# Drought Risk Assessment using Remote Sensing and GIS: A case study of Gujarat

Parul Chopra January, 2006

# Drought Risk Assessment using Remote Sensing and GIS: A case study of Gujarat

By

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INTERNATIONAL INSTITUTE FOR GEO-INFORMATION SCIENCE AND EARTH OBSERVATION ENSCHEDE, THE NETHERLANDS I certify that although I may have conferred with others in preparing for this assignment, and drawn upon a range of sources cited in this work, the content of this thesis report is my original work. Signed.....

#### Disclaimer

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# Dedicated to my loving Parents..... Prakash and Neelam Chopra

Sister Charu And Brother Kapil

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# Abstract

Drought is the most complex but least understood of all natural hazards. It is broadly defined as "severe water shortage". Low rainfall and fall in agricultural production has mainly caused droughts. A droughts impact constitutes losses of life, human suffering and damage to economy and environment. Droughts have been a recurring feature of the Indian climate therefore study of Historical droughts may help in the delineation of major areas facing drought risk and thereby management plans can be formulated by the government authorities to cope with the disastrous effects of this hazard.

In recent years, Geographic Information Science (GIS) and Remote Sensing (RS) have played a key role in studying different types of hazards either natural or man-made. This study stresses upon the use of RS and GIS in the field of Drought risk Evaluation. In the present work an effort has been made to derive drought risk areas facing agricultural as well as meteorological drought by use of temporal images from NOAA-AVHRR (8km) based Normalized Difference Vegetation Index (NDVI) (1981-2000) and meteorological based Standardized Precipitation Index (SPI).

Correlation and regression analysis was performed between NDVI, SPI, Rainfall anomaly and Food grain anomaly. SPI values were interpolated to get the spatial pattern of meteorological based drought. Food grain yield trend was plotted and an equivalent NDVI threshold was identified to get the agricultural drought risk. Similarly rainfall anomaly and NDVI were correlated and a threshold defined by IMD for meteorological drought was used to derive meteorological drought risk.

The NDVI and rainfall was found to be highly correlated (r=0.6) in water limiting areas. Apart from this, the highest NDVI-rainfall correlation associated with one-month time lag shows rainfall event induced vegetation growth in subsequent periods. The NDVI-rainfall correlation was found to be highly influenced by mean rainfall condition and vegetation types. Highest NDVI-rainfall correlation was obtained for vegetation types in rainfed crops, followed by irrigated crops and subsequently by forest with minimum correlation. It is therefore concluded that temporal variations of NDVI are closely linked with precipitation.

Results of correlation and regression analysis between SPI and crop yield showed that SPI could be used as an indicator of regional crop production. Since each of the factors; NDVI, SPI and detrended food grain yield anomaly had positive linear correlation with each other it was observed that the above factors can be effectively used for monitoring and assessing the food grain production and thereby, appropriate agricultural practices can be adopted to minimize drought effects.

Resultant risk map obtained by integrating agriculture and meteorological drought risk map indicates the areas facing a combined hazard. It also represents the frequency of years a particular area faced the hazard.

It was evident from the study that central and northeastern parts of Gujarat are more prone to drought either agricultural or meteorological. The research shows motivating results that can be used in taking corrective measures timely to minimize the reduction in agricultural production in drought prone areas. The results obtained provide objective information on prevalence, severity level and persistence of drought conditions, which will be helpful to the resource managers in optimally allocating scarce resources.

Keywords: Drought, NDVI, SPI, Food grain yield and Correlation, Risk assessment

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# Abbreviations

NBSS & LUP	National Bureau of Soil Survey and Land Use Planning
NDVI	Normalized Difference Vegetation Index
SPI	Standardized Precipitation Index
TCI	Temperature Condition Index
VCI	Vegetation Condition Index
CMI	Crop Moisture Index
NOAA	National Oceanic and Atmospheric Agency
AVHRR	Advanced Very High Resolution Radiometer
GIS	Geographic Information System
NIR	Near infrared
LOM	Law of minimum
LOT	Law of Tolerance
CC	Carrying Capacity
IMD	Indian Meteorological department
NASA	National Aeronautical Space Application
BISAG	Bhaskaracharya Institute of Space Application and Geoinformation

# 1. Introduction

#### 1.1. Background

Drought is considered by many to be the most complex but least understood of all natural hazards, affecting more people than any other hazard (G.Hagman 1984). However, there remains much confusion within the scientific and policy communities about its characteristics. It is precisely this confusion that explains, to some extent, the lack of progress in drought preparedness in most parts of the world. Drought is a slow-onset, creeping natural hazard that is a normal part of climate for virtually all regions of the world; it results in serious economic, social, and environmental impacts. Drought onset and end are often difficult to determine, as is its severity. The impacts of drought are largely non-structural and spread over a larger geographical area than are damages from other natural hazards. The non-structural characteristic of drought impacts has certainly hindered the development of accurate, reliable, and timely estimates of severity and, ultimately, the formulation of drought preparedness plans by most governments. The impacts of drought, like those of other hazards, can be reduced through mitigation and preparedness.

Drought preparedness planning should be considered an essential component of integrated water resources management. Increasing society's capacity to cope more effectively with the extremes of climate and water resources variability (i.e., floods and droughts) is a critical aspect of integrated water resources management. Drought preparedness planning will also provide substantial benefit in preparing for potential changes in climate. Historically, more emphasis has been given to flood management than drought management. With increasing pressure on water and other natural resources because of increasing and shifting populations (i.e., regional and rural to urban), it is imperative for all nations to improve their capacity to manage water supplies during water-short years.

Drought risk is a product of a region's exposure to the natural hazard and its vulnerability to extended periods of water shortage(D.A.Wilhite 2000). If nations and regions are to make progress in reducing the serious consequences of drought, they must improve their understanding of the hazard and the factors that influence vulnerability. It is critical for drought-prone regions to better understand their drought climatology (i.e., the probability of drought at different levels of intensity and duration) and establish comprehensive and integrated drought information system that incorporate climate, soil, and water supply factors such as precipitation, temperature, soil moisture, snow pack, reservoir and lake levels, ground water levels, and stream flow. All drought-prone nations should develop national drought policies and preparedness plans that place emphasis on risk management rather than following the traditional approach of crisis management, where the emphasis is on reactive, emergency response measures. Crisis management decreases self-reliance and increases dependence on government and donors.

# 1.2. Drought : Definitions

Droughts have no universal definition. As drought definitions are region specific, reflecting differences in climatic characteristics as well as incorporating different physical, biological and socioeconomic variables, it is usually difficult to transfer definitions derived for one region to another. However some of the common definitions of drought can be noted as under:

- The Director of Common Wealth Bureau of Meteorology in 1965 suggested a broad definition of drought as "severe water shortage".
- Definition given by Palmer states that "Drought is an interval of time, generally of the order of months of years in duration, during which the actual moisture supply at a given place rather consistently falls short of the climatically expected or climatically appropriate moisture supply (Palmer, 1965)
- According to Mc Mohan and Diaz Arena (1982), "Drought is a period of abnormally dry weather sufficiently for the lack of precipitation to cause a serious hydrological imbalance and carries connotations of a moisture deficiency with respect to man's usage of water.
- Another definition given by Flag is worth mentioning "Drought is a period of rainfall deficiency, extending over months or year of such a nature that crops and pasturage for stock are seriously affected, if not completely burnt up and destroyed, water supplies are seriously depleted or dried up and sheep and cattle perish".
- According to Hangman (1984), "Drought is considered by many to be the most complex but least understood of all natural hazards affecting more people than any other hazard." (Wilhite, 2000)

A drought is a complex phenomenon that can be defined from several perspectives ((D.A.Wilhite 2000). Wilhite & Glantz categorize drought definitions into conceptual (definitions formulated in general terms) and operational. Conceptual definitions formulated in general terms; help people understand the concept of drought but these normally do not provide quantitative answers. Operational definitions on the other hand help identify the drought beginning, end and degree of severity.

By studying the above definitions it ca be understood that drought is mainly concerned with the shortage of water which in turn affects availability of food and fodder thereby leading to displacement and loss to economies as a whole.

# 1.3. Types of drought

Droughts can be classified in four major categories:

- **Meteorological drought:** it simply implies rainfall deficiency where the precipitation is reduced by more than 25% from normal in any given area. These are region specific, since deficiency of precipitation is highly variable from region to region.
- **Hydrological drought:** these are associated with the deficiency of water on surface or subsurface due to shortfall in precipitation. Although all droughts have their origination from deficiency in precipitation, hydrological drought is mainly concerned about how this deficiency affects

components of the hydrological system such as soil moisture, stream flow, ground water and reservoir levels etc.

- Agricultural drought: this links various characteristics of meteorological or hydrological drought to agricultural impacts, focusing on precipitation shortages, differences between actual potential evapotranspiration, soil, soil water deficits, and reduced ground water or reservoir levels. Plant water demand depends on prevailing weather conditions, biological characteristics of the specific plant, and its stage of growth and the physical and biological properties of the soil.
- Socio-economic drought: it is associated with the demand and supply aspect of economic goods together with elements of meteorological, hydrological and agricultural drought. This type of drought mainly occurs when there the demand for an economic good exceeds its supply due to weather related shortfall in water supply

A relationship between the meteorological, agricultural and hydrological droughts can be analysed from the figure below Fig (1)



Figure 1-1: Relationship between meteorological, hydrological and agricultural drought

(Source: National Drought Mitigation Centre, <u>http://drought.unl.edu/whatis/concept.htm</u>)

#### 1.4. Impacts of Drought

The impacts of a drought can be economic, environmental or social. Drought produces a complex web of impacts that spans many sectors of the economy and reaches well beyond the area experiencing physical drought. This complexity exists because water is integral to society's ability to produce goods and provide services. Impacts are commonly referred to as direct and indirect. Direct impacts include reduced crop, rangeland, and forest productivity, increased fire hazard, reduced water levels, increased livestock and wildlife mortality rates, and damage to wildlife and fish habitat. The consequences of these direct impacts illustrate indirect impacts. For example, a reduction in crop, rangeland, and forest productivity may result in reduced income for farmers and agribusiness, increased prices for food and

timber, unemployment, reduced tax revenues because of reduced expenditures, foreclosures on bank loans to farmers and businesses, migration, and disaster relief programs.

#### 1.4.1. Economic impacts

Many economic impacts occur in agriculture and related sectors, including forestry and fisheries, because of the reliance of these sectors on surface and subsurface water supplies. In addition to obvious losses in yields in crop and livestock production, drought is associated with increases in insect infestations, plant disease, and wind erosion. Droughts also bring increased problems with insects and diseases to forests and reduce growth. The incidence of forest and range fires increases substantially during extended droughts, which in turn places both human and wildlife populations at higher levels of risk.

#### 1.4.2. Environmental Impacts

Environmental losses are the result of damages to plant and animal species, wildlife habitat, and air and water quality; forest and range fires; degradation of landscape quality; loss of biodiversity; and soil erosion. Some of the effects are short-term and conditions quickly return to normal following the end of the drought. Other environmental effects linger for some time or may even become permanent. Wildlife habitat, for example, may be degraded through the loss of wetlands, lakes, and vegetation. However, many species will eventually recover from this temporary aberration. The degradation of landscape quality, including increased soil erosion, may lead to a more permanent loss of biological productivity of the landscape. Although environmental losses are difficult to quantify, growing public awareness and concern for environmental quality has forced public officials to focus greater attention and resources on these effects.

#### 1.4.3. Social Impacts

Social impacts involve public safety, health, conflicts between water users, reduced quality of life, and inequities in the distribution of impacts and disaster relief. Many of the impacts identified as economic and environmental have social components as well. Population migration is a significant problem in many countries, often stimulated by a greater supply of food and water elsewhere. Migration is usually to urban areas within the stressed area, or to regions outside the drought area. Migration may even be to adjacent countries. When the drought has abated, the migrants seldom return home, depriving rural areas of valuable human resources. The drought migrants place increasing pressure on the social infrastructure of the urban areas, leading to increased poverty and social unrest.

## 1.5. History of droughts in India and Gujarat

Agriculture in India is often seen as a gamble on summer monsoon rainfall. Summer monsoon rains constitute the greatest climatic resource of the Indian subcontinent as these rains support not only the country's agriculture and food production but substantially contribute to power generation (H.P.Das 2000). Thus success or failure of the crops and economy are intimately linked with prospects of good or bad monsoon. One of the worst natural calamities that affect India is the large-scale incidence of drought during the summer monsoon season (June to September) wherein extensive and prolonged droughts have cumulative effects, which are often disastrous.

The Indian subcontinent is predominantly characterized by a tropical monsoon climate, where climatic regimes are governed by the differences in rainfall, rather than temperatures. The most important feature is the seasonal alteration of atmospheric flow patterns associated with monsoon. There are two monsoon systems operating in the region- the southwest or summer monsoon and the northeast or the winter monsoon. The summer monsoon accounts for 70 to 90 percent of the annual rainfall over major parts of South Asia (Krishnamurthy and Shukla, 2000). There is a large variability in the monsoon rainfall on both space and time scales. Consequently the Indian region experiences drought or flood in some part of the country or the other almost every year during the monsoon period (June-September). In past century, the country has experienced twenty-one large-scale droughts in the years 1891, 1896, 1899, 1905, 1911, 1915, 1918, 1920, 1941, 1951, 1965, 1966, 1972, 1974, 1979, 1982, 1986, 1987, 1988, 1999 and 2000 with greater frequencies during the periods 1891-20, 1965-90 and 1997-2000(Gore and Ponkshe 2004). The monsoon of 2000 was the 13th consecutive normal monsoon considering country as a whole, but on a regional basis, this was the third consecutive drought year in areas covered by the states of Rajasthan, Gujarat and Andhra Pradesh.

The drought of 1987 was one of the worst in the century. The monsoon rainfall was normal only in 14 out of 35 meteorological sub-divisions in the country. The overall deficiency in rainfall was 19% as compared to 26% in 1918 and 25% in 1972 being worst years. Agricultural operations were adversely affected in 43% (58.6 million ha) of cropped area in 263 districts in 15 States and 6 Union Territories. In the two worst affected states of Rajasthan and Gujarat, the rainfall was less than 50% from normal. In these states, the drought of 1987 was the third or fourth in succession resulting in distress to an unprecedented level. Gujarat is one such state where drought occurs with unfailing regularity. All India and Gujarat state drought years can be analysed from table 1.

1901-	1011_	1921-	1031-	1941_	1951-	1961-	1071_	1081_	1001_
1901-	1911-	1921-	1951-	1941-	1951-	1901-	19/1-	1901-	1991-
1910	1920	1930	1940	1950	1960	1970	1980	1990	2000
Gujarat	Gujarat state								
1901	1911	1923	1931	1942	1951	1962	1972	1982	1991
1904	1915	1924	1936	1948	1952	1963	1973	1985	1993
1905	1918	1925	1938		1955	1965	1974	1986	1995
	1920	1927	1939		1957	1966		1987	1998
		1929	1940		1960	1968		1990	1999
									2000
All Indi	a								
1901	1911			1941	1951	1965	1972	1982	
1904	1918					1966	1974	1987	
1905	1920					1968	1979		

#### Table 1-1 All India and Gujarat state Drought Years

#### (Source: Gore and Ponkshe, 2004)

Gujarat is chronically dry and prone to drought. Drought in the state is the result of a combination of natural factors, principally the scarcity of rain, and man-made factors such as deforestation and overgrazing, the absence of traditional rainwater harvesting systems etc. In 1999, as many as 98 out of

a total of 225 blocks in the state received less than 50% of the season's expected rainfall. In 1999, Gujarat faced the worst drought of the past 100 years. Some 7,500 villages spread over 145 blocks in 15 districts were severely affected. The state has been hit by the worst drought in 100 years. More than 25 million people living in 9,000 villages of 17 of the 25 districts have been hit. Though Saurashtra has always been drought prone, this year the districts of Jamnagar, Rajkot, Junagadh, Amreli, Bhavnagar, Surendranagar and Porbandar have also been badly affected. Almost all water sources have dried up; there is no food for the people and no fodder for over 7 million cattle. The water table in drought affected Saurashtra, Kutch and northern Gujarat is said to be falling by 10-15 feet each year (Bavadam 2001).

#### 1.6. Drought risk evaluation

Risk assessment involves evaluation of the significance of a risk, either quantitatively or qualitatively. Risk assessment/evaluation according to Kates and Kasperson (1983) comprises of three steps:

- Identification of hazards, which may cause disasters.
- Estimation of risks arising out of such events and
- Estimation of losses

Even though there has been a tremendous increase in food production since green revolution, frequent droughts offsets this gain and results in food shortages to feed the ever-growing population, thereby leading to famines, deaths and human suffering on the whole. It has been said, "Drought follows the plough" (Glantz1994), a statement which has proved true.

Since drought is basically related to shortage of water, it has far reaching economic, social and environmental impacts. These impacts affect a much greater area than is the case with the other natural hazards, which are limited in terms of spatial coverage. For example, floods are confined For example, floods are confined to areas along flood plains; tornadoes are local in coverage; hurricanes may affect relatively large areas but mainly along coastlines. Even the area affected by the recent tsunami doesn't compare in area affected to droughts. Droughts may affect hundreds of thousands of square kilometres. Impacts, therefore, occur every year and have cumulative effects because they are often multi-year events.

Drought impacts have not been well quantified economically; officials tend to underestimate the importance of drought and often fail to be proactive in preparing for droughts. Also society's vulnerability to drought is affected by population growth and shifts, urbanization, technology, demographic characteristics, water use trends, government policy, social behaviour and environmental awareness. These factors are continually changing and society's vulnerability to drought may rise or fall in response to these changes. Therefore assessment of probable risk arising out of this slow disaster would certainly help people adopt corrective measures in time to rule out the social and economic disruption caused.

#### 1.7. Need for drought risk evaluation and management- Indian scenario

In drought management, making the transition from crisis to risk management is difficult because little has been done to understand and address the risks associated with drought. Droughts cause misery to both human and livestock population, accelerate degradation of natural resources and put a heavy pressure on government's resources through relief measures. There are strong links between poverty

and proneness of an area to drought. Widespread crop failures leading to acute shortages of food and fodder adversely affecting human and livestock health and nutrition, scarcity of drinking water accentuated by deteriorating ground water quality and declining water tables leading to large scale migration are the major manifestation of droughts.

## 1.8. Problem Statement

Drought is one of the major environmental disasters, which have been occurring in almost all climatic zones and damage to the environment and economies of several countries has been extensive and death toll of livestock unprecedented. Drought damages are more pronounced or prominent in areas where there is a direct threat to livelihoods.

Gujarat with a population of 5.05 crore as per the figures of the 2001 census is an agricultural state, where two-third of population is engaged in agriculture and earn livelihood directly from this occupation. Moreover, agriculture provides indirect employment to large portion of population in agro-based occupations. Thus, prosperity and well being of people in Gujarat are closely linked with agriculture and allied activities. Agricultural development in the state is to a large extent dependent on availability of water. Arid climatic conditions in Gujarat, characterized by erratic rainfall and successive drought years together with high rate of industrial development and excessive water mining has adversely affected in production levels thereby increasing drought risk. Since there is not much scope to bring additional land under cultivation in Gujarat, evaluation of probable risk arising out of drought in the region would help in developing better management plans for mitigating drought impacts.

## 1.9. Objectives

Based on the research problem following research objectives have been framed

- To analyze changes in vegetation cover due to variation in rainfall (by using rainfall data and NDVI images of past 20 yrsi.e.1981-2000)
- Identify areas facing high drought risk by combining satellite data and other thematic information.

## 1.10. Research Questions

To achieve the objectives of the study following research questions have been framed

- How vegetation changes in response to rainfall over long-term period (1981-2001)?
- Can a relative comparison be established between vegetation anomaly and meteorological based SPI?
- How aptly drought risk can be evaluated by a combination of satellite, meteorological and ancillary data?

## 1.11. Research Hypothesis

The research hypothesis formulated to achieve the research objectives is that drought risk can be better evaluated by combining satellite, meteorological and thematic information.

# 1.12. Organisation of the Thesis

The structure of the thesis tries to follow the below mentioned sequence to achieve the objective of the study

#### Chapter 2: Literature Review

This chapter covers previous research carried out in the field of drought risk assessment as well as role of remote sensing and GIS technology in the arena of monitoring, prediction, and assessment of droughts so far.

#### Chapter 3: Study area

The chapter gives a brief overview of the study area.

#### Chapter 4: Materials and Method

The chapter describes about the data and methods to be followed to arrive at the final risk.

#### Chapter 5: Results and Discussion

This chapter covers the analysis of long-term NDVI temporal images to arrive at the agricultural drought. The ancillary data and meteorological data used helps in determining the meteorological drought. Both these type of droughts are then combined to arrive at risk arising out of combined drought. Also chapter describes about the results obtained after the analysis has been done. It covers description of the relationship established between rainfall and vegetation as well as correlation between SPI and NDVI. Also what effect does crop yield have as a result of variability in rainfall is being discussed.

#### Chapter 6: Conclusion and future Recommendations

The last chapter is concluding chapter covering the conclusion of the study being done as well as recommendations for future study and what could not be handled in this study as well.

# 2. Literature Review

# 2.1. Role of Remote Sensing and GIS in Drought Studies

The mitigation of the effects of disasters requires relevant information regarding the disaster in real time. Also the possible prediction and monitoring of the disaster requires rapid and continuous data and information generation or gathering. Since disasters that cause huge social and economic disruptions normally affect large areas or territories and are linked to global change, it is not possible to effectively collect continuous data on them using conventional methods. The space technology or remote sensing tools offer excellent possibilities of collecting this vital data. This is because the technology has capability of collecting data at global and regional scales rapidly and repetitively and the data is collected in digital form. The technology further provides an excellent communication medium.

The satellite or remote sensing techniques can be used to monitor the current situation- before, during or after disaster. They can be used to provide baseline data against which future changes can be compared while the GIS techniques provide a suitable framework for integrating and analysing the many types of data sources required for disaster monitoring.

In recent years, the ever-increasing population and overstress on natural resources, soil degradation, decrease in water resources, and future projected climate change scenarios have become important areas of concern. The main goal of global agriculture is to feed 6 billion people, a number likely to double by (Kogan 2000). The first requirement of living creature is food, and a setback in agricultural and fodder production leads to socio-economic unrest especially in developing countries. Therefore, management of natural resources in developing as well as developed countries requires information on the state and changes in a range of biophysical variables. Droughts has been viewed as such a disaster where in a shortfall in precipitation has led to substantial reduction in production levels thereby leading to conditions which causes large scale migration and death of men and animals. Therefore there is a need for proper quantification of drought impacts and monitoring and reporting of drought development in economically and environmentally sensitive areas.

The impact of drought on society and agriculture is a real issue but it is not easily quantified. Reliable indices to detect the spatial and temporal dimensions of drought occurrences and its intensity are necessary to assess the impact and also for decision-making and crop research priorities for alleviation (Seiler and Kogan et al. 1998). The development and advancements in space technology, to address issues like drought detection, monitoring and assessment have been dealt with very successfully and helped in formulation of plans to deal with this slow onset disaster. With the help of environmental satellite, drought can be detected 4-6weeks earlier than before and delineated more accurately, and its impact on agriculture can be diagnosed far in advance of harvest, which is the most vital for global food security and trade (Kogan ,1990).

Several indices have been developed for the quantification of drought based on the type of drought. Palmer Drought Severity Index developed by Palmer (1965), is the most widely used drought index based on the demand and supply concept of the water balance equation. Palmer (1968) derived another index, the Crop Moisture Index (CMI) by modifying PDSI to find out the severity of agricultural drought. Hydrological droughts characterized by low precipitation, lowering of groundwater tables, fall in the level of lakes and Surface Water Supply Index (SWSI) has assessed reservoirs. A brief review of these indices is given in the next section. With the advancements in remote sensing technology, the historical drought indices were over powered by the newly developed indices from remote sensing data that are considered to be real time. Also, the remote sensing has provided a complete coverage of extended regions with a spatial resolution of a few hundred meters to few kilometres.

Thus, for an accurate assessment of the occurrence extent and severity drought it is necessary to get a correct picture of the spatial and temporal distribution of a number of meteorological, hydrological and surface variables. Space observation having this potential has made a significant contribution in this field. The satellite sensors that have the capability to retrieve surface parameters with high spatial and temporal resolutions over large areas have provided a comprehensive view of the situation. Many drought studies have made an extensive use of the AVHRR derived data, as it monitors earth surface changes continuously, freely accessible and moreover it's widely recognized around the world.

## 2.2. Meteorological drought indices and drought detection

Drought indices have been developed as a means to measure drought. A drought index assimilates thousands of data on rainfall, snow pack, stream flow and other water-supply indicators into a comprehensible picture. There are several indices that measure how much precipitation for a given period of time has deviated from historically established norms. Some of the widely used drought indices include Palmer Drought Severity Index (PDSI), Crop Moisture Index (CMI), Standardized Precipitation Index (SPI), and Surface Water Supply Index (SWSI).

#### 2.2.1. Palmer Drought Severity Index (PDSI)

In 1965, W.C. Palmer developed an index to measure the departure of the moisture supply (Palmer, 1965). Palmer based his index on the supply-and-demand concept of the water balance equation, taking into account more than just the precipitation deficit at specific locations. The objective of the Palmer Drought Severity Index (PDSI) is to provide standardized measurements of moisture conditions so that comparison could be made between locations and between months. The PDSI is a meteorological drought index that is responsive to abnormal weather conditions either on dry or abnormally wet side. The index was specifically designed to treat the drought problem in semiarid and sub humid climates; with palmer himself cautioning that extrapolation beyond these conditions may lead to unrealistic results.

PDSI has been used in west –Hungary as soil moisture indicator and has been widely used in United States for drought monitoring. It has been utilised as a tool to trigger actions associated with drought contingency plans. Several researchers have given limitations of PDSI. The Palmer Drought Severity Index (PDSI, Palmer, 1965) has a time scale of about 9 months (Guttman, 1998), which does not allow

identification of droughts at shorter time scales. Moreover, this index has many other problems related to calibration and spatial comparability (Guttman et al., 1992; Karl, 1983; Alley, 1984). McKee et al. suggested that PDSI is designed for agriculture but does not accurately represent the hydrological impacts resulting from longer droughts. Also PDSI is applied within the United States and has less acceptance elsewhere (Kogan,1990). To solve these problems, McKee et al. developed the Standardized Precipitation Index (SPI), which can be calculated at different time scales to monitor droughts in the different usable water resources. Moreover, the SPI is comparable in time and space (Hayes, Svoboda et al. 1999).

#### 2.2.2. Crop moisture index (CMI)

Three years after the introduction of his drought index, Palmer (1968) introduced a new drought index based on weekly mean temperature and precipitation known as Crop Moisture Index (CMI). It was specifically designed as an agricultural drought index. It depends on the drought severity at the beginning of the week and the evapotranspiration, soil deficit or soil moisture recharge during the week (Heim 2000). It measures both evapotranspiration deficits (drought) and excessive wetness (more than enough precipitation to meet evapotranspiration demand and recharge the soil). CMI is designed to monitor short-term moisture conditions affecting a developing crop; therefore CMI is not a good long-term drought-monitoring tool. The CMI's rapid response to changing short-term conditions may provide misleading information about long-term conditions.

Nemani et al. (1992) used CMI for estimating surface moisture status, because CMI depicts changes in soil moisture situation more rapidly than PDSI. It was found that CMI indicates more favourable moisture conditions over a particularly wet or dry month even in the middle of a serious long-term wet or dry period.

#### 2.2.3. Standardized Precipitation Index (SPI)

Tom Mckee, Nolan Doesken and John Kleist of the Colorado Climate Centre formulated the SPI in 1993. The purpose is to assign a single numeric value to the precipitation that can be compared across regions with markedly different climates. Technically, the SPI is the number of standard deviations that the observed value would deviate from the long-term mean, for a normally distributed random variable. Since precipitation is not normally distributed, a transformation is first applied so that the transformed precipitation values follow a normal distribution.

The SPI was designed to quantify the precipitation deficit for multiple time scales. These time scales reflect the impact of drought on the availability of the different water resources. Soil moisture conditions respond to precipitation anomalies on a relatively short scale while groundwater, stream flow, and reservoir storage reflect the longer-term precipitation anomalies. Thus, McKee et al. (1993) originally calculated the SPI for 3–, 6–, 12–, 24–, and 48–month time scales.

The SPI calculation for any location is based on the long-term precipitation record that is fitted to a probability distribution, which is then transformed into a normal distribution so that the mean SPI for the location and desired period is zero (Edwards and McKee, 1997). A drought event occurs any time the SPI is continuously negative and reaches intensity of -1.0 or less. The event ends when the SPI becomes positive. Each drought event, therefore, has a duration defined by its beginning and end, and

SPI Values				
2.0+	Extremely wet			
1.5 to 1.99	Very wet			
1.0 to 1.49	Moderately wet			
99 to .99	Near normal			
-1.0 to -1.49	Moderately dry			
-1.5 to -1.99	Severely dry			
-2 and less	Extremely dry			

intensity for each month that the event continues. The positive sum of the SPI for all the months within a drought event can be termed the drought's "magnitude".

**Table 2-1 Standardised Precipitation Index** 

(Source: http://drought.unl.edu/monitor/spi)

# 2.2.4. Standardised Water Supply Index (SWSI)

Shafer and Dezman (1982) to complement the Palmer Index for moisture conditions across the state of Colorado developed the Surface Water Supply Index (SWSI). This index compliments the Palmer index for moisture condition. It is dependent on the season; SWSI is computed with only snowpack, precipitation, and reservoir storage in the winter. During the summer months, stream flow replaces snowpack as a component within the SWSI equation.

SWSI has been used along with PDSI, to trigger the activation and deactivation of the Colorado drought plan. Though, SWSI is easy to calculate yet it has the limitation that values between basins or a region is difficult to compare (Doesken et al, 1991) (URL: <u>www.drought.unl.edu</u>)

# 2.3. Satellite based drought indices for drought characterization

Drought indicators assimilate information on rainfall, stored soil moisture or water supply but do not express much local spatial detail. Also, drought indices calculated at one location is only valid for single location. Thus, a major drawback of climate based drought indicators is their lack of spatial detail as well as they are dependent on data collected at weather stations which sometimes are sparsely distributed affecting the reliability of the drought indices (Brown and Reed et al. 2002). Satellite derived drought indicators calculated from satellite-derived surface parameters have been widely used to study droughts. Normalized Difference Vegetation Index (NDVI), Vegetation Condition Index (VCI), and Temperature Condition Index (TCI) are some of the extensively used vegetation indices.

# 2.3.1. Normalized Difference Vegetation Index (NDVI)

Tucker first suggested NDVI in 1979 as an index of vegetation health and density (Thenkabail and Gamage et al. 2004). NDVI is defined as:

#### NDVI= (NIR-RED)/ (NIR+RED)

Where, NIR and RED are the reflectance in the near infrared and red bands. NDVI is a good indicator of green biomass, leaf area index, and patterns of production (Thenkabail and Gamage et al. 2004; Wang and Wang et al. 2004). NDVI is the most commonly used vegetation index. It varies from +1 to -1. Since climate is one of the most important factors affecting vegetation condition, AVHRR- NDVI data have been used to evaluate climatic and environmental changes at regional and global scales (Ji and Peters 2003; Singh, Roy et al. 2003; Li &Lewis et al. 2004). It can be used not only for accurate description of continental land cover, vegetation classification and vegetation vigour but is also effective for monitoring rainfall and drought, estimating net primary production of vegetation, crop growth conditions and crop yields, detecting weather impacts and other events important for agriculture, ecology and economics (Singh &Roy et al. 2003). NDVI has been used successfully to identify stressed and damaged crops and pastures but only in homogenous terrain. In more heterogeneous terrain regions their interpretation becomes more difficult (Vogt et al. 1998; Singh et al.2003). Many studies in the Sahel Zone (Tucker et al 2005), Argentina (Sullivan et al.1998), South Africa (Unganani & Kogan, 2004) and Mediterranean (Vogt et al., 1998), and Senegal (Li. et al., 2004) indicate meaningful direct relationships between NDVI derived from NOAA AVHRR satellites, rainfall and vegetation cover and biomass.

#### 2.3.2. Vegetation Condition Index (VCI)

It was first suggested by Kogan (1997) (Thenkabail et al.2004; Vogt et al. 1998). VCI is an indicator of the status of the vegetation cover as a function of the status of the vegetation cover as a function of the NDVI minimum and maxima encountered for a given ecosystem over many years. VCI is defined as:

#### VCIj = (NDVIj- NDVImin)/ (NDVImax- NDVImin) \*100

Where, NDVImax NDVImin is calculated from long-term record for a particular month and j is the index of the current month. The condition of the ground vegetation presented by VCI is measured in percent. The VCI values between 50% to 100% indicate optimal or above normal conditions whereas VCI values close to zero percent reflects an extreme dry month.

VCI has been used by (Kogan and Unganani) for estimation of corn yield in South Africa; drought detection in Argentina (Sullivan et al 1998); drought monitoring over India (Singh et al.2002); monitoring droughts in the southern Great Plains, USA (Wan et al.2004); drought detection and monitoring in the Mediterranean region (Vogt et al.2000) and drought assessment and monitoring in Southwest Asia (Thenkabail et al. 2004). These studies suggest that VCI captures rainfall dynamics better than the NDVI particularly in geographically non-homogeneous areas. Also, VCI values indicate how much the vegetation has advanced or deteriorated in response to weather. It was concluded from the above studies that VCI has provided an assessment of spatial characteristics of drought, as well as its duration and severity and were in good agreement with precipitation patterns.

#### 2.3.3. Temperature Condition Index (TCI)

TCI was also suggested by Kogan (1997), (Thenkabail et al. 2004). It was developed to reflect vegetation response to temperature i.e. higher the temperature the more extreme the drought. TCI is

based on brightness temperature and represents the deviation of the current month's value from the recorded maximum. TCI is defined as:

#### TCIj= (BT max- BTj)/ (BTmax- Btmin) \*100

Where, BT is brightness temperature. Maximum and minimum BT values are calculated from the long-term record of remote sensing images for a particular period j. low TCI values indicate very hot weather. TCI has been used for drought monitoring in the USA, China, Zimbabwe and the Former Soviet Union. A study in Argentina for drought detection revealed that TCI was useful to assess the spatial characteristics, the duration and severity of droughts, and were in good agreement in precipitation patterns (Seiler et al.1998). TCI has been related to recent regional scale drought patterns in South Africa (Kogan, 1998).

## 2.4. NDVI - Rainfall relationship as indicator of drought

Several studies have been devoted towards drought with the aid of satellite-derived information. Reflectance in the visible, near-infrared and thermal bands were combined into Vegetation Condition Index (VCI), Temperature Condition Index (TCI), and Normalised Difference Vegetation Index (NDVI), which considerably improved early drought detection, watch and monitoring of drought's impacts on agriculture. Using NOAA Advanced Very High Resolution Radiometer (AVHRR) data, researchers have successfully extended satellite data analysis to large-area vegetation monitoring (Kogan, 1990) and biomass productivity estimates (Townshend and Justice, 1986). Since vegetation indices derived from the AVHRR sensor are directly related to plant vigour, density, and growth conditions, they may also be used to detect unfavourable environmental variables. The relationship between NDVI and rainfall is known to vary spatially, notably due to the effects of variation in properties such as vegetation type and soil background (Li et al., 2002; Nicholson & Farrar, 1994), with the sensitivity of NDVI values to fluctuations in rainfall, therefore, varying regionally.

Vegetation amount and condition are a function of environmental variables such as rainfall. Consequently, a strong relationship, involving a brief time–lag in the vegetation response to rainfall, would be expected between vegetation indices, such as the NDVI [(infrared reflectance (IR)-red reflectance (R))/ (IR + R)] and rainfall (Li et al., 2002). Many studies have focused on the relationship between the NDVI and rainfall

A study regarding the modelling of drought risk areas by using remotely sensed was carried out by C.Mongkolsa Wat (et al.) in Northeast Thailand, where drought has the most profound effect on the lives and regional economy. In this paper the severity of drought was considered to be a function of rainfall, hydrology and physical aspect of landscape. Three different types of droughts i.e. meteorological, hydrological and physical drought were analysed after which an overlay matrix operation was performed that yielded the areas which faced drought risk wherein drought risk was classified into four classes. The result obtained was satisfactory confirming that the model developed in this study could help in the mapping of drought risk area in the Northeast Thailand.

Another study related to early detection of drought in East Asia was done by Song et al. (2004) NDVI from NOAA/AVHRR had been used wherein standard NDVI and up-to-date NDVI were calculated to derive difference NDVI image, to detect the intensity and agricultural area damaged by drought. The

difference images were used to create drought risk maps. The study was successful in detecting and monitoring drought effects on agriculture.

There have also been studies dealing with the estimation of grain production that is very vital for global food security and trade (Kogan). A study made by Kogan for drought early warning applied a new numerical method, introduced in late 1980's based on a three spectral channel combination visible, near infrared and infrared. The new method is built on three basic environmental laws: law of minimum (LOM), law of tolerance (LOT) and principal of carrying capacity (CC). This method was applied to the NOAA Global Vegetation Index (GVI). With the introduction of this method drought can be detected 4-6 weeks earlier and delineated more accurately and its impact on grain production can be diagnosed long before harvest.

Wilhelmi and Wilhite (2002) presented a method for spatial, Geographic Information Systems- based assessment of agricultural drought vulnerability in Nebraska. It was hypothesized that the key biophysical and social factors that define agricultural drought vulnerability were climate, soils, landuse and access to irrigation. The framework for derivation of an agricultural drought vulnerability map was created through development of a numerical weighting scheme to evaluate the drought potential of the classes within each factor. Results indicated that the most vulnerable areas to agricultural drought were non-irrigated cropland and rangeland located in areas with a very high probability of seasonal crop moisture deficiency.

A research done by Herrmann et.al investigates temporal and spatial patterns of vegetation greenness and explores relationships between rainfall and vegetation dynamics in the Sahel, based on analyses of NDVI time series and gridded precipitation estimates at different spatial resolutions.

Overall positive trends in NDVI and rainfall over the period 1982 to 2003 were confirmed. Linear correlations between the two variables were found to be highly significant throughout the entire Sahel. Herrmann et.al thus considered that rainfall is the most important constraint to vegetation growth in this semi-arid zone, which justifies the attempt to predict vegetation greenness from rainfall estimates through linear regression.

Similarly a case study relating to drought risk evaluation was carried out by K.Prathumchai et al. (2001), the objective of the study being to evaluate criteria for identifying drought risk areas. In this study physical and meteorological factors were analysed and drought risk areas were identified. Drought risk areas were calculated as a weighted linear combination of a set of input factors such as topography, soil drainage, ground water resource, irrigation area, annual evaporation, average annual rainfall and frequency of rainfall days. The relationship between NDVI change and drought risk area. The study concluded that NDVI can be used as a main indicator to evaluate drought. However the limitation of the study was that it was unable to consider change in species, type, age and characteristic of the vegetation.

Anyamba and Tucker (2005) analysed seasonal and interannual vegetation dynamics in Sahel using NOAA-AVHRR NDVI. The study concentrated only on NDVI patterns in growing season, which was defined by examining the long-term patterns of both rainfall and NDVI. Year to year variability in NDVI patterns was examined by calculating yearly growing season anomalies. The correlation

between NDVI and rainfall anomaly time series was found to be positive and significant, indicating the close coupling between rainfall and land surface response patterns over the region.

A study by Wang et al. (2003) concentrated on temporal responses of NDVI to precipitation and temperature in the central Great Plains, USA. In this study it was found that average growing season NDVI values were highly correlated with precipitation received during the growing season and seven preceding months. Relations between temperature and rainfall with NDVI were examined within growing season, across growing seasons and across years. It was concluded that precipitation has the primary influence on NDVI and by inference, on productivity.

## 2.5. SPI based drought identification

Hayes et al. (1999) used the standardized precipitation index (SPI) to monitor the 1996 drought in the United States of America. Hayes et al. (1999) shows that the onset of the drought in the USA in 1996 could have been detected one month in advance of the Palmer Drought Severity Index (PSDI). Although it is quite a recent index, the SPI was used in Turkey (Komuscu, 1999), Argentina (Seiler et al; 2002), Canada (Anctil et al.; 2002), Spain (Lana et al.; 2003), Korea (Min et al.; 2003), Hungary (Domonkos, 2003), China (Wu et al.; 2001) and Europe (Lloyd-Hughes and Saunders; 2002) for real time monitoring or retrospective analysis of droughts. The SPI is consistent with regard to the spatial distribution of rainfall that occurs with great variability in South Africa due to geographical location, orography and the influence of the oceans. Using that index to develop climatology of the spatial extension and intensity of droughts gives also an additional understanding of its characteristics and an indication of the probability of recurrence of drought at various levels of severity.

Lei and Peters (2003) undertook a study relating to assessing vegetation response in the northern Great Plains using vegetation and drought indices. The study aimed to determine the response of vegetation to moisture availability through analysis of monthly AVHRR-NDVI and SPI over grass and cropland cover types in the northern U.S.Great Plains. The study focused on three major areas namely relationship between NDVI and SPI at different time scales, response of NDVI to SPI during different time periods within a growing season and regional characteristics of the NDVI-SPI relationship. The relationship between vegetation and moisture availability was clarified by analysing the covariance of NDVI and SPI time series with the scatter plots and Pearson correlation analysis. It was found that NDVI response is not sufficiently sensitive to 1- or 2- month SPI and the scales longer that 6 months tend to reduce the covariation of SPI and vegetation vigour. It was found that the 3- month SPI has the highest correlation to the NDVI, because the 3- month SPI is best for determining drought severity and duration. Also it was found that seasonality has a very significant effect on the relationship between the NDVI and SPI.

A study was carried out by Chaudhari and Dadhwal (2004) to quantify the impact of drought on production of kharif and rabi crops using standardized precipitation index (SPI). SPI were computed at monthly (SPI 1), bimonthly (SPI 2) and tri-monthly (SPI 3) time scales with the suggested Pearson Type III distribution. SPI values were then classified into seven categories suggested by Hayes. Correlation coefficients were computed between state-wise production of major kharif crops (1980-2001) and SPI values (SPI1, SPI2, and SPI3). Production forecasts using SPI3 showed good agreement with the statistics from state department of agriculture, thereby suggesting that SPI at different time scales can be used as a predicator of regional crop production in India.

# 2.6. Rainfall anomaly based drought identification

Meteorological drought indicates the deficiency of rainfall compared to normal rainfall in a given region. Places where long-term average rainfall is less, year-to-year variability is greater and so the likelihood of drought is greater. The major impact of drought is felt in semiarid regions where the incidence of drought years is fairly high.

According to the Indian Meteorological Department (IMD), meteorological drought is defined as occurring when the seasonal rainfall received over and area is less than 75% of its long-term average value (Ray).

(Krishnamurthy and Shukla, 1999) analysed the interannual and intraseasonal variability of the summer monsoon rainfall over India and found that major drought years are characterized by large-scale negative rainfall anomalies covering nearly all of India and persisting for the entire monsoon season.

A large number of papers have analysed the interannual variability of the summer (June- September) mean monsoon rainfall averaged over India (Parthasarthy and Mooley1978; Shukla 1987; Parthasarthy et al 1994), stating an interannual standard deviation of the mean seasonal rainfall to be 10% of the long-term mean value.

Thus it can be conclude that these reviews highlight the numerous efforts made till date with developing relationship between various satellite and meteorological derived indices to point out a specific type of drought caused either by rainfall deficiency, or less vegetation vigour or low agricultural production. In the present study, both meteorological indices (SPI) and satellite based drought indices (NDVI) have been used to assess the drought risk. Relationship between NDVI and SPI have been derived and related with crop yield to study the risk. Ancillary data such as crop yields has been included in the study so that an analysis could be carried out about how crop yield changes as response to rainfall and eventually combine agricultural drought and meteorological drought so as to get a combined drought risk.

# 3. Study Area

# 3.1. Location and Extent of study area

Gujarat is situated on the western coast of India between 20°06' to24°42' north latitudes and 68°10'N to74°28' east longitudes (Fig 3.1). It comprises of 25 districts with a total geographical area of 1.96 lakh square kilometres. Gujarat shares a boundary with Rajasthan in the north east, Madhya Pradesh in the east and Maharashtra in the south and south east. It has a 1600 km long coast-line. Its northern boundary forms the international boundary with Pakistan

# 3.2. Topography and Drainage

Characterized by a varied topography, Gujarat has a fertile plain in the south cut by several rivers, low hills in the west and broad mudflats in the north that adjoin the Thar (Great Indian) Desert. The Gujarat state has been divided into three major physiographic regions, namely the Central Highlands, the Western Hills and the West Coast. The extreme part of the state is occupied by the Central Highlands, a wide belt of hilly region bordered by the Arravali Range on the west.

The Western Hills forms the part of the peninsular plateau while the Western Coast covers major portion of the state, comprising of Gujarat Plain, Kathiawar Peninsula and Kutch Peninsula. Deltaic plains by the alluvium laid by the Tapi, Narmada, Mahi, Sabarmati, Banas and Luni river systems have lead to the formation of Gujarat Plains progressively. Kathiawar Peninsula is a dissected basaltic plateau with flat-topped hills of Mesozoic sandstones in the northeast while the central part forms a high plateau bordered by scarps and dotted hills. The Kutch Peninsula comprises a central high plateau surrounded by dissected scarps and flat-topped mesas on all sides except in the east. The Rann of Kutch is a depositional plain of salt, sand and mud, marked with scattered islands. (NBSS & LUP)

# 3.3. Climate

The climate of Gujarat is also varied and can be divided into three seasons: (1) hot and dry season from May to June; (2) warm and rainy season from June to September; and (3) cool and dry post-rainy season from October to April (Agro climatology of Gujarat). The north-western part of the state is dry, with less than 500mm of rain every year. In the more temperate central part of the state, the annual rainfall is more than 700 mm. In the southern part, rainfall averages 2000 mm a year. Incidence and distribution of rainfall, particularly in Saurashtra and Kutch regions and in the northern part of Gujarat is highly erratic. As a result, these regions are very often subjected to drought. Most of the rain (90-95% of the annual total) falls during the period of June to September, when the southwest monsoon prevails. The north- west monsoon does not occur in Gujarat state. In the winter temperatures averages between 12° and 27°. In the summer temperatures average between 25° and 43° and have

been known to reach as high as 48°C. The highest temperatures have been recorded at Ahmedabad and in regions of Banaskantha while temperatures are relatively low at places located in coastal regions.

# 3.4. Soils

Soils are one of the most valuable life supporting natural resources for the society since they produce food, fibre and fodder, which are basic to our existence. Gujarat is endowed with a wide range of soil type. The soils of Gujarat can be broadly classified into nine groups namely, black soils, mixed red and black soils, residual sandy soils, alluvial soils, saline/alkali soils, lateritic soils, hilly soils, desert soils and forest soils.

# 3.5. Agroclimatic zones of Gujarat

The state is divided into seven agro climatic zones mainly based on amount of rainfall and soil types.

# 3.5.1. South Gujarat

This zone is a heavy rainfall area with rainfall ranging between 1500 mm and more, with deep black soils. Most of the area is cultivated. Cotton, paddy, sorghum and sugarcane are major crops grown in this zone. Whole of Dangs district and parts of Surat and Valsad districts comes under this agro climatic zone.

# 3.5.2. Middle Gujarat

This zone has rainfall ranging between 800-1000 mm. It consists of Panchmahals, Vadodara and Bharuch districts. Cotton, tobacco, bajra, pulses, wheat, paddy, maize, jowar and sugarcane are major crops.

# 3.5.3. North Gujarat

It includes whole of Sabarkantha district, parts of Ahmedabad and Banaskantha district, Mehsana and Kheda districts. Rainfall ranges between 625-875 mm. Paddy, bajra, pulse, cotton, groundnut, tobacco, wheat, jowar, millet, vegetables, spices and oil seeds.

# 3.5.4. Bhal and Coastal area

This zone is comprised of area around gulf of Khambhat and Bhal coastal region in Bharuch and Surat districts. The soils here are poorly drained and saline. Rainfall ranges from 625-1000 mm. Groundnut, cotton, bajra, wheat, pulses and jowar are the major crops grown.

# 3.5.5. South Saurashtra

Entire of Junagadh district and parts of Bhavnagar, Amreli and Rajkot districts forms this zone. Soils found here are shallow medium black and calcareous. Rainfall ranges between 625-750 mm. Groundnut, cotton and pulses are major cops.

# 3.5.6. North Saurashtra

Whole of Jamnagar and parts of Rajkot, Surendranagar and Bhavnagar districts make this zone with shallow medium black soils. Rainfall varies between 400-700 mm. Major crops cultivated in this zone comprise of cotton, groundnut, wheat, jowar, and bajra.

#### 3.5.7. North West Zone

The North West zone comprises of entire Kutch, parts of Rajkot, Mehsana, Banaskantha and Ahmedabad districts. Soils in these regions are sandy and saline. Rainfall ranges between 250 -500 mm. Cotton, sorghum, groundnut, pearl millet and wheat are major crops grown.

### 3.6. Water Resources

Gujarat has 2.28% of India's water resources and 6.39% of country's geographical area (Gupta, 2004). A large percentage of water is consumed by the agricultural sector, for irrigation. Water resources in Gujarat are mainly concentrated in the southern and central part. Saurashtra and Kutch in the northern part, with exceptionally high irrigation needs, have limited surface and groundwater resources. Groundwater has contributed to more than 80% of irrigation in the state (Gupta, 2004). This excessive groundwater mining has thereby reduced the water table by 3-4 cm per year. The depletion of ground water level manifests itself in a fall in the level of water table and an increase in salinity and fluoride content. The fall in ground water levels is a direct result of the rampant use of bore wells, which go as deep as 1,200 feet (360 meters). Water in more than 10,000 wells in Kutch is saline. Though Kutch and northern Gujarat receive low rainfall, has a poor aquifer system (Bavadam, 2001). Due to typical water-intensive crop varieties, water surplus areas of south and central Gujarat have also experienced a severe loss of utilizable groundwater as compared to water scarce regions.

## 3.7. Land use and Agriculture

Landuse is one of the driving forces behind water demand and critical factors of agricultural drought vulnerability (Wilhite 2002). Agriculture in Gujarat forms a vital sector of the states economy. In Gujarat, about 50% of the area is under cultivation of which only one-fifth is irrigated (NBSS&LUP, 1994). About 10% is under forests and the remaining is either left barren or uncultivable waste. A generalised landuse/cover map has been generated with seven major classes as rainfed crops, irrigated crops, forest, bare soil, fallow land, salt pans and water (fig3.1). Unsuitable climatic conditions in some parts and rocky terrain with thin or no soils in others, have limited the area suitable for cultivation. State's agriculture productivity fluctuates due to poor soils, inadequate rainfall, frequent droughts and floods, bad drainage and undeveloped irrigation facilities. The state's cropping pattern is unproportionately dominated by cash crops. Gujarat is the highest producer of cotton in the country claiming the best agricultural land. The state produces a large variety of crops namely groundnut (highest production in the country), tobacco (second highest production in the country), and isabgul, cumin, sugarcane, jawar, bajra, rice, wheat, pulses, tur and gram which are important crops of Gujarat.

## 3.8. Demography

The total population of Gujarat as at 0:00 hours of 1st March 2001 stood at 50,596,992 as per the provisional results of the Census of India 2001. This population includes the estimated population of entire Kachchh district, Morvi, Maliya-Miyana and Wankaner talukas of Rajkot district and Jodiya taluka of Jamnagar district where the population enumeration of Census of India, 2001 could not be conducted due to natural calamity. In terms of population it holds the tenth position among the States and Union territories in the country. This has registered a growth rate of 22.48% when compared to national average of 21.34% during the decade 1991-2001. The sex ratio (i.e., the number of females

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per thousand males) of population in the State has come down from 934 in the previous census to 921 in the present census. The literacy rate in the State has shown improvement. This has increased to 69.97% when compared to 61.57%.



Figure 3-1 Study area, Gujarat state

# 4. Materials and Method

This chapter gives a brief overview of the data used and the methodology adopted to work out the proposed research.

# 4.1. Data Acquisition

Data has been acquired mainly from two sources, firstly NDVI derived from satellite sources and secondly rainfall obtained from ground rainfall stations.

#### 4.1.1. Satellite data characteristics and acquisition

The National Oceanic and Atmospheric Administration (NOAA) of the USA operate the series of NOAA satellites which carry the Advanced Very High Resolution Radiometer (AVHRR) sensor. These sensors collect global data on a daily basis for a variety of land, ocean, and atmospheric applications. Specific applications include forest fire detection, vegetation analysis, weather analysis and forecasting, climate research and prediction, global sea surface temperature measurements, ocean dynamics research and search and rescue.

The first operational NOAA satellite (NOAA-6) was launched in 1979. This was followed by a series of additional NOAA satellites with the latest launch being NOAA-17 in June 2002. NOAA's 12, 15 and 16 are all still transmitting AVHRR data. The National Oceanic and Atmospheric Administration (NOAA) and the National Aeronautics and Space Administration (NASA) have initiated the Pathfinder Program to produce long –term data sets for global change research. Pathfinder AVHRR Land data are level 3 products. To produce composite data set which is useful for studies of temporal and interannual behaviour of surface vegetation, 8 to 11 consecutive days of data are combined, taking the observation for each 8km bin from the date with the highest NDVI value. Choosing highest NDVI pixel value eliminates most of the cloudy pixels as well as atmospheric contaminants.

Twenty years (1981-2000) of monthly NOAA Pathfinder NDVI data encompassing Asia were downloaded from Distributed Active Archive Centre at Goddard light Centre, Greenbelt, USA. The NOAA Pathfinder dataset was generated from original 1.1 km<sup>2</sup> NOAA AVHRR data as 10-day maximum value composites (MVC) aggregated to an 8 km  $\times$  8 km pixel resolution. Monthly MVC was then generated from 10-day composites in any given month. For a detailed review of NDVI data set generation see DAAC (1998). The quality and consistency of pathfinder data were assured by applying post-launch calibration of the satellite sensors, including corrections for degradation over time and a first order atmospheric correction. The high level of consistency was reported between original 1.1 km<sup>2</sup> NOAA AVHRR data and NOAA Pathfinder data suggests that Pathfinder NDVI data can be used for time series analysis of vegetation dynamics (Rigina and Rasmussen, 2003). The NOAA Pathfinder data was used in this study due to its long-term periodicity, global coverage and
free availability. For this study, we subset the Gujarat (India) region covering the domain  $18^{\circ} \text{ N} - 25^{\circ}$  N and  $68^{\circ} \text{ E} - 75^{\circ} \text{ E}$ , from the continental data set for the period Jun 1981 – December, 2000

## 4.1.2. Meteorological Data

Meteorological data pertaining to monthly rainfall has been collected for a period of 23 years ranging from 1981-2003. Monthly rainfall for 169 rain stations has been used to analyse relations between NDVI and rainfall and also to derive Standardized Precipitation Index (SPI). The data has been collected from Bhaskaracharya Institute of Satellite and Geoinformation (BISAG), Gandhinagar and Agro-Meteorological Department, Anand Agriculture University, Anand. The number of rainfall stations between 1981-1989 was 168, from 1990-1997 the number of these stations increased to 174 and reached to 218 in the year 2000-2003. Therefore to maintain consistency in data, rainfall data for 164 rain stations for which rainfall data was available for a period of 23 years was considered in carrying out required analysis.

## 4.1.3. Statistical Data

Statistical data relating to crop yield mainly food crops and oilseeds have been used to find out the relation between various parameters (like rainfall and NDVI) used in the study. Crop yield data for the period from 1981-2003 was collected from Department of Agricultural Statistics, Gandhinagar.

# 4.1.4. Ancillary Data

## 4.1.4.1. Toposheets

Toposheets of Gujarat have been downloaded from the website of University of Berkeley, California. In total 24 toposheets available at 1:250,000 scale have been downloaded from the website, which were reprojected in Albers Equal area Projection and mosaicked to get the entire Gujarat area. Toposheet numbers: NF 43- 1, 2, 5, 6, 9, 10, 13, 14 NG 42- 11, 12, 14, 15, 16 NF 42- 2, 3, 4, 7, 8, 11, 12, 16 NG 43- 9, 13, 14 (Source: <u>http://www.lib.berkeley.edu/EART/india</u>)

## 4.1.4.2. Landuse/landcover

A generalised Landuse/landcover map of Gujarat was prepared. The Landuse/landcover was made from MODIS –TERRA 8 day composite surface reflectance images (2004). The generalised landcover map presents five major types – rainfed crops, irrigated crops, fallow land, bare soil and forest (Fig.4.1).It is being used to extract rainfed areas in the study area which are of major concern in the present thesis.

## 4.1.4.3. Rain station map

Point map of 164 rainfall stations in Gujarat was prepared from the lat/long file. It has been used to interpolate rainfall and SPI values in the entire region (Fig 4.2)

# 4.2. Software Used

The following GIS packages have been used to perform the data processing and analysis. ERDAS 8.7, Arc GIS 9.0, ILWIS 3.2, Arc View and ENVI 4.0 Microsoft Excel for arrangement of data.



Generalised Landuse/cover map of Gujarat

Figure 4-1 Landuse map



Location of 164 weather stations in Gujarat

Figure 4-2 Weather stations, Gujarat

# 4.3. Methodology

The following section outlines the methodology used in the project. Correlation and regression techniques are used to verify if there is a correlation between NDVI and rainfall in Gujarat, between 1981-2000. NDVI, SPI and crop trend is then used to produce a drought risk classification map. A schematic presentation of the methodology that has been followed is mentioned in figure 4.3



Figure 4-3 Schematic presentation of Methodology

## 4.3.1. Pre-processing of Satellite data

For the purpose of this study, monthly NOAA-AVHRR Pathfinder NDVI images of 8km by 8km spatial resolution have been used. These satellite images were radiometrically corrected however; geometric corrections had to be done. Since the NOAA-AVHRR data set is of global coverage, India was extracted from it and finally Gujarat was extracted. The images were then reprojected into Albers Equal Area Projection. This projection has been chosen so that each pixel in the study area has an equal size thereby making pixel level analysis easy. Twenty year, monthly images (June-October) from 1981-2000 were rescaled to get the NDVI values ranging from +1 to -1 by using the following expression:

## (B1-128)\*0.008

Where, b1 is band 1 of the image; The entire processing of the NOAA data has been done using ENVI 4.0.

## 4.3.2. Post-processing of satellite data to derive vegetation Indices

For NOAA-AVHRR, NDVI is universally defined as (Lillesand and Kiefer, 1994) NDVI = (Ch2-Ch1) / (Ch2+Ch1)

To derive the seasonal pattern of NDVI for 1981-2000, firstly, average NDVI for each year was computed by using following expression:

## Average NDVIy = (NDVI6 + NDVI7 + -----+NDVI10)/ 5

Where, NDVI is NDVI for y year and NDVI6, NDVI7.....NDVI10 stands for NDVI of particular months in that year.

Mean NDVI for 20 years was then computed by using following expression

## Mean NDVI = (Average NDVIy1+ Average NDVIy2+.....+ Average NDVIy19)/ 19

Where, Average NDVIy1..... Average NDVIy19 stands for the yearly average NDVI value for 19 years.

To derive NDVI anomaly, maximum NDVI from 1981-2000 has been computed using the following formula:

## NDVI max i = (NDVI 1, NDVI 2 .....NDVI n)

Where, NDVI max i is maximum NDVI in  $i^{th}$  year and NDVI 1.....NDVI n is NDVI in month 1 to NDVI in n month in  $i^{th}$  year.

Maximum NDVI has been computed for the growing season for each year from 1981-2000, so as to minimise effects of cloud contamination, though being monthly composite the data was almost free from clouds and could be worked upon. NDVI composites using the maximum value compositing procedure minimises effects of cloud contamination, varying solar zenith angles and surface topography (Anyamba and Tucker, 2005; J.Li et al.2004).

After computing NDVI max, from1981-2000, an average of these NDVI max images was computed to get the mean NDVI max values during past 19 years. Anomaly was then computed as:

## Anomaly NDVI i = (NDVI max i, - mean NDVI max)/ (mean NDVI max)\*100

Where, Anomaly NDVI i is NDVI anomaly in i<sup>th</sup> year, NDVI max is maximum NDVI and mean NDVI max is the average of maximum NDVI during 1981-85 and 1987-2000.

Year 1986 was dropped because the data was contaminated by atmospheric noise. Lastly to compute district wise NDVI anomaly for all 19 images, zonal attribute function was performed in ERDAS imagine 8.7.



Figure 4-4 Schematic presentation of image processing

## 4.3.3. Rainfall Data

Monthly rainfall records for 164 stations were arranged into spreadsheets, provided by Anand Agro meteorological Department, Anand Agriculture University, Gujarat. Rainfall data for the crop-growing season ranging from June –October have been summed up to get the total rainfall received during this period. While the rain gauge data are point measurements, the satellite values are averages over pixel-sized areas. Thus to establish a relationship between these two types of data, geostatistical technique of interpolation has been performed with grid size of 8km and seasonal rainfall maps for 23 years have been prepared. A mean of 20 years of rainfall-interpolated maps has been computed to get the average rainfall condition map in Gujarat during last 20 years.

# 4.3.4. Relationship between NDVI and Rainfall

NDVI time series data for each of the 164 rain stations was extracted from the 19 years NDVI time series images using ENVI 4.0 image processing software. Correlation coefficient between NDVI and monthly rainfall has been calculated for each of the rain stations. Generally there is a time lag between precipitation events and response of vegetation to such events. The time interval between a precipitation event and the time when precipitated water might reach a plants root and affect plant growth can vary from 1 to 12 weeks depending on vegetation type (Li et al, 2002). In order to account for this interval and assess the real maximum correlation between NDVI and rainfall, the NDVI/rainfall correlation coefficients are calculated for time lags of 0,1 and 2 months. Temporal pattern of rainfall and NDVI has also been analysed to see variation in vegetation according to rainfall. Correlation between rainfall and maximum NDVI and correlation between rainfall and average NDVI has been computed to analyse which of these share a strong relationship amongst them.

## 4.3.5. Standardized Precipitation Index (SPI) and meteorological drought

SPI as has been mentioned earlier is an index that was developed to quantify precipitation deficit at different time scales. 1-month SPI reflects short-term conditions and its application can be related closely to soil moisture; the 3-month SPI provides a seasonal estimation of precipitation; 6- and 9month SPI indicates medium term trends in precipitation patterns (Lei Ji et al. 2003), therefore 3 month was calculated for 164 rainfall stations using monthly rainfall data for the period of 1981-2003 only for the crop growing season (June-October). The threshold for indicating severity of meteorological drought has adopted from Drought Mitigation been U.S. Centre (http://www.une.edu/~rowelett/units/scales/drought.html). The category column in drought severity classification table (table4.1) has been modified to suit the reclassification of the SPI maps. Initially SPI values had been interpolated using Ordinary Kriging taking grid size of 8km. Kriging has provided optimal areal estimates in any given situation and is applicable both for drought and flood (Kassa, 1999). But in the present work interpolation by Ordinary kriging did not gave good results as the range of SPI (-3 to +3) after interpolation was significantly reduced which could not be used to reclassify the interpolated maps into drought severity classes correctly. Therefore the method of Inverse Distance Weighted (IDW) has been used to interpolate the SPI values. IDW interpolation explicitly implements the assumption that things that are close to one another are more alike than those that are farther apart (ArcGIS 9.0) Interpolation has been performed in ArcGIS 9.0. The interpolated maps are thus been reclassified into different drought severity classes. Interpolated maps of September month were chosen to be reclassified, as September is moving average of 3 month SPI i.e. July, August and September that are the crucial months for major kharif crops in Gujarat. On the analysis of the obtained SPI values in September month, for each of the 19 years a threshold of -1.5 was chosen to reclassify SPI into binary mask of 1 and 0 where 1 stands for drought and 0 for no drought. Values below -1.5 were assigned 1 and values above -0.99 were assigned 0. The resultant maps were added to get meteorological drought risk map for last 19 years, showing frequency of droughts to obtain highly drought prone areas. Two model years for drought years (1982 and 1987) as well as two wet years (1988 and 1987) has been chosen to present the drought severity classes in these two different conditions.

Category	Description	Standardized Precipitation
		Index
		(SPI)
D0	No drought	-0.5 and above
D1	Abnormally dry	-0.50.7
D2	Moderate drought	-0.81.2
D3	Severe drought	-1.31.5
D4	Extreme drought	-1.61.9
D5	Exceptional drought	-2 or less

## Table 4-1 Drought Severity Classification (modified)

Source: (U.S. National Drought Mitigation Centre)

## 4.3.6. Rainfall Anomaly

Rainfall anomaly has been computed from 1981-2000 for the growing season June-October to indicate meteorological drought. Rainfall anomaly has been computed as:

## **RFA** $i = [(RF i - RF\mu)/(RF\mu)]*100$

Where,

RFA i is rainfall anomaly for i<sup>th</sup> year; RF i is seasonal rainfall for i<sup>th</sup> year and RF<sub>µ</sub> is mean seasonal rainfall.

According to Indian Meteorological Department (IMD), meteorological drought is defined as when the seasonal rainfall received over an area is less than 75% of its long-term average value. The meteorological is further classified into slight drought when rainfall is 25% less than the normal, moderate drought when rainfall is 50% less than the normal and severe drought when rainfall is 75% less than the normal (Ray). The same criterion as defined by IMD has been used to classify the meteorological drought.

Though Rainfall as well as SPI anomaly have been calculated but for further accomplishment of the objective, the method which gives close results as achieved by conventional methods have been used to identify meteorological drought.

## 4.3.7. Crop Yield Anomaly

To quantify the impact of drought on production of major Kharif crops in Gujarat correlation between SPI and district level crop yields have been analysed. Since NDVI takes advantage of the reflective and absorptive characteristics of plants in the red and near –infrared portions of the electromagnetic spectrum and has been used in research on vegetation yield and productivity, crop yield has also been correlated to NDVI. Yield trend has been computed to see for the yield trend over last 22 years (1981-2002). Yield trend has been computed on district basis. The table below summarizes the computation of trend, followed by the formulas for calculating trend and yield anomaly. The years where trend was missing an average of the yield in that particular year has been computed to derive anomaly in crop production. Yield anomaly has been calculated in the same fashion as the computation of NDVI anomaly.

Equation (I) Yield trend **YT = a+b** Where Yt is yield trend

Equation (II) Yield anomaly Ya = ((Yi – Yt)/ (Yt))\* 100 Where Ya is yield anomaly; Yi is yield in a particular year; Yt is yield trend in 20 years

DISTRICTS	Slope	Intercept	$R^2$
Ahmedabad	41.396	684.14	0.410
Banaskantha	44.147	1019.3	0.544
Bharuch	11.609	616.01	0.1479
Gandhinagar	73.841	812.47	0.687
Junagadh	32.6	760.88	0.113
Kutch	35.679	551.3	0.422
Kheda	15.407	671.33	0.242
Mehsana	38.072	1079.4	0.403
Panchmahals	34.548	516.52	0.364
Rajkot	26.489	329.49	0.140
Sabarkantha	50.432	608.52	0.568
Surat	16.556	791.19	0.223
Surendranagar	15.232	358.53	0.23
Vadodara	32.735	541.42	0.44

**(B)** 

DISTRICTS	Slope	Intercept	$\mathbb{R}^2$
Ahmedabad	18.755	649.41	0.155
Amreli	21.793	749.96	0.109
Banaskantha	-14.116	560.65	0.123
Bhavnagar	22.116	663.63	0.115
Gandhinagar	56.096	790.19	0.495
Jamnagar	10.032	392.53	0.1289
Junagadh	31.041	871.93	0.255
Kheda	18.532	1143	0.144
Sabarkantha	25.016	684.72	0.225
Surat	33.454	1018	0.510
Surendranagar	38.426	187	0.502
The dangs	11.161	636.5	0.102

### Table 4-2 Yield trend for (A) Oilseeds and (B) Food grains

Yield trend has been computed (table 4.2) and it was found that maximum correlation in case of food grain was found to be in Gandhinagar, Surat and Surendranagar during the last 20 years. The trend is

**(A)** 

apparent in figure 4.5, which shows that with the increase in number of years, crop yield for food grains has also shown an increasing trend. It can be analysed that in Gandhinagar approximately till 1994 the food grain yield was constant between 1000 – 1200 kg/ha but in the year 1997 it rose to 1500 stating that due to good rainfall in the year 1997 food grain production showed a hike. However it is also noticed that during years 1982, 1984 and 1987 food grain production fell to considerable levels between 500 -700 kg/ha approximately because of the failure of the monsoon rainfall. Similar is the case with Surat and Surendranagar where food grain production showed an increase in yield during normal rainfall years, while during drought years of 1982, 1984, and 1987 Surendranagar's yield was reduced drastically between 300-400 kg/ha.

In case of oilseeds in figure 4.6, only two districts showed a good correlation, which states that in comparison to other districts Gandhinagar and Sabarknatha have depicted a good increase in oil seeds production through out years (1981-2000).



Figure 4-5 Food grain yield trend from 1981-2000 (a) Gandhinagar (b) Surat and (c) Surendranagar



Figure 4-6 Oil seeds yield trend from 1981-2000 (a) Gandhinagar and (b) Sabarkantha

## 4.3.8. NDVI anomaly, Food grain yield and SPI

Agricultural areas have been masked from the entire study area and district wise NDVI anomalies for agricultural areas in Gujarat have been correlated with district wise SPI and crop yield. Linear regression between NDVI anomaly and food grain yield anomaly for the state as a whole, SPI and food grain yield anomaly and NDVI anomaly and SPI has been computed to assess impact of rainfall on crop yield that leads to agriculture drought.

Percentage departure in crop yield (0%, -10%, -25%, -50% and -75%) and the related NDVI anomalies have been computed to define the severity of agricultural drought. 0% to -10% yield equivalent NDVI anomalies have been classed into slight drought, -10% to -25% yield equivalent NDVI anomalies as moderate drought, -25% to -50% yield equivalent NDVI anomalies as severe drought and above -50% of yield equivalent NDVI anomalies have been reclassed into boolean image and 19 binary maps are generated for each of the drought severity classes. These binary mask images for 19 years are added to obtain frequency of slight, moderate and severe drought occurrence at each pixel level.

# 5. Results and Discussion

The chapter explains about how the analysis has been done taking into consideration different indices being computed as well as the statistical relationship computed between various indices and data related to crops. The final results achieved after the entire analysis are embedded in the chapter.

## 5.1. Seasonal pattern of Rainfall and NDVI

Considering the average kharif season rainfall and NDVI patterns for the entire study area for the period 1981-2000, it can be seen from the figure below (Fig.5.1) that their exist increasing correlation between NDVI and rainfall. As rainfall increases from 500 mm, NDVI increases and reaches up to a range of (0.4). However it can be analysed that at around 750 mm of rainfall NDVI almost saturates and there is no further increase in NDVI, despite rainfall increases up to a range of 2500 mm that eventually occur in south Gujarat. NDVI does not respond well to these rainfall events and still remains below (0.5). Since most of the rainfall occurs between July-October with a maximum in August, therefore averaging NDVI data for these months fairly represents the growing season for the region (Tucker 2005).



#### Mean seasonal rainfall

The seasonal pattern of rainfall and NDVI can also be analysed from (Fig 5.2) which shows that the western part of Gujarat is a low rainfall area where rainfall amounts to 300mm for the entire season and the corresponding NDVI values is also low (-0.3). Whereas if one moves towards the central and southern Gujarat comparatively high rainfall areas can be identified where rainfall shoots up to 2500mm and above thereby giving high NDVI values. Figure 5.3 shows the temporal pattern of NDVI

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and rainfall from 1981-2000. It is evident from the graph that during the low rainfall years NDVI values were also low and two major dips in 1982 &1987 shows low rainfall and NDVI which clearly marks that these were the drought years.



Figure 5-2 Average rainfall and Average NDVI (1981-2000)



Figure 5-3 Temporal trends of NDVI and Rainfall (1981-2000)

# 5.2. Spatial pattern of NDVI anomaly and rainfall anomaly

Figure 5.4 depicts the spatial pattern of NDVI and rainfall anomaly during drought year1987 and wet year 1997. It can be observed that during 1987, whole of Gujarat had negative NDVI anomalies and corresponding negative rainfall anomalies whereas in 1997, a wet year, rainfall and NDVI anomalies

were positive. This shows that rainfall has a great impact on the vegetation condition. At places with good amount of rainfall, vegetation shows a good response and NDVI values at these places is high as compared to low rainfall areas.



Figure 5-4 Spatial pattern of NDVI anomaly and rainfall anomaly (a) & (c) 1987 and (b) & (d) 1997

# 5.3. Relationship between rainfall and NDVI

During the 20 years (1981-2000), there was considerable year-to-year variation in precipitation and NDVI. NDVI responded more rapidly to precipitation during drought years particularly in 1982 and 1987 (Fig.5.5). By contrast NDVI responded more slowly to precipitation during wet years i.e. 1988 and 1997. These results are supported by strong relation between NDVI and seasonal rainfall (Fig.5.5). The result of systematic analyses of correlation coefficient values suggest that spatial correlation coefficients between NDVI and rainfall were quite different for different mathematical form of NDVI during growing season and time lag interval of monthly rainfall. The calculated NDVI/rainfall correlations. NDVI/rainfall correlation coefficients are presented as proportional dot maps, shown in (Fig.5.6).

Calculated NDVI/rainfall correlation coefficient show distinct differences in number of stations with significantly positive correlation obtained for different form of NDVI and time lag interval (Fig.5.8 &Fig.5.9). It was found that average and maximum NDVI during rainy season (June-October) had significantly positive correlation with seasonal rainfall for 29% and 37 % of stations respectively. While in monthly time scale NDVI had significantly positive correlation for 65% and 53% of stations with one and two month time lag of monthly rainfall respectively. The areas with large circles represent high correlation areas, which mean that these are the water limiting areas, and thereby are more prone to drought. The lowest correlation values (0.2) appear in south Gujarat, which is high rainfall area (1000mm- 2500mm) whereas high correlation (0.4-0.8) is vigilant in arid and semi- arid areas of north Gujarat and central part of Kathiawar peninsula. These are the areas where annual rainfall is between 400-700mm. maximum correlations values are obtained in this region because precipitation event serves as a primary source of water for plant growth.



Figure 5-5 NDVI/rainfall correlations in drought years (1982&87) and wet years (1988&1997)



Figure 5-6 Correlation coefficient of rainfall with Mean NDVI and Mean rainfall

## 5.3.1. Evaluation of relationship of Maximum NDVI with seasonal rainfall

The relationship between maximum NDVI and seasonal rainfall shows that there is a consistent increase in NDVI as a result of rainfall. Maximum values of NDVI have been taken because these maximum values are assumed to represent the maximum greenness during the period. Also (Li et al 2004; Kassa 1993) to evaluate land cover performance in Senegal used the time integrated NDVI (seasonal NDVI), because according to his study iNDVI is a measure of the magnitude of greenness available through time and therefore quantitatively reflects the capacity of the land to support photosynthesis and primary production. From the figure below (Fig.5.7) it can be analysed that NDVI linearly increased from 0.1 to 0.5 with an increase in seasonal rainfall from 300mm to 1000mm. but NDVI get saturates once seasonal rainfall exceeds 1000mm threshold, after this point there is no significant increase in NDVI even when there is increasing event of rainfall. As discussed above that the average NDVI and seasonal rainfall represents the growing season fairly, but what really can be analyzed from figure 5.1 and figure 5.7 is that NDVI attains a higher value in the maximum but low in average NDVI however correlation is higher in average than the maximum NDVI. This increase in R<sup>2</sup> due to data averaging might be attributed to the considerable decrease of observation rather than removal of outliers. Thus it can be said averaging the NDVI values to remove inter-annual variations reduce the NDVI that may not truly represent the vegetation condition prevailing during the growing season.



Figure 5-7 Relationship between mean seasonal rainfall and maximum NDVI

#### 5.3.2. Influence of seasonal rainfall on NDVI/ Rainfall correlation

In order to better understand whether there were any significant relation between correlation coefficient at different time-lag interval and mean rainfall condition over Gujarat, the data in (figure 5.8) indicates that coefficients at two time lag decreases with increase in rainfall. However coefficient remains at higher side for one-month time lag as compared to two-month lag for the same rainfall condition. Higher values for the correlation coefficients were noticed from the seasonal rainfall from 400-800mm. further increases in rainfall tends to rapidly decrease NDVI/rainfall correlation. These results are also in agreement with those reported by Nicholson and Farrar (1991) for Africa and Li et al. (2002) for China. Thus this study shows that NDVI-rainfall correlation is highly dependent on average rainfall condition in a region. Further it shows that annual rainfall is not associated with proportional increase in water availability and NDVI, resulting in degressive correlation values. Therefore it can be concluded that highest correlation occurs at one-month time lag and the vegetation cover in each month is affected by rainfall in previous month.





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Figure 5-9 Proportional dot maps showing correlation coefficient at monthly and bi-monthly time lags

## 5.3.3. Influence of landuse/cover types on Rainfall/ NDVI correlation

NDVI/rainfall correlations for five major classes of landuse namely irrigated crops, rainfed crops; bare soil, barren land and forest were analyzed. Table5.1 contains these correlations. It is observed that correlation values in irrigated and rainfed crops increases to (0.75 and 0.86) respectively in Lag1.Whereas these values are comparatively low in lag0, lag2, average and maximum correlation. NDVI/rainfall relationship in time lag 1 &2 can also be seen in (figure 5.9). Since rainfed crops grown in Gujarat are short duration and sensitive to water stress they show higher mean correlation values irrespective of time lags as well as average and maximum NDVI during growing season. These correlation values in general increase as one moves from forest to irrigated crops and to rainfed crops. This means correlation of seasonal rainfall with average and maximum NDVI for forest, rainfed and irrigated crops are 0.114, 0.22 and 0.28 and 0.09, 0.235, 0.31 respectively. Overall higher values of correlation are observed for all land use types with one-month time lag of rainfall. This is consistent with the adaptive strategies used by the plants to use water efficiently as deep rooted plants are more buffered from climatic fluctuations than from more-shallow rooted crop plants (Wang et.al). Thus time lag one can be considered as a good indicator of NDVI and rainfall relation in semi-arid areas like Gujarat.

# 5.4. SPI and drought

Drought risk has been identified using SPI in Gujarat by interpolating SPI values over 20 years. SPI during selected drought years of 1982 and 1987 and normal years of 1988 and 1997 have been presented to show the pattern of SPI during these years. In (figure5.10), 3months SPI for the months of August, September and October are presented. It can be seen that during the drought years of 1982 and 87, SPI values are low for the western, central and south-western Gujarat, which indicates that there has been low rainfall in these areas during the south-west monsoon season i.e. during June – September. SPI in 1987 indicated that, 1987 was a severe drought year (Bavadam; Gore and Ponkshe 2004; Gore and Ray 2002) where SPI was found to be below (-3.5) which is considered to be a situation of extreme drought. However, during the normal years of 1988 and 1997 SPI reached up to a value of 3, which states that these years were wet years.

From (figure 5.11), SPI for 164 rain stations in Gujarat can be analysed which indicates that in 1987 SPI dropped as low as -3.5 and most of the stations were below -1.5 further indicating that 1987 was severe drought year than 1982 where SPI dropped only up to -2 at two stations of Bhachau and Chotila. This indicates that 1982 was less severe drought affected than 1987. However if we look towards the normal years only few stations experienced SPI below (-1), which is considered to be a near normal situation, while majority of the rain stations had SPI between 0-2 indicating moderately wet conditions.

TUTRE	No et Stations		Average NDVI			NDVI			Lag			13er			Lag2	
		Mean	Max	Ă	Men	Max	Ā	Men	Max	ų.	Mem	Max	ų	Men	Max	ų
tmigated a cross	14	0.22	0.78	-0.64	025	0.75	10.74	0.4	10.01	0	0.42	0.75	ō	정	80	-000
Rainfied C tys	8	0.28	67.0	-0.62	0.31	<i>W</i> 0	-0.61	0.44 10	0.%	0	0. <del>48</del> 0.48	<b>8</b> 80	0	680	0.71	99 9
Fallow land		-0.11	ΠĐ	-011	-0.02	-002	0.02	80	80	022	00	0:0	00	019	0.19	0.19
Baresol	T	0.16	016	0.16	0.34	청	평 8	047	0.47	0.47	12.0	120	10.51	0 <del>4</del> 9	049	049
Foret	ы	0.114	03	-04	600	90 980	03	035	80	015	0.45	970	82	0.21	<u>لا ال</u>	-0.18

Lag0, Lag1 and Lag2 indicates same, one month and two month previous rainfall

Table 5-1 NDVI/ Rainfall correlation coefficients for different land use/cover types

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## 5.4.1. SPI and drought severity

After the interpolation of SPI, selected drought years were reclassified into severity classes as presented in (figure 5.12) below. Year 1982 had drought up to class 3 indicating severe drought whereas 1987 had extreme drought in western, parts of central and south-western Gujarat. It is well recognised the usefulness of SPI to quantify different drought types. Since SPI can be calculated at different time scales, it often serves as indicator of different drought types. Many studies have demonstrated that short term (3 month) and long term (6 month) are considered as agricultural and hydrological drought indicators (Mc fee et al.1993; Hayes et al, 1999). Hence 3 month SPI of September month was used in the present work to quantify severity of drought for selected drought and wet years.



# Figure 5-12 Drought severity for drought years (a) 1982 and (b) 1987 and Wet years (c) 1988 and (d) 1997

## 5.4.2. Evaluation of relationship of SPI with NDVI anomaly and crop yield anomaly

NDVI anomaly and SPI have been computed for the state as whole and it shows that when SPI is positive NDVI anomaly is also positive, which states that NDVI anomaly and SPI shares a liner

correlation (fig 5.13). Since SPI represents the water deficit or excess, positive SPI represents that water has been available to plants in just the right amount so that the NDVI has a Positive value. It can be observed in (figure 5.13) that NDVI anomaly was nearly -40% when SPI was -1.5. These low values pertain to year 1987, which was severe drought year. Also SPI value of -1.5 indicates severe drought (Drought severity Classification, NDMC). Therefore it can be said that a strong relationship exist between SPI and NDVI anomaly, according to which a drought can be declared when SPI values fall below the threshold of -1.5. District wise correlation between SPI and NDVI anomaly showed that NDVI anomaly and SPI had a significant correlation in almost of the districts of the state. Based on the relationships between NDVI anomaly and 3 month SPI of September, SPI threshold of -1.5 corresponds to 25% of negative anomaly in NDVI.

If we look at (figure 5.13) which shows the relationship between SPI and detrended food grain yield anomaly then it can be concluded that September 3month SPI also shares a positive correlation with crop yield anomaly. Results of correlation and regression analysis between SPI and crop yield is summarized in Table 5.2. It is observed that September was critical month for most of the kharif crops in Gujarat as during September crops are in a reproductive stage and drought at this stage is likely to affect the production of crops. Ahmedabad, Amreli, Bharuch, Bhavnagar, Jamnagar, Junagadh, Panchmahal, Rajkot, Sabarkantha and Surendranagar had shown positive correlations with SPI values of September. Thus an overall outcome of this analysis can be summed up that SPI can be used as an indicator of regional crop production.



Figure 5-13 Relationship of September 3 month SPI with NDVI anomaly and Food grain yield anomaly

S.No.	Districts	NDVI anomaly& SPI	Detrended food grain
			Yield & SPI
1	Ahmedabad	0.723 **	0.631 **
2	Amreli	0.814 **	0.676 **
3	Banaskantha	0.573 **	0.302
4	Bharuch	0.547 **	0.538 **
5	Bhavnagar	0.710 **	0.631 **
6	Gandhinagar	0.593 **	0.055

7	Jamnagar	0.639 **	0.725 **
8	Junagadh	0.754 **	0.640 **
9	Kachh	0.438 *	0.097
10	Kheda	0.639 **	0.317
11	Mahesana	0.621 **	0.334
12	Panchmahals	0.488 **	0.706 **
13	Rajkot	0.624 **	0.655 **
14	Sabarkantha	0.463 *	0.599 **
15	Surat	0.130	0.356
16	Surendranagar	0.386	0.540 **
17	The Dangs	0.057	0.344
18	Vadodara	0.317	0.666
19	Valsad	-0.156	0.361

Table 5-2 Correlation of September 3 month SPI with NDVI anomaly and Detrended yield

\*\* Significant

\* Less significant

## 5.4.3. Drought characterization based on SPI

SPI had been mainly computed to derive meteorological drought. To do so, as the images had been converted to binary images, the addition of these to compute the frequency of years having drought had been done, which did not, gave a true picture of meteorological drought in Gujarat. September 3 month SPI was chosen for computing the meteorological drought. It was found that 3 month SPI is not suitable to derive meteorological drought in Gujarat. Since 3 month SPI is a moving average over July, August and September, the SPI values have been averaged over 3 months thereby reducing the range of SPI values.

Drought severity out of SPI has been correctly classified however when 19 years of 3 month SPI has been added the drought risk has been reduced to merely three classes i.e. no risk, moderate and severe (figure5.14), which does not represent the true picture of the drought situation during 1981-2000. When the time scale increases the frequency of dry periods decreases. Droughts have a different frequency according to the time scale used for analysis. At shorter time scales dry and moist periods change with a high frequency. At the longest time scales the droughts are less frequent but their duration is higher. (Serrano and L'opez-Moreno). Hayes et al. (1999) have shown that for some regions a good rainfall for one month can create the impression that the drought is over but until the SPIs are not above a certain value at all scales (typically -1) a drought will still affect a region one way Therefore further use of SPI in this study to get a combined drought risk of meteorological and agriculture drought risk has been dropped and meteorological drought has been obtained from computation of rainfall anomaly.



Figure 5-14 SPI based meteorological drought risk

# 5.5. NDVI anomaly and food grain yield anomaly

Trend was computed to know the pattern of production from 1981-2000. Increasing trend was noticed in 12 out of 19 districts (Table4.2). It can be seen from the table below that NDVI anomaly and food grain anomaly is giving a good correlation while oilseeds show a weak correlation with NDVI anomaly. This is because oilseeds are not grown in each of the districts in Gujarat. Gandhinagar and Junagadh have good correlation with NDVI anomaly as these are the major castor producing areas in Gujarat similarly Mahesana and Surendranagar are major groundnut producing districts therefore they show a strong relationship with NDVI anomaly. Since oilseeds did not show a strong relationship with NDVI anomaly. It was thus found that their exist a strong correlation between NDVI and food grain yield. (Figure 5.15) represents that as NDVI anomaly increases so do food grain yield which means that when NDVI anomaly is above normal food grain yield anomaly also follows a negative value which indicates that crop yield can be assessed by analysing NDVI anomaly.

Table 5.3 depicts that food grains have a strong correlation with NDVI anomaly rather than oil seeds. Since oilseeds are mainly grown in Surendranagar, Mahesana, Gandhinagar and Junagadh whereby Gandhinagar and Junagadh are leading producers of castor and Surendranagar and Mahesana are major groundnut producing areas. Significant correlation has been observed in Gandhinagar and Junagadh only; therefore study of oilseeds has been eliminated from the study.



Figure 5-15 NDVI anomaly Vs detrended food grain yield anomaly

No of	Districts	Slope	Intercept	Foodgrains	Oilseeds
Districts				(R)	(R)
1	Ahmedabad	0.964	1.597	0.539 **	0.256
2	Amreli	1.771	-1.688	0.777 **	-0.367
3	Banaskantha	1.2995	3.9892	0.523 **	0.280
4	Bharuch	1.0935	0.3055	0.498 **	0.038
5	Bhavnagar	1.348	1.7623	0.617 **	-0.107
6	Gandhinagar	1.307	2.947	0.415 **	0.529 **
7	Jamnagar	1.3518	14.303	0.549 **	-0.09
8	Junagadh	1.1736	-3.593	0.332	0.601 **
9	Kacchh	-0.0058	1.096	-0.013	0.075
10	Kheda	0.3248	-0.68	0.457 **	0.254
11	1 Mahesana		-0.77	0.462 **	0.426 *
12	Panchmahals	1.006	0.883	0.550 **	-0.131
13	Rajkot	1.966	-2.001	0.637 **	-0.054
14	Sabarkantha	2.494	-4.99	0.629 **	0.33
15	Surat	0.4032	0.479	0.184	-0.015
16	Surendranagar	1.0814	2.65	0.427 **	0.326 *
17	The Dangs	0.5254	-0.95	0.123	0.490
18	Vadodara	2.317	-1.778	0.655 **	0.00
19	Valsad	0.1098	5.093	0.402	-0.083

 Table 5-3 District wise correlation between crop yield anomaly and NDVI anomaly (\*\* indicates significant correlation)

# 5.6. NDVI and food grain yield anomaly based agriculture drought risk

Initially Percentage departure in food grain yield anomaly (0%, -10%, -25%, -50% and -75%) and the related NDVI anomalies have been computed to define the severity of agricultural drought. 0% to - 10% yield equivalent NDVI anomalies have been classed into slight drought, -10% to -25% yield equivalent NDVI anomalies as moderate drought, -25% to -50% yield equivalent NDVI anomalies as severe drought and above -50% of yield equivalent NDVI anomalies very severe drought. But these computations based on district level yields gave a wrong picture of agriculture drought. Therefore approximate NDVI equivalent threshold from crop yield trend for the state as a whole was computed and agriculture drought risk was thus delineated as slight, moderate and severe. Where NDVI equivalent threshold for slight drought was -10%, moderate as -25% and severe as -50%. (Figure 5.16) shows the frequency of each type of risk in agricultural drought.

Table 5.4 summarizes the frequency of each risk class. It is clear from the table that Kucchh is the only district that has a high frequency of slight, moderate and severe risk. Frequency of slight risk ranged between 3-5 and almost all districts faced severe drought 3-5 times in past 19 years. In case of moderate risk Banaskantha, Bhavnagar and Jamnagar lies next to Kucchh having a frequency of 4 moderate drought years out of 19 years. Severe drought has occurred in Jamnagar and Kucchh for most number of times in contrast to other districts. If we look at the complete scenario it can be concluded that Jamnagar (49%), Kucchh (52%), Banaskantha (44%), Bhavnagar (43%) and Ahmedabad, Rajkot and Surendranagar (40%) have been more prone to agricultural drought during 1981-2000. Also it is understood that The Dangs, Valsad and Vadodara are not much affected by agricultural drought as these districts belong to high rainfall area where average rainfall is above 2000mm.

	Agı	ricult	ural	droug	nt		Μ	eteorol	ogica	al drou	ıght	
Districts		%										
	S	F	Μ	% F	Se	% F	S	% F	Μ	%F	Se	%F
Ahmedabad	5	24	3	16	2	10	5	26	2	12	1	8
Amreli	4	22	3	14	2	9	5	26	3	16	1	8
Banaskantha	5	25	4	18	2	11	5	27	5	24	2	13
Bharuch	4	22	3	13	2	8	5	26	2	12	1	7
Bhavnagar	5	24	4	19	2	12	5	26	3	17	1	6
Gandhinagar	4	19	1	7	1	5	5	26	3	15	2	8
Jamnagar	5	27	4	22	3	15	5	28	5	25	3	16
Junagadh	4	22	3	15	2	11	5	26	3	18	2	10
Kheda	4	22	2	10	1	6	5	26	3	15	1	6
Kucchh	5	27	5	25	4	20	5	27	5	25	3	15
Mahesana	4	23	3	15	2	8	5	26	4	22	2	10
Panchmahals	4	21	2	11	2	9	5	27	5	25	2	10
Rajkot	4	23	3	17	2	10	5	26	4	18	2	10
Sabarkantha	4	21	2	12	2	9	5	27	4	21	2	13

Surat	4	21	2	13	2	8	5	25	2	9	2	8
Surendranagar	4	23	3	17	2	10	5	26	2	13	2	8
The Dangs	3	18	3	14	2	10	4	21	1	6	1	6
Vadodara	4	20	2	8	1	7	5	27	3	17	1	6
Valsad	4	19	2	13	2	10	4	20	2	9	2	9

S- Slight	Se- Severe
<b>M- Moderate</b>	% F – Frequency

## Table 5-4 Frequency of different drought risk classes in agriculture and meteorological drought

Finally to get agricultural risk map (Figure 5.18 B), the maps in figure 5.16 which shows the frequency of years in each risk level were multiplied by weights according to the risk level and therefore high weight of 0.5 was given to severe, 0.3 to moderate and 0.2 to slight risk. Table 5.5 reveals the percentage area facing agriculture drought risk. Only 2 districts namely Kutch and Jamnagar face high agricultural drought risk covering 30% of the total area, while 6 districts Mehasana, Surendranagar, Ahmedabad, Banaskantha, Rajkot and Bhavnagar face moderate drought risk covering 32% of the total area. Sabarkantha, Gandhinagar, Panchmahal, Kheda, Bharuch, Junagadh, Amreli and Surat has moderate agricultural drought risk whereas Vodadara, Valsad and Dangs are free from drought risk.

Code	Description	Agri	cultural dro	ught	Meteo	orological dr	ought
		No. of Districts	Area (sq.km.)	% Area	No. of Districts	Area (sq.km.)	%Area
1	No risk	3	13687	6.98%	2	5893	3.01%
2	Slight	8	59276	30.25%	4	35240	17.98%
3	Moderate	6	63284	32.28%	11	100212	51.12%
4	High	2	59777	30.49%	2	54679	27.89%
Total		19	196024	100%	19	196024	100%

# Table 5-5 Percentage area of districts affected by different degrees of drought risk in terms of Agriculture and meteorological drought



Frequency of Agriculture drought risk in three differnt severity classes (A) Slight (B) Moderate and (C) Severe

Figure 5-16 Frequency of agricultural drought risk



Frequency of Meteorological drought risk in three different severity classes (A) Slight (B) Moderate and (C) Severe

Figure 5-17 Frequency of meteorological drought risk



(A) Meteorological Drought Risk and (B) Agriculture Drought Risk Figure 5-18 Meteorological & Agriculture drought risk

# 5.7. Rainfall anomaly based meteorological drought

Rainfall anomaly gave an approximate picture of the meteorological drought prevailing in the state. The criteria for declaring a meteorological drought by Indian Meteorological Department (IMD) was adopted to identify the risk and hence on previous page in (figure5.17), it can be analyzed that in past 19 years frequency of slight meteorological drought was 14, moderate was 10 and severe drought was 7 times. Slight drought was identified when rainfall anomaly was 25%less than normal, moderate when rainfall deficit was 50% and severe when rainfall deficit was 75%. The resultant severity maps were then given weight similar to those given to the agricultural drought severity maps i.e. 0.5 (severe), 0.3 (moderate) and 0.3(slight), which were then added to get meteorological drought risk map (figure 5.18 A). The figure explains the presence of very severe drought risk in Kutch, whereas the southern portion of the state has no to slight risk. Since the areas with moderate and severe risk are major areas for crop and oilseeds production, dry land agriculture in these areas should be aimed at generating management skills required for adjusting cropping patterns and cultivation practices as the situation demands, depending upon the occurrence of rain/drought. Table 5.5 summarizes the percentage area affected by meteorological drought.

# 5.8. Drought risk classification

Final drought risk map, which has been obtained by integrating the risk maps generated from agriculture and meteorological drought. These maps were integrated using ENVI 4.0. The accompanying Table 5.6 and (figure 5.19) and (figure 5.20) shows the percentage area affected by the combined risk. Valsad and Dangs are the only two districts free from drought risk while, slight and

moderate risk areas encompass 21.68% and 22.66% of total geographical area. High risk prevails in nearly 30% of the area which comprises of districts that are major producers of food grains as well as oilseeds; therefore a stress has to be given more on these districts while drought management plans are prepared. Percentage frequency for each of the risk severity class for agricultural and meteorological drought risk can be referred in (Appendix 2).

Code	Description	No. Of	Name of Districts	Area (sq.km.)	% Area
		districts			
1	No risk	2	Valsad, The Dangs	5893	3.01%
2	Slight	6	Bharuch, Gandhinagar,		
			Panchmahals,	42509	21.68%
			Sabarkantha, Surat,		
			Vadodara		
3	Moderate	5	Ahmedabad, Amreli,		
			Bhavnagar, Junagdh,	44423	22.66%
			Kheda		
4	High	5	Banaskantha,		
			Jamnagar, Mahesana,	57547	29.36%
			Rajkot, Surendranagar		
5	Very High	1	Kacchh	45652	23.29%
Total		19		196024	100%

## Table 5-6 Percentage area facing agricultural and meteorological drought risk



# Drought risk areas delineated by combining agricultural and meteorological drought risk areas

Figure 5-19 Areas facing a combined drought risk



Figure 5-20 Total percentage of area facing a combined drought risk

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# 6. Conclusion and Recommendations

# 6.1. Summary

The main objective of the study was to identify the relationship between rainfall and NDVI and to see how appropriately drought risk areas can be delineated by integration of satellite, meteorological and other ancillary data.

The first research question as well as objective which say about the relationship between rainfall and NDVI, it was concluded from the study that the temporal variations of NDVI are closely linked with precipitation and there is strong linear relationship between NDVI and precipitation in cases where monthly or seasonal precipitation is within a certain range. In case of Gujarat 300mm of rainfall is the identified threshold for rain fed agriculture, therefore in the areas of eastern and south Gujarat where the rainfall is above this threshold moisture is no longer a limiting factor and NDVI increases very slowly with increased precipitation.

It was also found that rainfall has a positive relation with NDVI and also correlation of rainfall/NDVI was found to be strong in water limiting areas, which sates that these areas are more prone to drought. Though many studies have dealt with establishing relation between rainfall/NDVI, showing that NDVI is a good indicator of vegetation vigour, yet efforts towards a union of different factors to define risk areas was still to be attempted for better describing an area at risk.

The first chapter gives an overview of the problem under study, the different definitions, concept describing drought types and impacts and need for risk evaluation. The chapter also contains the objectives of the study and thereafter research questions framed to achieve the study objective.

The second chapter deals with the previous drought related studies, different methods used to study, monitor and assess drought. It was seen that most of the studies has studied about relating either of the satellite derived parameters as NDVI, VCI, TCI with each other and other meteorological parameters to assess drought conditions but inclusion of agricultural drought from the point of agricultural production and its linkage with the satellite parameters could not be found in the literature referred. Thus this part was undertaken as the second objective of the study, so that drought risk can be marked out taking into consideration the crop yield.

The third chapter gives a brief description of the study area. The fourth chapter discusses about the methodology followed to achieve the framed research questions and objectives. Correlation regression relation has been worked out between different factors such as: NDVI, rainfall, NDVI anomaly, SPI and crop yield anomaly have bee computed to study the effect of each factor on risk possibilities.

The fifth chapter deals with the results obtained after the entire processing of the data and preparation of final risk map. The seasonal pattern of rainfall and NDVI obtained from the last 20 years of data, suggest that the western part of Gujarat is a low rainfall area where rainfall amounts to 300mm for the entire season and the corresponding NDVI values is also low. However it is noticed that at around 750 mm of rainfall NDVI almost saturates and there is no further increase in NDVI, despite rainfall increases up to a range of 2500 mm that eventually occur in south Gujarat. Thus it can be said that NDVI/rainfall shares a strong correlation where water is a major limiting factor for plant growth. Study of NDVI/rainfall relation with respect to different lag-time and different landuse/cover types also suggest that rainfed crops show a good correlation with monthly time-lag, stating that monthly NDVI/rainfall correlation can be used as an indicator of plant health/condition in semi-arid areas like Gujarat.

From the entire work it is evident that the north western and central part of Gujarat are water limiting areas which are therefore more susceptible to drought. It is also noticed that SPI had shown significant relation with NDVI anomaly and food-grain yield anomaly, which suggests that SPI can be used as an indicator of regional crop production and vegetation status. Meteorological drought risk areas have been identified using rainfall anomaly, an alternate to SPI. Combination of drought risk from agricultural and meteorological drought risk states that nearly 30% of the total geographical area in Gujarat faces both types of drought risk.

Thus an overall outcome presents that risk areas can be assessed appropriately by the integration of various data sources and thereby management plans can be prepared to deal with the hazard.

# 6.2. Problems and limitations

The major area of concern during the entire thesis work was to deal with SPI. Though SPI has shown to be a good indicator of meteorological drought at different time-scales, 3 month time scale in this study could not provide appropriate results to identify risk areas correctly. Hence it is recommended that SPI should be computed on a monthly time scale for semi-arid areas so that a precise demarcation can be made in identifying risk areas. One problem which I could feel have affected the SPI is that since SPI computation requires at least 30 years of time-series rainfall data, the data available for this study was for only 23 years which might have affected the SPI derived meteorological drought risk. The SPI allows monitoring operationally any location with a 30-year time series (Rouault and Richard).

Due to time constraint, SPI on one-month time scale could not be computed and worked up on. But it's clear from the study that 3 month SPI can give only seasonal variation of rainfall thereby reducing the drought probability.
#### 6.3. Future work

Though the present work deals with satellite and meteorological parameters as well as crop yield statistics to arrive at a combined risk yet due to unavailability of ancillary data, still some of the portions which could not be handled and can be taken up in further research are listed below.

- Drought from socio-economic aspect could not be studied. Besides delineating areas under drought risk, relevancy of risk assessment can be made more meaningful when the human population as well as livestock population under risk can be assessed. Therefore it is recommended to include the socio-economic data to better understand the vulnerable factors.
- Also inclusion of different sources of livelihood besides agriculture can help know the percentage of population directly affected by droughts. Other information about the state as to growth of industrial sector, tourism, handicrafts and other small-scale industries can be further associated with the study to precisely mark out areas that are likely to be worst affected by droughts, either agriculture, meteorological or socio-economic drought.
- Also it is recommended that higher SPI timescales may not be useful for drought quantification in the present study area hence shorter timescales of 1 month and 2 month should be considered to identify meteorological drought risk.
- Further more as the final risk map gives the areas facing a high drought risk, a detailed study of these areas in terms of soil, water availability, temperature conditions, rainfall, crops grown, the economic importance of the area, and the social conditions prevalent can further help in preparing better management plans.
- Final risk areas delineated from the integration of various data sources has given a correct pattern of the risk areas. This is because the results presented in the present thesis has been based on two selective drought years (1982&1987) and two wet years (1988 &1997), which according to the literature referred were drought and non drought years. However since no published reports were available for the validation of the results, therefore there is an urgent requirement of the validation of the maps being prepared.

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## **Appendix 1**

### **Field Photographs**



Cotton field with parched land



Groundnut field



Cotton at flowering stage



Maize at panicle stage

### Contd..



**Rice cultivation** 

LAI measurement in groundnut field



Parched maize field

# Appendix 2

#### Frequency of agricultural and Meteorological drought risk in different districts



