STUDY OF SPATIAL VARIABILITY OF HYDROLOGICAL VARIABLES OVER KRISHNA RIVER BASIN, INDIA

Submitted by

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(92313003)

In partial fulfillment of the requirements for the award of
Master of Science in GEO INFORMATICS
Of

COCHIN UNIVERSITY OF SCIENCE AND TECHNOLOGY, KOCHI

Conducted by

Indian Institute of Information Technology and Management-Kerala
Techno Park Campus
Thiruvanathapuram-695 581

June 2015

BONAFIDE CERTIFICATE

This is to certify that the project report entitled **"STUDY OF SPATIAL VARIABILITY OF HYDROLOGICAL VARIABLES OVER KRISHNA RIVER BASIN, INDIA"** submitted by **ANEESH KUMAR.R (92313003)** in partial fulfillment of the requirements for the award of **Master of Science in GEOINFORMATICS** is a bonafide record of the work carried out at **"INDIAN INSTITUTE OF TECHNOLOGY HYDERABAD"** under our supervision.

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TO WHOMSOEVER IT MAY CONCERN

This is to certify that Mr. Aneesh Kumar M, second year MSc student in Geoinformatics from the Indian Institute of Information Technology and Management, Kerala has successfully completed an internship under my guidance during 1st Januaray 2015 to 30th April 2015. Mr. Aneesh Kumar M. worked on analyzing the variability of hydrologically relevant variables over the Krishna river basin, India.

He was very sincere towards his assigned tasks and I wish him all the best for his future endeavors.

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DECLARETION

I, ANEESH KUMAR R of course GEOINFORMATICS hereby declare that this report is substantially the result of my own work , expect, where explicitly indicated in the text and has been carried out during the period January 2015-April 2015.

Place: Thiruvananthapuram

Date: 15/06/2015 Student's signature

ACKNOWLEDGEMENT

I take this opportunity to express my sincerest gratitude to my guide Dr. Riddhi Singh, Assistant Professor, Indian Institute of Technology, Hyderabad for sparing his invaluable time for me and guiding me throughout the duration of the project work. Also, thankful to Director and executive director for selecting me to do my internship at IIT-H.

I am extremely grateful to Mr T. Radhakrishnan, Faculty and course coordinator of MSc Geoinformatics, Indian Institute of Information Technology and Management- Kerala, Thiruvananthapuram, for the opportunity he gave me to carry out project work at Indian Institute of Technology Hyderabad.

I am thankful to my family and friends at bottom of heart, for co-operating with me in the non-technical works and constantly inspiring me for doing the work.

Aneesh kumar R

ABSTRACT

Availability of water is a major issue facing by the planet during several years. On the present context there need a scientific method for analyzing the nature and processes behind the availability of water, so that the water that is available can be utilized optimally. On that scenario a study has carried out using the influencing factors about the water availability. The factors that are precipitation and evapotranspiration. Both these factors, their trends and their nature in variation are studied on a sub basin scale by selecting Krishna river basin in India and on its seven sub basins. As the variables are changing its nature spatially its variability has to be studied in various spatial extents. So the technique of Geographic Information System is used to study the spatial variability. The data of precipitation from Indian Meteorological Department (IMD), Pune and the evapotranspiration data from the Moderate Resolution Imaging Spectroradiometer (MODIS), database is used. By using the GIS software Arc Map 10.3 the studies about the spatial variability in the variables like precipitation and evapotranspiration is done. The availability of water is thus calculated from the precipitation and evapotranspiration, as the available water is the difference in the gain due to precipitation and the loss due to evapotranspiration. The study was carried out for a time scale of eleven years from 1983 – 1993. By correlating the average values of these three parameters such as precipitation, evapotranspiration and the availability of water, shows that there is a spatial variability in hydrologic variables over space.

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LIST OF SYMBOLS AND ABBREVIATIONS

GIS	-	Geographic Information System.
DEM	-	Digital Elevation Model.
SRTM	-	Shuttle Radar Topography Mission.
WRIS	-	Water Resource Information System.
MODIS	-	Moderate Resolution Imaging Spectrometer.
NTSG	-	Numeric Terradynamic Simulation Group.
ET	-	Evapotranspiration.
TM	-	Thematic Mapper.
USGS	-	United States Geological Survey.
TCC	-	True Color Composite.
FCC	-	False Color Composite.
S	-	Storage in the basin.
dS/dt	-	Rate of change in storage in the basin.
P	-	Precipitation input in the basin.
Q	-	Streamflow from the outlet of the basin
GWin	-	Input of ground water to the basin
GWout	-	Output of ground water from the basin

CHAPTER 1. INTRODUCTION

Water is the elixir of life as plants and animals cannot live without it. Water is needed to ensure food security, feed livestock, sustain organic life, maintain industrial production, and to conserve the biodiversity in the environment. While 70% of the earth surface is covered with water, only 2.5% of the available total water exists as freshwater (Anon, 2006). Out of the total available freshwater, 68.7% is frozen in ice caps, 30% is stored underground and only 0.3% water is available on the surface of the Earth (Anon, 2006). Most of the surface water exists in lakes (87%) and swamps (11%) and only 2% is available in rivers (Anon, 2006). Even these surface water resources are not evenly distributed and present variability across space as well as time. In addition, demand for water is also characterized by spatio-temporal variability due to different populations and life styles across the globe. The pattern of water use in different countries is driven by their culture, lifestyle and industrial development and generally, a close correlation between economic prosperity and water use has been observed (Table 1.1). As the global population grows and more countries transition towards a developed lifestyle, the demand for water has increased substantially (Table 1.2). Consequently, many countries are facing severe water crisis. This calls for immediate attention by the stakeholders to make sustainable use of the available water resources.

Continents	Per Capita Water Use (m^3/yr)
Africa	245
Asia	519
North and C. America	1861
South America	478
Europe	1280
USSR (Former)	713

Table 1.1 Per capita water use in major continents (G. Hegde. 2010)

Year	Agriculture	Industry	Domestic	Total	Per Capita
India		Billion Lit/Day			Lit/Day
2000	1658	115	93	1866	88.9
2050	1745	441	227	2413	167.0
China					
2000	1024	392	105	1521	82.7
2050	1151	822	219	2192	155.4
USA					
2000	542	605	166	1313	582.7
2050	315	665	187	1167	484.6

Table 1.2 Temporal patterns of water usage in India, China and the United States of America (USA) (G. Hegde. 2010)

1.1 WATER RESOURCES IN INDIA

India is blessed with good rainfall well distributed over five to six months in the year. The average annual rainfall in the country is 1170 mm with a wide range between 100 mm in desert areas of Rajasthan to 10000 mm in Cherapunji (Moni, 2004). The total available sweet water in the country is 4000 billion m^3 per annum out of which over 1047 billion m^3 water is lost due to evaporation, transpiration and runoff, thus reducing the available water to 1953 billion m^3 and the usable water to 1123 billion m^3 (Moni, M. 2004). Out of the total usable water, 728 billion m^3 is contributed from surface water and 395 billion m^3 is contributed by replenishable ground water (Moni, 2004).. As the potential for increasing the volume of utilization of water is hardly 5-10%, India is bound to face severe scarcity of water in the near future.

Although water for consumption is most crucial, it is also important to provide water for irrigation to increase the food production and livestock husbandry, to ensure food security for the increasing population. Growing population is a serious concern as it will create further burden on the per capita water availability in the future. Based on the average requirement of water for various purposes, a water stressed situation is defined as one when the per capita water availability ranges from 1000 to 1700 m^3 per year, and when the availability reduces to 1000 m^3 per year, the situation is termed water scarce

Therefore, accurate estimation of the availability of the water is crucial for proper planning and utilization of these available water resources. The availability of water is influenced by variables such as precipitation, evapotranspiration, and ground water. Due to their control on water availability, we term these variables as hydrologically relevant variables. In absence of measurements of direct streamflow, these variables can be analyzed to arrive at estimates of water availability by making assumptions regarding the water budget equation. If components such as ground water are neglected, the difference between precipitation and evapotranspiration gives an estimation of available surface water in a region. We select the Krishna river basin in India for studying the spatial variability of these two hydrologically relevant variables – precipitation and evapotranspiration. The Krishna river basin is one of the largest river basins in India and spans three states (Maharashtra, Telangana, and Andhra Pradesh). It has been further divided into seven sub basins, across which we also analyze the spatial variability of these variables. Thus, we show a step by step methodology to estimate water availability by using two hydrologically relevant variables.

1.2 OBJECTIVES

1. Delineation of water sheds of the Krishna river basin and its seven sub basins.
2. Calculation of evapotranspiration for the Krishna river basin and its seven sub basins.
3. Calculation of rainfall for the Krishna river basin and its seven sub basins.
4. Creation of land Use land cover map of Krishna river basin and its seven sub basins.
5. Estimation of availability of water for Krishna river basin and its seven sub basins.

CHAPTER 2. THE KRISHNA RIVER BASIN

The river basins in India have been classified into three groups depending upon their catchment area (Rao, 1975).

(i) Major rivers - catchment area> 20,000 sq.km.

(ii) Medium rivers - catchment area 2,000 - 20,000 sq.km.

(iii) Minor rivers - catchment area< 2,000 sq.km.

As per this classification, India has fourteen major, forty four medium and several minor rivers. Krishna flowing across the Peninsular India is one of the major rivers of South India. In this chapter, the catchment characteristics, geology and geography of the basin is described in brief.

2.1 LOCATION

The Krishna River flows through the states of Maharashtra, Karnataka and Andhra Pradesh. Its most important tributary is the Tungabhadra River, which itself is formed by the Tunga and Bhadra rivers that originate in the Western Ghats. Other tributaries include the Koyna, Bhima, Mallaprabha, Ghataprabha, Yerla, Warna, Dindi, Musi and Dudhganga rivers. The Krishna is an inter-state river whose catchment lies between the latitudes of 13º 0’ N and 19º 30’ N and longitudes of 73º 14’ E and 81º 23’ E. The basin has a drainage area of 2, 58,945 sq.km of which 26.8% lies in Maharashtra, 43.8% in Karnataka and 29.4% in Andhra Pradesh (Rao, 1975). In terms of catchment area, this basin is fifth among the Indian rivers and the largest river after Godavari in Southern India. The hydrological and geological aspects of the Krishna river basin are discussed in detail in the following chapters. Figure 2.1 shows the location of the Krishna river basin in the Indian sub-continent.

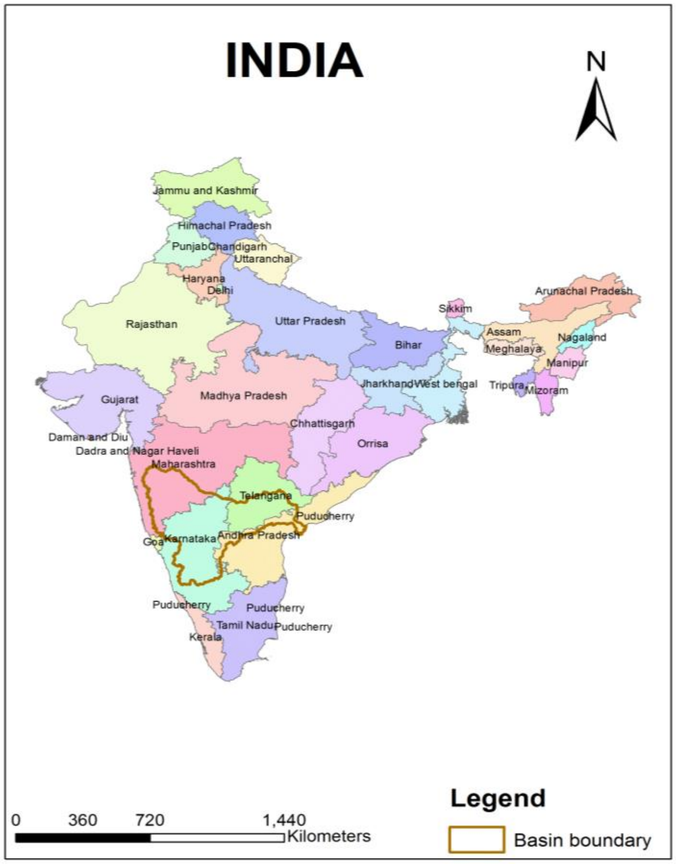

Figure 2.1 The Krishna river Basin in India Sub- continent.

2.2 GEOLOGY

The major geological formations traversed by the Krishna river consist of Deccan traps which comprise nearly one third area of the drainage basin and range in age from upper cretaceous to Eocene (International Journal of Social Science & Interdisciplinary Research Vol.1 Issue 7, July 2012, ISSN 2277 3630). Upon weathering, the trap rock usually gives either laterite or bauxite and the soil derived from the weathering is called black cotton soil. Descending along the Deccan plateau, the Krishna river traverses through unclassified crystalline rocks comprising essentially of Dharwars, various gneisses and granites including charnockites (International Journal of Social Science & Interdisciplinary Research Vol.1 Issue 7, July 2012, ISSN 2277 3630). Dharwars are regionally metamorphosed igneous and sedimentary (pelitic) rocks composed of phyllites, schists, quartizites, amphibolites and granites. The Krishna River in its last phases of journey traverses through Khondalities, which upon intensive weathering has given rise to brick red soil (International Journal of Social Science & Interdisciplinary Research Vol.1 Issue 7, July 2012, ISSN 2277 3630). The mouth of the basin is constituted by Alluvium deposits which is composed of clays and silts.

2.3 GEOGRAPHY

Spatial distribution of rainfall in the Southern Indian is strongly influenced by the interaction between the monsoonal circulation and orography (Subramanyam and Sarma, 1978). The Western Ghats having an average elevation of about 900 m and running in an unbroken range of hills from north to south down to Kerala play a prominent role in determining the rainfall climate of Southern India. During the South-west monsoon season they are mainly responsible for heavy rainfalls on their windward side and scanty rainfall on the leeward side, resulting in the formation of humid climates on the west coast and dry climates in tile Peninsular interior. It is for this reason that all the peninsular river systems of the region originate on the Western Ghats and flow both eastward and westward (Subramanyam et.al, 1984). Humid zones are found only in the west on the hills. Except for a narrow strip along the Western Ghats and a small portion at the lower end, the Krishna basin has an average annual rainfall of less than 500 mms of which 75% occurs during the South-west monsoon (International Journal of Social Science & Interdisciplinary Research Vol.1 Issue 7, July 2012, ISSN 2277 3630).

CHAPTER 3 MATERIALS AND METHODS

In this chapter the detailed description of various data, methodologies and the application modules that are used for the study are defined. The following methods are described:

1. Watershed Delineation: Watershed is defined as the water contributing area to a specific outlet or a point of interest on a stream network. Watershed delineation is the method of finding the boundary of this contributing area to an outlet.
2. Evapotranspiration Data Processing: Evapotranspiration is defined as the sum of evaporation from the land surface and transpiration from vegetation. One of the most important factors that determines the availability of the water in a region is the quantity of evapotranspiration as it is the largest source for the loss of water (Wikipedia). So, assessing the rate of evapotranspiration is needed to understand the water loss from the Krishna river basin and its sub-basins.
3. Precipitation Data Processing: Precipitation is one of the most important input to the water budget of a region. We estimated precipitation over Krishna basin and its sub basins by using district wise precipitation data for the region. Therefore, the available data was processed to convert its spatial scale from district level to basin/sub basin level
4. Land Use Land Cover Classification: Land cover is defined as the physical materials on the earth that forms the surface, which includes the natural vegetation, bare ground, water bodies etc. Land use characterizes socio-economic activities like the buildings, agricultural lands etc. The land use and the land cover type and quantity of a region is a dominant factor in determining the hydrologic character of the basin.
5. Water Availability Calculation: This section outlines the water budget equation and accompanying equations required for approximating the available water in the Krishna River Basin.

3.1 WATERSHED DELINEATION

3.1.1 DATA COLLECTION

Digital Elevation Model (DEM) is the input data that is used for identifying the watershed boundary and for stream network analysis. The DEM stores the elevation values in each cell. In this study, the DEM of Shuttle Radar Topography Mission (SRTM) is used. The United States Geological Survey's official database provides DEM data in tiles of 5º x 5º with 90 meter resolution. USGS Earth Explorer was used for the purpose of searching and downloading the DEM from the database (https://earthexplorer.usgs.gov).

3.1.2 GENERATING MOSAIC

The downloaded tiles of the DEM of the Krishna river basin is mosaicked from the individual tiles of 5º x 5º to a single raster dataset using the 'Mosaic to New Raster tool' of Data Management Tools of ArcMap 10.3. The tool combines multiple raster to a single one provided every input datasets has equal number of bands and pixel depth. Mosaicking tool inputs the individual DEM tile comprising of the Krishna river basin to form a single raster dataset of DEM. Figure 3.1 shows the mosaicked DEM for Southern India.

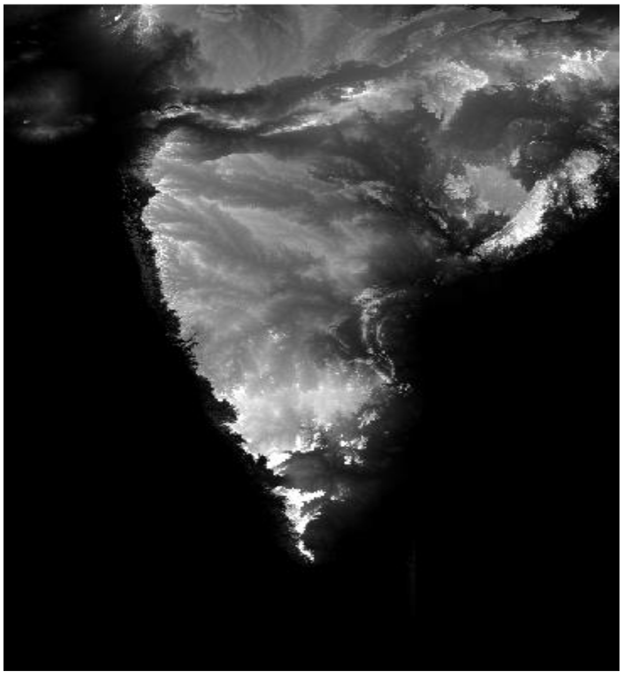

Figure 3.1. The mosaicked DEM for Southern India.

3.1.3 CREATING DEPRESSIONLESS DEM

In some cases, depressions in the land surface may cause the watershed delineation algorithm to drain all water from a surrounding cells to a single cell. This hinders the process of watershed identification. Hence, filling such depressions or sinks is one of the most important and primary steps of data processing. The 'fill' tool in the Spatial Analyst toolbox is used to create depression less DEM.

3.1.4 CREATING FLOW DIRECTION

The 'Flow direction tool' of Hydrology tool set in the Spatial Analyst tool determines the direction of flow. The tool determines the direction of the steepest descent or more drop from each cell to the adjacent cells. When the steepest descent is found, the cell stores the value of the direction. Thus, for every cell in the input raster, the steepest descent is stored. The tool takes the filled DEM as the input and calculates the values to give the output flow direction raster of Krishna River Basin. From the depression less DEM data, the Flow direction tool calculates the continuous path of flow of the Krishna River and its various tributaries as shown in Figure 3.2

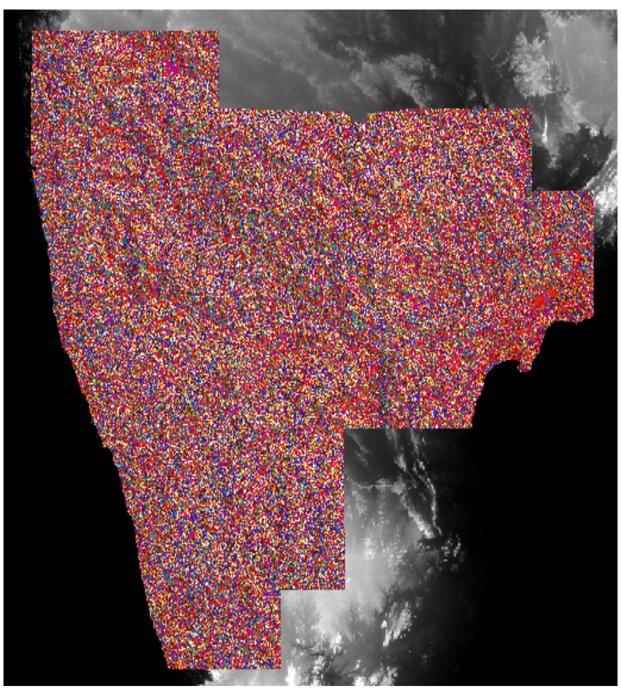

Figure 3.2. The flow direction map created by using the DEM.

3.1.5 CREATING FLOW ACCUMULATION

The quantity of water that accumulates within a cell is estimated using the Flow Accumulation tool of Hydrology in Spatial Analyst in ArcMap 10.3. From the flow direction raster of the Krishna river basin, the tool calculates the accumulated flow as the accumulated weight of all cells flowing into each down slope cell. Thus, the areas of high flow concentration can be identified from the flow accumulation values of each cell. The flow direction data is the input raster dataset for the flow accumulation. Figure 3.3 is the flow accumulation created using the flow direction map of the Krishna River Basin.

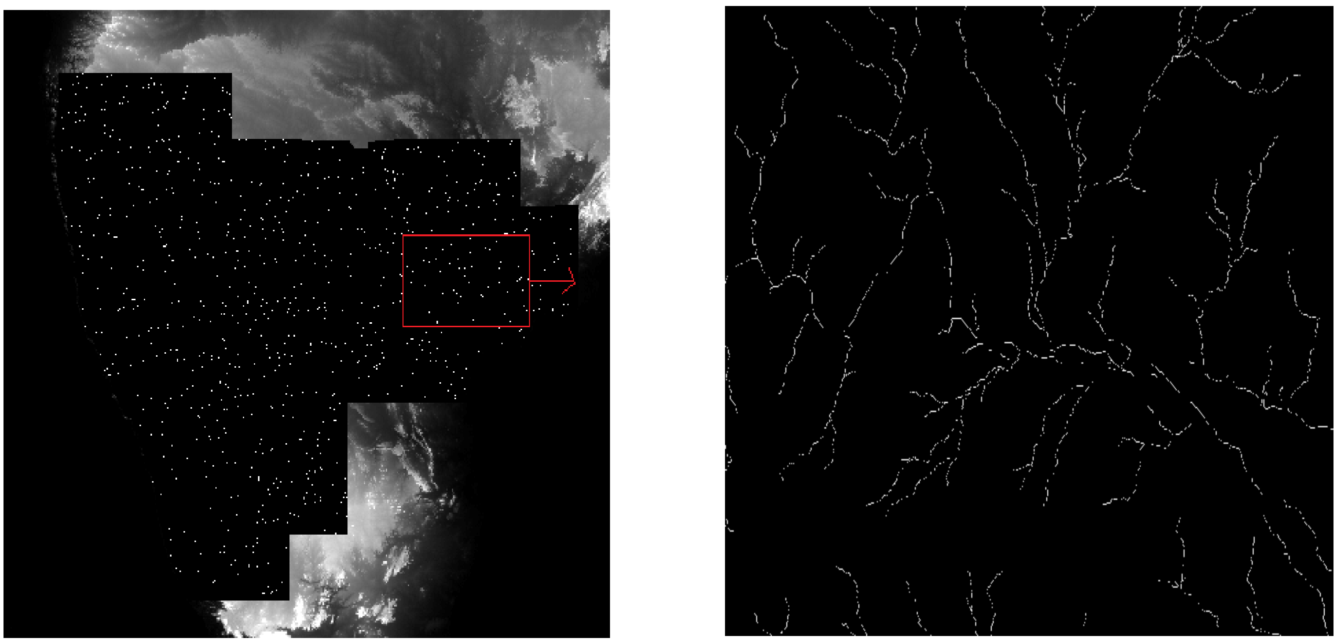

Figure 3.3 (left) Flow accumulation created from flow direction. (Right) Zoomed in view of the flow accumulation values of the cells

3.1.6 POUR POINT IDENTIFICATION

The outlet or the mouth of a stream is the point of maximum water accumulation in a river network. All points upslope to this point contribute water to it. Here, for the purpose of delineating watersheds of Krishna River Basin and the seven sub-basins the latitudinal and longitudinal values of the pour points are identified from the Water resource Information System (WRIS) database (Ref/link) and verified visually using Google earth. The 'Snap Pour Point' tool in the Hydrology toolbox identifies the location on the flow accumulation grid which is closest to the geographically chosen pour point. The tool will take the input file as the flow direction of the Krishna basin (or each of the sub basins when estimating boundary of sub basins) and the location data of the basins (or sub basins) for the selection of maximum accumulated points. Figure 3.4 shows the location of pour points selected to delineate the Krishna River Basin.

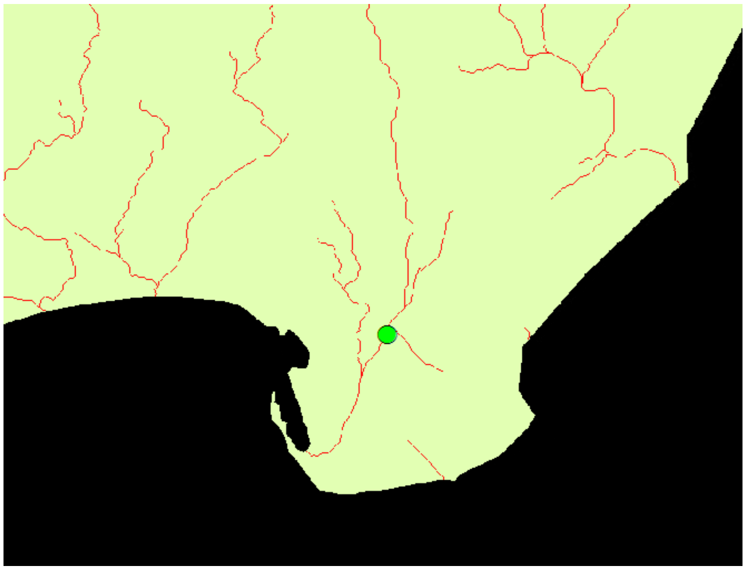

Figure 3.4 Pour point on the flow accumulation stream network

3.1.7 WATERSHED DELINEATION

The watershed of the Krishna basin and the sub-basins are delineated from the flow direction raster and the pour point location. The ‘Watershed’ tool of the Hydrology toolbox is used to delineate the watershed of the Krishna and its sub basins. The basins and sub basins boundary data are stored in the raster file format. For various analytical purposes in future the datasets are converted to vector file format. The ‘Raster to Polygon’ conversion tool in the ‘From raster’ menu of the Conversion toolbox is used for the conversion of the raster dataset to a vector file.

3.2 EVAPOTRANSPIRATION DATA PROCESSING

3.2.1 DATA COLLECTION

The data needed for the calculation of evapotranspiration is used from the Moderate Resolution Imaging Spectroradiometer (MODIS) at the official database of the Numerical Terradynamic Simulation Group (NTSG) (ftp://ftp.ntsg.umt.edu/pub/data/global_monthly_ET/Global_8kmResolution/Raster/). The product Global monthly evapotranspiration (MOD16) data is downloaded from the months of January to December from the years 1983 to 1993. The data is downloaded in the form of raster image files. Figure 3.5 shows the global evapotranspiration data for January 1983.

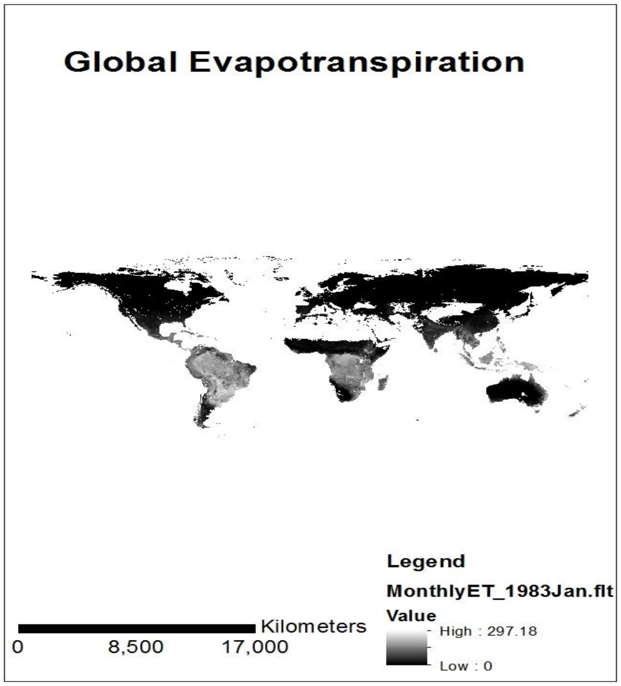

Figure 3.5 Global ET data for January, 1983

The evapotranspiration data is available at month time steps. From this global data, the evapotranspiration data needed for the Krishna River Basin is obtained by the use of the tool ‘Extract by Mask’ in the Extraction tool of the Spatial Analyst toolbox. The boundary of the Krishna River Basin is used as the mask for obtaining the Krishna Basin’s evapotranspiration data from the global data. Thus, eleven years of monthly evapotranspiration data from January 1983 to December 1993 for the Krishna river basin is obtained.

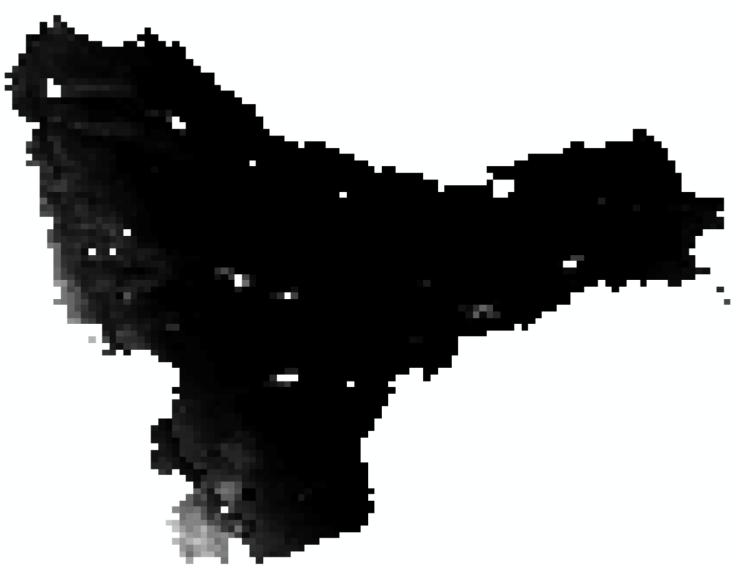

Figure 3.6 Evapotranspiration data of the Krishna River Basin for January, 1983.

3.2.2 CALCULATION OF SUB-BASIN WISE DATA

From the extracted evapotranspiration data of the Krishna river basin, the sub basin evapotranspiration is estimated. The 'Zonal statistics as table' tool of the zonal tool set of Spatial Analyst toolbox is used to calculate the evapotranspiration data of the sub basins of the Krishna river basin. The different zones in the Krishna river basin are set as the seven sub basins. The tool calculates the values of evapotranspiration for the sub basins from the evapotranspiration raster dataset. From the raster set, the process gives the mean values of the seven sub basins as the numerical values in an attribute table layer in the ArcMap 10.3. These numerical values of mean evapotranspiration data of the seven sub-basins that are stored as the attribute table layer.

3.3 RAINFALL DATA PROCESSING

3.3.1 DATA COLLECTION

The time period of precipitation data is set at 1983-1993, same as that of the evapotranspiration data. The district wise data is collected from the Indian Meteorological Department (IMD), Pune. The district wise data is converted to sub basin and basin scale averaged precipitation by following the procedure outlined below.

3.3.2 ESTIMATION OF SUB BASIN LEVEL DATA

The excel files containing the district wise rainfall data were joined to the shape files of the respective districts using the 'Join' option in Arc Map 10.3. Only those districts are considered that lie fully or partially within the Krishna River Basin. Following this, the 'Zonal Statistics' tool the Spatial Analyst toolbox is used to estimate basin wise data. The tool uses the district shape files and the shape files of the sub basins of Krishna River Basin. It calculates the precipitation data for each sub basins based on areal averaging.

3.4 LAND USE LAND COVER CLASSIFICATION

3.4.1 DATA ACQUISITION

For the land use land cover classification, the satellite images from the Landsat satellite series Landsat 4 and Landsat 5 with the sensor thematic Mapper (TM) are used (Figure 3.7). The Landsat 4 and Landsat 5 satellite images were downloaded from the official portal of United States Geological Survey database

(www.earthexplorer.usgs.gov). The study area Krishna river basin contains 20 tiles of Landsat images. The Landsat Thematic Mapper(TM) has seven bands; three in the visible band (blue, green and red), two near infrared band, and one each in the thermal band and mid-infrared band. The supervised image classification method was used for land use classification. The land use type that were classified are: forest, agricultural land, water bodies, built up area and barren land.

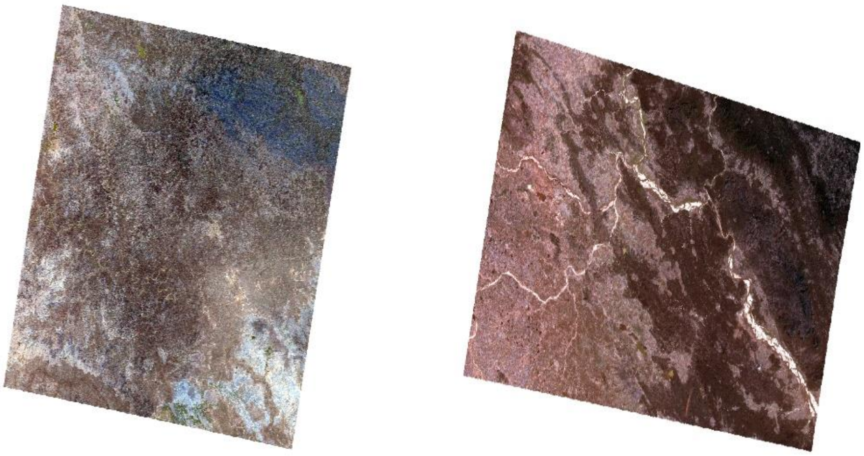

Figure 3.7. Individual tiles of Landsat images

3.4.2 COMBINING THE SATELLITE IMAGES

The downloaded tiles of the Landsat images are converted into a single satellite image raster in this step using the processes of mosaicking. The 'Mosaic to New Raster' tool in the raster dataset of the raster tool of the data management tools in ArcMap 10.3. The tool uses the defined set of raster images to combine them together to form a new one, provided every images have the same number of bands. The 20 satellite images were thus made to a single satellite image comprising the Krishna river basin. Figure 3.8 shows the mosaicked 20 tiles of Landsat Images.

Figure 3.8 Mosaic of 20 tiles of Landsat Images

3.4.3 EXTRACTION OF THE KRISHNA RIVER BASIN

From the combined satellite image, the Krishna River Basin is extracted using the 'Extract by Mask' tool of the extract tool box of the Spatial analyst extension of ArcMap 10.3.The base image or the input to extract is the satellite image. The tool uses the boundary of the Krishna river basin to extract the satellite image of the study area. Figure 3.9 shows the extracted area of Landsat images, the Krishna river basin, India.

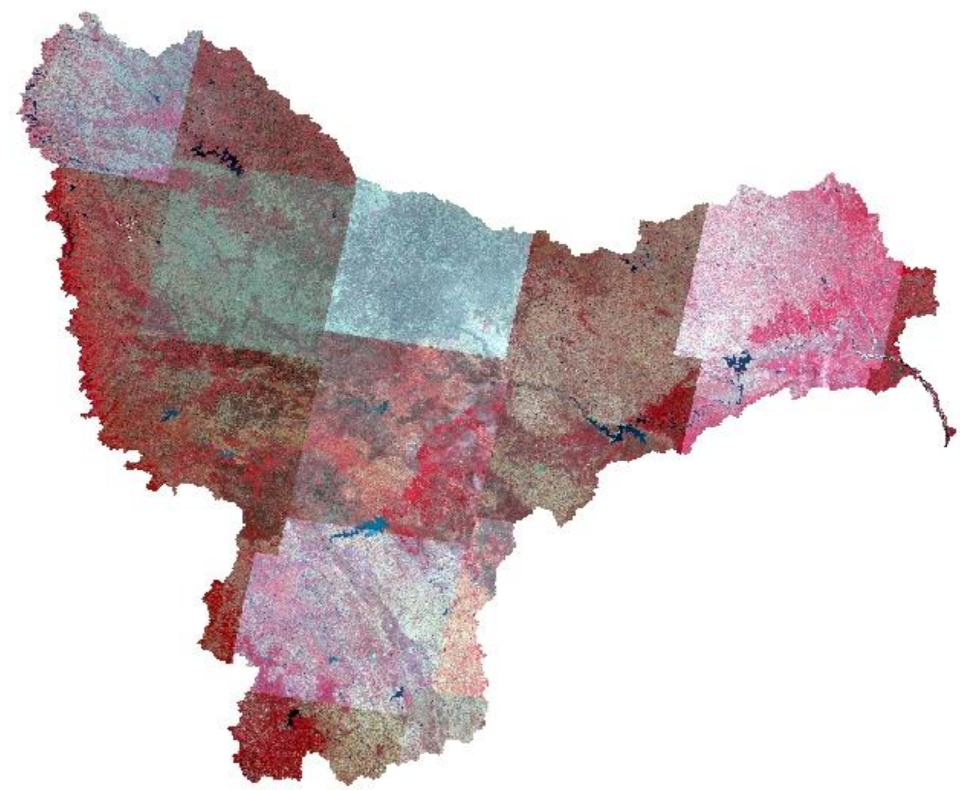

Figure 3.9. The extracted area of Landsat images for the Krishna River Basin, India

3.4.4 IMAGE CLASSIFICATION

3.4.4.1 IDENTIFICATION OF THE FEATURES

Feature identification is carried out by assigning the image a band combination of True Color Composite (TCC) with band 1 as blue, band 2 as green, and band 3 red. The choice of True Color Composite (TCC) implies that the features in the satellite image will represent the color of the features in the real world, like blue to water bodies. The shape of the feature in the satellite image is also an indicator for the identification of the feature, like dark green features with shapes like rectangle or circular is recognized as the agricultural land and the greenish feature without any specific shape as forested area or natural vegetation. Likewise the clustered bright features show the presence of the settlements or the built up in the image. Along with visual inspection of the satellite images, google earth imagery is also used for the identification of features.

3.4.4.2 CREATION OF TRAINING SITES

Following the identification of features base on the color of the cells in the satellite image, training samples or training sites are created. Training sites for a feature define the tones of the same color of a feature, e.g. dark blue and light blue colors in the satellite image represents water bodies. Likewise, different shades of the same color are selected and saved as various training samples. The software will store the range of values of the colors that define a feature. Finally, the different shades of the same color are merged to form a new class or value that defines all the values that are merged.

The process of creating training sites for water bodies is done by the identification and selection of the different tones of blue. For forested land, the irregularly shaped green features were selected and merged. The same method is used for the creation of the training sites for the agriculture by the storing the values of the reddish cells with specific shapes such as rectangular. The clustered features with bright color indicates the presence of the urban areas in the image. All such values are stored and merged to form the class of built up area. The brownish color in the True Color Composite indicates the presence of the barren land in the image. The values are stored to form the classes of the barren land. After the selection of all the classes in the image, the training sites are saved as the shape files to create the signature files.

3.4.4.3 IMAGE CLASSIFICATION

The image classification is the method of classifying the image on the basis of the color of the classes that are defined in the training sites. The process of image classification outputs the features that have the same class value in the training site and also in the signature files. The classification method uses the satellite image as the input and the signature file for defining the values of each feature. In this analysis, the ‘Maximum Likelihood Classification’ method in the image classification tool is used for image classification.

3.4.5 PERCENTAGE AREA CALCULATION

This step is used to find out how much percentage of the Krishna River Basin and each sub basin is covered by various land use types. For the process of area calculation, the classified land use map of the basin and the sub basins are converted to the vector file format. After the conversion of the files into vector format, the area of each feature can be calculated by the 'Area' option available in the calculate geometry method in the attribute table. By using this method, the area of every feature in the Krishna river basin and sub basins is calculated. This data can then be used to calculate the percentage of each land use type in the basin.

3.5 WATER AVAILABILITY CALCULATION

The water budget of a river basin can be represented by using the following formula:

$$\frac{dS}{dt} = P - ET - Q + GW_{in} - GW_{out}$$

Where, S is the storage in the basin, dS/dt is the rate of change in storage in the basin, P is the precipitation input in the basin, ET is the evapotranspiration from the basin, Q is the streamflow from the outlet of the basin, GW_{in} is the input of ground water to the basin and GW_{out} is the output of ground water from the basin. If we neglect the change in storage in a basin at a given time scale (annual or larger) and the ground water inputs/outputs from the basin, this equation can be simplified to:

$$Q_{approx} = P - ET$$

where the suffix approx. is used to suggest that the estimate of streamflow is approximate and conditional on the assumptions made above. In data scarce region, such an approximate can be a first step towards assessment of water availability in a region.

CHAPTER 4. RESULTS

4.1 WATERSHED DELINEATION

The output form the watershed delineation is shown in Figure 4.1. The Krishna River basin and its seven sub basins are shown. The areas of each sub basin is provided in Table 4.1. The seven sub basins are: Bhīma upper, Bhīma lower, Krishna upper, Krishna Middle, Krishna Lower, Thungbadra upper, Thungbadra middle and Thungbadra lower. These are depicted in Figure 4.2.

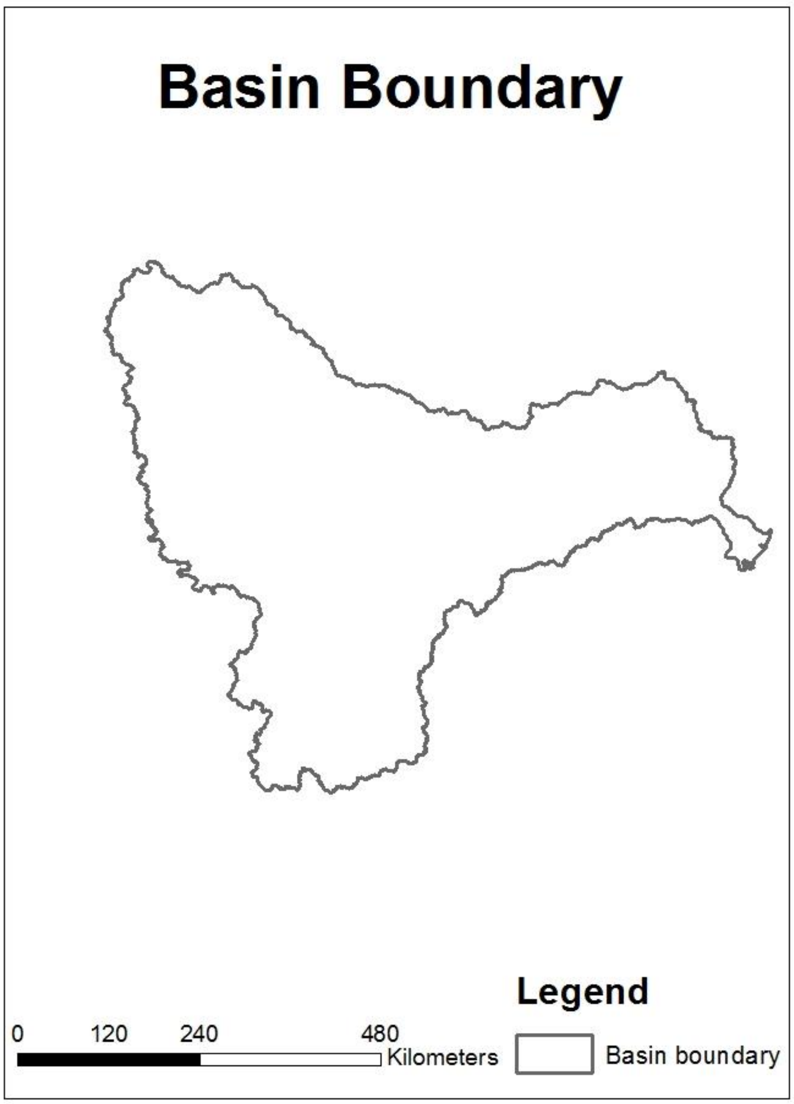

Fig 4.1 Basin boundary Krishna river basin

S.no	Sub basin	Area (km^2)	Percentage contribution to the Krishna River Basin (%)
1	Bhima Upper	24245	18
2	Bhima Lower	46006	9
3	Krishna Upper	55691	22
4	Krishna Middle	22788	9
5	Krishna Lower	37105	15
6	Thungbadra Upper	28844	11
7	Thungbadra Lower	42144	16

Table 4.1. Area of the sub basins in the Krishna River Basin

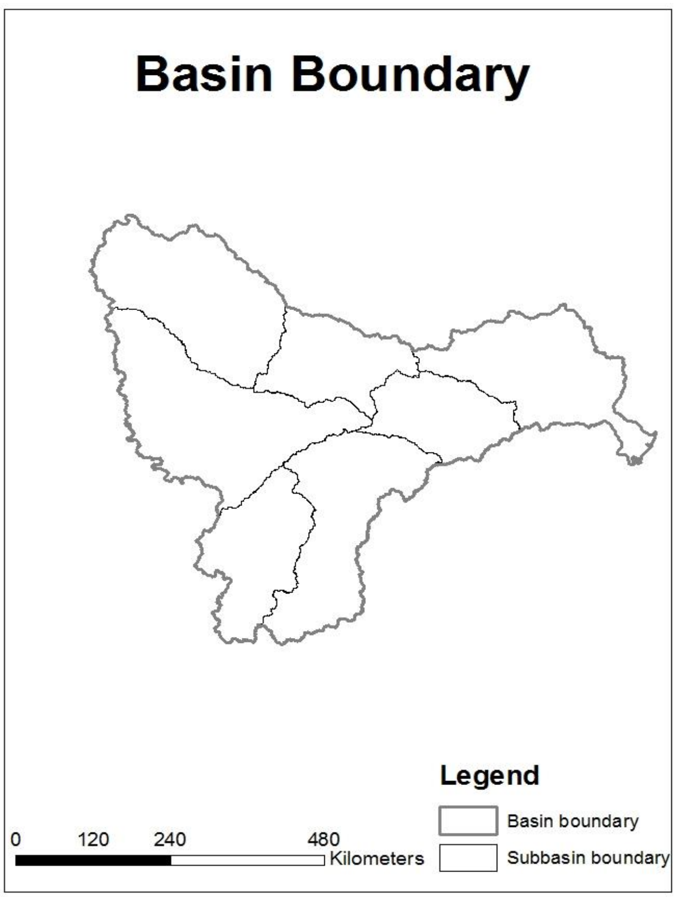

Fig 4.2. Sub basin map of the Krishna River Basin

4.2 EVAPOTRANSPIRATION DATA

The evapotranspiration data that is collected from the Moderate Resolution Imaging Spectroradiometer (MODIS) at the official database of the Numerical Terradynamic Simulation Group (NTSG) is extracted for the entire Krishna river basin. Table 4.2 shows the evapotranspiration values of the Krishna River Basin from January 1983 to December 1993. The data for each month across the eleven years is visualized in Figure 4.3.

1983	37.8	29.4	15.8	2.4	8.7	34.8	51.8	53.8	57.1	76.2	64.2	48.4
1984	39.9	36.8	13.6	12.5	8.0	42.9	51.3	58.6	71.9	70.9	58.5	49.4
1985	40.8	21.6	8.3	9.8	13.1	36.6	51.2	58.7	68.5	70.2	55.7	45.2
1986	42.8	33.0	12.0	4.7	13.2	37.9	52.3	61.4	70.8	73.4	59.2	51.3
1987	41.6	28.2	15.4	5.7	8.9	41.5	56.0	59.1	73.9	77.2	65.6	57.1
1988	43.3	27.6	12.6	8.4	9.4	39.1	48.5	53.9	66.0	80.8	55.8	46.4
1989	37.2	23.0	17.6	4.3	10.3	42.3	53.4	53.7	67.5	81.1	60.1	50.5
1990	36.9	29.9	21.1	7.1	19.8	43.0	53.1	53.5	67.7	73.5	60.1	49.9
1991	40.5	29.9	11.5	10.4	8.8	45.8	47.0	51.8	63.9	65.9	56.2	46.6
1992	42.4	31.9	7.4	5.8	10.7	29.0	50.7	55.7	71.0	74.7	59.8	51.7
1993	40.3	28.7	15.9	6.8	9.1	39.0	51.6	58.0	72.2	73.7	59.5	46.7

Table 4.2. Evapotranspiration values of Krishna river basin from January 1983 to December 1993.

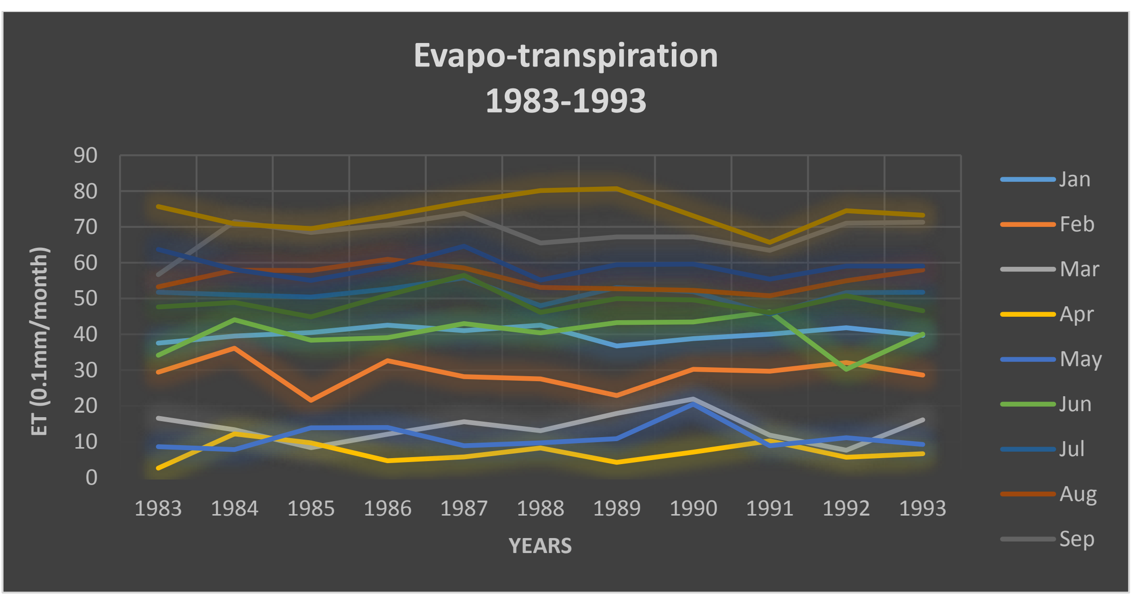

Fig 4.3 Monthly ET (mm/month) for the years 1983 to 1993 for the Krishna River Basin

The average monthly ET rate from 1983 to 1993 show that the months of June, July, August, September and October generally have a high ET, while the months of November, December, January, February, March, April and May show relatively less ET. The highest and lowest ET occur in the months of October and April respectively. High ET values are experienced due to the high rainfall in the Indian sub-continent during the months of June, July, August, September and October. At the same time, the lowest ET experienced in the month of April is likely due to the lack of rainfall during this month and its preceding months. ET during the month of October shows an average ET of 74.0 mm/month while average ET value of 7.0 mm/ month are observed in the month of April. These variations in ET can be attributed to rainfall variation in the country across the months (Table 4.3).

S.No	Monsoonal classification	Actual months	Season
1	Pre-monsoon	March, April, May	Summer season
2	Monsoon	June, July, August, September, October	South-west monsoon and North-east monsoon
3	Post-monsoon	November, December, January, February	Winter season

Table 4.3. Monsoonal classification of months

Thus, the highest rate of ET is experienced during the months of monsoon while pre-monsoon and post-monsoon months have comparatively less ET. The rate of evapotranspiration during the three classified groups for the year 1983 to 1993 are shown in the table 4.4.

Year	Pre-monsoon	Monsoon	Post-monsoon
1983	27.8	271.5	178.4
1984	33.3	295.4	182.6
1985	31.8	284.6	162.0
1986	30.7	296.3	184.9
1987	30.2	308.0	190.3
1988	30.9	287.0	171.3
1989	32.9	296.9	169.0
1990	49.5	288.0	178.3
1991	30.8	271.9	171.2
1992	24.4	282.4	183.7
1993	31.9	294.4	173.9

Table 4.4 Monsoonal classification of ET (mm/month) for the year 1983 to 1993

Table 4.4 shows that monsoonal period experience the highest ET while pre monsoonal period experiences the lowest ET. This information is also visualized in Figure 4.4.

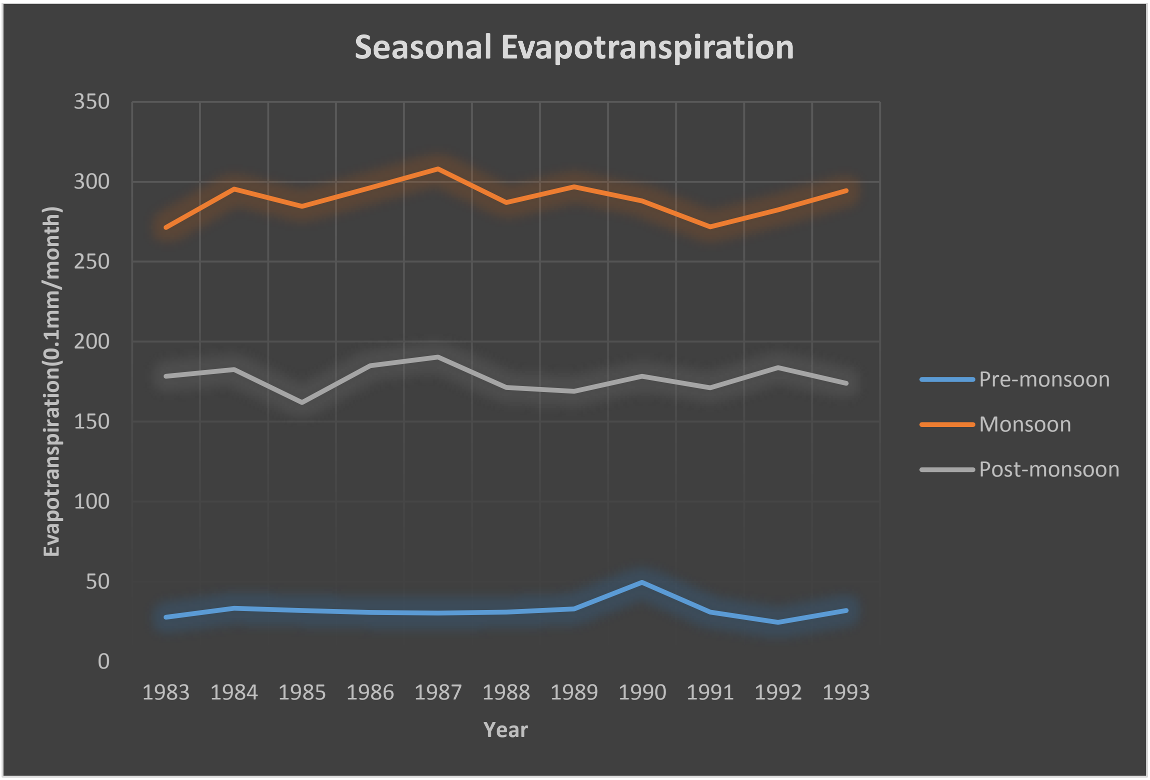

Fig. 4.4 Monsoonal classification of ET for the Krishna River Basin for the years 1983 to 1993

If we consider the pre-monsoonal, monsoonal and post-monsoonal ET at the scale of sub basins, it shows a similar trend as the basin level ET. The pre-monsoonal ET is the lowest and the monsoonal ET is the highest over the seven sub-basins (Tables 4.5-4.7 and Figures 4.5-4.7). These graphs show that the ET has a significant temporal variability over the sub basins of the Krishna River Basin.

NAME	Thunga_upper	Thunga_lower	Krish_upper	Krish_Middle	Krish_lower	Bhi_Upper	Bhi_lower
1983	69.6	18.9	38.6	13.0	16.0	25.9	6.4
1984	111.8	37.2	37.2	19.0	18.8	8.6	6.4
1985	97.5	27.7	44.3	11.1	9.1	20.2	8.7
1986	82.7	24.5	43.1	15.7	16.1	20.1	7.7
1987	87.2	27.9	37.9	15.0	19.4	15.5	7.3
1988	96.2	28.2	41.6	10.7	16.5	15.7	3.1
1989	79.7	29.1	46.4	17.8	17.5	20.7	14.0
1990	102.6	43.5	63.3	28.4	41.1	37.9	19.8
1991	103.2	26.0	42.3	12.2	14.2	12.7	4.1
1992	86.7	18.4	35.9	6.8	6.2	12.6	0.9
1993	99.2	29.4	39.1	13.5	18.4	17.1	6.1

Table 4.5 Pre-monsoonal ET (mm/month) for the sub-basins of the Krishna River Basin (1983 to 1993)

Name	Thunga_upper	Thunga_lower	Krish_upper	Krish_Middle	Krish_lower	Bhi_Upper	Bhi_lower
1983	275.1	268.0	264.9	279.4	284.0	259.6	284.6
1984	309.5	285.7	307.1	297.8	291.2	285.3	291.7
1985	311.5	275.9	292.1	278.3	281.4	271.4	286.5
1986	337.5	290.1	317.0	284.7	275.6	277.7	288.1
1987	336.0	302.3	325.5	284.7	271.8	304.7	328.5
1988	304.7	285.9	288.9	287.7	275.7	278.2	296.9
1989	315.8	293.1	301.4	301.2	280.8	290.7	302.9
1990	297.4	281.5	288.5	303.0	281.3	274.5	308.9
1991	284.5	275.6	268.5	289.8	277.4	248.8	276.4
1992	316.1	282.7	299.6	263.1	241.7	283.7	280.8
1993	322.9	299.2	304.4	278.4	262.7	287.9	305.1

Table 4.6 Monsoonal ET (mm/month) for the sub-basins of the Krishna River Basin for the year 1983 to 1993

Name	Thunga_upper	Thunga_lower	Krish_upper	Krish_Middle	Krish_lower	Bhi_Upper	Bhi_lower
1983	190.4	155.6	192.9	175.8	180.0	160.4	204.3
1984	230.3	183.2	183.3	172.4	193.0	148.8	181.0
1985	206.5	164.9	160.3	148.0	175.3	133.8	154.2
1986	223.7	185.9	189.3	174.9	200.0	149.4	181.1
1987	217.3	191.0	184.1	184.7	208.2	163.7	198.3
1988	220.4	172.7	170.3	165.0	189.3	136.3	157.7
1989	208.9	170.3	167.1	159.8	188.4	136.6	164.4
1990	216.2	175.4	178.9	162.7	196.5	154.4	167.9
1991	211.2	177.2	163.8	172.8	200.2	133.4	155.7
1992	229.2	183.7	185.0	181.5	204.5	143.7	173.3
1993	211.7	182.5	173.7	164.3	181.4	143.8	169.3

Table 4.7 Post-monsoonal ET (mm/month) for the sub-basins of the Krishna River Basin for the year 1983 to 1993

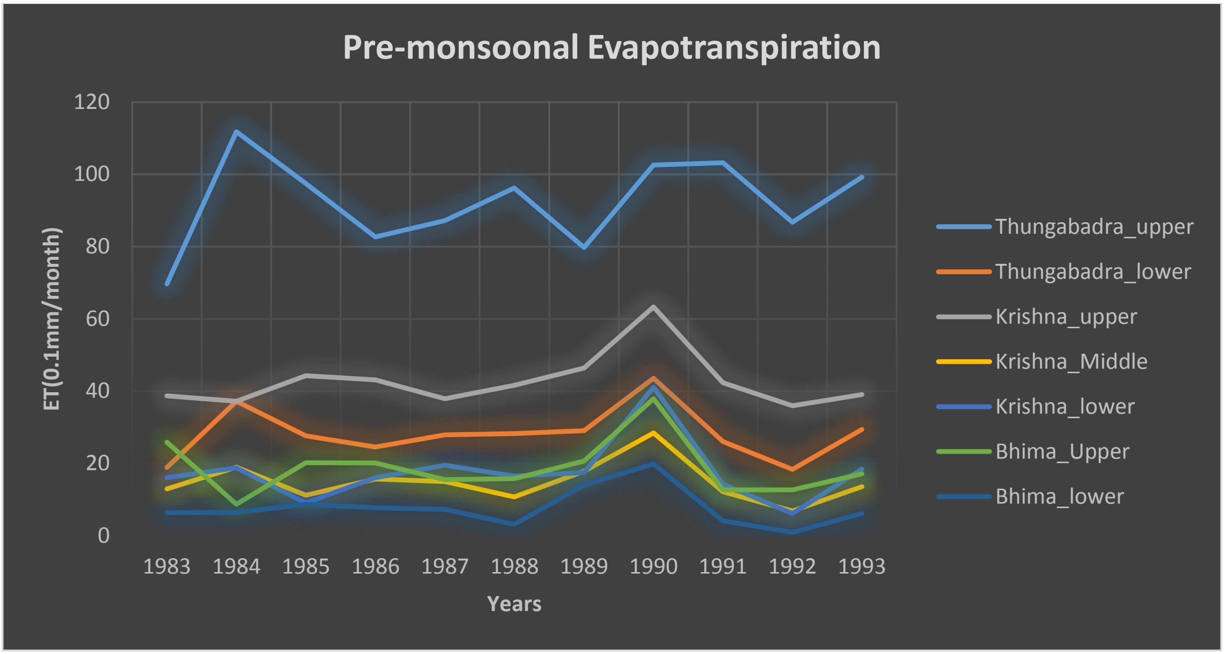

Figure 4.5 Pre-monsoonal ET (mm/month) for the sub basins of the Krishna River Basin for the years 1983 to 1993

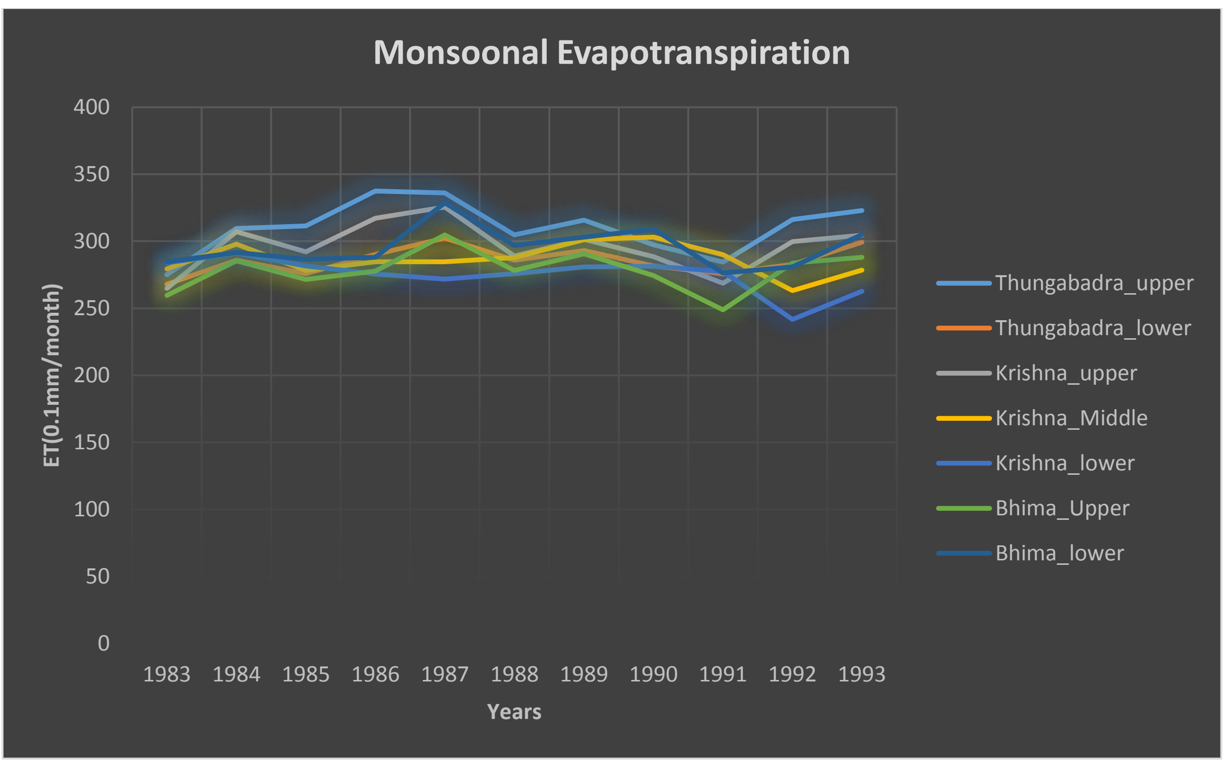

Figure 4.6 Monsoonal ET (mm/month) for the sub basins of the Krishna River Basin for the years 1983 to 1993

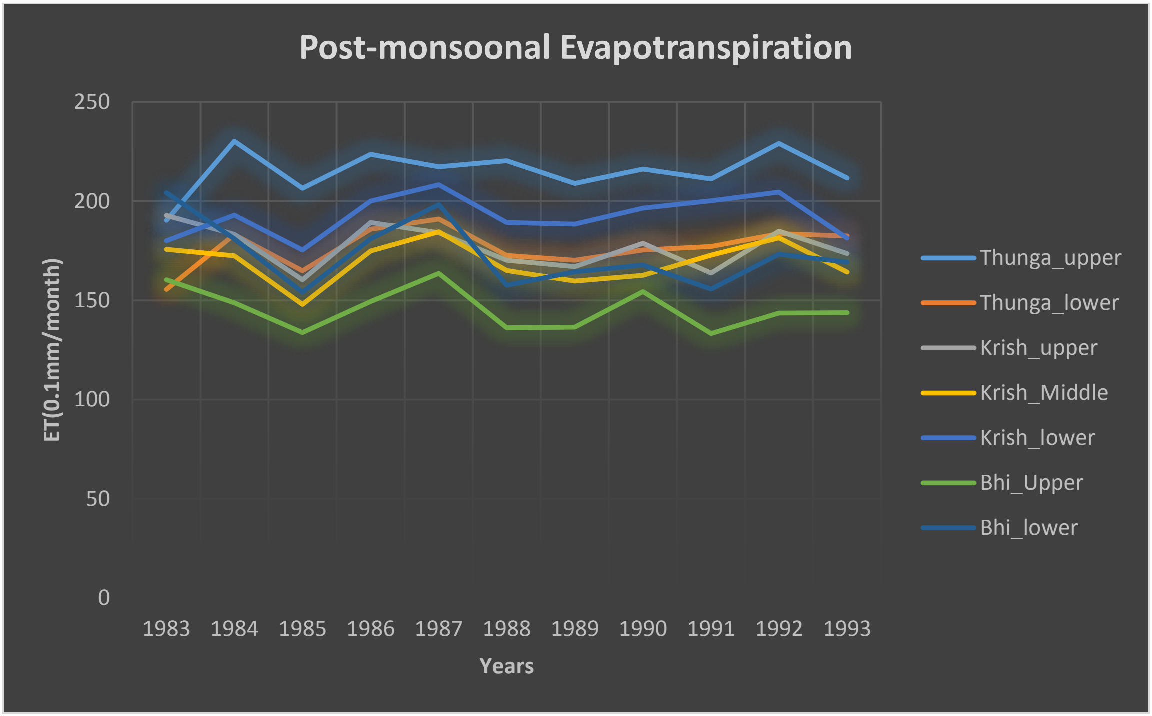

Figure 4.7 Post-monsoonal ET (mm/month) for the sub basins of the Krishna River Basin for the years 1983 to 1993

4.3 RAINFALL

The district wise rainfall data was scaled to the basin and sub basin level by using the methodology described earlier. Table 4.8 (and Figure 4.8) shows the eleven years of rainfall data from 1983 to 1993 for the Krishna River Basin, India. Observations reveal that July and August are the months with highest rainfall for the river basin. Figure 4.9 shows the average rainfall (mm/month) of each month over the eleven years from 1983 to 1993. When considering an average across eleven years, July is the month of highest rainfall while February is the month of lowest rainfall. If we consider the rainfall data of the Krishna River Basin as per the monsoonal classification, we can estimate the rainfall data for the Krishna River Basin as pre-monsoonal, monsoonal and post-monsoonal (Table 4.9). On extending the analysis to sub basin level, a similar pattern in the rainfall data is revealed. As expected, the monsoonal rainfall is much higher than the pre-monsoonal and post-monsoonal rainfall (Figures 4.10-4.12).

Year	January	February	March	April	May	June	July	August	Septembe	October	Novembe	December
1983	0.1	1.3	0.5	1.7	28.7	234.9	343.9	421.0	312.1	106.2	15.0	31.5
1984	1.9	6.7	19.4	21.5	12.5	264.6	380.6	173.2	147.6	122.2	7.1	2.1
1985	49.5	0.2	7.7	16.7	33.0	254.9	258.1	230.3	105.8	120.8	13.5	24.1
1986	12.6	11.6	2.8	14.7	22.4	271.2	198.2	269.6	115.9	41.1	59.9	8.5
1987	2.9	1.0	5.8	4.7	40.2	203.7	235.2	277.3	105.6	156.1	87.7	21.3
1988	0.5	3.2	1.9	34.2	30.0	172.1	452.9	318.4	299.1	33.3	2.1	16.6
1989	0.0	0.0	22.3	8.5	21.0	276.0	423.3	251.4	201.3	49.7	14.2	6.9
1990	3.9	3.5	7.0	5.1	161.1	259.9	279.0	385.1	128.4	165.8	36.5	0.9
1991	4.5	0.4	2.3	34.5	54.6	350.1	413.4	231.4	103.8	67.3	36.6	1.6
1992	1.7	0.1	0.1	13.4	37.8	229.1	274.7	335.6	152.2	78.1	107.3	0.9
1993	0.0	0.5	7.6	14.5	40.5	181.4	389.2	239.4	165.2	218.6	17.2	35.9

Table 4.8 Rainfall (mm/month) for the Krishna River Basin for the period 1983 to 1993

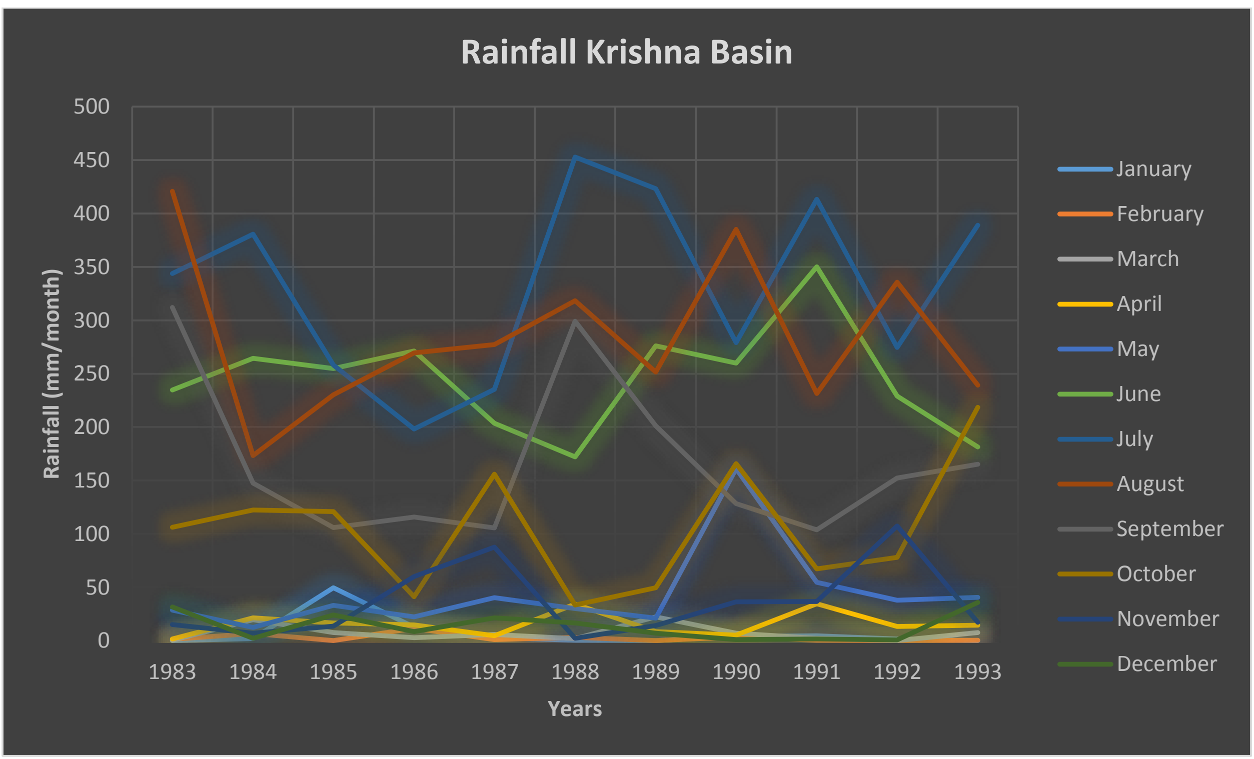

Figure 4.8 Rainfall (mm/month) for the Krishna River Basin for the period 1983 to 1993

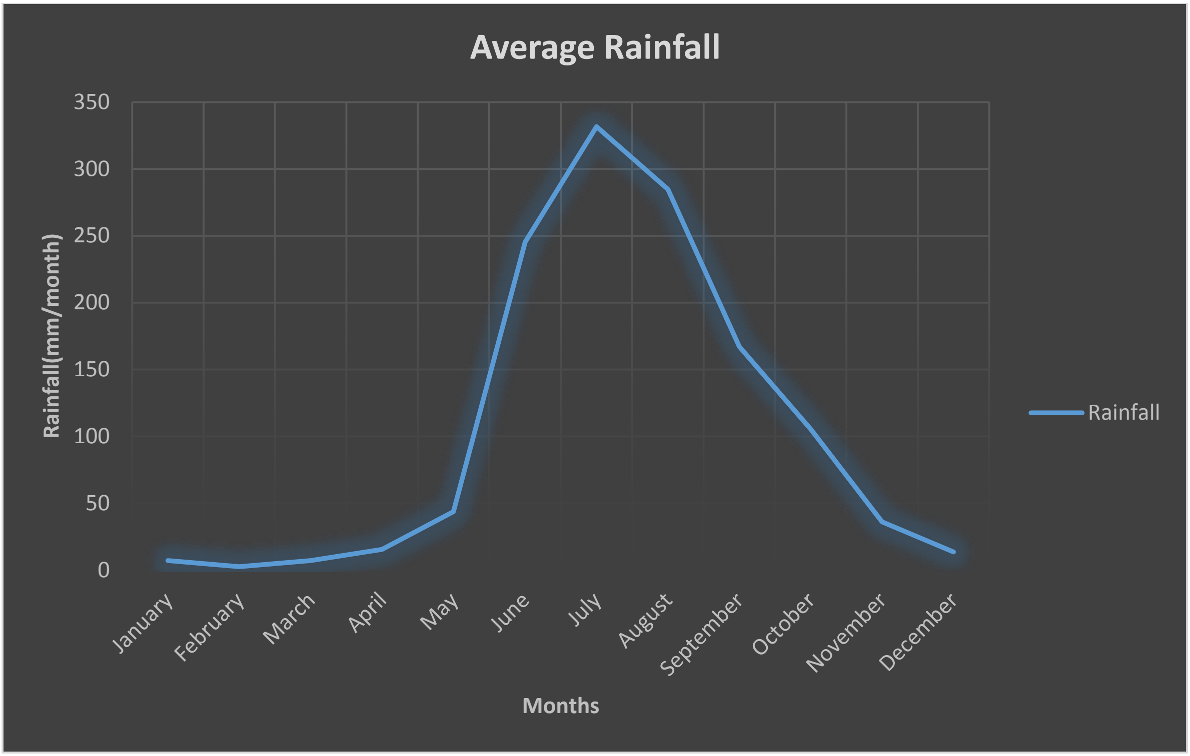

Figure 4.9 Average rainfall (mm/month) for each month across 1983-1993

Year	Pre-monsoonal	Monsoonal	Post-monsoonal
1983	30.9	1418.0	47.9
1984	53.4	1088.2	17.9
1985	57.3	969.9	87.3
1986	39.8	896.0	92.6
1987	50.8	977.9	112.9
1988	66.0	1275.8	22.5
1989	51.7	1201.7	21.1
1990	173.2	1218.2	44.8
1991	91.4	1166.1	43.2
1992	51.4	1069.7	109.9
1993	62.5	1193.7	53.6

Table 4.9 Rainfall (mm) in the Krishna River Basin classified according to the monsoonal classification

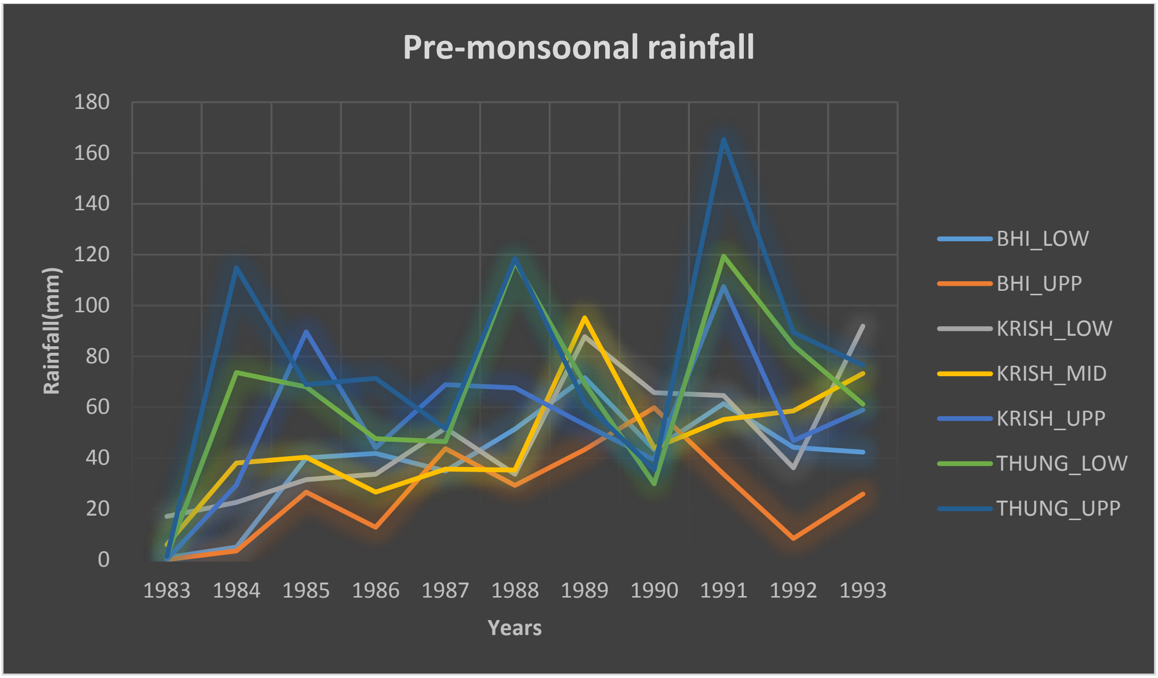

Figure 4.10 Pre-monsoonal rainfall (mm) in the sub basins of the Krishna River Basin for the years 1983-1993.

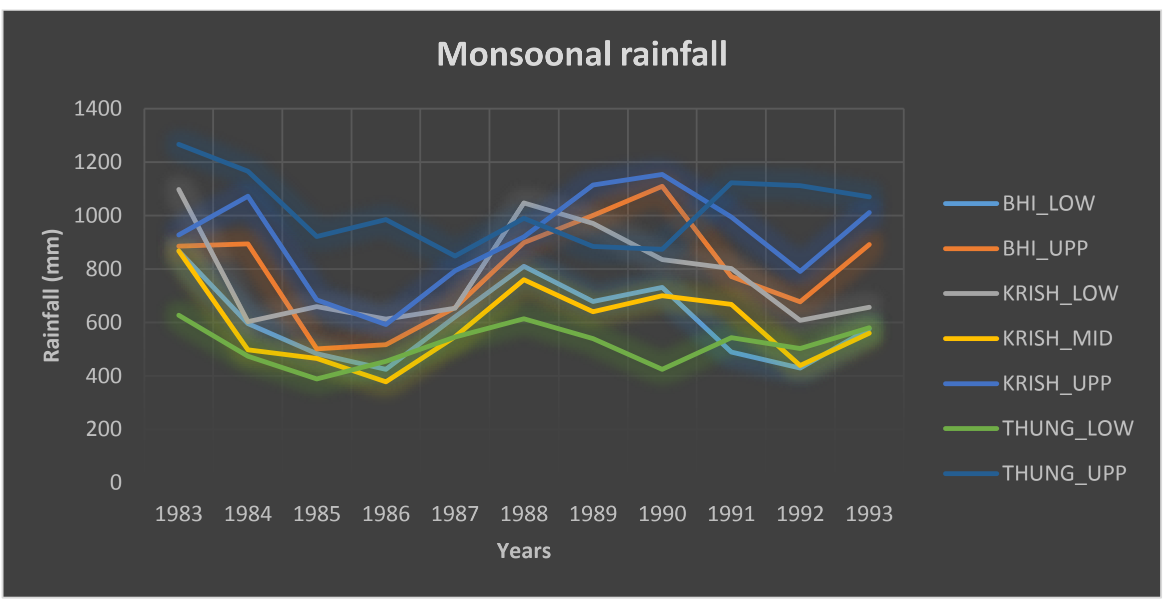

Figure 4.11 Monsoonal rainfall (mm) in the sub basins of the Krishna River Basin for the years 1983-1993

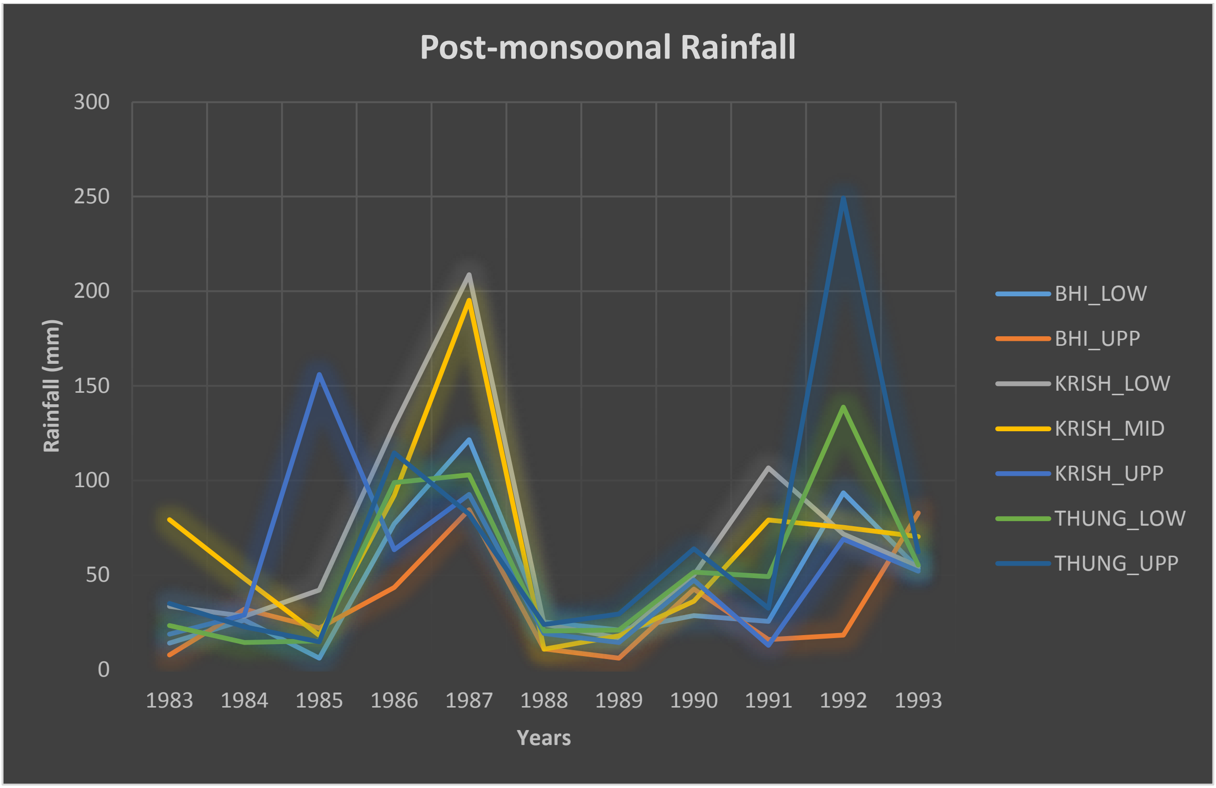

Figure 4.12 Post-monsoonal rainfall (mm) in the sub basins of the Krishna River Basin for the years 1983-1993

4.4 LAND USE AND LAND COVER CLASSIFICATION

The land use and land cover map of the Krishna River Basin using supervised classification is given in Figure 4.13. Table 4.10 lists the percentage of each land use type in the basin. The table shows that agriculture is the dominant land use type in the basin. Built up areas constitute the smallest percentage of land use types in the basin. Land use classification at the sub basin level is presented in Table 4.11. Agriculture is the dominant land use type even at the sub basin scale averaging to about 75% of the total land use. Similarly, built up areas constitute the smallest land use type even at the sub basin level with an average coverage of 0.6%. Forests, water bodies and barren land cover 15%, 3% and 7% of the sub basins on an average.

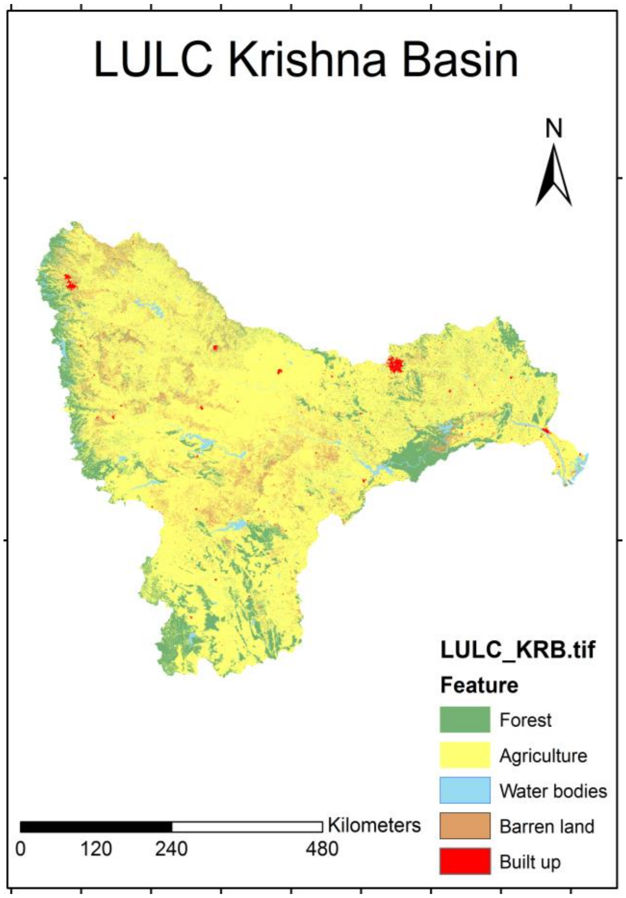

Figure 4.13 Land use land cover map of the Krishna River Basin India using satellite data from years 1989- 1993.

Feature	Krishna basin(%)
Forest	15.1
Agriculture	75.2
Water bodies	2.5
Built up	0.6
Barren land	6.6

Table 4.10 Percentage area of each land use type in the Krishna River Basin

Feature	Bhi_Low	Bhi_Upp	Krish_ low	Krish_Mid	Krish_Upp	Thung_ Low	Thung_Upp
Forest	5.0	11.4	14.5	24.5	12.7	12.8	24.5
Agriculture	89.2	74.1	75.5	64.4	75.7	78.4	69.2
Water bodies	1.2	2.4	3.3	4.2	2.6	1.1	2.5
Built up	0.4	0.6	2.2	0.6	0.2	0.3	0.1
Barren land	4.2	11.5	4.4	6.3	8.8	7.3	3.7

Table 4.11 Percentage area of each land use type in the sub basins of the Krishna River Basin

4.5 AVAILABILITY OF WATER

By using the difference between precipitation and ET at relevant time scale, an approximation to available water in the Krishna River Basin and its sub basins can be calculated. We estimate these differences at the monthly and then at the annual time scales. Due to the seasonal variability in P and ET, monthly differences do not satisfy the water balance at monthly time steps for all the months (Table 4.12). Therefore, we do not interpret this figure was available water. Ideally, P-ET should be positive on a large time scales (provided the assumptions regarding ground water hold), as ET is then being supplied by P alone. Therefore, interpreting this data at the annual and decadal time scale is most relevant. Tables 4.13 presents the water availability information at the annual time scale for the Krishna river basin and its sub basins. Table 4.14 presents the water availability information for the Krishna River Basin and its sub basins across the entire eleven years of analysis. This information is visualized geographically in Figure 4.13 (decadal water availability for the Krishna River Basin) and Figure 4.14 (decadal water availability for the sub basins of the Krishna River Basin.)

YEAR	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec
1983.0	-3.7	-1.7	-1.1	1.5	27.8	231.4	338.7	415.6	306.4	98.6	8.6	26.6
1984.0	-2.1	3.0	18.1	20.2	11.7	260.3	375.5	167.3	140.4	115.2	1.2	-2.8
1985.0	45.4	-2.0	6.8	15.7	31.7	251.2	253.0	224.4	99.0	113.7	7.9	19.6
1986.0	8.3	8.3	1.6	14.2	21.1	267.4	193.0	263.5	108.8	33.7	54.0	3.4
1987.0	-1.2	-1.9	4.3	4.1	39.4	199.6	229.6	271.4	98.2	148.3	81.2	15.6
1988.0	-3.8	0.4	0.6	33.3	29.0	168.2	448.1	313.0	292.5	25.3	-3.5	12.0
1989.0	-3.7	-2.3	20.6	8.0	19.9	271.8	417.9	246.1	194.6	41.6	8.2	1.8
1990.0	0.2	0.5	4.8	4.4	159.1	255.6	273.7	379.7	121.6	158.4	30.5	-4.1
1991.0	0.5	-2.6	1.2	33.4	53.7	345.5	408.7	226.2	97.5	60.7	31.0	-3.0
1992.0	-2.5	-3.1	-0.6	12.9	36.8	226.2	269.6	330.1	145.1	70.6	101.3	-4.3
1993.0	-4.0	-2.4	6.0	13.8	39.6	177.6	384.0	233.6	157.9	211.2	11.3	31.3

Table 4.12 Difference between monthly precipitation and ET (mm) in the Krishna River Basin, India in the period 1983 to 1993

Year	BHIMA_LO	BHIMA_U	KRISH_LO	KRISH_MI	KRISH_U	THUNG_I	THUNG_	KRISHNA_BA
1983	32.2	37.3	80.8	40.4	37.5	17.5	64.0	84.7
1984	15.3	36.7	10.5	6.5	52.3	6.8	54.3	53.8
1985	8.6	9.3	23.6	2.2	38.4	0.4	32.5	52.9
1986	5.5	10.5	23.6	1.7	12.5	8.3	43.9	43.0
1987	20.3	24.9	34.5	24.4	33.9	14.5	28.5	48.0
1988	35.7	42.4	52.0	28.5	42.2	22.0	42.6	72.7
1989	24.1	50.2	49.0	22.8	55.6	11.4	31.0	64.5
1990	25.5	62.1	36.0	23.9	59.2	0.4	29.7	76.7
1991	11.7	35.6	40.0	27.2	53.3	19.4	60.1	68.5
1992	9.3	21.9	21.9	10.0	32.2	20.0	68.2	61.7
1993	16.0	45.9	28.4	20.6	50.4	15.4	47.9	67.4

Table 4.13 Annual water availability for the Krishna River Basin and its sub basins from the years 1983 to 1993

Basins	Water
BHIMA_LOWER	18.6
BHIMA_UPPER	34.2
KRISHNA_LOWER	36.4
KRISHNA_MIDDLE	18.9
KRISHNA_UPPER	42.5
THUNG_LOWER	12.4
THUNG_UPPER	45.7
KRISHNA_BAS	63.1

Table 4.14 Eleven year average water availability for the Krishna River Basin and its sub basins from the years 1983 to 1993.

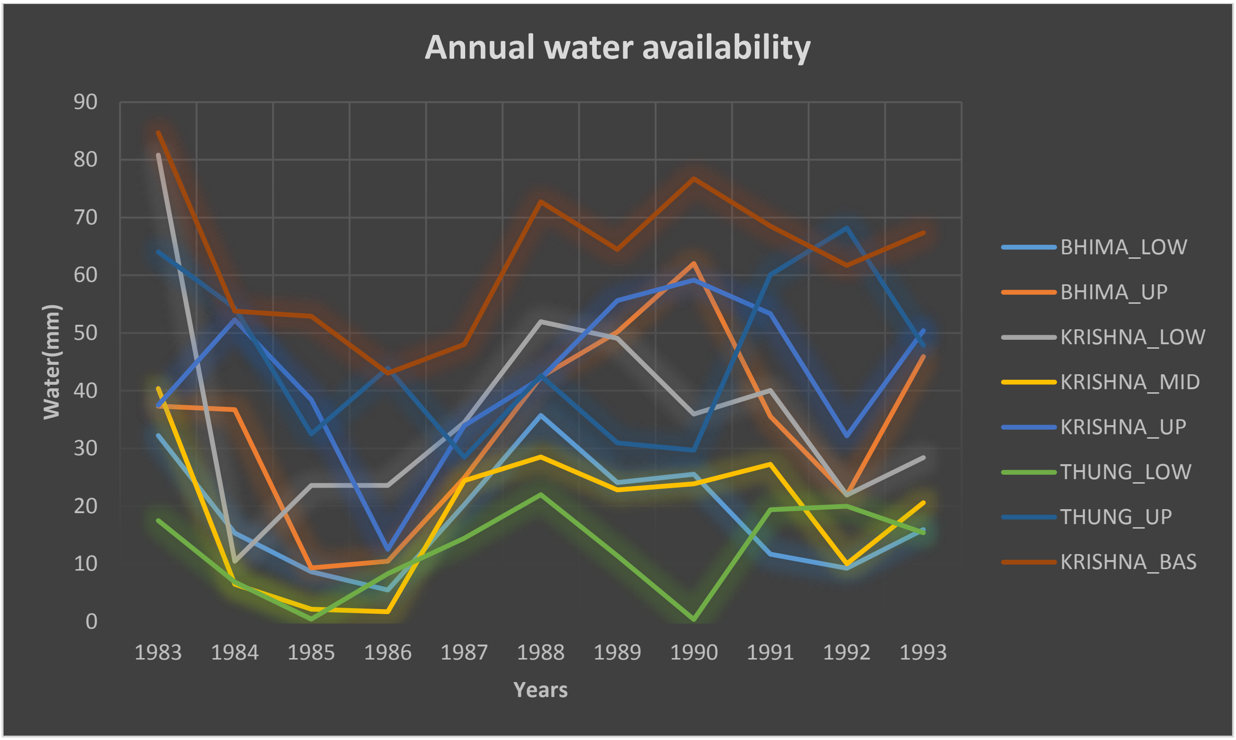

Figure 4.13 Annual water availability for the Krishna River Basin and its sub basins from the years 1983 to 1993

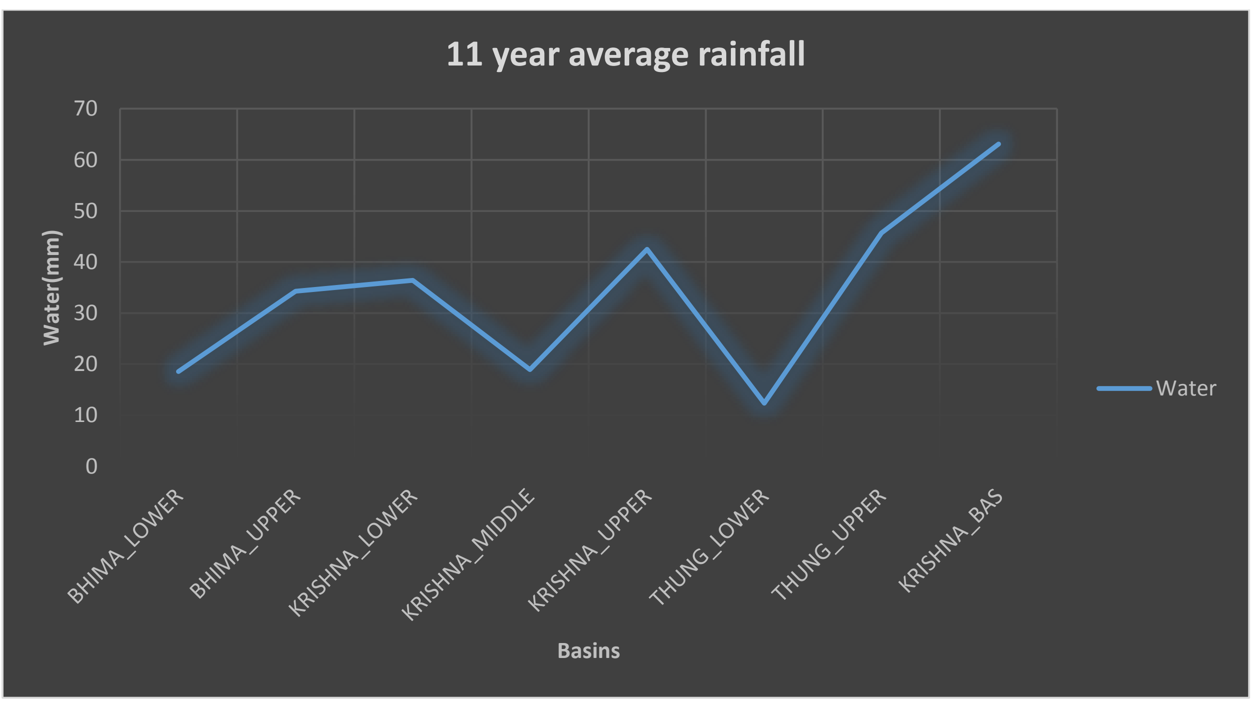

Figure 4.14 Eleven year average water availability for the Krishna River Basin and its sub basins from the years 1983 to 1993

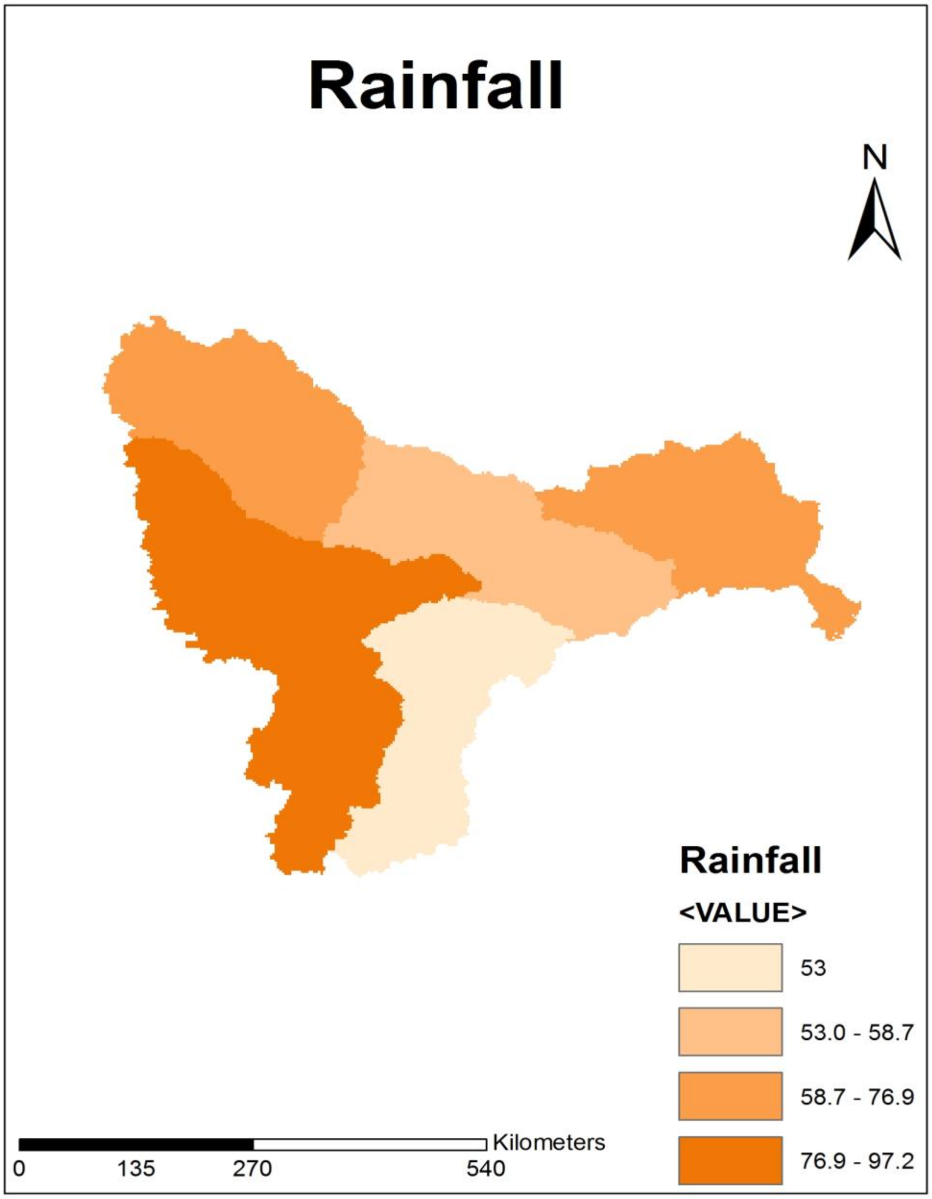

Figure 4.15 Eleven year average rainfall availability for the sub basins of the Krishna River Basin from the years 1983 to 1993

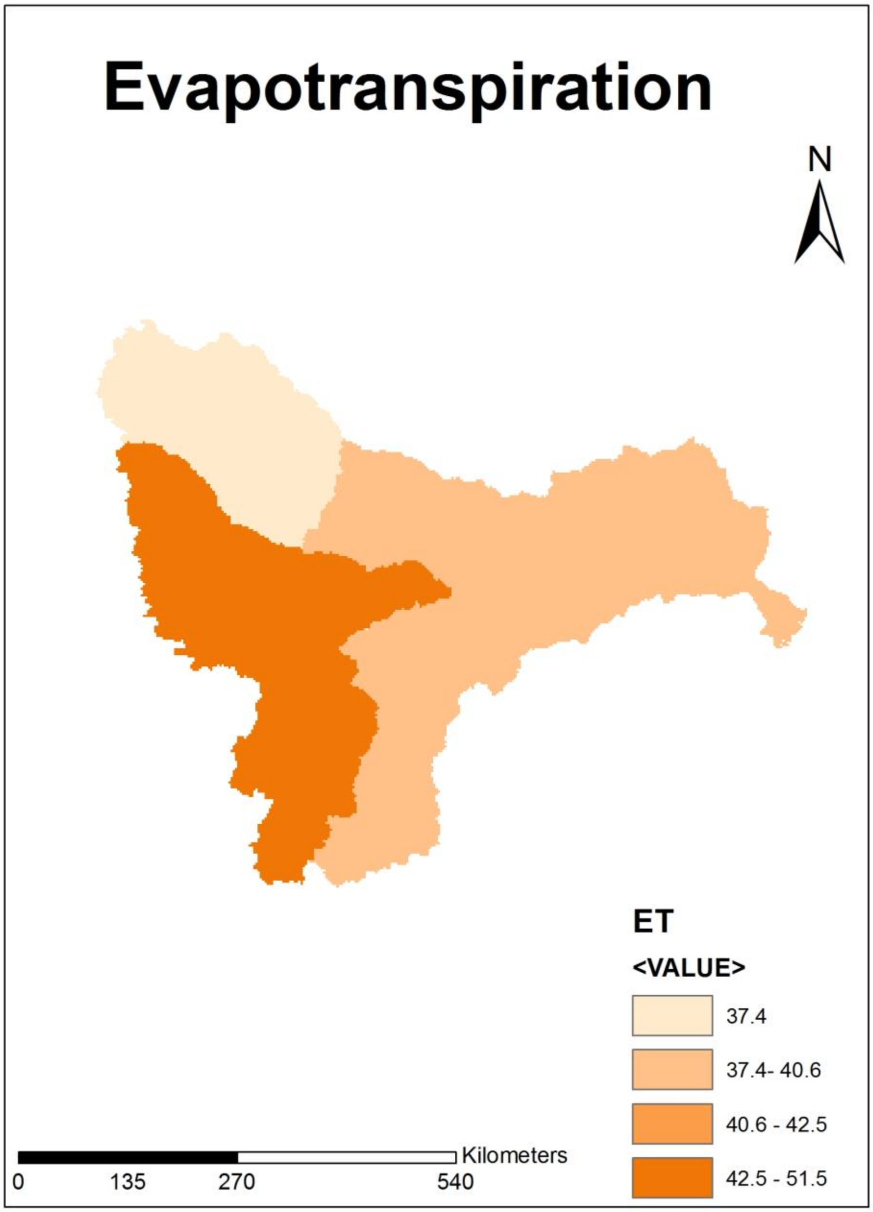

Figure 4.16 Eleven year average evapotranspiration for the sub basins of the Krishna River Basin from the years 1983 to 1993

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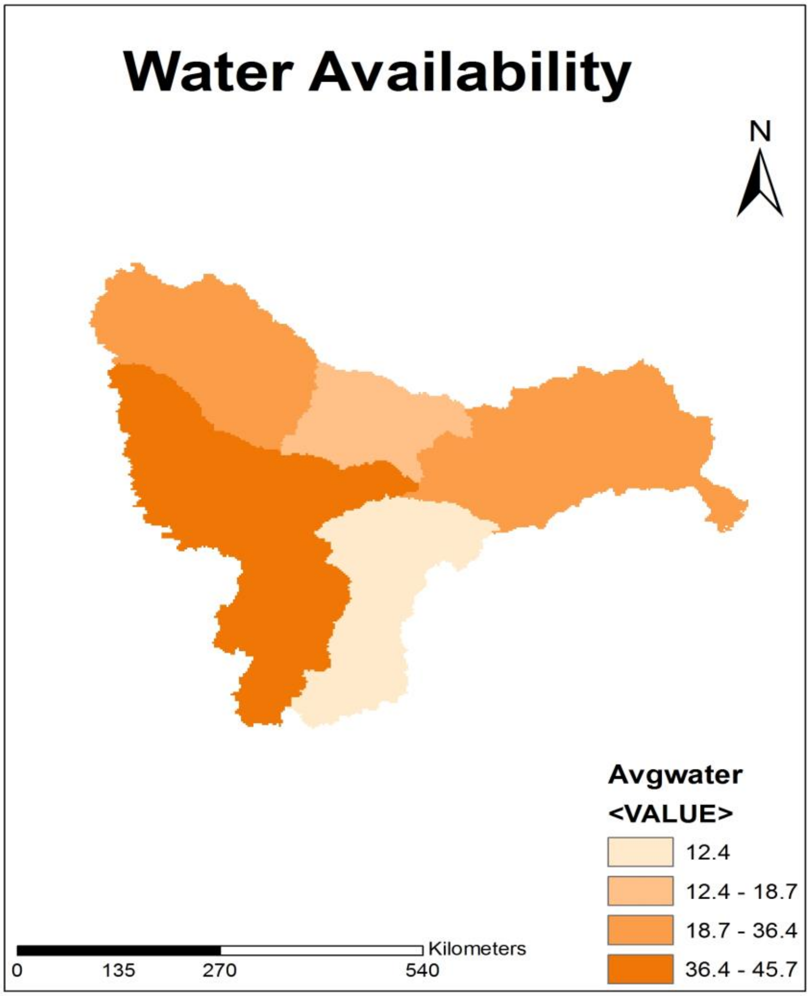

Figure 4.17 Eleven year average water availability for the sub basins of the Krishna River Basin from the years 1983 to 1993.

By combining all these three, which is the hydrological variables such as the precipitation and the evapotranspiration and the availability of water we will get the plot as such it is in Figure 4.18.

ID	Name	Rainfall	ET	Water available
1	Bhima_lower	57.8	39.3	18.6
2	Bhima_Upper	71.6	37.4	34.2
3	Krishna_lower	76.9	40.5	36.4
4	Krishna_Middle	58.7	39.8	18.9
5	Krishna_upper	85.1	42.6	42.5
6	Thungabadra_lower	53	40.6	12.4

Table 4.15 Eleven year average Rainfall, ET and Water availability for the sub basins of the Krishna River Basin from the years 1983 to 1993

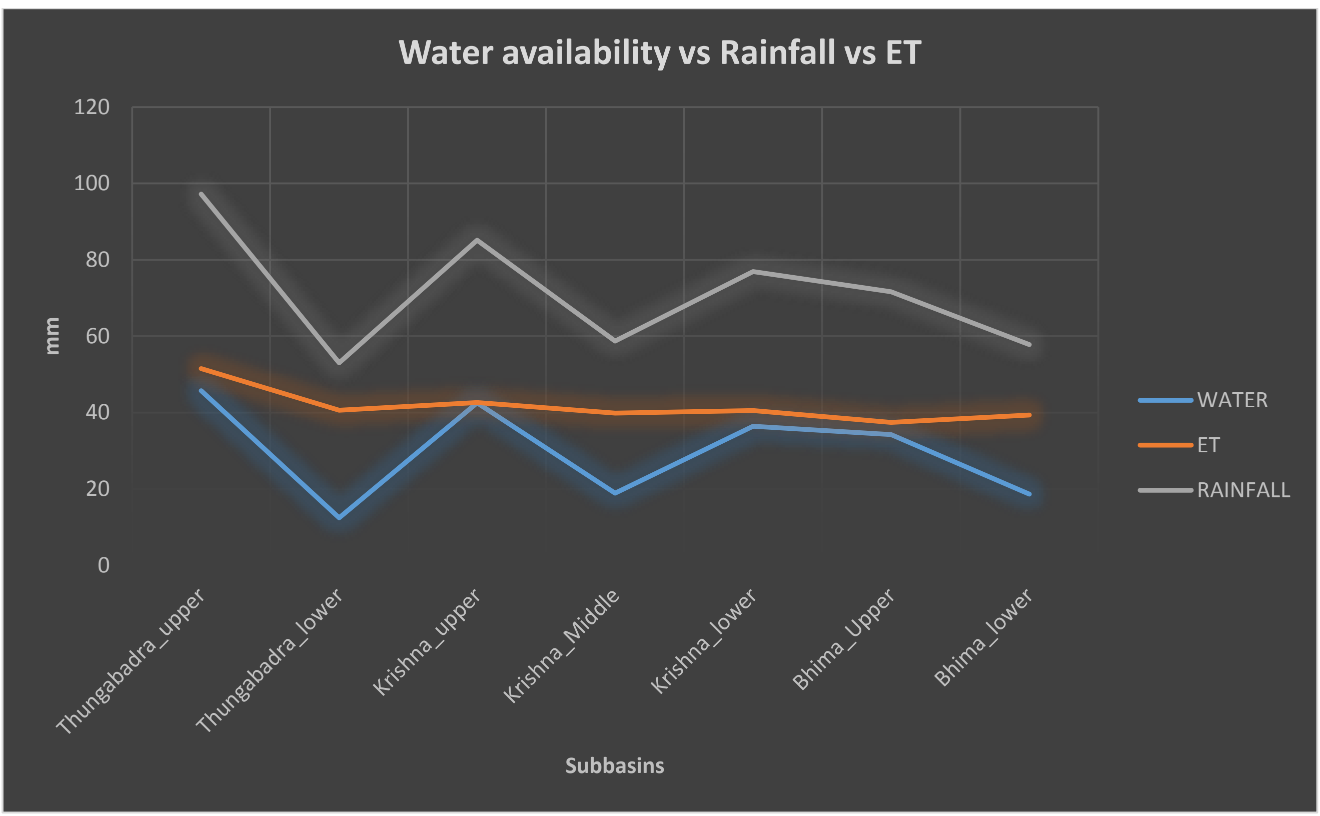

Figure 4.17 Eleven year average water availability vs rainfall vs ET for the sub basins of the Krishna River Basin from the years 1983 to 1993.

CHAPTER 5. CONCLUSION

The water availability is one of the major issues that the planet is now keen about. This water availability is relying upon some major depending factors such as precipitation and evapotranspiration. These two factors are called as the hydrologic variables as they are varying spatially and temporally. These two factors decide the water availability, among these precipitation is the major and prime factor. At the same time the major water loss is due to the process of evapotranspiration which the human can take no action. From the present study it is clear and evident that these factors precipitation and evapotranspiration vary spatially, hence they are the hydrological variables.

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