RAINFALL PATTERN OVER KATHMANDU VALLEY DURING SUMMER MONSOON SEASON AND ITS LONG - TERM CHANGE

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Recommendation Letter

This is to certify that Mr. Ramchandra karki has prepared the dissertation entitled “"**RAINFALL PATTERN OVER KATHMANDU VALLEY DURING SUMMER MONSOON SEASON AND ITS LONG - TERM CHANGE"** to fulfill the partial requirements for Master's degree in meteorology. The study done by him has been carried out under my supervision and guidance.

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Abstract:

In this study, the spatial variability of rainfall over Kathmandu valley is investigated on the basis of observational record of rainfall from 15 stations of valley for the period 1970-2005(With more than 10 years data in each station).The spatial distribution of summer monsoon rainfall is similar to the annual distribution with the highest rainfall pocket area in the Northwestern mountain in the periphery of Kakani with more than 2300 mm of mean monsoonal rainfall, while the lowest rainfall is found in southern side of valley floor in the periphery of Khumaltar with average monsoonal rainfall less than 950 mm. Rainfall pockets over valley are also noted in the periphery of Mountain stations Nagarkot, Godavari, Thankot, Sundarijal and Sankhu with mean monsoonal rainfall greater than 1500 mm. Inter annual variability of monsoonal rainfall is found to be relatively low in the central part of valley floor than that of the base and top of mountains.

Based on daily rainfall data of 6 stations of valley for the period of 1971-2005, overall (Valley average) trend on various rainfall characteristics over Kathmandu valley during monsoon season are found as:

1) Overall (Valley average) rising trend in total monsoon rainfall but it does not have statistical significance. 2) Overall (Valley average) significant rising trend in no. of rainy days (> 1 mm /day) in Kathmandu valley. (At 5% level) (3) Overall (Valley average) significant rising trend (at 1% level) in no. of days with precipitation rate 0.1-10 mm /day but the rising trend on that threshold in valley floor is not significant. 4) Though, there is overall (Valley average) falling trend in rain of categories 60-90 mm /day in valley, it doest have statistical significance. (5) Overall (Valley average) rising trend in accumulated rain with rain rate 40-60 mm /day and > 90 mm /day with low statistical significance.

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CHAPTER 1

Preliminary

1.1 Introduction:

Rainfall is the end product of a number of complex atmospheric processes, which vary both in space and time. It can be considered as one of the dominant factor of the meteo-climatic features of investigated area. The temporal and spatial distribution of precipitation is also a very important index reflecting the climatic state and climatic change.

Nepal, lying in the southern periphery of the Tibetan Plateau receives about 80% of the total annual rainfall during summer monsoon (June–September). Rainfall analysis shows that summer monsoon is more active in the southern part of Nepal but in the high Himalayas and Trans-Himalayan region other weather systems like western disturbances are also as effective as monsoon in giving rainfall (Shrestha, 2000)

Nepal Mountains are very rugged and complex so the spatial feature of the rainfall in the country is highly influenced by the topography and altitude difference resulting to significant local change. Spatial variation of rainfall in the valley is quite different from the other hilly region. This study is particularly carried out in the Kathmandu valley due to the higher number of rain gauges and its unique terrain.

The global climate change has important effects on various environmental variables including rainfall in many countries. Changes in precipitation pattern directly affect water resources management, agriculture pattern, hydrology and natural ecosystems.

But, most actual research on climate change has concentrated on possible increases in mean values only (temperature, rainfall, etc.); however, other aspects such as variability should also be considered. In particular, an interesting topic is the study of a possible change of frequency and intensity of rainfall characteristics.

Concerning Nepal, there were no evidence of trend in monsoon rainfall but the change in rainfall was influenced by large scale phenomenon like ElNINO (Shrestha et al., 2000). But ,A study (Shrestha,2004) conducted in the central Nepal clearly indicates the significant increase in extreme rainfall events in the recent decade (1991-2000) by three fold compared to 1971-1980 decade. Previous research has not identified a trend in total monsoon rainfall over country but they have noted the significant increase in extreme rainfall. These studies clearly indicate the evidence of change in daily rain rate over Nepal.

In Kathmandu valley, there is rapid urbanization leading to the change of land use and land cover, and the rising concentration of atmospheric pollutants or aerosols such as sulphate and black carbon aerosols. These changes are throughout the most of the cities of Nepal but it is most significant in Kathmandu valley being the capital city. So these changes may also directly or indirectly affect the daily rain rate in local scale also.

The change in daily rainfall rate during summer monsoon season over Kathmandu valley would not only directly affect flooding pattern in Kathmandu valley but also in the Northern part of India. So this study is mainly focused on the study of change in daily rainfall rate during summer monsoon season over Kathmandu valley. Besides this, study on various aspects of rainfall characteristics in the valley are also carried out.

The knowledge of the diurnal cycle of precipitation is also important for the evaluation of the evaporation especially on daily values, because the precipitation time of a day and successive sunshine duration affects the amount of daily evaporation. Similarly the knowledge is also important for flood forecasting work in hydrology. Variability of rainfall over short timescales, such as the diurnal cycle, result from complex interactions between dynamic and radiative forcing, and the degree of our success in explaining them serves as a useful measure of our understanding of the physics of the atmosphere on this timescale.

In this study, the diurnal cycle of precipitation during monsoon season is also investigated on valley floor by using the hourly observation data of Kathmandu airport for more than 10 years (1992-2002) and the mechanism of the diurnal cycle of precipitation is also discussed.

1.2 Objectives of the study:

- To analyze the spatial variation of Rainfall over Kathmandu valley.
- To analyze the distribution pattern of rainfall during Monsoon season over Kathmandu valley.
- To analyze the trends in Monsoonal rainfall over the Kathmandu valley.

- To analyze the distribution pattern of daily rate during Monsoon season and its change during the recent decades over Kathmandu valley.
- To test the significance of the change in rainfall characteristics over Kathmandu valley by using Mann Kendall rank correlation method.
- To analyze the diurnal cycle of precipitation in valley floor and discuss its mechanism.

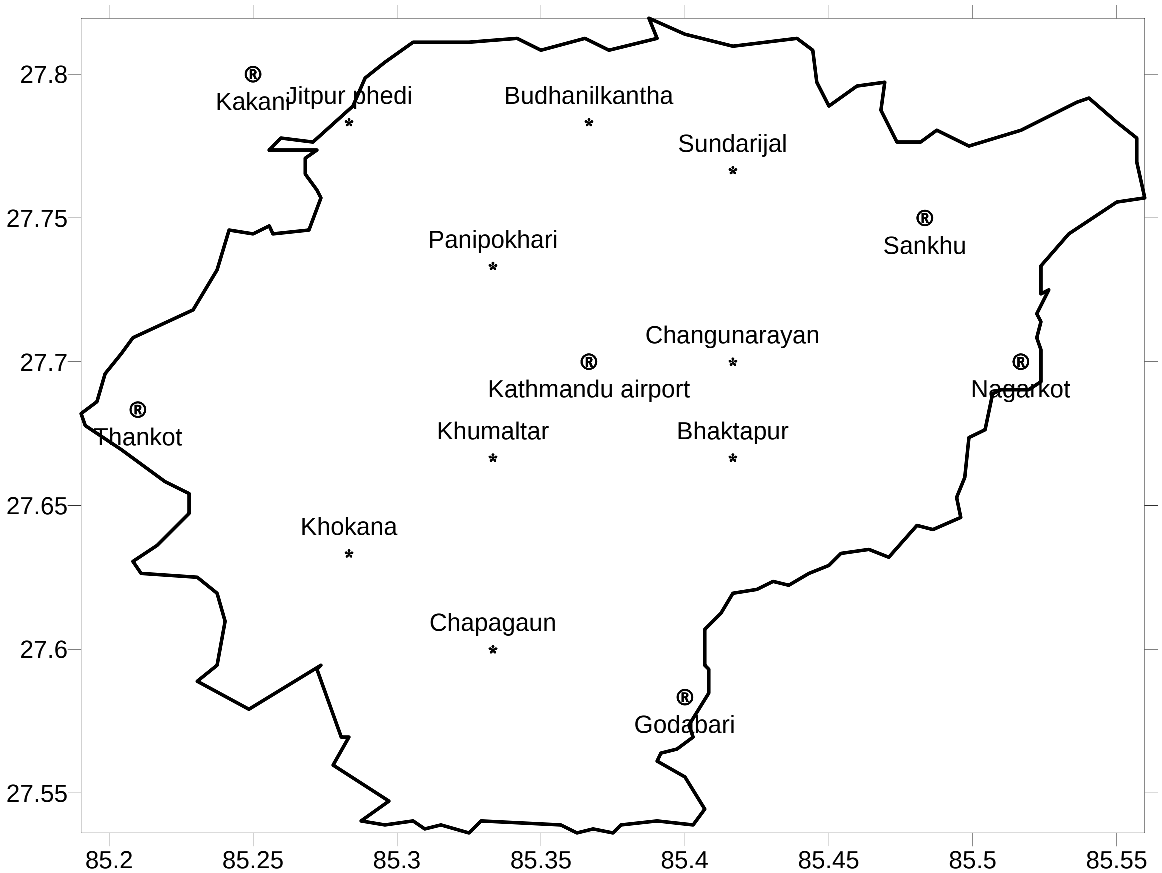
1.3 Data used and Methodology:

1.3.1 Data used:

The present study incorporates precipitation data of Kathmandu valley. The monthly data of 15 stations for the period 1970-2005, daily data of 6 stations for the period of 1971 to 2005 and hourly data of 1 station for the period 1992-2002 obtained from Department of Hydrology and Meteorology of Nepal were utilized for analysis. Only the stations with regular daily data for the entire period are utilized to study change in precipitation in daily rain rate. The location of stations is as shown in Map-1.

S.N	Name of the station	latitude	longitude	Elevation in metre
1	Bhaktapur	27.67	85.42	1330
2	Budhanilkantha	27.78	85.37	1350
3	Changunarayan	27.70	85.42	1543
4	Chapagaun	27.60	85.33	1448
5	**Godavari**	**27.58**	**85.40**	**1400**
6	Jitpur phedi	27.78	85.28	1320
7	**Kakani**	**27.80**	**85.25**	**2064**
8	**Kathmandu airport**	**27.70**	**85.37**	**1337**
9	Khokana	27.63	85.28	800
10	Khumaltar	27.67	85.33	1350
11	**Nagarkot**	**27.70**	**85.52**	**2163**
12	Panipokhari	27.73	85.33	1335
13	**Sankhu**	**27.75**	**85.48**	**1449**
14	Sundarijal	27.77	85.42	1490
15	**Thankot**	**27.68**	**85.21**	**1630**

Table 1: List of stations



Map-1: Locations of the Rainfall stations in Kathmandu valley.

(®-Stations selected for daily rainfall analysis also)

1.3.2 Methodology

In this study, Isohyetal analysis of rainfall data has been carried out using "surfer 7.02" developed by Golden software (INC, Colorado, USA) and Ms Excel was used for the data analysis and presentation.

A. Mann-Kendall tests:

Mann-Kendall tests are non-parametric tests for the detection of monotonic trend in a time series. These tests are widely used in environmental science, because they are simple, robust and can cope with missing values and values below a detection limit.

Let Y be rainfall characteristics and X year then

H_0 : T = 0, No correlation exist between X and Y

H_1 : $T \neq 0$ X and Y are correlated.

Then S = A-B

Where A= Number of cased when Yi<Yj for i<j

B= Number of cases when Yi>Yj for i<j

$$T = \frac{2S}{(n-1)n}$$

The variable T is normally distributed with mean zero and has a variance of

$$\sigma_z^2 = \frac{2(2n+5)}{9n(n-1)}$$

$$Z_T = T * \left(\frac{9n(n-1)}{2(2n+5)} \right)^{1/2}$$

The null hypothesis is rejected at significance level α if $/Z_T/ > Z_{\alpha/2}$, in the case of positive trend $Z_T > Z_{\alpha/2}$, and in case of negative trend $Z_T < Z_{\alpha/2}$.

B.Skewness:

Skewness characterizes the degree of asymmetry of a distribution around its mean. Positive Skewness indicates a distribution with an asymmetric tail extending toward more positive values. Negative Skewness indicates a distribution with an asymmetric tail extending toward more negative values.

$$\text{Skewness coefficient} = \frac{n\Sigma(x_i\text{-}x)^3}{(n\text{-}1)(n\text{-}2)S^3}$$

$$\text{Where, } \bar{x} = \frac{1}{n}\Sigma\, x_i,\ S = \left(\frac{\Sigma(x_i\text{-}x)^2}{n\text{-}1}\right)^{1/2}$$

C. Range

This is the simplest measure of the variability and is the difference between the largest and the smallest data values. The presence of outliers can distort the effect of the range.

D. Variance and standard deviation

Sample variance is given as

$$S^2 = \frac{\Sigma(x_i\text{-}\bar{x})^2}{n\text{-}1}$$

The square root of the variance is the **standard deviation**. It has the same units as that of the data.

E. Coefficient of variation, C_v :

$$C_v = \frac{s}{\overline{X}} \times 100$$

Where s is standard deviation and $\bar{X}$ is mean.

F. The trend line method:

The trend line helps to determine the rate of change, understanding past behavior, planning future operations, evaluation of the current accomplishment and facilities comparison and can be ascertained tentative estimates concerning future can be made accordingly. Trend means the general, smooth, long-term, average tendency. The graphic method and the method of curve fitting by principles of least squares can be used for determining trend. In the study of the rainfall, the slope of the line gives the trend.

F. 1 Principles of least squares Method:

Let ($x_{i,}$ y_i) where i = 1, 2, 3…... n be a given set of n pair values. x being the independent variable and y the dependant variable. The general problem in curve fitted is to find, if possible, an analytic expression of the form y = f(x), for the functional relationship suggested by the given data. It is the mathematical method and with its helps a trend line is the fitted to the data in such a manner that the following two conditions are satisfied.

1. Σ (y - y_c) = 0 i.e. the sum of the deviations of the actual values of y and the computed values of y_c is zero.

2. $\Sigma (y - y_c)^2$ is minimum. I.e. the sum of the square of the deviation of the actual and computed value is least. From this line by method of least squares is obtained using this criterion is known as the line of the best fit.

This method is most widely used in practice. When the time series of increasing or decreasing is almost constant, the straight line trend is used.

$y_c = a + bx$

Where, a and b are the constant and x be the slope the trend.

F.2 Moving Average Method:

Moving average method is used to give the smoother curve, lessening the influence of fluctuation. When a trend is to be determined by the method of moving average, the average value for a number of years is secured, and this average is taken as the normal or trend value for the unit of time falling at the middle of the period covered in the calculation of the average .While applying this method, it is necessary to select a period for moving average such as 3-years moving average, 5-years moving average, 8-year moving average, etc.

CHAPTER – 2

Physical and Climatic characteristics

2.1 Topography of Nepal:

Nepal is small landlocked country that covers an area of 147,181 km^2 in the centre of Hindu Kush Himalayas between India and china (Map 2). Nepal stretches from 26º 22' to 30º 27' North latitude and from 80º 04' to 88 º 12' East longitudes. The country looks roughly rectangular in shape with the length from east to west of about 885 km and width ranging from 130 to 260 km. It contains 8 of the 10 highest mountain peaks in the world, including Mount Everest (at 8848 m), although some of its low lying areas are only about 80 m meters above sea level.

The country is divided into three broad ecological regions, i) The higher Himalayas in the north, ii) Hills and Valleys in the middle, and iii) Terai, an extension of Indo-Gangetic plain, in the south.

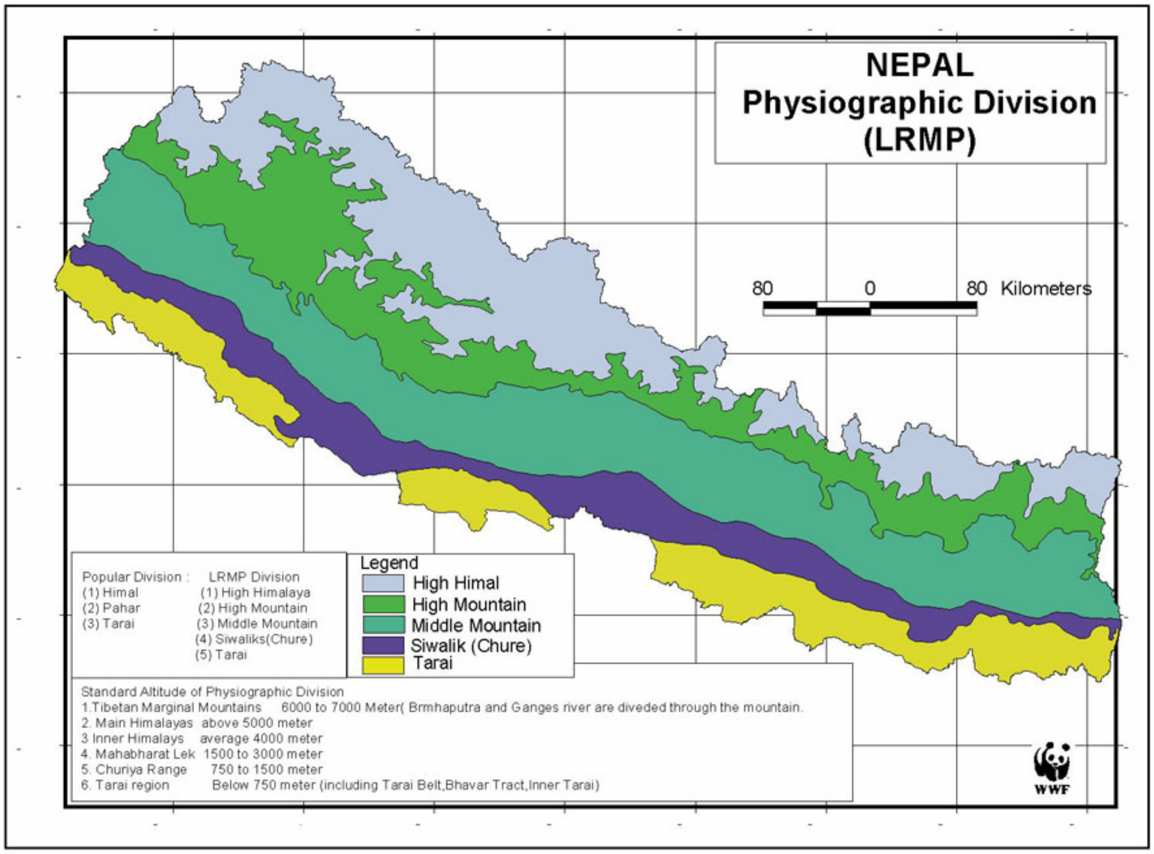
Map 2: Location map of Nepal

2.1.1 Geographic region of Nepal:

Nepal is divided into five geographic regions according to physiographic as well as topographic region : Terai plan, Siwalik hills, Middle Mountains, High Mountains (consisting of the Main Himalayas and the Inner Himalayan Valleys), and the high Himalayas. (CBS, 2004)

Region	Geology and soil	Elevation(m)	Climate	Average temp.
Terai (14%)	Gently sloping recently deposited alluvium	200	Humid tropical	>25 ^{o}c
Siwaliks (13%)	Testing mudstone,siltstone,sandstone,steep slopes, and weakly consolidated bedrock tends to promote surface erosion despite thick vegetation	200-1500	Moist subtropical	25 ^{o}c
Middle mountains (30 %)	Phyllite, schist, quartzile, granite, limestone, stony and course textured soil, conifer forests commonly found associated with quartzite.	1000-2500	temperate	20 ^{o}c
High mountains (19 %)	Phyllite, schists, quartzite. soil is generally shallow and resistant to weathering	2200-4000	Cool to sub alpine	10-15 ^{o}c
High Himalayas (14 %)	Limestone and shale, physical weathering predominates ,stony soils	>4000	Alpine to arctic	<0 to 5 ^{o} c

Table 2: Geographic regions of Nepal



Map 3: Geographic regions of Nepal

2.2 Climate of Nepal:

Nepal has a great deal of variations in climate. Although Nepal lies near the northern limit of the Tropics, a very wide range of climates from Subtropical in the southern Terai to Tundra in the northern high Himalayas exists here. The remarkable differences in climatic conditions are primarily related to the enormous range of elevation within a short north-south distance. The presence of the east-west extending Himalayan massifs to the north and the monsoonal alteration of wet and dry seasons also greatly contribute to local variations in climate.

Generally country can be divided into five climatic types.

1. Tundra – climatic type: - Tundra type of climate is found in the higher Himalayas region of Nepal. Almost above snowline (5000 m), a permanent cover of snow and ice, Precipitation mostly falls in the form of snow occurs only.
2. Alpine – climatic type:- In the lower part of the Himalayas region, alpine type of climate is found. Above 4000m, cool summer and frosty winter, snow and ice, precipitation in the form of snow occurs only.
3. Cool temperate – climatic type: - This type of climate is found in the region of High Mountain region of Nepal. Cool summer and cool winter, winter precipitation in the form of snow at high altitude occurs only.
4. Warm temperate – Climatic type: - This type of climate is found in the region of Mahabharata range of middle mountain region of Nepal. Warm summer and cool winter, occasionally snowfall in higher region of hills and precipitation in the form shower may occur.
5. Tropical/Subtropical – climatic type: - The sub-tropical type of climate is found in the lower region of Chure range or Terai of Nepal. The tropical type of climate is found in the Chure range or Siwalik of Nepal. Hottest and humid summer, mild and dry winter occurs. (Adopted from Regmi, 1998)

2.3 General season in Nepal:

According to season, Season of Nepal is divided into four parts; these are as follows (Nayava, 1981):

A. Pre-monsoon season: (March - May)

B. Monsoon season: (June – September)

C. Post monsoon season: (October - November)

D. Winter season: (December -February)

A. Pre-monsoon season: It starts from March to May. In this period, much of the days of the month remain under the domination of the dry westerly wind. This wind system produces dusty and windy weather in the most of the country. Convective activity produces high to moderate rain shower especially in the hilly region. As a matter of the fact, the distribution of pre-monsoonal rainfall in the country are associated with the thermal convection associated with orographic effects which results thunderstorm associated with precipitation over the narrow bands with in the region.

B. Monsoon season: The season starts from June to September in Nepal is known as rainy season. Monsoon arrives from eastern Nepal on June 10th, and it arrives at Kathmandu on June 12th, within 2 to 3 days, it covers the whole country. The normal date of the retreat of the monsoon is September 23. When the monsoon circulation pattern is established, temperature begins to fall; air becomes most compared to other season. Relative humidity of this season becomes high. In Nepal, 60% to 80% of the annual rainfall falls during this season. Rainfall varies sharply from one place to another due to impact of the topography. When the moist south easterly wind approaches, the air stream is forced to rise resulting rainfall on the slope facing southwards. The month of July is the rainiest month of the rainy season.

C. Post monsoon season: The season is the changing period from season to another and harvesting season of monsoon crop field preparation is done for winter season crops. Sometimes, the country receives precipitation by cyclonic storm that develops in the bay of Bangal and Arabian Sea. Regmi (1998) indicates the domination of westerly wind flow with falling in temperature gradually as an indication of pre-winter activity, negligible amount of rainfall occurs in this period.

D. Winter Season or Cold weather season: It runs from December to February. Northwesterly wind pre-dominates the country in this season. Except in the region of great Himalayan and a high mountain, the winter is normal with great sunny days (Nayava, 1981). In winter, major weather effective elements are the western disturbances and so western Nepal receives higher amount of rainfall than eastern Nepal. This region is relatively dry & cool weather, lowest temperature and rainfall amount is very less but greater than post monsoon.

2.4 Description of study area:

2.4.1 Topography:

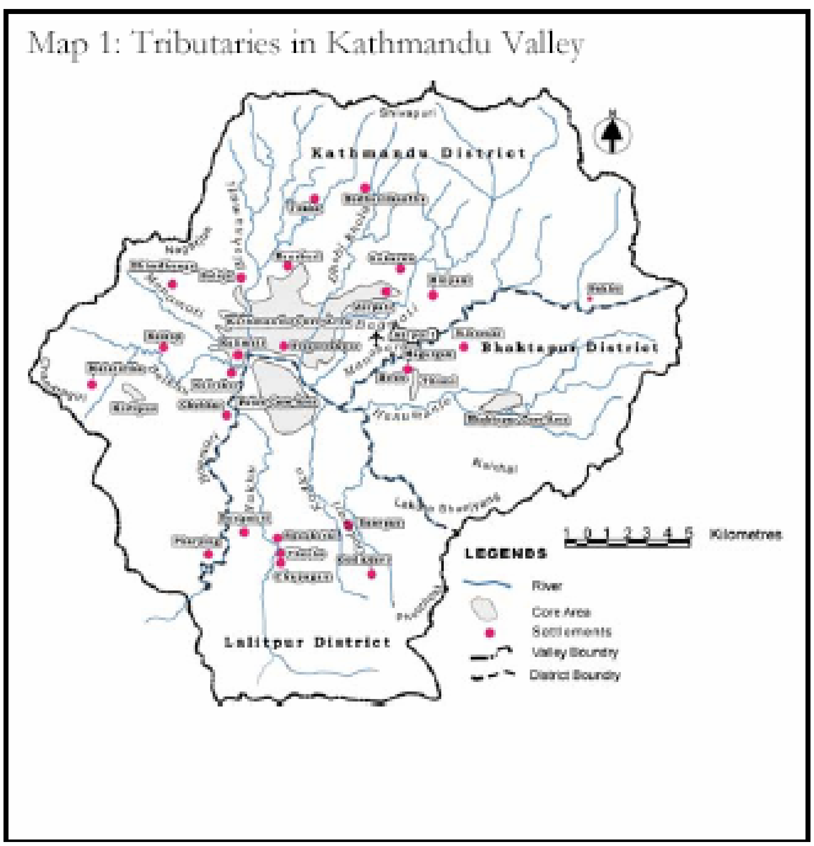
Kathmandu is surrounded by hills in all sides and is almost circular in shape. Elevation of surrounding hills range from 2000 to 2750m and valley is flat with elevation ranging from 1300 to 1400m .The east to west and north to south axes of valley are about 26 km and 37km.kathmandu valley lies between 27°32 to 27°49 E and 85°11to 85° 32 N .

The Kathmandu valley, which has the capital city Kathmandu along with four other municipal towns, Lalitpur, Bhaktpur, Kirtpur and Madhyapur-Thime, are the main urban area of Nepal. The valley is located between the Himalayan in the north and the Mahabharata mountains in the south.

2.4.2 Climate:

The climatic condition of Kathmandu valley depends on the prevailing wind regime from central Asia and the northern hemisphere's cold pole. Summer monsoon (June, July, August, and September) and western disturbance (Dec-May) are considered the main rain weather producing system. In the summer and early autumn the prevailing wind regime in Kathmandu valley is the southwest monsoon. During March to May the valley experiences pre-monsoon thundershower activities and there is a strong wind in this season. The temperature in Kathmandu drops below freezing in winter and in summer it may rise to35^{o} C. The mean annual air temperature in Kathmandu is 18^{o}c. The coldest month is January, with a mean temperature of 10^{o}C. The warmest month is July and august with an average temperature of 24^{o}C.Fog is common in the morning during the months of October to February (pandey, 1987, Yogacharya, 1998).

Map 4a: Location of Kathmandu Valley



Map -4b: Kathmandu Valley (Basin map)

CHAPTER – 3

Literature review on Precipitation and its change

3.1 Precipitation:

The term precipitation denotes all forms of water that reach the earth from the atmosphere .Precipitation may reach the surface of the earth in the form of drizzle, rain, snow, hail, sleets etc.The magnitude of precipitation varies with time and space. For precipitation to form :I) the atmosphere must have moisture, II) there must be sufficient condensation nuclei present III) weather condition must be good for condensation of water vapour to take place, and IV) the product of condensation must reach the earth. The net precipitation at a place and its form depends upon wind, temperature, humidity and pressure within the regions enclosing the cloud and the ground surface at the given place.

3.2 Types of precipitation:

For the formation of clouds and subsequent precipitation, it is necessary that the moist air masses cool to form condensation. This is normally accomplished by the adiabatic cooling of moist air through a process of lifting to higher altitudes. Some of the terms and process connected to the weather system associated with precipitation in Nepal are given below.

3.2.1 Convective precipitation:

This is the type of precipitation due to the upward movement of air that is warmer than its surrounding .Generally, this kind of precipitation occurs in tropics .In the hot day the ground surface becomes heated, as does also the air to expand and rise by the contact with it. This causes the air to expand and rise by convection. As it rises it cools dynamically at the dry adiabatic rate of about 1^0C /100m which in turns results in condensation and precipitation.

3.2.2 Orographic precipitation:

The precipitation caused by lifting of moist air from mountain barrier is called orographic precipitation. When moisture bearing winds usually blowing from oceans to land surfaces are forced far above the ground surface by the influence of the mountain ranges, the adiabatic cooling take place resulting condensation and precipitation on the windward ridge of the mountains.

3.2.2 Cyclonic (Tropical) precipitation:

A cyclone is a large low pressure region with the circular wind motion. Cyclone precipitation results due to the low atmospheric pressure over the water surface which moves to the land wards from lifting of air masses converging into a low pressure area or cyclone.

3.3 Precipitation climatology of Nepal:

The distribution of precipitation has high spatial variation in Nepal. Nepal experiences the seasonal summer monsoon rainfall from June to September. Most of the days during June to September are cloudy and rainy. About 80 % of the annual precipitation in the country falls between June and September under the influence of the summer monsoon circulation system. The amount of precipitation varies considerably from place to place because of the non-uniform rugged terrain. However, the amount of summer monsoon rains generally declines from southeast to northwest.

The winter months December to February are relatively dry with clear skies. However, few spells of rain do occur during these months. In winter, major weather effective elements are the western disturbances so rain decreases in amount from northwest to both southward and eastward direction. The direction of predominating wind is Northwesterly during this season.

During March to May the country experiences pre-monsoon thundershower activities. The pre-monsoon rainfall activities are more frequent in the hilly regions than in the southern plains.

The period of October and November is considered as a post monsoon season and a transition from summer to winter. During October the country receives a few spells of post-monsoon thundershowers, similar in character to the pre-monsoon ones. The annual mean precipitation is around 1800 mm in Nepal. But owing to the great variations in the topography, it ranges from more than 5000 mm along the southern slopes of the Annapurna range in the central Nepal to less than 250 mm in the north central portion near the Tibetan plateau.

3.4 Previous studies on precipitation in Nepal:

There are many reports about the study on precipitation in Nepal. With regard to rainfall Nepal is highly dominated by summer monsoon and its circulation arising from Bay of Bengal. It is estimated that the summer monsoon accounts for 80 % of the annual rainfall in Nepal. The mean rainfall for Nepal during monsoon season amounts to be 1422.8mm with standard deviation of 132.6 mm and coefficient of variation 9.3 % (Shrestha, 2000). According to Pokhrel, (2003), summer precipitation is high over middle mountains i.e. Mahabharata range; and decreased slightly over Terai and decreased rapidly over Himalayan range.

In a recent study, Barros et al. (2000) and Lang and Barros (2002) have noted significant spatial variability in precipitation in central Nepal (factor of 4 differences over; 10 km distance), but it did not show any specific dependence on elevation, particularly at the seasonal scale.

Studies by Barros et al. (2000); Shrestha (2000); and (Lang and Barros 2002) have shown that large rainfall amounts, on the order of 300 – 400 cm / yr, can fall along the south-facing slopes of the Himalayas.

Studies also have shown that the climatology of Himalayan rainfall variability differs markedly from the rest of the Indian subcontinent (Shrestha et al. 2000). Shrestha et al. (2000) have also analyzed the precipitation trend in Nepal and did not found any significant trend in annual and seasonal precipitation. But, a study (Shrestha, 2004) conducted in Central Nepal clearly indicates the significant increase in extreme rainfall event in the recent decade (1991-200) by three fold compared to 1971-1980 decade. GCM estimate shows the total precipitation in June, July and august will increase with 9.1% by 2030A.D

(OECD, 2003).Similarly, other Model based projection have also shown the rising trend in annual precipitation over Nepal.

Long term trend from 1900 to 2005 have been observed in precipitation amount over many large regions. Significantly increased precipitation has been observed in eastern parts of North and South America. Drying has been observed in the Sahel, the Mediterranean, southern Africa and parts of southern Asia. Precipitation is highly variable spatially and temporally, and data are limited in some regions .long term trend have not been observed for the other large regions assessed. (IPCC report, 2007)

Similarly IPCC report (2007) has also shown that the frequency of heavy precipitation events has increased over most land areas, consistent with warming and observed increase of atmospheric water vapour.

Though there are various studies on the precipitation pattern over Nepal .There are limited studies on the precipitation pattern and the change in distribution pattern of daily rain rate of different threshold over valleys of Nepal. In the present paper, the authors have attempted to study various characteristics of rainfall over Kathmandu valley and its change during recent decades.

This study is mainly focused on the analysis of frequency of rainy event and the accumulated rainfall by various rainfall intensity during monsoon season and its trend. In addition to this, the significance of trend in various rainfall characteristics is also tested by using Mann Kendall rank correlation method.

3.5 The projections for global climate change by the IPCC 2007:

1) It is *very likely* that hot extremes, heat waves, and heavy precipitation events will continue to become more frequent.

2) Warming is expected to be greatest over land and at most high northern latitudes, and least over the Southern Ocean and parts of the North Atlantic ocean

Table shows the projected global average surface warming and sea level rise at the end of the 21st century

Case	Temperature change (^oC at 2090-2099 relatives to 1980-1999)	Sea level rise (m at 2090-2099 relative to 1980-1999)	
	Best estimate	Likely range	Model based range excluding future rapid dynamical change in ice flow
Constant year 2000 concentrations	0.6	0.3 - 0.9	Not available
B1 scenario	1.8	1.1 - 2.9	0.18 – 0.38
A1T scenario	2.4	1.4 - 3.8	0.20 - 0.45
B2 scenario	2.4	1.4 - 3.8	0.20 - 0.43
A1B scenario	2.8	1.7 - 4.4	0.21 - 0.48
A2 scenario	3.4	2.0 - 5.4	0.23 - 0.51
A1F1 scenario	4.0	2.4 - 6.4	0.26 - 0.59

- GHG estimation for various scenario B1,A1T,B2,A1B,A2 and A1F1 scenario are respectively 600,700,800,850,1250,and 1550 ppm respectively.

These estimates are assessed from a hierarchy of models that encompass a simple climate model, several earth system models of intermediate complexity and a large number of atmospheric ocean General circulation models (AOGCMs)

3) Extra-tropical storm tracks are projected to move pole ward, with consequent changes in wind, precipitation, and temperature patterns, continuing the broad pattern of observed trends over the last half-century.

4) Based on a range of models, it is likely that future tropical cyclones (typhoons and hurricanes) will become more intense, with larger peak wind speeds and more heavy precipitation associated with ongoing increases of tropical SSTs.

5) Increase in amount of precipitation are *very likely* in high-latitudes, while decreases are likely in most subtropical land regions (by as much as about 20% in the A1B scenario in 2100,), continuing observed patterns in recent trends.

CHAPTER 4

RESULT AND DISCUSCUSSION

4.1 Isohyetal analysis of rainfall over Kathmandu valley:

Isohyetal analysis of rainfall data for annual as well as for the four seasons namely Monsoon, Post monsoon,Winter,Premonsoon season are shown in Map 5,6,7,8,and 9 respectively.

Annual map depict that the highest rainfall are observed in the Northwestern part of valley in the periphery of Kakani with more than 2800 mm of annual rain.

The second highest rainfall is observed in the Northern part of the valley in the periphery of Sundarijal and Sankhu with more than 2000 mm of annual rainfall. Annual high rainfall pockets are also noted in the eastern, western and Southeastern side, in the mountains of valley with an annual value of more than 1900 mm at the stations Nagarkot, Thankot and Godavari respectively.

The rainfall is observed lowest in the southern side of valley floor at the periphery of Khumaltar with average annual value less than 1200 mm.

Rainfall in the Kathmandu valley shows the marked increase in rainfall with increasing elevation but the increase in rainfall with elevation at Northern side of the valley is quite high in comparisons to other side of valley.

Similar pattern has been identified in all four seasons (monsoon, Monsoon, Post Monsoon, winter and pre monsoon) (Map 6-9).

In winter, there is shifting of lowest rainfall area from the southern belt to the northern side of valley (near Panipokhari).Highest rainfall pocket are observed in the periphery of Thankot during this season.

In post monsoon season, and pre monsoon season, the slightly shifting of lowest rainfall area towards South (Chapagaun) is quite remarkable.

Winter season is very dry and rainfall occurs due to western disturbance during this season. The winter season mean value of rainfall for the Kathmandu valley is 53 mm and varies from 44 mm (Panipokhari) to 66 mm (Thankot).Frequent fog appears over the valley during this season.

In the pre-monsoon period the precipitation is associated with low pressure area which have formed in mediterian sea and moved eastward by western disturbance.Similarly convective rainfall is also most frequent during this season in the valley. The pre-monsoon mean rainfall value of Kathmandu valley is 232 mm.

During post monsoon period the mean rainfall value of the valley is 67 mm.

Annual rainfall follows the monsoon pattern as 80% of total rainfall occurs during this season. The mean value of rainfall during this season is 1387 mm.

The main cause for the highest monsoonal rainfall in the North western mountain is primarily due to the moisture laden air entering from southwestern side of valley and traveling towards the northern mountain and the lowest rainfall in the southern part of the valley floor may be due to the subsidence of air.

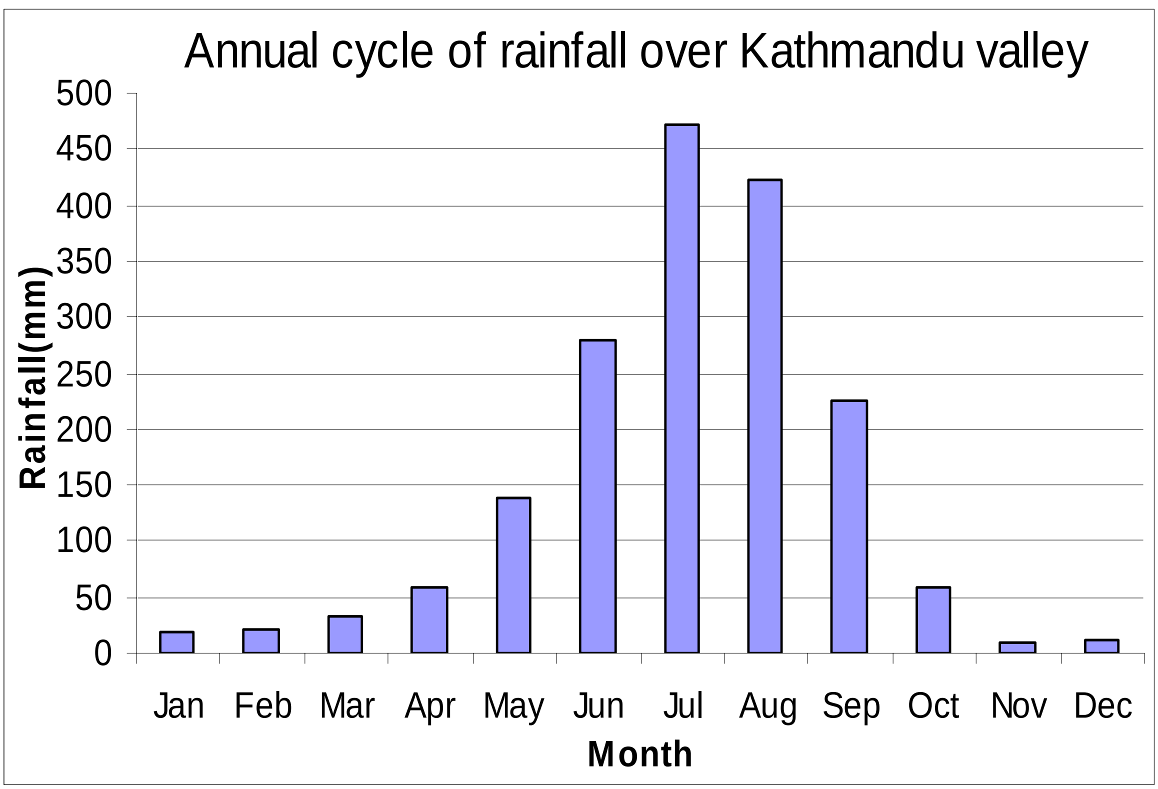


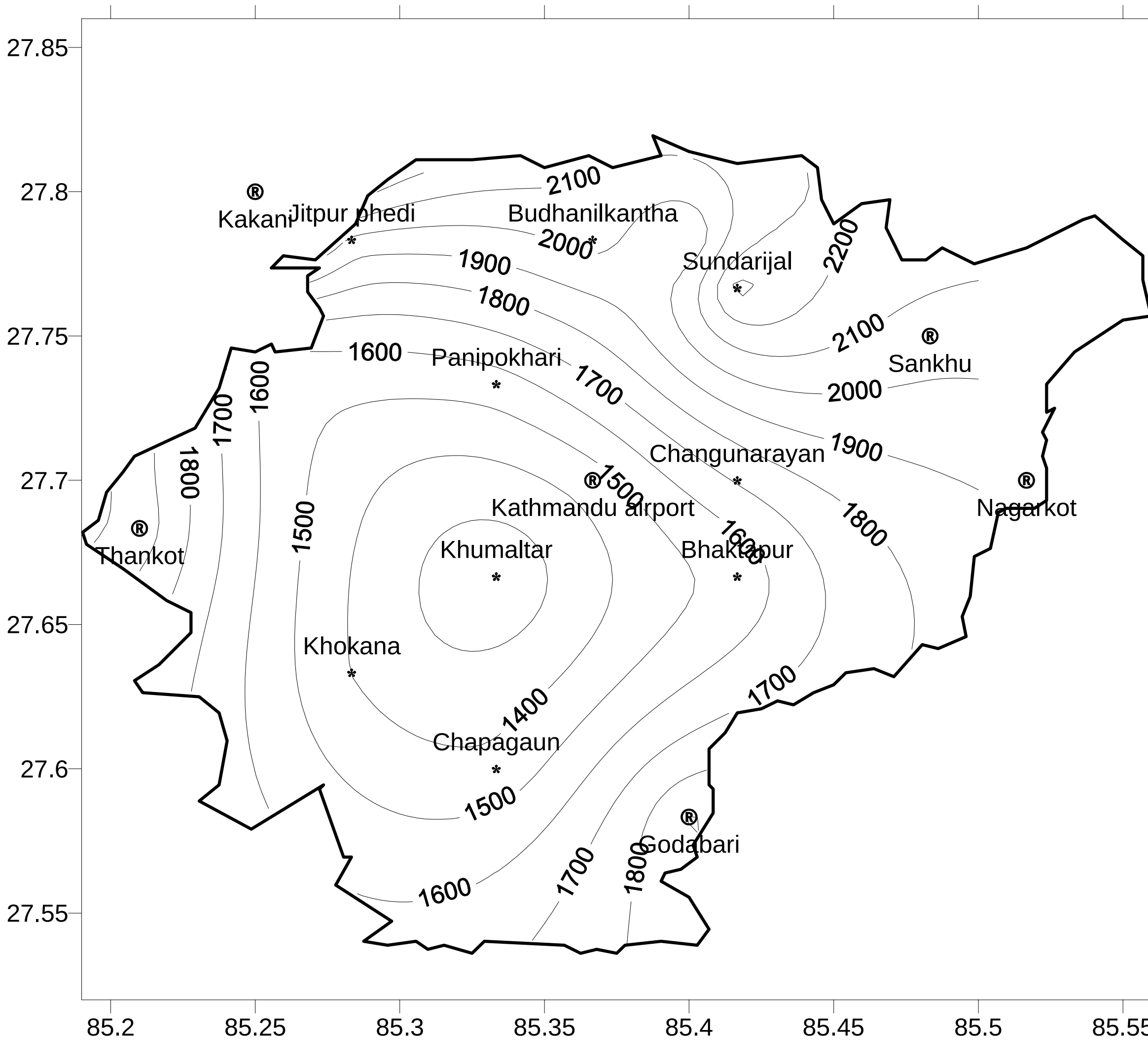
Fig.1: Annual cycle of rainfall over Kathmandu valley

Name of station	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Bhaktapur	15	20	32	57	137	259	387	360	185	55	6	14
Budhanilkantha	16	21	38	62	190	339	553	511	236	56	8	9
Changunarayan	18	22	32	57	155	255	439	425	222	60	9	15
Chapagaun	17	18	28	49	97	232	404	325	191	44	5	20
Godavari	20	23	31	59	127	311	525	445	267	69	9	19
Jitpur phedi	24	24	39	76	158	252	582	510	243	59	5	3
Kathmandu airport	16	18	34	57	115	254	374	321	183	60	8	12
Khumaltar	17	18	28	53	104	202	322	253	149	55	5	15
Nagarkot	19	20	30	54	145	328	484	481	269	73	9	11
Panipokhari	13	18	34	75	123	266	400	351	194	59	9	13
Sankhu	14	25	31	52	151	318	547	538	283	64	10	11
Sundarijal	34	18	38	52	180	329	685	631	299	51	13	7
Thankot	21	27	40	70	151	298	525	455	280	67	11	18
Khokana	24	22	33	61	118	255	376	302	144	43	9	11
Average	19	21	33	60	139	278	472	422	225	58	8	13

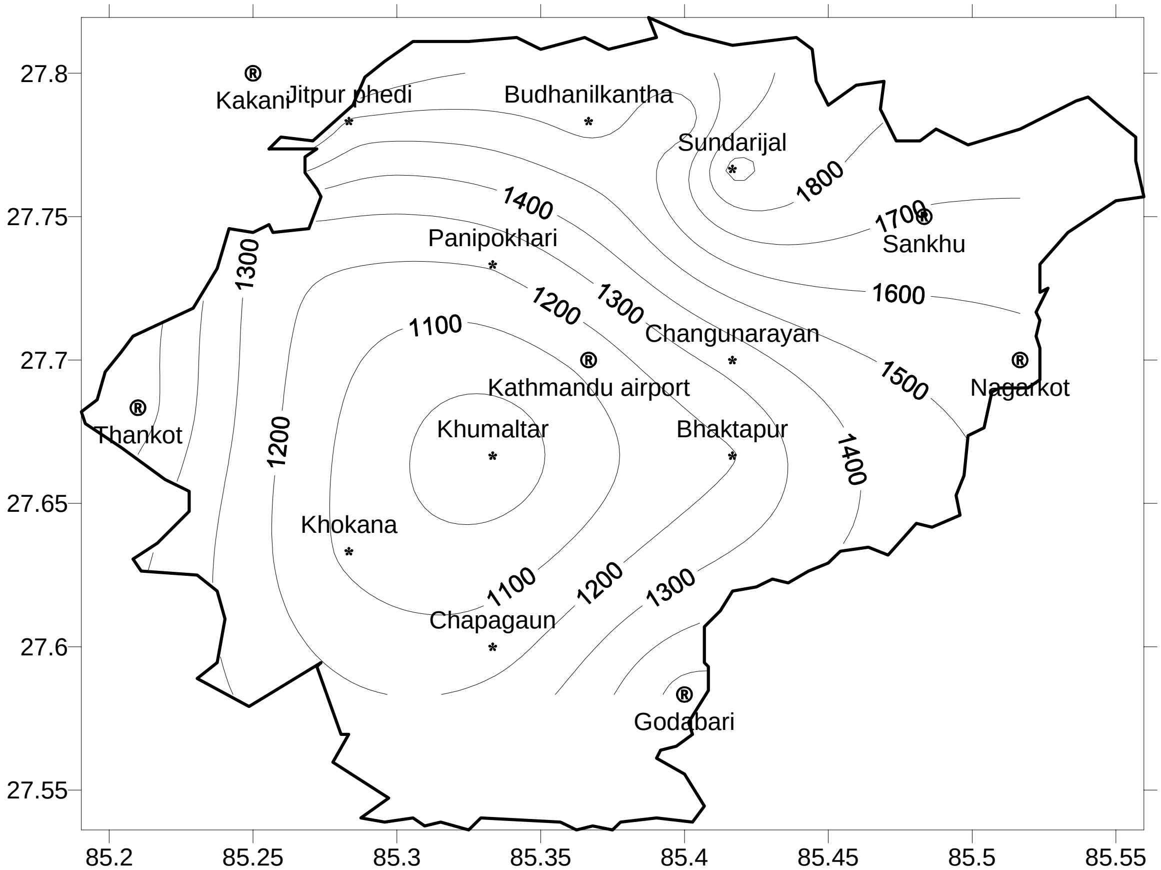
Table 3a: Mean monthly rainfall (mm) in various stations of Kathmandu valley (1970-2005)

Name of station	Winter	Pre monsoon	Monsoon	Post monsoon	Total
Bhaktapur	49	226	1191	61	1527
Budhanilkantha	46	290	1639	64	2039
Changunarayan	55	244	1341	69	1709
Chapagaun	55	174	1152	49	1430
Godavari	62	217	1548	78	1905
Jitpur phedi	51	273	1587	64	1975
Kathmandu airport	46	206	1132	68	1452
Khumaltar	50	185	926	60	1221
Nagarkot	50	229	1562	82	1923
Panipokhari	44	232	1211	68	1555
Sankhu	50	234	1686	74	2044
Sundarijal	59	270	1944	64	2337
Thankot	66	261	1558	78	1963
Khokana	57	212	1077	52	1398
Average	53	232	1397	67	1784
Percentage of total	3	13	80	4	100

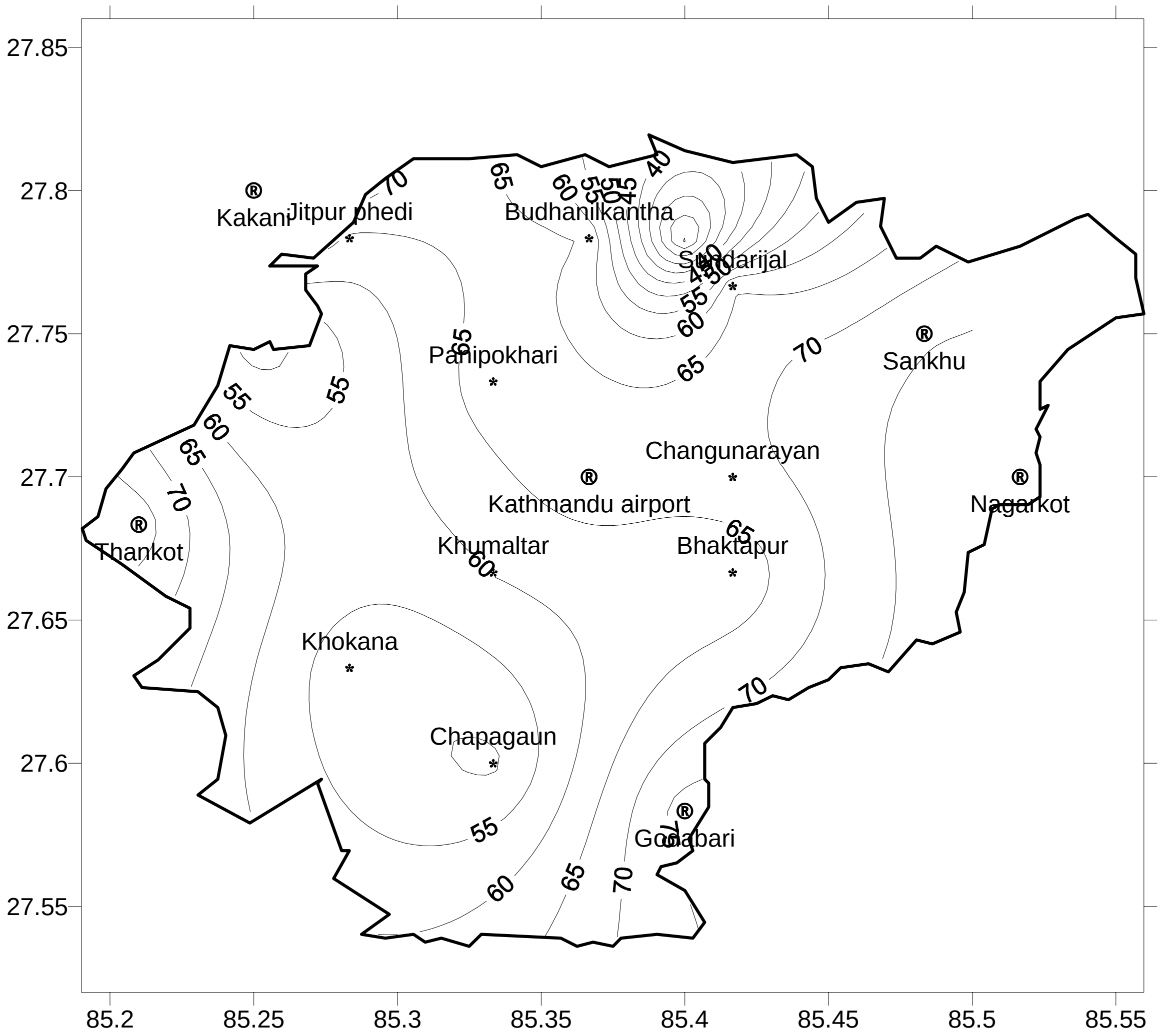
Table 3b: Mean Seasonal rainfall in various stations of Kathmandu valley. (1970-2005)



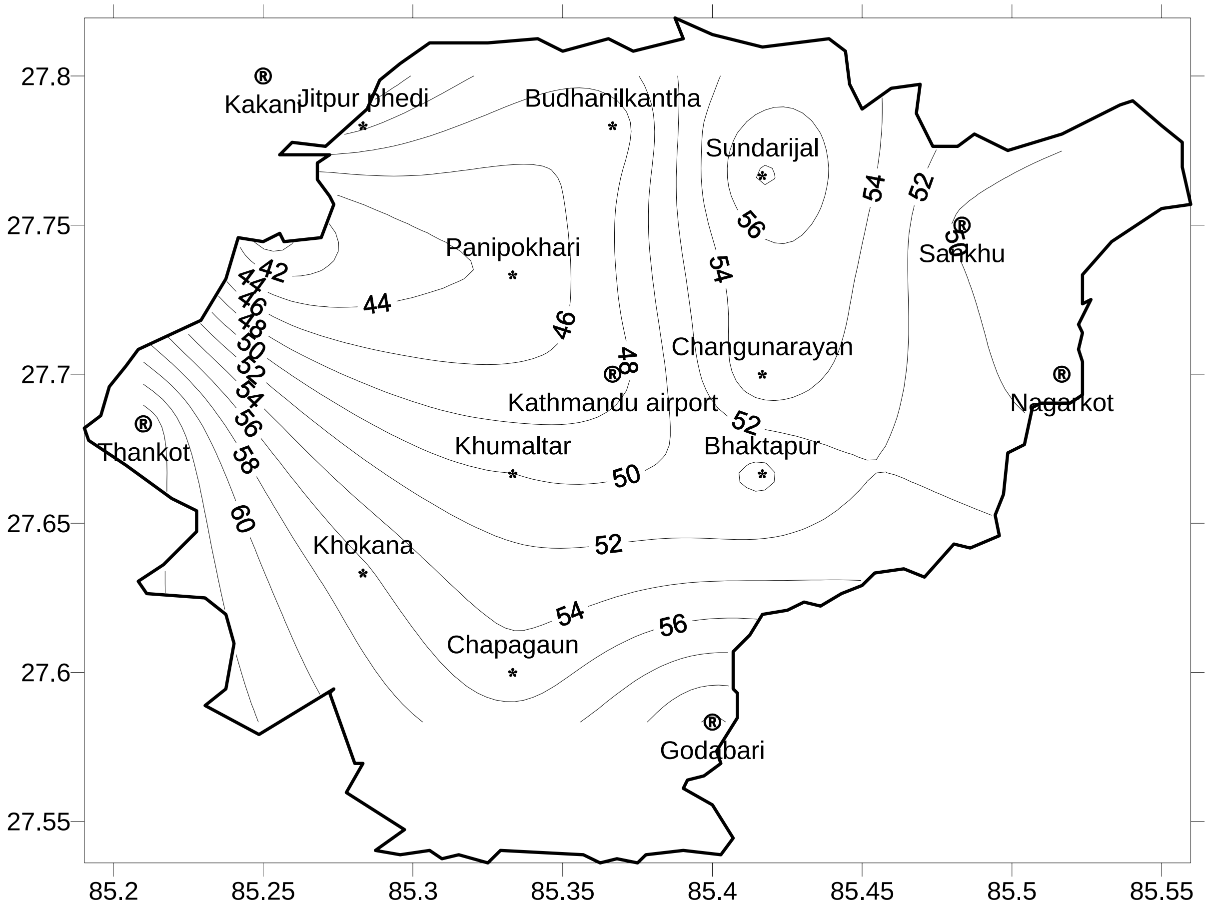
Map-5: Isohyets of total annual rainfall within Kathmandu valley



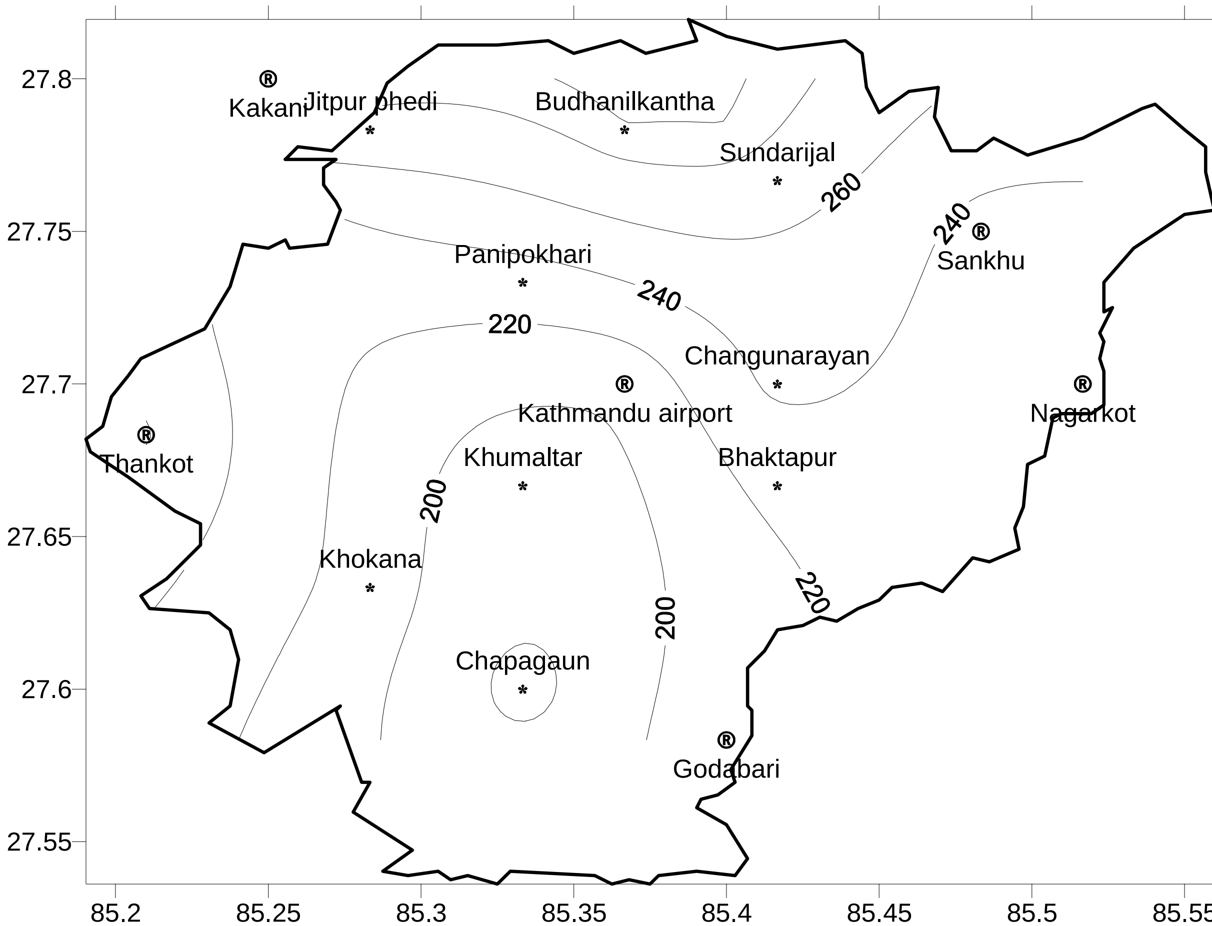
Map-6: Isohyets of Monsoon rainfall within Kathmandu valley



Map-7: Isohyets of Post Monsoon rainfall within Kathmandu valley



Map-8: Isohyets of winter rainfall within Kathmandu valley



Map-9: Isohyets of Pre monsoon rainfall within Kathmandu valley

4.2 Study on distribution and variation of monsoon rainfall over Katmandu valley:

To study the spatial variation in the variability of monsoon rainfall, the coefficient of variation and Range were calculated.

Coefficient of variation in monsoon rainfall of Thankot, Bhaktapur, Nagarkot, and Sankhu are relatively higher than that of the other stations in the valley, Which indicates monsoon rainfall in these places (east and west side of valley) are relatively less consistent than that of the other parts in valley. Similarly, range (Max-Min) is also higher at Sankhu, Nagarkot and Thankot.The high value of Range is due to the high chances of extremities in these stations.

From the study of coefficient of variation and range, it can be concluded that inter annual variability in monsoonal rainfall over Kathmandu valley are relatively low in the central part of valley floor than that of the base and top of mountains. (Table-4)

Name of station	Coefficient of variance (%)	Range(mm)	Skewness
Bhaktapur	21	1227.60	0.13
Changunarayan	18	963.90	0.09
Chapagaun	16	616.63	-0.09
Godavari	15	993.90	0.01
Kakani	16	1607.30	-0.47
Kathmandu airport	17	747.70	0.09
Khumaltar	18	716.20	-0.04
Nagarkot	25	2369.90	1.91
Sankhu	22	2129.80	-0.05
Thankot	24	1524.20	-0.32

Table 4: Various parameters for monsoon rainfall.

In order to know whether the distribution of monsoon rainfall is symmetrical or not the coefficient of Skewness for the various stations of valley were calculated.
From the study of Skewness following conclusions are drawn,

1) In the North western and western side of the valley [Kakani (-0.5) and Thankot (-0.3), rainfall distribution has a negative Skewness.

2) The distribution of monsoon rainfall shows almost asymetricity in the valley floor and base of mountains. The value of Skewness is almost near to zero at the stations Panipokhari, Khumaltar, Kathmandu airport, Godavari and Sankhu.

3) All the stations on the ridge of mountain show the asymetricity with the highest value of positive Skewness in the station Nagarkot (North East Mountain).

So the rainfall in the stations Nagarkot can not be well approximated by normal distribution, either the data should be transformed or other distributions should be used to get the well approximation in the total monsoon rainfall for station Nagarkot.

4.3 Study on daily rainfall pattern and its change over Kathmandu valley during monsoon season:

4.3.1 Distribution pattern of daily rain rate during Monsoon season (1971-2005):

For the study of monsoon daily rainfall pattern five stations in the mountains side (Kakani,Thankot,Sankhu,Nagarkot,Godavari) and one station in almost central part of valley floor Kathmandu airport) are selected .The data period for the study is 1971-2005.

Three distinct type of rainfall distributions are found in the stations of valley. Rainfall distribution in the mountain stations Sankhu, Nagarkot, Thankot and Godavari are almost similar.Kathmandu airport represents the station in valley floor and Kakani in the mountain side with relatively high monsoon rainfall than that of other stations in mountain side. Climatologically, during the southwest monsoon season, the rainfall amount is larger in the base and top of the mountains than those of the central part of valley floor. The average number of rainy days in all the stations of valley excluding Kakani, which has 100 rainy days, is about 90 days.

The average monsoon rainfall is about 1590 mm in the mountain stations (Not including Kakani), 1151mm and 2366 mm in (Kathmandu airport) Valley floor and Kakani, respectively.

For example, light precipitation with daily rain rate of less than 10 mm occupies most of the rainy days, with 61%, 47%, and 35% for the valley floor, overall mountain stations and Kakani respectively. The frequency falls off rapidly to less than 28% for precipitation rate between 10 to 20 mm /day. Approximately 80%, 70%, 60% of rainy events consist of days with the precipitation rate less than 30 mm /day in the Valley floor, Mountain stations and Kakani, respectively. Heavy rain events > 90 mm /day are very infrequent with less than 2% of the total occurrence.

The importance of heavy rainfall events in contributing to the total rainfall amount is clearly depicted in the fig.2 to 9

While about 48% [Kakani (35%), Mountain stations (47%), Valley floor (61%)] of the whole rainy events belong to precipitation rate less than 10 mm /day, these events contribute only 7%, 12% and 17% of the total rainfall to the Kakani, Valley floor and Mountain stations, respectively.

On the other hand, the heavy rain events (> 30 mm / day) contribute 45%, 52%, 65% of the total rainfall, with corresponding frequency of only 12%, 19%and 30% to the Valley floor stations, Mountain stations and Kakani, respectively.

For heavy rain events (30-90 mm / day), the frequency drops sharply because of extremely low chance of the event. However, the rainfall contributed from these rain events is about 48% of the total rainfall. For extremely heavy rainfall events (> 90 mm / day), which happen about once in one summer, the contribution is about 6% of the total rainfall.

Contribution of rainfall frequency (%) and accumulative rainfall (%) for various thresholds of precipitation rate (i.e., 0.1-10, 10-20, 20-30, 30-40,40-60, 60-90, and greater than 90 mm /day), respectively to the whole rainy days and rainfall amount during monsoon season for the various stations of Kathmandu valley (data period 1971-2005) are presented in Table 5 to10.(Fig 2 to 9)

4.3.2 Study on change in rainfall amount (mm) and frequency (days) as a function of daily precipitation rate in the Kathmandu valley during monsoon season:

The difference of monsoonal rainfall between the two periods (1971-1989 and 1990-2005), for the stations of Kathmandu valley indicates a enhanced rainfall by 106 mm, 109 mm, 160 mm, and 165 mm in the stations Sankhu, Kathmandu airport, Nagarkot and Kakani respectively but there is reduced rainfall by 207 mm and 108 mm at Thankot and Godavari respectively in the later period (Average of 1990-2005) compared to the earlier period (Average of 1971-1989).

Mann Kendall rank correlation method , a non parametric test is performed to test the significance of monotonic trend in total monsoonal rainfall in all the 6 stations of valley (1971-2005) .The performed test at 5% level doesn't show the significance of trend in 4 stations(Kakani,Sankhu,Kathmandu airport and Godavari) of valley. But the falling (rising) trend in Thankot (Nagarkot) is significant at 5% level.

Similarly, Five year moving average curve for the period 1971-2005 also shows the rising trend in monsoonal rainfall in most of the stations of valley but the stations Thankot and Godavari have falling trend.(Fig16-20)

In valley, stations located in southern and western side of valley shows the falling trend but there is overall rising trend in valley. The average trend of monsoonal rainfall in the Kathmandu valley is not significant at 5% level.

To investigate the change in rainfall amount (mm) and frequency (days) as a function of precipitation rate in the Kathmandu valley, the difference(Average of 1990-2005 minus average of 1971-1989) of accumulative rainfall attribute from each threshold precipitation rate is a shown in Figures 10 to 15 (Table5-10).

In Sankhu, the accumulative rainfall in the categories > 40 mm/day and 0.1-10 mm/day has increased in the decades since 1989 with the majority of the changes in the precipitation rate 40 - 90 mm/day.

In Kathmandu airport, there is increase in accumulated rainfall in the categories 0.1-10 mm/day, 20-60 mm/day and > 90 mm with majority of change in precipitation rate 20-30 mm/day and 40-60 mm/day.

In Nagrkot, the accumulative rainfall in all the categories except 60-90 mm/day has increased in the decades since 1989 with the majority of the changes in the precipitation rate 40 - 60 mm/day and > 90mm/day.

In Kakani, there is increase in accumulated rainfall in the categories 0.1-20 mm/day, 40-60 mm/day and > 90 mm/day in the decades since 1989 with the majority of the changes in the precipitation rate 40 – 60 mm/day.

In Thankot, the accumulative rainfall from all categories has decreased during the recent period.

In Godavari, accumulative rainfall from the categories 0.1-10 mm /day, 20-30 mm /day, 40-60 mm/day and > 90 mm/day has increased but there is the decrease in the rainfall from the categories 60-90 mm/day, 30- 40 mm/day and 10-20 mm /day with majority of change in 60-90 mm /day, leading to reduction in total rainfall amount in the recent decades.

Then, Mann-Kendall rank correlation (MK) method is employed to test the significance of monotonic trends in whole time series (1971-2005) to the above change in days and accumulated rainfall for the various threshold of precipitation during Monsoon season. (Table 11)

There is rising trend in no. of rainy days in the categories 0.1-10 mm/day in all the stations of valley excluding Godavari during Monsoon season. The trend is significant at 5% level in all the mountain stations but the significance is quite low in valley floor.

Similarly, In Monsoon season, there is also a rising trend in accumulated precipitation in the categories 40-60 mm/day and >90 mm/day in all the stations of valley excluding Thankot. But the trend is significant only in some stations. On the other hand, there is falling trend in accumulated rain in the categories 60-90 mm/day in all the stations of valley excluding Sankhu.

But the falling and rising trend in accumulated rain of other categories are quite random and varies from station to station.

Only the overall (average of valley) rising trend (excluding station Thankot) of accumulated rainfall in the categories 40-60 mm/day and > 90 mm/day in Kathmandu valley have very low statistical significance. The overall (valley average) time series on this category is not significant on including Thankot.

On the other hand, the overall (Average of valley) rising trend in no of rainy days in the categories 0.1-10 mm/day is significant even at 1% level. Similarly, the rising trend in no. of rainy days (>1 mm/day) is also significant at 5% level. The significant rising trend in the number of rainy days with precipitation rate 0.1-10 mm /day may be due to the increasing number of condensation nuclei in the air. But, the causes for the change in the threshold of precipitation on decadal scale in the region are very complicated and they may be involved in the natural variability and anthropogenic change as well as interaction between them.

Rain rate (mm /day)	Rainfall amount (mm)	Rainy days	Percentage of total rainfall amount	Percentage of total days	Change in amount (mm)	Days
0.1-10	198.5	38.9	12.6	43.5	-0.2	9.9
10-20	342.5	24.3	21.7	27.3	-51.4	-3
20-30	241.5	10.1	15.3	11.3	-34.3	-1.6
30-40	204.2	6.1	12.9	6.8	-1.1	0
40-60	293.3	6.2	18.5	6.9	-83.3	-1.7
60-90	195.4	2.8	12.4	3.1	-18.6	-0.3
>90	105.8	0.9	6.7	1	-18.8	-0.3
Total	1581.1	89.3	100	100	-207.8	3

Table 5: Contribution of rainfall frequency and accumulative rainfall and their Change(Average of 1990-2005 minus Average of 1971-1989) for various thresholds of precipitation rate (i.e., 0.1-10, 10-20, 20-30, 30-40,40-60, 60-90, and greater than 90 mm /day), respectively to the whole rainy days and total rainfall during monsoon season in Thankot

Rain rate (mm /day)	Rainfall amount (mm)	Rainy days	Percentage of total rainfall amount	Percentage of total days	Change in amount (mm)	Days
0.1-10	193.8	40.7	11.4	44.1	18.6	7.4
10-20	321.1	21.2	18.9	22.9	-29	-1.7
20-30	284.2	11.2	16.8	12.2	-63.4	-2.6
30-40	313.9	8.7	18.5	9.5	-58.4	-1.5
40-60	346.5	7.4	20.4	8	69.8	1.3
60-90	176.4	2.5	10.4	2.7	126.5	1.8
>90	59.7	0.6	3.5	0.6	42.3	0.4
Total	1695.6	92.3	100	100	106.4	5.1

Table 6: Contribution of rainfall frequency and accumulative rainfall and their Change(Average of 1990-2005 minus Average of 1971-1989) for various thresholds of precipitation rate (i.e., 0.1-10, 10-20, 20-30, 30-40,40-60, 60-90, and greater than 90 mm /day), respectively to the whole rainy days and total rainfall during monsoon season **Sankhu**

Rain rate (mm /day)	Rainfall amount (mm)	Rainy days	Percentage of total rainfall amount	Percentage of total days	Change in amount (mm)	Days
0.1-10	190.6	55.5	16.5	60.9	1.3	0
10-20	235.9	16.3	20.5	17.9	-25.9	-2.2
20-30	206.5	8.4	17.9	9.2	34.4	1.4
30-40	169.3	4.9	14.7	5.3	21.8	0.6
40-60	191.5	4	16.6	4.4	59.4	1.2
60-90	121.9	1.7	10.6	1.9	-3.4	0
>90	36.1	0.3	3.1	0.4	21.9	0.2
Total	1151.7	91.1	100	100	109.6	1.2

Table 7: Contribution of rainfall frequency and accumulative rainfall and their Change(Average of 1990-2005 minus Average of 1971-1989) for various thresholds of precipitation rate (i.e., 0.1-10, 10-20, 20-30, 30-40,40-60, 60-90, and greater than 90 mm /day), respectively to the whole rainy days and total rainfall during monsoon season in **Kathmandu airport**

Rain rate (mm /day)	Rainfall amount (mm)	Rainy days	Percentage of total rainfall amount	Percentage of total days	Change in amount (mm)	Days
0.1-10	184	46.3	12.5	50.7	6.8	-2
10-20	274.4	18.8	18.6	20.7	-30.5	-1.9
20-30	243.3	9.9	16.3	10.9	12.7	0.4
30-40	236.4	6.8	15.7	7.4	-69.6	-2.1
40-60	279.3	5.8	18.3	6.3	23.9	0.6
60-90	182.7	2.5	11.8	2.8	-76.4	-1
>90	107.2	0.9	6.8	1	24.3	0.2
Total	1507.3	91	100	100	-108.8	-5.8

Table 8: Contribution of rainfall frequency and accumulative rainfall and their Change(Average of 1990-2005 minus Average of 1971-1989) for various thresholds of precipitation rate (i.e., 0.1-10, 10-20, 20-30, 30-40,40-60, 60-90, and greater than 90 mm /day), respectively to the whole rainy days and total rainfall during monsoon season in **Godavari**

Rain rate (mm /day)	Rainfall amount (mm)	Rainy days	Percentage of total rainfall amount	Percentage of total days	Change in amount (mm)	Days
0.1-10	172.4	42.2	10.9	47.4	20.4	8
10-20	279.6	18.9	17.7	21.2	7.7	0.7
20-30	246.6	10.1	15.6	11.3	11.8	0.7
30-40	274.8	7.8	17.4	8.7	13	0.5
40-60	309.8	6.3	19.6	7.1	78.6	1.6
60-90	238.4	3.3	15.1	3.7	-15	-0.1
>90	56.3	0.5	3.6	0.6	44.2	0.4
Total	1577.9	89.1	100	100	160.6	11.8

Table 9: Contribution of rainfall frequency and accumulative rainfall and their Change(Average of 1990-2005 minus Average of 1971-1989) for various thresholds of precipitation rate (i.e., 0.1-10, 10-20, 20-30, 30-40,40-60, 60-90, and greater than 90 mm /day), respectively to the whole rainy days and total rainfall during monsoon season in **Nagarkot**

Rain rate (mm /day)	Rainfall amount (mm)	Rainy days	Percentage of total rainfall amount	Percentage of total days	Change in amount (mm)	Days
0.1-10	163.4	35.2	6.9	35.3	13.4	8
10-20	300.6	20.5	12.7	20.6	51.4	4.3
20-30	371.1	14.9	15.7	15	-16.9	-0.3
30-40	373.9	10.5	15.8	10.5	-35.1	-0.6
40-60	512.7	10.7	21.7	10.7	147.7	3.3
60-90	424.5	5.9	17.9	5.9	-46.6	-0.5
>90	220.1	2	9.3	2	51.3	0.6
Total	2366.3	99.8	100	100	165.2	14.7

Table 10: Contribution of rainfall frequency and accumulative rainfall and their Change(Average of 1990-2005 minus Average of 1971-1989) for various thresholds of precipitation rate (i.e., 0.1-10, 10-20, 20-30, 30-40,40-60, 60-90, and greater than 90 mm /day), respectively to the whole rainy days and total rainfall during monsoon season **Kakani** .(data period 1971-2005)

Name of Station	Rainfall characteristics	Z_T
Sankhu	No of days with precipitation rate 0.1-10 mm/day	2.3184
Kakani		3.2366
Nagarkot		2.8578
Thankot		2.9925
Kathmandu airport		0.1140
Valley average		3.38
Kakani	Accumulated precipitation with rate 40-70 mm/day	2.3352
	Accumulated precipitation with rate > 90 mm/day	1.4922
Nagarkot	Accumulated precipitation with rate 40-60 mm/day	0.3693
	Accumulated precipitation with rate > 90 mm/day	2.4866
Kathmandu airport	Accumulated precipitation with rate > 90 mm/day	1.3059
Sankhu	Accumulated precipitation with rate > 40 mm/day	2.6557
	Accumulated precipitation with rate > 90 mm/day	2.3130
Godavari	Accumulated precipitation with rate 40-60 mm/day	0.4744
Valley average (excluding Thankot)	Accumulated precipitation with rate > 90 mm/day	1.65
	Accumulated precipitation with rate 40-60 mm/day	1.54
Valley average	No of rainy days (>1 mm/day)	2.25
Thankot	Total monsoonal rainfall	2.25
Nagarkot		2.0

Table11: Parameters of Mann Kendall Rank correlation to various rainfall characteristics (Kathmandu valley) (Data period 1971-2005)

($|Z_T|$ >1.96 significant limit for 5% significance level.)

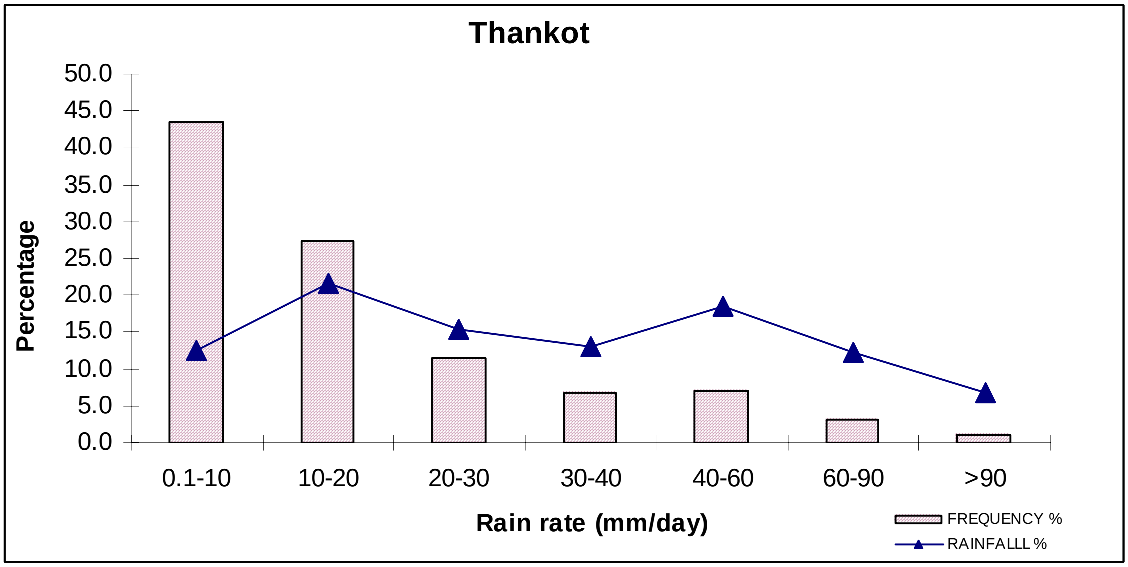


Fig 2: Contribution of rainfall frequency (%) and accumulative rainfall (%) for various thresholds of precipitation rate (i.e., 0.1-10, 10-20, 20-30, 30-40,40-60, 60-90, and greater than 90 mm /day), respectively to the whole rainy days and total monsoon rainfall in Thankot.

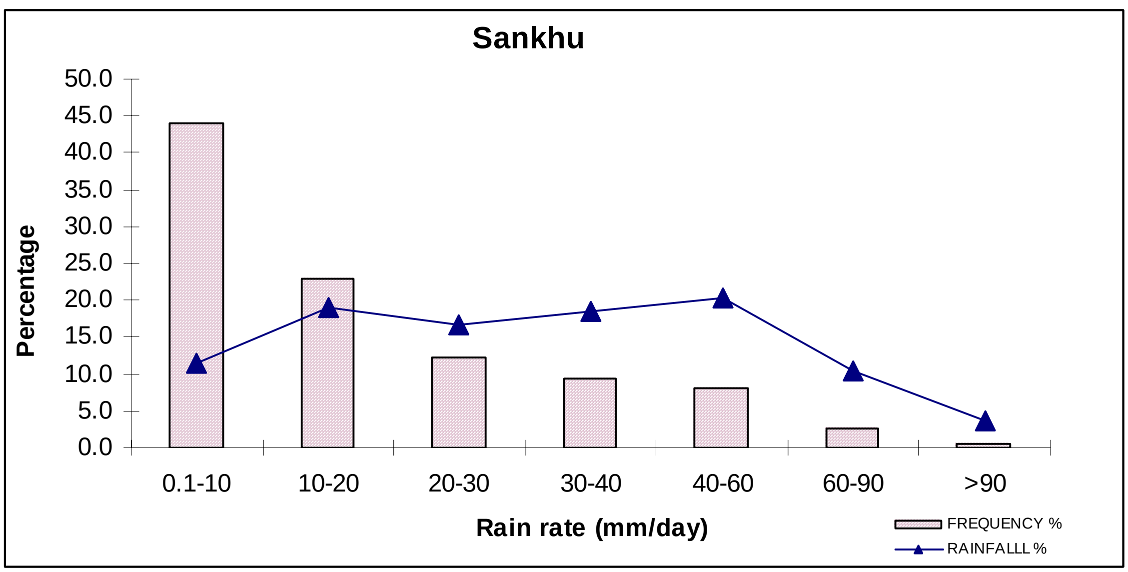


Fig 3: Contribution of rainfall frequency (%) and accumulative rainfall (%) for various thresholds of precipitation rate (i.e., 0.1-10, 10-20, 20-30, 30-40,40-60, 60-90, and greater than 90 mm /day), respectively to the whole rainy days and total monsoon rainfall in Sankhu (Monsoon season)

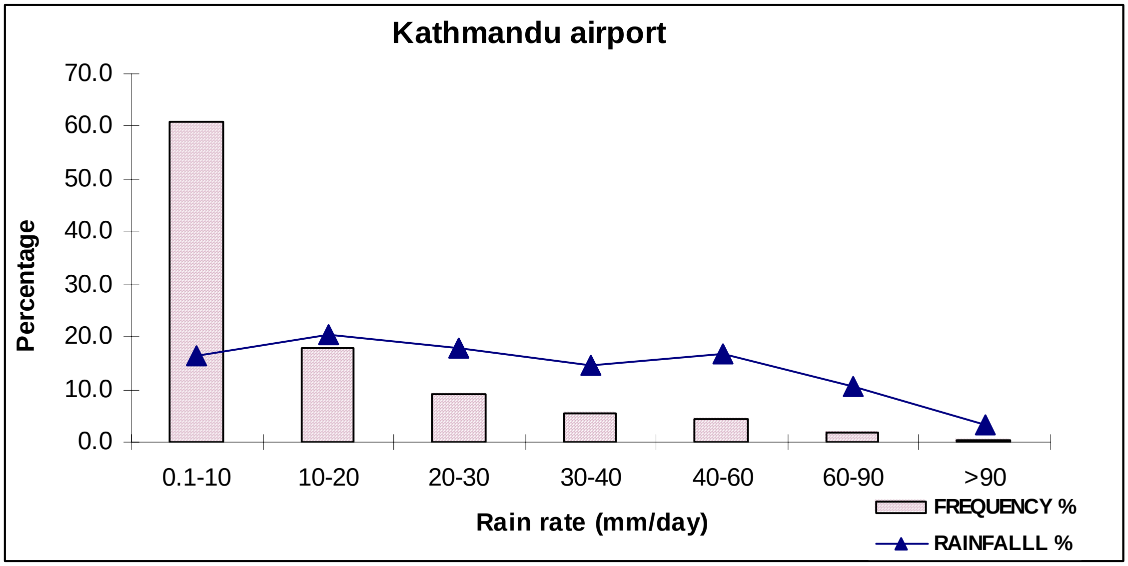


Fig 4: Contribution of rainfall frequency (%) and accumulative rainfall (%) for various thresholds of precipitation rate (i.e., 0.1-10, 10-20, 20-30, 30-40,40-60, 60-90, and greater than 90 mm /day), respectively to the whole rainy days and total monsoon rainfall in Kathmandu airport (Monsoon season)

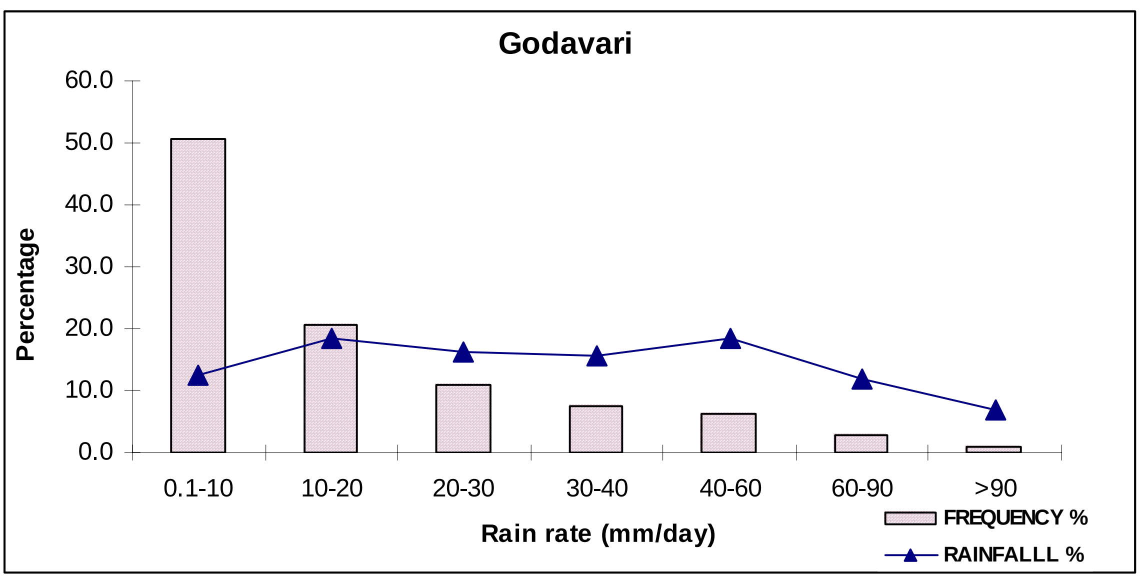


Fig 5: Contribution of rainfall frequency (%) and accumulative rainfall (%) for various thresholds of precipitation rate (i.e., 0.1-10, 10-20, 20-30, 30-40,40-60, 60-90, and greater than 90 mm/ day), respectively to the whole rainy days and total monsoon rainfall in Godavari(Monsoon season)

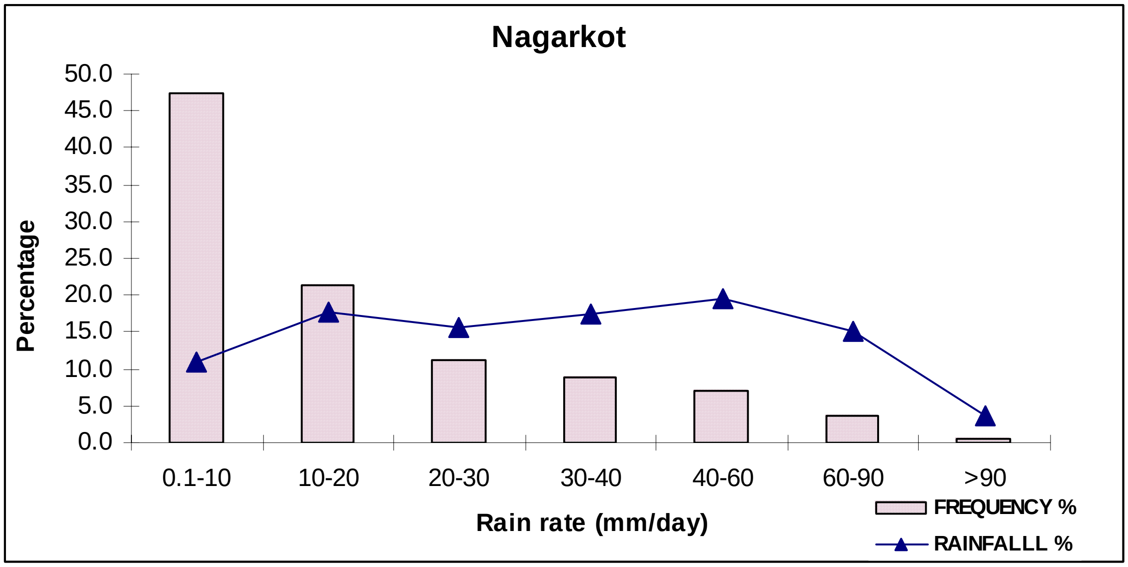


Fig 6: Contribution of rainfall frequency (%) and accumulative rainfall (%) for various thresholds of precipitation rate (i.e., 0.1-10, 10-20, 20-30, 30-40,40-60, 60-90, and greater than 90 mm / day), respectively to the whole rainy days and total monsoon rainfall in Nagarkot.(Monsoon season)

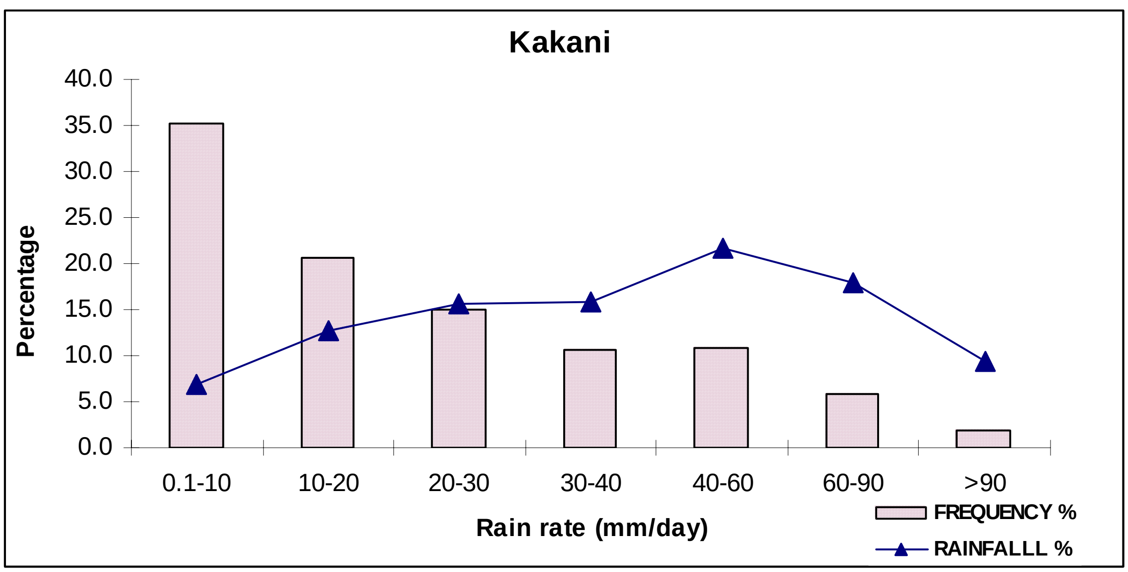


Fig 7: Contribution of rainfall frequency (%) and accumulative rainfall (%) for various thresholds of precipitation rate (i.e., 0.1-10, 10-20, 20-30, 30-40,40-60, 60-90, and greater than 90 mm /day), respectively to the whole rainy days and total monsoon rainfall in Kakani.(Monsoon season)

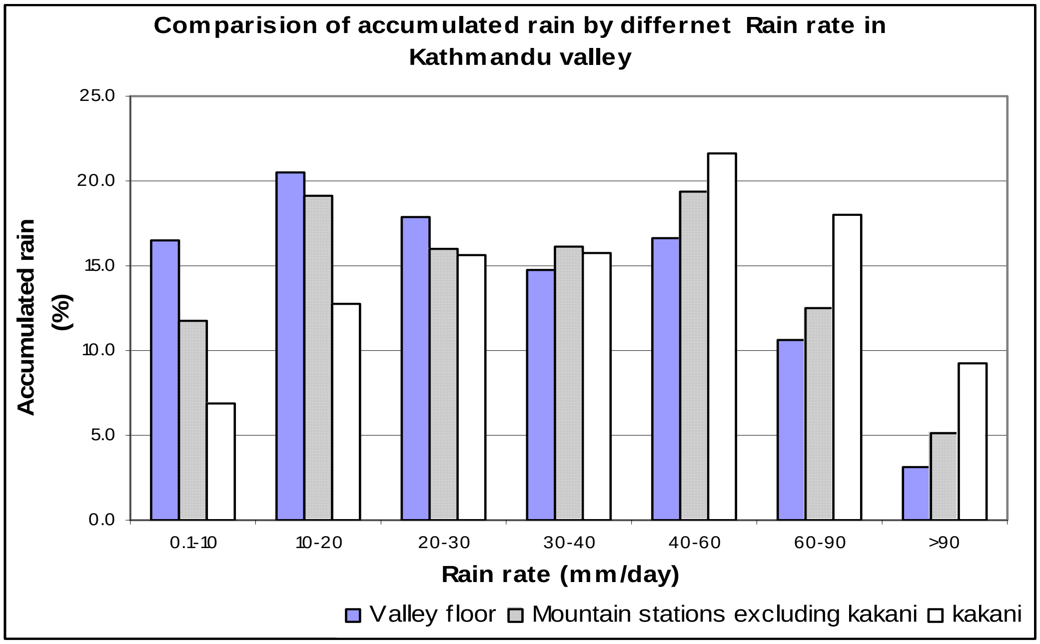


Fig 8: Comparison of accumulated rainfall (%) by various thresholds of precipitation rate Over Kathmandu valley during Monsoon season.
(Mountain stations: Sankhu, Nagarkot, Godavari and Thankot)

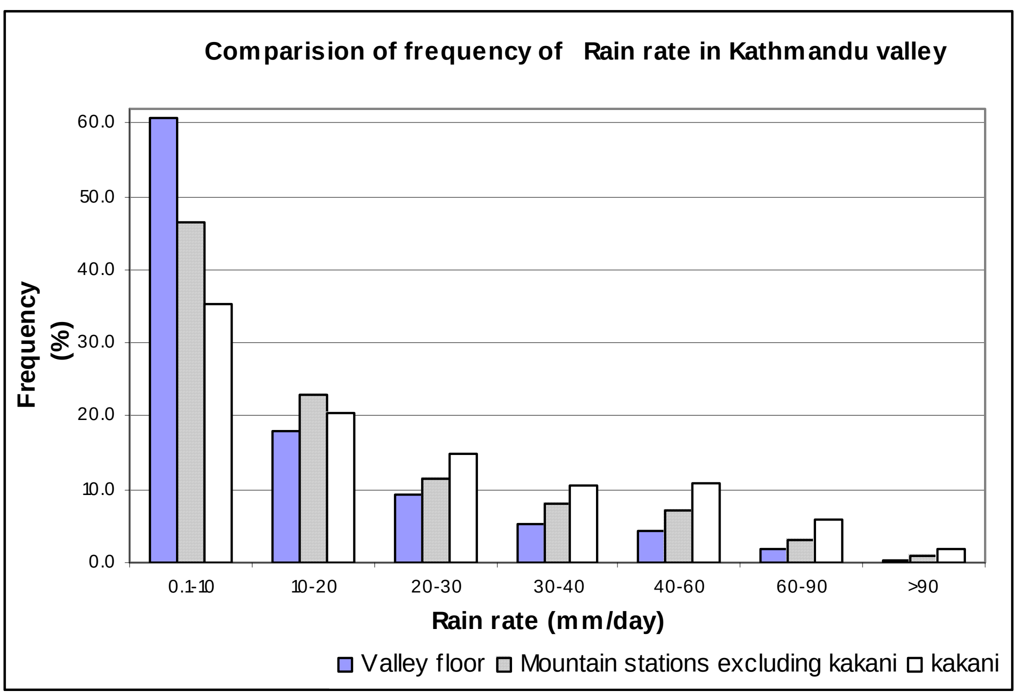


Fig 9: Comparison of Frequency (%) for various thresholds of precipitation rate Over Kathmandu valley during Monsoon season.(Mountain stations: Sankhu, Nagarkot, Godavari and Thankot)

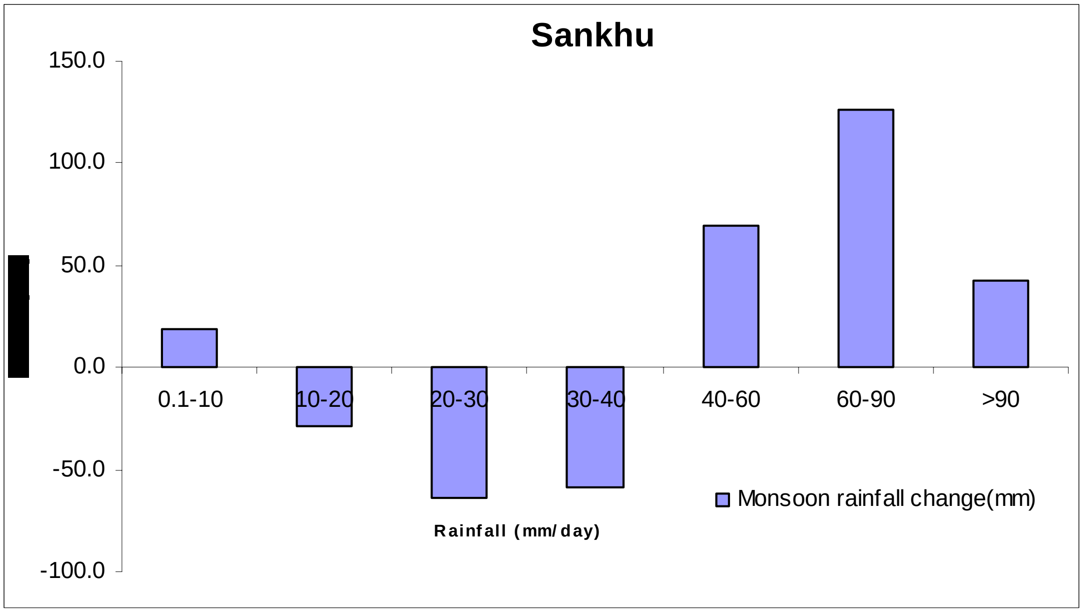


Fig 10: Change (Average of 1990-2005 minus average of 1971-1989) in contribution of accumulative rainfall (mm) for various thresholds of precipitation rate 0-10,10-20, 20-30, 30-40,40-60, 60-90, and greater than 90 mm /day) in Sankhu (monsoon rainfall)

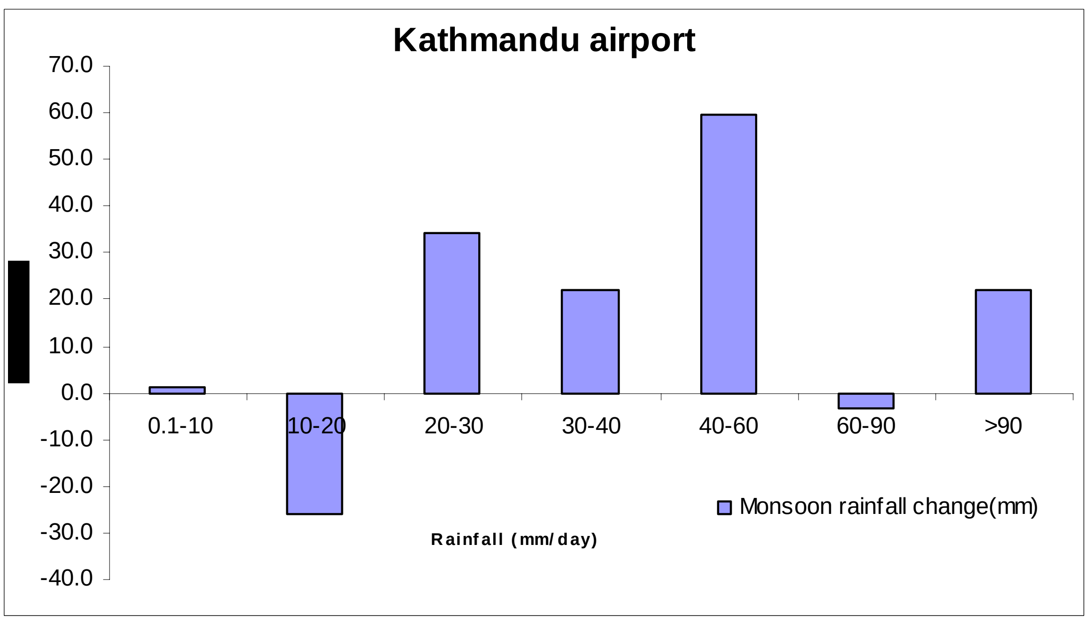


Fig 11: Change (Average of 1990-2005 minus average of 1971-1989) in contribution of accumulative rainfall (mm) for various thresholds of precipitation rate 0-10,10-20, 20-30, 30-40,40-60, 60-90, and greater than 90 mm/ day) in Kathmandu airport (Monsoon rainfall)

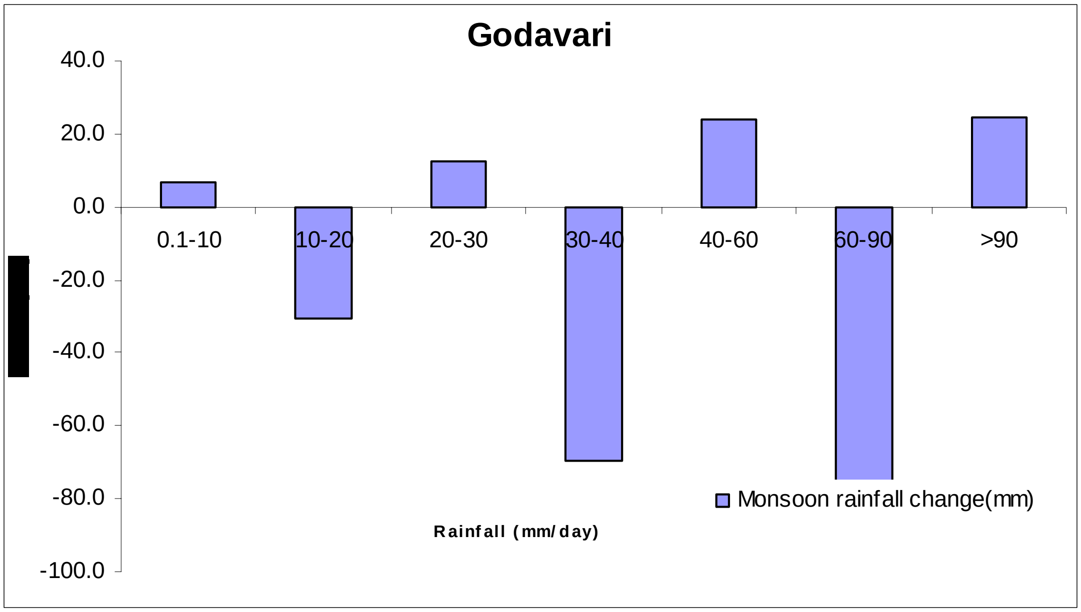


Fig 12: Change (Average of 1990-2005 minus average of 1971-1989) in contribution of accumulative rainfall (mm) for various thresholds of precipitation rate 0-10,10-20, 20-30, 30-40,40-60, 60-90, and greater than 90 mm /day) in Godavari (Monsoon rainfall)

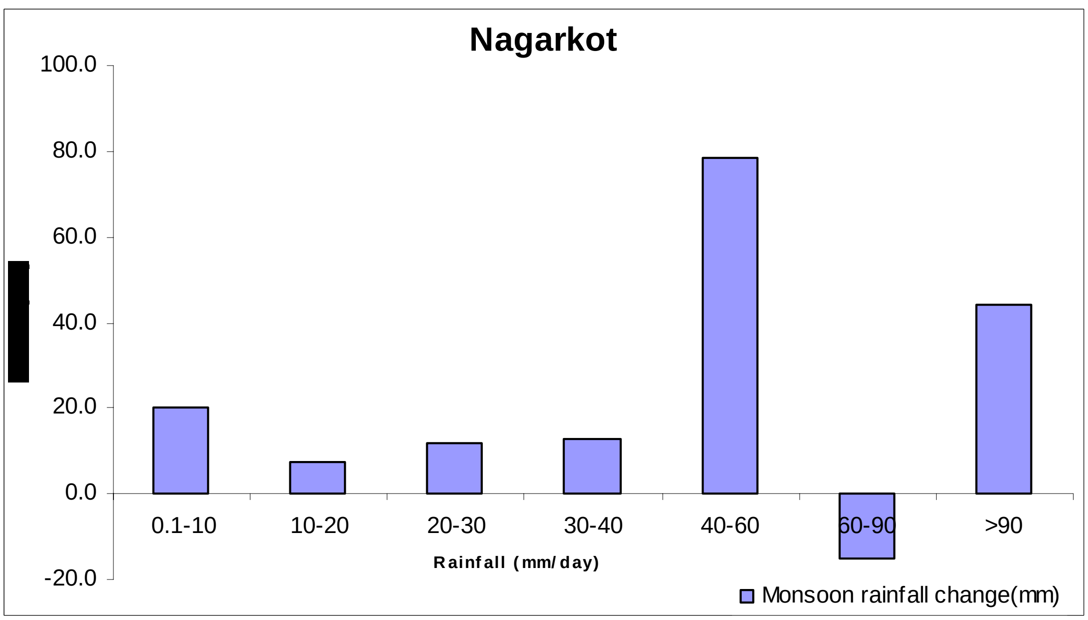


Fig 13: Change (Average of 1990-2005 minus average of 1971-1989) in contribution of accumulative rainfall (mm) for various thresholds of precipitation rate 0-10,10-20, 20-30, 30-40,40-60, 60-90, and greater than 90 mm/ day)
in Nagarkot.(monsoon rainfall)

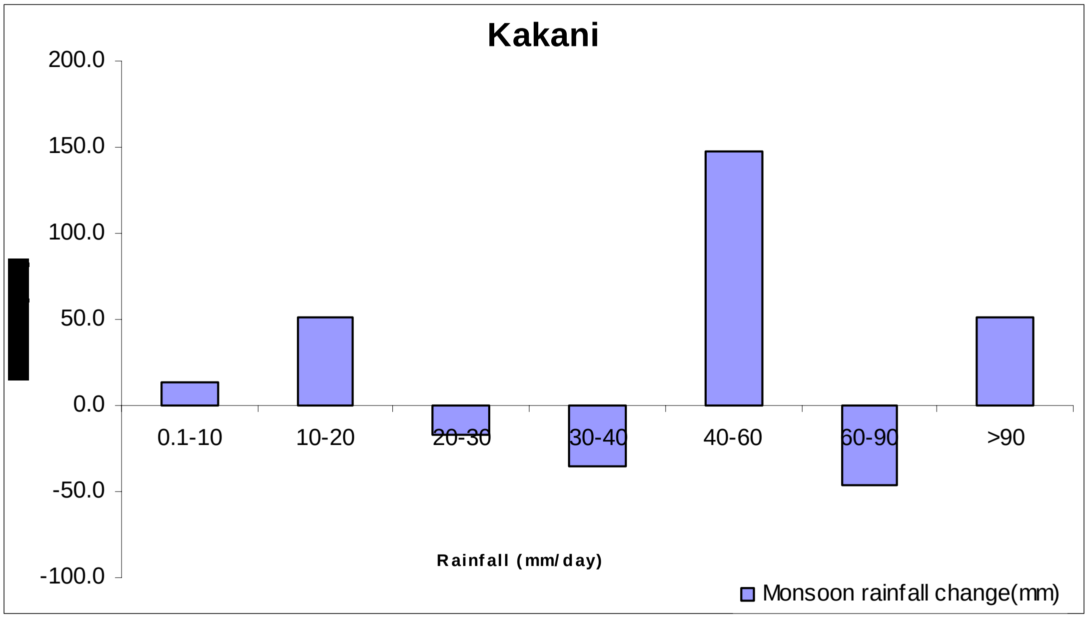


Fig 14: Change (Average of 1990-2005 minus average of 1971-1989) in contribution of accumulative rainfall (mm) for various thresholds of precipitation rate 0-10,10-20, 20-30, 30-40,40-60, 60-90, and greater than 90 mm /day) in Kakani(Monsoon rainfall)

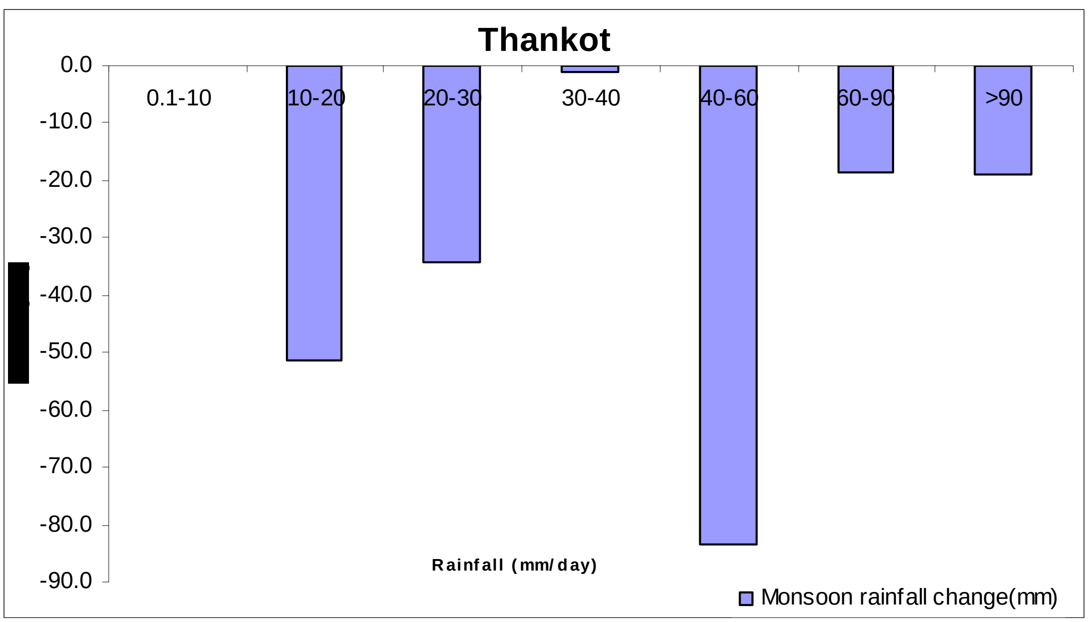


Fig15: Change (Average of 1990-2005 minus average of 1971-1989) in contribution of accumulative rainfall (mm) for various thresholds of precipitation rate 0-10,10-20, 20-30, 30-40,40-60, 60-90, and greater than 90 mm/ day) in Thankot(Monsoon rainfall)

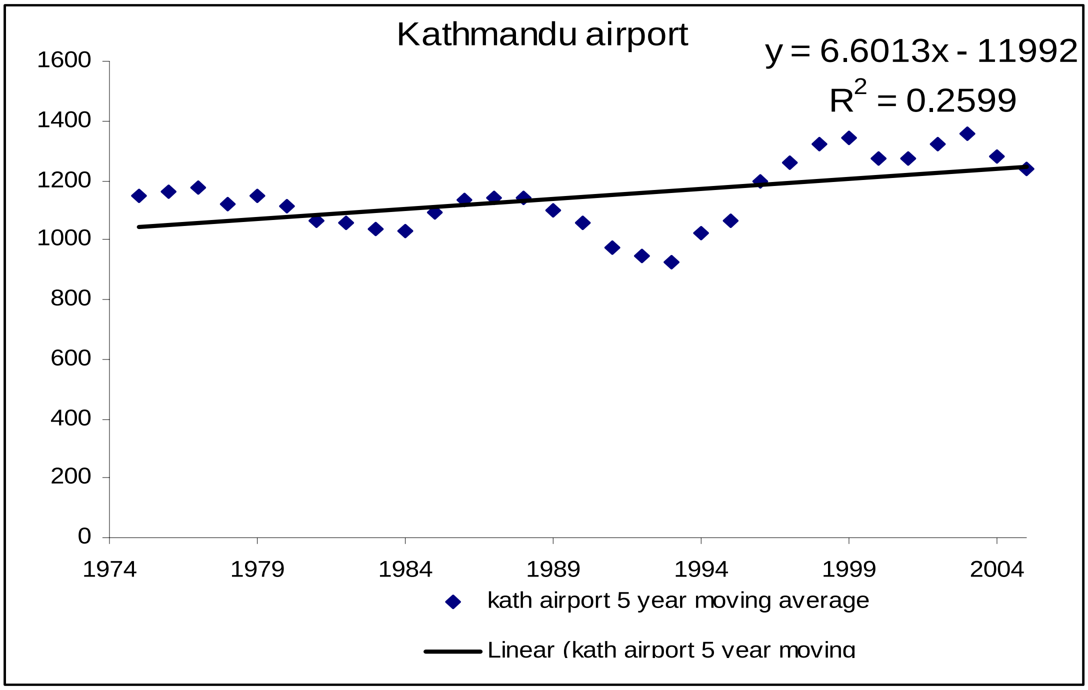


Fig16: Five year moving average of Monsoon rainfall (mm) in Kathmandu airport

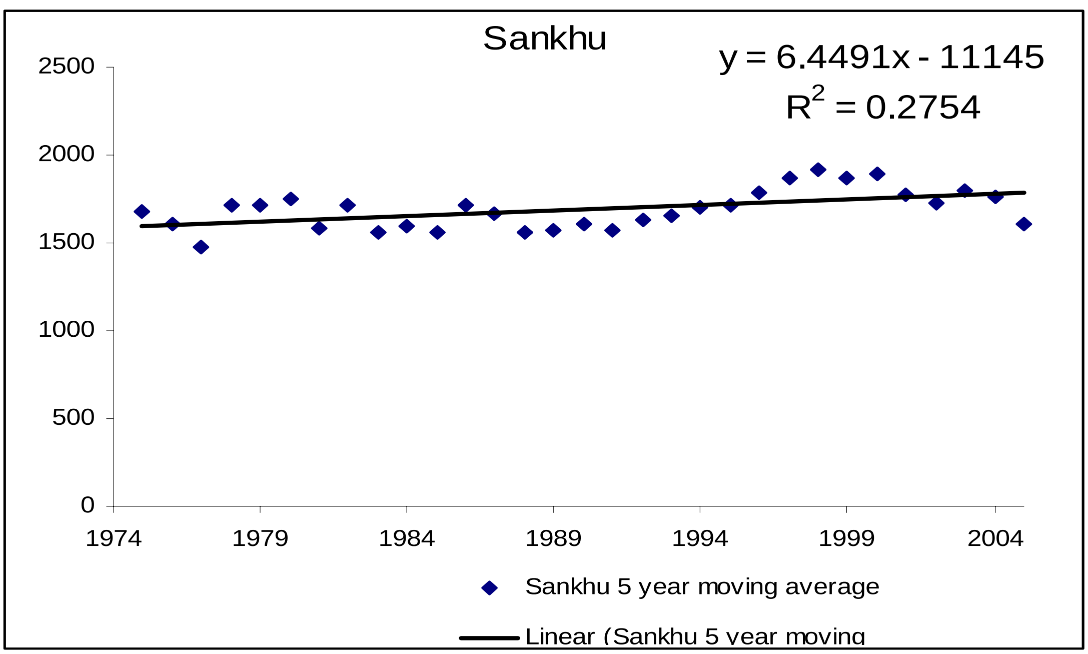


Fig17: Five year moving average of Monsoon (mm) rainfall in Sankhu

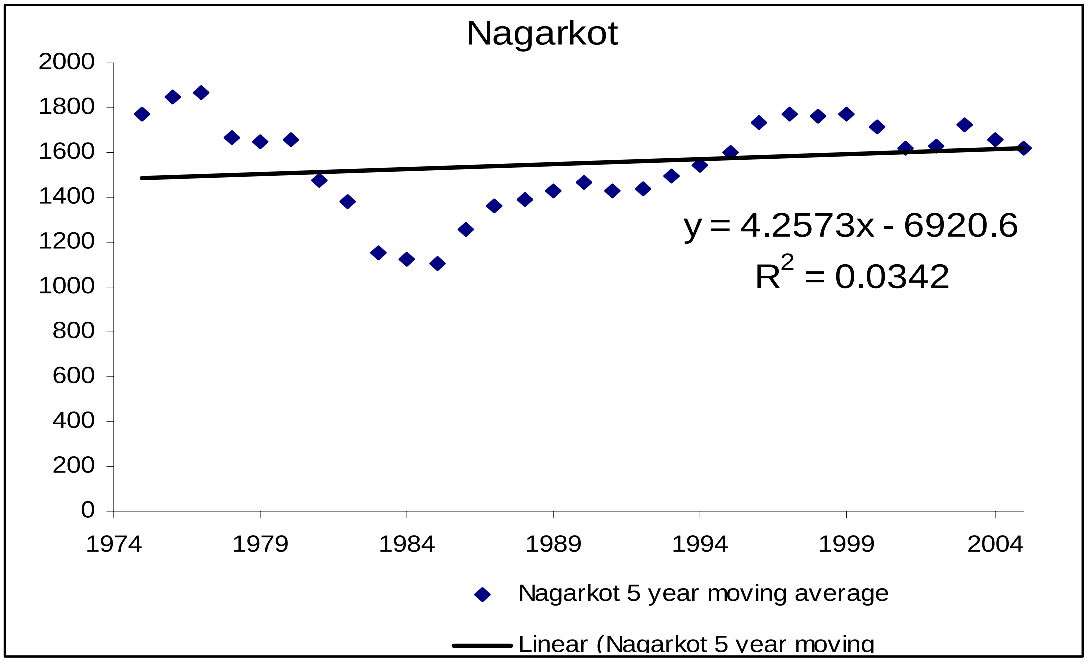


Fig18: Five year moving average of Monsoon rainfall (mm) in Nagarkot

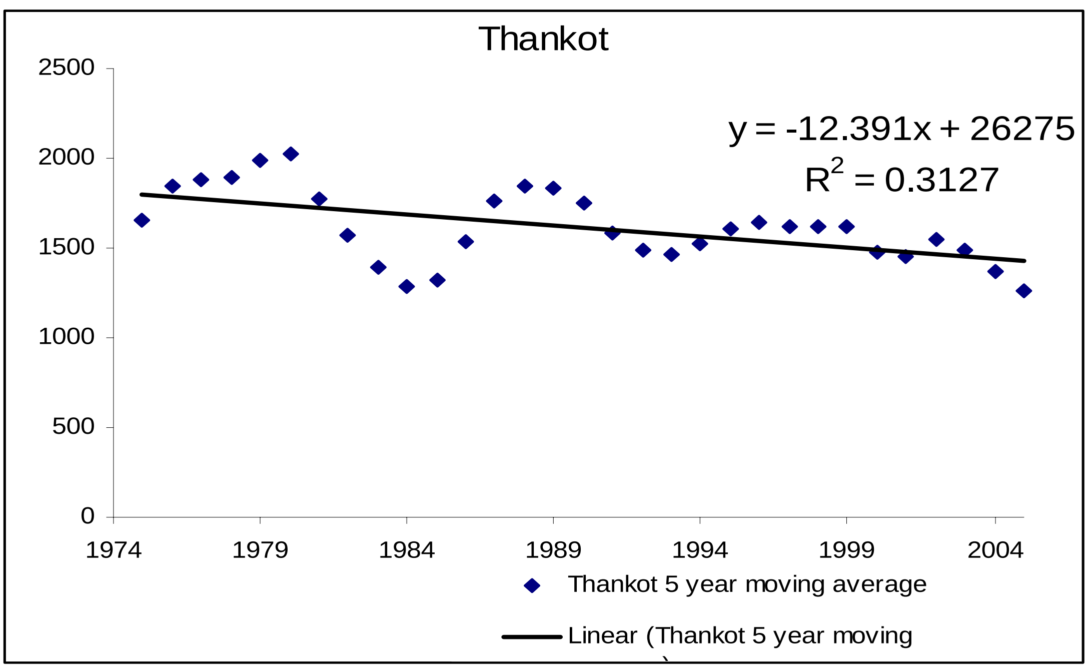


Fig19: Five year moving average of Monsoon rainfall (mm) in Thankot

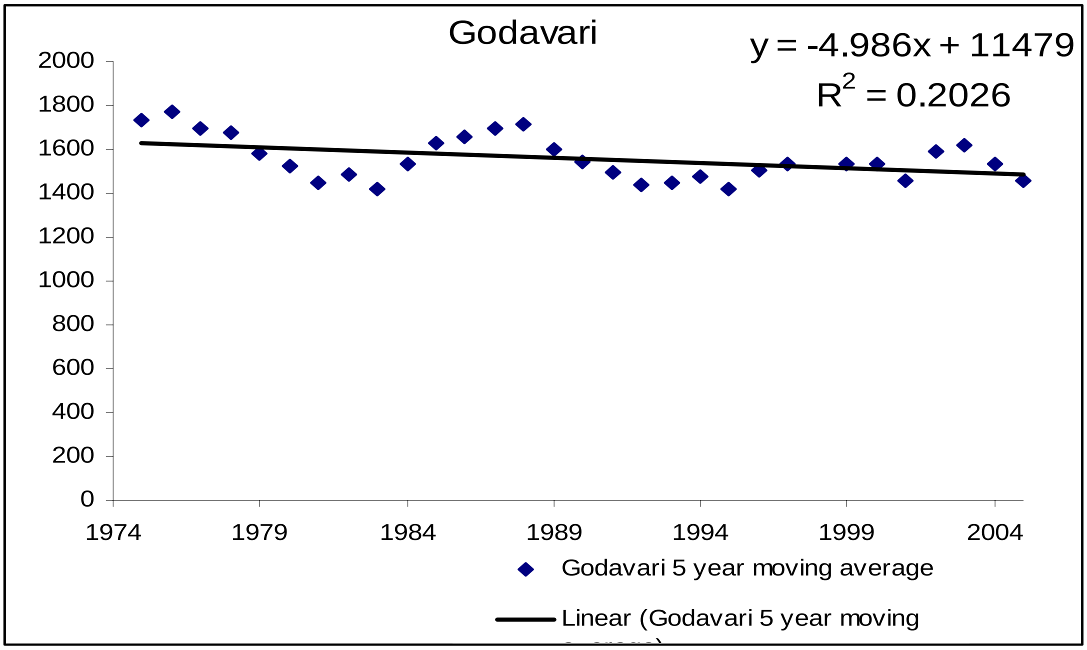


Fig 20: Five year moving average of Monsoon rainfall (mm) in Godavari.

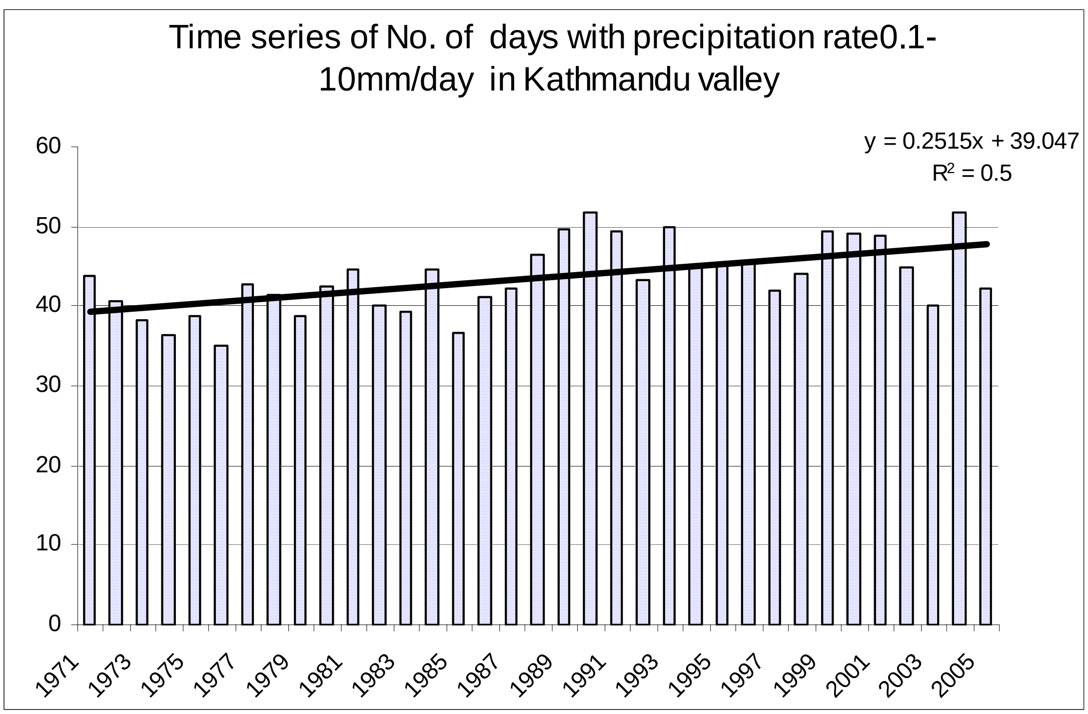


Fig21: Valley average time series of No. of days with precipitation rate 0.1-10 mm/day in Kathmandu during Monsoon season.

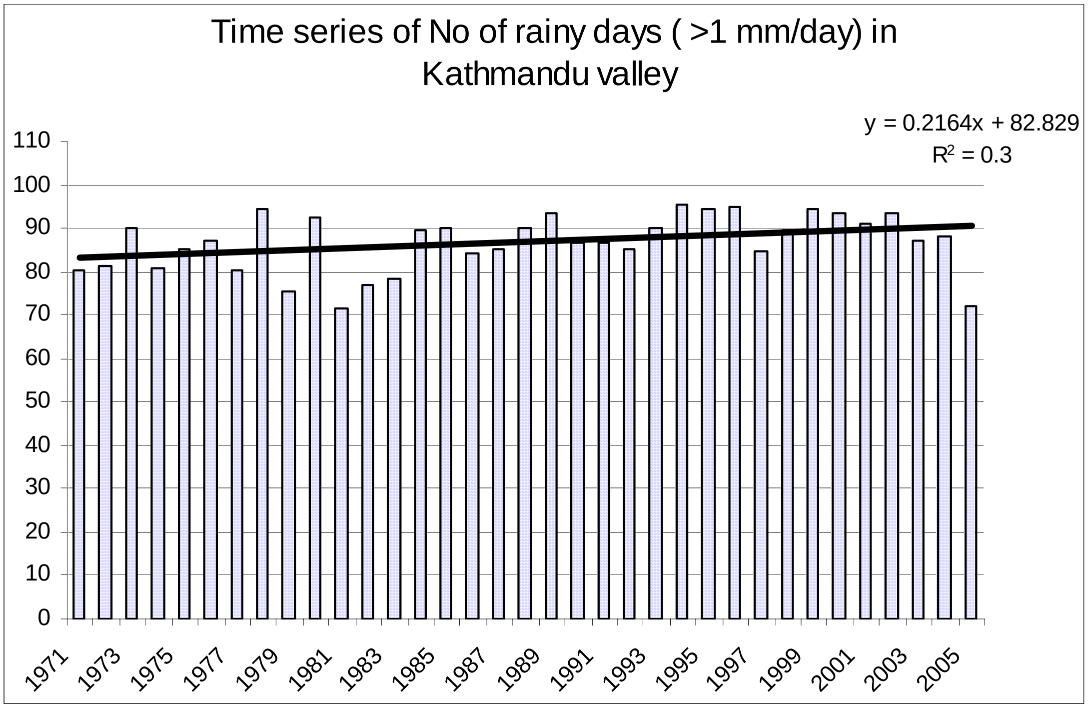


Fig22: Valley average time series of No. of rainy days in Kathmandu during Monsoon season.

4.4 Diurnal variability of rainfall:

4.4.1 Study on diurnal variability of rainfall in Kathmandu airport:

The diurnal cycle of precipitation during monsoon season in valley floor of Kathmandu is investigated using ground based hourly observation for the period 1992-2002 of station Kathmandu airport.

The diurnal cycle of precipitation shows two pronounced peak one in the midnight between 23 -1 NST and another in the evening between 16-18 NST (Fig22).Which is similar to the previous study by Barros et al.(2001) in the Marsyangdi River basin of Nepal. During this season, the precipitation amounts in the mid night and early evening are greater by about 200 % than the daily mean (daily rainfall/24).On the other hand, the minimum amount of rainfall is observed in between 10-12 NST.

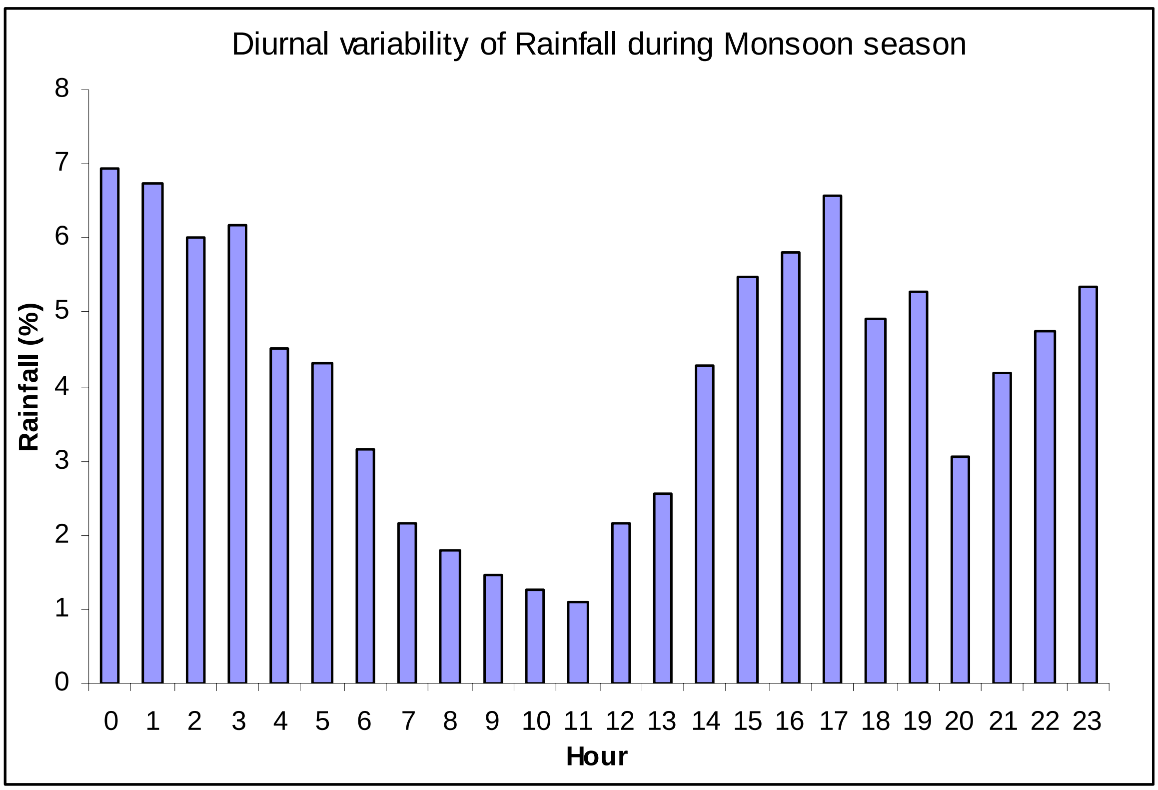


Fig 23: Diurnal variability of Rainfall in valley floor of Kathmandu. (Data period 1992-2002)

4.4.2 Peaks of diurnal cycle and its mechanism:

As has been proposed, it should be reasonable to consider that the evening peak is carried by the convective rainfall, which is caused by the thermal forcing by the sun. The mean intensity of precipitation is higher around the peak of precipitation amount.

The precise mechanism of the midnight peak of precipitation is still uncertain. In Kathmandu valley, during Monsoon season the wind flow is southwesterly .The radiative cooling at night time enhances the down valley wind. The surface collision of down valley wind with monsoon current may forces the precipitation system to produce night time maximum. (Upward movement due to collision).Then question may appear why they occur only during monsoon season, this may be due to significant increase of the moisture in the mature monsoon season.

CHAPTER – 5

Conclusion and Recommendation

5.1 Conclusion:

Following conclusion are made from the study of rainfall pattern over Kathmandu valley.

- Mean Monthly rainfall have been found to be Maximum in July and Minimum in November.

- Mean Annual rainfall over Kathmandu valley is 1784 mm, with Mean seasonal value of 53 mm, 232 mm, 1397 mm and 67 mm during winter, Pre-Monsoon, Monsoon and post Monsoon season, respectively.

- Isohyetal analysis for annual rainfall shows, that the highest rainfall over Kathmandu valley are observed in the Northwestern mountain in the periphery of Kakani with more than 2800 mm of mean annual rainfall, while the lowest rainfall are noted in southern side of valley floor in the periphery of Khumaltar with average annual rainfall less than 1200 mm.

- As rainfall over Kathmandu valley is dominated by Southwest Monsoon so the spatial pattern during Monsoon season is almost similar to the annual pattern.

- Average annual value in the Northern Mountains are quite higher in comparison to other side of Mountain and this is mainly due to the moisture laden air entering from the South eastern side of valley and traveling towards Northern Mountain during Monsoon season.

- Inter annual Variability in monsoonal rainfall over Kathmandu valley is relatively low in the central part of valley floor than that of the base and top of mountains.

- The distribution of average monsoonal rainfall is symmetrical in the valley floor and base of mountain. But almost all the stations in the mountain ridge shows asymetricity with negatively skewed distribution in the Northwestern and western side and positively skewed distribution in eastern mountains.

- Three distinct type of rainfall pattern on daily rain rate are found in the Kathmandu valley. Mountain stations (Sankhu, Nagrkot, Thankot and Godavari), valley floor (Kathmandu airport) and Kakani in the mountain side with relatively high monsoon rainfall than that of other stations in mountain side.

- Light precipitation with daily rain rate less than 10 mm occupies most of the rainy days, with 61 %, 47 %, and 35 % for the valley floor, overall mountain stations, and Kakani, respectively. The frequency falls off rapidly to less than 28% for precipitation rate between 10 to 20 mm /day.

- Approximately 70 %, 80 %, 60 % of rainy events consist of days with the precipitation rate less than 30 mm /day in the Mountain stations, Valley floor and Kakani, respectively.

- Heavy rain events > 90 mm /day are very infrequent with less than 2% of the total occurrence.

- While about 48 % [Kakani (35%), Mountain stations (47%), Valley floor (61%)] of the whole rainy events belong to precipitation rate less than 10 mm /day, these events contribute only 7 %, 12 % and 17 % of the total rainfall to the Kakani, Valley floor and Mountain stations, respectively.

- Heavy rain events (> 30 mm /day) contribute 45 %, 52 %, 65 % of the total rainfall, with corresponding frequency of only 12 %, 19 % and 30 % to the Valley floor stations, Mountain stations and Kakani, respectively.

- Rainfall contributed from the rain events 30 - 90 mm /day is about 48 % of the total rainfall but it has low frequency.

- For extremely heavy rainfall events (> 90 mm/ day), which happen about once in one summer, the contribution is about 6 % of the total rainfall.
- In Kathmandu valley, there is rising trend in total monsoonal rainfall in most of the stations. Only some of the stations located in southern and western side of valley show the falling trend in total rainfall during monsoon season. But the overall trend is not significant in Kathmandu valley.

- During monsoon season, in overall (valley average), there is rising trend in no of rainy days in the categories 0.1-10 mm /day in most of the stations of valley (Significant at 5 % level)

- Similarly, there is also a rising trend in accumulated precipitation in the categories 40-60 mm/day and >90 mm /day in all the stations of valley excluding Thankot during monsoon season. But the trend is significant only in some stations of valley at 5% level.

- There is falling trend is accumulated rain in the categories 60-90 mm/day in all the stations of valley excluding Sankhu.But it does not have statistical significance.

- The overall (valley average) rising trend of accumulated rainfall in the categories 40-60 mm /day and >90 mm /day (excluding station Thankot) in Kathmandu valley have low statistical significance.
- The overall (valley average) rising trend in no of rainy days in the categories 0.1-10 mm /day is significant at 1% level.
- The diurnal cycle of precipitation shows two pronounced peak, one in the midnight between 23 -1 NST and another in the evening between 16-18 NST in valley floor, during summer monsoon season. Whereas, minimum rainfall is observed in the morning between 10-12 NST.

5.2 Recommendation:

- The distribution of rain gauge stations is very poor in the southern mountains of Kathmandu valley as compared to the northern and eastern mountains, sufficient stations network density in accordance with the world meteorological organization criteria is recommended.
- There are some problems in data missing and /or poor in data quality. This may affect on analysis of meteorological condition. Thus the missing of the data and their quality should be controlled and updated as far as possible.
- The causes for the change in the threshold of precipitation on decadal scale in the region are very complicated and they may be involved in the natural variability and anthropogenic change as well as interaction between them. This change may be related with the long cycle of solar activity .So the detail analysis on the change is necessary.
- Further research on non-linear trend in time series is also necessary.
- Detail spatial comparison and aggregation of the results is also necessary as the climate change would have a large spatial influence not a single localized influence.
- Automatic rain gauge stations are also essential for the study of diurnal variability in rainfall.

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Annexes:

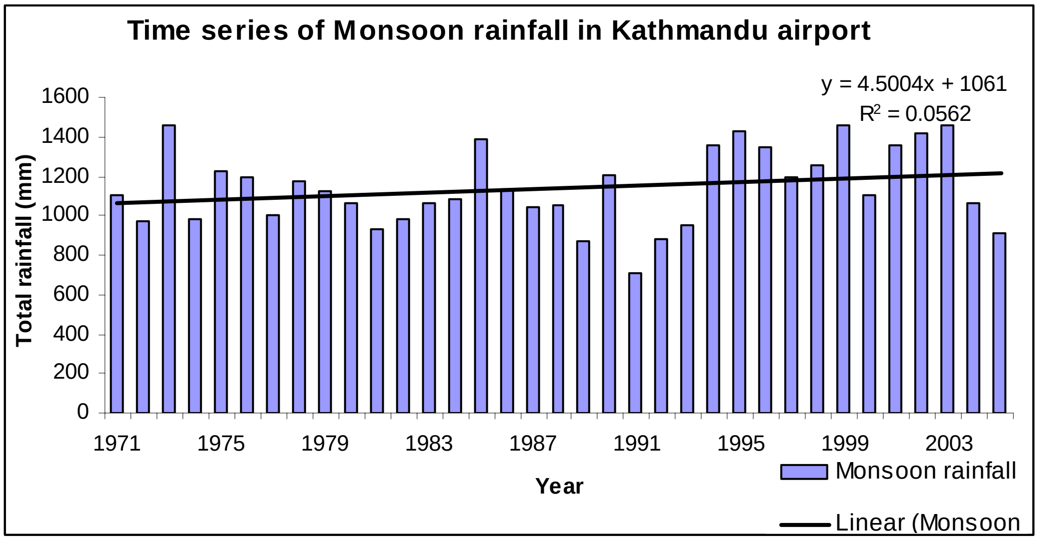

Fig 24: Time series of monsoon rainfall in Kathmandu airport

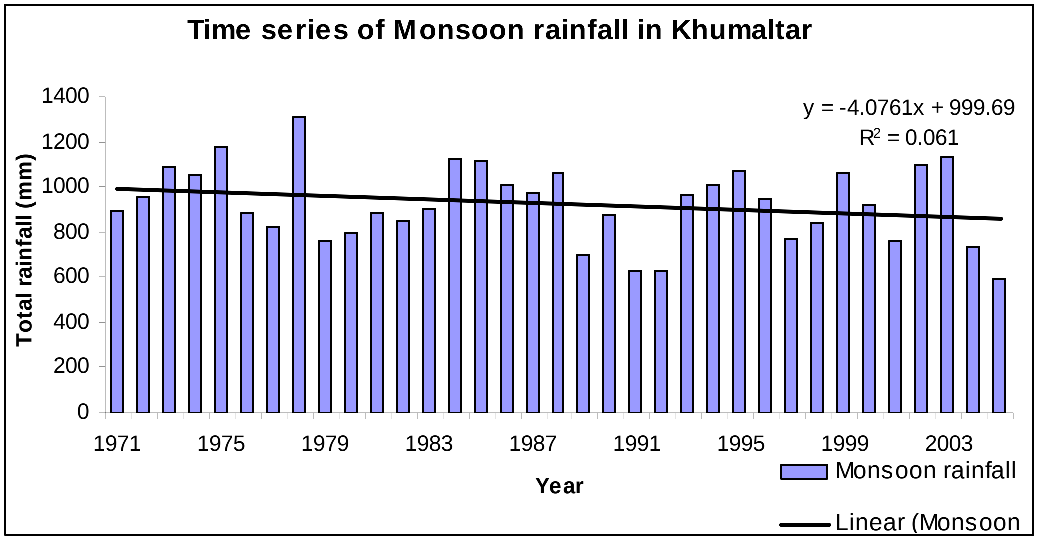

Fig 25: Time series of monsoon rainfall in Khumaltar

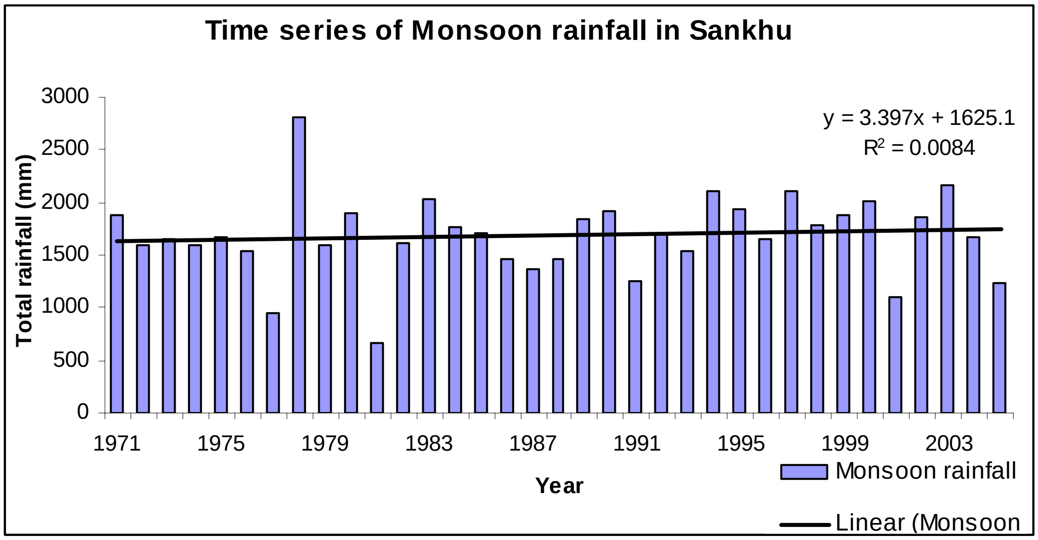

Fig 26: Time series of monsoon rainfall in Sankhu

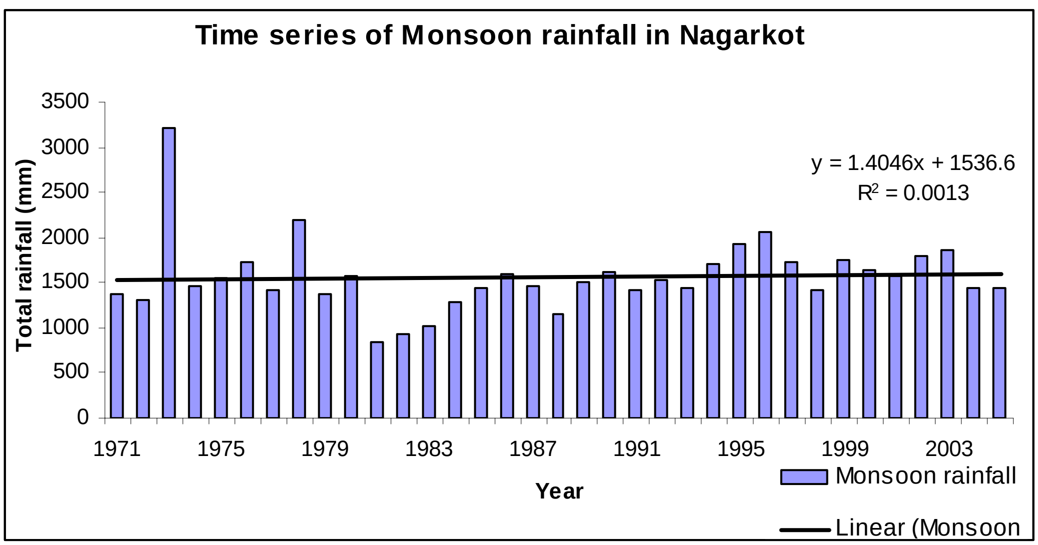

Fig 27: Time series of monsoon rainfall in Nagarkot

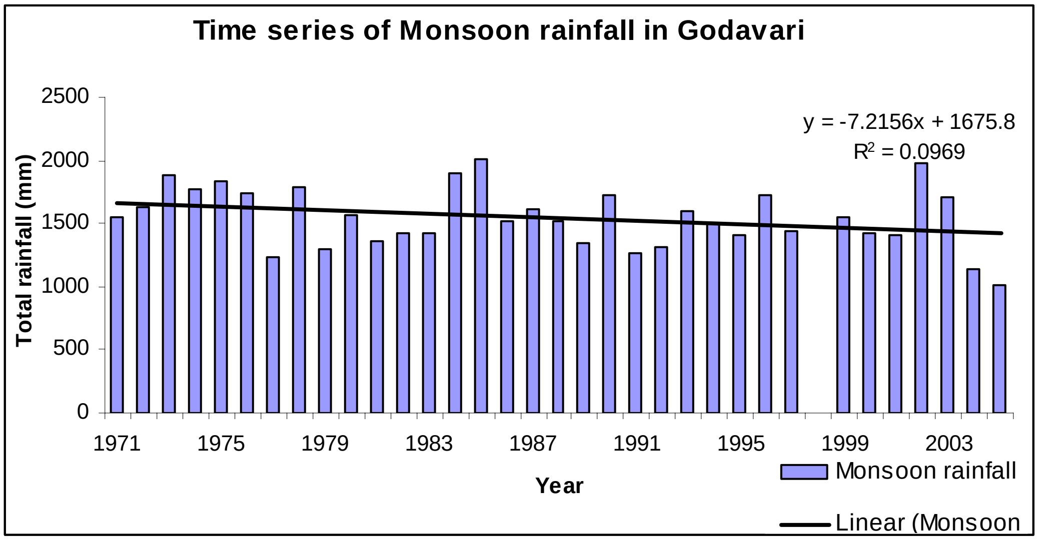

Fig 28: Time series of monsoon rainfall in Godavari

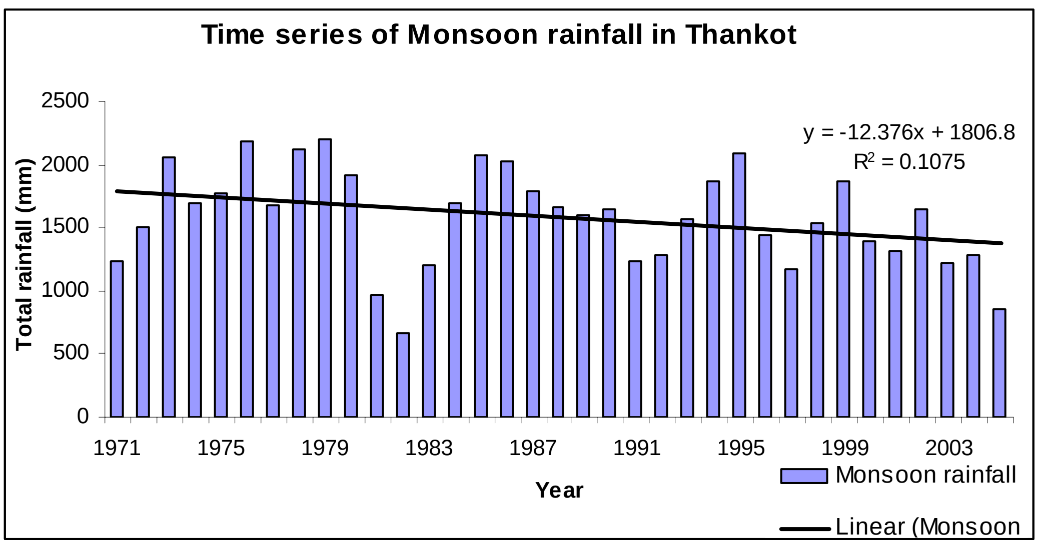

Fig 29: Time series of monsoon rainfall in Thankot

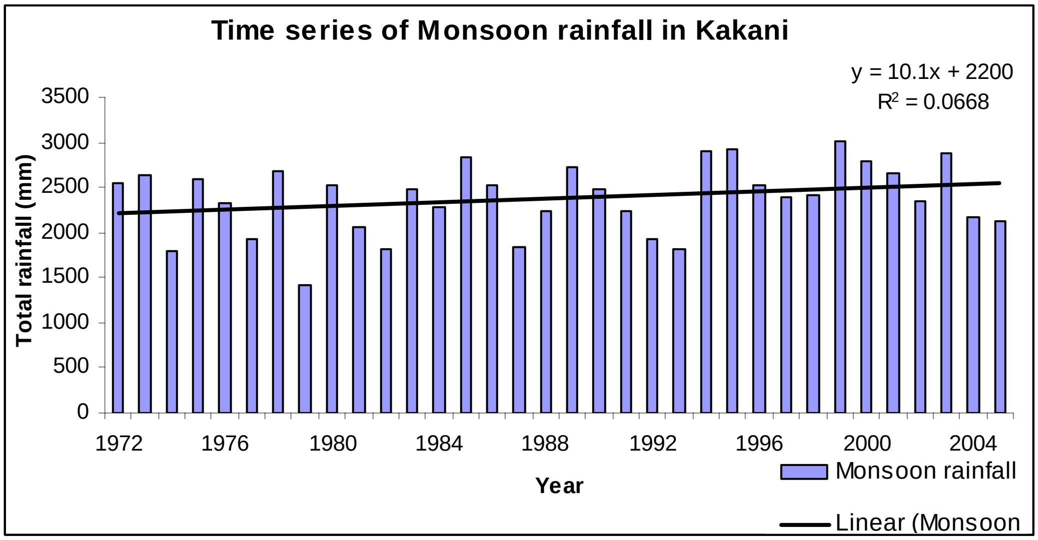

Fig 30: Time series of monsoon rainfall in Kakani

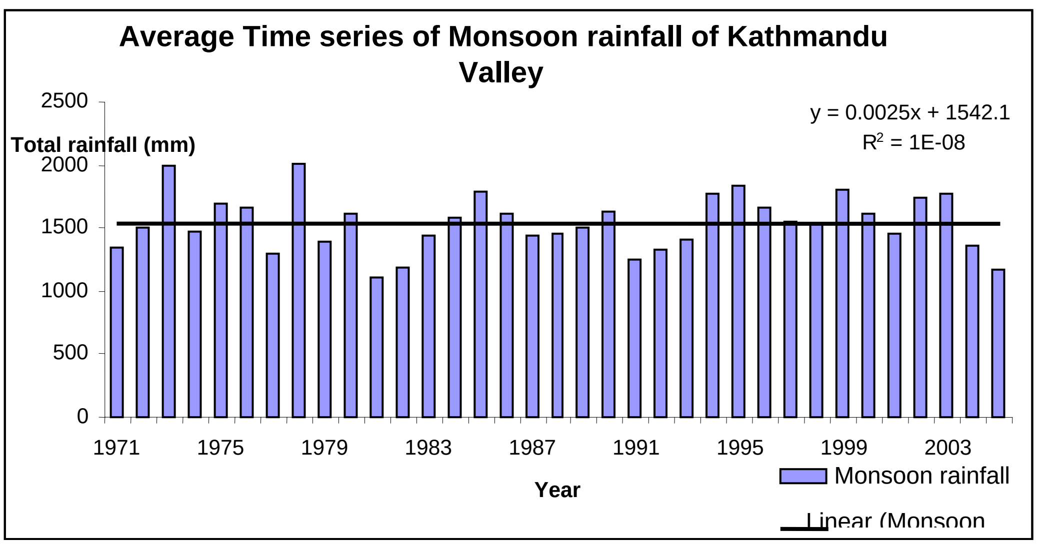

Fig 31: Average time series of monsoon rainfall of Kathmandu valley.

Year	Kathmandu airport	Kakani	Khumaltar	Sankhu	Nagarkot	Godavari	Thankot
1971	1101.7		894	1876.2	1375.1	1546.1	1238
1972	968	2544.8	959.1	1588.6	1300.4	1630.3	1508.8
1973	1454	2627.1	1093	1658.6	3206.2	1889.2	2058.8
1974	983.2	1794.9	1050.45	1588.2	1457.2	1774.5	1700
1975	1221.1	2588.2	1175.7	1670	1540.4	1838	1767.4
1976	1199.6	2327.1	885.1	1535.2	1726.7	1735.1	2177.8
1977	1005.5	1920.5	821.8	958.4	1416.6	1239.3	1684
1978	1174.8	2684.4	1311.8	2800.7	2192.5	1781	2125
1979	1124.8	1411.1	764.9	1592.5	1383	1293.7	2195.1
1980	1067.4	2532.6	794.1	1892.5	1574.6	1561.1	1913
1981	936.7	2049.6	889.4	670.9	836.3	1367.6	961
1982	978.4	1806.4	854.1	1615.7	920.5	1430.1	670.9
1983	1063.2	2477.3	901.1	2023.9	1024.5	1430.2	1207.6
1984	1087.2	2272.9	1122.2	1759.1	1285.2	1892.7	1693.5
1985	1389.1	2827	1112.7	1709.4	1439.9	2011.6	2068.8
1986	1136.3	2523.2	1008.2	1463.5	1594.7	1521.9	2024.1
1987	1042.7	1842.8	970.9	1372	1471.4	1611.7	1789.3
1988	1049.9	2244.3	1065.1	1468	1142.1	1522	1668.9
1989	866	2718.1	704	1833.5	1499.1	1352.3	1596.5
1990	1207	2474.4	875.9	1915.2	1607.6	1722.3	1649.8
1991	713.5	2233.5	630	1257	1407.9	1259.3	1240.6
1992	885.3	1930.1	629.9	1707	1539.2	1315.3	1284.1
1993	950.7	1819.7	963.9	1538.2	1442.6	1593.3	1569.2
1994	1356.5	2900	1010.1	2104.8	1696.6	1501.5	1860.6
1995	1431.3	2925.9	1069.8	1946	1923.4	1410	2086.7
1996	1349.1	2519.6	944.5	1651.2	2056.2	1723.4	1432.2
1997	1197.8	2397.8	773.5	2116.7	1721.1	1446.8	1174.2
1998	1257.8	2413.1	838.4	1779.5	1411		1528.8
1999	1461.2	3018.4	1059.6	1881.6	1750.8	1547.3	1872.2
2000	1106.9	2795	919.8	2007.1	1629.6	1422.3	1385.4
2001	1355	2668	760.1	1101.3	1572.3	1415.9	1311.3
2002	1420.1	2356	1098.7	1857.3	1791.2	1970.9	1649.1
2003	1454.2	2876.2	1136.1	2168.7	1855.9	1715.9	1216.6
2004	1061	2163	737.8	1673.2	1428.8	1143.2	1274.2
2005	912.2	2126.4	595.6	1236.4	1445.8	1017.7	856.8

Table11: Time series of Monsoon rainfall (mm) in various stations of Kathmandu valley