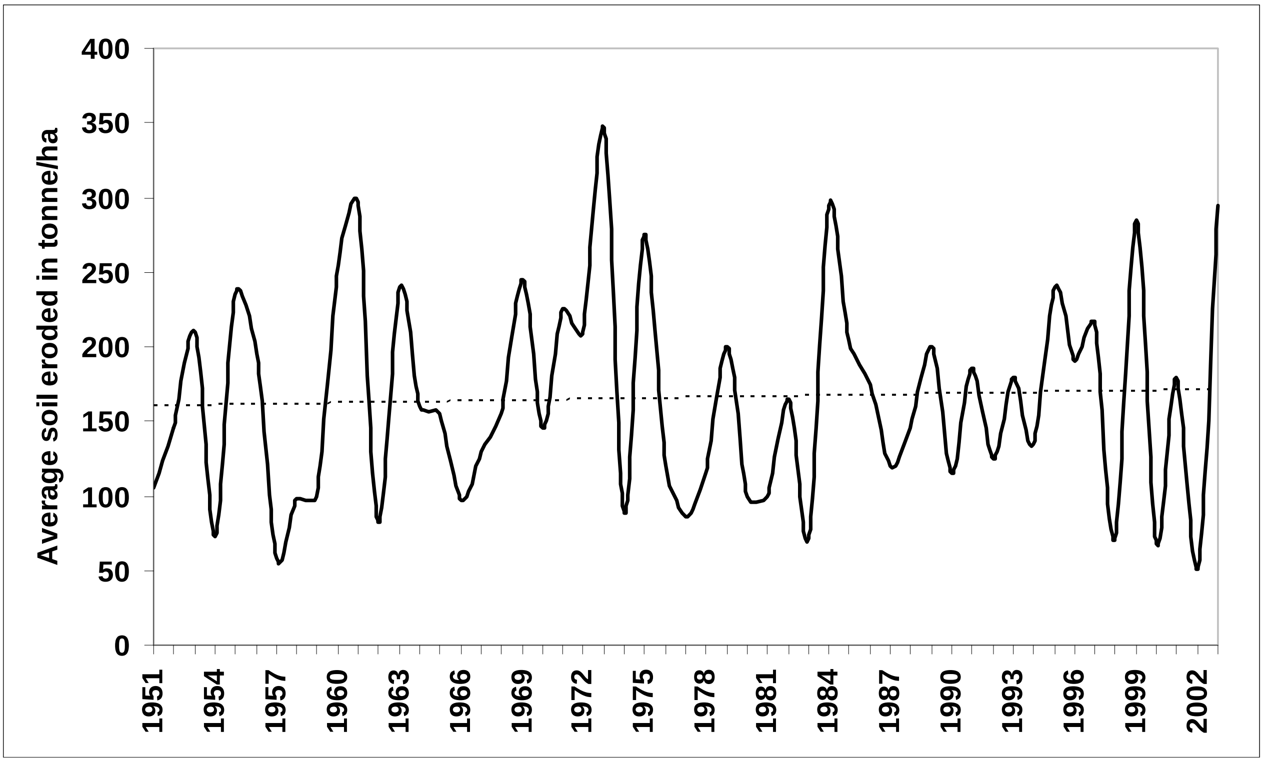


Figure 5.35: Annual variation of soil eroded in Sukinda in 1951-2003.

Figure 5.36: Decadal variation of soil erosion amounts in Sukinda in 1951-2003.

It was discussed in sections 3.10.3.2 and 3.10.3.3 (Table 3.22) in Chapter 3 that temperature is increasing in North Eastern temperature region, where Sukinda region is located. Therefore, this increase in temperature may aggravate soil erosion problem in this region as well in addition to an increase in annual rainfall (and/or extremes) since increase in temperature increases evapotranspiration and therefore decreases rainfall effectiveness to store soil moisture, as discussed in section 4.6.2.2.

If it is assumed that the 53-year annual rainfall pattern in Figure 5.33 will continue for the next 50 years, the trend would look like Figure 5.37, which also includes the projection for soil erosion. Both sets of data show that a 7% increase in average annual rainfall will lead to a 5% increase in soil erosion in the next 50 years, which is consistent with the data in Table 4.4 in section 4.3 (Ebeid et al., 1995).

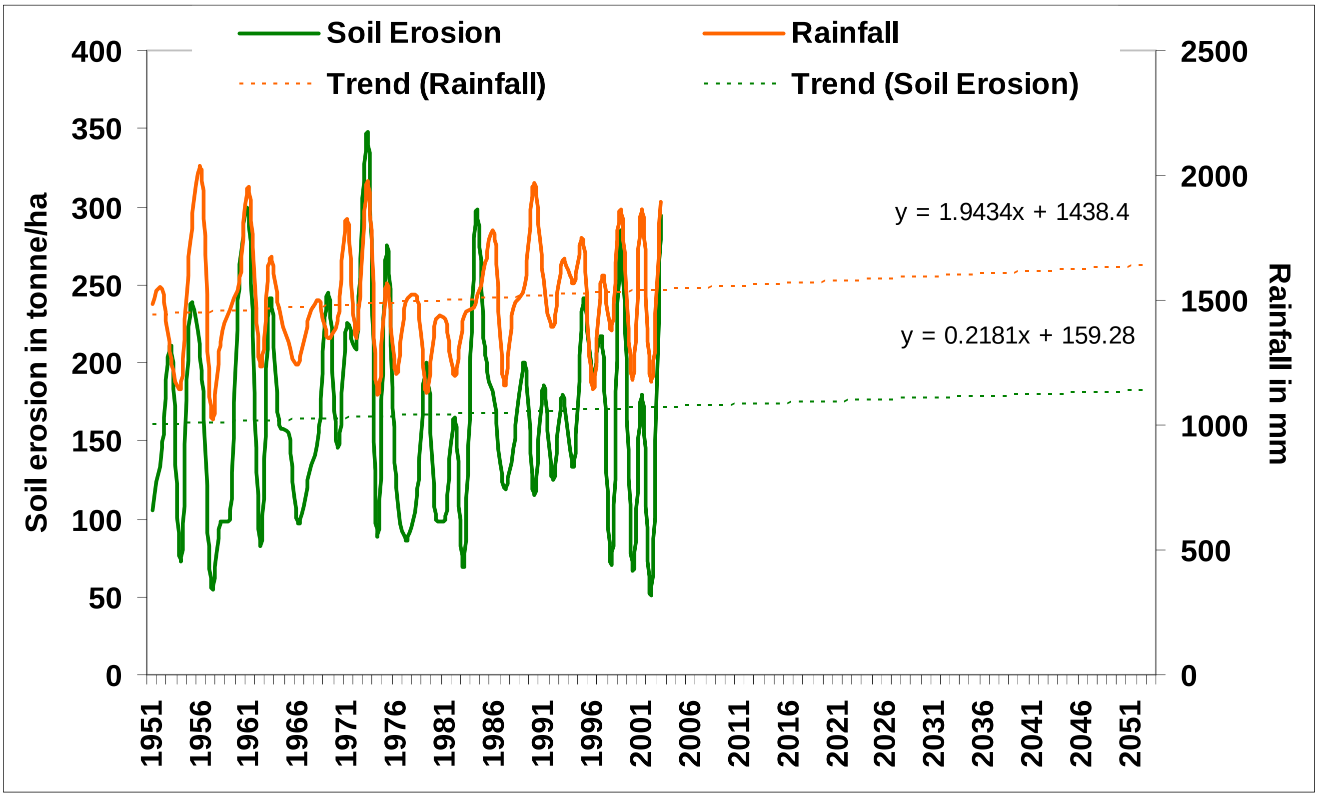


Figure 5.37: 50-year (2004-2054) rainfall and soil erosion projections using 53-year (1951-2003) data for Sukinda region.

5.2. Impact of Soil Erosion Trends on Contaminant Transport from the Study Sites

5.2.1. Introduction

This section presents the results of the work performed on the Bhoj and Sukinda sites in India for the assessment of the impact of rainfall data on contaminant transport with soil erosion. One major impact of soil erosion is the associated transport of contaminants from the polluted sites, as discussed in detail in Chapter 4 (section 4.4). It was also discussed that increase in soil erosion will very likely increase contaminant transport problem (sections 4.2.2, Table 4.2). Hence the study presented here related to both sites primarily focussed on rainfall patterns (and hence soil erosion pattern) on the potential for associated contaminant loss from both the sites. The knowledge gained by this study will assist the scientific community and the local government in taking the necessary steps to manage the problems in those regions.

5.2.2. Bhoj Wetland

One important impact of rainfall-induced erosion is the transport of contaminants with the runoff carried sediments impacting on the environment in general and the quality of water resources in particular, as discussed in previous chapter (section 4.4). This section presents simple quantification analyses of contaminants transported due to rainfall-induced erosion in Bhoj catchment. In addition, an assessment was also carried out to look at how the contaminants transported with sediments get affected by the regional rainfall pattern.

As mentioned in section 5.1.2.2.1, 70% of the 361 km^2 Bhoj catchment area is used for agricultural purposes. Therefore, 252.7 km^2 area was considered for this study. Table 5.6 shows the nutrient data available for the Bhoj site. Table 5.6 shows that potassium has the highest level of concentration at the top soil of Bhoj agricultural area. The phosphorous intake of the upper lake in Bhoj area is the highest and no information was available for the potassium intake in both the lakes. The WHO (1998) maximum permissible limits for nitrate and phosphorous in India are 10-50 mg/l and 0.40 mg/l respectively. From these permissible limits, it will be deduced whether the concentrations of nitrate and phosphorous in the runoff water from Bhoj is within those acceptable limits.

Table 5.6: Nutrients data for the agricultural sites in Bhoj wetland (Wanganeo, 2000).

Top Soil	Nitrate = 43.6-92.6 mg/kg Phosphorous = 1.7-8.7 mg/kg Potassium = 95.5-263.7 mg/kg
Phosphorous output from watershed	0.5-2 kg/ha/yr
Phosphorous in upper lake	In the system - 14.2 tonnes/year; Input – 31.53 tonnes/year
Nitrate in upper lake	Input – 3.543 tonnes/year
Phosphorous in lower lake	Input – 1135 kg/yr
Nitrate in lower lake	Input – 2452 kg/yr

Referring to section 4.5.1 and the expressions 4.22-4.25, sediment yield and the contaminants reaching downstream were also calculated. Since mass-conservation was the prime phenomena that was used for calculating the sediment load (Y in expression 4.22) and contaminant concentration reaching surface water (C_w in expression 4.25), Y and C_w followed the same trend as soil erosion in Figures 5.24 and 5.25 and therefore the trends corresponding to Y and C_w were not repeated here. But the maximum and minimum nutrients availability in the surface water based on the data in Table 5.6 were shown in Table 5.7 (column 4 and 5) along with the contaminants reaching at catchment outlet with the sediments as well.

Table 5.7: Average concentrations of the agricultural contaminants reaching the upper lake catchment outlet in Bhoj region.

Pollutants	***With Sediments in tonne/year***		***With Runoff in mg/lit***	
	Min	***Max***	***Min***	***Max***
Nitrate	14.45	30.69	0.87	1.84
Phosphorous	5.63	28.84	0.03	0.17
Potassium	316.6	874.1	1.9	5.24

As seen in Table 5.7, the results corresponding to phosphorous are quite consistent with Wanganeo (2000) in Table 5.6. They showed that, input of phosphorous in the upper lake is 31.53 tonne/year and output from the watershed (in Table 5.6) is 0.5-2 kg/ha/yr, which is 12.6-50.5 tonne/year, both of which are very close to the value corresponding to maximum phosphorous reaching the lake with the sediments (28.84 tonne/year). Zhang et al. (2004) investigated the non-point source pollution by phosphorus (P) posing threat to water in the Taihu Lake basin in China under simulated conventional irrigation-drainage management. He found that the P loss rate in this region was 0.74 kg/ha from a paddy field and 0.25 mg/lit with the runoff water from the drainage basin. Incidentally, those results are quite close to the findings for the Bhoj area as well, which estimated that the average total phosphorous reaching the outlet was 0.69 kg/ha and the maximum phosphorous transport is 0.17 mg/lit, as shown in Table 5.6.

5.2.3. Sukinda Valley

Research work on mining lands in India is limited to existing surfaces in terms of weathering and erosion processes in spite of the knowledge that these regions experience high intensity storms and have one of the highest erosion potentials in India (Babu et al., 1978; Singh et al., 1992). Runoff while overflowing from over burden dumps may get mixed with fine soil particles containing toxic hexavalent chromium and carry it to the surface water or nearby sites, as also discussed in Chapter 4, section 4.4.3. Also, Cr^{III}, which is insoluble in water, can get converted into Cr^{VI} through oxidation in the presence of natural rain water containing free oxygen and get dissolved into rain water (section 4.4.3). These scenarios make it very clear that rainfall-induced contaminant transport is quite important to address for the Sukinda valley. Therefore, this study carried out a quantitative risk assessment of soil erosion and contaminant transport in Sukinda region.

Table 5.8 shows the contamination data collected for the Sukinda chromite mining site from various resources as detailed in the table. As Table 5.8 shows, although the drinking water standard of hexavalent chromium is 0.05 mg/lit, it is present in much higher concentration in the river nearby.

Table 5.8: Contamination data for the Sukinda chromium mining site.

	Hexavalent Chromium content (Cr^{VI})
Top Soil	Total chromium (VI) = 1400 mg/kg; Insoluble Cr^{VI} = 29% of total = 400 mg/kg (James et al., 1996) In the waste rock samples collected from the study area **- <u>12-311 mg/kg</u>** (Ministry of Environment and Forests (MoFF))
Hexavalent chromium in Damsala River (1 – 10 km distance from mine)	0.018- 0.172 mg/l (in pre-monsoon); goes up to 0.201 mg/l (in monsoon) (Ministry of Environment and Forests (MoFF)) 0.03 to 0.567 mg/lit (Indian Institute of Soil Science (IISS)) 0.104-0.147 mg/l in downstream; 0.03-0.07 mg/l in upstream (Dakate and Singh, 2008)
Prescribed drinking standard	0.05 mg/l for class B and C categories of inland surface water
Ground water	0.001-0.018 mg/l (Dakate and Singh, 2008)
Mine water	0.366 to 1.993 ppm (Indian Institute of Soil Science (IISS))
Plant Leaves (in different plants)	20 to 250 ppm (Chromium) (Indian Institute of Soil Science (IISS))

Referring to section 4.5.1 and the expressions 4.22-4.25, sediment yield and the contaminants reaching downstream were calculated. Since mass-conservation was the chief phenomena that was also used here for calculating the sediment load (Y in expression 4.22) and contaminant concentration reaching surface water (C_w in expression 4.25), Y and C_w follow the same trend as soil erosion in Figures 5.35 and 5.36 and therefore the trends corresponding to Y and C_w were not shown here. But the maximum and minimum contaminants availability in the surface water based on the data in Table 5.8 were shown in Table 5.9.

Table 5.9: Decadal and 53-years average concentrations of the hexavalent chromium reaching the water body in Sukinda valley.

Years	***With Runoff in mg/lit***	
	Min	***Max***
1951-1960	0.121	3.14
1961-1970	0.140	3.63
1971-1980	0.145	3.75
1981-1990	0.126	3.27
1990-2003	0.133	3.45
Average	0.133	3.45

Although Figure 5.34 shows that the rainfall and runoff are the highest in the last decade (1991-2003), average decadal surface water contaminant concentrations, as shown in Table 5.9, show decade wise variations and do not follow the similar variation to Figure 5.34 since they are explicitly dependent on the amount of soil eroded and sediment transported. Furthermore, soil eroded is dependent on rainfall intensity. Therefore, maximum soil erosion and contaminant transport both occurred in 1973, the decade when maximum rainfall intensity as well as amount occurred, as seen in Figures 5.31 and 5.32.

Table 5.9 indicates that, contaminants available in surface water come in a range of 0.13-3.45 mg/lit, which is consistent with the monitoring results by The Indian Bureau of Mines (IBM) (Cottard, 2004). They showed that, as far as water resources are concerned, most wells and watercourses in the central part of the watershed of Sukinda valley are contaminated by Cr^{VI} up to a value of 3.4 mg/l in surface water and 0.6 mg/l in groundwater. However, although the top soil contamination data provided by the Ministry of Environment and Forests (MoFF) was used for this study, the results in Table 5.9 shows over estimation as compared to the data in Table 5.8 which might be because of the assumption that no contaminant is partitioned and reduced. Because of the highly solubility and reduction properties of Cr^{VI} in the presence of Fe^{II} and organic matter, Cr^{VI} could be expected to become reduced very easily to Cr^{III}, as discussed in section 4.4.3 (Khaodhiar et al., 2000; Echeverria et al., 1999; Fendorf, 1995). Since the soil in Sukinda region is lateritic soil, meaning there is high level of Fe content, part of Cr^{VI} might have reduced before reaching the surface water body and hence the inconsistency.

5.2.4. Comparison between Bhoj and Sukinda Sites

A comparative study between the case study sites was carried out based on the soil erosion potential. Comparison between Figures 5.20 and 5.31 indicates that, daily rainfall is more intense in Bhoj wetland than Sukinda Valley. However, average annual rainfall is less in Bhoj (1207 mm) than that in Sukinda (1490 mm), as in Figures 5.21 and 5.32. On the other hand, average annual runoff generated in Bhoj (660mm) is slightly higher than Sukinda (640 mm) (Figures 5.22 and 5.33). This is primarily because of more evaporation in Sukinda due to higher air temperatures. Also Bhoj soil is rich in clay and organic matter (> 50%), and therefore the infiltration capacity of the soil is less and the runoff potential is higher (see Table 5.3). Because the rainfall is more in Sukinda, rainfall erosivity is more in this region, as in Figure 5.32; however, the soil in this region is rich in sand (> 33-65%), as in Table 5.5. Therefore, average annual soil erosion is lesser in Sukinda (165 tonne/ha) as compared to Bhoj (240 tonne/ha), as in Figures 5.24, 5.25, 5.35 and 5.36. Therefore, less runoff and less soil erosion carry less contamination from Sukinda mine to the water body as compared to Bhoj. However, Cr^{VI} is far more toxic than the nutrients in Bhoj even in much smaller quantities. Therefore, both sites are quite vulnerable to soil erosion and contaminant loss and therefore necessary steps should be taken to reduce such processes.

5.3. Qualitative Determination of the Risk of Contaminant Loss from the Study Sites

5.3.1. Introduction

When extensive site specific data are not available, a knowledge survey can provide some idea on risk of contaminant transport from the surface soil but as a qualitative substitute, as discussed in Chapter 4 (section 4.5.2). While the previous section (5.2) looked at the quantitative estimate of the contaminants transporting downstream with runoff carried sediments and how it changes both with the rainfall intensity and amount at a particular site, this section deals with the potential of the contaminant transport from the study sites to a nearby water body in qualitative terms taking into account various transport and site management factors affecting the same, as described in detail in sections 4.5.2.2 and 4.5.2.3 in Chapter 4 (Table 4.8).

The methodology of determining phosphorous (P) loss potential from a site was described in (Sharpley et al., 2001) and also briefed in Chapter 4, section 4.5.2.4. The P-loss potential for Bhoj region was determined following that methodology and the results are illustrated in section 5.3.2. A qualitative study was also carried out for the risk of contaminant loss from Sukinda valley and presented in section 5.3.3. Although contaminant transport potential was determined for Sukinda, management factors for Sukinda site was difficult to determine because of insufficient data availability. Only an average concentration of Cr^{VI} was available but according to section 4.5.2.3 and 4.5.2.4 and Table 4.10, many more site specific information such as partitioning coefficient value of Cr^{VI}, the break points between low, medium and high indices were still needed in order to determine site management value (see Tables 4.10 and 4.11). Therefore, only the 'transport potential' for Cr^{VI} was determined for the site of Sukinda valley.

This qualitative information on contaminant loss from land to water could be used to define and support contaminant transport management strategies that protect the water quality.

5.3.2. Bhoj Wetland

A P-loss index is a qualitative assessment of P-loss from a contaminated site (Sharpley et al., 2001). This index was primarily developed by the NRCS in the US, as described in section 4.5.2.4 based mainly on the general assessment of the site conditions. The site conditions include transport and site management factors, as mentioned in Table 4.8. The risk of P-loss from the Bhoj region was determined using the methodology steps in section 4.5.2.4 and Tables 4.9-4.11 (Sharpley et al., 2001).

The average annual soil loss value from the Bhoj site (240 tonne/ha-yr), which is required as a transport factor (Table 4.9), was taken from the previous study in section 5.1.2.2.3, Figure 5.24 (53-year average). Tables 5.10 and 5.11 show the qualitative results. Table 5.10 displays all the transport characteristics (column 1) that are taken into account to find out the contaminant transport potential and their field values (in terms of numerical numbers only) that include soil erosion, soil runoff class, subsurface drainage, leaching potential and connectivity of the site to the nearby water body based on the information available from Tables 5.1 and 5.3. Since the soil in Bhoj region has the highest runoff and very low permeability (see Table 5.3), the soil runoff class was taken to be the highest (= 8 from Table 4.9) and subsurface flow/leaching potential were taken to be very low (= 0 from Table 4.9) in Table 5.10.

Table 5.10: P-loss potential in Bhoj region due to transport characteristics in the contaminant index.

Transport Characteristics	***Field Value***
Soil Erosion	**240**
Soil Runoff Class	**8**
Subsurface Drainage	**0**
Leaching potential	**0**
Connectivity	**8**
Total site value (sum of erosion, surface runoff, leaching, and connectivity values): T_1 = 256 Transport potential for the site (total value/23): = 256/23 = 11.1 >> 1.0	

In order to find out whether the contaminants from the Bhoj site actually reach the lakes, it is necessary to know whether runoff water leaving the site is actually reaching there, as was discussed in section 4.5.2.2. Therefore, location of the study site with respect to the water body will determine whether runoff from the field actually leaves the site and reaches the lake. Therefore, 'connectivity' factor in Table 5.10 was considered to be 'connected' (= 8 from Table 4.9) i.e. the site is just next to the water body i.e. surface runoff from the field always enters the water body.

To determine the transport potential for Bhoj region, soil erosion, surface runoff, leaching potential and connectivity were first summed up, and then divided by 23, the value corresponding to 'high' transport potential as of NRCS (erosion is 7, surface runoff is 8, leaching potential is 0 and connectivity is 8), as also mentioned in section 4.5.2.4. The transport potential for the Bhoj site was calculated to be 11.1 in Table 5.10, which is much higher than the maximum transport value (= 1). Even though Black Cotton Soil in Bhoj has moderate silt content and moderate to high organic matter (Table 5.3), the very low permeability of the soil and high rainfall in Bhoj region leads to high soil erosion and surface runoff (refer to section 5.1.2.2.3 and Figure 5.22) and therefore high contaminant transport potential from this area that is much higher than the highest potential assigned by the NRCS.

Like P-loss potential due to transport factors, P-loss due to site management characteristics was also determined for Bhoj following sections 4.5.2.3 and 4.5.2.4 in Chapter 4 (Sharpley et al., 2001). The site management characteristics include contaminant concentration in the top soil, information of the applied nutrients and application timing. The soil test contaminant value was taken to be the maximum value of phosphorous in the top soil of Bhoj (= 8.7 mg/kg in Table 5.6). Therefore, the loss rating value of P in Table 5.11, according to Table 4.10 was found to be 1.74 (= 8.7 × 0.2), which took the fraction of soil contaminant value in runoff water (= 0.2 in Table 4.10) into account. The information for fertiliser P rate, manure P rate and their application methods and timings for the agricultural areas of Bhoj in Table 5.11 were collected from Wanganeo (2000) and thus loss rating value of fertiliser P and manure P were calculated following Table 4.10 (Sharpley et al., 2001). Total site management value for Bhoj site was found to be 247.74 (summation of all loss rating values marked as bold numbers in Table 5.11).

Table 5.11: P-loss potential due to site management characteristics in the P index.

Site Characteristics	***Field Value***
Soil test contaminant	8.7
Soil test contaminant loss rating value	**1.74**
Fertilizer P rate (agro only)	210
Fertilizer application method and timing (agro only)	0.6
Fertilizer loss rating value (agro only)	**126**
Manure P rate (agro only)	200
Manure application method and timing (agro only)	0.6
Manure P loss rating value (agro only)	**120**
Total Site Management Value (sum of soil, fertilizer, and manure P loss rating values) for Bhoj site: T_2 = 247.74	
P index rating for Bhoj = transport potential value × Site management value /145 Transport Potential Value = 11.1 (Table 5.10) Site Management value/145 = 1.71 P index rating for Bhoj site = 19 < 30; therefore, LOW potential for P loss.	

Taken together the transport potential and site management values, the Phosphorous index, as calculated using the information in Table 4.11, was found to be 19 (in Table 5.11). This value was less than the value 30 in Table 4.11, which means LOW potential for P loss. Therefore, the chance for adverse impacts on surface waters is low although the contaminant transport potential is very high, as in Table 5.10. Therefore, minor remediation could be taken to minimize the probability of P reaching the water body but care should be taken to reduce the contaminant spreading onto other areas nearby (Table 4.11). Although, this study is purely based on the methodology adopted for the US, it gives some idea in terms of assessing the risk of P loss from the Bhoj site.

5.3.3. Sukinda Valley

Like Bhoj wetland in section 5.3.2 and following the method in section 4.5.2, a general assessment was also carried out to find out the transport potential of Cr^{VI} from Sukinda. The site conditions included transport factor only (Table 4.9) and not the site management factor (Table 4.10) because of absence of data.

The value of average annual soil loss from the Sukinda site (165 tonne/ha-yr) was required as a transport factor (Table 4.9), which was derived from the study as discussed in section 5.1.2.3.3, Figure 5.35. Table 5.12 shows the qualitative results. Like Bhoj in Table 5.10, Table 5.12 displays all the transport characteristics taken into account for Sukinda to find out the contaminant transport potential that include soil erosion, soil runoff class, subsurface drainage, leaching potential and connectivity of the site to the nearby water body based on the information available in Table 5.5. Since the soil in Sukinda has moderate infiltration and moderate permeability (see Table 5.5), the soil runoff class was taken to be medium (= 2 from Table 4.9) and subsurface flow/leaching potential were also taken to be medium (= 2 from Table 4.9) in Table 5.12.

Table 5.12: Cr^{VI} loss potential due to transport characteristics in the contaminant index.

Characteristics	***Field Value***
Soil Erosion in (tonnes/ha/year)	**165**
Soil Runoff Class	**2**
Subsurface Drainage	**2**
Leaching potential	**2**
Connectivity	**2**
Total site value (sum of erosion, surface runoff, leaching, and connectivity values): T_1 = 173 Transport potential for the site (total value/23) [d]: = 173/23 = 7.52 >> 1.0	

In order to determine whether the contaminants from the Sukinda valley actually reach the river, its location with respect to the water body will determine whether runoff from the field actually leaves the site and reaches the river. Since the river is 1-10 km distant from the mine site, the ‘connectivity’ factor was considered to be ‘partially connected’ (= 2 from Table 4.9) in Table 5.12 i.e. the site is near but not next to the water body and surface runoff from field sometimes enters water body e.g. during large intense storms.

As in the previous section, the transport potential for the Sukinda region was calculated to be 7.52 (Table 5.12), which is again much higher than the maximum transport value (= 1) but lower than that of Bhoj. Because of high erosion and moderately high runoff, contaminant transport potential with runoff sediments is high in Sukinda region. Therefore, immediate soil and water conservation measures are needed and a management plan must be implemented to minimise the contaminant loss from the site.

5.4. Effects of Rainfall and Temperature Changes on Soil Carbon Sequestration at the Study Sites

As presented earlier in Chapter 4 soils play an important part of the carbon cycle (section 4.6.2). The primary route through which carbon is stored in the soil is as soil organic matter (SOM). SOM provides important benefits for soil, crop and environment quality, prevention of erosion and desertification, the enhancement of bio-diversity, and decrease in toxicity of pollutants in a soil through fixation, discussed earlier in section 4.6.2.1. Therefore, top soil management through soil carbon sequestration process will be an effective option for both the study sites to reduce their erosion and contaminant transport potential. On the other hand carbon sequestration potential of a soil changes with change in climate, as also discussed earlier in Chapter 4 (section 4.6.2.2). All the information as discussed in section 4.6.2.2 in Chapter 4, are together displayed here schematically in Figure 5.38. An assessment was performed to see how the top soil management option that enhances soil organic matter to improve soil health are changing with rainfall and temperature changes in Bhoj and Sukinda sites, which is presented in qualitative terms below.

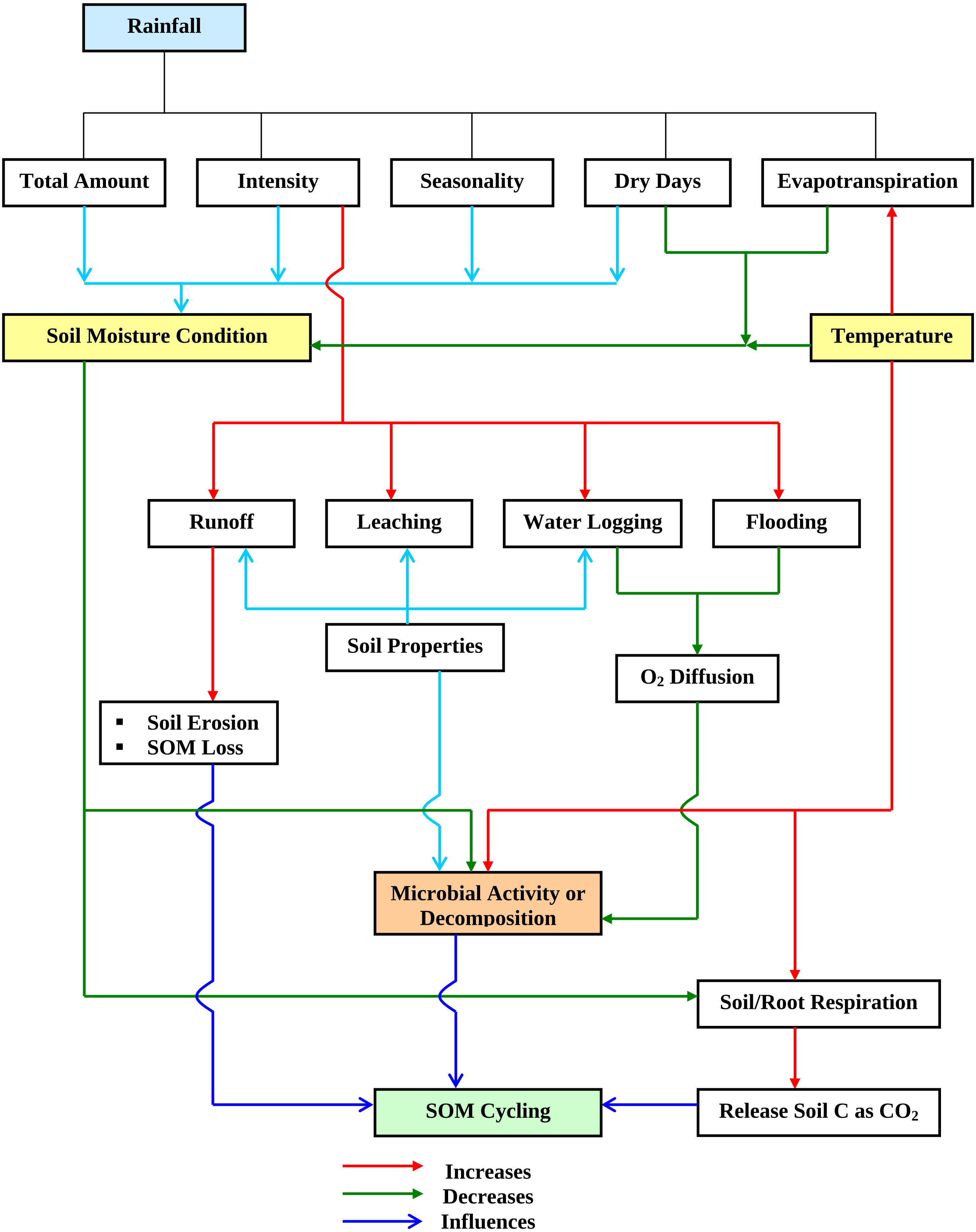


Figure 5.38: Climate factors affecting soil carbon cycle.

Evidence from this research work suggests that the changes in rainfall and temperatures are regionally variable in India. Bhoj is situated in the West Central India (WCIN) and Sukinda is situated in Central North East India (CNEIN). Both regions had warmed significantly with maximum (day time) temperatures increasing more rapidly than the corresponding minimum (night time) resulting in a rise in the mean temperature (refer to section 3.10).

The analysis performed in this chapter also suggests that annual rainfall has been increasing both in Bhoj and Sukinda, as in Figures 5.22 and 5.33 while seasonal rainfall variabilities were quite strong for both the regions (sections 5.1.2.2.2 and 5.1.2.3.2). Increasing pattern of annual extreme rainfall intensity, frequency and percent contribution to total rainfall in both regions (Tables 5.2 and 5.4) is likely to have a significant impact on soil moisture conditions (Figure 5.38). Furthermore, seasonality of changing extremes and changing pattern of total number of dry days in both regions are also important factors to consider because they will also have an impact on soil moisture conditions.

As discussed in Chapter 4 (section 4.6.2.2), both moisture and temperature are known to be primary drivers for plant growth and litter decomposition (also in Figure 5.38). The balance between these two processes influences the cycling of soil organic matter (SOM) and associated microbial processes. In addition, belowground CO_2 is a function of several other interrelated factors such as root respiration, soil type, and season, as shown in Figure 5.38. Temperature-soil moisture-organic matter interaction is a very complex process that depends on the interface of many factors, as also evident in Figure 5.38. Therefore, it is difficult to predict precisely what would happen to soil carbon sequestration at the case study sites due to climatic changes unless until simulation studies under various possible conditions are carried out.

It is however speculated that even if annual rainfall volume is increased in both areas, rainfall effectiveness could be greatly reduced through evapotranspiration or a decrease in the number of rainfall events. Increase in maximum and minimum daily temperatures (refer section 3.10) will most likely increase evapotranspiration in both regions.

Presumably, increased evapotranspiration should render both areas drier than present. Since annual extreme rainfall events have increasing tendencies in both places, either much of the excess rainfall would be lost through surface runoff, or it might enhance leaching – which entirely depends on the soil properties (Figure 5.38). Soil carbon could be lost due to enhanced soil erosion and soil organic carbon transport from the study regions, thus counteracting soil carbon sequestration.

In some cases, increase in temperature may enhance soil respiration and therefore releasing soil C as CO_2, as also seen in Figure 5.38. High temperature also enhances microbial activity but excessive moisture restricts the same. It is therefore speculated that the increase in extreme rainfall events may increase water logging in both regions and particularly in Bhoj resulting into further decrease in microbial decomposition. Bhoj wetland holds black cotton soil (Table 5.3) which is rich in clay and organic matter content and therefore holds more water than Sukinda site soil. That is why the tendency of water logging in Bhoj is more. On the other hand, flooding slows oxygen diffusion to decomposition, which includes fewer and generally slower decomposition. These effects are slow and will be over shadowed in the near term by changes in management or erosion.

Although soil respiration is largely controlled by soil temperature, soil moisture is also a major factor that may influence soil respiration in different ways (Figure 5.38). Low soil water content strongly limits the response of root and microbial activity to temperature. High water content can hinder the diffusion of O_2 in soil. On the other hand, low soil water content can inhibit soil microbial activity and root respiration (Figure 5.38).

Increased soil organic matter will store atmospheric carbon and result in greater soil fertility, better soil tilt, greater water holding capacity, and reduced erosion. It also will make plants more stress resistant and thus able to better withstand the greater predicted climatic fluctuations. However, interaction of soil organic matter with temperature and rainfall changes is complex and subject to more detailed investigation.

5.5. Managing Soil Erosion

The previous sections discussed soil erosion in various study sites and how it is affected by climate change at different magnitudes. It was also shown that contaminant transport increases as soil erosion increases and vice versa. Therefore, in order to manage soil erosion to protect the surrounding environment from contaminant spreading, top soil management is necessary, which also forms part of the land management option that was discussed in section 4.6 in Chapter 4. Not only does soil erosion cause the loss of soil organic matter, less SOM also cause more soil erosion. Exploring the various options, this section assesses the type of management action that could be employed for the different study regions.

Planting and maintaining vegetation cover seems to be a natural and cheap way to manage soil erosion and enhance soil carbon sequestration, as also specified in section 4.6.1.2. This is such an option that could be employed for all types of lands. While any type of management plan that could be applicable for agricultural soils could be employed for Bhoj and Kerala soils for those are mainly agricultural grounds, vegetation that can live in chromium rich soil is needed to find out for Sukinda. Plant cover is expected to reduce soil erosion drastically, as noticed for Kerala (Figures 5.10 and 5.11) and the same could be expected for Bhoj and Sukinda as well. Since the highest erosivities usually occur in monsoon season in India, care should be taken not to keep the lands bare in this season.

In addition to planting vegetation, artificial methods such as matting and the application of biochar and mulch are some of the options that could also be considered for the study regions. But matting is usually used for private gardens and it is also an expensive option. On the other hand, the use of biochar is becoming more popular because of its multiple actions to enhance soil fertility and quality. Therefore, this could be considered as an effective option to manage agricultural lands in Bhoj and Kerala. However, it is not known whether this option will be suitable for Sukinda valley. Retaining walls are usually effective to control sediment and contaminant transports only. Therefore, this option could be employed for any type of land to retard overland flow.

CHAPTER 6

CONCLUSIONS AND FUTURE RECOMMENDATIONS

6.1. Conclusions

The objective of this research was to look at Indian rainfall trends and their implications on soil erosion, contaminant transport and land management. The whole work was done in two parts. The first part was to assess the rainfall and temperature patterns of India and world wide at different spatial and temporal scales using existing literature and the rainfall and temperature data collected for Indian region. And the second part was the preliminary application of the study carried out in the first part using quantitative and qualitative methods. Detailed review of the literature relating the first and second parts of this research were documented in Chapters 2 and 4, and all the results relating to the new work performed on Indian climate patterns, soil erosion, contaminant transport and top soil management were discussed in Chapters 3 and 5. This section summarises the findings from the research presented in all those chapters.

6.1.1. Part I: Indian Climatic Pattern

6.1.1.1. Literature Review

Chapter 2 presented a comprehensive literature review that brought forward the up to date knowledge on Indian and global climatic patterns. Various datasets relating to rainfall and temperature those were used to assess Indian climate patterns were also presented in this chapter. The key findings from the literature review are summarised below.

6.1.1.1.1. Indian Rainfall Patterns

53-year (1951-2003) high resolution daily gridded rainfall data that was used for a major part of this research was found to be a better dataset than the global gridded rainfall data. The previous studies those used this high resolution daily gridded rainfall data indicated that monsoon rainfall is the highest along the west coast of India and north-east India, and lowest over the north-west and south-east India. Very heavy rains have gone up in central, north-west coast, north and north east India and decreased in western and south-western Indian regions, and the spells of moderate rain have been going down in central India. Both the temporal length and spatial coverage of summer monsoon rainfall are decreasing and especially in the continental Indian region.

The 135-years (1871-2005) monthly rainfall data for India that was also used in this research was found to be relatively older than the daily gridded rainfall data. However, this monthly dataset has been in use extensively for various research purposes in India and found to be equally good as Climate Research Unit, University of East Anglia dataset. The previous studies those used this dataset indicated a decreasing tendency of monsoon rainfall over central, western and north-eastern Indian regions, which were also found to be related to the Pacific ENSO phenomena. In the recent years, however, the ENSO-monsoon relationship has been noticed weakening.

While a number of studies were performed on Indian monsoons previously, negligible number of studies was carried out for the other seasonal rainfalls in India, which might have important socio-economic consequences. In addition, change in seasonal/annual rainfall total or extreme at very local level often causes the biggest impacts, which has also been least considered in the literature. These issues were taken into account in this PhD research and the findings are summarised later.

6.1.1.1.2. Global Rainfall Patterns

In addition to the patterns of annual/seasonal rainfall totals in India research was also carried out on the changes in global rainfall patterns. Global Circulation Models predicted an increase in global rainfall over the oceans and high latitudes; whereas, drought is projected to rise throughout the 21st century on the tropical land regions. The changes in rainfall in the local regions can be different than changes in global averages. For example, in addition to India, decreasing trends of seasonal and annual rainfalls were observed for Iberian Peninsula, Indonesia, Italy, Hungary, Mid Atlantic regions, South-Eastern Australia, Sri Lanka, major part of Japan, southern Beijiang region of China, sub Antarctic Marion Island, Turkey, UK, western Tibetan Plateau and Zimbabwe. Wherein, increasing trends in annual/summer rainfall were observed for eastern and central parts of Tibetan Plateau, Norway, northern Beijiang region of China, Spain and the USA and in winter rainfall for Canada and a part of Japan adjacent to the sea. Such changes were connected to the changes in frequency of surface circulation patterns, proximity to the sea, and Pacific ENSO.

6.1.1.1.3. Global Extreme Rainfall Patterns

With changes in seasonal/annual rainfall total in India and worldwide, research showed that the global warming is also leading to a variable probability of extreme rainfall events, both in terms of intensity and frequency. It was found that the extreme rainfalls have increased almost everywhere in the globe and the relative change in extreme rainfall is larger than change in total rainfall. Model studies also predicted that there will be a greater frequency of heavy rainfall and high-quantile events, although with substantial geographical variability. While global datasets usually refer to increase in rainfall extremes, regional studies tend to give different results since changes in total and extreme rainfall vary depending upon geographic location.

Statistically significant increase in heavy rainfalls was found in Asian part of Russia, northern Japan, Natal in South Africa and Nord-Este Brazil while mean rainfall total in those regions did not change or even decreased and the frequency of rainfall events was decreased during the same period. Increases in heavy rainfalls were also observed in most parts of Australia that was correlated with the total rainfall. As for New Zealand, South Africa, Europe, Asia and the USA, extreme rainfall patterns were different in different parts. No trend in extreme rainfall was noticed in Belgium, decreasing trends were noticed for Italy, Norway, Spain and the southern UK, and increasing trends were noticed in Germany, northern England and Scotland. Number of raindays was found to be decreasing significantly throughout south-east Asia and the western and central south Pacific but increased in the north of French Polynesia and Fiji.

Model studies indicated that the trend patterns in extreme rainfalls in the continental areas in the period of 2000-2099 will follow the tendency for 1900-1999 but with significantly increased magnitudes. Negative trends were found in the number of wet days over most of the land areas except high latitudes in the Northern Hemisphere suggesting more and more intense rainfalls in shorter interval of time. A shift was noticed in the probability distribution functions of tropical rainfall during the period of 1979-2003, which featured a positive trend in the occurrence of heavy (top 10%) and light (bottom 10%) rain events and a negative trend in moderate (25-75%) rain events.

6.1.1.1.4. Extreme Temperature Patterns in India and Globally

In addition to the study relating to the change in rainfalls, research was also carried out on the change in extreme temperature patterns in India and worldwide. The 103 years (1901-2003) maximum and minimum temperature data that was used in this study had also been used previously, which revealed that the range of diurnal (difference between maximum and minimum) temperature has increased in India and the recent period of 1971-2003 is the period of accelerated warming. There have been increases in the warm summer nights and decreases in the number of frost days globally. On the other hand, region-wise, the data showed differential patterns. The maximum temperatures have increased in European countries (Germany, France, Italy, Turkey), South Africa, southern Egypt, Australia and New Zealand; decreased in China, northern Egypt; and no trend and irregular variation was found for the US and central Africa respectively. The minimum temperatures have increased both in China and the US. Winter warming has been more pronounced than summer in Western Europe.

6.1.1.2. Results and Discussion

Chapter 3 discussed the results from the analyses carried out mainly on Indian rainfall data and partly on extreme temperature. The findings are as below,

6.1.1.2.1. Changes in Monsoon Rainfall in Indian Regions

Long-term trends of extreme monsoon rainfall deficit and excess were assessed for five Indian regions using non-parametric Mann-Kendall technique. It was noted that north east Indian region (NEIN) receives maximum annual rainfall which is followed by west central India (WCIN) and central north east India (CNEIN). All the five regions comprising of the whole of India (except north most hilly regions) were found to be distinct with respect to the interannual variability and seasonal cycle of monsoon rainfall. WCIN had the greatest interquartile range. Rainfall recessions were found occurring leading to an increase in deficient monsoon years in most parts, except peninsular Indian region. However, the magnitudes of the regional differences in the results were very high. The recession was relatively strong in the north-east, west-central and central north east India, the regions of usual maximum monsoon rainfall, making the north India most vulnerable to summer droughts and water shortage.

An analysis was further carried out to detect regional trends of the severities of the meteorological droughts and floods in India over the period of 1871-2005. It was found that the probabilities of moderate droughts were frequent in almost all parts of India. However, the magnitudes of the regional differences in the results were high due to small spatial correlations for rainfall. Drought probability was the highest in NEIN and followed by WCIN; and peninsular India (PENIN) had an entirely opposite trend.

Another study that was carried out on the periodical cycles of monsoon rainfalls in various study regions of India showed that the decadal changes have been much more versatile and statistically significant than at half decadal basis. Highest variability of monsoon rainfall was usually accompanied with prolonged dry spell at most of the regions. Monsoon rainfall exhibited a decreasing trend everywhere except peninsular

India and Costal Karnataka contributed the most to this differential behaviour of Peninsular Indian monsoon.

Increasing frequency and intensity of meteorological summer droughts in various parts of India was attributed to rise in temperature in the drier summer months, reduction of the number of rainy days and increase in ENSO events. All ‘extreme’ all-India monsoon seasonal droughts were found occurring in El-Niño years and ‘severe’ floods coincided well with La-Niña. The influence of ENSO varied among the regions. PENIN and NWIN, which are at the side of Arabian Sea or Indian Ocean, were found undergoing maximum associations between monsoon rainfall variability and ENSO.

From the above findings it was clear that the patterns of mean trends for all the Indian regions were not similar and most notably the behaviour of peninsular India, which was entirely different in all aspects of seasonal rainfalls from the other regions in India. Therefore, a region specific study is always important and essential in order to better understand the local climate that is vital for various local developments.

6.1.1.2.2. Changes in Other Seasonal Rainfalls in Indian Regions

In addition to monsoons, this research also looked at the significant changes in three other seasonal (winter, spring and autumn) rainfalls in various regions in India at different scales. Two methods were employed for estimation of the magnitude of the trends. It was noted that the trends in various seasonal rainfalls had considerable regional variations in India. No significant trends were found in annual or seasonal rainfall totals for the period of 1871-2005 but significant changes were observed for the period of 1954-2003. Rainfall had variable tendencies for various Indian regions; an increasing tendency was noted in the winter and autumn seasons and a decreasing tendency in spring and monsoon seasons in Kerala state, the place where monsoon onset initiates every year. Therefore, a negative trend in pre-monsoon seasonal rain or late spring over Kerala would very likely cause significant decrease in monsoon rainfall in the other regions in India as well.

The parametric and non-parametric estimates of trend magnitudes and directions agreed well with each other and fell well within the significant level, except a few. Therefore, the normality assumption of the Indian seasonal or annual rainfall amount for the parametric method usage for trend detection was found to be harmless.

6.1.1.2.3. Changes in Extreme Rainfalls in Kerala

Using gridded daily rainfall data, an assessment was made to present a previously unseen local picture of changes in daily monsoon rainfall extremes during second half of the 20^{th} Century. The extreme rainfall characteristics were analysed for the entire Kerala state divided into a total of six grids for the 50-year period of 1954-2003. Various categories of indices were considered for the analysis, which described a variety of characteristics of the extremes that are easy to understand. With the help of these indices and their trends a better understanding of observed monsoon rainfall extremes was gained for the Kerala state.

A first impression for all the indices was the substantial intra-grid differences as regards to trend patterns and magnitudes due to poor spatial correlations for monsoon rainfall even at gridded scales in Kerala. It was found that, between 1954 and 2003, almost all the gridded regions exhibited tendencies toward drier conditions and a decrease in total rainfall quantity and the number of raindays although not all showed statistically significant changes. For some indicators, significant changes were noted in rainfall extremes especially in the period of 1979-2003 but not in 1954-1978. Also, it was found that despite an overall trend towards drier summers in Kerala was found, an emerging frequency of destructive flash floods are also likely to be seen in some places in the current and next decades. Fairly to significantly high positive correlations revealed that the upper 1 to 5 percentiles of the monsoon daily rainfall, number of rain days, number of low-moderate and heavy rainfall (at certain regions) are very important decisive factors for the total monsoon rainfall in Kerala region.

A further study was carried out on the changes in other three seasonal extremes in the gridded regions of Kerala and the entire state as a whole using certain indices. Although the mean and standard deviation of daily seasonal rainfalls over all the gridded regions were comparatively homogeneous, trends in seasonal extremes were not regular throughout the state. A change in the regional circulation pattern because of temperature changes might be the cause of differences in spatial variations. Kerala had positive trends in the winter total rainfall, extreme amount, and intensity, and negative trends in the frequency of the dry days, which were always true especially for the higher elevation and north most grids. In contrast, Kerala has been undergoing a significant decrease in the spring rainfall in all the grids due to increasing number of dry days. Spring season also showed negative significant trends in amount, intensity and frequency. Studies relating seasonal extremes in Kerala are expected to help to define and assess the risk of flooding and droughts, agricultural planning and other developments associated with the mitigation and adaptation strategies for climate change in the state of Kerala.

6.1.1.2.4. Changes in Extreme Temperatures in Indian Regions

Variability of the monthly and seasonal extreme temperatures and their trends were also investigated over India in the time period of 1901-2003. It was found that Indian region had warmed significantly with maximum temperatures increasing more rapidly than the corresponding minimum resulting in a rise in the mean temperature over India. Minimum temperature changes were of lesser significance but had more variability than maximum temperature changes. The highest variation in the monthly maximum and minimum temperatures in most of the regions in India studied was found to be in the months of January and February. With the highest variation and highest temperature increase, Western Himalaya was the most vulnerable region to climate change in India. The least variation in maximum and minimum temperatures in all the regions was found to be in the month of August. Therefore, winter season is the highest variable and monsoon season is the least variable in terms of extreme temperature in most of the regions in India.

The maximum and minimum temperatures increased quite unevenly, over all the months in 1901-2003. However, there were few significant exceptions for the case of minimum temperature especially in the months of June to September. Significant maximum seasonal temperature increases spatially ranged from 0.37°C-1.6°C/100years (minimum in monsoon and maximum in winter and autumn). In the North East, West Coast and Western Himalaya regions, the magnitudes of the trend of maximum temperature warming were highest in winter and autumn because of the largest changes in November, December and February. Highest maximum temperature changes in spring and monsoon seasons, among all the 7 regions of interest, were also found in North East and West Coast.

November, December and February were vital for winter and autumn seasonal trends of minimum temperatures. Autumn had the greatest changes in minimum temperature because of changes in November. Monsoon seasonal minimum temperatures had decreasing trends (cooling) in northern India and increasing trends (warming) in southern India (Interior peninsula and West Coast). Significant minimum seasonal temperature increase spatially ranged from 0.1°C-1.1°C/100years (min in spring and max in autumn).

Overall, the majority of the findings regarding extreme temperatures showed the importance of site-wise changes in both minimum and maximum monthly, seasonal and average annual temperatures in India, which were consistent with the global temperature changes due to green house gases in the atmosphere. This warming affects the severity of droughts as it means greater evaporation. Since the average monsoon rainfall across the whole of India is decreasing giving rise to more droughts and water shortage, this together with the increases in temperature is a strong indicator for economic and social developments in India.

6.1.1.2.5. Future Rainfall Projections

The last part of Chapter 3 was about the 50-year future projections (2004-2053) of the seasonal and annual rainfall trends for all the Indian regions. It was found that there could be a maximum increase in winter average rainfall in North West India (46%), which is followed by PENIN (30%). A 25% increase in all-India, 24% increase in

WCIN and 23% increase in NEIN in winter average rainfall is expected to occur in the next 50-years from the 1954-2003 average. On the other hand a 19-63% increase in north India and a 38-39% decrease in south India in average spring seasonal rainfall is expected in 2004-2053 from 1954-2003 average. An increase in average spring seasonal rainfall in CNEIN and NEIN regions means that the pre-monsoon disasters will very likely increase. As for monsoon rainfall, studies showed that the maximum decrease in average amount will most likely occur in NWIN (18%) and followed by WCIN (16%), which have harmful indication for the agriculture. A large decrease (70%) in average autumn rainfall is expected to be in 2004-2053 in NWIN but an increase (44%) in the same is expected in its immediate neighbouring region of CNEIN.

6.1.2. Part II: Impacts of and Adaptation Strategies for Observed Regional Climatic Patterns in India

6.1.2.1. Literature Review

Chapter 4 documented existing knowledge relating impact of climate change on soil erosion, effect of soil erosion on soil properties and contaminant transport, and top soil management. The findings are summarised below.

6.1.2.1.1. Climate Change and Soil Erosion

The climate change is expected to increase risks of soil erosion by affecting hydrological cycle, increasing intensity, amount and seasonality of rainfall, which can exacerbate soil degradation and desertification. Change in rainfall affects soil erosion processes by altering soil features, vegetation, cultivation systems, plant litter and landform. Decrease in rainfall rates may not always result in lower soil erosion rates because the magnitude of soil erosion changes depends on local and regional conditions and a combination of various physical and management factors. Sedimentation of downstream water bodies due to runoff is also a concern under the changing climate since sediment yield has a non-linear response with respect to storm patterns, soil water deficit and vegetation cover, which are bound to change due to climate change.

6.1.2.1.2. Soil Erosion and Soil Properties

Soils with faster infiltration rates, higher levels of organic matter and improved soil structure have a greater resistance to erosion whereas soils with higher content of intermediate particle size fractions such as very fine sand and silt are easily eroded. On the other hand, rainfall induced soil erosion modifies soil properties and soil carbon dynamics and reduces the productivity of the top soil. Soil texture is changed and organic matter, porosity and available water holding capacity, and soil fertility are reduced due to soil erosion. Sand and clay fractions of eroded soil horizons usually increase and silt fractions decrease with increasing degree of soil erosion. The decrease in silt content with increasing degree of erosion appears to be due to the susceptibility of silt to detachment and transport by agents of erosion. Soil bulk density generally increases with soil erosion mainly due to high compactability of the eroded phases.

6.1.2.1.3. Contaminant Transport with Eroded Soil

Heavy metals and nutrients have an affinity for the fine (silt, clay and organic matter) fractions of soil particles. Therefore, soil is the ultimate and most important sink of trace elements. Top soil (0-15cm) may possess maximum levels of contaminants than in the soil underneath. Since erosion specifically detaches finer-sized soil particles (mainly silt) and organic matter, presence of the nutrient/contaminant content in eroded soil materials is usually greater than the source soil. Also, sediments which arrive at catchment outlet also tend to contain more contaminant concentrations than the eroded soil at the source. The projected increases in soil erosion by climate change can cause pollution of water resources with dissolved and suspended loads. In a humid zone, the majority of contaminants reach most water bodies with sediments in particulate phase depending on the physical and chemical environment, geomorphology of the site, and the concentration of the contaminants in soil.

All top soil nutrients are lost during erosion but the most economically significant losses are those of nitrogen, phosphorus and potassium. This research emphasised particularly on the transport of nutrients (phosphorous, nitrogen and potassium), and chromium (Cr) as a mining pollutant since these were available at the study sites.

Nutrients/Agricultural Pollutants

Erosion removes nutrients from the soil not only in forms available to plants but also from soil reserves of nutrients in 'fixed' forms that are unavailable to plants. In addition to N, P and K, the loss of exchangeable Ca, Mg and cation exchange capacity (CEC) increase with increasing degree of erosion for various depths of soil. Phosphorous and nitrogen are the nutrients in agricultural soils that cause freshwater eutrophication. There is a proportional relationship between the amount of nitrogen, phosphorous and potassium transfer and soil losses (correlation coefficient ~ 0.78-0.97) and soil carbon loss. As much as 90% of the total phosphorous flux in rivers can be associated with suspended sediment from agricultural lands, post mining sites, suburban lawns, construction sites and golf courses. There could be an enrichment of total phosphorous in suspended solids even when the erosion risk is very low. However, P-enrichment ratio decreases with increasing erosion rate since as erosion rate increases, particle size separation decreases that result in decreased enrichment.

Nitrogen is susceptible to transport by soil erosion predominantly in the ammonium-N form, because it is adsorbed to the negatively charged surface soil clay particles or is associated with soil organic matter. K loss is lesser especially in presence of N since N fertilizer increase plant uptake of K, sometimes as much as 90% or because K is a mobile ion in soils and significant amounts can be lost by leaching. The concentration of potassium in runoff carried sediment from a fertilised field could be as high as 13 times as that of its level in the original soil.

Climate, soil properties, nutrient properties, and erosion management affect nutrient transport in runoff. Climate factors include rainfall intensity, rainfall duration, time for runoff after inception of rainfall, temperature and rainfall/runoff timing. Soil factors include soil texture and organic matter content, soil surface crusting and compaction, soil water content, slope and degree of aggregation and stability. Nutrient related factors include water solubility, adsorption and polarity characteristics with soil organic matter, persistence to remain at the soil surface, formation (liquid or otherwise) and the quantity of nutrient selectively adsorbed onto the eroding soil particles or aggregates.

Mining Pollutants and Chromium

The mining sites, which sometimes remain abandoned for rehabilitation, or the sites which are still operating, could lead to contamination of the surrounding land, watercourses and sediments introducing a significant number of pollutants into the environment. In addition to rainsplash detachment, topsoil in mining areas typically undergo considerable physical disturbance that can lead to high level of soil erosion. Soils with higher clay and organic matter contents usually exhibit higher metal concentrations and chromium is not an exception. Iron and aluminium rich clays are predominant carrier of chromate since they commonly have a net positive charge and a potential chemical affinity for anionic Cr^{VI}. Cr^{VI} is known to be up to 1000 times more toxic than the Cr^{III}. Chromate sorption by soils is a very complex phenomenon because of the many soil components, their individual surface configuration, the multi component nature of solute and soil interactions, and possible reduction of Cr^{VI} to Cr^{III}, with subsequent precipitation or sorption of trivalent species. However, many researchers have reported that the adsorbed amount of Cr^{VI} onto the soil is controlled by the pH values of the medium, the electrostatic charge of the mineral particles present and the presence of other anions, notably SO_4^{2-} and $H_2PO_4^-$, presence of copper, organic matter, Fe^{II} and sulphides.

6.1.2.1.4. Climate Change and Soil Carbon Sequestration

Carbon compounds added to soil through soil organic matter influences a wide range of physical, chemical and biological properties including supplying nutrients and trace metals to soil, developing strength of soil aggregates and stabilising the soil structure, which increases permeability, reduces soil erodibility and provide important benefits in the prevention of erosion and desertification and for the enhancement of bio-diversity. However, soil carbon gets affected due to climate change. The components of the climate that are most important for soil carbon sequestration are temperature and rainfall.

In addition to reduction through soil erosion, soil organic carbon storage decreases with increase in temperature and increases with increase in soil water content. It was found that soil erosion in India depletes the SOC pool severely and rapidly up to ~ 60%. It is widely believed that increases in ambient temperature due to global climate change and resulting decrease in soil moisture will decrease the organic matter content of soils. However, the effects of rainfall and temperature on soil carbon dynamics are likely to vary regionally and depend on several factors because of the complex interaction between soil moisture and temperature effects on microbial activity.

6.1.2.2. Results and Discussion

Chapter 5 presented the results of the study performed on the impact of observed and projected climate trends on soil erosion using RUSLE2, contaminant transport using suitable numerical and qualitative methods, and land management. The studies were carried out for the data from two gridded regions of Kerala and two contaminated study sites namely Bhoj agricultural area and Sukinda chromite mining site in west central India (WCIN) and central north east India (CNEIN) respectively. The main findings of the results presented in Chapter 5 are summarised below.

6.1.2.2.1. Soil Erosion Studies in Gridded Regions of Kerala

Parametric studies carried out for the data from Kerala state led to the following conclusions. Soil loss increases with increase in erosivity, is maximum when erosivity is maximum, and, like erosivity, depends both on rainfall amount and intensity. Soil loss has a linear variation with soil erodibility factor as computed by RUSLE2 for different soils in Kerala. High silt content, low organic matter and low permeability tend to cause more erosion. However, it is also possible that at the same silt content the erodibility and thus the soil erosion remains the same due to the influence of the combinations of clay content, organic matter content and permeability of the soil. Therefore, the combination of soil parameters is also an important deciding factor on how much they would affect soil erosion. Slope steepness has more effect than slope length on soil loss that increases linearly with increase in slope steepness. There could be a substantial reduction in soil loss due to vegetation establishment because of the effect of vegetation retarding erosion. Therefore, maintaining ground vegetative cover especially when rainfall erosivity is the highest in a given year is important in order to reduce the impact of rain drops and overland flow.

The study relating the comparison between two gridded regions in Kerala indicated that the gridded region 1 experiences the highest average rainfall in monsoon season and gridded region 2 experiences the highest daily rainfall extremes; whereas, gridded region 1 has the second highest daily rainfall extremes. Considering this and the increasing trends of winter, monsoon (daily rainfall > 150mm/day only) and autumn seasonal extremes it could be concluded that these two gridded regions in Kerala, which are located at the extreme northern part of the state, are the worst affected areas in terms of rainfall induced soil erosion.

50-year annual rainfall totals and erosivities in gridded regions 1 and 2 in Kerala showed decreasing trends, which also affected the soil erosion in the same way making its pattern decreasing as well. However, a certain consensus wasn't reached on whether soil erosion is indeed decreasing in the gridded regions 1 and 2 in Kerala since RUSLE2 model could not capture the effect of increasing temperature on soil water content and organic matter which are very important deciding factors of soil loss.

6.1.2.2.2. Soil Loss, Contaminant Transport and Land management in the Study Sites

Studies relating Bhoj site in west central India (WCIN) showed that annual rainfall is increasing in this area, which is different from the rainfall pattern noted for WCIN region in India. Greater number of dry days but more intense rainfall events characterise

Bhoj climate, which, together with increasing temperature could produce more soil erosion, depending on the soil moisture and organic matter status of the soil. Both annual rainfall and runoff had increasing tendencies and the current most years of 1990-2003 had the highest average rainfall and surface runoff. Bhoj soil is rich in clay and organic matter and therefore the infiltration capacity of the soil is less and the runoff potential is higher. Highest rainfall and runoff values in 1990-2003 didn't cause greatest soil erosion in that decade but in 1981-90 primarily due to the variation of daily rainfall intensities. Soil erosion pattern showed an increasing trend due to increase in both the extremes and total accumulated rainfalls. The projection of the same suggested that there could be an 8% increase in average annual soil erosion in 2004-2053 due to a 13% increase in average annual rainfall in Bhoj if other factors remain fixed.

Studies relating Sukinda site in central north east India (CNEIN) also showed an increasing trend of annual rainfall wherein seasonal variabilities were high. The pattern of annual rainfall was similar to that observed for CNEIN annually and in all the seasons except monsoon. Number of dry days in all the seasons except autumn was noted decreasing making the soil wetter. Extremes were noticed having mixed results since different indices showed different patterns but there were positive trends from the contribution of extremes to annual rainfall total in spring and monsoon seasons. These seasonal changes contributed to increasing trend of annual rainfall and therefore total runoff. The current most years of 1990-2003 had the highest average rainfall and surface runoff. There was an average increase in soil erosion profile due to increase in rainfall and runoff and increase in rainfall extremes but the decadal changing pattern of soil erosion quantity was different from that of rainfall-runoff, like Bhoj. Projections showed a 7% increase in average annual rainfall that may lead to a 5% increase in soil erosion in the next 50 years (2004-2053). Average annual soil erosion was lesser in Sukinda as compared to Bhoj even though Sukinda had higher rainfall erosivity. This was because Sukinda soil has lesser runoff potential because of high sand content.

Studies for both the sites also indicated that maximum soil erosion and contaminant transport occurred in the decade when maximum rainfall intensity as well as amount occurred. The qualitative estimates of the risk of contaminant spreading from both the sites were very high; however, due to better management practices at Bhoj site, the potential of overall contaminants reaching the nearby lakes is less but spreading of pollutants on to the neighbouring sites is very high.

Since temperature-soil moisture-organic matter interaction is a very complex process and depends on the interface of many factors, it was difficult to predict precisely what would happen to soil erosion and soil carbon at Bhoj and Sukinda sites due to rainfall and temperature changes. It was however speculated that even if annual rainfall volume was found increasing in both the areas; rainfall effectiveness could be greatly reduced through increase in evapotranspiration due to temperature increase or a decrease in the number of rainfall events.

In order to manage soil erosion to protect the surrounding environment from contaminant spreading, top soil management is necessary, which also forms a part of the land management option. Exploring different alternatives, it was found that planting and maintaining vegetation cover is a natural and cheap way to manage soil erosion and enhance soil carbon sequestration for all types of lands. Since the highest erosivities usually occur in monsoon season in India, care should be taken not to keep the lands bare in this season.

6.2. Recommendations for Further Research

The investigation of impact of rainfall and temperature trends on soil erosion, contaminant transport and land management, which was carried out in the second part of this research work was limited because of the data constraints. This section presents the recommendations for further research that could be built on the existing study.

- As an extension to the parametric modelling work that was carried out by RUSLE2, laboratory experiments could be developed to look at how soil erosion changes with change in rainfall patterns, soil parameters, topographical changes and different cover management practices. This will also validate the model findings in this research.

- The contaminant transport related work was restricted here due to limited data from the study sites. More realistic datasets on top soil contaminant information and more time are needed to improve the predictions of contaminant transport with sediments further. In addition, more sophisticated modelling that takes realistic contaminant chemistry (for example, partitioning information) into consideration will add more value to the results.
- An outstanding question that could be answered by future research is what are the roles of soil temperature, soil moisture, elevated CO_2, soil texture and structure in the distribution and turnover of soil carbon. Shortage of suitable techniques to follow carbon flows through the plant-root-soil system is largely responsible for the current lack of information. As only a small percentage of the carbon added to soil becomes stabilized, it is important to understand those soil physicochemical reactions that stabilize soil carbon and protect it from microbial respiration in more detail. In particular, it is crucial to understand how land management processes and climate factors such as global warming and increases in atmospheric CO_2 concentration regulate these processes, which have the potential to sequester substantial amounts of carbon in the future.
- The major unanswered question is the change of top soil management practices to climate change. If soil carbon stores become an important issue in carbon emission agreements, it seems likely from this study that changing the management practices has an important potential. So, climate change impacts must be studied holistically, requiring integration of climate, plant, ecosystem and soil sciences.
- Very little research was directed towards soil carbon and no research on top soil creation in India, issues that could also be addressed in future are:
  - Impacts of land-use and land management on soil carbon sequestration and ways to increase the storage time of carbon in the soil
  - Top soil creation and management
  - Remediation of contaminants through vegetation and its impacts on carbon sequestration

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