Role of rainfall in urban floods: A case of Pune city

A Thesis

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Indian Institute of Science Education and Research Pune in partial fulfilment of the requirements for the BS-MS Dual Degree Programme

by

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Certificate

This is to certify that this dissertation entitled Role of rainfall in urban floods: A case of Pune city towards the partial fulfilment of the BS-MS dual degree programme at the Indian Institute of Science Education and Research, Pune, represents study/work carried out by Ayushman Singh at Indian Institute of Science Education and Research under the supervision of Dr. Bejoy K. Thomas, Associate Professor, Department of Humanities and Social Sciences, during the academic year 2020-2021.

Dr. Bejoy K. Thomas

Committee:

Dr. Bejoy K. Thomas

Dr. Joy Merwin Monteiro

This thesis is dedicated to my late grandmother and my parents, who are there with me in all things great and small.

Declaration

I hereby declare that the matter embodied in the report entitled Role of rainfall in urban floods: A case of Pune city are the results of the work carried out by me at the Department of Humanities and Social Sciences, Indian Institute of Science Education and Research, Pune, under the supervision of Dr. Bejoy K. Thomas and the same has not been submitted elsewhere for any other degree.

Ayushman Singh

Date: 15/5/2021

Table of Contents

List of Figures

Abstract

The frequency of floods and disasters have been increasing in the past few decades. The reason behind these incidents could be varied: Climate change, urbanisation and change in land-use pattern. We have taken the case of Pune city, where urban flooding events have been increasing, notably the 2019 floods. We have tried to assess the role of rainfall in these incidents of urban flooding. We have looked at rainfall trends over the past 70 years. Our results show that the rainfall pattern has changed, especially in the last 15 years. Annual accumulation and intensity of rainfall have increased, but whether it has led to increasing floods cannot be confirmed with just rainfall data. There are multiple socio-institutional factors in association with biophysical factors such as rainfall that contribute to urban flooding. A more integrated approach to understanding the causal factors behind urban floods allows us to come up with ways to mitigate and adapt to urban floods.

Acknowledgements

First, I would like to thank my supervisor Dr Bejoy K Thomas and my expert Dr Joy Merwin Monteiro. This would not have been possible without their patience and guidance. I want to thank you very much for your support and understanding throughout the project.

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Chapter 1. Introduction

The frequency of natural disasters has been increasing all over the globe in the past century(Banholzer et al., 2014). The economic losses caused due to these disasters disrupt the growth and well-being of society. The devastating effects of these natural hazards are a significant concern. It is essential to understand the causes behind natural disasters to come up with ways to mitigate or avoid the damaging effects. Figure 1.1shows the increasing average number of natural disasters worldwide.

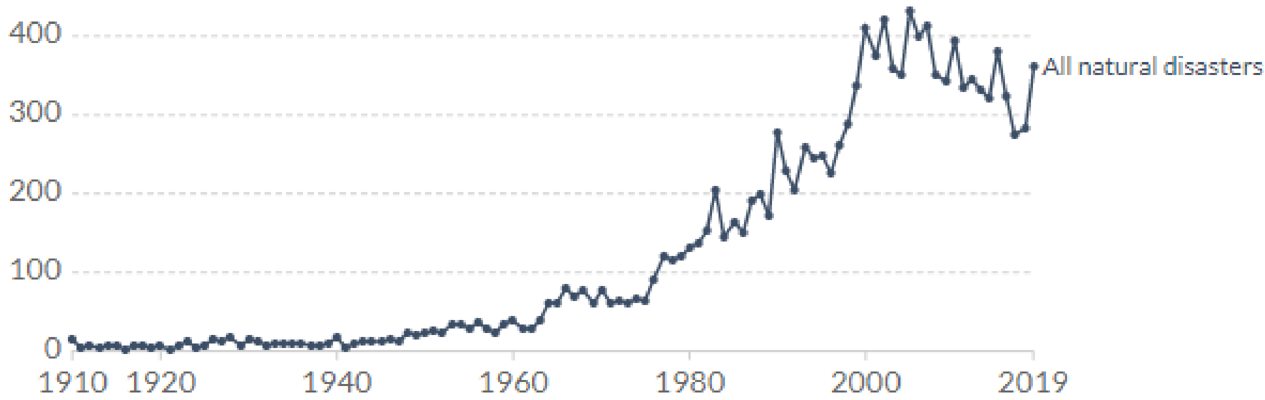

Figure1.1 Annual recorded number of disaster events reported worldwide.
Source: EMDAT (2020): International Disaster Database, Université catholique de Louvain – Brussels – Belgium

We can see a continuous increase in the total number of natural disasters all over the world. The economic damage caused by these natural disasters has also increased over time with population growth. The reasons behind the increase in natural disasters could be attributed to various anthropogenic factors.
Flash floods and urban flooding is some of the most frequent and economically damaging natural disasters, especially in developing countries like India. From 2001 to 2011, there were thousands of fatalities every year caused due to floods. The south and south-eastern regions of Asia seem to show the highest mortality rate(Kundzewicz et al., 2013) all over the world. The causes behind the high mortality rate in the region could be varied, but it is seen that proper governance and disaster management strategies can reduce the mortality rate of events like floods.
Institutions play a vital role in mitigating the damage caused to the economy by these natural disasters. It is seen that less democratic nations and countries with more economic inequality suffer higher death tolls during natural disasters(Kahn 2005). To some extent, Institutions can shield the population from natural disaster deaths and losses.
Climate change, urbanisation and change in landform affect the frequency of floods in different ways worldwide. Climate change plays a very important role in the increase in floods. According to a special report on extreme events and disasters by IPCC (Internal governmental panel on climate change), the number of extreme climatic events seems to have increased and is expected to increase further in the 21st century. This frequency of heavy

precipitation events has also increased, leading to a potential increase in the frequency of floods(Banholzer, 2014) in the 21st century.

The occurrence of flash floods and urban flooding in India is very common. Most of the Indian settlements are around river basins. Every year many urban regions of the country experience flash floods. These Flash floods have to be studied locally for a given region, its occurrence and effects depend on the geography and climate. We have taken the case of Pune city, where the occurrence of flash floods has been increasing.

Pune is a rapidly growing city in India. The population in Pune has seen a substantial increase in the last 20 years. Figure 1.2 shows the population growth in Pune according to census data.

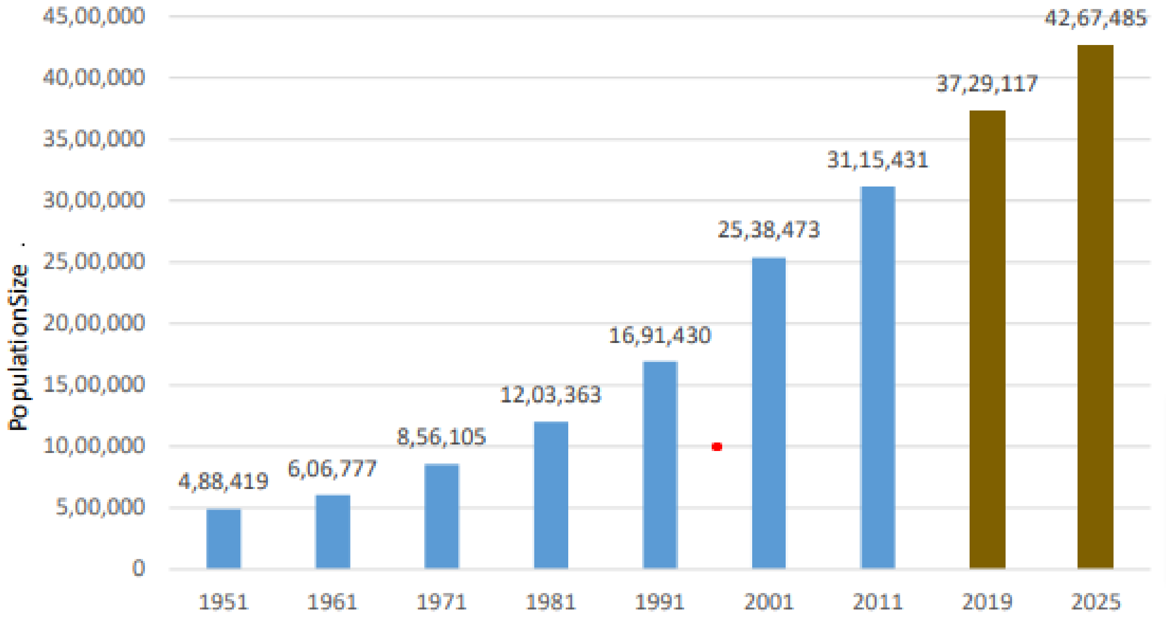

Figure 1.2 Population growth according to census data[1]

The population growth is estimated to increase further in the coming years, considering the existing population growth rate. Several IT companies and educational institutions are expanding their business in Pune city. Such rapid development draws in a major migrant population from all over India and foreign countries. Pune is also an attraction centre for many migrant labourers and unskilled workers from surrounding regions who come to the city looking for jobs and better quality of living. Such rapid urban expansion has put pressure on development in Pune. Rapid urbanisation and expansion of cities lead to unsustainable and haphazard development methods; one of the major consequences of these are urban flooding. The causes of urban flooding can be attributed to various different causes in Pune city. The recent 2019 floods in Pune city was one of the most devastating floods, the city has seen since the 1961 Panshet dam burst. Twenty-two people were killed, many houses and vehicles were washed away, many people lost their livelihood.

History of floods in Pune

According to a webinar series(Pune Monsoon, 3rd July 2020) by Jeevitnadi(A civil society organisation that works on improving the condition of rivers in Pune), floods were common

[1] https://www.teriin.org/sites/default/files/2020-10/water-sustainability-assessment-pune-city.pdf

in Pune city throughout history. The banks of Mula and Mutha used to get flooded every year in the monsoon season. There was a gradual rise in the water level of these water bodies every monsoon. These floods never resulted in any major economic losses or deaths. In some ways, they were helpful as the receding water left very fertile land which was used for agricultural purposes. The floods were never very catastrophic. On the flip side, they were helpful to the agrarian community living on the banks of Pune city. However, this was only the case before the last 50 to 60 years. The nature of these riverine floods has changed a lot in the past 50 years.

Change in nature of floods

Unlike the 1950s, the rise in the water level of the rivers in Pune water bodies is not gradual anymore. Dams have been constructed over Mula and Mutha in order to regulate the flow of these rivers and to provide water to the city. But construction of these dams (two dams on Mutha and two dams on Mula) has worsened the situation. The Khadakwasla dam on the Mutha river is the source of fresh water for a major portion of the city. These dams release large amounts of water instantaneously, which contributes to flash floods in the lower-lying regions of the area. Dams are not the only cause of flash floods in Pune city. Most of the urban flooding in Pune happens upstream along the banks of tributaries("nullahs") of Mula and Mutha. These nullahs run throughout the city to the rivers Mula and Mutha.

According to the webinars by Jeevitnadi, the major causes behind the 2019 floods have been attributed to climate change and poor development methods. Rapid urbanisation and development have led to the construction of illegal structures and encroachments in the river basins. These constructions decrease the water holding capacity of the soil, thus promoting flash floods. Climate Change has also fuelled the fury of floods in Pune. It is claimed that there are changes in rainfall trends leading to flash floods and challenging dam management. In this thesis, we ask the questions has the rainfall pattern in Pune changed? If yes, how? We look at rainfall trends and patterns over the past 70 years. We have tried to look at the changes in rainfall intensity and how it affects the floods in Pune. The 2019 floods were one of the major destructive events in the history of Pune. We aim to highlight the role of rainfall in the backdrop of 2019 floods.

Chapter 2. Methods

Area of Study

Pune is located in Maharashtra, having the late latitude and longitude coordinates as 18.5204° N and 73.8567° E. It is the second-largest city in Maharashtra after Mumbai. Pune district has a total population of 94,29,408. Out of which, 58.1 per cent is urban population. Pune city has an estimated population of 3.99 million and a population density of 5,600 people per square kilometre as of the 2011 census.

Geographically Pune is located on the western side of the Deccan plateau at the confluence of the rivers Mula and Mutha. Pune district is further divided into 15 talukas, which include two city talukas. The two city talukas are Pune city taluka and Pimpri-Chinchwad city taluka. Pune city Taluka has an area of 331.26 km. sq. Pune Municipal Corporation administers it (PMC). Similarly, Pimpri-Chinchwad city taluka has an area of 181 km. sq. and is regulated by Pimpri-Chinchwad Municipal Corporation (PCMC). For the purpose of the climatic aspects of this study, we have considered the Pune city taluka and Pimpri-Chinchwad city taluka. The data used in the study for the rainfall analysis is of 1 grid point, which includes the governance area of both PMC and PCMC.

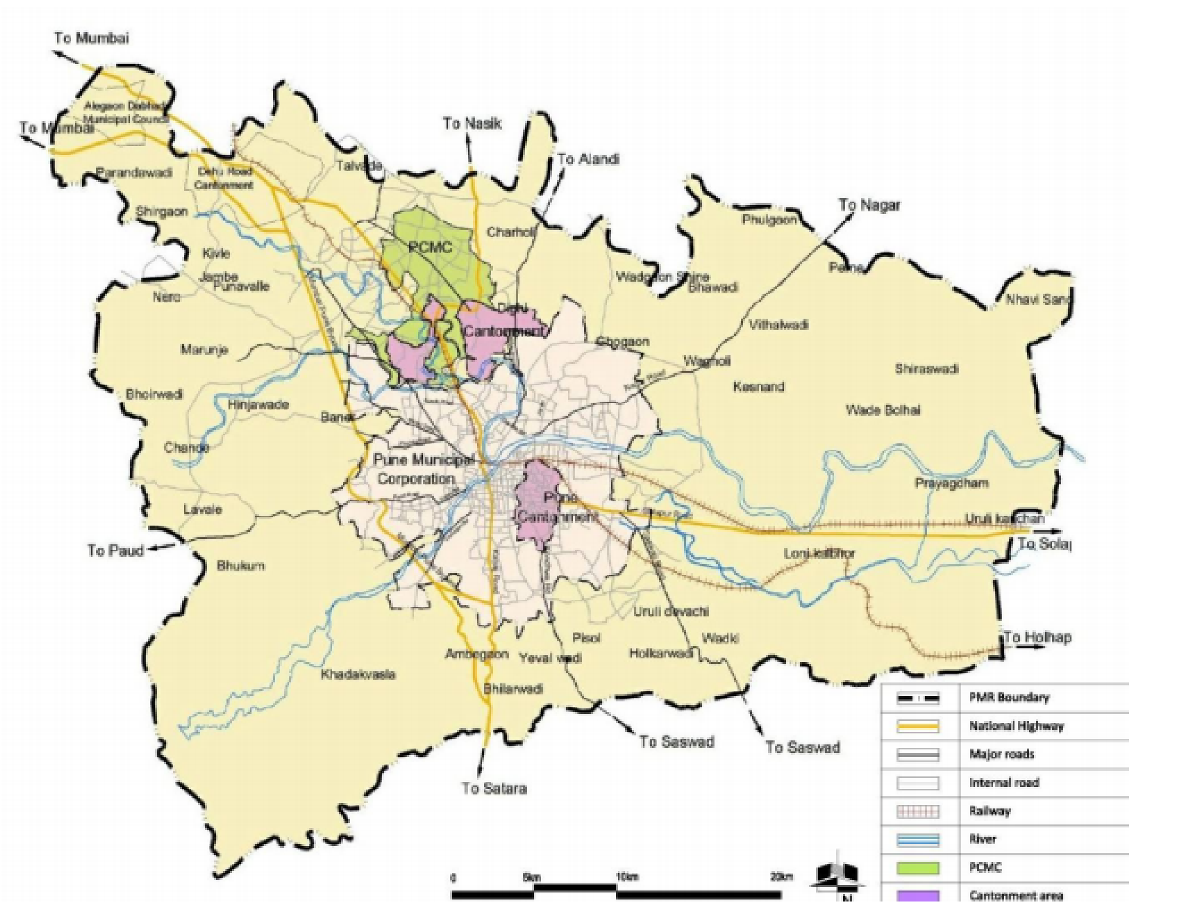

Figure 2.1 Geographical location of Pune city Taluka[2]

[2] City Development Plan, PMC (https://pmc.gov.in/informpdf/CDP/1_CDP_Intro.pdf)

Figure 2.1 shows the whole of Pune district. The red dotted line shows the location and governance areas of PMC, PCMC and the cantonment areas. The light yellow region in the centre represents the PMC governance area, the green area north of PMC represents the PCMC governance region. The three pink areas are cantonment zones in Pune city.

Geography of Pune

Pune city is located 560m above the ground. It forms a part of western ghats as well as the Deccan Plateau on the east. Pune is surrounded by hills from three sides. The Western Ghats on the West and the Deccan Plateau on the East. Thus, the rainfall pattern around the Pune regions seems to change significantly after a few grid points South and East. Figure 1.2 shows the topology of Pune city. The yellow regions represent flatlands (≈ 560m). The darker regions show the high altitude areas around Pune city. The resolution of data used covers only the Pune city area. Although, We have analysed the data from the outskirts and surrounding regions of Pune also.

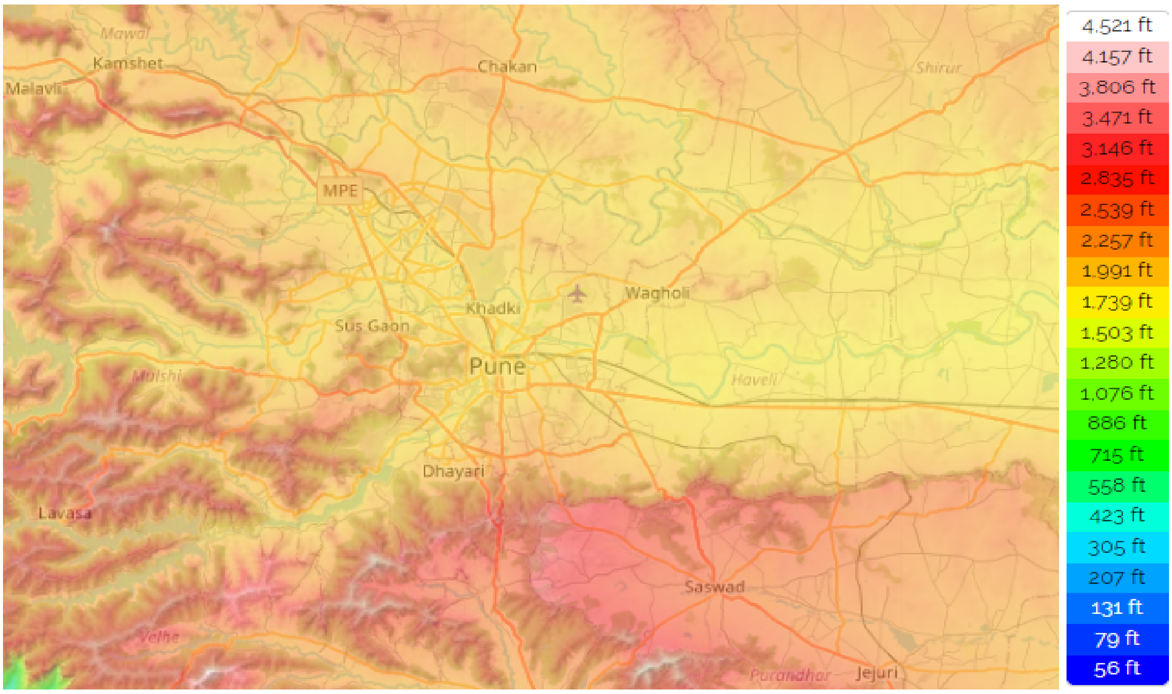

Figure 2.2 Topographical map of Pune city.[3]

Pune is situated on the catchment areas of Mula and Mutha rivers. These rivers originate in the Sahyadri ranges and meet to form the Mula-Mutha river in Pune city. After their confluence, these rivers cross Pune city and further drain into Bhima river and eventually, in river Krishna. The main source of freshwater in Pune and Pimpri-Chinchwad city is from the dams situated on Pavana, Mula and Mutha rivers. Some of the smaller dams are situated on their tributaries. Most of the recent instances of flooding(5- 10 years) in Pune city have been due to unplanned construction and blockage around the tributaries of these rivers. The grid used for the climate analysis of Pune city with respect to flooding includes some part of the flood plains of these tributaries of Mula, Mutha and Pavana river. Pavana river is a tributary of Mula river and is the main source of water in PCMC region.

[3] Pune topographic map, elevation, relief (topographic-map.com)

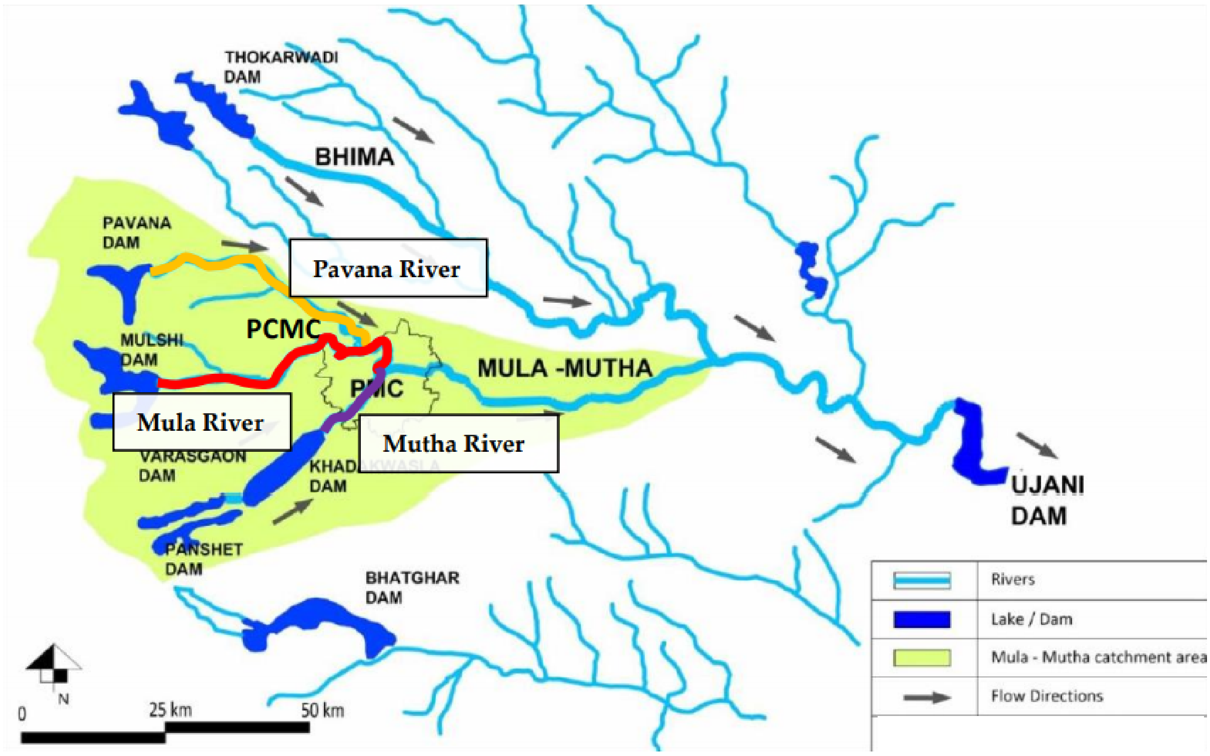

Figure 2.3 Water Bodies in Pune city[4]

The yellow line represents the Pavana river. The red and violet lines are Mula and Mutha rivers. The green region represents the Mula-Mutha catchment area. We can see in the figure that the PCMC and PMC governance regions lie in the Mula-Mutha catchment area.

Dataset

To assess the rainfall patterns in Pune, We have looked at rainfall data of Pune from the last 70 years. The significant sources of rainfall data available for the Indian subcontinent are IMD (Indian Meteorological Department) and APHRODITE(Asian Precipitation - Highly-Resolved Observational Data Integration Towards Evaluation Of Water Resources). Both the data sources are available in two resolutions, 1° x 1° and 0.25° x 0.25°. The 0.25-degree resolution is much better for looking at a small area like Pune city. We started working with APHRODITE data since it was available in a much more user-friendly format. However, there were some limitations to this data source. High-resolution data was available only till 2015. Moreover, the data was not homogenised (no corrections for station location, gauge type and other factors).

We started using IMD gridded data(Pai et al., 2014) after that. This data is available on the IMD website (in .grd format). The spatial resolution of this data is very high(0.25 x 0.25 degree), and it is arranged over multiple grid points(135x129 grid points). The first data in the record is at 6.5N & 66.5E, and the second is at 6.5N & 66.75E, and so on. The quality control of the IMD data seems to be much better compared to APHRODITE in the Indian subcontinent. Furthermore, the higher data resolution allowed us to look closely into urban parts of Pune District (Pune city), which is my area of study.

Pune is located at 18.5204° N, 73.8567° E. The grid point that corresponds to that location is

[4] City Development Plan, PMC (https://pmc.gov.in/informpdf/CDP/1_CDP_Intro.pdf)

18.5 degrees N and 73.5 degrees E. The area of that grid is 720 sq. km. It includes most of the PMC and PCMC governance areas. The overlap of the PMC and PCMC governance area and Pune grid is around 400 sq. km which is 78 per cent of the total governance areas of PMC and PCMC. Figure 3.1 shows the latitude and longitude resolution of the data on a map of Pune city. The horizontal black lines are latitudes that are 0.25° apart, 27.7 km on the ground. The vertical black lines represent the longitude which is 0.25° apart, which translates to 26kms at this latitude(resolution of the available data). The red lines indicate the Pune grid point.

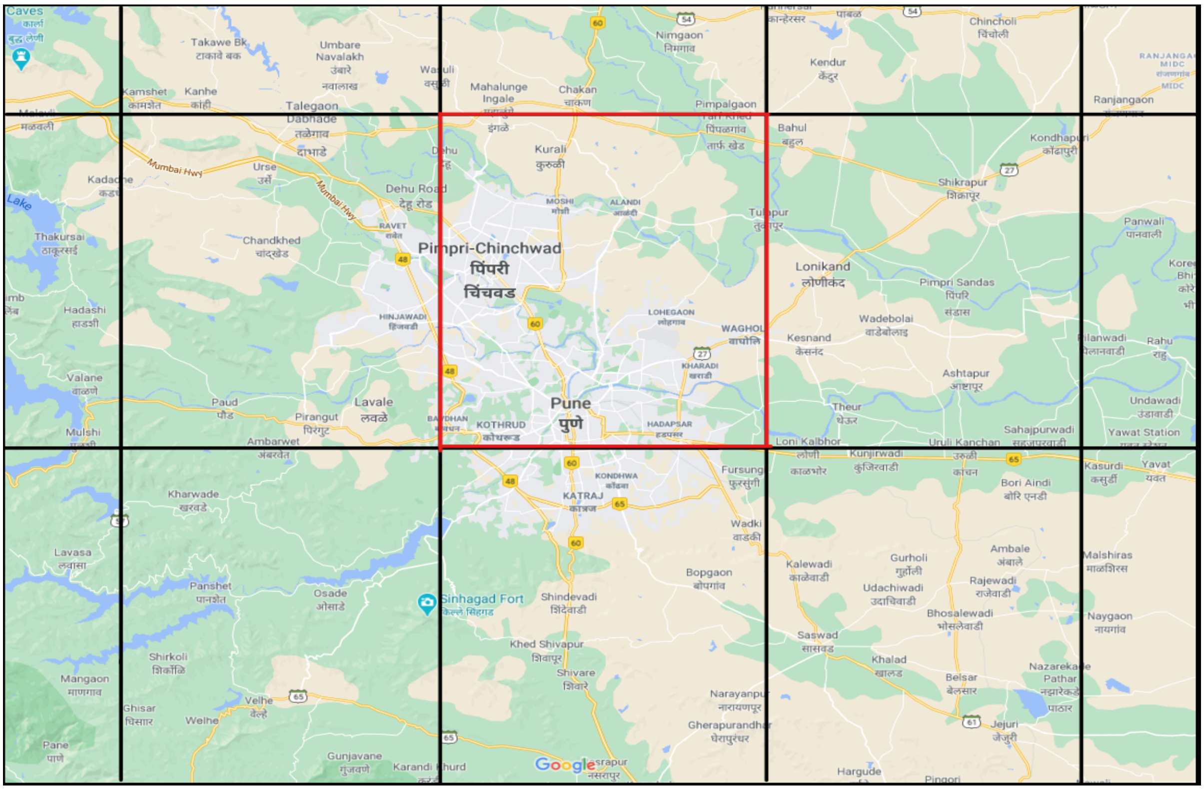

Figure 2.4 Resolution of grid lines

There are multiple rain gauges at different weather stations, which have contributed to building the given data set provided by IMD. In our location of interest (Pune city and surrounding regions), there are a total of 27 weather stations that have been active and recorded rainfall data for different periods. The figure below shows the list of all the weather stations in the Pune district and their functioning time period. The weather stations highlighted in red are the ones that contributed rainfall data to our concerned grid point. These stations are located in Pune city.

Serial Number	District Name	Station Name	Station Type	From	To	Total Years	Missing Years
348	PUNE	ALANDI		1901	1990	75	1965, 1966, 1967, 1968, 1969, 1970, 1971, 1972, 1973, 1974, 1975, 1976, 1977, 1978, 1979,
349	PUNE	ARVI	OBSY	1978	1988	8	1979, 1981, 1982,
350	PUNE	BARAMATI	OBSY	1954	1994	41	
351	PUNE	BARAMATI		1901	2016	113	1976, 1977, 2002,
352	PUNE	BHOR		1901	2016	114	1985, 2002,
353	PUNE	DHOND	HYDRO	1971	1976	6	
354	PUNE	DHOND		1901	2016	114	1965, 2002,
355	PUNE	GHODA AMBEGAON		1901	2016	111	1966, 1982, 1985, 1997, 2002,
356	PUNE	INDAPUR		1901	2016	113	1966, 1987, 2002,
357	PUNE	JEJURI		1902	1991	83	1968, 1969, 1970, 1971, 1972, 1973, 1982,
358	PUNE	JUNNAR		1901	2016	113	1968, 1980, 2002,
359	PUNE	KHANDALA	OBSY	1930	1983	45	1945, 1946, 1947, 1948, 1949, 1950, 1969, 1978, 1980,
360	PUNE	KHED		1901	2016	113	1968, 1991, 2002,
361	PUNE	LONAVALA	OBSY	1971	1996	11	1981, 1982, 1983, 1984, 1985, 1986, 1987, 1988, 1989, 1990, 1991, 1992, 1993, 1994, 1995,
362	PUNE	LONAVALA		1901	1997	85	1959, 1966, 1967, 1969, 1970, 1977, 1981, 1983, 1985, 1986, 1994, 1995,
363	PUNE	PASHAN (PUNE)	OBSY	1999	2009	11	
364	PUNE	PAUD		1901	2016	113	1965, 1967, 2002,
365	PUNE	PUNE	OBSY	1901	2016	116	
366	PUNE	PUNE (NDA.KHADAKWASALA)	OBSY	1977	1980	3	1979,
367	PUNE	PUNE CITY		1998	2016	18	2002,
368	PUNE	PUNE HAVELI		1998	2016	18	2002,
369	PUNE	PUNE(WANORIE)	OBSY	1951	1996	46	
370	PUNE	PURANDHAR		2005	2016	11	2013,
371	PUNE	SASVAD		1901	2013	99	1967, 1979, 1990, 1991, 1992, 2002, 2005, 2006, 2007, 2008, 2009, 2010, 2011, 2012,
372	PUNE	SIRUR		1901	2016	113	1963, 1991, 2002,
373	PUNE	TALEGAON D-DHERA		1901	1997	82	1966, 1969, 1970, 1971, 1972, 1973, 1974, 1975, 1976, 1977, 1978, 1979, 1982, 1983, 1984,
374	PUNE	VADGAON %MAVAL		1901	2016	112	1966, 1967, 1972, 2002,
375	PUNE	VELHE		1955	2016	59	1965, 1981, 2002,

Figure 2.5 List of weather stations in Pune district[5].

The data from IMD was available on a yearly basis. The yearly data file consists of 365/366 records corresponding to non-leap/ leap years. Each data file included one rainfall value for each day of the year for a particular grid point. There are a total of 135 x 129 grid points in each data file. The extensive spatial coverage of the grid points in the data file includes most of the Indian subcontinent. Depending on whether the year is a leap year or not, there are a total of 365/366 x 135 x 129 values in a single annual data file. These daily rainfall values are obtained from the rain gauges located at weather stations in that grid point. The readings are collected from all the rain gauges, and after some quality control, added to the database. We have cropped the data to the required grid points.

Limitations of the data

Urban flooding happens at a fast rate. It would be beneficial to have hourly data for Pune city. The highest resolution of data available in time is 24 hours (Daily rainfall data). Whereas flooding, especially urban flooding, can happen in a matter of minutes. It is possible that some region of Pune got flooded even though the recorded daily rainfall value was not too high. It depends on the intensity or the time scale over which the downpour happens. For example— a slow drizzle over 5 hours might have the same accumulation as a cloudburst over 15 minutes. However, a slow drizzle allows enough time for the water to drain, whereas heavy precipitation over a few minutes can result in clogging and flash floods.
We will not be able to disentangle such a question using a daily dataset. That will remain a limitation of the data and the analysis.

Research tools and analysis

We used Python and some additional python packages (xarray, numpy) as a programming tool for the analysis. The data from IMD was available in a gridded format. We wrote a program on Python using the xarray package to convert the gridded data files(.grd) to a more

[5] https://www.imdpune.gov.in/ndc_new/stations.html

readable and user-friendly format(NetCDF). This format is much more usable and easy to work with on Python. We used the analytic tools in xarray data package to analyse the NetCDF data files. After converting the yearly data files into a usable format, We were left with annual data files for the last 70 years(1950-2019). We combined and stitched together the time series of these data files to make a single file that includes the rainfall data of the past 70 years for the whole of the Indian subcontinent. From there, we used the rainfall data from the relevant grid points.

Chapter 3. Results

With the intention of understanding the role of climatic factors concerning the flooding in Pune, we have attempted to analyse the rainfall pattern in Pune city. How has rainfall changed in the past few decades, and what is its association with Pune floods?
In order to understand the large-scale rainfall patterns in Pune city, we have closely looked into the annual accumulation of rainfall in Pune. We have tried to look at the rainfall patterns over a considerable period of time to see the changes in the total annual rainfall of the city. An increased or decreased total annual rainfall does not contribute to flooding events in any way, but it does help us understand the changes in water accumulation from precipitation over a long-time period. We have plotted the annual accumulation of water in Pune city over the last 70 years. Fig3.1 shows the annual accumulation of rainfall in Pune City.

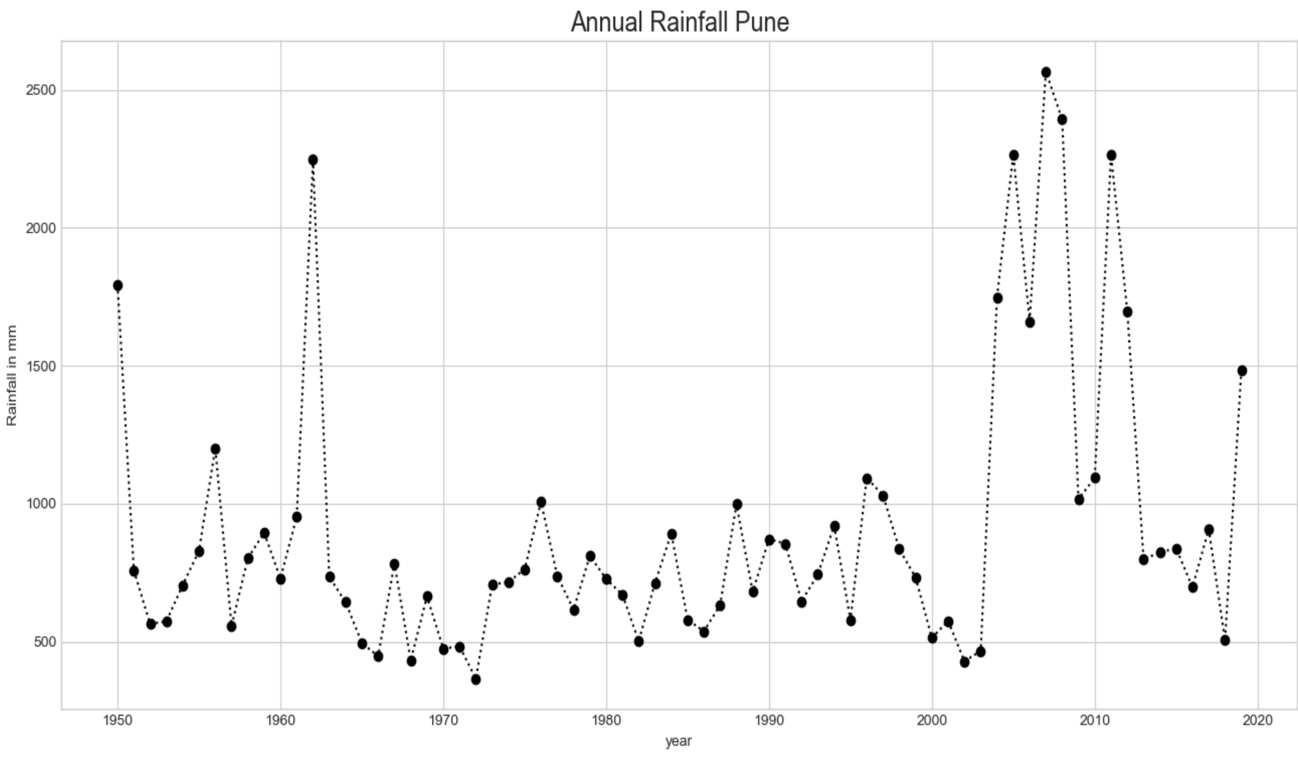

Figure 3.1 Annual accumulation of rainfall Pune city (1950-2019)

The mean total annual rainfall for Pune city from 1950 to 2019 was 906.9mm. As we can see from the graph until 2003, there have been only two spikes in the total annual rainfall. 1950 and 1962 (1800mm and 2250mm) were the only instances when the rainfall was very high compared to the mean. Other than that, there are no substantial changes in the annual accumulation of rainfall until 2003. After 2003, there were some dramatic spikes in total

annual rainfall. The years 2004, 2005, 2006, 2007, 2008, 2011, 2012, and 2019 have experienced heavy annual rainfall(more than 1500mm).
It has been observed that the annual rainfall of Pune City has seen a significant increase in rainfall in the first decade of this century (after 2002) compared to the rainfall trend from 50 years since. We have evaluated the difference in mean annual rainfall of the two-time intervals where this trend is noticeable(1970 to 1999 and 2000 to 2019) to highlight this observation.
The mean annual rainfall for the first time interval (1970 to 1999) is 741mm. The mean annual accumulation for the 2000 to 2019 time period is 1229mm. There is a difference of 488mm of rainfall between the two-time intervals, which clearly shows a significant rise in rainfall in the past two decades.
Even though we see such a substantial rise in annual rainfall, we need to look at the daily rainfall values to see if it is significant enough to contribute to flooding in the region. We have taken the daily rainfall values of every year and calculated the 90 percentile rainfall value, and compared it for the last 70 years. We have taken the months of June, July, August, September and October for our calculations since these are the months that contribute the most to the annual rainfall in this region. We have taken the rainy days from these months and calculated the 90 percentile rainfall for Pune. We have eliminated the days with zero rainfall for this calculation to get a better picture. Figure 3.2 shows us the 90 percentile value of rainfall across the last 70 years in Pune city.

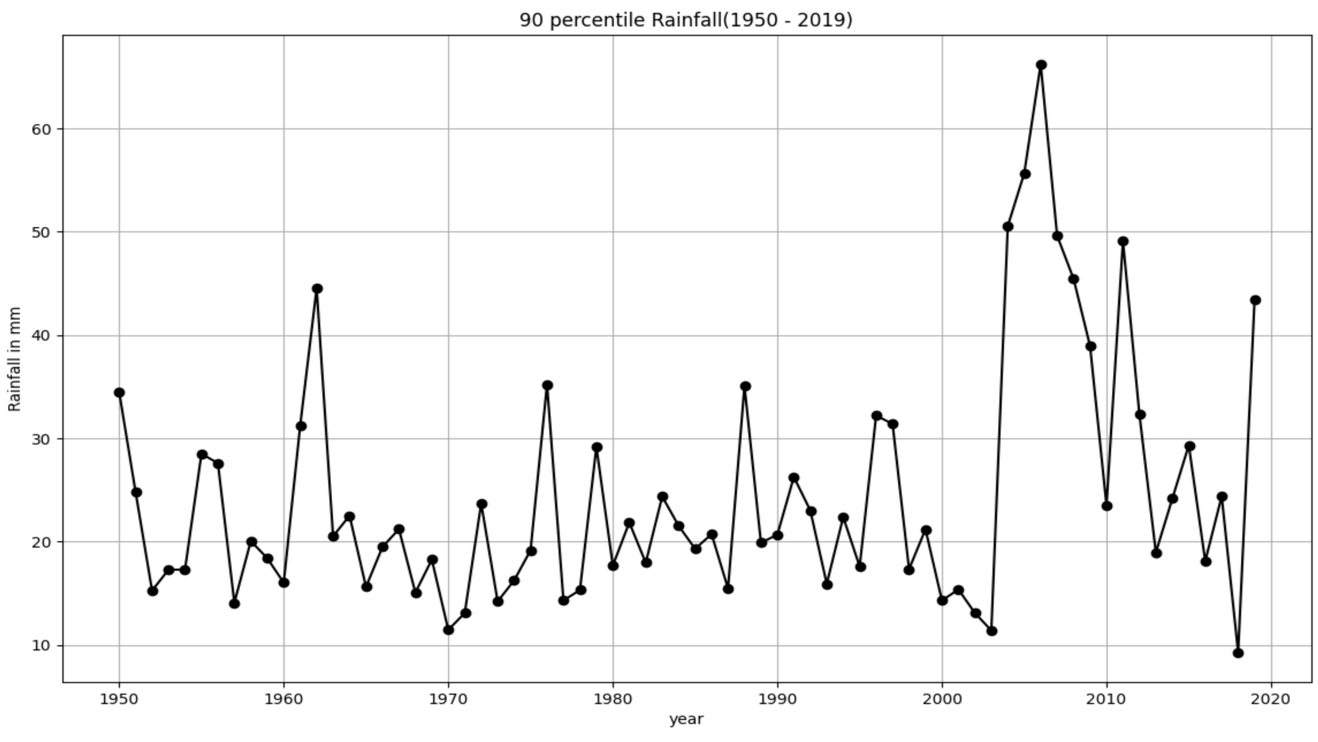

Figure 3.2. Ninety Percentile rainfall.

As we can see, the ninety percentile rainfall value follows a similar trend as the annual accumulation of rainfall values. The 90th percentile of daily rainfall was highest in 2006

(≈68mms). The lowest 90th percentile rainfall was in 2018(≈9mm). After 2003, we saw a very similar spike in rainfall for the whole region which is also seen in the 90 percentile plot. To calculate the intensity of the downpour in Pune, We have attempted to plot the number of days with zero rainfall in the rainy season. I have included the months of June to October for this calculation. A high number of days with no rain in the monsoon season with high overall accumulation is suggestive of high-intensity rainfall. I have plotted the number of no rain days over the past 70 years in the monsoon season to see if there has been a shift from continuous, low-intensity rainfall to rare, high-intensity rainfall. Figure 3.3 shows us the number of days with no rain in the monsoon season from 1950 to 2019.

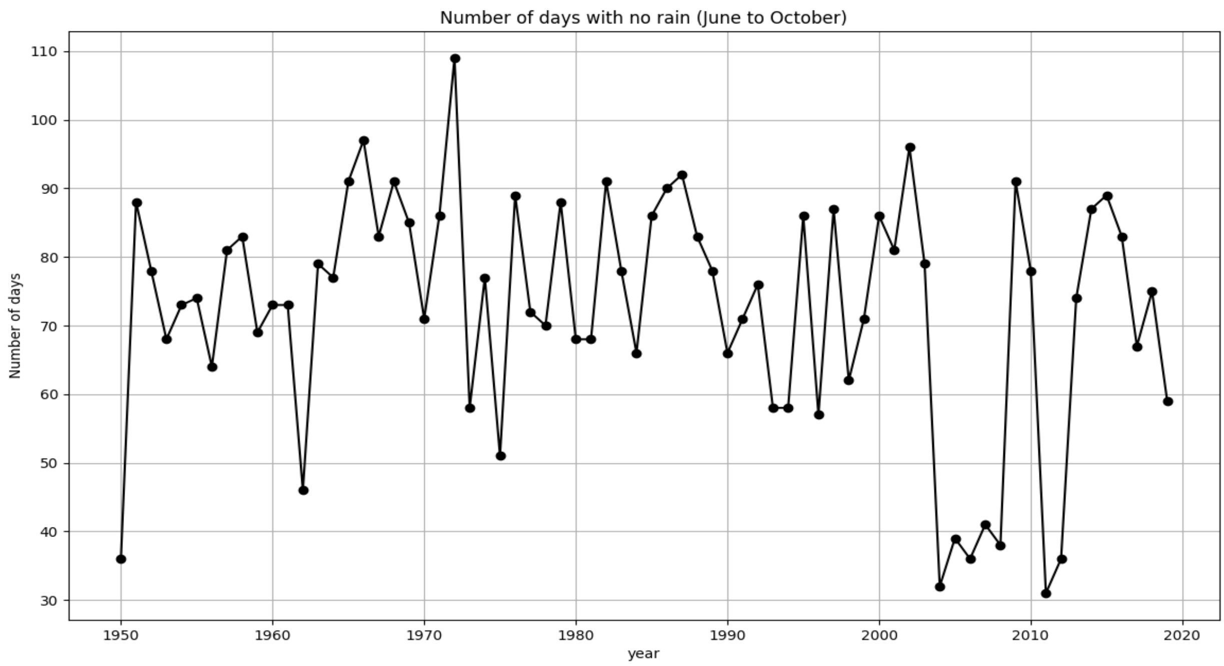

Figure 3.3 Number of days with no rain(June to October)

As we can see from the figure, the number of days with no rain follows a regular pattern until 2003. After that, we had a constant drop. The season with the lowest number of days with no rain was in 2011 (31 days from 122 days). The years 2004 to 2009 also show a very low number of days without rain (30-40 days out of 122 days), supporting the annual accumulation plot.

The annual accumulation and the 90 percentile plots show a dramatic change after 2003. Such a dramatic change can also be caused by changes in the number of weather stations used to prepare the gridded data. I looked into the active rainfall weather stations in Pune. Fig1.4 shows the list of IMD weather stations that collect rainfall data in the Pune district. The ones highlighted in red are the ones that were added recently.

Serial Number	District Name	Station Name	Station Type	From	To	Total Years	Missing Years
348	PUNE	ALANDI		1901	1990	75	1965, 1966, 1967, 1968, 1969, 1970, 1971, 1972, 1973, 1974, 1975, 1976, 1977, 1978, 1979,
349	PUNE	ARVI	OBSY	1978	1988	8	1979, 1981, 1982,
350	PUNE	BARAMATI	OBSY	1954	1994	41	
351	PUNE	BARAMATI		1901	2016	113	1976, 1977, 2002,
352	PUNE	BHOR		1901	2016	114	1985, 2002,
353	PUNE	DHOND	HYDRO	1971	1976	6	
354	PUNE	DHOND		1901	2016	114	1965, 2002,
355	PUNE	GHODA AMBEGAON		1901	2016	111	1966, 1982, 1985, 1997, 2002,
356	PUNE	INDAPUR		1901	2016	113	1966, 1987, 2002,
357	PUNE	JEJURI		1902	1991	83	1968, 1969, 1970, 1971, 1972, 1973, 1982,
358	PUNE	JUNNAR		1901	2016	113	1968, 1980, 2002,
359	PUNE	KHANDALA	OBSY	1930	1983	45	1945, 1946, 1947, 1948, 1949, 1950, 1969, 1978, 1980,
360	PUNE	KHED		1901	2016	113	1968, 1991, 2002,
361	PUNE	LONAVALA	OBSY	1971	1996	11	1981, 1982, 1983, 1984, 1985, 1986, 1987, 1988, 1989, 1990, 1991, 1992, 1993, 1994, 1995,
362	PUNE	LONAVALA		1901	1997	85	1959, 1966, 1967, 1969, 1970, 1977, 1981, 1983, 1985, 1986, 1994, 1995,
363	PUNE	PASHAN (PUNE)	OBSY	1999	2009	11	
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372	PUNE	SIRUR		1901	2016	113	1963, 1991, 2002,
373	PUNE	TALEGAON D-DHERA		1901	1997	82	1966, 1969, 1970, 1971, 1972, 1973, 1974, 1975, 1976, 1977, 1978, 1979, 1982, 1983, 1984,
374	PUNE	VADGAON %MAVAL		1901	2016	112	1966, 1967, 1972, 2002,
375	PUNE	VELHE		1955	2016	59	1965, 1981, 2002,

Fig 3.4 weather stations added after 1995

There were two stations added in 1998 and one in 2005 in the Pune district. The first two weather stations might have contributed to the spikes in rainfall seen in fig 3.1 and fig 3.2. Unfortunately, there is no other way to confirm this postulate unless we look at the data collected by the rain gauges at these individual stations. I have also tried to look at the data from the immediate neighbouring points to see if this trend is a general feature of the region or particular to this grid point. If the rainfall trend is not consistent with the surrounding region, these could be artefacts of the data collected from the newer weather stations. We have made similar plots for a bunch of neighbouring grid points to see if this is limited to one particular grid point or a general feature($\approx$ 30 grid points around the chosen grid). I have shared the plots of the grid points adjacent to the chosen grid. Figure 3.5 shows the 90 percentile rainfall of the grid points adjacent(North, East, South, West) to the Pune grid.

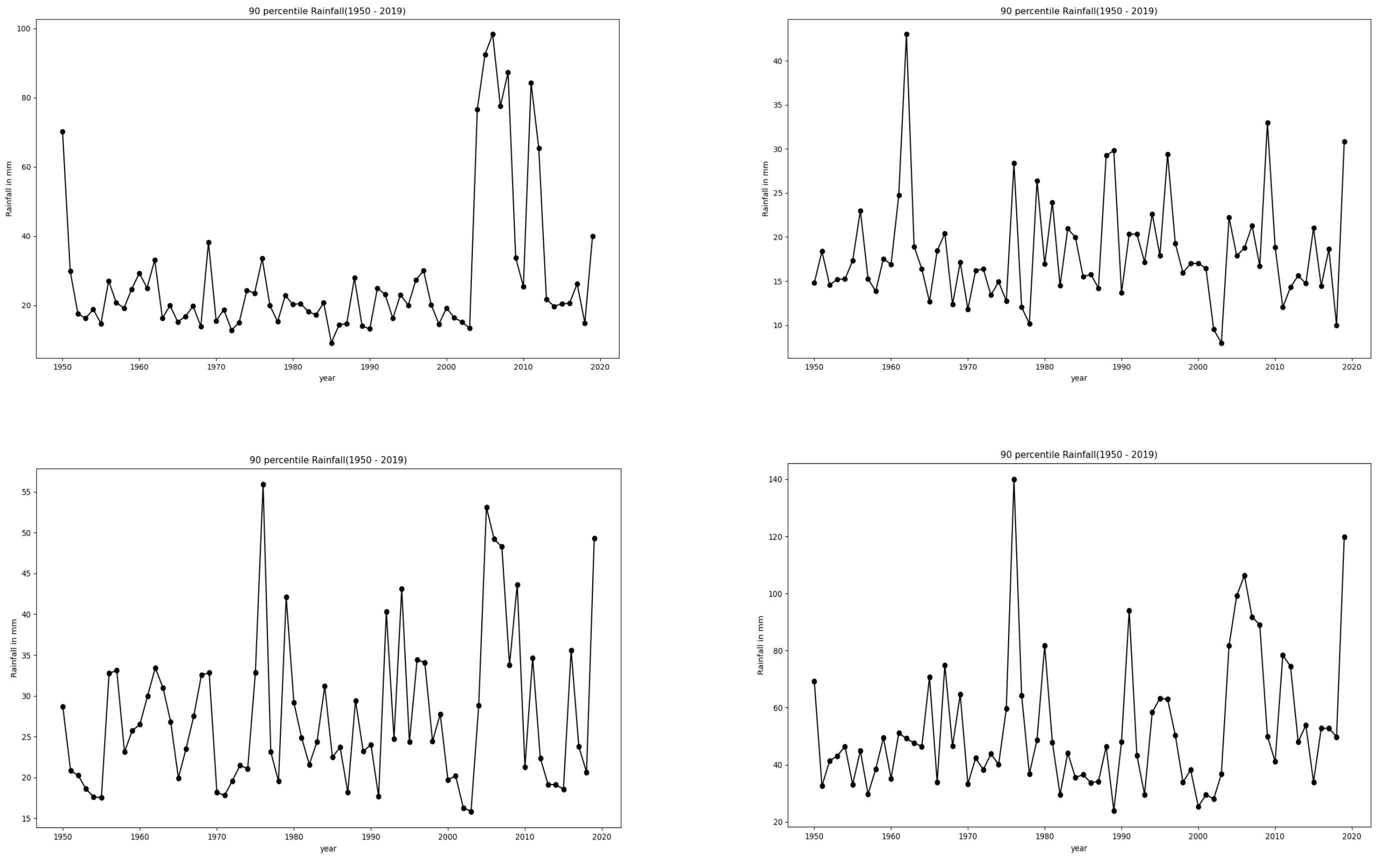


Figure 3.5 Ninety percentile plots of the grid points adjacent to the Pune grid(1950 to 2019). a)North of Pune, b)East of Pune, c)South of Pune, d)West of Pune.

The dimensions of these grid points are ≈25 sq. km. figure3.5a shows the ninety percentile plot for the area(≈25 sq.km.) to the immediate north of Pune and Pimpri Chinchwad(chosen grid point). We see a very similar trend in the grid points to the North and South of Pune, especially after 2003. The grid point to the West of Pune shows a similar pattern, but it diminishes fast as we move to the next grid point(see appendix). Figure 3.6 shows the number of days with no rain in the grids around Pune city. Moreover, we have a very similar pattern of rainfall around Pune. The number of days without rain seems to be similar in the regions having the exact longitude as Pune. The trend seems to change much rapidly as we move away from the city in the east and west directions(fig3.6).

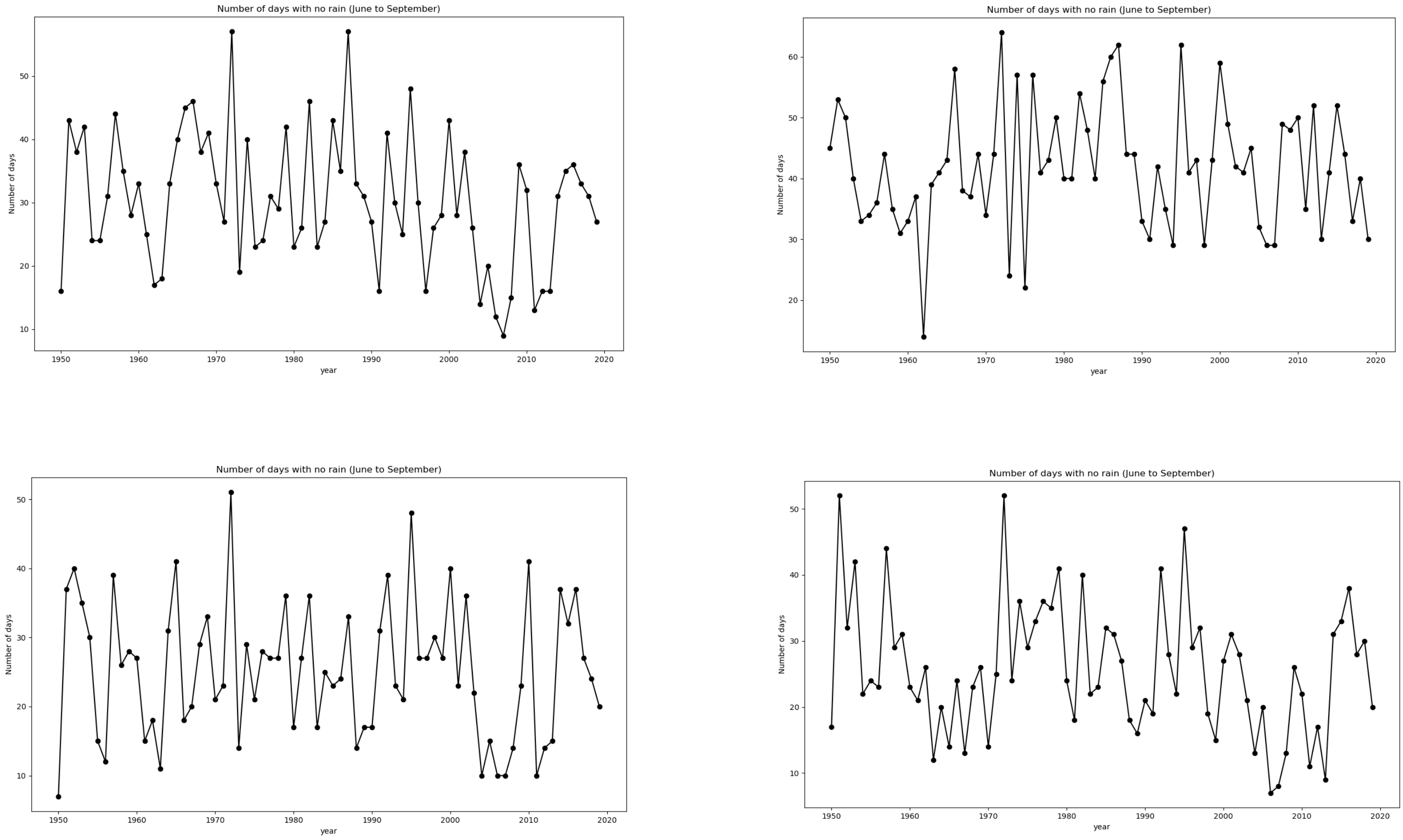


Figure 3.6 Number of days with no rain plots of the grid points adjacent to the Pune grid. a)North of Pune, b)East of Pune, c)South of Pune, d)West of Pune.

We checked if the pattern remains consistent for 30 grid points around the chosen grid point in every direction. It is observed that the grid points to the North and South of Pune maintain a very similar pattern for ≈3-4 grid points and seem to diminish after that(see appendix). Along with the horizontal directions, the rainfall trend seems to diminish much faster. This is to be expected since rainfall also depends on the landform of the region. Geographically Pune is located to the east of Western Ghats, with the Deccan Plateau in the West. The landform around Pune changes rapidly in the horizontal directions, which affects the rainfall patterns. The eastern slopes of western ghats get a lot more rainfall than the leeward side on which Pune is located. Thus, these rainfall trends seem to diminish much faster to the East and West of Pune city. The topography along the north-south direction of the Pune grid point changes slowly, and since the monsoon winds come from the southwest direction, we see a slow change in rainfall trends vertically.

The analysis of the seasonality index across different years shows the gradual impact of climate change on the rainfall of the Pune district from 1900 to 2006(Guhathakurta and Saji, 2013). The total amount of rainfall in Pune city seems to have increased in the monsoon season, and the first five months of the year see a decrease in rainfall. This suggests the expected consequences of climatic variations. The dry months are getting drier, and the wet months are experiencing higher rainfall. In our study, we see a rise in 90 percentile rainfall after 2002; this sort of sub-regional rise in 90/95 percentile rainfall is seen across many regions on a global scale. There has been a statistically significant increase in the number of heavy rainfall events than there have been decreases in regional rainfall worldwide(Kundzewicz et al., 2013).

Pune has seen an increased amount of rainfall in the last 20 years. The rainfall patterns seem to be drastically different when compared to the last five decades of the 20th century. When we closely look at the rainfall patterns in the last two decades(2000-2019). There have been multiple instances of heavy rainfall in Pune city.

The 2019 flood caused 22 deaths and the evacuation of more than 28000 people living in southern regions of the city. The effects and impact of the 2019 floods stand out even though the rainfall pattern does not seem to be very extreme compared to the increments seen in the last 20 years.

When we look at the intensity of rainfall in the instances where the annual accumulation was very high(2004, 2005, 2006, 2007, 2008, 2011, 2012, and 2019), we can see that the number of days with no rain was relatively low for six out of the eight years. For example, Pune recorded a total rainfall of ≈2250mm in the monsoon season of 2005; the number of days with no rainfall in that monsoon season was ≈32/153 days. This suggests that the rainfall was widespread over four months. In the case of 2019 floods, the number of days with no rain was relatively high(≈58 days) and the annual accumulation was high (≈1500mm), suggesting that rainfall intensity was comparatively higher than the rest of the year. The urban floods in 2019 are related to heavy rainfall on the 25th of September 2019. To completely understand the intensity of rainfall for 2019 floods, we would require higher resolution data(hourly/half-hourly).

Chapter 4. Discussion

A flooding event usually refers to the overflow of water, submerging areas that are usually dry. Heavy rainfall over a particular region can lead to surplus water in the water bodies. The most frequent flooding occurs on river banks, coasts, and areas close to water bodies. In many ways, it seems appropriate to attribute the damage caused by floods to the precipitation over the area. However, that is not always the case. The intensity of floods and the damage caused by them depends on multiple factors and varies from region to region. Rainfall is indeed an essential aspect in understanding the environmental causes of urban floods but not the only one. An integrated approach to recognising the causes of urban flooding is required. As we can see from the rainfall analysis of Pune city, There were various instances of heavy rainfall over the last 20 years(more rainfall than 2019), but they did not result in more destructive floods.

The 2019 floods cannot be understood just with the help of rainfall data. The effect of such change in rainfall patterns on floods has to be understood in combination with the larger context of land cover change as well. Moreover, urbanisation and land-use patterns have changed a lot over the past decade, which might have also contributed to the devastating effect of the 2019 floods. Thus, we need a different and more comprehensive approach to understand the destructive effects of the 2019 floods. The vulnerability (Ribot et al. 1995) approach to climate impact analysis is an appropriate way of interpreting the causes of the 2019 floods.

The vulnerability approach tries to map all the causal factors responsible for a particular outcome of the disaster. According to Ribot (2005), "Vulnerability does not fall from the sky". High rainfall over a region is not the only factor responsible for the devastating effects of a flood. The damaging effects of a flood can be retraced to the causal factors responsible for the outcome. It is the existing gaps in the social structure of the region that decide the impact and damage done by the natural disaster. Vulnerability already is embedded in the prevailing social structure of the region.

Vulnerability analysis could be classified into two, the risk-hazard and the social constructivist approaches (Füssel and Klein 2006; also see O'Brien et al. [2007] and Adger [2006]). The risk-hazard model aims to assess the multiple outcomes of a single climatic event(see fig 2.1), while the social constructivist approach outlines the multiple causes of a single outcome (Ribot, 1995). The Impact analysis model(risk-hazard model) tries to anticipate the potential after-effects of a climatic event or strain by assessing the damage caused by circumstances expected in the climatic event. This method sees people as vulnerable to hazards, thus locating the risk in the hazard itself. It does not do justice to the social dimensions of risk(Ribot, 2009). This impact analysis method might be regarded as misleading since it attributes the outcomes as "impacts" of climate variability or change. This way, we end up tracing the outcomes of natural events, which can be related more effectively to a social structure. Figure 2.1 shows the Impact analysis flow chart of a flooding event.

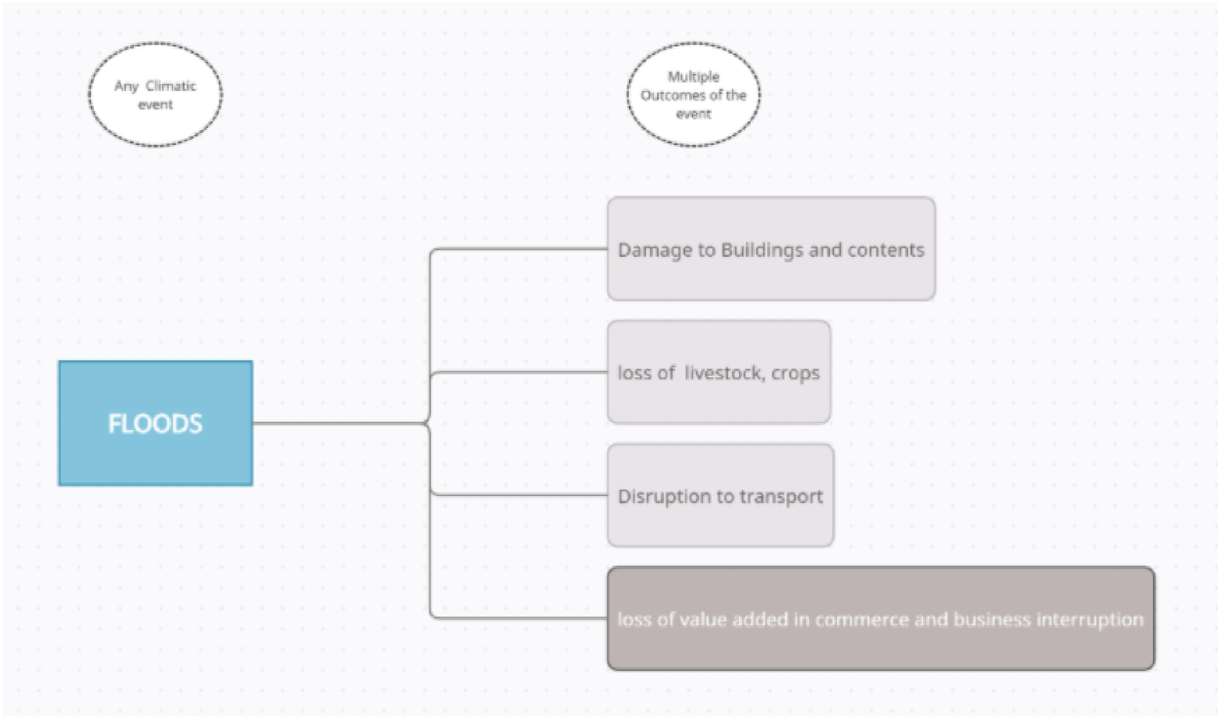


Fig 4.1 Impact analysis flow chart

The social-constructivist approach to vulnerability is different from the impact analysis method.

Unlike Impact analysis, where we start from a single event and then trace its outcomes, we begin with the final outcomes or the instances of vulnerability and branch out from there to the natural, social and economic causes of the vulnerability. By following this approach, we place the climatic events in the same space as social and institutional causes; this does not diminish the importance of environmental causes. Instead, it enhances the environmental effects by clarifying how vital these factors are in a social context(Ribot, 2009). Loss of livelihood and property is the most concerning repercussion of urban floods in Pune city. To understand urban flooding in Pune, we have to understand the causal factors responsible for the property damage and loss of livelihood. We have developed a causal diagram for the 2019 Pune floods using the vulnerability framework. This diagram shows the causal factors responsible for the loss of property and livelihood in the 2019 floods.

The 2019 Pune floods had many diverse consequences. Three days of uninterrupted heavy rainfall from 24th to 27th September led to intense flooding in the urban areas of the Pune district.

The southern part of Pune was the worst affected area of the city. Seventeen people died from the overflowing water and instances of wall collapse over the city. Sixteen thousand people were evacuated to safer locations. Katraj, Kondwa, Kothrud, and Wanori areas of Pune were the worst affected areas; water had completely flooded the basements and ground floor of these areas. We mapped the causal factors that might be responsible for the 2019 flooding.

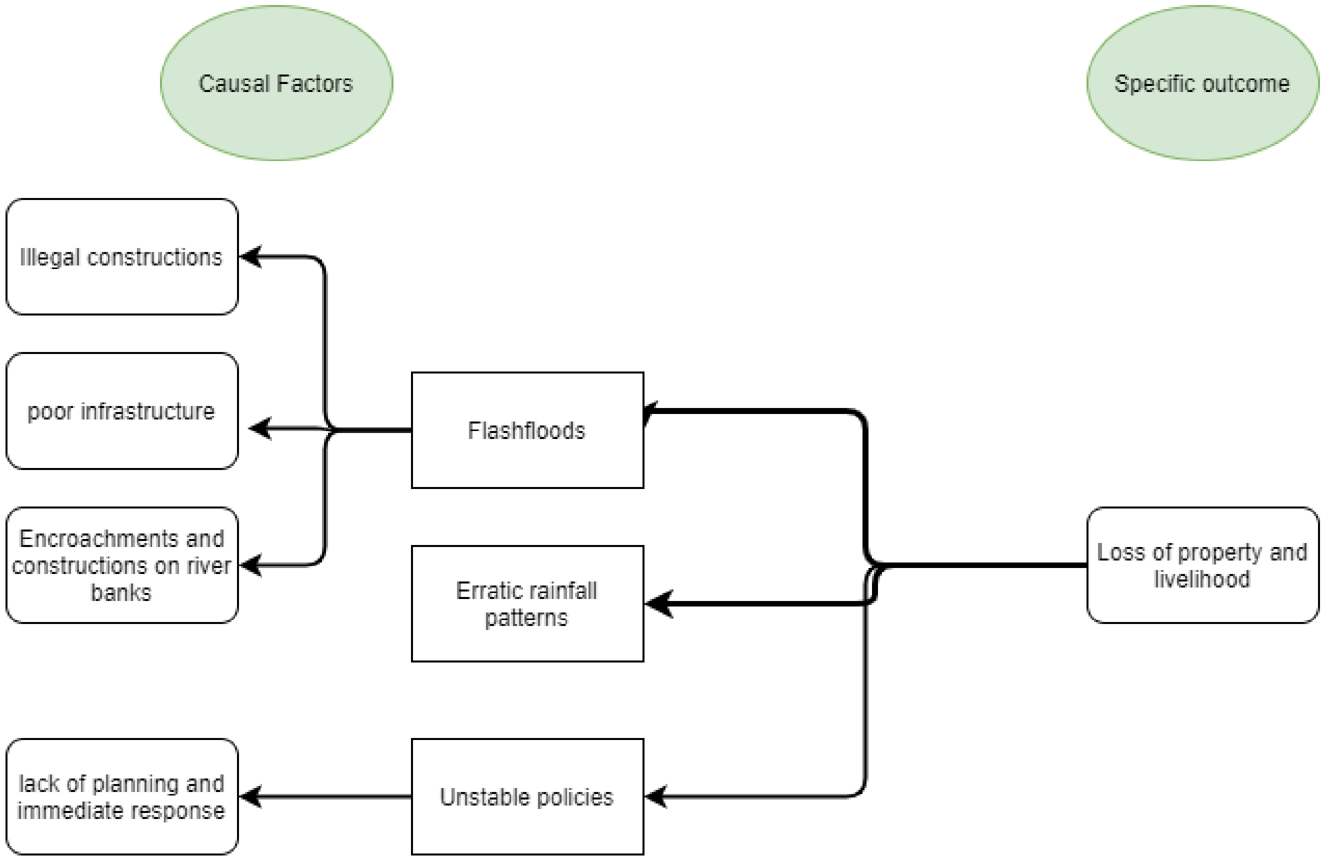


Fig 4.2 Causal factors responsible for loss of livelihood in 2019 floods

The worst affected areas of Pune were along the banks of a stream called Ambil Odha. Ambil Odha is a tributary to the Mutha river in Pune. It originates at Katraj lake and flows into the Mutha river after travelling a distance of ≈15kms through a very densely populated region of Pune city(Gabale et al. 2015).
The population density of the Ambil stream catchment area is about 3700 per km2. The banks of this river are densely populated. A major portion of the area is covered by slums, housing societies, individual bungalows and commercial buildings(Gabale et al. 2015). The area is inhabited by varying economic sections of society. However, most of the inhabitants of this area are people from economically weaker sections. This makes them more vulnerable to the effects of flooding since they do not have a buffer to negate the effects of such flash floods(Ribot, 1999). The residents of the housing societies found shelter on the upper floors of their buildings. Nearly 700 cars and 1300 two-wheelers were submerged entirely in water. The masses living in the slums were affected the most as their houses were completely submerged and destroyed in the floods due to poor infrastructure quality. There were reports of deaths caused due to wall collapses and drowning. People found shelter in the bungalows and houses located at higher altitudes of the area. The government and the flood management authorities were slow to react to the situation. Local people and civil society organisations offered immediate and quick help. After the deluge, most civil society institutions were quick to respond and appeared first on the scene to offer help to the needy after the catastrophe of the 2019 floods. Pri-move, a PMC appointed private body, was given the task to look into the illegal constructions on the banks of Ambil odha. According to their report, they found 77

illegal constructions on the banks of Ambil. PMC took action against these settlements, but it was described as an exaggeration by the citizen activists since most of these constructions still exist. In 2020, heavy rainfall over the one hour in June created a flood-like situation on the banks of Ambil odha again. This situation was just caused by 1 hour of intense rainfall, and it reminded the residents of the distressing memories of the 2019 floods. This area still seems to be very vulnerable to flash floods, and PMC has not yet taken any appropriate action. This physical vulnerability(Cho et al. 2017) seems to be caused by the encroachments and illegal constructions on the banks of Ambil.

Pune is a rapidly expanding city. Urbanisation has caused a rapid change in land use and landform in the Mula and Mutha sub-basins which has led to an increase in streamflow during monsoon and a decrease in stream flows during the drier periods of the year(Wagner et al. 2016). There have been multiple studies(e.g., Costa et al., 2003; Guo et al., 2008; Koch et al., 2012). Kim et al. (2013)) which assesses seasonal streamflow across different periods in accordance with urbanisation. Urbanisation leads to an increase in the run-off of streams and rivers during the monsoon. Pune is covered by multiple networks of streams running from the hills surrounding the city to the rivers Mula and Mutha. Urbanisation and rapid land change have resulted in increased peak flows of these streams. The most affected areas of Pune city in the 2019 floods were also along the banks of these small streams and tributaries to the Mutha river. Ambil is just one example of many such streams. Poor maintenance and blockage of these streams could be one of the major causes of the 2019 floods. Encroachments and illegal constructions over the flood plains of these water bodies resulted in flash floods in the southern parts of the city. Another possible reason that could be contributing to the cause of the 2019 floods is the time at which the rainfall took place. At the onset of the monsoon season, the soils are usually dry and are able to take up a large amount of water until saturation. Thus we do not see much increase in the streamflow during the onset of the monsoon season(Wagner et al. 2016). On the 25th of September, Pune experienced heavy rainfall for 24 hours, which led to the 2019 floods. It was a very high-intensity rainfall, but it was not something that Pune had not seen in the past. This high-intensity rainfall took place very close to the end of the monsoon for this region. The soil was saturated with water which led to torrential amounts of streamflow and water drainage. The poor condition of these streams led to immediate flash floods. Moreover, the northern catchment(comes under Pune district) area of Mula-Mutha had experienced flooding early in September 2019. So the water holding capacity of the catchment had reached close to its peak.
According to a webinar series by Jeevitnadi, there are multiple natural seasonal streams in Pune. These streams run across the hilly areas of Pune and remain empty and dry for eight months of a year. According to citizen activists, these streams are getting destroyed by constructions and garbage disposal during the drier periods of the year. Thus, resulting in clogging and improper drainage of water during the monsoon periods.

Chapter 5. Conclusion and future directions

The overall rainfall over the region seems to have increased; the monsoon season of the last two decades has experienced much higher and intense rainfall compared to the previous 50 years. According to IMD, there was no cloudburst in 2019, but the impact of the 2019 floods seemed similar to a cloudburst as described by Pune citizens. The daily rainfall records of Pune also show that there have been instances of higher daily rainfall before in the same grid point but never resulted in such extreme floods. This directs us to the prospect that rainfall is just one of the causal factors influencing floods in the city. The cause of urban flooding cannot be attributed to just rainfall increase. Fig.4.2 highlights the causal factors behind the 2019 floods, which only consider rainfall as one aspect of urban flooding. This compels us to look into the land use and land cover of the floodplains of the tributaries across Pune and how it changed with time. PMC should maintain a clean and encroachment-free area along the banks of these rivers to support heavy water flow. The Pune city development plan of 1987 needs to be revised. The width of these water bodies needs to be reconsidered, and the flood lines should be redefined to compensate for the increased flow caused in monsoon due to urbanisation. There are reports of illegal constructions over the current flood lines of these water bodies, which makes the situation worse.

Due to the current pandemic situation, our study was limited to the role of rainfall in Pune floods, and we could not follow this up with a deeper field assessment. Pune seems to be vulnerable to floods in social and institutional aspects as well. Interviews with people from PMC and Civil Society organisations will give us more perspective on the 2019 floods. The responses of stakeholders to the 2019 floods from different Institutions could give us critical insights into the social and institutional vulnerability.
PMC officials could give us information about their flood management plans and their response to the 2019 floods. What they could have done better, and what steps have they taken with respect to future flood risk? Members of civil society institutions could give insights to the awareness of the public to flood-prone regions and PMC’s response and action on the 2019 floods. Were they equipped to handle such situations? Such interviews will help us understand how different viewpoints of actors and their interest affected the 2019 flood situation.

It is possible to quantify the social and institutional aspects of vulnerability and derive a flood vulnerability index(Nasiri 2013). This has to be done by collecting data from the households in the worst affected areas of Pune. These areas of vulnerability could be identified by further investigating the land use pattern on the watersheds of the tributaries of Mula-Mutha. This will highlight the physical vulnerability of the area and help us focus on the areas of high flood risk. Combining the social and Institutional aspects of flood vulnerability will help us get a broader picture of the causes, impacts, and possible ways of adapting to floods in the future. A comprehensive understanding of the climatic, social and institutional causal factors will help us develop the most effective solutions to control the damage done by flash floods. This could also help develop flood response protocols and act as a guiding principle for future policymaking.

References

1. Adger, W. & Brooks, Nick & Bentham, Graham & Agnew, Maureen & Eriksen, Siri. (2004). New Indicators of Vulnerability and Adaptive Capacity. from https://www.researchgate.net/publication/257343107_New_Indicators_of_Vulnerability_and_Adaptive_Capacity

2. Banholzer, S., Kossin, J., & Donner, S. (2014). The impact of climate change on natural disasters. In Reducing Disaster: Early Warning Systems for Climate Change (Vol. 97, pp. 21–49). Springer Netherlands. https://doi.org/10.1007/978-94-017-8598-3_2

3. Costa, M. H., Botta, A., & Cardille, J. A. (2003). Effects of large-scale changes in land cover on the discharge of the Tocantins River, Southeastern Amazonia. Journal of Hydrology, 283(1–4), 206–217. https://doi.org/10.1016/S0022-1694(03)00267-1

4. Füssel, H. M., & Klein, R. J. T. (2006). Climate change vulnerability assessments: An evolution of conceptual thinking. In Climatic Change (Vol. 75, Issue 3, pp. 301–329). Springer. https://doi.org/10.1007/s10584-006-0329-3

5. Gabale, S. M., & Pawar, N. R. (2015). Quantitative Morphometric Analysis of AmbilOdha (Rivulet) In Pune, Maharashtra, India. IOSR Journal of Environmental Science, 9(7), 41–48. https://doi.org/10.9790/2402-09714148

6. Guhathakurta, P., & Saji, E. (n.d.). Detecting changes in rainfall pattern and seasonality index vis-` a-vis increasing water scarcity in Maharashtra.

7. Guo, H., Hu, Q., & Jiang, T. (2008). Annual and seasonal streamflow responses to climate and land-cover changes in the Poyang Lake basin, China. Journal of Hydrology, 355(1–4), 106–122. https://doi.org/10.1016/j.jhydrol.2008.03.020

8. Kahn, M. E. (2005). The death toll from natural disasters: The role of income, geography, and institutions. In Review of Economics and Statistics (Vol. 87, Issue 2, pp. 271–284). MIT Press. https://doi.org/10.1162/0034653053970339

9. Kim, J., Choi, J., Choi, C., & Park, S. (2013). Impacts of changes in climate and land use/land cover under IPCC RCP scenarios on streamflow in the Hoeya River Basin, Korea. Science of the Total Environment, 452–453, 181–195. https://doi.org/10.1016/j.scitotenv.2013.02.005

10. Kundzewicz, Z. W., Kanae, S., Seneviratne, S. I., Handmer, J., Nicholls, N., Peduzzi, P., Mechler, R., Bouwer, L. M., Arnell, N., Mach, K., Muir-Wood, R., Brakenridge, G. R., Kron, W., Benito, G., Honda, Y., Takahashi, K., & Sherstyukov, B. (2014). Le risque d'inondation et les perspectives de changement climatique mondial et régional. Hydrological Sciences Journal, 59(1), 1–28. https://doi.org/10.1080/02626667.2013.857411

11. Mearns, Robin; Norton, Andrew. 2010. Social Dimensions of Climate Change : Equity and Vulnerability in a Warming World. New Frontiers of Social Policy. World Bank. https://doi.org/10.1596/978-0-8213-7887-8

12. Modrick, T. M., & Georgakakos, K. P. (2015). The character and causes of flash flood occurrence changes in mountainous small basins of Southern California under projected climatic change. Journal of Hydrology: Regional Studies, 3, 312–336. https://doi.org/10.1016/j.ejrh.2015.02.003

13. Nasiri, H., & Shahmohammadi-Kalalagh, S. (n.d.). Flood vulnerability index as a knowledge base for flood risk assessment in urban area Shahram Shahmohammadi-Kalalagh. Retrieved May 14, 2021, from www.jnasci.org

14. O'BRIEN, K., Eriksen, S., Nygaard, L. P., & Schjolden, A. (2007). Why different interpretations of vulnerability matter in climate change discourses. Climate Policy, 7(1), 73–88. https://doi.org/10.1080/14693062.2007.9685639

15. Pai D.S., Latha Sridhar, Rajeevan M., Sreejith O.P., Satbhai N.S. and Mukhopadhyay B., 2014: Development of a new high spatial resolution (0.25° X 0.25°)Long period (1901-2010) daily gridded rainfall data set over India and its comparison with existing data sets over the region; MAUSAM, 65, 1(January 2014), pp1-18.

16. Ribot, J. C. (1995). The causal structure of vulnerability: Its application to climate impact analysis. GeoJournal, 35(2), 119–122. https://doi.org/10.1007/BF00814058

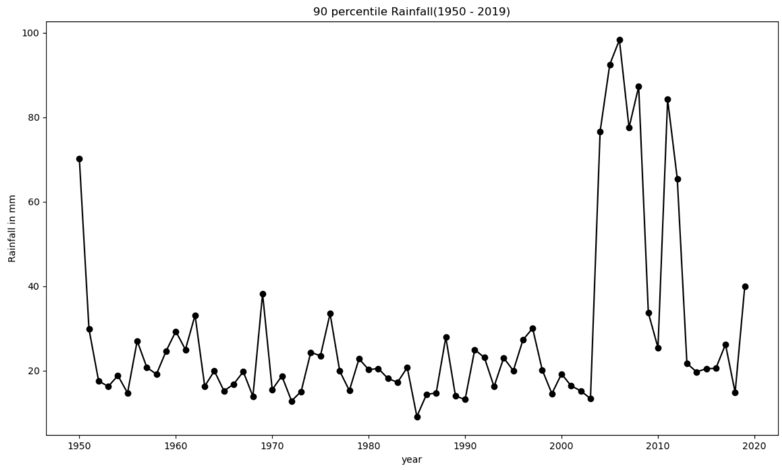
17. Wagner, P. D., Bhallamudi, S. M., Narasimhan, B., Kantakumar, L. N., Sudheer, K. P., Kumar, S., Schneider, K., & Fiener, P. (2016). Dynamic integration of land use changes in a hydrologic assessment of a rapidly developing Indian catchment. Science of the Total Environment, 539, 153–164. https://doi.org/10.1016/j.scitotenv.2015.08.148

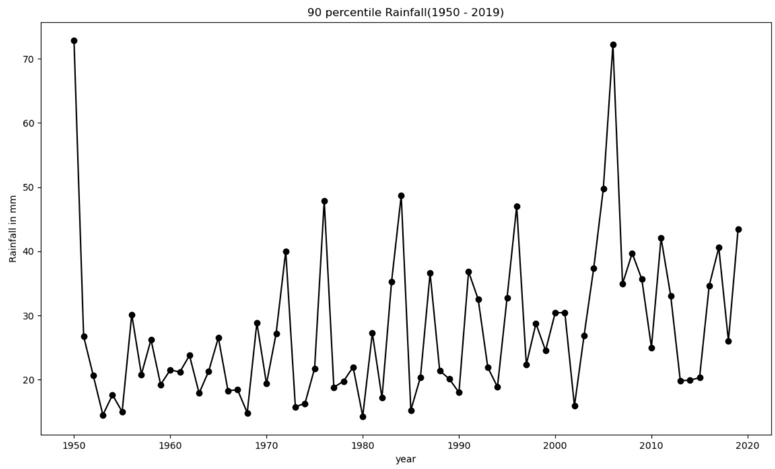
18. Yun Cho, S., & Chang, H. (2006). Recent research approaches to urban flood vulnerability, 2006–2016. Natural Hazards, 88. https://doi.org/10.1007/s11069-017-2869-4

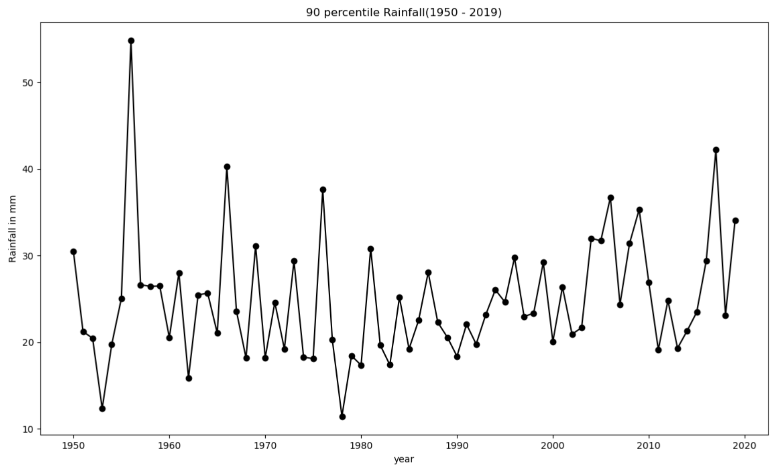
19. Zhou, Q., Leng, G., Su, J., & Ren, Y. (2019). Comparison of urbanization and climate change impacts on urban flood volumes: Importance of urban planning and drainage adaptation. Science of the Total Environment, 658, 24–33. https://doi.org/10.1016/j.scitotenv.2018.12.184

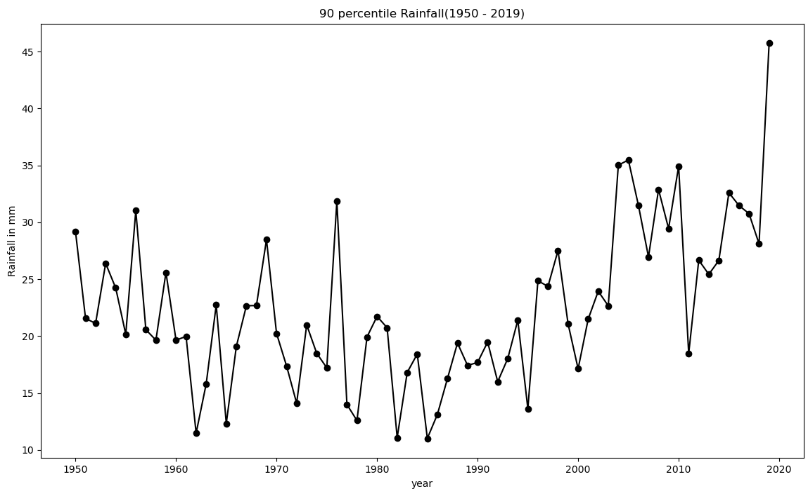
Appendix

Ninety percentile Plots of grid points North of Pune starting from the first grid point.








90 percentile Rainfall(1950 - 2019)
Rainfall in mm
year
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1950
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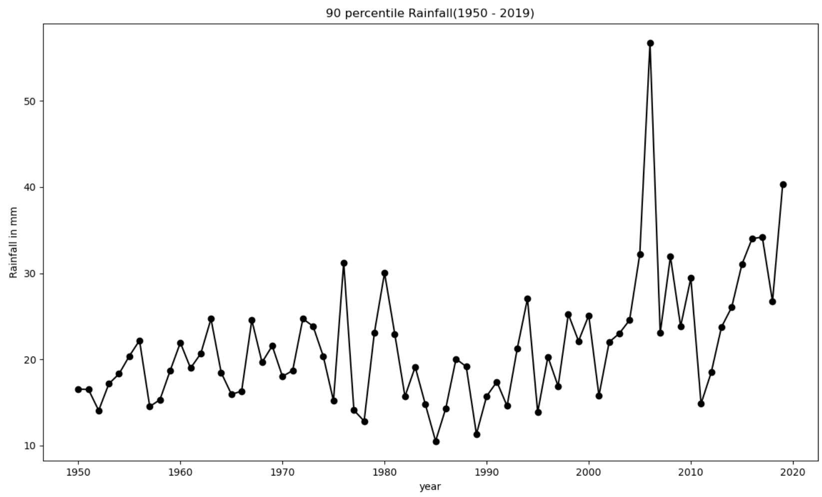
90 percentile Rainfall(1950 - 2019)
Rainfall in mm
year
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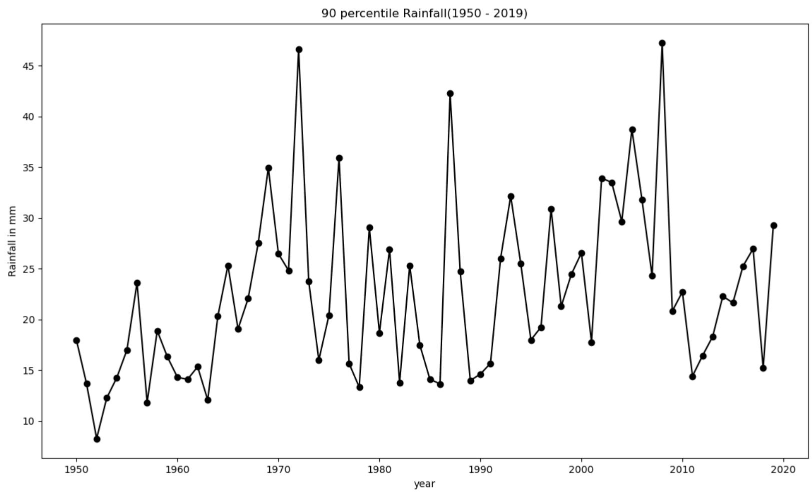
90 percentile Rainfall(1950 - 2019)
Rainfall in mm
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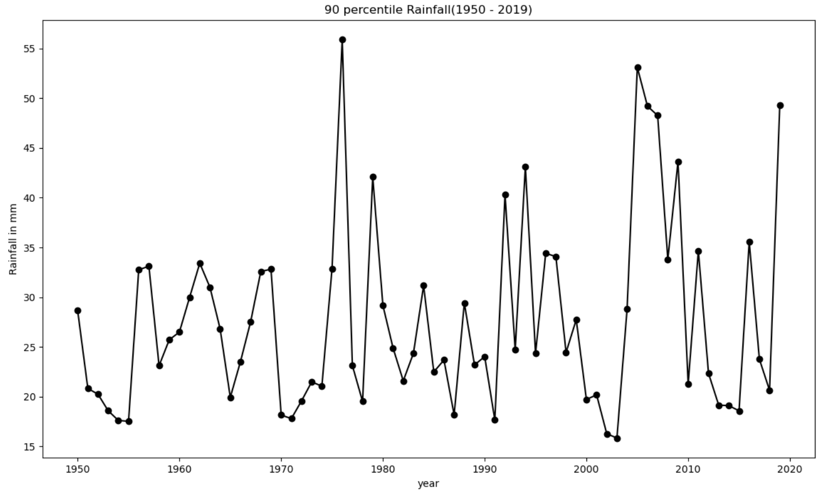
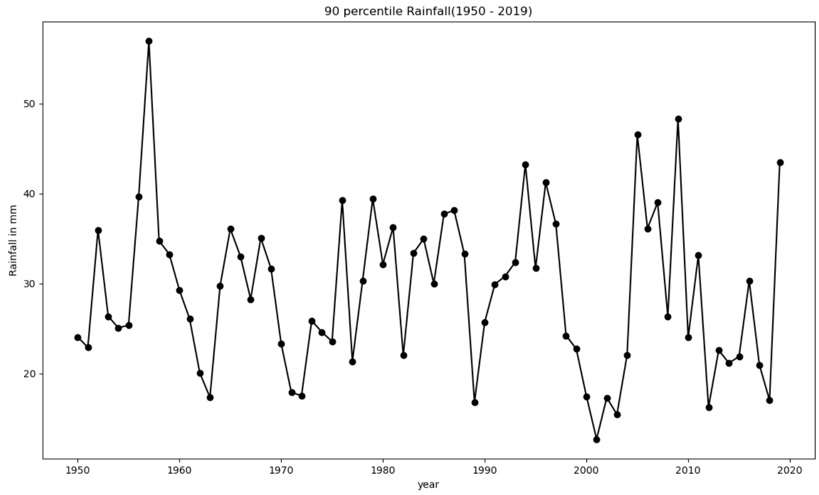
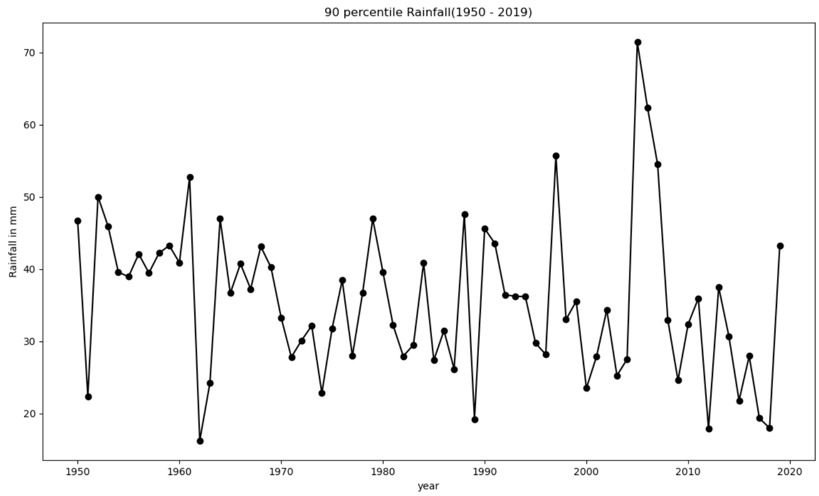
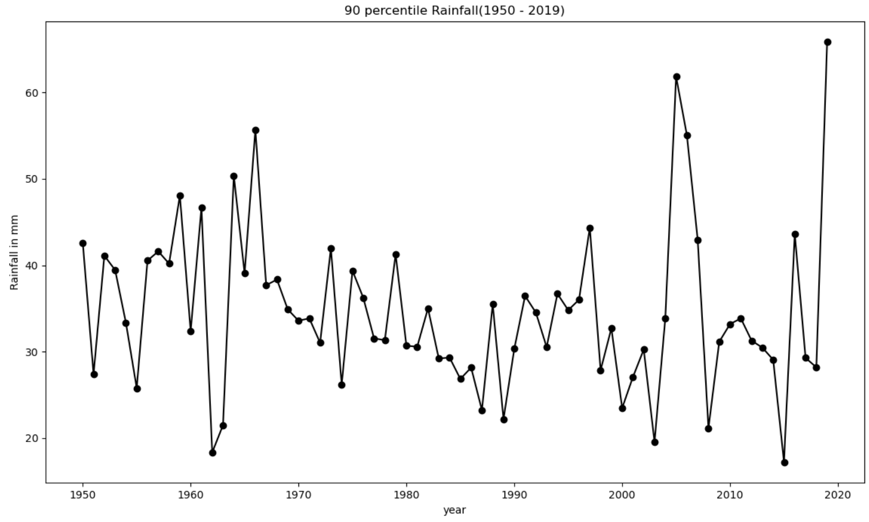
Ninety percentile plots of grid points South of Pune after Pune grid








90 percentile Rainfall(1950 - 2019)
Rainfall in mm
year
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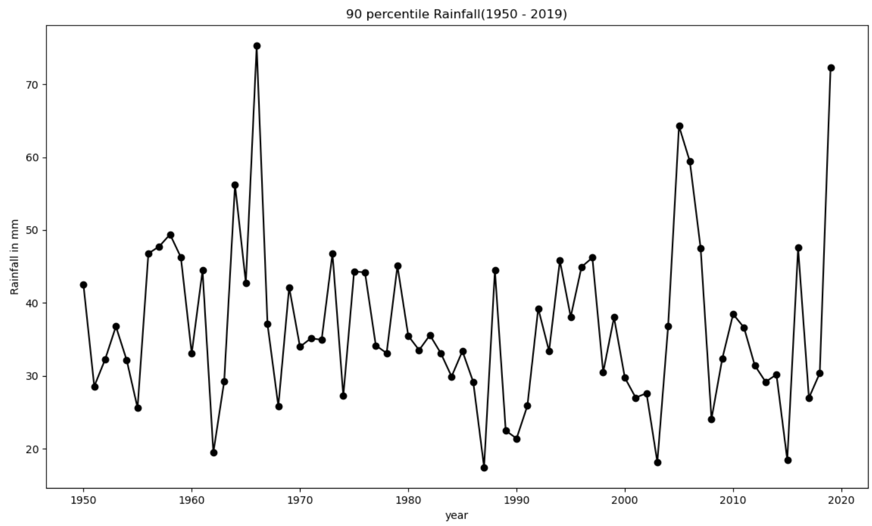
90 percentile Rainfall(1950 - 2019)
Rainfall in mm
year
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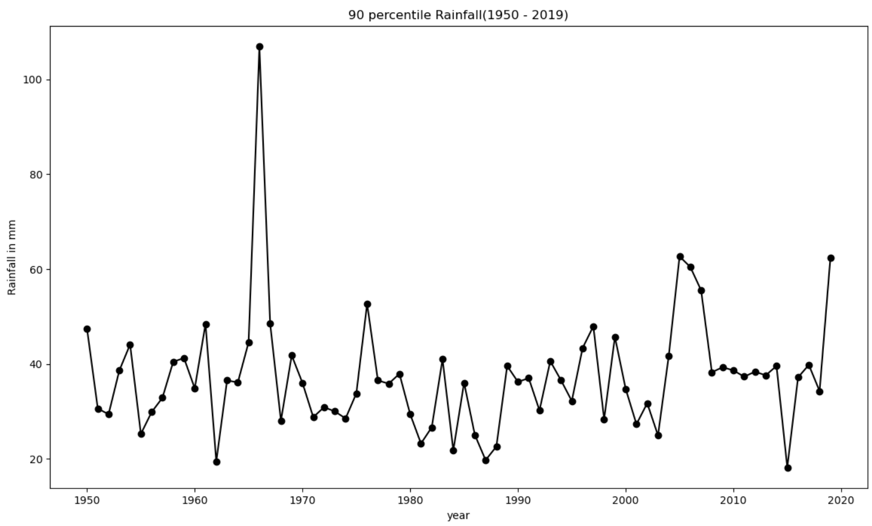
90 percentile Rainfall(1950 - 2019)
Rainfall in mm
year
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1950
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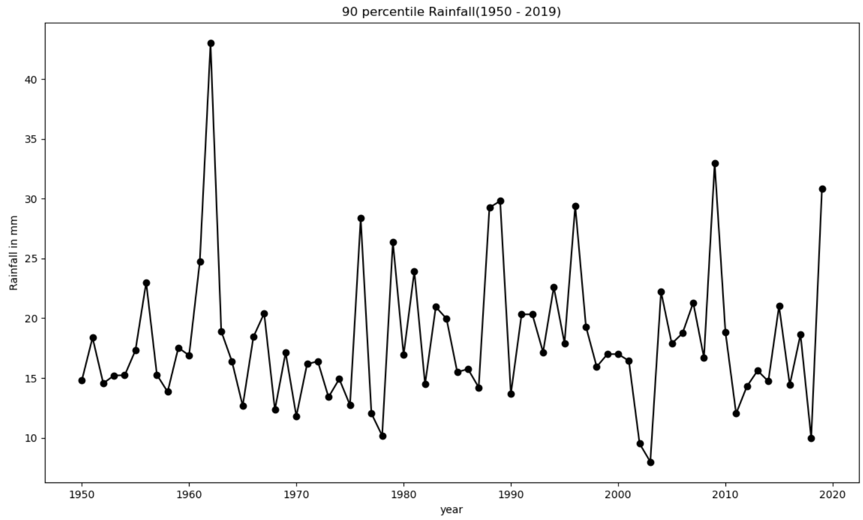
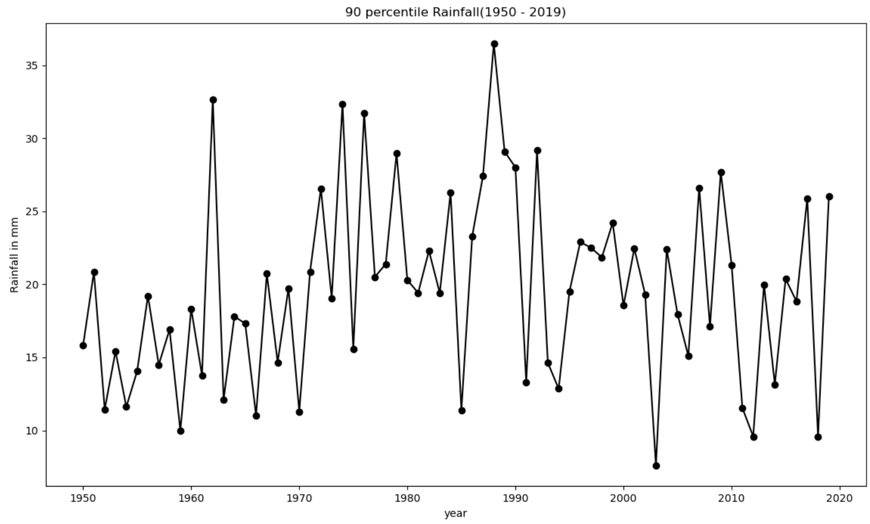
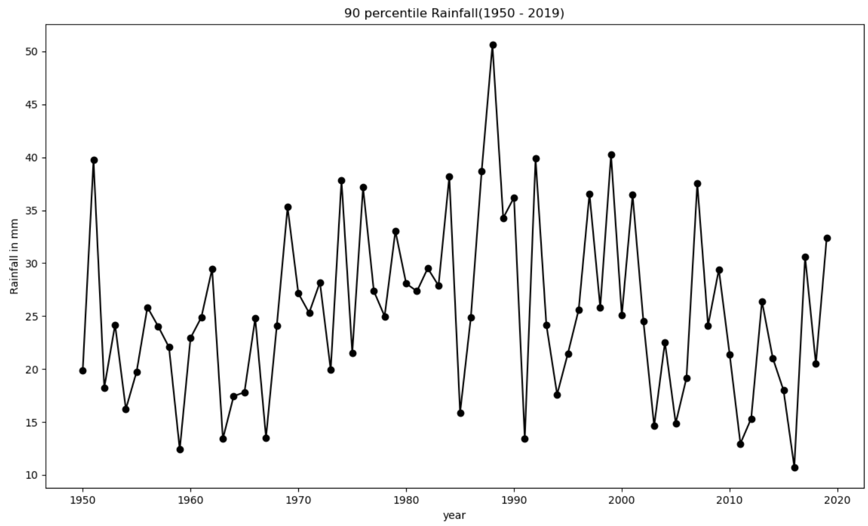
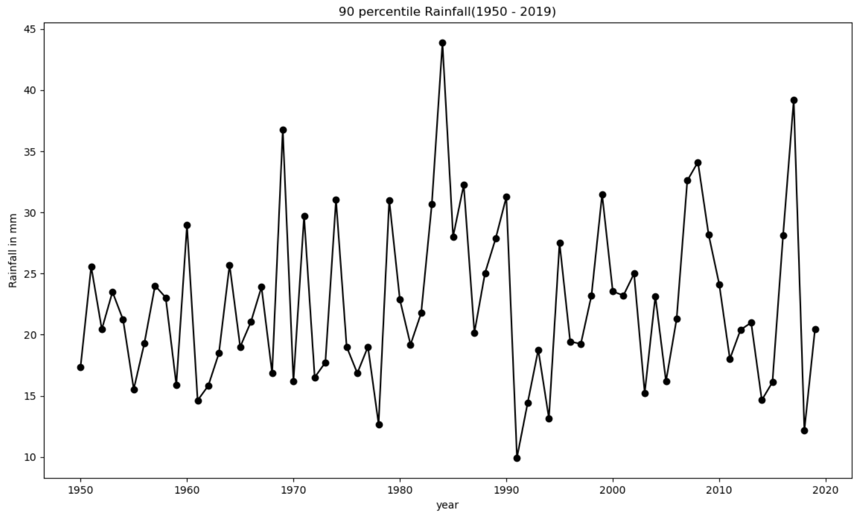
1970
1980
1990
2000
2010
2020

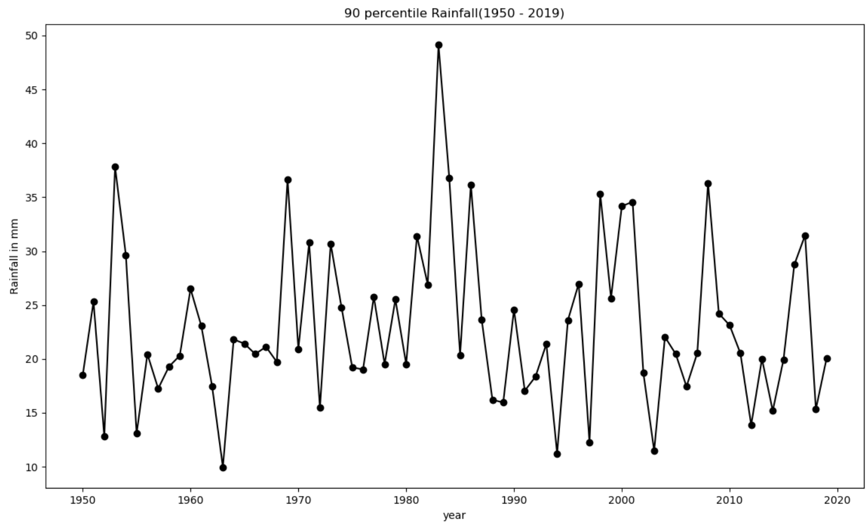
Ninety percentile plots of grid points East of Pune

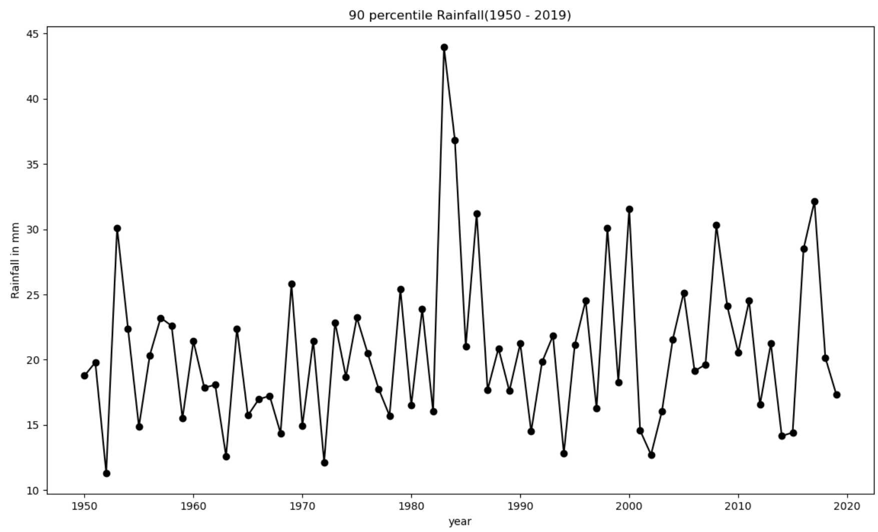




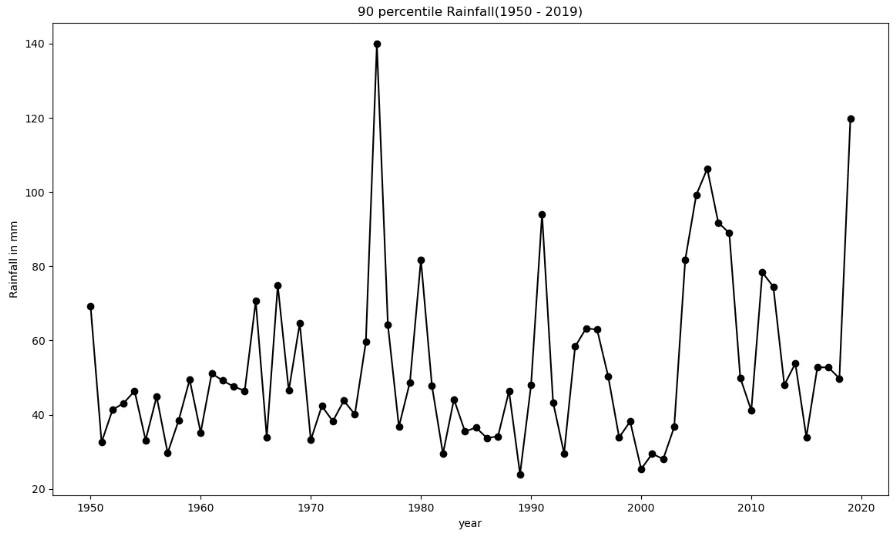


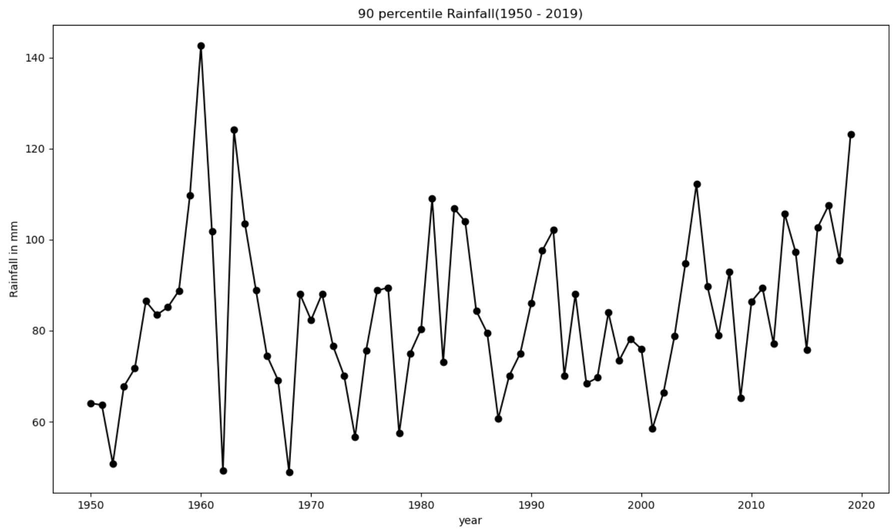

90 percentile Rainfall(1950 - 2019)
Rainfall in mm
year

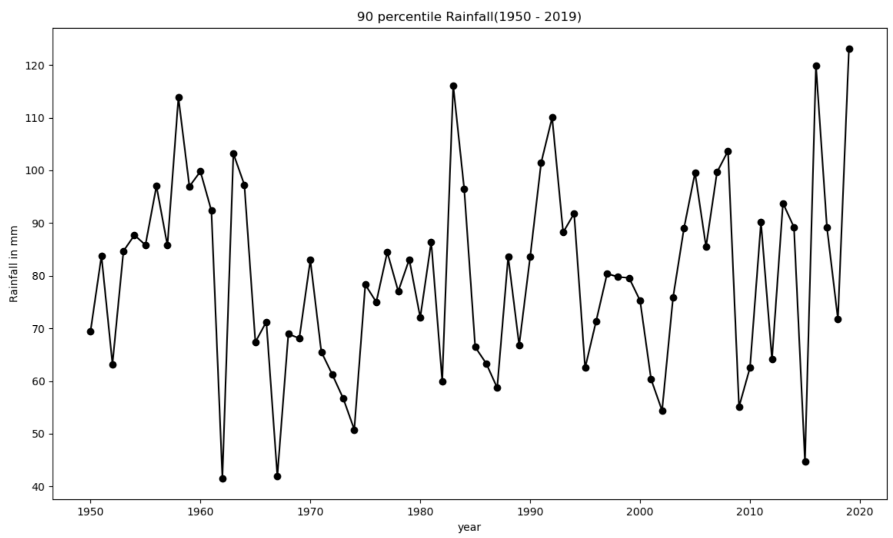

90 percentile Rainfall(1950 - 2019)
Rainfall in mm
year

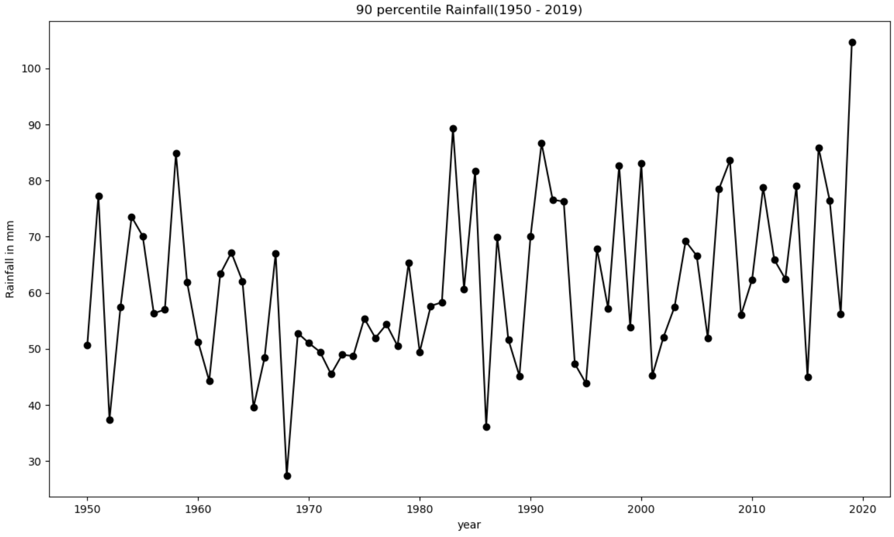

90 percentile Rainfall(1950 - 2019)
Rainfall in mm
year

Niney percentile plots for grid points West of Pune

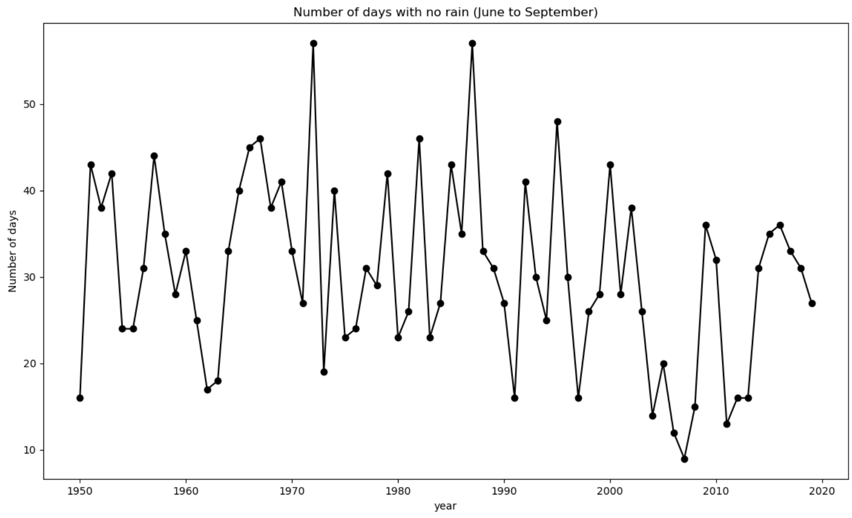


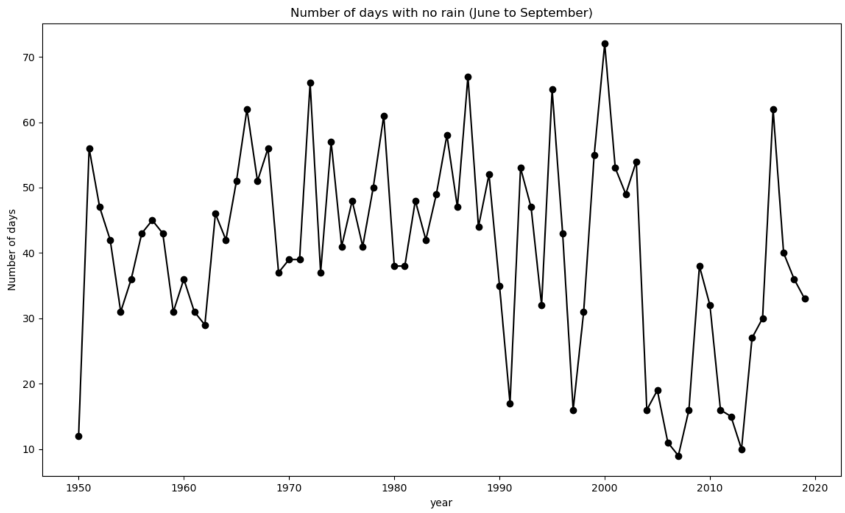


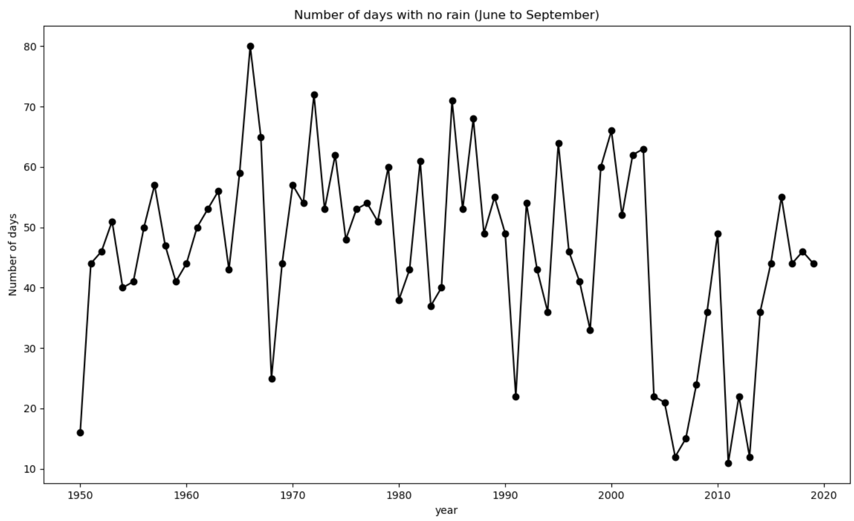


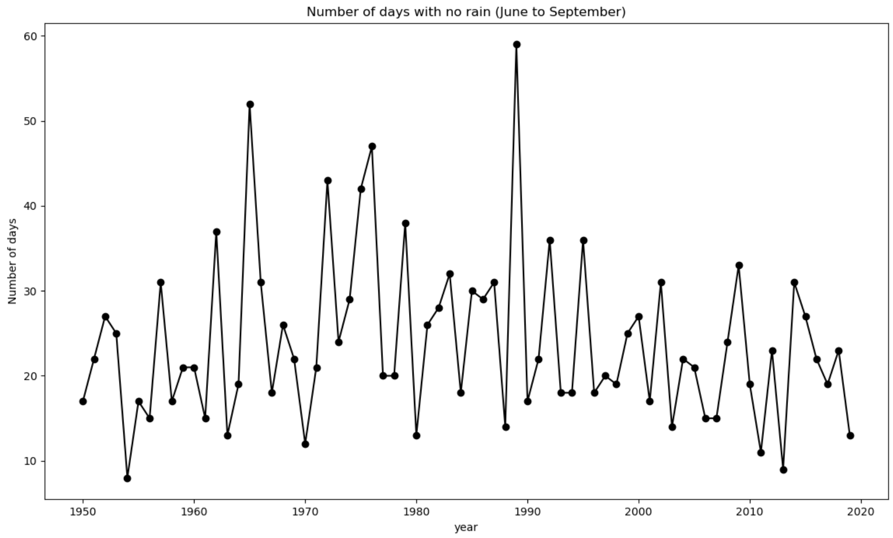

90 percentile Rainfall(1950 - 2019)
Rainfall in mm
year
100
90
80
70
60
50
40
30
1950
1960
1970
1980
1990
2000
2010
2020

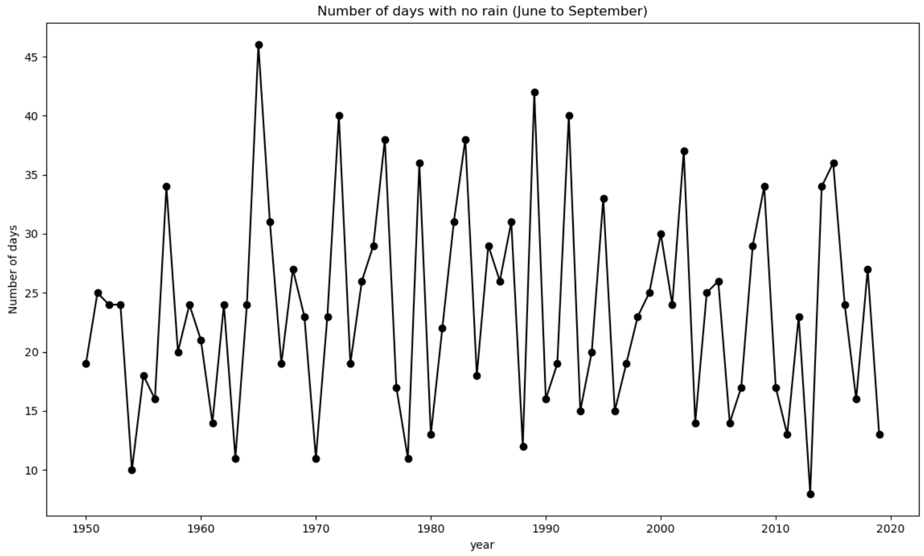
Number of days with no rain for grid points North of Pune

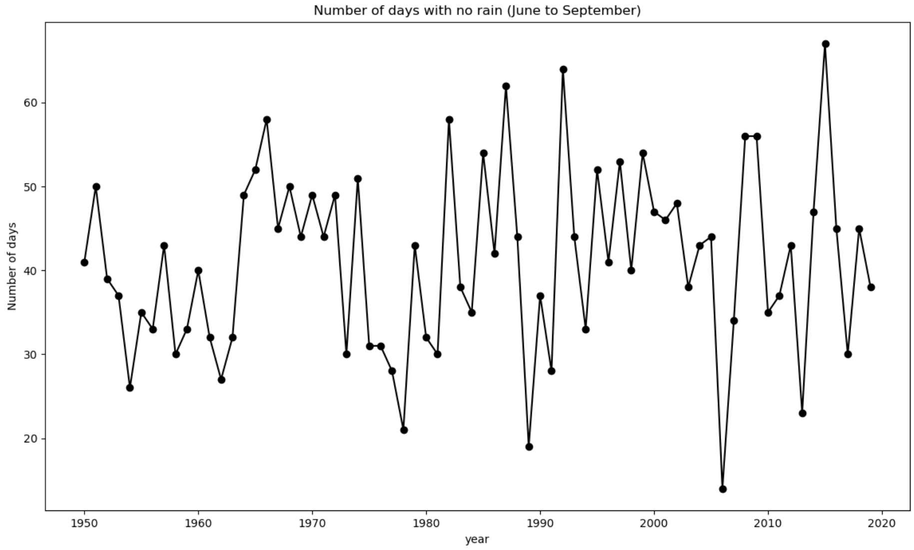




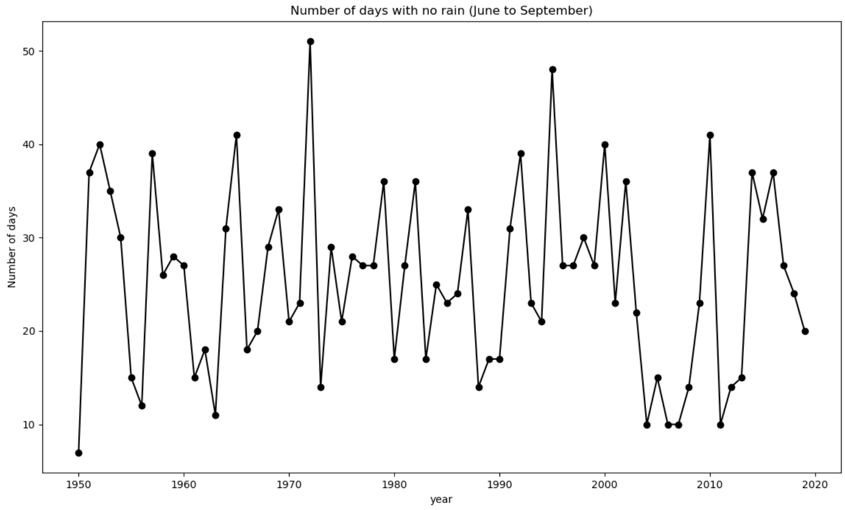


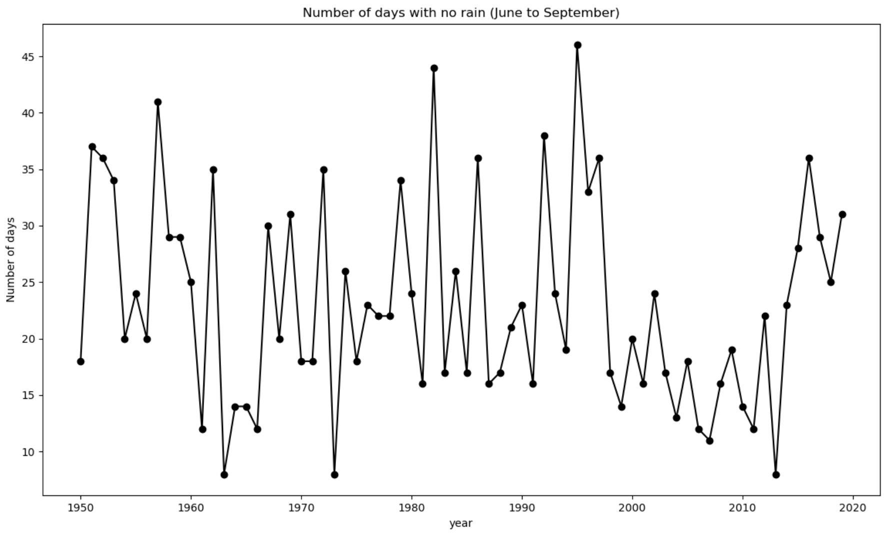

Number of days with no rain (June to September)
Number of days
year
60
50
40
30
20
10
1950
1960
1970
1980
1990
2000
2010
2020

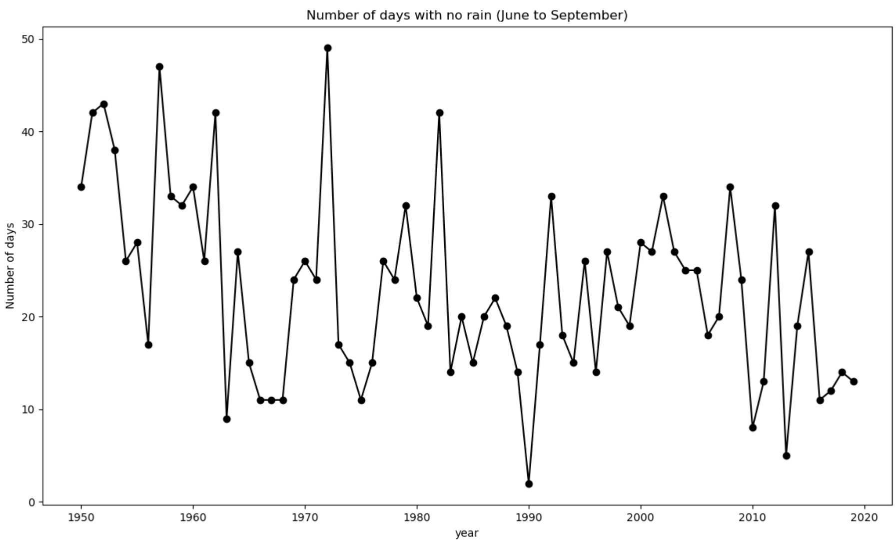

Number of days with no rain (June to September)
Number of days
year
45
40
35
30
25
20
15
10
1950
1960
1970
1980
1990
2000
2010
2020

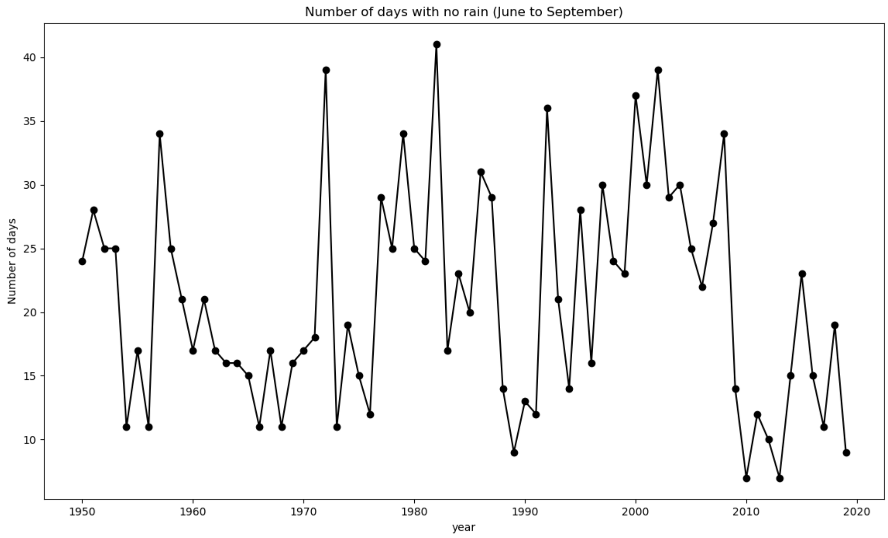

Number of days with no rain (June to September)
Number of days
year
60
50
40
30
20
1950
1960
1970
1980
1990
2000
2010
2020

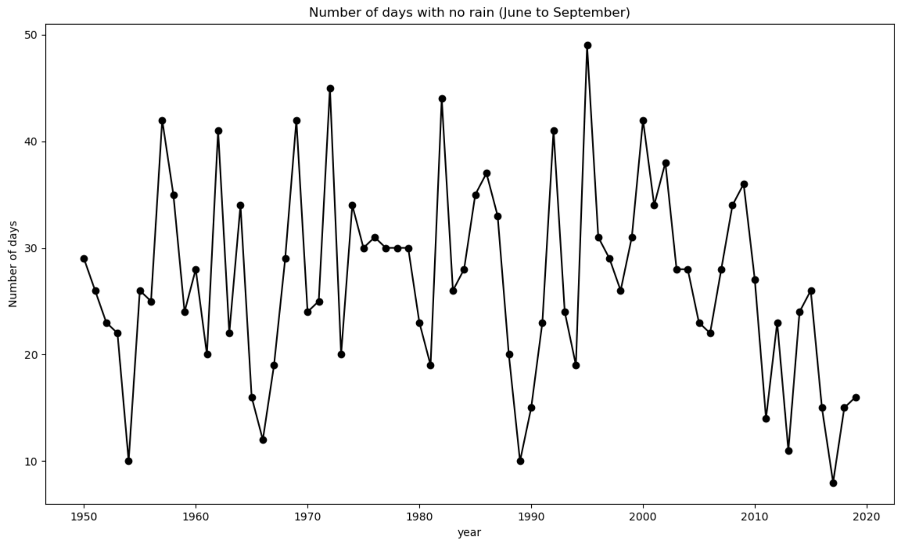
Number of days with no rain for grid points South of Pune

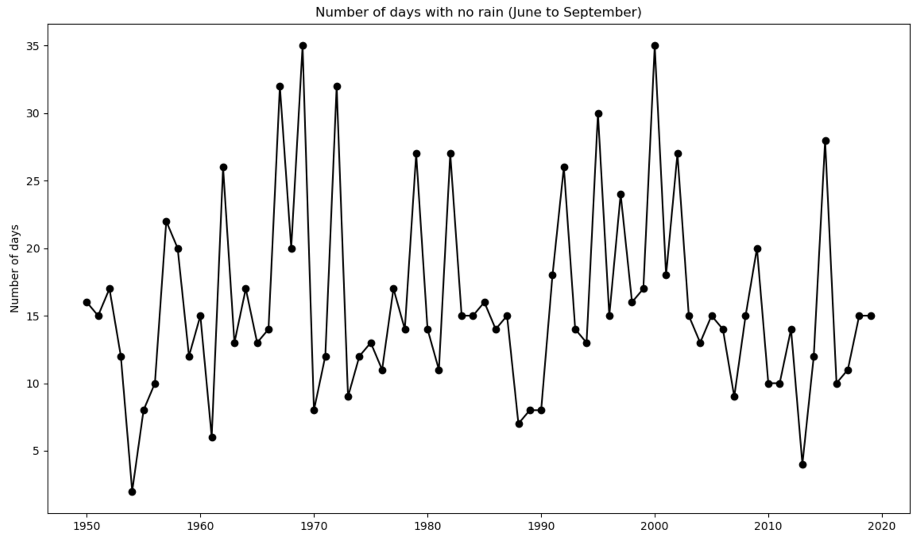




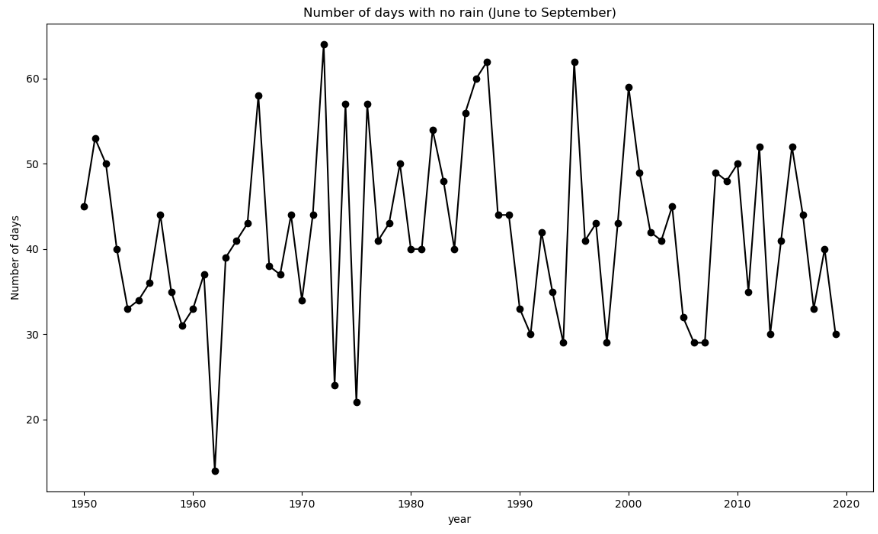


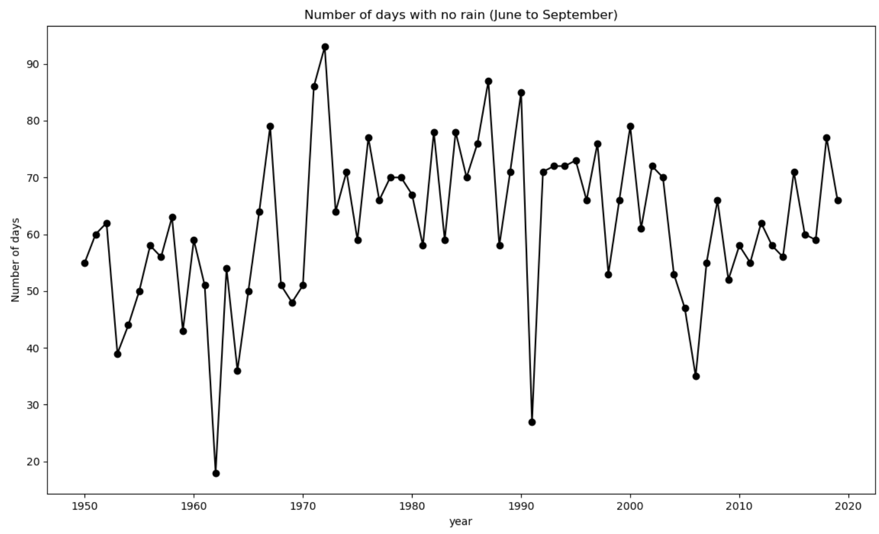

Number of days with no rain (June to September)
Number of days
year
10
15
20
25
30
35
40
1950
1960
1970
1980
1990
2000
2010
2020

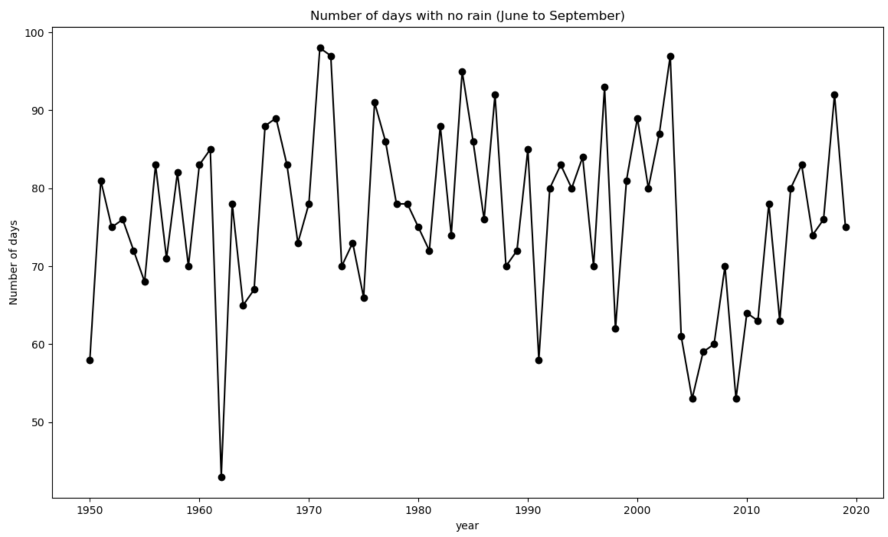

Number of days with no rain (June to September)
Number of days
year
10
20
30
40
50
1950
1960
1970
1980
1990
2000
2010
2020

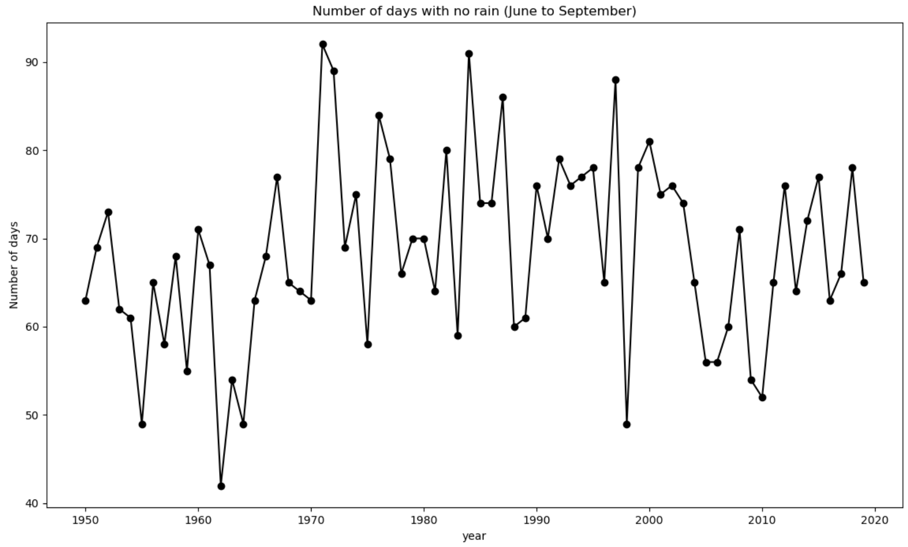

Number of days with no rain (June to September)
Number of days
year
5
10
15
20
25
30
35
1950
1960
1970
1980
1990
2000
2010
2020

Number of days with no rain for grid points East of Pune

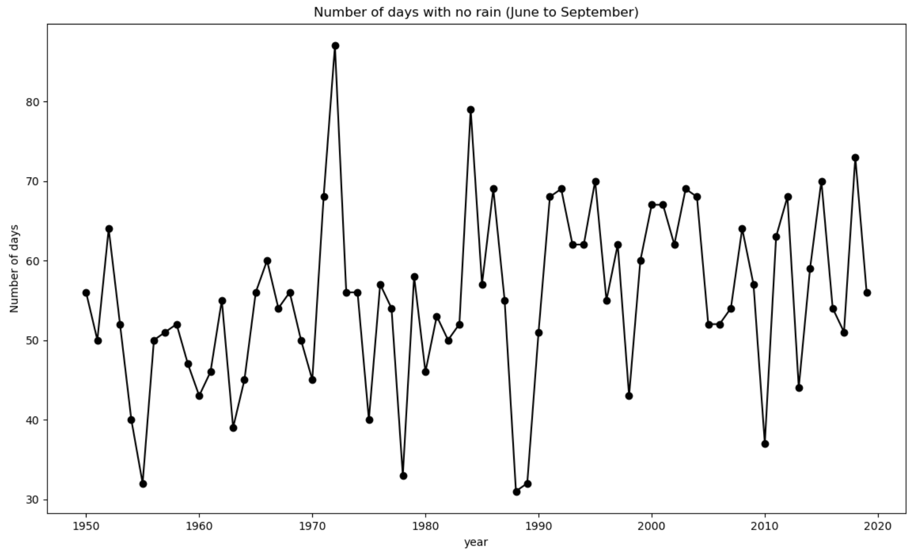




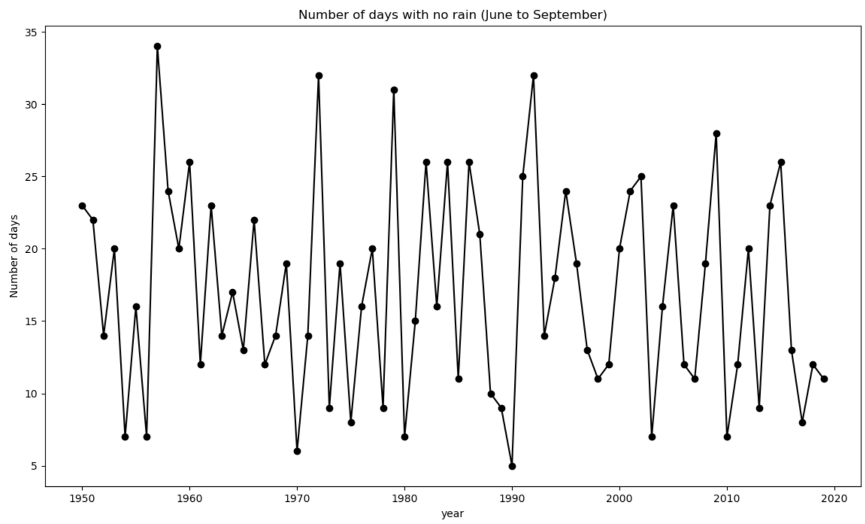


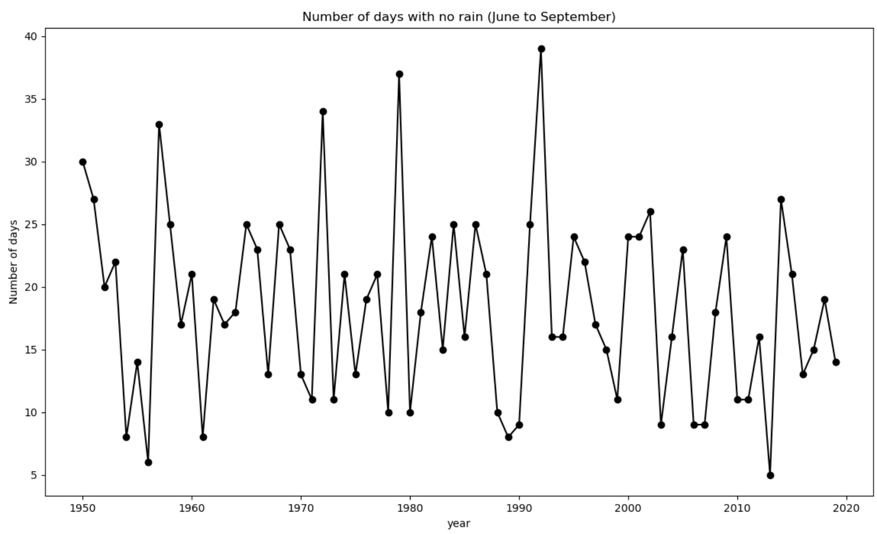

Number of days with no rain (June to September)
Number of days
year
40
50
60
70
80
90
1950
1960
1970
1980
1990
2000
2010
2020

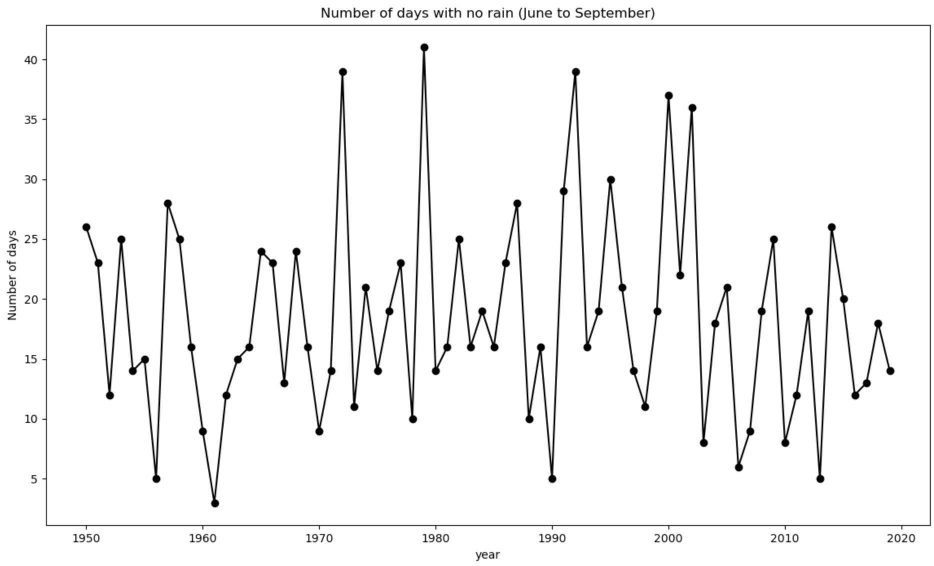

Number of days with no rain (June to September)
Number of days
year
40
50
60
70
80
90
1950
1960
1970
1980
1990
2000
2010
2020


Number of days with no rain (June to September)
Number of days
year
30
40
50
60
70
80
1950
1960
1970
1980
1990
2000
2010
2020

Number of days with no rain for grid points West of Pune







Sources used for the description of 2019 floods in Chapter 4 (Discussion).

1. Overflowing Ambil Odha in one-hour rainfall brings back tragic memories of 2019 flash floods in Pune | Hindustan Times

2. What fuelled this year's flood fury in Pune? (downtoearth.org.in)

3. Pune floods: 77 illegal constructions identified along Ambil odha; PMC serves notices | Hindustan Times

4. Despite court order... 'White elephant' sits locked and bolted on Pune's Ambil Odha floodline for 17 years | Hindustan Times

5. https://www.punekarnews.in/pune-make-ambil-odha-encroachment-free-local-corporators-demand-to-municipal-commissioner/

6. https://economictimes.indiatimes.com/news/politics-and-nation/flooding-in-pune-after-heavy-rain-7-killed-500-rescued/articleshow/71306297.cms?from=mdr

7. https://www.hindustantimes.com/pune-news/overflowing-ambil-odha-in-one-hour-rainfall-brings-back-tragic-memories-of-2019-flash-flood-in-pune/story-tluXHBxWuOtzvPlrwWEcUJ.html

8. https://weather.com/en-IN/india/monsoon/news/2019-09-27-21-killed-heavy-rains-pound-maharashtra

9. https://www.indiatoday.in/india/story/pune-rain-flash-floods-cause-damage-casualty-all-you-need-to-know-1604054-2019-09-28