AGRICULTURAL DROUGHT ASSESSMENT UNDER IRRIGATED AND RAINFED CONDITIONS

Thesis submitted to the Andhra University, Visakhapatnam in partial fulfillment of the requirement for the award of *Master of Technology in Remote Sensing and GIS*

Submitted By:

Suman Kumar Padhee

Supervised By:

Dr. Bhaskar R. Nikam
Scientist 'SD'
Water Resources Department
IIRS

Dr. S. P. Aggarwal
Scientist 'SF' & Head
Water Resources Department
IIRS

Indian Institute of Remote Sensing, ISRO,
Dept. of Space, Govt. of India, Dehradun – 248001
Uttarakhand, India

August, 2013

CERTIFICATE

This is to certify that this thesis work entitled ***"Agricultural Drought Assessment Under Irrigated And Rainfed Conditions"*** *submitted by* ***Mr. Suman Kumar Padhee*** *in partial fulfillment of the requirements for the award of Master of Technology in Remote Sensing and GIS by the Andhra University. The research work presented here in this thesis is an original work of candidate and has been carried out in Water Resource Department under the supervision of Dr. Bhaskar R. Nikam and Dr. S. P. Aggarwal, Scientists at Indian Institute of Remote Sensing (IIRS), ISRO, Dehradun, India.*

Supervisors:

Dr. Bhaskar R. Nikam
Scientist/Engineer 'SD'
Water Resources Department,
Indian Institute of Remote Sensing
Dehradun

Dr. S. P. Aggarwal
Scientist/Engineer 'SF'& Head
Water Resources Department,
Indian Institute of Remote Sensing
Dehradun

Dr. Y.V.N Krishna Murthy
Director,
Indian Institute of Remote Sensing
Dehradun

Dr. S.K. Saha,
Dean (Academic)
Indian Institute of Remote Sensing
Dehradun

The love of family and the admiration of friends are much more important than wealth and privilege...

Dedicated to my family and my friends.

ACKNOWLEDGEMENT

First and foremost I convey my thanks to Andhra University for providing me the degree of Masters of Technology in Remote Sensing and GIS.

I feel glad to offer my sincerest gratitude and respect to my supervisor, Dr. Bhaskar R. Nikam, Scientist/Engineer ‘SD’, Water Resources Department, IIRS for his precious guidance and ideas to me during my study. I consider myself extremely fortunate to have had the opportunity of associating myself with him. This thesis was made possible by his patience and persistence.

I express my sincere thanks to Dr. S. P. Aggarwal, Head, Water Resources Department, IIRS for providing me the necessary facilities in the department. His cooperation at every stage of project work made us possible to learn and work, which helped us in completing this project successfully.

I feel immense pleasure in expressing my profound sense of gratitude to Dr. Y. V. N. Krishna Murthy, Director, IIRS for his consistent inspiration and motivation during the project work.

I also appreciate the help from India Water Resources Information System and India Meteorological Department in the research work during the project.

After the completion of this thesis, I experience feeling of achievement and satisfaction. Looking into the past, I realize how impossible it was for me to succeed on my own. I wish to express my deep gratitude to all those who extended their helping hands towards me in various ways during my tenure at IIRS, especially my friends. I will always remember the light moments spent with my friends Deepak sir, Vineet. Raj, Tarul, Bikram, Dinesh, Gaurav, Priyanka, Neha and Tejaswi and my colleague, friend and roommate, Anudeep, which relieved the work pressure of the immense tensed situations during project. I am thankful to them evermore, for their support beside me.

I am also thankful to Arpit Chouksey, Scientist ‘SC’, Water Resources Department, for setting a motivational example for me to acquire knowledge and grow in life.

I greatly appreciate & convey my heart full thanks to my juniors Shishant, Ponraj, Kritika, Brajesh, Anirudha, Jitendra Pratiman, Anand and Bhoopathi and my friends Prateek, Surojit, Sanjukta, Suruchi, Anupriya and Mansi.

Finally, I am especially indebted to my parents for their love, sacrifice, and support. They are my first teachers after I came to this world and have set great examples for me about how to live, study, and work.

Date: 19/08/2013 Suman Kumar Padhee

ABSTRACT

Drought is an extreme condition due to moisture deficiency and has adverse affect on society. The drought can be classified into three categories *viz.* Meteorological, Hydrological and Agricultural drought. The Meteorological drought occur when actual rainfall is 25% less than the climatological mean, Hydrological drought occur when there is marked depletion of surface water causing very low stream flow and Agricultural drought occur when scarce soil moisture produces serious crop stress and affects the crop productivity. The soil moisture regime of rain-fed agriculture and irrigated agriculture behaves differently on both temporal and spatial scale, which means the impact of meteorologically and/or hydrological induces agriculture drought will be different in rain-fed and irrigated areas. However there is a lack of Agricultural drought assessment system which considers irrigated and rain-fed agriculture spheres as dissimilar parameters. On the other hand recent advancements in the field of earth observation through different satellite based remote sensing sensors have provided researches a continuous monitoring of soil moisture at global scale, which can aid in Agricultural drought assessment/monitoring. Keeping this in mind, the present study has been envisagedwith the objective to utilize Meteorological drought indicator along with the satellite data to assess and predict the Agricultural drought separately for rain-fed and irrigated spheres. The Bundelkhand Region, a semi-arid area has beenselected as the study area.

In this research, Effective Drought Index (EDI) derived from precipitation observations by IMD has been employed for Meteorological drought identification. The RS derived NDVI and soil moisture are popular elements for drought identification and monitoring. MODIS NDVI and ESA CCI blended soil moisture data has been utilized in the research. The soil moisture, probably having relationships with the Meteorological drought indicator and NDVI, could serve as estimator plus in prediction elements for Agricultural drought. But the satellite soil moisture has the limitation of coarse spatial resolution which demands the spatial downscaling. Linking model based on Triangle method has been used for spatial downscaling using MODIS Enhanced Vegetation Index (EVI) and Land Surface Temperature (LST). Due to unavailability of LST in Kharif season (June-September), the focus has been kept on Rabi seasons (October – April), the major agricultural season for the region, in this research.

An attempt has been made, to indentify sensitiveness of downscaled soil moisture to Meteorological drought for assessment of Agricultural drought. Anomalies in NDVI & soil moisture (16 day composites) for Rabi seasons of 2000-01 to 2009-10 were computed. Correlation between EDI & soil moisture anomaly and soil moisture anomaly & NDVI were found to have larger valuein rain-fed areas, than in irrigated. The analysis has been done for different agro climatic zones within Bundelkhand region. Owing to inferences of sensitivity analysis, regression models have been developed to determine the relationship between EDI & soil moisture anomaly and soil moisture anomaly & NDVI anomaly, for irrigated and rain-fed regions in different agro climatic zones. Hence, the developedmodelare the efficient agriculture drought assessment model for the region, having capability to assess and predict the effect of EDI on soil moisture and soil moisture on vegetation at 16 day time scale. The developed model

also have predictive capability based on future meteorological data availability, which enhances its utility in analyzing future Agricultural conditions if meteorological data is available.

TABLE OF CONTENTS

CONTENTS **PAGE**

LIST OF FIGURES

LIST OF TABLES

CHAPTER 1

INTRODUCTION

1.1 BACKGROUND

Drought is a very less understood and complex phenomenon (Hisdal and Tallaksen, 2003). It is a natural hazard as the result of an extreme event due to prolonged insufficiency in water availability. The causes for this phenomenon to occur may be sub-normal rainfall, uneven rainfall distribution, greater requirement of water than availability or the combinations of all the three. As a result, the demand on water resources increases which can lead to inconsistency in supply to users. These can create conflicts among the various competitors which is most definite throughout severe droughts. Incorrect estimation of drought might have serious consequences for ecology and economy as well. The damage caused by drought is not specific in global domain. It is slow and gradual process due to which the degree of this particular calamity varies from place to place.

1.2 DROUGHT DEFINITIONS

The drought has no precise definition. Diversified hydro-meteorological variables, socio-economic factors and different water demands in different regions have kept researchers away from compiling/modifying any precise definition of drought. The definition of drought which is good enough for one field does not help its implementation in another field. However, some broad definitions are sited below:

(i) The World Meteorological Organization (WMO, 1986) describes “drought means a sustained, extended deficiency in precipitation.”

(ii) The UN Convention to Combat Drought and Desertification (UN Secretariat General, 1994) defines “drought means the naturally occurring phenomenon that exists when precipitation has been significantly below normal recorded levels, causing serious hydrological imbalances that adversely affect land resource production systems.”

(iii) The Food and Agriculture Organization (FAO, 1983) of the United Nations defines a drought as a hazard, “the percentage of years when crops fail from the lack of moisture.”

(iv) The encyclopedia of climate and weather (Schneider, 1996) defines a drought as ‘an extended period – a season, a year, or several years – of deficient rainfall relative to the statistical multi- year mean for a region.”

(v) Linsley *et al.*, (1959) defined “drought as a sustained period of time without significant rainfall.”

(vi) Gumbel (1963) defined “drought as the smallest annual value of daily stream flow.”

(vii) Palmer (1965) described “drought as a significant deviation from the normal hydrologic conditions of an area.”

However, its definition varies according to the causes and transaction phases for which it occurs and the fields which it effects. Hence, the definitions of drought can be organized into the categories generally known as type of droughts.

1.3 TYPES OF DROUGHT

The droughts are broadly classified in three categories. They are Meteorological drought, Hydrological drought and Agricultural drought. Any one of these categories or combinations of these could generate a fourth category of drought called as Socio economic drought.

1.3.1 Meteorological Drought

The occurrence of any category of drought is considered to be started with the deficiency in precipitation. The Meteorological droughts are based on deficits in precipitation (Dracup *et al.*,, 1980). Whenever the actual rainfall over a region is less than 75% of the long term climatological mean, the resulting drought is known as Meteorological drought. This category is estimated as a region specific matter because the occurrence of precipitation highly varies from region to region.

1.3.2 Hydrological Drought

The occurrence of Hydrological drought is noticeable from the available water in the surface water resources due to reduced precipitation events or quantity. (Hisdal and Tallaksen, 2003) showed in their study that Hydrological droughts are often lagged compared to Meteorological droughts. Hydrological drought occurs when there is marked depletion of surface water causing very low stream flow and drying of lakes, reservoirs, rivers etc.

1.3.3 Agricultural Drought

The deficiency of water from either meteorological or hydrological sources lessens the irrigation water for crop production. This water is supposed to be stored in soil as soil moisture which is ultimately affected as well. As a result, scarce soil moisture leads to Agricultural drought occurrence due to serious crop stress and affects the crop productivity. Hence, Agricultural drought refers to a period with declining soil moisture content and consequent crop failure (Mishra and Singh, 2010).

1.3.4 Socio-Economic Drought

Socio-economic drought is associated with failure of water resources systems to meet water demands and thus associating droughts with supply of and demand for an economic good (water) (AMS, 2004). It occurs when the demand for an economic good passes ahead of its supply due to weather related deficit in water supply. It can result from either of the three categories discussed above or their combined effects for an extended term.

1.4 IMPACT OF DROUGHT

Drought is one of the most costly disasters as compared to other natural disasters. It has a negative impact on various sectors of the society (e.g., economy, energy, recreation, agriculture, water resources, ecosystems and human health) (Dai *et al.*,, 2004,Watson *et al.*,, 1997). Some of the major dire effects of drought are discussed below.

1.4.1 Impact on Economy

The impact of drought on sectors like agriculture, forestry and fisheries, can blow on economy of the country. These sectors have their basic requirements dependent on the surface and ground water supplies. The occurrence of a drought event can become the basis for the losses in yields in crop and livestock production. As a result, the GDP of a country finally reduces and hence the economy also.

1.4.2 Impact on Environment

The impact of drought to environment is seen as damages to flora and fauna including different species, wildlife habitat, forests; degradation of landscape quality, loss of biodiversity, and soil erosion. Normal conditions are reestablished in case of short-term effects. But when these effects linger for long term, the damages may even become permanent. For example, increased soil erosion due to degradation of landscape quality, may result into an everlasting loss of biological productivity.

1.4.3 Impact on Society

The social impact of drought is due its length of persistency and extremity. The shortage of crop production resulting in suicides of farmers is a common nuisance around India. It can also cause loss of human lives due to food shortages, which can create panic and violence in the society as well. Water user conflicts are common during extreme drought, which are mostly political, social and industrial in nature. Social unrest can cause public dissatisfaction with government regarding drought response. The most common concern in developing countries like India is drought directly or indirectly hits to poverty.

1.5 HISTORY OF DROUGHT IN INDIA AND BUNDELKHAND

The Agricultural drought is one of the severe problems in India the documents records of Agricultural droughts are available since 18th century and these droughts have affected many states in the country like Southern and Eastern Maharashtra, Northern Karnataka, Andhra Pradesh, Odisha, Gujarat, Uttar Pradesh, Madhya Pradesh and Rajasthan. The drought years in last century are given in Table.1.1. The impact of Agricultural drought on the society has always been numerous deaths.

Table 1.1 All India Drought years (Gore and Ponkshe, 2004)

1901-1910	1911-1920	1921-1930	1931-1940	1941-1950	1951-1960	1961-1970	1971-1980	1981-1990	1991-2000
All India									
1901	1911			1941	1951	1965	1972	1982	
1904	1918					1966	1974	1987	
1905	1920					1968	1979		

Throughout the 19^{th} and 20^{th} century, there have been only twelve drought years from historical records in Bundelkhand with a frequency of once in 16 years. The frequency of drought gradually increased to thrice in 16 years during 1968-1992. The past years since 2004-05 are under going through drought (NRAA, 2008). As a result, various sectors of the region including the agricultural sector are accounted to suffer in recent days. Moderate to severe Agricultural drought were reported to be occurring for 2-4 years in the 13 districts of Bundelkhand in last 10 years with an increased frequency of mostly 2.5 times in 10 years.

1.6 AGRICULTURAL DROUGHT ASSESSMENT AND ITS NEED

Assessment means to quantify the degree of something. Assessment of droughts is one of the most important aspects in agricultural planning and management. Agricultural drought assessment is a crucial element for planning suitable actions for improvement of conditions in drought like situations. It demands analysis and understanding of past droughts in the regions and its impact for the period of occurrences. For developing drought assessment models, the understanding of concept of drought is must.

Regions where a majority of the population is dependent on agriculture are affected severely by occurrence of Agricultural drought. Agricultural drought causes despair in population and livestock in the whole region. The reduction in agricultural production can lead to additional pressure on government resources. These resources could be meant for being utilized in other productive purposes. (Awosika *et al.*,, 1998; IPCC, 2007) stated that due to global warming, droughts are predicted to turn into more prominent in some of the dry regions of world. Research is a requirement, therefore, to understand more about droughts and its impact on food security. The focus lies on need of assessment systems of Agricultural drought with better approaches than existing ones.

1.7 ASPECTS OF REMOTE SENSING AND GIS IN AGRICULTURAL DROUGHT STUDIES

In recent days the remote sensing techniques and GIS environment are established well enough for Agricultural drought assessment. There are a variety of remotely sensed data acquired from the space by the sensors like MODIS, ASTER, AMSR-E, AVHRR, SMOS, AWiFS, LISS-III, ETM+ etc. serves as input for the various methods throughout the electromagnetic spectrum which are capable for the identification, location and severity of the Agricultural drought.

The final products that could be acquired by these methods are products on drought related parameters like rainfall, soil moisture, crop areas etc., Agricultural vegetation condition images & maps at state level or even at national and global level if spatial extent is concerned, and Agricultural drought assessment maps. National Agricultural drought Assessment and Monitoring System (NADAMS) is very successful project since 1989 under ISRO (Indian Space Research Organization) in India which utilizes the drought information from satellite products for contingency planning and for drought declaration process. Hence, a large number and variability of assistance is available as remotely sensed data parameters for Agricultural drought assessment and prediction.

1.8 PROBLEM STATEMENT

At present, India is a country where over 1.22 billion of population exists and is highly dependent on the agriculture. Bundelkhand is a region in Central India where 80% people are dependent on agriculture. The agricultural returns from this region in Rabi season (October – April) are dominant to that of Kharif season (June – September). An equivalent part of agriculture is dependent on rain-fed system for crop production as compared to irrigated system in Bundelkhand. For this reason, the agricultural lands over this region have enormous pressure for crop production in Rabi. In these situations efforts are required regarding the Agricultural drought monitoring, assessment and prediction during Rabi. The Meteorological drought may not necessarily result in Agricultural drought for the crops under irrigation, but the rain-fed crops are always affected by it. Therefore, there is a necessity to implement the observations from irrigated and rain-fed agricultural areas as different inputs for drought assessment in order to obtain a better accuracy in real time. Moreover, the predictions should be based on the results from such assessment rules to get a closer forecast regarding future climate scenario on Agricultural drought. Evaluation of a seasonal assessment and prediction model for Agricultural drought with different approaches for irrigated and rain-fed areas would help the management plans for Bundelkhand having a better prospect in the future.

1.9 OBJECTIVES

Keeping the basic knowing of Agricultural drought and future challenges in mind, present study has been conceptualized with following objectives:

- To downscale Remotely Sensed parameters available at different scales to a common scale for integration in Agricultural drought Assessment Model.
- To analyze the sensitivity of input parameters (derived from Remote Sensing) with meteorological drought indicators and use them to assess the magnitude of Agricultural drought under different Management practices.
- To utilize future climate parameter (Rainfall) and predict its impact on Agricultural drought.

1.10 RESEARCH QUESTIONS

- How to integrate the data of different spatial scale in Agricultural drought assessment model?
- Which Remote Sensing derived parameters (Vegetation Indices, soil moisture and Land Surface Temperature) are significantly sensitive with Meteorological derived indicators to assess the Agricultural drought?
- How the irrigated and rain-fed Management practice areas responds to the Agricultural drought at both spatial and temporal domain?

CHAPTER 2

LITERATURE REVIEW

Drought is a creeping phenomenon having a slow onset, evolution and end. The impact of drought could create vegetation stress leading to serious damages which is well shown by Breshears *et al.* (2005). The monitoring of onset and evolution of drought and identification of its end has always been a challenge to the decision makers for decades. Although the drought events begin with the deficit in precipitation, the dependency only on rainfall as indicator for assessing severity of drought and its resultant impacts is insufficient. An effective drought assessment system must include various indicators, and these indicators must be regularly monitored to examine both drought's severity and its potential consequences. Some of the indicators in comprehensive drought assessment system are elements like temperature, stream flow, ground water level, reservoir lake level and soil moisture, evapotranspiration etc. The selection of these indicators is decided by the type of application for which the drought assessment is intended.

2.1 REMOTE SENSING AND GIS FOR DROUGHT STUDIES

The remote sensing community have defined drought specifically as a period of abnormal dry weather, which affects the vegetation cover (Heim, 2002).The traditional approaches for drought monitoring that uses ground-based data are laborious, difficult and time consuming (Prasad *et al.*, 2007). Satellite measurements of the biosphere have gained their importance in various aspects of environmental monitoring including the drought monitoring. For drought monitoring, assessment and prediction, Remote sensing and GIS technologies are capable to cover the earth surface, better than traditional techniques. Several new approaches have been developed to extract information from past and real time remote sensing data for the purpose of drought studies. This remark was achieved only after the launch of AVHRR, on June 27, 1979 onboard obtained from National Oceanic and Atmospheric Administration (NOAA). There is an intense use of AVHRR to study in depth regarding the drought. Singh *et al.* (2003) have shown the integration of vegetation condition index and temperature condition index derived from data NOAA AVHRR, to monitor drought over entire India. Another study by Berhan *et al.* (2011) demonstrated the use of NDVI from NOAA AVHRR and Meteosat Second Generation (MSG) to monitor drought over Ethiopia. Gao *et al.* (2011) integrated LANDSAT TM/ETM+ derived temperature vegetation dryness index (TVDI) and regional water index (RWI) to assess drought over Shandong Province in China. Tao *et al.* (2011) represents the effective use of GIS for drought monitoring on Tongjinvallage of Dafang county located in Bijieprefecture of west Guizhou province. The Moderate-Resolution Imaging Spectroradiometer (MODIS) presents a generational advancement over AVHRR. The narrower spectral bandwidths in MODIS for the red band and NIR band, which have increased sensitivity towards chlorophyll and water vapor absorption respectively, makes it more efficient for thematic applications (Huete *et al.*, 2002).

Drought is one of the most dominant causes for crop loss (Wilhite, 2002). Remote sensing is also helpful for Agricultural drought monitoring and assessment. Some of the approaches developed by implementing Remote sensing data are established well enough for Agricultural drought identification and assessment as well. The assessment of drought probability for agricultural areas in Africa have been well shown by Rojas *et al.* (2011) by coarse resolution NDVI and VHI from NOAA AVHRR. Son *et al.* (2012) illustrated the use of monthly MODIS normalized difference vegetation index (NDVI) and land surface temperature (LST) data to monitor Agricultural drought along with integration to Tropical Rainfall Measuring Mission (TRMM) data. It is possible to use Remote sensing and GIS for Agricultural drought monitoring, assessment and prediction in areas with large extent.

However, Remote sensing derived techniques solely are inefficient for generating a clear picture on drought studies. It needs to be integrated to other field variables like ground-based climate, hydrological, biophysical and surface datasets. Some unique approaches like collaboration of Remote sensing data to other fields have been also developed to take a step towards accuracy in assessment and prediction of Agricultural drought. Tadesse *et al.* (2005) integrated AVHRR NDVI 14 day dataset along with Meteorological drought indices from climate data and some biophysical parameters like land cover, ecoregions etc. to predict drought related vegetation stress over U.S. Central Plains. Uniting Remote sensing data with other variables is a significant approach to have potential outcomes.

2.2 DROUGHT INDICES

Drought indices are developed and meant for decision making. It is a value representing the extent of drought, which is used for execution of action during drought. The drought indices are broadly classified into four categories, Meteorological drought indices, Hydrological drought indices, Agricultural drought indices or Remote Sensing data derived drought indices.

2.2.1 Meteorological Drought Indices

Some widely used and advanced Meteorological drought indices are Rainfall Anomaly Index, Palmer Drought Severity Index, Bhalme and Mooley Drought Index, Drought Severity Index, Standardized Precipitation Index, Effective Drought Index and Reconnaissance Drought Index.

The "Rainfall Anomaly Index" (RAI) (Van Rooy, 1965) was one the most popular and basic Meteorological drought index in earlier days. It is completely dependent on long term meteorological rainfall observations. RAI shows the relation between a regional humidity index and the actual evaluation of dry periods during the rainy seasons. It is still used in certain drought studies due to its simplicity in estimation and easiness in usage. The demerit of this index is that it uses the observations from only rainfall.

The "Palmer Drought Severity Index" (PDSI) (Palmer, 1965) was developed for Meteorological drought assessment using precipitation, evapotranspiration and soil moisture conditions as the key inputs. It is based on hydrological accounting and a number of assumptions which are either empirically developed or location specific. It uses the supply and demand concept of water balance and also includes evapotranspiration in the concept for calculation. The PDSI is efficient in addressing two of the most significant properties of drought and they are the intensity of drought and its onset and offset time. The standard PDSI values are given in Table 2.1.

Table 2.1 Palmer Drought Severity Index

PDSI Values	Drought Condition
>=4.00	Extremely wet
3.00 to 3.99	Very wet
2.00 to 2.99	Moderately wet
1.0 to 1.99	Slightly wet
0.50 to 0.99	Incipient wet spell
0.49 to -0.49	Near normal
-0.50 to -0.99	Incipient drought
-1.00 to -1.99	Mild drought
-2.00 to -2.99	Moderate drought
-3.00 to -3.99	Severe drought
<= -4.00	Extreme drought

However, PDSI is very complicated to compute and requires a long term observations of multiple parameters which makes it usable at only limited regions. It has some other limitations too, due to which, the conventional time series models may not be able to capture the stochastic properties of PDSI (Alley, W.M., 1984).

Bhalme and Mooley (1980) introduced "Bhalme and Mooley Drought Index" which is a regional level based Meteorological drought index developed in India. It is simple to calculate as it is dependent on monthly rainfall only compared from its long term mean. The evaluation of drought intensity was identified with the help of accumulated monthly humidity. The "Drought Severity Index" (DSI) (Bryant *et al.*, 1992) was found for European regions. Its entire computation is based on cumulative monthly precipitation. It can be used in four forms depending on the time of observation period. They are, (DSI3) for droughts lasting between 3 and 6 months, (DSI6) for droughts lasting at least 6 months, (DRO3) for droughts lasting between 3 and 6 months with an accumulated deficit exceeding 10% of mean annual rainfall and (DRO6) for droughts lasting at least 6 months, where the accumulated deficit exceeds 30% of annual mean precipitation. Flower and Kilsby (2004) showed the work of DSI based prediction for increase in water resources drought in UK using along with Global Climatic Model (GCM). However, the dire side of these drought indices is that these are purely based only on rainfall of regional observations due to which it is not accepted over a wide range.

The PDSI is one of the most used drought indices in US conditions but it lags in the property of small time scale definition. The need of a drought index for global standards led to the development of "Standardized Precipitation Index" (SPI) (McKee, 1995) with characteristic of a variety of time scale flexibility. It is a potential Meteorological drought index which is easily calculable, requires modest data, independent of the magnitude of mean rainfall and comparable over a range of climatic zones (Agnew, 2000). It overcomes the traditional drought indices like PDSI. It can be also applied for any location by using a transformation of precipitation from a skewed distribution to the normal distribution, which makes it a suitable indicator accepted around the world. Guttman (1997) explained the advantages of SPI being probabilistic in nature and thus, its usability in risk and decision analysis over other drought indices. The identification of extreme drought with SPI presents a better spatial standardization as compared to the PDSI (Hughes and Saunders, 2002). The use of SPI is standardized to a variety of time scales i.e. 1, 2, 3, 6, 12 24, 26, 48 months. The positive value of SPI represents wet conditions whereas the negative values show drought conditions. The intensity of drought is signified by the standardized numbers ranging from 0 to (-2 and less). The Table of standards for SPI is as Table 2.2.

Table 2.2 Standardized Precipitation Index

SPI Value	Drought Condition
2.00 and above	Extremely wet
1.50 to 1.99	Very wet
1.00 to 1.49	Moderately wet
-0.99 to 0.99	Near normal
-1.00 to -1.49	Moderately dry
-1.50 to -1.99	Severely dry
-2.00 and less	Extremely dry

The SPI have also a constraint of minimum time scale up to 1 month. Enormous studies had been carried out for the development of a Meteorological drought index, which can overcome the limits of the most widely known Meteorological drought index ever i.e. SPI. The "Effective Drought Index" (EDI) (Byun and Wilhite, 1999) is a reply to the limitations of SPI. It is developed with a new concept of Effective precipitation. The effective precipitation is the accumulation of the parts of precipitation of the certain days before estimation time, which affects the available water resources at the estimation time (e.g., rainfall of 3 days prior to present day can affect soil moisture of present day). It is based on certain advantages over certain limitations that most of the drought indices share. Firstly, most of the indices are not accurate in detection of arrival and end of the drought and its accumulated stress. Secondly, the time scale for even some of the very advanced drought indices is limited up to one month step, which restricts their usefulness in monitoring ongoing drought. Finally, the majority of them are incapable of differentiating the effects of drought on subsurface and surface water supply. The EDI have the potential to deal with all of the limitations mentioned above. In a comparative study between EDI and SPI, the EDI was found to be better than SPI in detecting long term, extremely long term and short term drought, short term rainfall and also dealing with the problem of over estimation and under estimation (Byun and Kim, 2010).

The EDI provides a series of indices which is meant to draw information other than just a value for drought quantification. Collectively they are, duration and severity of rainfall deficit; rainfall departure from the normal in a definite period; rainfall for the return to normal; a standardized index that can be used for assessment of drought severity at a global level. The standard values for EDI other than rainy season are given in Table 2.3.

Table 2.3 Effective Drought Index

EDI Value	Drought Condition
0 > EDI	Mild Drought
-0.7 > EDI	Moderate Drought
-1.5 > EDI	Severe Drought
-2.5 > EDI	Extreme Drought

The “Reconnaissance Drought Index” (RDI) (Tsakiris and Vangelis, 2005) is relatively new drought characterization index similar to SPI, established on the ratio between accumulated amounts of rainfall and potential evapotranspiration. RDI stands superior to SPI because of using two climatic parameters instead of only rainfall. The RDI can be utilized in three forms: Initial RDI, Normalized RDI and Standardized RDI. When compared, it was found that the RDI is more representative of the deficient water than SPI (Pashiardis and Michaelides, 2008). The RDI can be calculated for any time scale and can be more effectively associated with hydrological and Agricultural drought.

2.2.2 Hydrological Drought Indices

The Hydrological drought indices have been developed for the applications in the hydrological domain. They are generally the indices pointing towards low flow in streams. It is important to analyze the data from stream flow from various gauging stations to estimate he Hydrological drought indices values. This category of drought indices serves their usefulness in the irrigation water estimation (Tallaksen and Lanen, 2004). The Palmer Hydrological drought index and Surface Water Supply Index are the best known drought indices in this category. Another popular Hydrological index Reclamation Drought Index.

The “Palmer Hydrological drought Index” (PHDI) (Palmer, 1965) is derived from PDSI. The difference between PDSI and PHDI is that the criteria for discarding or accepting of drought spells and wet spells are stringently defined in case of PHDI. The end of drought is decided by PDSI when moisture begins to rise but PHDI considers the complete disappearance of moisture deficit. As the meteorological phenomenon is faster than the hydrological phenomenon, the retarding criterion in PHDI discussed above is reasonable for a Hydrological drought index. The PHDI have also the scope to work on real time as well irrespective of the nature of PDSI, which can only work for past records.

The “Surface Water Supply Index” (SWSI) (Shafer and Dezman, 1982) is developed from the concept of water balance in a watershed. Its main motive is to quantify the processes producing discharge. It is particularly used for management purposes. The SWSI calculation also commits to the involvement of snow accumulation which is an improvement over PHDI. Hence, it can be used in the snow covered areas also. It can also be taken to the standards of PDSI for the purpose of comparisons by certain techniques described by Garen (1992). The best suitable area of this particular Hydrological drought index to work out is the mountainous regions.

Another advancement over PHDI is “Reclamation Drought Index” (RDI) (Weghorst, 1996), which is able to act good in real time. It demands air temperature, precipitation, water storage, stream flow, snow data, and duration of drought as input parameters to return the drought severity level. It is developed on the foundation of requirement of action plans at certain severity level. It is mainly used for operational detection of drought occurrence for triggering of necessary actions.

2.2.3 Agricultural Drought Indices

The agriculture is a very crucial sector for the well existence of the socio-economic situations. Drought is a potential threat with a destructive damage to agricultural production. The necessity of a drought index specialized for agriculture led to development of various indices with explicit characteristics for Agricultural drought assessment. They included indices based on the theories of rainfall, soil moisture, actual and potential evapotranspiration and many other factors. Some of the Agricultural drought indices are Moisture Adequacy Index, Crop Moisture Index, Crop Specific Drought Index, soil moisture and Evapotranspiration Deficit Indices.

The “Moisture Adequacy Index” (MAI) (McGuire and Palmer, 1957) is the basic Agricultural drought index to implement the concept of potential evapotranspiration. It compares a location’s moisture need to the actual moisture supply. Hence, the idea behind development of MAI was, to address the understanding of moisture adequacy. The return outcome from MAI is easy to understand and utilize. MAI returns percentage value, signifying supply sufficiency to need. At 100% the supply of moisture meets the requirement.

The “Crop Moisture Index” (CMI) (Palmer, 1968) is developed from PDSI as per the specific requirement of drought assessment in agriculture. This drought index also looks at evapotranspiration and soil moisture recharge rather than only rainfall deficits, making it better than MAI. It is designed with considerations of short term crop moisture needs at weekly time scale. Wilhite and Glantz (1985) identified CMI as an indicator of availability of moisture to meet agricultural crop needs.

The contest for advanced approaches to develop a better Agricultural drought index originated “Crop Specific Drought Index” (CSDI) (Meyer *et al.*, 1993). It integrates three critical factors namely, crop specificity, soil specificity, and weather specificity. These factors are derived from potential crop yield, actual and potential evapotranspiration. When these factors are combined together, they are considered to behave as physical growth stage descriptors for a specific crop. CSDI acts on four stages of crop growth which are vegetative development, ovule development, early grain fill and ripening. The sensitivity of the parameters listed above at these growth stages reveals the drought conditions which crops suffering from. CSDI have also the potential to monitor and assess probable weather impact on crop yields at any point during the growing season. The CSDI do not judge the moisture supply or moisture surplus. However, CSDI has been parameterized for only a limited number of crops like corn, wheat and sorghum.

The "Soil moisture Deficit and Evapotranspiration Deficit Indices" (SMDI & ETDI) (Narasimhan and Srinivasan, 2005) are two recently developed Agricultural drought indices. These indices reflect short-term dry conditions, thus respond to Agricultural drought. The SMDI and ETDI have no any seasonality (i.e., the indices are able to indicate a drought irrespective of season. Both of the drought indices are spatially comparable, irrespective of climatic zones. The time scale of SMDI and ETDI is flexible at least to weekly scale. It can be extended to more by addition of weekly values on incremental basis. The SMDI is depends on weekly soil moisture whereas the ETDI uses potential and actual evapotranspiration to calculate water stress ratio as indicator.

2.2.4 Satellite Derived Drought Indices

The various remotely sensed data serves as input for the various methods, which are used for the identification, monitoring and assessment of the drought. It is facilitated by several satellite based indices like (NDVI, VCI, SVI, NDWI, CWSI, TCI, VHI, TVDI) in Visible, Near Infrared and Thermal Infrared and Microwave regions, to target and analyze the concerned areas. Among these, the NDVI is one of the most popular and globally accepted remote sensing indices for Agricultural drought.

The "Normalized Difference Vegetation Index" (NDVI) (Tucker, 1979) is the most prominent vegetation index derived from remote sensing data to be used in identification and monitoring of vegetation. The first most application of NDVI in drought monitoring is demonstrated by Tucker and Choudhury (1987). The formulation of NDVI is:

$$NDVI = (NIR - Red) / (NIR + Red)$$

Where, NIR is the reflectance in Near Infrared band, Red is the reflectance in Red band

The NDVI Ranges between (-1 to +1) with positive values for vegetation and negative values for non-vegetative areas. The NDVI is not only used in its primary form but also used in several other forms to relate with the phenology of the vegetation cover (Chen *et al.*, 2001; Lee *et al.*, 2002; Stockli and Vidale, 2004; Hermance *et al.*, 2007). The mean of NDVI is used for overall greenness, maximum of NDVI for peak greenness, NDVI amplitude for real time greenness and multi-temporal NDVI for vegetation monitoring. Ozdogan and Gutman (2008); Thenkabail *et al.* (2009); Dheeravath *et al.* (2010) illustrated the valuable use of MODIS NDVI for identification of the mapping of irrigated agricultural areas. The NDVI is a foundation for derivation of various other advanced Remote sensing indices.

The “Vegetation Condition Index” (VCI) (Kogan, 1990; 1995) is a Remote sensing index which is derived from the NDVI. The VCI is computed as pixel-wise normalization of the NDVI. It was first developed from AVHRR NDVI from Goddard Earth Sciences Distributed Active Archive Center (GES-DAAC), for the control of local differences in ecosystem productivity. The Equation for the VCI is:

$$VCI_i = 100 *[(NDVI_i - NDVI_{min}) / (NDVI_{max} - NDVI_{min})]$$

where, $NDVI_i$ is the smoothed 10-day NDVI, $NDVI_{max}$ is the absolute maximum NDVI and $NDVI_{min}$ is the minimum NDVI. The VCI values can be averaged spatially and temporally to facilitate comparison with the Meteorological drought indices (Quiring and Ganesh, 2010; Rhee *et al.*, 2010).

The condition of vegetation was thought to be supported by additional information. Temperature is one of those supporting parameters which have ability to address drought. With the same idea, “Temperature Condition Index” (TCI) (Kogan, 1995) is developed to support the VCI. It is derived from the thermal band which is converted to brightness temperature. The primary use TCI is to determine vegetation stress related to temperature. It is also useful in estimating stress caused by excessive wetness. The TCI is generated from the following equation:

$TCI = 100 [(BT_{max} - BT_j) / (BT_{max} - BT_{min})]$ where, BT_j, BT_{max} and BT_{min} are the smoothed weekly brightness temperature, multi-year maximum and multi-year minimum, respectively, for each grid cell. Kogan(2000) developed another index called as “Vegetation Health index” (VHI) from the joint information of VCI and TCI. The TCI teams up along with VCI to forms VHI as a substitute index characterizing vegetation health. The VHI is defined as:

$$VHI = a\ VCI + (1 - a)\ TCI$$

where, ‘a’ is the coefficient determining the contribution of the two indices. The value for VHI less than 40 represents presence of vegetation stress and greater than 60 favors good condition for vegetation. The global VHI, VCI and TCI maps are available in NOAA.

The “Normalized difference water index” (NDWI) (Gao, 1996) is another advanced remote sensing derived index which follows a completely different theory from that of the NDVI. The bands from which it is formulated are near infrared and short-wave infrared bands.

$$NDWI= [(NIR - SWIR) / (NIR + SWIR)]$$

NIR and SWIR are the reflectance from near infrared and short-wave infrared bands. NDWI is sensitive to water content of vegetation canopy. It is often useful for interpretation of drought assessment with focus on moisture content in vegetation. According to a study done at Rajasthan by Chakraborty and Sehgal (2010), real time MODIS data implementing NDWI can be functional for Agricultural drought detection and monitoring at a regional extent and can be better than NDVI. After the introduction of NDWI, drought studies have taken a diversion regarding approaches for identification and monitoring of drought.

Diversified concepts other than just vegetation condition have led to modification of supplementary Remote sensing derived indices. The "Standardized Vegetation Index" (SVI) (Peters *et al.*, 2002) is one of them. It is a useful index which provides the beginning, amount, intensity and span of vegetation stress. It is derived on the base of the NDVI. The SVI have a potential to unite with traditional drought indices along with other weather and supplementary information for taking responsive decisions during drought.

Other concepts included relating various parameters to vegetation condition. Temperature studied against NDVI was revealed to be having relationship with it. Based on the same concept, "Temperature Vegetation Dryness Index (TVDI) (Sandholt *et al.*, 2002) was introduced. It is one of the most advanced Remote sensing indices at current. It follows the parameterization of empirical relationship between surface temperature and NDVI which forms a virtual triangle. It is computed on purely satellite driven data. The TVDI can be calculated as:

$$TVDI = (Ts - Ts_{min}) / (a + bNDVI - Ts_{min})$$

where, Ts_{min} is the minimum surface temperature in the triangle, Ts is the observed surface temperature at the given pixel, NDVI is the observed normalized difference vegetation index, a and b are parameters defining the dry edge modeled as a linear fit to data ($Ts_{max} = a + b\,NDVI$), and Ts_{max} is the maximum surface temperature observation for a given NDVI. The TVDI for a given pixel (NDVI/Ts) is estimated as the proportion between lines A and B (Figure 3.1). The TVDI usage is good enough for application over large areas.

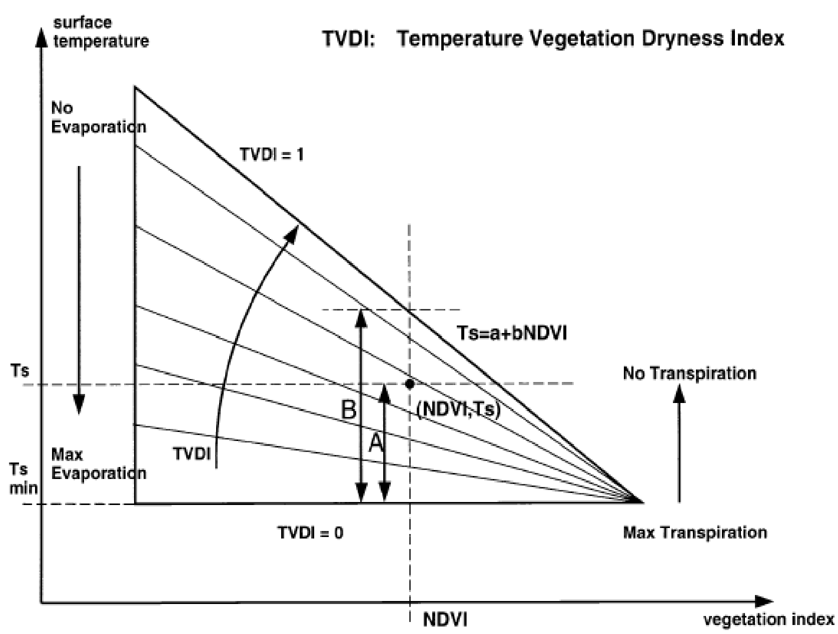

Figure 2.1 Temperature Vegetation Dryness Index (Source: Sandholt *et al.*, 2002)

In addition to all the indices discussed above, some recently developed advanced remote sensing indices are Vegetation Temperature Condition Index (VTCI; Wan *et al.*, 2004), Modified Perpendicular Drought Index (MPDI; Ghulam *et al.*, 2007c), Normalized Multi-Band

Drought Index (NMDI; Wang and Qu, 2007).The entire remote sensing derived drought indices discussed above are more or less comparable with each other, but the service returned by them is fulfilled for the same purpose.

The various indices relating to different categories are explained with their application and usage. Each index in each category has its own advantages and limitations due to which their usage is limited and applied wherever the respective index is appropriate. The application of each index is defined which is taken into consideration in deducing the best index suitable for the present research work.

2.3 SOIL MOISTURE IN AGRICULTURAL DROUGHT STUDIES

Soil moisture monitoring is generally a superior executive mean for Agricultural drought assessment than precipitation (www.fao.org). The only precipitation is not that good indicator for assessment of Agricultural drought because of variable water supply modes (Irrigation from canal, ground water, storage tank, rainfall harvested and rain-fed water). Only rain-fed agricultural practices have a strong relationship between rainfall amount and soil moisture. On the other hand, the irrigated agriculture areas are frequently watered due to which they face less Agricultural drought and that too irrespective of rainfall. Hence, the condition of soil moisture at different areas following different water supply dependency explains the Agricultural drought occurrence. The soil moisture has a major impact in soil temperature, evaporation, water available for plants, biological activities and soil compaction. The soil moisture directly or indirectly affects the soil chemical, physical, and biological properties and thus on agriculture for which, it is remarked as an important Agricultural drought indicator.

New and improved methods of remote sensing have tremendously increased the understanding of land and its parameters. The measurement of the soil moisture from the microwave remote sensing is an achievement. It works at a wavelength range from a few millimeters to several meters. Microwaves have the capability to penetrate by clouds and into the ground, so they can operate in all weather conditions and regions. These are highly sensitive to the moisture content. The depth of penetration is function of moisture content in the soil. Remote measurements from space provide us the possibility of obtaining frequent, global sampling of soil moisture over a large fraction of the Earth's land surface. As it is well known that, microwave measurements have the benefit of being largely unaffected by cloud cover; it has the potential to be used in Agricultural drought assessment. There are several mission/projects running globally which provides products derived from microwave remote sensing (passive). The advantage of passive microwave remote sensing derived products is the global coverage and high temporal resolution. However the global coverage and high temporal resolutions comes at the cost of low spatial resolution of the order 25 to 100 km. These data products can not directly contribute in Agricultural drought assessment/monitoring due to the limitation of spatial resolution, so new streams of research have come up to bring the low spatial resolution geophysical product to high spatial resolution called as downscaling.

2.4 SPATIAL DOWNSCALING OF RS SOIL MOISTURE

The mapping of using the remotely sensed data has been done since a long time. These variations in are observed by passive and as well as active microwave sensors. The greater part contribution in this direction is shared by passive microwave remote sensing which generates data of global extent. It is sound out of the two to use for the application in a large region. But the spatial resolution of the satellite data is very coarse which makes it an unsuitable option for applications at finer resolution level. This reaction for this particular problem can be encountered with the idea of downscaling. Various such attempts of disaggregation were made earlier with different datasets, regions and approaches. Merlin *et al.*, (2009 and 2010) have presented a model which requires information on soil properties, surface micrometeorological and atmospheric observations for the spatial downscaling of from AMSE-E. The linking model based on Triangle method (Carlson *et al.*, 1994) is another method which utilizes remote sensing data for downscaling and it has a statistical approach over the spatial extent. The triangle method has the potential to utilize large image data sets and turn out non-linear solutions for availability (Carlson, 2007). It uses a land surface temperature vs. vegetation index plot for predicting regional condition. Approaches for disaggregation of supported by the surface temperature/vegetation index have significant physical principles (Wang *et al.*, 2007). The linking model based on Triangle method have been used for downscaling of retrieved from satellite sensors like SMOS (Piles *et al.*, 2011) and AMSR-E (Kim and Hogue, 2012). The involvement of the *in-situ* measurements could be a valuable element towards for a closer accurate spatial downscaling approach (Kaheil *et al.*, 2008). In another relative approach, Kim and Hogue (2012) have illustrated after the work of Jiang and Islam (2003) the spatial downscaling of AMSR-E by derivation of a soil wetness index at MODIS scale, and utilization of the index as a factor for downscaling. The spatial downscaling is a more appropriate technique than simply resampling, when the spatial disaggregation is meant for parameters like soil moisture, because its variability does not rely on neighboring conditions.

2.5 DROUGHT ASSESSMENT

The quantification of drought severity is called as drought assessment. Drought assessment can be done with the use of a suitable drought index. The drought index selection depends upon the application of drought assessment. It could be meteorological, hydrological or Agricultural drought assessment. Remote sensing derived drought indices could aid a helping hand in this context. Those can be used for all of the three applications stated above.

2.5.1 NDVI Based Drought Assessment

The phenology of vegetation closely reflects the seasonal cycle of rainfall, the knowledge of which can be very useful towards drought monitoring and assessment using NDVI. Similar attitudes have been used in forming drought monitoring, assessment and prediction systems around various countries. The most successful data regarding this is AVHRR NDVI data which is used as primary data for input to generate vegetation specific drought information product called as (Vegetation Drought Response Index) VegDRI (Brown *et al.*, 2002 & 2008). Another successful use of AVHRR NDVI for drought assessment is attained by (National Drought

Assessment and Monitoring System) NADAMS over India. Discussing at global level, FAO have created Global Information and Early Warning System on Food and Agriculture (GIEWS), which is primarily based on near real time AVHRR NDVI.

In early days there was lack of long term time series analysis for drought monitoring assessment. By early 1990s, time series of 20 years AVHRR NDVI had been collected for research. Such long term analysis studies included techniques such as principal component analysis (Eastman and Fulk, 1993). Other advanced analysis had also been carried out including the Fourier analysis to extract information on NDVI response to vegetation out of past records (Azzali and Menenti, 2000).

However, NASA’s Terra and Aqua MODIS available from 1999 onwards providing data with improved sensitivity to vegetation than AVHRR, is a benefit. The spatial resolution of NDVI offered by MODIS is at 200m, 500 m and 1000m. Many fruitful applications of MODIS NDVI for drought monitoring and assessment had been attained. Son *et al.* (2012) have shared one of those success stories over Lower Mekong Basin including four countries namely Laos, Cambodia, Thailand and Vietnam on monitoring Agricultural drought.

The enormous use of NDVI as an Agricultural drought monitoring and assessment indicator around the globe makes it the most suitable remote sensing derived drought index for applications in Agricultural drought assessment.

2.5.2 EDI Based Drought Assessment

The SPI is one of the best known Meteorological drought indices around the world. Other traditional indices have the limitations to be used in specific regions and climate. The SPI overcomes those traditional limitations with a better time scale of up to one month. But, when finer time scale requirement is the priority, a similar efficient index to SPI with better time scale than that of SPI is the demand. The EDI and RDI are such two advancements over SPI. EDI is known to be dealing with relation between precipitation and subsequent (Byun and Wilhite, 1999). Therefore, EDI is considered to have an upper hand over other indices to be a Meteorological drought indicator for the present research.

Many comparative studies of EDI with other drought indices including SPI had been done which stated EDI as a key Meteorological drought indicator. In a comparative study by Usman *et al.* (2005), it was concluded that only EDI satisfied a key requirement of the same index incorporating monitoring and assessment potentials out of a list of compared indices. Morid *et al.*(2006) compared seven Meteorological drought indices in Iran out of which EDI was found to be capable of perceiving the drought’s onset, it spatial and temporal deviations with a good consistency, and it was suggested for operational drought monitoring as well. The forecast by EDI carried better RMSE and MAE errors than SPI in an experiment done by Morid *et al.*(2007), concluding EDI as a better forecasting Meteorological drought index.

The application of EDI can be done in various climate including arid, semi arid, humid, sub humid etc. and can work with integration to a variable software and environments. In a key research carried out by Smakhtin and Hughes (2006), EDI was included in (Spatial and Time Series Information Modeling) SPATSIM software for water resource analysis studies on environmental flow assessments and hydrological model based water resource determinations. Morid *et al.* (2007) had assessed drought with integration in Artificial Neural Network (ANN) for meteorological stations around Tehran. Pandey *et al.*, (2008) had successfully implemented EDI for drought assessment in districts of Kalahandi, Bolangir, and Koraput in Orissa, popularly known as the KBK districts. In the same study EDI proved to be superior to another popular Meteorological drought index named Deciles. An experiment done by Akhtari *et al.* (2009) assessed aerial interpolation methods for spatial analysis EDI drought indices over Tehran. Kim *et al.* (2009) reassessed and summarized primary droughts that have occurred in Seoul over the past 200 years, using the modified EDIs.

All of the above mentioned studies establish EDI as a better meteorological index than traditional meteorological indices and have a good workability in variable climate and regions. The assessments by EDI are closer to accuracy and its predictions carry less error than that of other meteorological indices.

CHAPTER 3
STUDY AREA

3.1 GEOGRAPHY AND EXTENT

The Bundelkhand region of India was selected as the study area for this research project. This region comprises of 13 districts; 7 districts from southern parts of Uttar Pradesh namely (Jhansi, Jalaun, Lalitpur, Hamirpur, Mahoba, Banda and Chitrakoot) and 8 districts from northern parts of Madhya Pradesh namely (Datia, Tikamgarh, Chattarpur, Damoh, Sagar and Panna). The total geographical area of the study area is approximately 29418 km^2 which extends from 23°10'N to 26°27'N in Latitude and 78°40'E to 81°34'E in Longitude (Figure 3.1).The range of altitude in the study area varies from 600 m above the mean sea level in the southern parts to 150 m near above the mean sea level in the northern parts near the Yamuna River.

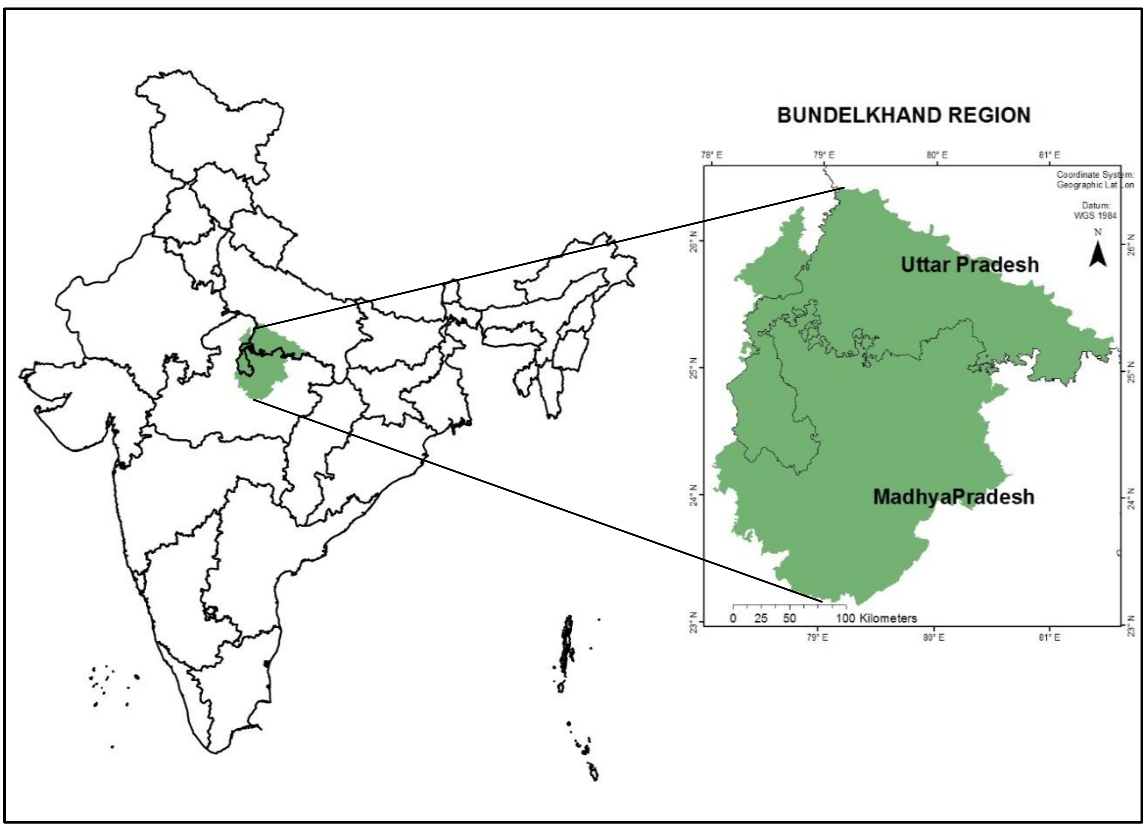

Figure 3.1 Location of Bundelkhand region in India

3.2 GEOLOGY

The entire Bundelkhand region is divided into four important geological systems along the Uttar Pradesh and Madhya Pradesh. They are Archaean, Vindhyan, Transitional and Recent systems.

In Archaean system, the geological systems are made up of metamorphic and igneous rocks. The areas having these systems are crystalline and impermeable which make up a poor aquifer (1-5 lps) and high runoff potential regions. The Vindhyan system holds relatively more ground water (5-25 lps) because they are developed from massive sandstone and limestone escarpments. The Transitional systems are comprised of sedimentary layers of sandstone and limestone of pre Vindhyan and post Aravali period. These systems have a nature of being a reasonable aquifer (5-25 lps).The Recent system is contained with high ground water yield potential (20-40 lps) due to large scale alluvial deposits (NRAA, 2008).

3.3 SOILS AND MINERALOGY

Soil is one of the most significant natural resource, which is essential for the life support on earth. Soil plays an important role in the production of crops in agriculture. The Bundelkhand region is endowed with a classified range of soil type, texture and hydrological group.

As far as soil type is concerned, in southern parts of Bundelkhand, deep and medium black soil is found, mixed red & black, red & yellow soil is found in central parts, and alluvial in the northern parts. These soils are regionally known as Rakar and Parwa in red soil group and Kabar and Mar in black soil group. Soils of heavy black and light red types are widely distributed in the region.

The classification of soil texture and hydrological soil group in Bundelkhand region done by the Food and Agriculture Organization (FAO) states that, it is covered with mostly sandy clay loam textured soil with D type Hydrological Soil Group (HSG) in Uttar Pradesh and Clay textured soil with D type HSG in Madhya Pradesh. The two major minerals distributed over the Bundelkhand region are Kaolinite and Montmorillonite. The Central Bundelkhand regions have Kaolinite whereas Montmorillonite is found is parts of Northern and Southern Bundelkhand as per National Bureau of Soil Survey and Land Use Planning (NBSS&LUP).

3.4 CLIMATE

The climate of the Bundelkhand region is semi-arid in general. It is one of the hottest regions of India. The minimum temperature varies from 6°C to 12°C and the maximum temperature variation is from 38°C to 48°C. Chattarpur district is recorded to have the lowest temperature while Banda district scores for the highest temperature record in Bundelkhand region. Bundelkhand gets a moderate annual rainfall, fluctuating from 750 mm in the northwestern parts, to 1250 mm in the southeastern parts. However rain is an inconsistent; an inundation is generally trailed by stretched period of no rain.

3.5 RAINFALL PATTERN AND AGRICULTURAL SEASON

The occurrence of rainfall events over this region is twice in a year due to which two major agricultural seasons namely Kharif and Rabi subsist. The major rainfall events show during the month of July to end of the month of September because of South West Monsoon. These events contribute around 90% of total rainfall in the region and support the entire Kharif season for the maturity of Kharif crops as well as the sowing of Rabi crops. The minor rainfall events appear during the month of January and February down to Western disturbances. The occurrence of these trivial events is important for the Rabi season as the agriculture of a large part in the Bundelkhand region depends on it.

3.6 WATER RESOURCES

Most of the agricultural areas of the Bundelkhand in Uttar Pradesh are under irrigated water supply whereas the maximum agriculture in Madhya Pradesh is dependent upon rain-fed practice. Betwa, Ken and Dhasan are three most important rivers adding to the irrigation systems in Bundelkhand. Also the existence of areas of mixed practices for water supply is evenly distributed over both the states. These areas have their water supply from either minor irrigation systems like ground water, tanks, small reservoirs etc. or precipitation water depending on the availability. However, ground water is the largest source of water supply for agriculture in the region after rain-fed practice. The water yield from ground in the region is very low due to hard rock hydro-geological conditions except a belt along the Yamuna River.

3.7 AGRO ECOLOGICAL ZONES

The Bundelkhand region falls under two important Agro Ecological systems; Northern Plains Ecoregion in the North and upper central Bundelkhand; Central Highlands (Malwa and Bundelkhand) Ecoregion in lower central and South Bundelkhand. The two major ecoregions of Bundelkhand are shown in Figure 3.2.

3.7.1 The Northern Plains

The Northern Plains (and Central Highland) Ecoregion includes the Aravallis and have a hot semi-arid climate. This region is further divided into two four sub regions out of which the Bundelkhand region includes two. They are Ganga Yamuna Doab, Rohikhand and Avadh Plains and Madhya Bharat Plateau and Bundelkhand uplands. The Ganga Yamuna Doab, Rohikhand and Avadh Plains Ecological System Region (ESR) is hot moist semi-arid with deep loamy Alluvium derived soils which includes sodic phase. The Available Water Capacity (AWC) ranges from 100-200 mm which is medium to high. The Length of Growing Period (LGP) in this ESR is 120-150 days. Another part of Northern Plains is Madhya Bharat Plateau and Bundelkhand Uplands ESR, which is a hot moist semi-arid ESR with deep loamy and clayey mixed Red and Black soil. The AWC ranges between medium to high i.e. 100-200 mm and LGP varies from 120-150 days.

3.7.2 The Central Highlands

Unlike Northern Plains ecoregion, The Central Highlands ecoregion is a hot sub humid dry region. The Central Highlands (Malwa and Bundelkhand) Ecoregion includes four sub divisions out of which two lies in the Bundelkhand Region. They are Malwa Plateau, Vindhian Scarpland & Narmada Valley and Vindhian Scarpland Baghelkhand Plateau. The Malwa Plateau, Vindhian Scarpland & Narmada Valley ESR is hot sub humid with medium deep clayey Black soil. The

AWC is generally high i.e. around 150-200mm and LGP is 150-180 days. Whereas, the Vindhian Scarpland Baghelkhand Plateau ESR, is hot dry sub humid ESR with deep loamy and clayey mixed Red and Black soils. This ESR has Medium to high AWC of around 100-200 mm and a general LGP of 150-180 days.

3.8 AGRICULTURE

A total of 51% and 43% of geographical area of Bundelkhand region is under cultivation in UP and MP respectively. Larger part of the agriculture in Bundelkhand region is rain-fed as compared to irrigated practice. The Rabi sowing (69%) leads over Kharif (31%) in Bundelkhand region conflicting to other agro-ecologies, which is an irony (NRAA, 2008, 2011). In Kharif season, Rice is the major crop which is grown in irrigated and rain-fed areas all over the Bundelkhand. The other Kharif crops are Black Gram/Urd, Green Gram and Red Gram/Arhar, which are raised to a limited proportion of area during the Kharif season. Contrasting to this scene, the major crops to be cultivated during the Rabi season are Wheat and Gram in rain-fed areas while in irrigated parts these crops may or may not be under cultivation. The additional Rabi crops which are cultivated in Bundelkhand are Lentil/Masur, Black Gram and Green Gram. Apart from food grains and pulses, the region also shares a hand on oil seeds, Sugarcane and other crops in the normal rainfall. The region is good with pulses and cereal production but deficient in oil seeds.

3.9 POPULATION

The combined population of Bundelkhand region from UP and MP is approximately 50 million out of which 80% population rely on agriculture. The agriculture dependent population includes marginal, small, medium and large farmers whose 96% income is earned by crop and livestock enterprise.

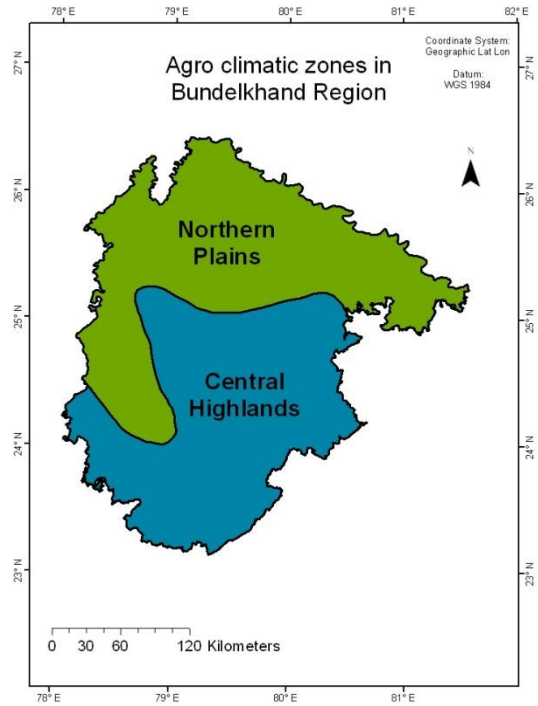

Figure 3.2 Agro climatic zones in Bundelkhand region. (Source: NBSS&LUP)

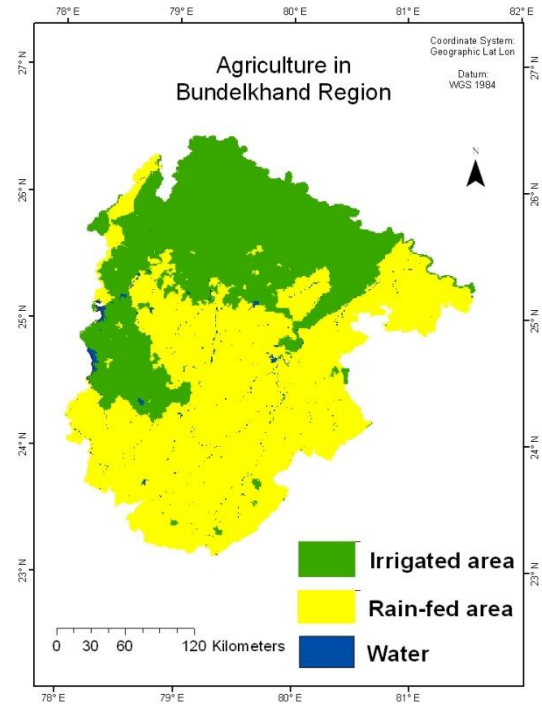

Figure 3.3 Agriculture in Bundelkhand region. (Source: India WRIS)

CHAPTER 4
MATERIALS AND METHODS

This chapter covers the detailed outline of the data and software used, procedure of methods implemented and environment in which the objectives were attempted to achieve for the proposed research.

4.1 DATA PROCUREMENT

The data used is mainly comprised of three categories. Those are products derived from the Satellite sensors, Meteorological records acquired from ground stations and Ancillary data from various foundations.

4.1.1 Satellite Data

(a) MODIS data: The MODIS data used for this work are the MODIS/Terra daytime 8-day Land Surface Temperature (LST) composite of 1 km resolution (MOD11A2) and MODIS/Terra 16-day NDVI product of 1 km resolution (MOD13A2). The NDVI composite is free from cloud, while the LST composite is not. The MODIS products of NDVI and LST available from year 2000 to 2010 in Rabi seasons (October to April) for Bundelkhand region has been used for processing in the study. The MODIS products are freely distributed by the U.S. Land Processes Distributed Active Archive Center (http://lpdaac.usgs.gov) or USGS Global Visualization Viewer (http://glovis.usgs.gov).

(b) ESA CCI global Soil Moisture: The global soil moisture data from (European Space Agency) ESA's Climate Change Initiative (CCI) program, which is generated using active and passive microwave space borne instruments for 32 years (1978 to 2010), has been used for this research. The active data set has been generated by the Vienna University of Vienna (TU Wien) by the observations from the C-band scatterometers of ERS-1, ERS-2 and METOP-A. The passive data set has been generated by the VU University Amsterdam in coalition with NASA by the passive microwave observations from Nimbus 7 SMMR, DMSP SSM/I, TRMM TMI and Aqua AMSR-E. The soil moisture of the Bundelkhand region has been clipped out of global coverage from 2000 to 2010 for the study. The global soil moisture is freely distributed by ESA at website (http://www.esa-soilmoisture-cci.org).

4.1.2 Meteorological Data

The Meteorological data for Bundelkhand region has been procured from India Meteorological Department (IMD), Pune. It consisted of the daily precipitation records from 1975 to 2010, total of 36 years with some data gaps in some of the stations in the entire period. Making the meteorological data compatible with other remote sensing data is required due to which daily rainfall data has been chosen for the research. These daily rainfall records have been used to identify the Meteorological drought seasons and rainfall deficient seasons. These have been also employed to generate Meteorological drought indicator and identify Meteorological drought over Bundelkhand region.

4.1.3 Ancillary Data

The ancillary data includes command area map obtained from India Water Resources Information System (India WRIS) an Indian Space Research Organization (ISRO) initiative, the agro-ecological zones map is acquired from NBSS&LUP, and the administrative boundary maps from Survey of India (SOI). These maps have been used for the separating different environment for analysis having irrigated and rain-fed areas in varying agro ecological zones.

4.2 SOFTWARE USAGE

The software used for the data processing and analysis are as follows:

- ERDAS Imagine 9.3
- Arc GIS 10.0
- Statistica

However the 10 year period bulk processing was handled with the interactive codes in Python 2.7.3 and 2.6.5 programming language mostly with arcpy and GDAL modules.

4.3 METHODOLOGY

This section explains the detailed procedure followed for the proposed research. The entire methodology includes four major parts. The first part is preparation of rainfall distribution images for the study area, preparation of the Meteorological drought condition images out of them and identification of drought effected Rabi seasons within the study period. The second part is pre-processing in which all the datasets from remote sensing being used in this study are brought to a common platform in terms of temporal extent. It is followed by the third part that includes spatial downscaling of soil moisture from low to high spatial resolution and the sensitivity analysis of meteorological and remote sensing derived parameters. The sensitivity analysis has been done with the anomalies prepared for the RS data, which are probable to be sensitive with Meteorological drought indicator. This has been accomplished for irrigated and rain-fed areas separately to create an effective Agricultural drought assessment model for the region. The final part of the methodology involves the assessment and prediction of the Agricultural drought in the region by incorporating future climatic parameter. The entire flow diagram of the method for this research is demonstrated in Figure 4.1.

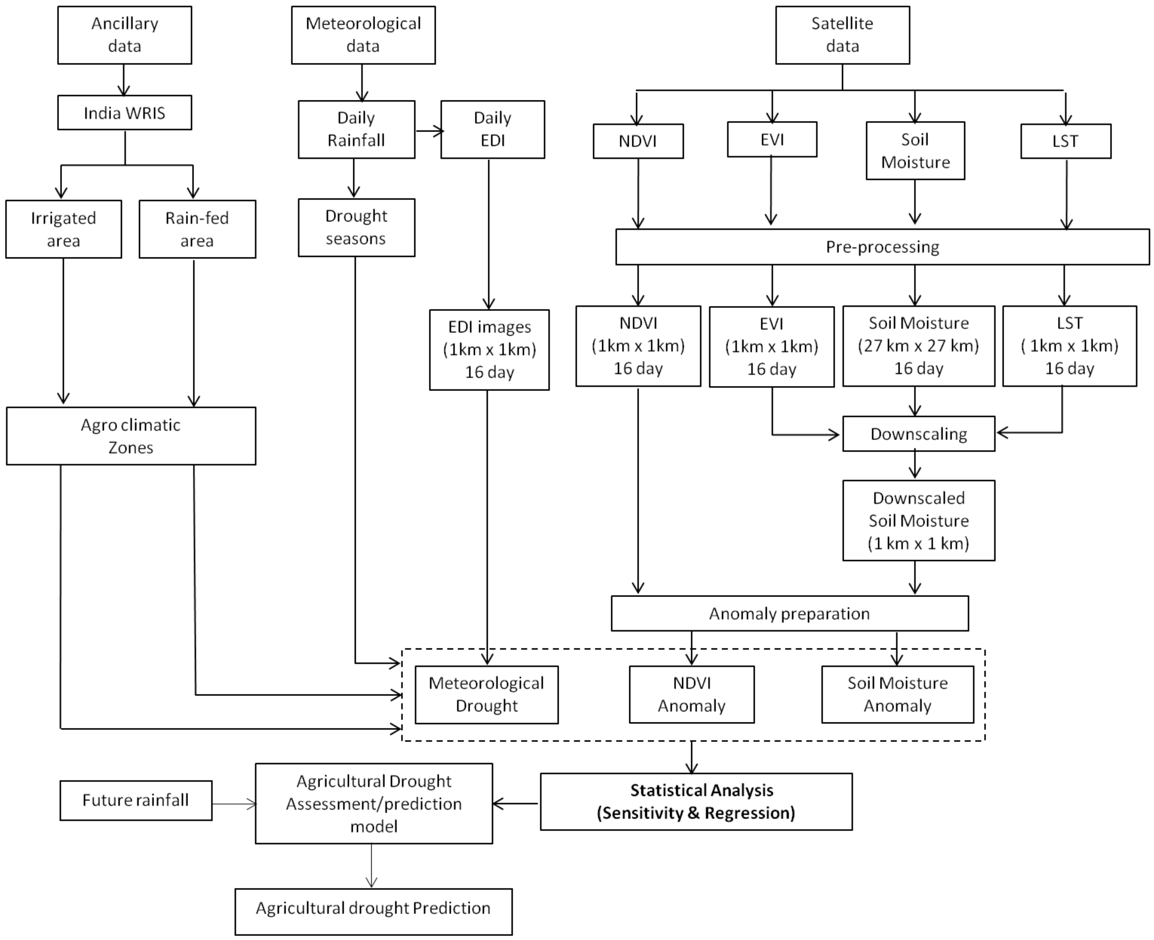

Figure 4.1 Flow diagram showing the development and use of agricultural drought assessment model.

4.3.1 Rainfall Distribution and Meteorological Drought Condition Images

(a) Rainfall distribution maps: The rain station point layers with rainfall observations in mm, at each point (station) have been prepared from the IMD data. This has been done for each day, since the first day of 1975 to last day of 2010. After that, Inverse Distance Weighted (IDW) interpolation technique has been used to generate daily rainfall distribution maps (raster format) out of all point layers for the entire study area. The reason for selecting IDW technique for interpolation is that, it distributes the value in cells with an assumption that things that are more close to one another are alike than those that are farther apart. However, a station with the existence of data gaps was excluded in the interpolation for the period of gap. Figure 4.2 shows the point layer map prepared out of the information of meteorological station's location, which is used to interpolate the rainfall distribution images.

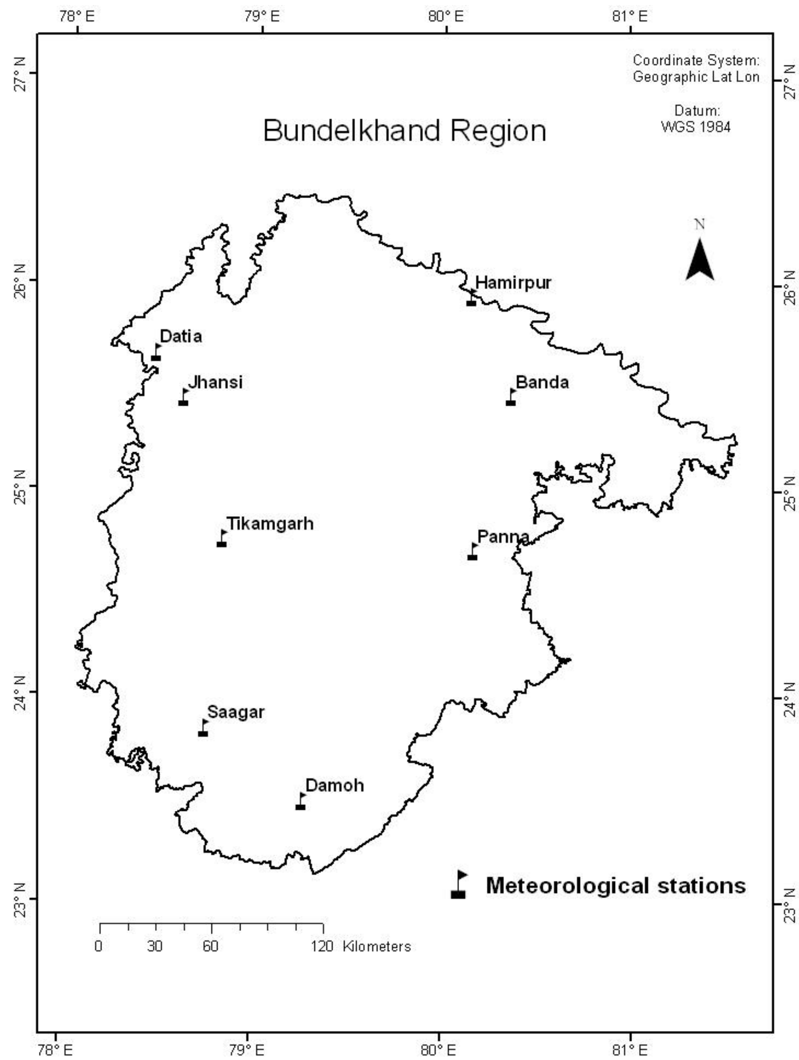

Figure 4.2 Meteorological stations in Bundelkhand

(b) Meteorological drought condition maps: The Effective drought index (EDI) (Byun and Wilhite, 1998) was selected as the Meteorological drought condition indicator, because of the advantage of well-suited flexibility to daily time scale. The EDI was calculated for each day from 1975 to 2010. EDI is calculated from the concept of Effective precipitation (EP) which is the effective part of total rainfall prior to a definite number of days which adds to total water resources. It is assumed in this research that, rainfall even three days prior have a lasting effect on the soil moisture of an existing day. The following equations were implemented to calculate EDI is mentioned below.

$$EP_3 = \sum_{n-1}^{3}[(\sum_{m-1}^{n} Pm) /n] \quad (4.1)$$

$$DEP_3 = EP_3 - MEP_3 \quad (4.2)$$

$$EDI_3 = DEP_3 / SD(DEP_3) \quad (4.3)$$

where, EP_3 is effective precipitation of a particular day accumulated for three days, Pm is the precipitation for a day m days prior to a specific day, DEP_3 is deviation of EP_3 from the mean of EP_3 i.e. (MEP_3), and was calculated for each calendar date, in present case the mean value is estimated using 36 years of data, EDI_3 is the Effective drought index value and SD (DEP_3) is the standard deviation of DEP_3 in 36 years range.

4.3.2 Pre-processing

The aim of pre-processing is to get all the datasets to a common time scale and a common projection & coordinate system for the purpose of spatial downscaling.

(a) Temporal Scaling and reference system: The datasets used for the research were incompatible with each other due to difference in their spatial properties and temporal scale. Spatial rescaling of remote sensing products is prerequisite for present study. Out of three major remote sensing product used in the study only the soil moisture data was having spatial resolution of 0.25 decimal degrees, where as LST and NDVI products were having same spatial resolution of 1 km. Hence to bring the soil moisture data at the scale of 1 km downscaling is necessary. On the other hand the highest time scale among the datasets was for MODIS composite NDVI product, i.e. 16 days. Therefore 16 days was decided as the base time scale for temporal scaling and composites of 16 days were derived for the datasets (*viz.* LST and soil moisture). However, the compatibility of EDI condition as per the time scale, has been managed by the average of the corresponding 16 days EDI conditions. The 16 days period for which the composites are made is shown in Table 4.1. The MODIS datasets and ESA CCI soil moisture were having their coordinate systems as (UTM, Sinusoidal) and (Geographic Lat-Lon, WGS 1984) respectively and spatial resolution of 1km and 0.25 decimal degrees respectively. Therefore, they were brought to a common projection & coordinate system i.e. (UTM, WGS 1984) with the linear unit in ‘m’. During the time to bring the spatial reference of all datasets to a common reference system, the pixel sizes were kept at 1km and 27750 km for MODIS and soil moisture respectively, in order to keep the pixel values undisturbed after resampling.

(b) Selection of Rabi season: The Rabi seasons have been taken under consideration for the study because of the following reasons:

(i) The agricultural production of Bundelkhand region in Rabi season dominates to that of Kharif season (NRAA, 2011).

(ii) The spatial downscaling of coarse resolution soil moisture (as discussed below) requires LST and Vegetation index (VI) as input. But the cloud cover over the study area for most of the time in Kharif season makes it difficult to get continuous remote sensing data/data products of LST and VI, whereas Rabi season is mostly cloud free in this area.

Table 4.1 16 days periods in terms of Julian days for which the composites have been prepared.

Onset of Rabi season in staring year	17-32
273-288	33-48
289-304	49-64
305-320	65-80
321-336	81-96
337-352	97-112
353-365	113-128
1-16	**End of Rabi season in next year**

After this the post-processing of this data is performed, which included creation of spatial downscaled soil moisture product and sensitivity analysis between Meteorological drought index and anomalies in Vegetation index and soil moisture data for the same period and time step lag periods for developing an effective Agricultural drought assessment model for the study area.

4.4 SPATIAL DOWNSCALING OF SOIL MOISTURE DATA

The Linking model based on Triangle method for downscaling, have a statistical approach over the spatial extent. According to Carlson, (1994), the theoretical Triangle plot from Vegetation index vs. Land Surface Temperature (LST) defines soil moisture dependency on Vegetation index and Land Surface Temperature. So, to predict the downscaled soil moisture, a second order multivariate polynomial regression model has been derived with soil moisture as dependent variable and EVI* & LST* as independent variables over the spatial domain.

The EVI* map is derived from the parameter, Enhanced Vegetation Index (EVI) which is available with the MODIS NDVI product. EVI is selected in the Linking model over NDVI because of less soil background interference in EVI (Huete et al., 2002). Similarly, LST* map is derived from Land Surface Temperature. The equations to find LST* and EVI* are in equations 4.4 and 4.5 respectively. The job of LST* map and EVI* map are to standardize the values of LST and EVI maps from 0 to 1.

$$\mathrm{EVI}^* = \frac{\mathrm{EVI} - \mathrm{EVI}_{min}}{\mathrm{EVI}_{max} - \mathrm{EVI}_{min}} \tag{4.4}$$

$$\mathrm{LST}^* = \frac{\mathrm{LST} - \mathrm{LST}_{min}}{\mathrm{LST}_{max} - \mathrm{LST}_{min}} \tag{4.5}$$

where, EVI is Enhanced vegetation index, LST is Land surface temperature, the subscript *max* and *min* represents the maximum and minimum parameter value over the spatial extent respectively.

The observations of EVI^* and LST^* has been extracted out pixel by pixel, along with the simultaneous soil moisture at same geographic location. It has been achieved with the help of python programming code. These observations have been used for the second order polynomial regression mentioned above. The regression has been performed by importing the observations in the software *Statistica*, and generating a regression equation as in equation 4.6.

$$SM_{coarse} = \sum_{i=0}^{2} \sum_{j=0}^{2} \boldsymbol{a}_{ij} (\mathrm{EVI}^{*})(\mathrm{LST}^{*}) \tag{4.6}$$

$$SM_{fine} = \sum_{i=0}^{2} \sum_{j=0}^{2} \boldsymbol{a}_{ij} (\mathrm{EVI}^{*})(\mathrm{LST}^{*}) \tag{4.7}$$

where, SM_{coarse} is the coarse resolution soil moisture at of a location, a_{ij} represents the set of coefficients from the second order polynomial regression. SM_{fine} is the fine resolution soil moisture at the same location as that of SM_{coarse}.

Equation 4.6 generates the coefficients for second order polynomial regression (a_{ij}**)** which has been used again with LST* and EVI* as in equation 4.7, with pixel by pixel approach, to predict the downscaled soil moisture values at spatial resolution of LST* and EVI* (1 km). The coarse resolution soil moisture has been downscaled from a resolution of around 27 km to a fine resolution of 1 km intended for the entire study area for the time (October – April) of 2000-01 to 2009-10 with the procedure explained above.

It is important to validate the downscaled soil moisture product before putting it for further use. Therefore, the RMSE of downscaled soil moisture has been checked with coarse resolution soil moisture. Since the spatial scale/resolution of both the data sets were different, the validation was not possible by one to one comparison. Hence it has been done by observing each pixel in the predicted soil moisture product with respect to the value in same geographic location of coarse soil moisture and utilized these observations to check for the Root Mean Square Error (RMSE). Also the change of soil moisture variability to that of coarse resolution soil moisture has been checked. It is because the ESA CCI soil moisture is claimed to have the values in each pixel to be the spatial average of soil moisture soil moisture, within the area of the pixel. The high variation in spatial average of the soil moisture values in the downscaled product to coarse resolution soil moisture product may not represent the accurate moisture conditions in the area. Soil moisture variability acceptance can be defended only if difference between spatial average of both original and downscaled soil moisture products remain within range. This has been tested by comparing the soil moisture values at randomly selected areas common for both the initial and downscaled soil moisture. The error analysis has been performed to quantify the accuracy of the downscaled soil moisture data with respect to original course resolution soil moisture data.

4.5 SENSITIVITY ANALYSIS

Agricultural drought is more complex phenomenon compared to Meteorological drought. In Meteorological drought assessment, the information about rainfall is sufficient to assess the existence and magnitude of Meteorological drought in the area. However by definition Agriculture drought is the condition when water/moisture available is not sufficient for the crops grown in the area. Moisture status of soil depends on many factors along with the rainfall, so it becomes essential to understand the parameters on which Agricultural drought existence and magnitude depends on. Now a days the methodology of Agricultural drought mapped using vegetation index derived using remote sensing data has been well established and accepted globally. Hence in present research the vegetation index is assumed as indicator of effect of Agricultural drought on the crops. The underlying assumption here is the negative deviation in vegetation index values in the drought affected areas is because of water shortage to the crops only. As discussed in previous section Agricultural drought will have strong correlation with soil moisture then with rainfall data. Hence to test this assumption the sensitivity analysis between Meteorological drought index, soil moisture and vegetation index is formatted for the study area. Since the drought is the main objective of this study, to avoid the voluminous data analysis, the sensitivity analysis of the anomalies of all the parameters mentioned above is done instead of the real data.

(a) Anomaly Preparation: The sensitivity analysis has been carried out to find out the behavior of the RS derived parameters with respect to Meteorological drought indicator (EDI). First, the anomaly maps of the RS parameters have been computed for the Bundelkhand region. This has been done to search for the effect of meteorological conditions on change in RS parameters in a particular period of the season (in this case period of 16 days, same as in Table 4.1). Anomaly means percentage deviation of the value of a parameter (soil moisture or vegetation index) from its long term mean. Therefore, it is important to have the long term mean before any processing. The long term mean maps for 16 days in Rabi season has been computed for soil moisture and NDVI, from observation period of Rabi seasons in 2000-01 to 2009-10. The downscaled soil moisture and NDVI for which anomalies have been prepared were already as 16 day composites, due to which they have been directly used with their long term mean to prepare anomaly images. The anomaly maps for 16 day composites of soil moisture and NDVI were made by the equation described below.

$$X_{anomaly} = [(X_{16} - X_{mean})/ X_{mean}] * 100 \qquad (4.8)$$

where, $X_{anomaly}$ is the anomaly map of a 16 day composite, X_{16} is the 16 days composite raster image, X_{mean} is the long term mean raster image of the particular 16 days for which, the anomaly is being derived. The anomaly images for soil moisture and NDVI has been prepared by python programming codes.

(b) Statistical Analysis: The sensitivity of soil moisture anomaly and NDVI anomaly with EDI and sensitivity of NDVI anomaly with soil moisture anomaly has been analyzed using statistical measures (correlation coefficient). This has been done to utilize the behavior of these parameters, which can help in developing Agricultural drought assessment model. The effect of rainfall deficit in a particular time step will not only have impact on soil moisture and vegetation health of that time step but it will also affect these parameters of successive time steps. To find the best assessment and prediction result possible, the RS derived parameters have been correlated to the EDI having a no lag, 16 days lag and 32 days lag. Various ground studies have revealed soil moisture as a better parameter than meteorological measures, to be related to preceding vegetation conditions (www.fao.org). Therefore, effort has been made for developing relationship between soil moisture anomaly and NDVI anomaly.

The variation in the impact of meteorological parameters is expected to be different in irrigated and rain-fed agricultural regions. It is well known that the deficiency in soil moisture is not very frequent in irrigated agriculture. The rain-fed areas are however reliant on rainfall and experiences arid conditions during deficient rainfall. But, some parts of irrigated agriculture are supposed to behave like going through arid conditions. It is because these regions might not be frequently endowed with required soil moisture by irrigation even being within the command area. Such regions are prone to be victimized by Agricultural drought. Therefore, it is quite essential to test out the sensitivity of all the parameters in irrigated and rain-fed areas as distinct domains. Hence, the sensitivity analysis for irrigated and rain-fed areas has been done separately.

Moreover, this analysis was carried out in varying agro climatic zones around the entire Bundelkhand for irrigated and rain-fed regions. Inclusion of agro climatic zones was preferred because of the vastness of Bundelkhand in area and different crop practice according to rainfall pattern in each zone.

The entire statistical analysis has been observed for the irrigated and rain-fed areas in different agro climatic zones in Bundelkhand region and accordingly an efficient agricultural drought assessment model has been generated with the ability to predict for future agricultural drought.

The output of sensitivity and other statistical parameter will be a robust relationship between Meteorological drought index and soil moisture anomaly and also between soil moisture anomaly and vegetation anomaly. All these relationship, derived separately for irrigated and rain-fed areas of both the agro climatic zones of the study area, arranged in hierarchical manner of their occurrence in nature in mathematical terms will make a model having capability of assessing impact of Meteorological drought condition on Agricultural drought as well as all other parameters. This structure of mathematical relationships is called as Agricultural drought assessment model in present study. The Agricultural drought assessment/prediction capability of this model is tested using rainfall and NDVI soil moisture data for the year 2010 of the Bundelkhand region. These data sets belong to the time period which is never used for the model development. Hence, the time period used for comparison, is a prediction case for the developed model. The Meteorological drought periods at first marked using EDI and then impact of these Meteorological droughts on soil moisture and vegetation condition has been predicated using developed model. The accuracy of Agricultural drought and vegetation condition prediction has been assessed using satellite observed soil moisture and vegetation index maps of the basin.

CHAPTER 5
RESULTS AND DISCUSSIONS

5.1 METEOROLOICAL DROUGHT OVER BUNDELKHAND REGION

5.1.1 Meteorological Droughts in Bundelkhand

Table 5.1 (a) and (b) shows the observations of various meteorological stations spread in Bundelkhand region. IMD has set up eight meteorological observation stations in the Bundelkhand region. Those are namely Datia, Jhansi, Hamirpur, Banda, Tikamgarh, Panna, Saagar and Damoh. The average annual rainfall for 36 years of observation (1975-2010) is shown in the table, according to which, the Meteorological drought years has been identified for the respective station. The Meteorological drought years has been categorized, if the rainfall of a year is less than 75% of average annual rainfall of 36 years in the corresponding meteorological station. All the years from 2000 to 2010 except 2003, were found to be Meteorological drought years for various stations. The interpretations of the meteorological observations in these stations wraps up that, the Meteorological drought years were found to be frequently occurring in the meteorological stations of Bundelkhand region.

Table 5.1 (a) Meteorological drought Years observed from 1975 to 2010 at the Meteorological stations Datia, Jhansi, Hamirpur and Banda

Station code	**42460**	**42463**	**42469**	**42473**
Station name	**DATIA**	**JHANSI**	**HAMIRPUR**	**BANDA**
Average annual rainfall (mm)	729.84	831.34	621.59	889.64
Drought years	1979	1979	1986	1979
	1981	1986	1988	1981
	1982	1996	1991	1984
	1983	1998	1993	1998
	1997	2005	1994	2007
	2005	2006	1995	2009
	2007	2009	2000	
			2001	
			2002	

Table 5.1 (b) Meteorological drought Years observed from 1975 to 2010 at the Meteorological stations Tikamgarh, Panna, Saagar and Damoh

Station code	42562	42570	42671	42674
Station name	**TIKAMGARH**	**PANNA**	**SAAGAR**	**DAMOH**
Average annual rainfall (mm)	750.76	1186.58	1168.40	999.28
Drought years	1988	1979	1976	1986
	1991	1982	1981	1988
	1992	1988	1984	1991
	1994	1997	1986	1997
	1998	2006	1988	
	2002	2007	1989	
	2007		2002	
	2008		2007	
			2010	

5.1.2 Meteorological Drought in Entire Bundelkhand

The rainfall deficit years and Meteorological drought Years observed from 1975 to 2010 for the Bundelkhand Region are shown in Table 5.2. The total of rainfall observed in all stations of Bundelkhand, is used for identification of rainfall deficit years and Meteorological drought years. The mean of annual average rainfall for 36 years in Bundelkhand region is found to be 898.25 mm. The deviation of rainfall from this mean for a year decided the rainfall deficit, if annual average rainfall is less than that of the mean. The Meteorological drought year is recognized, if deficit is less than 75% of the mean. As per a report by the Central govt., it has been shown that since 2000, the region is subjected to frequent drought like situations. According to these Indian Meteorological Department (IMD) observations, the region have observed only two Meteorological drought years since 2000, i.e. 2006 and 2009. But the years 2000, 2002, 2004, 2005, 2006, 2007, 2009 and 2010 are the rainfall deficit years observed. It gives an idea that, the Meteorological drought identification as per IMD is not sufficient to categorize drought conditions for the region. The simple rainfall deviations proved to be a glitch for drought identification and the observations suggested the use of a potential Meteorological drought index for the research.

Table 5.2 Rainfall deficit Years and Meteorological drought Years observed from 1975 to 2010 for Bundelkhand Region

Annual rainfall (mm)		Year	Rainfall deficit from the mean of annual rainfall		Year	Meteorological drought as per IMD
1155.19		1975	Normal		1975	normal year
912.83		1976	Normal		1976	normal year
1118.89		1977	Normal		1977	normal year
1023.86		1978	Normal		1978	normal year
753.78		1979	Deficit		1979	normal year
1185.96		1980	Normal		1980	normal year
620.15		1981	Deficit		1981	drought year
1051.89		1982	Normal		1982	normal year
1001.66		1983	Normal		1983	normal year
815.16		1984	Deficit		1984	normal year
1151.44		1985	Normal		1985	normal year
844.99		1986	Deficit		1986	normal year
870.30		1987	Deficit		1987	normal year
645.76		1988	Deficit		1988	drought year
726.35		1989	Deficit		1989	normal year
1276.95		1990	Normal		1990	normal year
995.29		1991	Normal		1991	normal year
925.40		1992	Normal		1992	normal year
919.75		1993	Normal		1993	normal year
856.79		1994	Deficit		1994	normal year
916.70		1995	Normal		1995	normal year
914.00		1996	Normal		1996	normal year
671.41		1997	Deficit		1997	drought year
892.41		1998	Deficit		1998	normal year
1097.20		1999	Normal		1999	normal year
844.41		2000	Deficit		2000	normal year
962.43		2001	Normal		2001	normal year
806.20		2002	Deficit		2002	normal year
1072.40		2003	Normal		2003	normal year
800.10		2004	Deficit		2004	normal year
858.14		2005	Deficit		2005	normal year
552.18		2006	Deficit		2006	drought year
778.33		2007	Deficit		2007	normal year
1124.53		2008	Normal		2008	normal year
457.63		2009	Deficit		2009	drought year
736.60		2010	Deficit		2010	normal year
The mean of annual rainfall in Bundelkhand region is **898.25 mm**						

5.2 RAINFALL DEFICIT AND METEOROLOGICAL DROUGHT IN BUNDELKHAND DURING RABI

The rainfall observed in Rabi season for individual meteorological stations were computed accordingly to check for deficit and Meteorological drought. The deviation of total rainfall from mean seasonal rainfall is indicator for deficit. The deviation if less than 75% of the mean seasonal rainfall, remarks whether the corresponding season is a drought season or normal season. The observations are presented in Table APPENDIX - I to APPENDIX - VII.

Reports by Inter - Ministerial Central Team, NRAA in lead (2008) have reported that, the presence of Agricultural drought in Rabi season in Bundelkhand is frequent. In Bundelkhand region, the rain-fed agriculture is highly practiced. Since Agricultural drought is initiated from Meteorological drought, the region is supposed to have frequent Meteorological drought seasons. The observations above tell that, there is existence of frequent rainfall deficit periods in the region. But, the Meteorological drought identification method as per IMD is not satisfying to locate the primary reason of Agricultural drought, i.e. rainfall deficit. From the observation in the table series presented above, it can be deduced that, the Meteorological drought identification in this case requires use of a good Meteorological drought index.

5.3 EDI OVER BUNDELKHAND

The above observations and interpretations strongly demand the use of a potential Meteorological drought index for the research. The EDI was selected as the Meteorological drought indicator because of its capability to relate with subsequent soil moisture after rainfall events. The observations from EDI 16 day composites prepared from daily rainfall distribution images are presented in Table 5.3.The table shows mean of EDI conditions in 16 days against the composite represented as **(Year + Julian day)**. The EDI 16 day observations shows frequent occurrence of mild to severe Meteorological drought conditions over Bundelkhand region with a consistency in negative values in Rabi seasons.

Table 5.3 (a) Spatial Average of EDI 16 day in Bundelkhand for Years 2000, 2001, 2002 and 2004.

2000		2001		2002		2003	
Composite	**EDI**	**Composite**	**EDI**	**Composite**	**EDI**	**Composite**	**EDI**
2000001	-0.55	2001001	1.64	2002001	-0.54	2003001	0.08
2000017	-0.24	2001017	1.88	2002017	0.05	2003017	-0.02
2000033	-0.44	2001033	-0.18	2002033	0.46	2003033	1.01
2000049	-0.54	2001049	1.91	2002049	-0.49	2003049	0.41
2000065	-0.42	2001065	-0.07	2002065	-0.32	2003065	-0.01
2000081	-0.92	2001081	6.86	2002081	-0.92	2003081	-0.44
2000097	-1.05	2001097	5.86	2002097	-0.92	2003097	-0.37
2000113	1.00	2001113	1.33	2002113	-0.57	2003113	-0.44
2000129	1.38	2001129	0.51	2002129	-0.46	2003129	-0.51
2000145	-0.04	2001145	3.87	2002145	-0.39	2003145	-0.79
2000161	0.80	2001161	0.59	2002161	-0.46	2003161	-0.33
2000177	-0.74	2001177	2.00	2002177	-0.73	2003177	0.01
2000193	-0.06	2001193	0.83	2002193	-0.84	2003193	0.29
2000209	0.13	2001209	-0.21	2002209	-0.15	2003209	0.11
2000225	0.19	2001225	-0.04	2002225	0.72	2003225	-0.14
2000241	0.07	2001241	-0.54	2002241	0.25	2003241	1.55
2000257	-0.42	2001257	-0.53	2002257	-0.20	2003257	1.37
2000273	-0.55	2001273	2.21	2002273	-0.66	2003273	0.34
2000289	-0.31	2001289	-0.30	2002289	0.44	2003289	0.35
2000305	-0.91	2001305	6.73	2002305	-0.63	2003305	-0.91
2000321	-0.33	2001321	-0.33	2002321	-0.31	2003321	-0.33
2000337	-0.19	2001337	-0.19	2002337	0.18	2003337	-0.19
2000353	-0.31	2001353	-0.31	2002353	0.24	2003353	0.76

Table 5.3 (b) Spatial Average of EDI 16 day in Bundelkhand for Years 2005, 2006, 2007 and 2008.

2004		2005		2006		2007	
Composit	**EDI**	**Composite**	**EDI**	**Composite**	**EDI**	**Composite**	**EDI**
2004001	-0.06	2005001	0.01	2006001	-0.54	2007001	-0.54
2004017	0.81	2005017	0.39	2006017	-0.59	2007017	-0.51
2004033	-0.41	2005033	0.03	2006033	-0.44	2007033	0.75
2004049	-0.54	2005049	0.17	2006049	-0.54	2007049	0.92
2004065	-0.44	2005065	0.88	2006065	1.59	2007065	-0.14
2004081	-0.92	2005081	-0.33	2006081	-0.92	2007081	-0.92
2004097	-0.50	2005097	-1.05	2006097	-0.31	2007097	-0.83
2004113	0.17	2005113	0.11	2006113	-0.47	2007113	0.24
2004129	0.20	2005129	-0.55	2006129	0.12	2007129	0.34
2004145	-0.56	2005145	-0.01	2006145	0.50	2007145	-0.89
2004161	0.55	2005161	-0.47	2006161	-0.68	2007161	-0.19
2004177	-0.51	2005177	1.06	2006177	-0.34	2007177	-0.39
2004193	-0.55	2005193	0.21	2006193	0.39	2007193	-0.56
2004209	0.49	2005209	-0.21	2006209	-0.08	2007209	0.09
2004225	0.49	2005225	-0.15	2006225	-0.07	2007225	-0.44
2004241	-0.77	2005241	-0.46	2006241	-0.35	2007241	-0.20
2004257	0.38	2005257	0.43	2006257	-0.52	2007257	-0.05
2004273	0.32	2005273	-0.62	2006273	-0.57	2007273	-0.55
2004289	-0.10	2005289	-0.31	2006289	0.51	2007289	-0.31
2004305	-0.90	2005305	-0.91	2006305	-0.25	2007305	-0.91
2004321	-0.33	2005321	-0.33	2006321	-0.33	2007321	-0.33
2004337	-0.19	2005337	-0.19	2006337	0.22	2007337	0.18
2004353	-0.31	2005353	0.67	2006353	-0.31	2007353	-0.31

Table 5.3 (c) Spatial Average of EDI 16 day in Bundelkhand for Years 2008, 2009 and 2010.

2008		**2009**		**2010**	
Composite	**EDI**	**Composite**	**EDI**	**Composite**	**EDI**
2008001	-0.54	2009001	0.55	2010001	0.49
2008017	-0.59	2009017	-0.59	2010017	-0.59
2008033	-0.44	2009033	-0.44	2010033	0.10
2008049	-0.54	2009049	-0.54	2010049	-0.24
2008065	-0.40	2009065	-0.23	2010065	-0.44
2008081	0.34	2009081	-0.92	2010081	-0.92
2008097	-0.89	2009097	-0.08	2010097	-1.05
2008113	-0.57	2009113	-0.57	2010113	-0.21
2008129	-0.38	2009129	-0.24	2010129	-0.41
2008145	-0.55	2009145	-0.39	2010145	-0.76
2008161	1.42	2009161	-0.59	2010161	-0.65
2008177	0.42	2009177	-0.25	2010177	-0.53
2008193	-0.17	2009193	0.29	2010193	0.17
2008209	0.60	2009209	-0.91	2010209	0.14
2008225	-0.46	2009225	-0.07	2010225	-0.03
2008241	-0.52	2009241	0.83	2010241	0.14
2008257	-0.07	2009257	-0.54	2010257	0.14
2008273	-0.13	2009273	0.67	2010273	-0.44
2008289	-0.30	2009289	-0.01	2010289	0.34
2008305	-0.91	2009305	-0.04	2010305	-0.55
2008321	0.50	2009321	0.45	2010321	1.66
2008337	-0.19	2009337	0.02	2010337	0.56
2008353	-0.31	2009353	0.50	2010353	-0.31

5.4 SPATIAL DOWNSCALING OF SOIL MOISTURE

The satellite soil moisture data used for the current research was having very coarse spatial resolution which needed disaggregation. The Linking model based on Triangle method is used to downscale the soil moisture spatially to a finer level for proper usability. Figure 5.1 (a) and (b) shows the coarse resolution satellite soil moisture and spatially downscaled soil moisture maps of Bundelkhand region. Figure 5.1 (c) and (d) shows the EVI and LST images which has been used as input to downscale the coarse resolution soil moisture to fine resolution. To validate the use of spatially downscaled soil moisture datasets, it is verified against the original soil moisture datasets. The verification includes the ensuring of two important parameters. Those parameters are the individual predicted soil moisture value in spatially downscaled soil moisture and the spatial variability of the downscaled soil moisture, for which root mean square error (RMSE) and spatial average difference error is checked respectively.

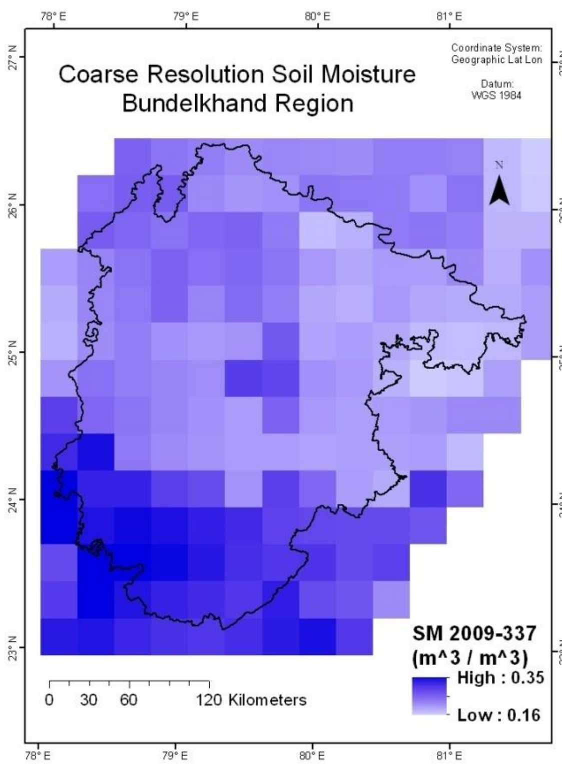

Figure 5.1(a) Coarse resolution soil moisture average of 16 days starting from 337th Julian day of 2009.

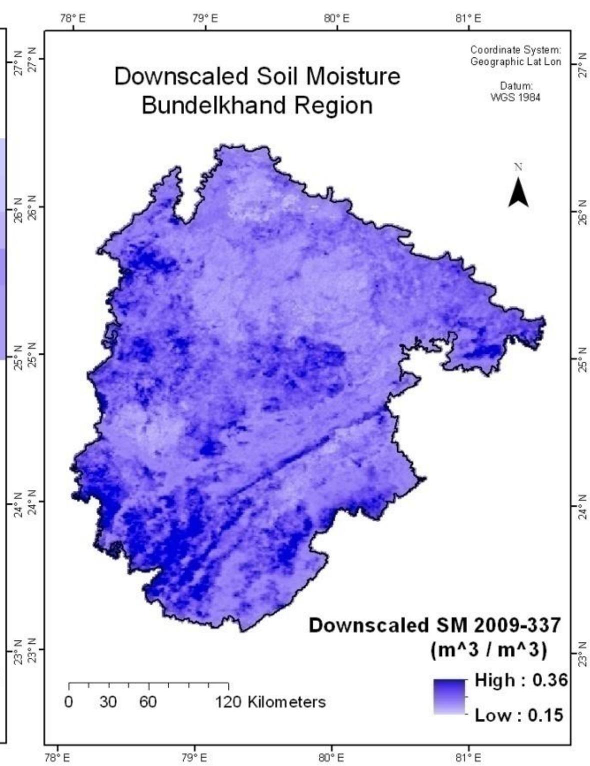

Figure 5.1(b) Downscaled soil moisture of 16 days starting from 337th Julian day of 2009.

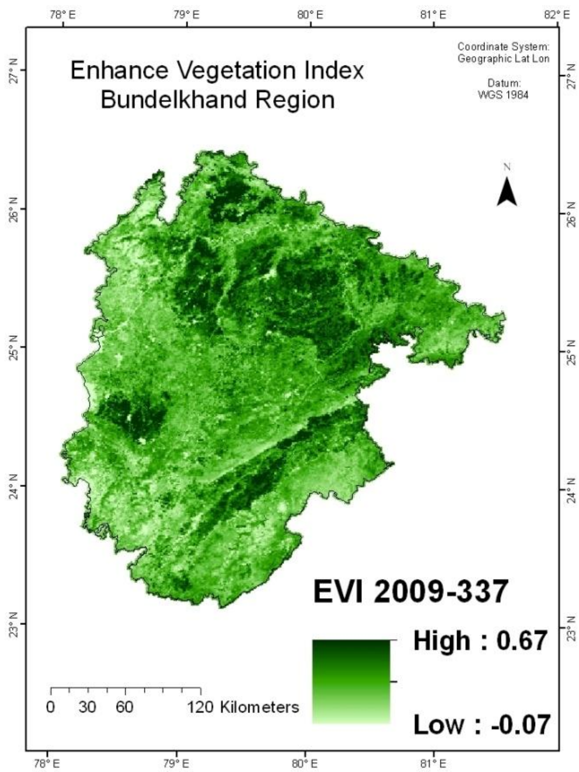

Figure 5.1(c) Fine resolution Enhanced Vegetation Index composite of 16 days starting from 337th Julian day of 2009.

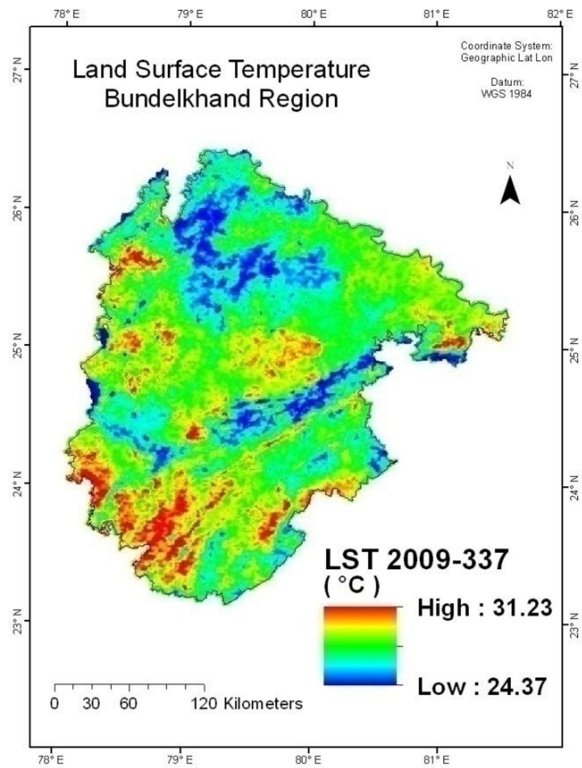

Figure 5.1(d) Fine resolution Land Surface Temperature composite of 16 days starting from 337th Julian day of 2009.

5.4.1 Root Mean Square Error of Downscaled Soil Moisture

Table 5.4 (a), (b) and (c) shows the RMSE between coarse resolution soil moisture and downscaled soil moisture values. It has been done by observing each pixel in the predicted soil moisture product with respect to the value in same geographic location of coarse soil moisture product. The downscaled soil moisture contains predicted values, based on the finer resolution of LST and EVI of the region. The RMSE never exceeded 0.05 (m^3/m^3) from which it was deduced that, the use of downscaled soil moisture is acceptable.

Table 5.4 (a) RMSE of Spatially Downscaled Soil Moisture for the Seasons 2000-2001, 2001-2002, 2002-2003 and 2003-2004

Composite	RMSE	Composite	RMSE	Composite	RMSE	Composite	RMSE
2000273	0.035	2001273	------	2002273	0.025	2003273	------
2000289	0.029	2001289	0.029	2002289	------	2003289	0.040
2000305	0.025	2001305	0.039	2002305	0.038	2003305	------
2000321	0.027	2001321	0.028	2002321	0.030	2003321	0.028
2000337	0.033	2001337	------	2002337	0.028	2003337	0.032
2000353	0.033	2001353	0.028	2002353	------	2003353	------
2001001	0.041	2002001	------	2003001	0.037	2004001	0.034
2001017	------	2002017	------	2003017	0.034	2004017	0.033
2001033	0.024	2002033	------	2003033	0.048	2004033	0.029
2001049	0.025	2002049	0.032	2003049	0.034	2004049	0.030
2001065	0.026	2002065	0.035	2003065	0.026	2004065	0.025
2001081	0.026	2002081	0.026	2003081	------	2004081	0.022
2001097	0.040	2002097	0.024	2003097	0.022	2004097	0.023
2001113	0.025	2002113	0.025	2003113	0.024	2004113	0.023

Table 5.4 (b) RMSE of Spatially Downscaled Soil Moisture for the Seasons 2004-2005, 2005-2006, 2006-2007 and 2007-2008

Composite	RMSE	Composite	RMSE	Composite	RMSE	Composite	RMSE
2004273	0.049	2005273	0.049	2006273	0.049	2007273	0.049
2004289	0.028	2005289	0.049	2006289	0.033	2007289	0.040
2004305	0.033	2005305	0.033	2006305	0.040	2007305	0.040
2004321	0.023	2005321	0.031	2006321	0.048	2007321	0.035
2004337	0.024	2005337	0.033	2006337	0.042	2007337	0.048
2004353	0.023	2005353	0.041	2006353	0.047	2007353	0.043
2005001	0.034	2006001	0.040	2007001	0.012	2008001	0.043
2005017	0.038	2006017	0.037	2007017	0.034	2008017	0.046
2005033	0.038	2006033	0.031	2007033	0.033	2008033	0.039
2005049	0.032	2006049	0.031	2007049	0.035	2008049	0.029
2005065	0.025	2006065	0.044	2007065	0.024	2008065	0.029
2005081	0.024	2006081	0.027	2007081	0.024	2008081	0.032
2005097	0.026	2006097	0.030	2007097	0.029	2008097	0.025
2005113	0.029	2006113	0.025	2007113	0.028	2008113	0.026

Table 5.4 (c) RMSE of Spatially Downscaled Soil Moisture for the Seasons 2008-2009 and 2009-2010.

Composite	RMSE	Composite	RMSE
2008273	0.047	2009273	0.046
2008289	0.031	2009289	0.041
2008305	0.027	2009305	0.035
2008321	0.028	2009321	0.048
2008337	0.032	2009337	0.043
2008353	0.036	2009353	0.045
2009001	0.034	2010001	0.037
2009017	0.039	2010017	0.039
2009033	0.037	2010033	0.040
2009049	0.026	2010049	0.037
2009065	0.024	2010065	------
2009081	0.022	2010081	0.026
2009097	0.033	2010097	0.028
2009113	0.026	2010113	0.029

5.4.2 Spatial Variability of Soil Moisture

The remote sensing derived soil moisture dataset used for this research were having the spatial average of soil moisture distributed over the approximate area. For this reason, it is important to check for the spatial variability of soil moisture of downscaled soil moisture. The validation of change in spatial variability of soil moisture has been done by checking difference in average soil moisture. This average soil moisture value is obtained for downscaled soil moisture as well as satellite soil moisture from 8 randomly chosen locations, common for both datasets. Figure 5.2 shows the map of selected locations around the region from where the spatial average is computed and Table 5.5 (a), (b) and (c) shows the spatial average difference error between spatial average of coarse resolution soil moisture and downscaled soil moisture. The observations from the table infer that, the difference error between spatial average of downscaled and satellite soil moisture never exceeded ±0.05 (m^3/m^3). Therefore, it can be said that the soil moisture variability have changed within the agreeable level.

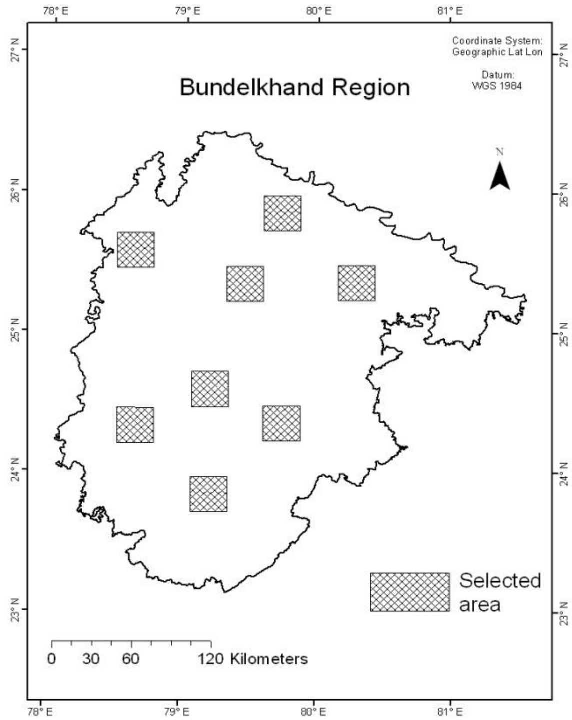

Figure 5.2 Selected Locations around the Bundelkhand region for Testing Degradation of spatial variability in downscaled soil moisture.

Table 5.5 (a) Difference Error between Spatial Average of Coarse Soil Moisture and Spatially Downscaled Soil Moisture for the Seasons 2000-2001, 2001-2002, 2002-2003 and 2003-2004

Composite	Error	Composite	Error	Composite	Error	Composite	Error
2000273	-0.015	2001273	------	2002273	-0.009	2003273	------
2000289	-0.014	2001289	-0.009	2002289	------	2003289	-0.010
2000305	-0.010	2001305	-0.008	2002305	-0.008	2003305	------
2000321	-0.013	2001321	-0.010	2002321	-0.010	2003321	-0.007
2000337	-0.020	2001337	------	2002337	-0.010	2003337	-0.010
2000353	-0.022	2001353	0.003	2002353	------	2003353	------
2001001	-0.009	2002001	------	2003001	-0.005	2004001	-0.001
2001017	------	2002017	------	2003017	-0.010	2004017	-0.002
2001033	-0.009	2002033	------	2003033	-0.014	2004033	-0.011
2001049	-0.011	2002049	-0.015	2003049	-0.007	2004049	-0.002
2001065	-0.006	2002065	0.002	2003065	-0.015	2004065	-0.009
2001081	-0.005	2002081	-0.005	2003081	------	2004081	-0.009
2001097	0.007	2002097	-0.007	2003097	-0.010	2004097	-0.009
2001113	-0.007	2002113	-0.011	2003113	-0.010	2004113	-0.009

Table 5.5 (b) Difference Error between Spatial Average of Coarse Soil Moisture and Spatially Downscaled Soil Moisture for the Seasons 2004-2005, 2005-2006, 2006-2007 and 2007-2008.

Composite	Error	Composite	Error	Composite	Error	Composite	Error
2004273	-0.013	2005273	-0.009	2006273	-0.010	2007273	-0.001
2004289	-0.012	2005289	-0.017	2006289	-0.019	2007289	-0.013
2004305	-0.008	2005305	-0.017	2006305	-0.018	2007305	-0.016
2004321	-0.004	2005321	-0.013	2006321	-0.019	2007321	-0.016
2004337	-0.002	2005337	-0.015	2006337	-0.044	2007337	-0.020
2004353	-0.001	2005353	-0.010	2006353	-0.016	2007353	-0.018
2005001	0.001	2006001	-0.017	2007001	-0.012	2008001	-0.021
2005017	-0.004	2006017	-0.015	2007017	-0.016	2008017	-0.021
2005033	-0.010	2006033	-0.010	2007033	-0.017	2008033	-0.020
2005049	-0.008	2006049	-0.014	2007049	-0.017	2008049	-0.014
2005065	-0.012	2006065	-0.012	2007065	-0.013	2008065	-0.013
2005081	-0.012	2006081	-0.011	2007081	-0.013	2008081	-0.012
2005097	-0.010	2006097	-0.012	2007097	-0.014	2008097	-0.012
2005113	-0.010	2006113	-0.011	2007113	-0.013	2008113	-0.009

Table 5.5 (c) Difference Error between Spatial Average of Coarse Soil Moisture and Spatially Downscaled Soil Moisture for the Seasons 2008-2009 and 2009-2010.

Composite	Error	Composite	Error
2008273	-0.012	2009273	-0.015
2008289	-0.010	2009289	-0.009
2008305	-0.009	2009305	0.001
2008321	0.000	2009321	-0.008
2008337	-0.004	2009337	-0.007
2008353	-0.003	2009353	-0.008
2009001	-0.013	2010001	-0.013
2009017	-0.017	2010017	-0.023
2009033	-0.014	2010033	-0.007
2009049	-0.006	2010049	-0.015
2009065	-0.010	2010065	------
2009081	-0.010	2010081	-0.010
2009097	-0.029	2010097	-0.010
2009113	-0.009	2010113	-0.015

5.5 SENSITIVITY ANALYSIS

The sensitivity analysis has been done to build an effective Agricultural drought assessment model for Bundelkhand region. It includes the analysis of relationship between meteorological parameters (rainfall), soil moisture, vegetation health indicators (vegetation index) for the different rainfall availability periods for the irrigated and rain-fed areas of the two major agro climatic zones, i.e. The Northern Plains ecoregion and Central Highland ecoregion. The irrigated and rain-fed areas in these ecoregions are sighted in Figure 5.3. The complete discussion is presented below.

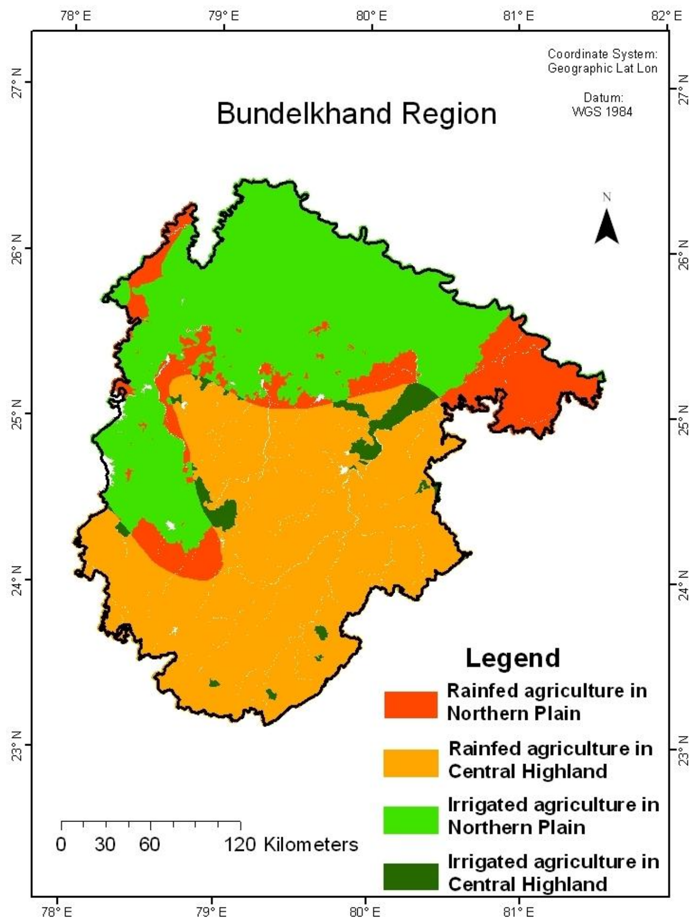

Figure 5.3 Irrigated and Rain-fed Agriculture in Northern Plains and Central Highland ecoregions of Bundelkhand region.

5.5.1 The Northern Plains

(a) Soil moisture anomaly and EDI:

This zone includes its larger part as irrigated areas over the presence of rain-fed areas. The soil moisture anomaly for this region shows a better correlation with EDI having no lag and tends to decrease with increasing lag in EDI. So it can be inferred that, particular soil moisture anomaly composite is most sensitive to its corresponding EDI composite, as compared to its lagging EDI composites. Hence, the Meteorological drought occurrence is found to affect the soil moisture instantly, in case of both irrigated and rain-fed areas in the Northern Plains of Bundelkhand region. However, the correlation coefficient between EDI and soil moisture anomaly, for rain-fed areas is more than in case of irrigated areas. This is numerically proved that the soil moisture status of rain-fed area is more dependent on rainfall then that of irrigated area. In other words, it means the probability of parallel occurrence of Agricultural drought with Meteorological drought is more in rain-fed area than in irrigated areas. The correlation between soil moisture anomaly and EDI laggings in this zone is shown in Table 5.6 and their variation graph of 10 years with 16 days intervals during Rabi is presented in Figure 5.4 (a) and (b). The variation graphs show the change in one parameter with change in other parameter.

(b) NDVI anomaly and EDI:

The NDVI shared a good relationship with EDI at 32 days lag, than EDI with no lag and 16 days lag, with a greater correlation coefficient value for rain-fed areas, than irrigated ones. This implies that, in this ecoregion, the NDVI is affected mostly after 32 days from Meteorological drought occurrence. Also, the frequency of Meteorological drought hits to NDVI of the rain-fed areas is more than to that of irrigated areas. The correlation between NDVI anomaly and EDI laggings in this zone is shown in Table 5.7.

(c) NDVI anomaly and soil moisture anomaly:

The sensitivity of NDVI anomaly is tested with soil moisture anomaly having no lag, 16 days lag and 32 days lag, for best relation. The relation between NDVI anomaly and soil moisture anomaly is revealed to be strongest at 16 days lag for this zone, for both irrigated and rain-fed areas. Moreover, the correlation between NDVI anomaly and soil moisture anomaly at 16 days lag is found to be better than the correlation between NDVI anomaly and EDI. The correlation between NDVI anomaly and soil moisture anomaly at 16 days lag in this zone is shown in Table 5.8 and their variation graph of 10 years with 16 days intervals during Rabi is presented in Figure 5.5 (a) and (b).

5.5.2 The Central Highlands

(a) Soil moisture anomaly and EDI:

The domination of rain-fed agriculture is higher to the irrigated areas in this zone. The soil moisture anomaly for this region shows similar sensitiveness as to that of the Northern Plains. The correlation coefficient value however, shows more strong relationship as compared to the Northern Plains regarding irrigated and rain-fed regions. The soil moisture anomaly is again most sensitive to its corresponding EDI in both irrigated and rain-fed areas. Therefore, the Meteorological drought occurrence is found to affect the soil moisture instantly in the Central Highlands of Bundelkhand region.

The correlation coefficient for rain-fed areas is almost similar to that of irrigated areas. The Meteorological drought occurrence therefore can be said to affect its parallel soil moisture in rain-fed and irrigated areas, almost equivalent number of times. The impact of Meteorological drought on both areas has a very little difference. The correlation between soil moisture anomaly and EDI laggings in this zone is shown in Table 5.6 and their variation graph in 10 years with 16 days intervals during Rabi is presented in Figure 5.6(a) and (b).

(b) NDVI anomaly and EDI:

The NDVI again is found to be more sensitive to EDI at 32 days lag than EDI with no lag and 16 days lag. The correlation coefficient value of rain-fed areas is a less than that of irrigated regions by very small difference. Thus, NDVI is affected mostly after 32 days from Meteorological drought occurrence and the frequency of Meteorological drought hits to NDVI of all the areas more or less equivalently in this ecoregion. The correlation between NDVI anomaly and EDI laggings in this zone is shown in Table 5.7.

(c) NDVI anomaly and soil moisture anomaly:

The sensitivity of NDVI anomaly with soil moisture anomaly is found to be good for 16 days lagging. The relation between NDVI anomaly and soil moisture anomaly is exposed to be again better than relation with EDI. The NDVI anomaly in irrigated areas is found to be again equally sensitive to that of rain-fed areas to their corresponding soil moisture anomaly lagging at 16 days. The correlation between NDVI anomaly and soil moisture anomaly at 16 days laggings in this zone is shown in Table 5.8 and their variation graph of 10 years with 16 days intervals during Rabi is presented in Figure 5.7 (a) and (b).

Table 5.6 Correlation between Soil Moisture Anomaly and EDI Laggings in Bundelkhand region.

EDI lagging to soil moisture anomaly	**Northern Plains**		**Central Highland**	
	Irrigated	Rain-fed	Irrigated	Rain-fed
No lag	0.19	0.25	0.29	0.29
16 days lag	0.06	0.12	0.14	0.12
32 days lag	0.09	0.11	0.15	0.16

Table 5.7 Correlation between NDVI Anomaly and EDI Laggings in Bundelkhand region.

EDI lagging to NDVI anomaly	**Northern Plains**		**Central Highland**	
	Irrigated	Rain-fed	Irrigated	Rain-fed
No lag	0.02	0.03	0.03	0.01
16 days lag	0.07	0.11	0.14	0.09
32 days lag	0.10	0.15	0.16	0.12

Table 5.8 Correlation between NDVI Anomaly and Soil Moisture Anomaly Laggings in Bundelkhand region.

Soil moisture anomaly lagging to NDVI anomaly	**Northern Plains**		**Central Highland**	
	Irrigated	Rain-fed	Irrigated	Rain-fed
No lag	0.51	0.54	0.53	0.53
16 days lag	0.57	0.58	0.59	0.60
32 days lag	0.50	0.56	0.58	0.59

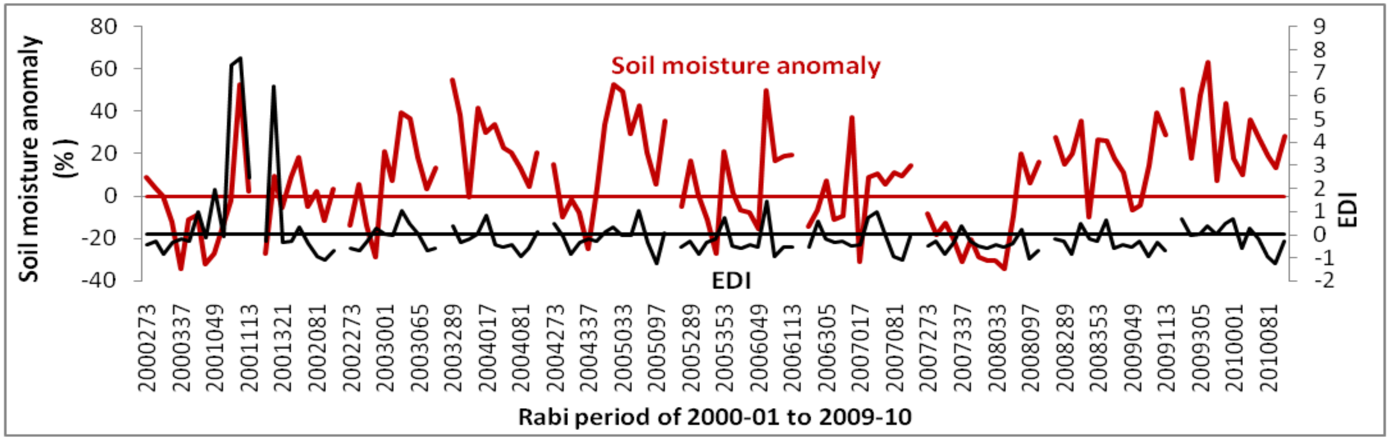

Figure 5.4 (a) Soil Moisture Anomaly and EDI Variation Graph of 10 Years during Rabi Season in Irrigated areas of Northern Plains

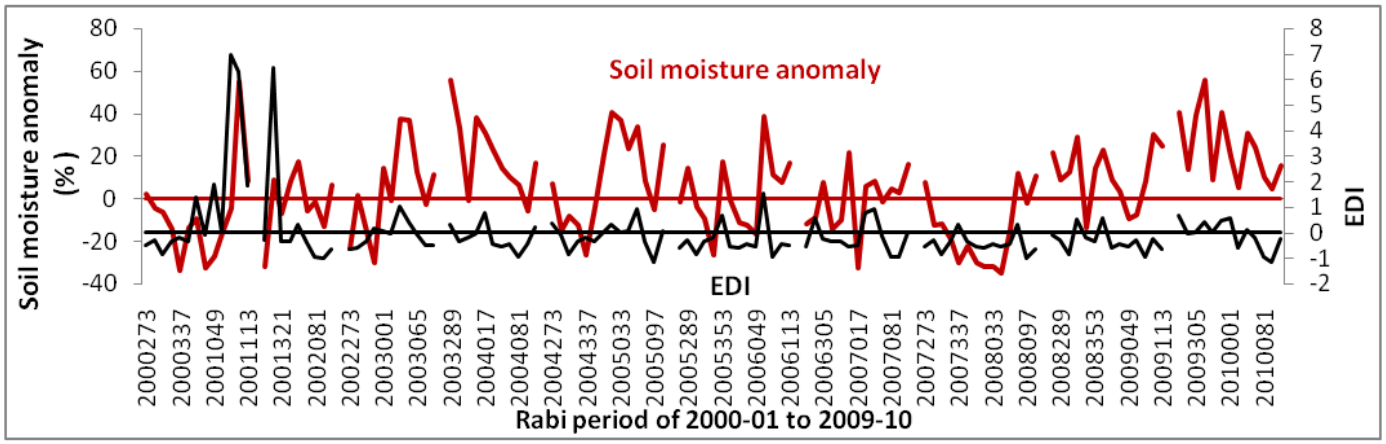

Figure 5.4 (b) Soil Moisture Anomaly and EDI Variation Graph of 10 Years during Rabi Season in Rain-fed areas of Northern Plains

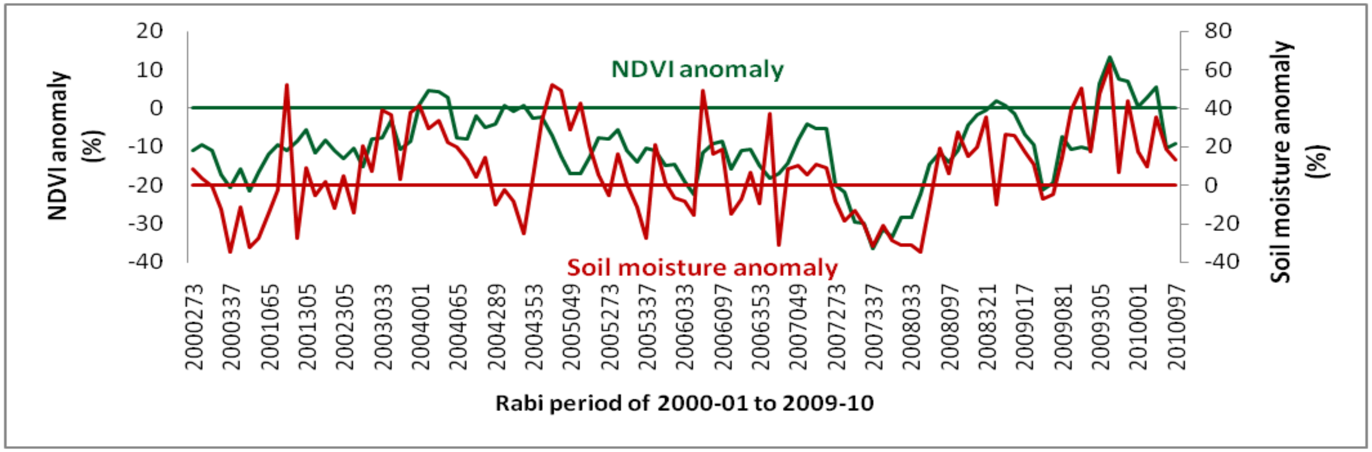

Figure 5.5 (a) NDVI Anomaly and Soil Moisture Anomaly Variation Graph of 10 Years during Rabi Season in Irrigated areas of Northern Plains

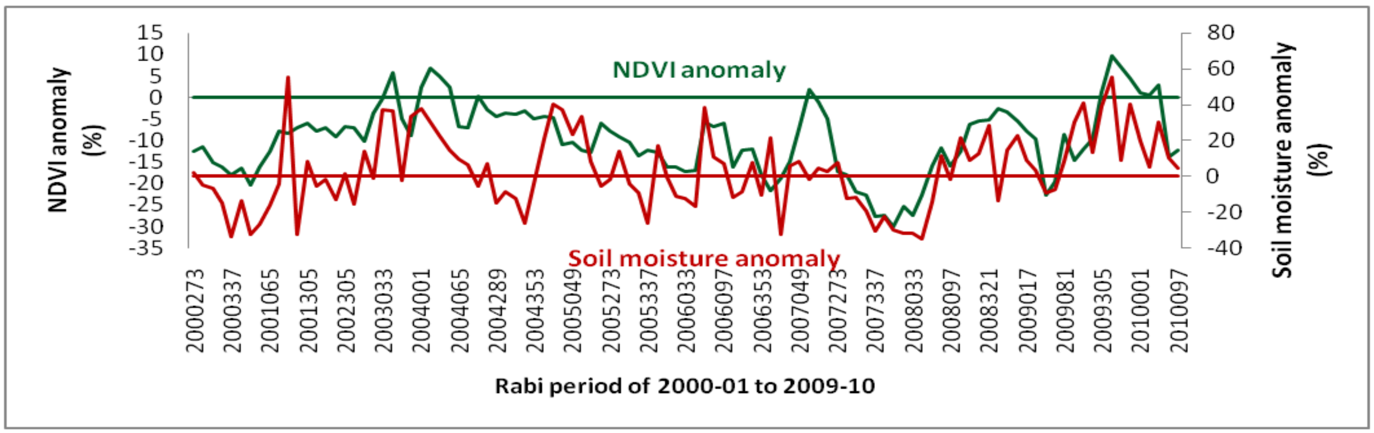

Figure 5.5 (b) NDVI Anomaly and Soil Moisture Anomaly Variation Graph of 10 Years during Rabi Season in Rain-fed areas of Northern Plains

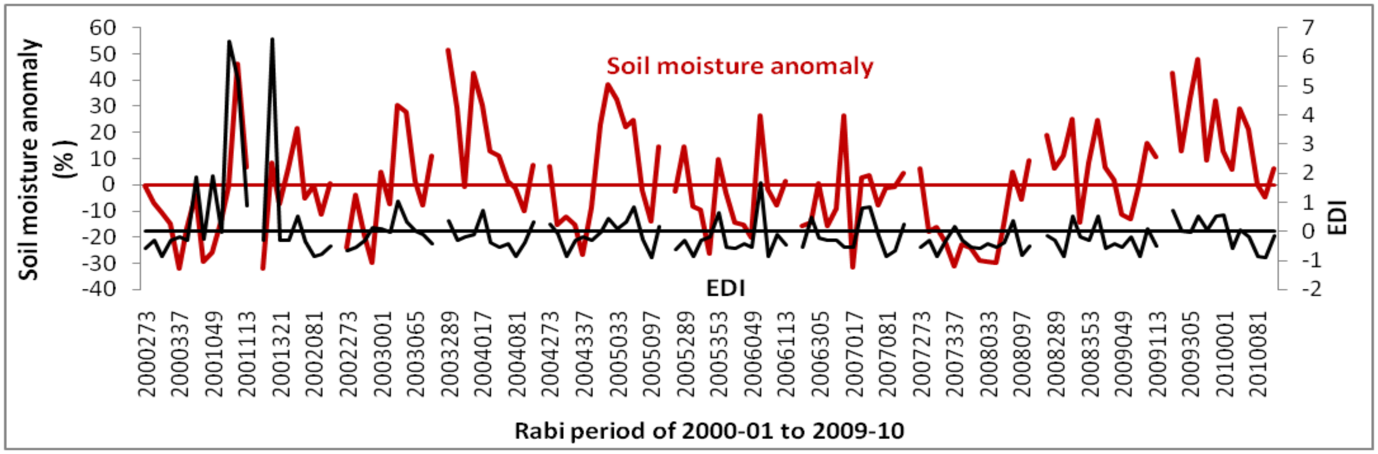

Figure 5.6 (a) Soil Moisture Anomaly and EDI Variation Graph of 10 Years during Rabi Season in Irrigated areas of Central Highlands

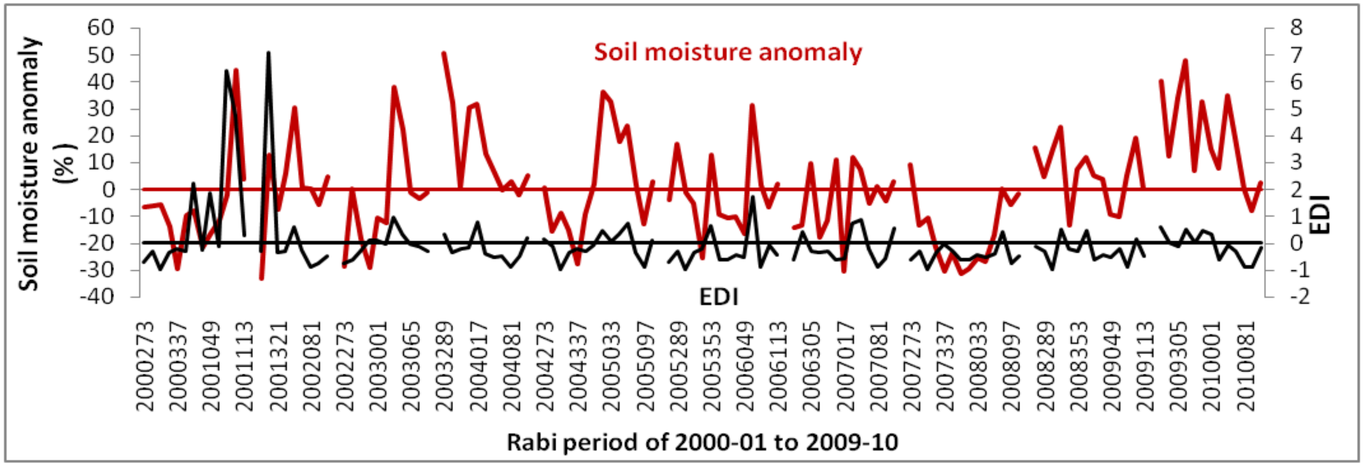

Figure 5.6 (b) Soil Moisture Anomaly and EDI Variation Graph of 10 Years during Rabi Season in Rain-fed areas of Central Highlands

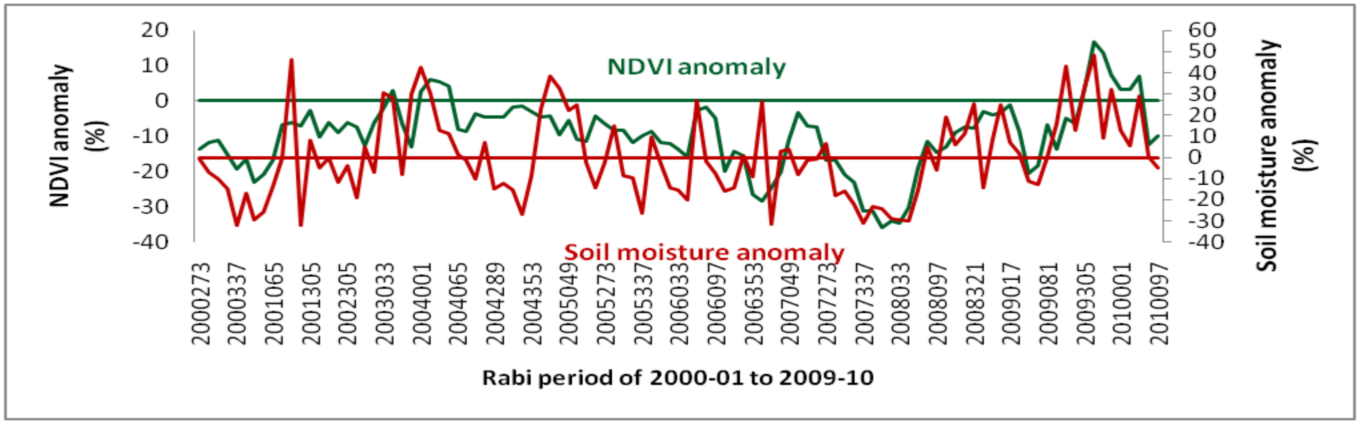

Figure 5.7 (a) NDVI Anomaly and Soil Moisture Anomaly Variation Graph of 10 Years during Rabi Season in Irrigated areas of Central Highlands

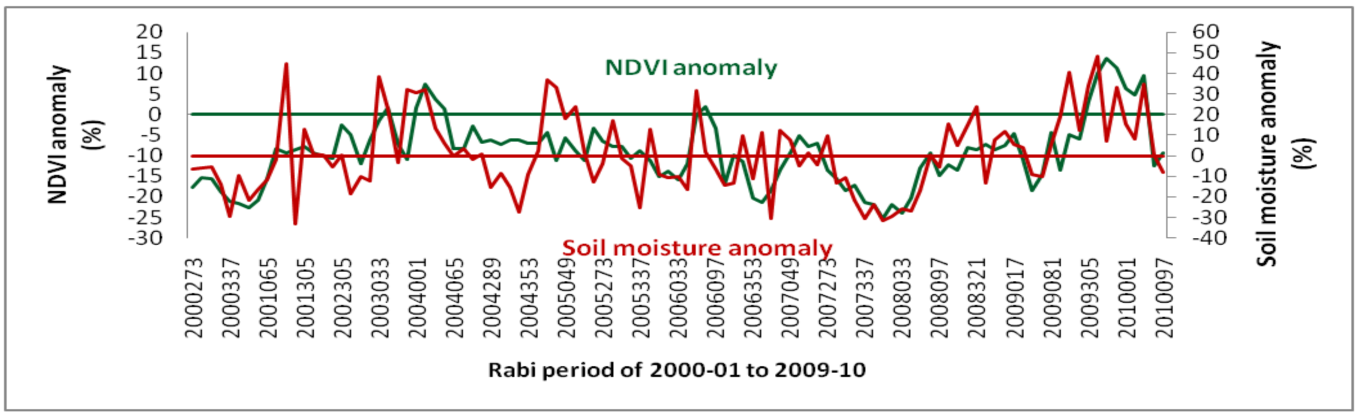

Figure 5.7 (b) NDVI Anomaly and Soil Moisture Anomaly Variation Graph of 10 Years during Rabi Season in Rain-fed areas of Central Highlands

5.6 DEVELOPMENT OF THE AGRICULTURAL DROUGHT ASSESSMENT MODEL

The sensitivity analysis concludes some important behavior of soil moisture anomaly and NDVI anomaly which is important in order to build an efficient Agricultural drought assessment model. The Agricultural drought assessment on basis of only EDI can mislead to pseudo assessment values faraway from absolute. The EDI may not predict its best impact on NDVI anomaly but soil moisture can, because NDVI anomaly is more dependent on soil moisture anomaly as per the regional observations. Also, the interpretations from EDI and soil moisture anomaly could be different. The difference in stress for stress experiencing zones according to EDI and soil moisture anomaly is sighted in Figure 5.8 (a) and (b). Therefore, it is essential to include soil moisture in the Agricultural drought assessment model.

The assessment model includes the idea of using EDI for estimation of soil moisture anomaly at its simultaneous time step, and that soil moisture anomaly could estimate the NDVI anomaly at 16 days lead. The preparation of model required the removal of outliers in the observations. To achieve it, a general concept developed from above sensitivity analysis is followed. The concept states that, with improvement or decline in meteorological conditions, the corresponding subsequent soil moisture conditions behaves similarly. And the same concept is applied for the case of soil moisture anomaly and its subsequent NDVI anomaly at 16 days lead. The observation following this concept is considered as the true representing observation for the model. The rest of the observations have been discarded as outliers. The correlation of observations after removing outliers is shown in Table 5.9 (a) and (b), which was further used to build Agricultural drought assessment models.

Table 5.9 (a) Correlations between Soil Moisture Anomaly and EDI after Removing Outliers, in Bundelkhand region.

Agriculture system	**Agro climatic region**	
	Northern Plains	Central Highland
Irrigated	0.64	0.65
Rain-fed	0.71	0.70

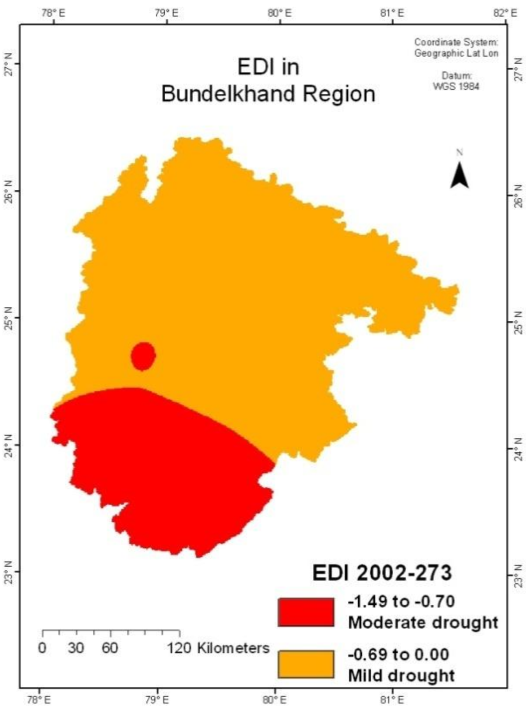

Figure 5.8 (a) EDI Conditions in Bundelkhand of 16 days Starting From 273th Julian Day of Year 2002.

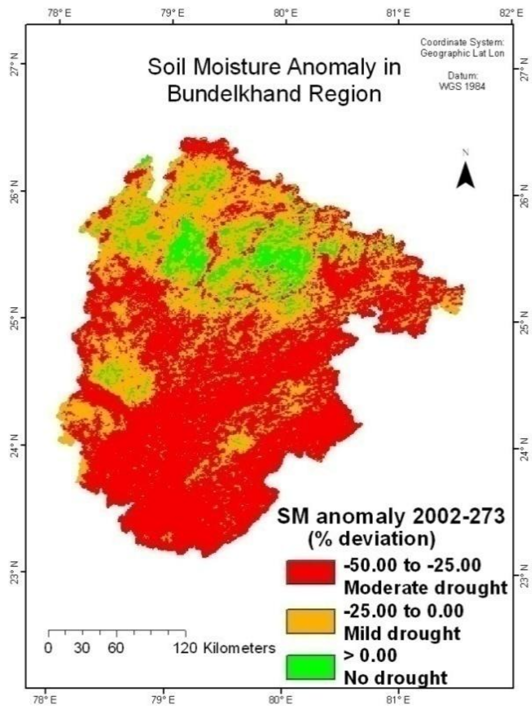

Figure 5.8 (b) Soil Moisture Anomalies in Bundelkhand for 16 days Starting From 273th Julian Day of Year 2002.

Table 5.9 (b) Correlations between NDVI Anomaly and Soil Moisture Anomaly at 16 days Lag after removing Outliers, in Bundelkhand region.

Agriculture system	**Ecoregion**	
	Northern Plains	Central Highland
Irrigated	0.77	0.84
Rain-fed	0.84	0.80

The Agricultural drought assessment model contains a set of equations, developed by linear regression between the respective observations. The soil moisture anomaly estimation models are presented in Figure 5.9 (a), (b), (c) and (d) and the NDVI anomaly estimation models are shown in Figure 5.10 (a), (b), (c) and (d). These set of equations were developed individually for irrigated and rain-fed regions in the Northern Plains and Central Highland zones.

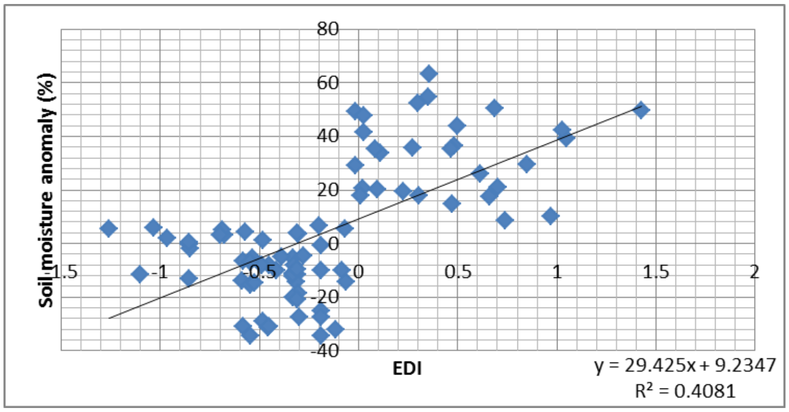

Figure 5.9 (a) Soil Moisture Estimation Model for Irrigated areas in Northern Plains.

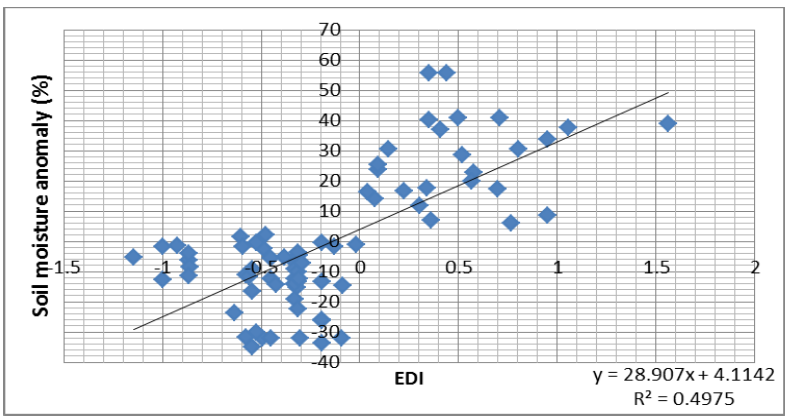

Figure 5.9 (b) Soil Moisture Estimation Model for Rain-fed areas in Northern Plains.

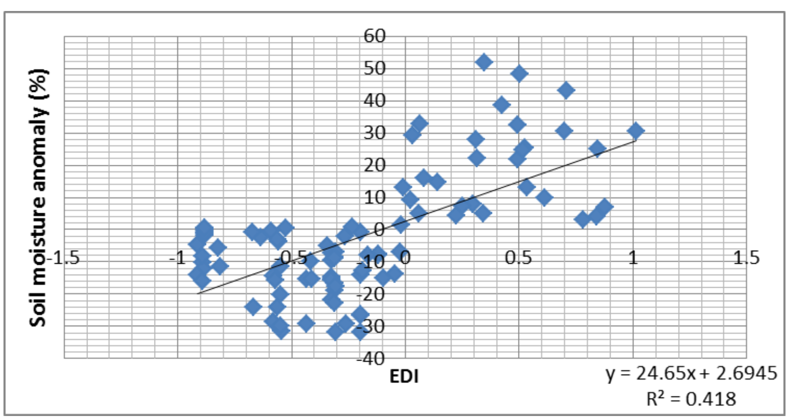

Figure 5.9 (c) Soil Moisture Estimation Model for Irrigated areas in Central Highlands.

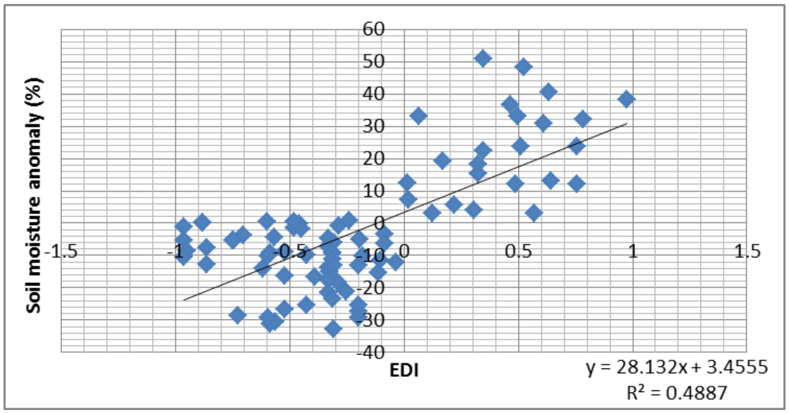

Figure 5.9 (d) Soil Moisture Estimation Model for Rain-fed areas in Central Highlands.

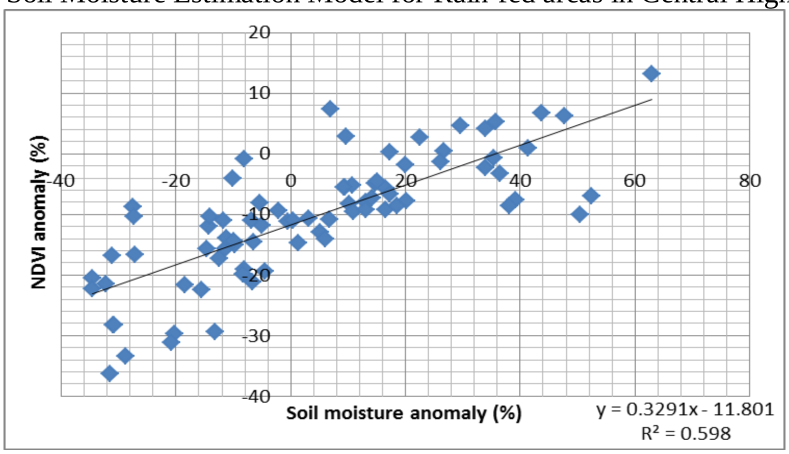

Figure 5.10 (a) NDVI Anomaly Estimation Model for Irrigated areas in Northern Plains.

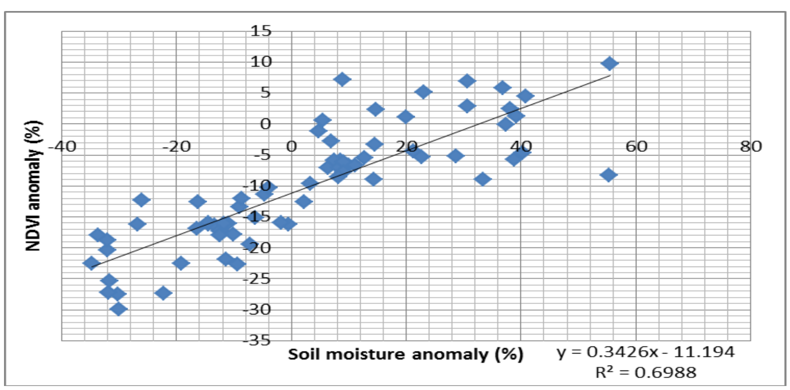

Figure 5.10 (b) NDVI Anomaly Estimation Model for Rain-fed areas in Northern Plains.

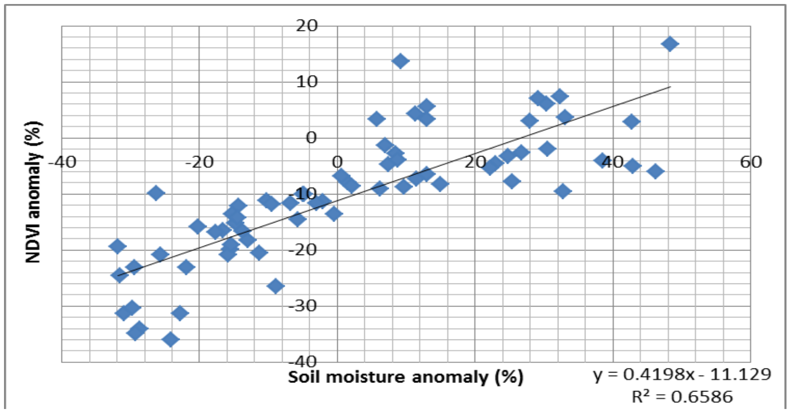

Figure 5.10 (c) NDVI Anomaly Estimation Model for Irrigated areas in Central Highlands.

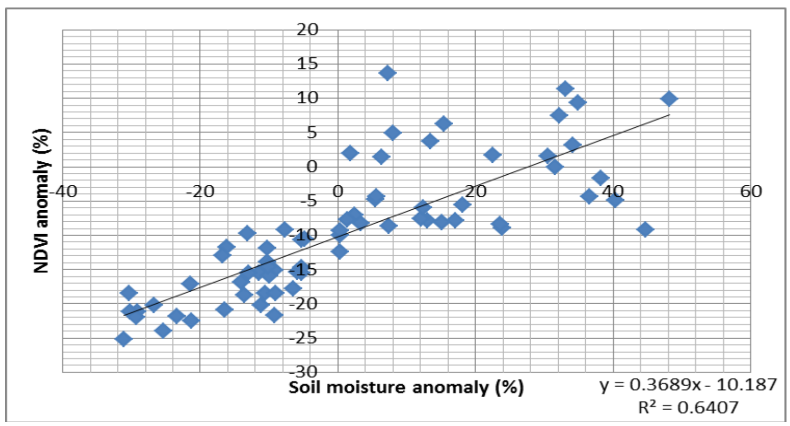

Figure 5.10 (d) NDVI Anomaly Estimation Model for Rain-fed areas in Central Highlands.

5.7 AGRICULTURAL DROUGHT ASSESSMENT AND PREDICTION MODEL

The developed Agriculture assessment model requires rainfall data as the only input. The rainfall data includes rainfall records from three day prior to the period for which drought condition has to be estimated and the information regarding the zone in which the rainfall data lies (Northern Plains/ Central Highlands). The effective precipitation needs to be calculated from the input data as:

$$\text{EP}p = \sum_{n-1}^{3}[\,(\textstyle\sum_{m-1}^{n} \text{P}_\text{m})/n]$$

where, EPp is effective precipitation of a particular day accumulated for three days, Pm is the precipitation for a day m days prior to a specific day. The EDI computation is followed by including EPp as:

$$\text{EDI}_{cal} = (\text{EP}p\text{-X}p) \,/\, \text{Y}p$$

where, EDI_{cal} is EDI to be calculated, Xp is the mean of effective precipitation and Yp standard deviation of difference between observed effective precipitation and Xp for the p^{th} Julian day. The values of Xp and Yp are there in APPENDIX -VIII.

Then the soil moisture anomaly is calculated utilizing which we can estimate NDVI anomaly. The Soil moisture anomaly and NDVI anomaly estimation equations are in Table 5.10 and Table 5.11 respectively.

Table 5.10 Soil Moisture Anomaly Estimation Equations for Different Agro Climatic Zones in Bundelkhand region.

Agro climatic zone	**Agricultural system**	**Estimation Equation**
Northern Plains	Irrigated	$SM_a = (29.425 * EDI_{cal}) + 9.2347$
	Rain-fed	$SM_a = (28.907 * EDI_{cal}) + 4.1142$
Central Highlands	Irrigated	$SM_a = (26.650 * EDI_{cal}) + 2.6945$
	Rain-fed	$SM_a = (28.132 * EDI_{cal}) + 3.4555$
SM_a is soil moisture anomaly to be estimated. EDI_{cal} is the input EDI computed out of input rainfall data.		

Table 5.11 NDVI Anomaly Estimation Equations for Different Agro Climatic Zones in Bundelkhand region.

Agro climatic zone	**Agricultural system**	**Estimation Equation**
Northern Plains	Irrigated	$NDVI_a = (0.3929* SM_a) - 11.801$
	Rain-fed	$NDVI_a = (0.3426* SM_a) - 11.194$
Central Highlands	Irrigated	$NDVI_a = (0.4198* SM_a) - 11.129$
	Rain-fed	$NDVI_a = (0.3689* SM_a) - 10.187$
$NDVI_a$ is soil moisture anomaly to be estimated. SM_a is the input soil moisture anomaly estimated		

The models for estimation of soil moisture anomaly and NDVI anomaly generates anomaly (%), which needs to be computed with their corresponding mean to obtain the assessed value of average soil moisture and average NDVI respectively. The soil moisture and NDVI (SM and NDVI) can be assessed as:

$$SM = \frac{(SM_a * SM_{mean})}{100} + SM_{mean} \quad (5.1)$$

$$NDVI = \frac{(NDVI_a * NDVI_{mean})}{100} + NDVI_{mean} \quad (5.2)$$

where, SM and NDVI are soil moisture and NDVI values to be assessed for a particular period; SM_a and $NDVI_a$ are the estimated anomalies in the particular period; SM_{mean} and $NDVI_{mean}$ are the mean of soil moisture and NDVI respectively for the particular period. APPENDIX – IX and APPENDIX – X gives SM_{mean} and $NDVI_{mean}$ of different periods in irrigated and rain-fed areas of different climatic zones in Bundelkhand, which are essential to calculate soil moisture and NDVI respectively. These tables have mean of the parameters against period represented as Julian days, for which parameters are to be estimated.

The NDVI anomaly estimation models discussed above are capable to estimate NDVI in any conditions. In case of irrigated areas, EDI showing Meteorological drought may or may not tend the soil moisture anomaly in negative direction, but in case of rain-fed regions it is probable to tend. If the estimated soil moisture anomaly is found to be negative, it can lead to Agricultural drought. Therefore, a different set of models, analyzed from only negative soil moisture anomaly observation has been developed, to best estimate the NDVI anomaly during droughts. These set of models are usable only in cases, where soil moisture anomaly is suspected to guide towards Agricultural drought. The correlations of NDVI anomaly to soil moisture anomaly at 16 days lag, only observed for situations vulnerable to drought like consequences is shown in Table 5.12 and the models which are based on it, are in Figure 5.11 series. The NDVI anomaly estimation equations are shown in Table 5.13, meant for only negative estimated soil moisture anomaly.

Table 5.12 Correlations between NDVI Anomaly and Soil Moisture Anomaly at 16 days Lag from negative soil moisture anomaly, in Bundelkhand region.

Agriculture system	**Ecoregion**	
	Northern Plains	Central Highland
Irrigated	0.74	0.84
Rain-fed	0.84	0.86

Table 5.13 NDVI Anomaly Estimation Equations for Drought Periods in Different Agro Climatic Zones of Bundelkhand region.

Agro climatic zone	**Agricultural system**	**Estimation Equation**
Northern Plains	Irrigated	$NDVI_a = (0.658^* SM_a) – 5.250$
	Rain-fed	$NDVI_a = (0.632^* SM_a) – 3.708$
Central Highlands	Irrigated	$NDVI_a = (0.607^* SM_a) – 4.486$
	Rain-fed	$NDVI_a = (0.758^* SM_a) – 4.279$
$NDVI_a$ is soil moisture anomaly to be estimated SM_a is the input soil moisture anomaly estimated		

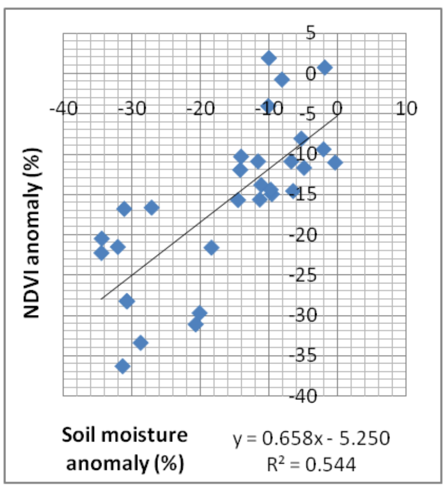

Figure 5.11 (a) NDVI Anomaly Estimation Model From Negative Soil Moisture Anomaly for Irrigated areas in Northern Plains.

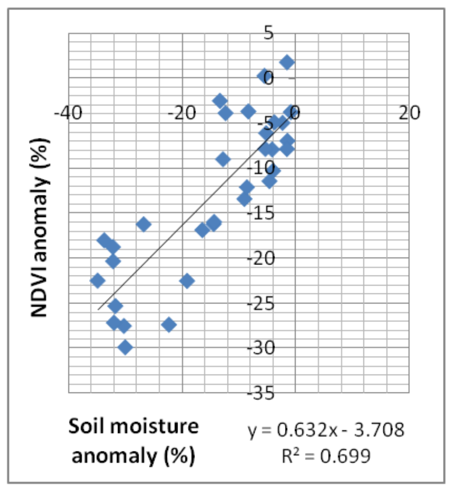

Figure 5.11 (b) NDVI Anomaly Estimation Model From Negative Soil Moisture Anomaly for Rain-fed areas in Northern Plains.

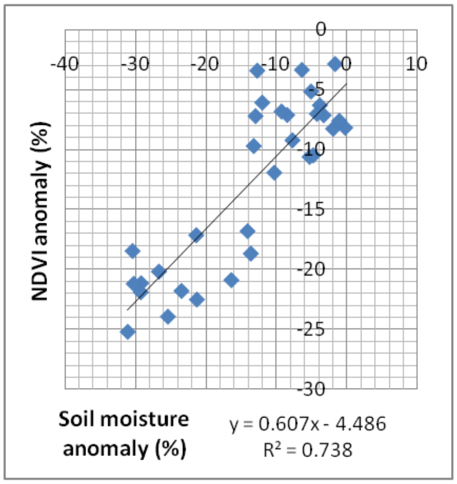

Figure 5.11 (c) NDVI Anomaly Estimation Model From Negative Soil Moisture Anomaly for Irrigated areas in Central Highlands.

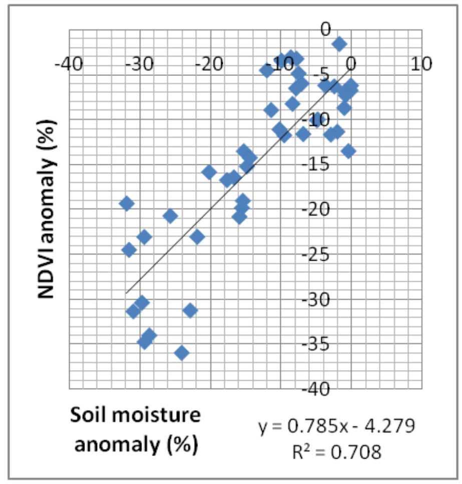

Figure 5.11 (d) NDVI Anomaly Estimation Model From Negative Soil Moisture Anomaly for Rain-fed areas in Central Highlands.

However, this model is limited to assess or predict only the NDVI and Soil moisture in irrigated and rain-fed agriculture in different climatic zones of Bundelkhand region. The reason is unavailability of crop yield and production data in irrigated and rain-fed areas for different agro climatic zones. The estimation of crop yield and crop production can be achieved only if the factors stated above will be implemented.

5.8 VALIDATION OF DEVELOPED MODEL

The Agricultural drought assessment model has been used for estimation of NDVI for 16 days period starting on day 289, 305, 321, 353 of year 2010 and 1st day of 2011. As these periods were never included for the model development, it can also be considered as a prediction case for the model. The daily rainfall data in all stations in Bundelkhand for these periods has been taken as primary input. It has been interpolated and calculated for EDI as mentioned in section 5.7. The EDI has been taken as input for the model which generates output as predicted NDVI considering irrigated and rain-fed areas of Northern Plains and Central Highlands with different set of prediction for NDVI. Then comparison between predicted NDVI and MODIS NDVI for same period has been done. For comparison, only irrigated areas in Northern Plains and rain-fed areas in Central Highlands has been done. It has been selected on the basis of dominating management system in agriculture in the respective agro climatic zone. Figure 5.12 and Figure 5.13 shows the obtained maps of predicted NDVI along with MODIS data product of same period for visual comparison. Figure 5.12 includes the maps of irrigated areas Northern Plains and Figure 5.13 shows rain-fed areas in Central Highlands.

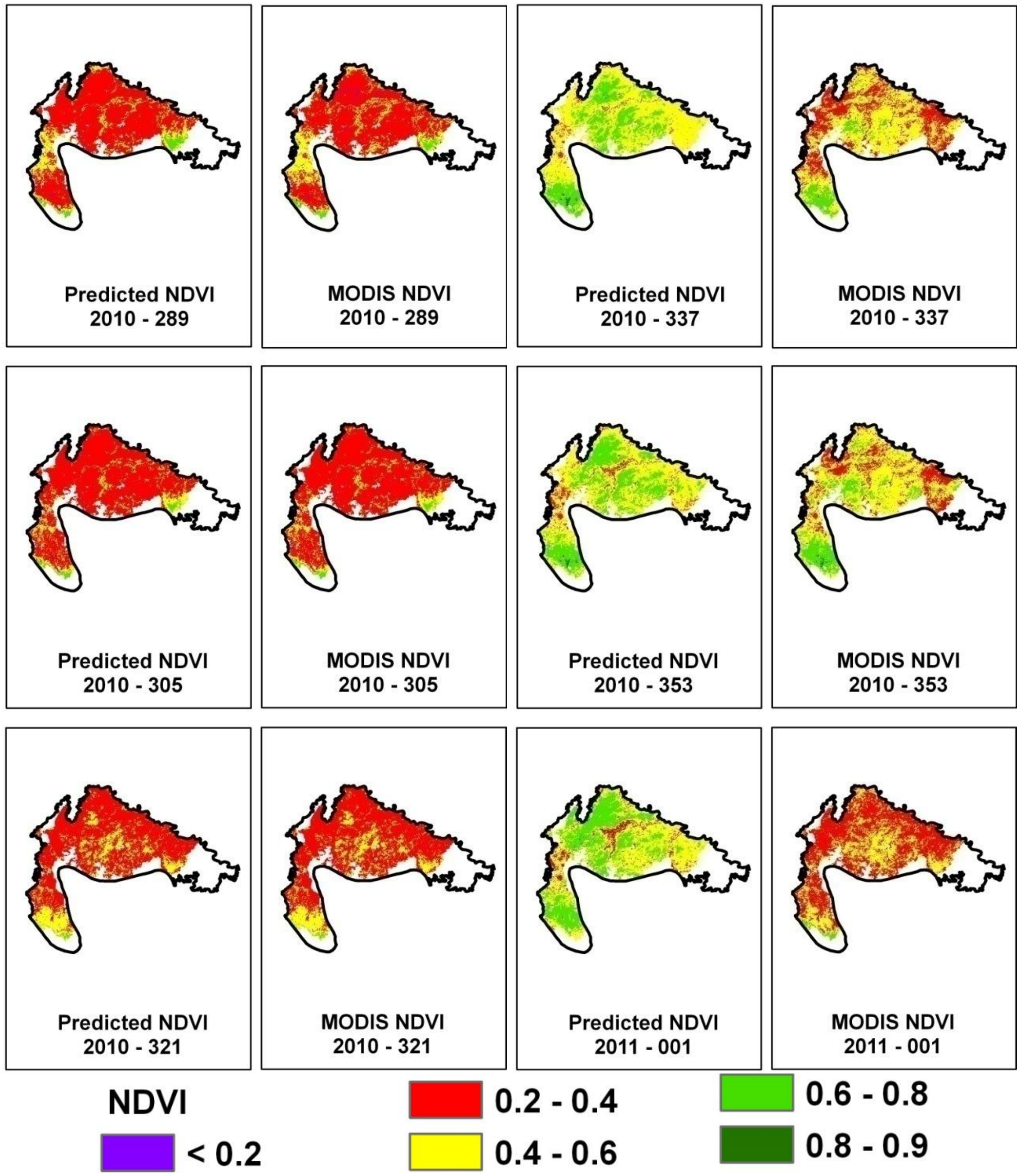

Figure 5.12 Predicted NDVI and MODIS NDVI for Irrigated Agriculture in Northern Plains.

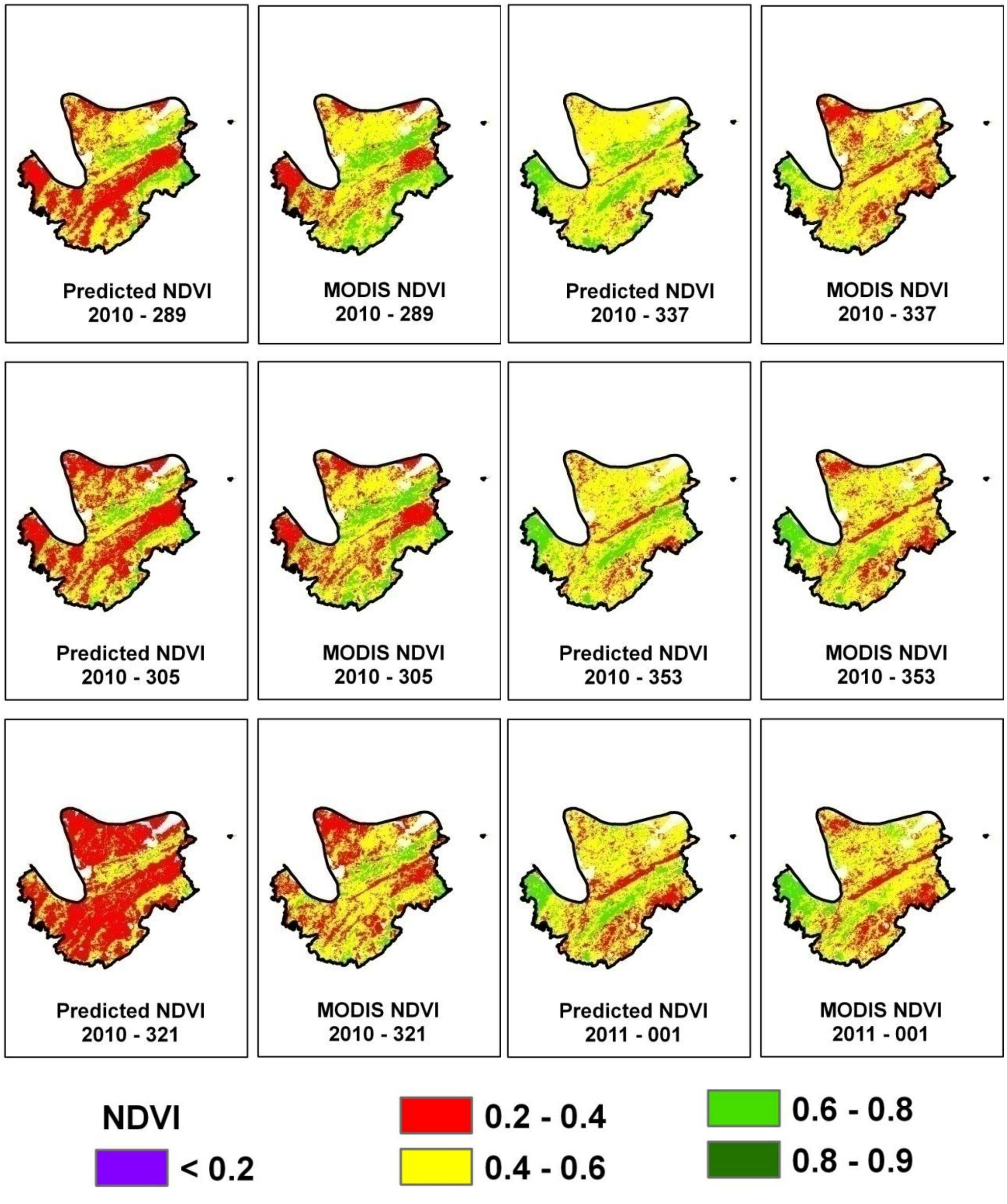

Figure 5.13 Predicted NDVI and MODIS NDVI for Rain-fed Agriculture in Central Highlands.

From the visual interpretation of the maps in Figure 5.12 and 5.13, it can be seen that the predicted values of NDVI in irrigated areas around are not close to that of MODIS NDVI. It is because the model relies on rainfall as primary input. The rainfall events decide the Meteorological drought occurrence, but do not affect the areas which are frequently irrigated due to suitable soil moisture. But, still there is existence of some regions in irrigated areas in predicted NDVI which shows close values to MODIS NDVI. These areas are within the irrigated command area, but it behaves like arid areas. The reason for this can be explained as insufficient soil moisture for subsequent crop health. This explanation is also headed for Figure 5.13. It can be seen that the predicted NDVI in rain-fed areas are almost successful to be close to MODIS NDVI. Conclusions can be drawn that, there is existence of areas within the irrigated command area, where water supply is insufficient. Also, the rain-fed areas are better predicted from the model than the irrigated areas. Figure 5.14 and Figure 5.15 shows the graphs of spatial averages of long term mean NDVI observed for development of the model, predicted NDVI out of the model and NDVI from MODIS product for irrigated areas in Northern Plains and rain-fed areas in Central Highlands.

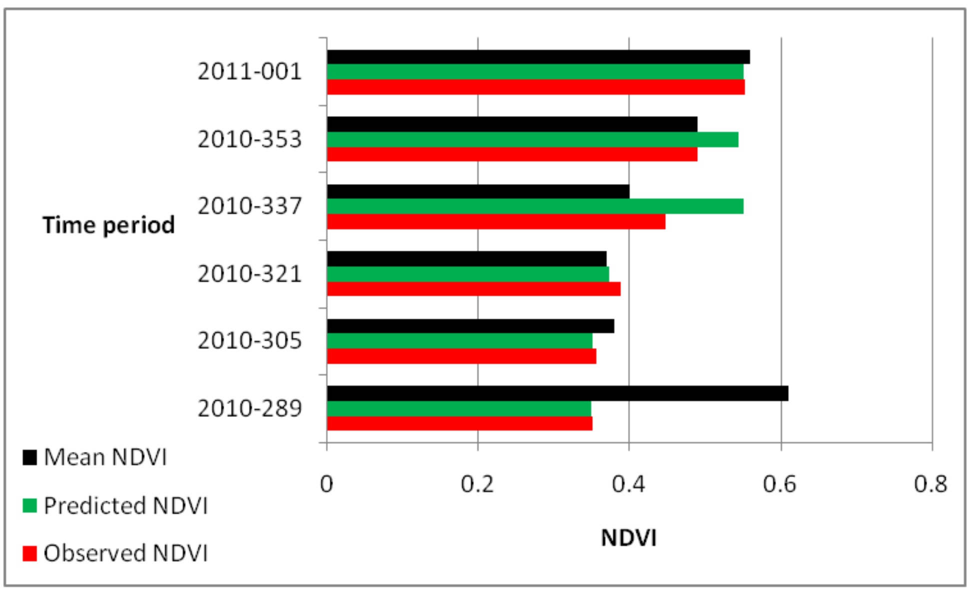

Figure 5.14 Spatial Averages of Long Term Mean NDVI Observed for Development of the Model, Predicted NDVI out of the Model and NDVI from MODIS Product for Irrigated areas in Northern Plains.

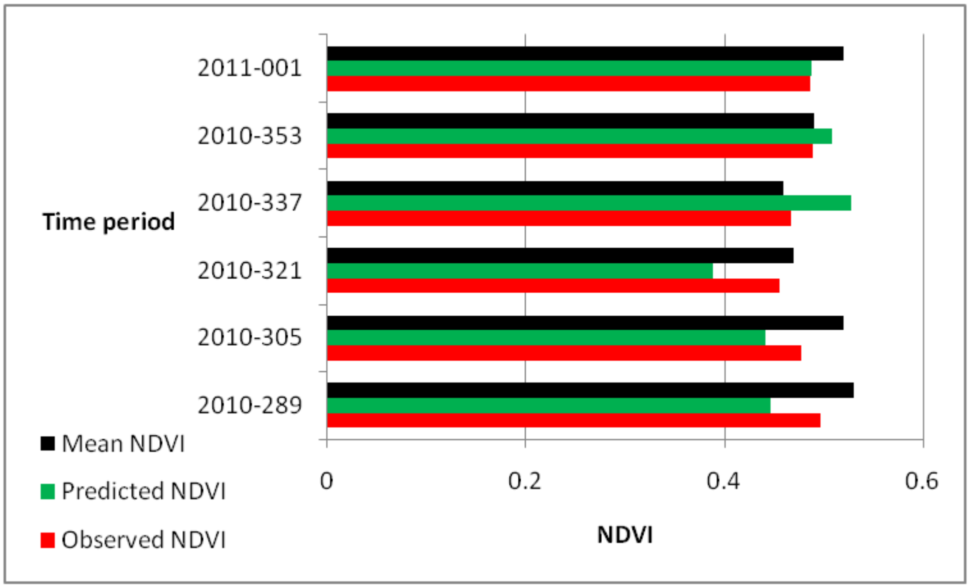

Figure 5.15 Spatial Averages of Long Term Mean NDVI Observed for Development of the Model, Predicted NDVI out of the Model and NDVI from MODIS Product for Rain-fed areas in Central Highlands.

The graphs in Figure 5.14 and Figure 5.15 contains spatial average of long term mean NDVI from which if the spatial average of MODIS NDVI is less, represents the area heading towards agricultural drought. If the spatial average of predicted NDVI is also less than to that of long term mean NDVI, the prediction is acceptable. In most of the cases, spatial average of the prediction shows similar behavior to that of MODIS NDVI with respect to long term mean of NDVI. This is observation is for both agro climatic zones. Therefore, the model has a good predictive capability for both irrigated and rain-fed areas in Northern Plains and Central Highlands.

CHAPTER 6

CONCLUSIONS AND RECOMMENDATIONS

6.1 CONCLUSIONS

The main objective of this research work was to analyze the sensitivity of remote sensing parameters with Meteorological drought indicators and use them to prepare an efficient model capable of assessing the magnitude of Agricultural drought under irrigated and rain-fed agriculture.

An attempt is done in present study to incorporate satellite observed soil moisture data in Agricultural drought assessment technique, as the soil moisture is supposed to have strong impact on agriculture system. The coarse spatial resolution satellite soil moisture data is downscaled to a finer resolution. The spatial resolution of soil moisture product was improved from around 27 km to 1 km using Linking model based on Triangle method. The RMSE and spatial variability of downscaled soil moisture against initial soil moisture has been found to be within acceptable range (RMSE values in the range of 0.05), which justifies the technique used for soil moisture downscaling and the potential applicability of downscaled soil moisture data.

The sensitivity analysis has been carried out in which, sensitiveness of downscaled soil moisture and NDVI has been tested with respect to Meteorological drought indicator EDI of same time step as well as lagged time steps. The entire sensitivity analysis brings out various inferences. As per the assumption of increase or decrease in soil moisture anomaly with to that of EDI, the effect of EDI on soil moisture anomaly is most strong for simultaneous period (same time step) with a correlation coefficient over 0.6 in irrigated areas and 0.7 in rain-fed areas, in both agro climatic zones (Northern Plains and Central Highlands). When pertaining to agricultural water supply practice, as expected the rain-fed areas have a better sensitivity of soil moisture anomaly to EDI than irrigated areas. The reason for this difference can be best explained as repeated water supply in irrigated regions and persisting arid conditions in rain-fed areas. Concerning NDVI anomaly, in both the systems of agriculture (irrigated and rain-fed) shows good sensitivity to soil moisture anomaly lagged by one time step (16 days), with the better part in rain-fed areas. NDVI anomaly with soil moisture anomaly has correlation coefficient values 0.77 & 0.84 in irrigated areas and 0.84 & 0.80 in rain-fed areas, of Northern Plains and Central Highlands respectively. The explanation can be enlightened by the reason of more dependency of subsequent crop health to soil moisture relatively than on rainfall. Also, due to this reason, the NDVI anomaly shows better response to soil moisture anomaly in rain-fed areas, than in irrigated areas. The NDVI anomaly has a better relationship with soil moisture anomaly than with EDI along the entire region for which EDI and NDVI anomaly has not been encouraged for model development.

The soil moisture anomaly, when compared in both agro climatic zones, is found to behave differently in terms of relation with EDI. The same thing is observed in relation of NDVI anomaly to soil moisture anomaly. This reason fortifies the idea of using irrigated and rain-fed areas as different spheres.

The sensitivity analysis for different agricultural system (irrigated/rain-fed) of different agro climatic zone (Northern Plains/Central Highlands) proved to be helpful for development of an agricultural drought assessment model. The model is free of spatial resolution, because it is developed with a set of equations for which it directly depends on the spatial resolution of EDI as input. Also, the developed model has an inherent capability of predicting effect of meteorologically induced Agricultural drought on health (vegetation index) of crop and in turn on yield and production from the region.

6.2 LIMITATIONS

The downscaling of soil moisture through Linking model based on Triangle method works on the basis of second order polynomial regression between soil moisture, EVI and LST. Since it is a statistical model, problem of over fitting and under fitting exists. Often the approximation under the prediction surface attains negative values, which is rare in case, but unreasonable. Such downscaled pixels with these negative values, needs to be avoided.

The spatial resolution dealt in this research was kept up to 1 km due to which it is limited to be used for further sub regions (land parcel/agricultural field level).

The developed model is limited to assess or predict only the NDVI and Soil moisture in irrigated and rain-fed agriculture and not the crop parameters. The reason is unavailability of crop yield and crop production data in irrigated and rain-fed areas with respect to drought conditions.

6.3 RECOMMENDATIONS FOR FUTURE WORK

Future sensors like on boarding Soil Moisture Active Passive (SMAP), an American environmental research satellite to be launched in 2014, with higher spatial resolution of soil moisture products can be utilized to downscale soil moisture to further fine resolution. This can be used for better agricultural drought assessment in sub region (village level/field level). It can enhance the agricultural drought assessment in spatial domain.

To overcome the negative prediction in downscaling of coarse satellite soil moisture, it is suggested to use a better downscaling technique incorporating *in-situ* measurements.

Regarding the agricultural drought assessment model, the estimation of crop yield and crop production can be achieved, only if the crop factors stated above are implemented. These factors when included in the model can estimate other crop parameters also.

REFERENCES

Agnew, C. T. (2000). Using the SPI to identify drought. *Drought Network News*, 12 (1).

Akhtari, R., Morid, S. M., Mohammad, H., & Smakhtind, V. (2009). Assessment of areal interpolation methods for spatial analysis of SPI and EDI drought indices. *International Journal of Climatology*. 29, 135–145.

Alley, W. M. (2007). The Palmer Drought Severity Index: Limitations & assumptions. *Journal of Climate and Applied Meteorology*, 23, 1100-1109.

American Meteorological Society (2004). Statement on meteorological drought. *Bull. Am. Meteorol. Soc*., 85, 771–773

Awosika, L, Diop, E.S., Downing, T.E., El-Raey, M., Le Sueur, D., Magadza, C.H.D., Tour, S., & Vogel, C., 1998. Chapter 2: Africa, IPCC Special Report on The Regional Impacts of Climate Change An Assessment of Vulnerability,http://www.grida.no/publications/other/ipcc_sr/?src=/climate/ipcc/regional/006.htm

Azzali, S., & Menenti, M. (2000). Mapping vegetation-soil-climate complexes in southern Africa using Fourier analysis of NOAA-AVHRR NDVI data. *International Journal of Remote Sensing*, 21, 973–996.

Berhan, G., Hill, S, Tadesse, T., & Atnafu S. (2011). Using satellite images for drought monitoring: A knowledge discovery approach. *Journal of Strategic Innovation and Sustainability*, 7(1).

Bhalme, H.N., & MooIey, D. A. (1980). Large-scale drought/floods and monsoon circulation. *Monthly Weather Review*, 108,1197.

Breshears, D. D., Cobb, Neil S., Rich, Paul M., Price, Kevin P., Allen, Craig D., Balice, Randy G., Romme, W. H., Kastens, Jude H., Floyd, M. Lisa, Belnap, Anderson, Jayne, Jesse, J., Myers, Orrin B., & Meyer, C. W. (2005). Regional vegetation die-off in response to global-change-type drought. *Proceedings of the National Academy of Sciences*, 102 (42), 15144 –15148.

Brown, J.F., Reed, B.C., Hayes, M.J., Wilhite, D.A., & Hubbard. K. (2002). A prototype drought monitoring system integrating climate and satellite data. *Pecora 15/Land Satellite Information IV/ISPRS Commission I/FIEOS, Conference Proceedings*, Denver, CO, Nov 10–14.

Brown, J.F., Wardlow, B.D. Tadesse, T. Hayes, M.J., & Reed. B.C. (2008). The vegetation drought response index (VegDRI): A new integrated approach for monitoring drought stress in vegetation. *GIScience and Remote Sensing*, 45(1), 16–46.

Bryant, S.J. Arnell, N.W., & Law F.M. (1992). The long term context for current hydrological drought. *In: proceeding of IWEM conference on The Management of Scarce Water Resources*.

Byun, H.R., & Kim, D.W. (2010). Comparing the Effective Drought Index and the Standardized Precipitation Index. *Options Méditerranéennes, A*, 95, 85-89.

Byun, Hi Ryong, & Wilhite, D. A. (1999). Objective quantification of drought severity and duration. *American Meteorological Society*, 12, 2747-2756.

Carlson, T. N., Gillies, R. R., & Perry, E. M. (1994). A method to make use of thermal infrared temperature and NDVI measurements to infer soil water content and fractional vegetation cover. *Remote Sensing Reviews*, 52, 45–59.

Carlson, T.N. (2007). An overview of the "triangle method" for estimating surface evapotranspiration and soil moisture from satellite imagery. *Sensors*, 7, 1612–1629.

Chakraborty, A., & Sehgal, V.K. (2010). Assessment of agricultural drought using MODIS derived Normalized Difference Water Index. *Journal of Agricultural Physics*, 10, 28-36.

Chen, Xiaoqiu, Xu, Chengxin, & Tan Zhongjun (2001). An analysis of relationships among plant community phenology and seasonal metrics of Normalized Difference Vegetation Index in the northern part of the monsoon region of China. *International Journal of Biometeorology*, 45, 170–177.

Dai, A., Trenberth, K.E., & Qian, T. (2004). A global dataset of Palmer Drought Severity Index for 1870-2002: Relationship with soil moisture and effects of surface warming. *Journal of Hydrometeorology*, 5, 1117–1130.

Dheeravath, V., Thenkabail, P.S., Chandrakantha, G., Noojipady, P., Reddy, G.P.O., Biradar, C.M., Gumma, M.K., & Velpuri, M. (2010). Irrigated areas of India derived using MODIS 500 m time series for the years 2001–2003. *ISPRS Journal of Photogrammetry & Remote Sensing*, 65, 42–59.

Dracup, J.A., Lee, K.S. & Paulson, E.G. Jr. (1980). On the definition of droughts. *Water Resources Research*, 16 (2), 297-302.

Eastman, R.R., & Fulk M. (1993). Long sequence time series evaluation using standardized principal components. *Photogrammetric Engineering and Remote Sensing*, 59, 991–996.

Flower, H. J., & Kilsby, C. G. (2004). Future increase in UK water resource drought projected by a Regional climate model. *Hydrology: Science and Practice for 21st century*, 1, 15 – 21.

Gao, B.C. (1996). NDWI - a normalized difference water index for remote sensing of vegetation liquid water from space. *Remote Sensing of Environment*, 58, 257- 266.

Gao, Z., Gao, W., Chang, N.B. (2011). Integrating temperature vegetation dryness index (TVDI) and regional water stress index (RWSI) for drought assessment with the aid of LANDSAT TM/ETM+ images. *International Journal of Applied Earth Observation and Geoinformation*, 13, 495–503.

Garen, D.C. (1992). Improved techniques in regression-based streamflow volume forecasting. *Journal of Water Resources Planning and Management, ASCE*, 118 (6), 654-670.

Ghulam, Abduwasit, Qin, Qiming, Teyip, Tashpolat, & Li, Zhao-Liang (2007). Modified perpendicular drought index (MPDI): a real-timedrought monitoring method. *ISPRS Journal of Photogrammetry & Remote Sensing*, 62, 150–164.

Gore, P.G., & Ponkshe, A.S. (2004). Drought in Gujarat districts and State as key indicators to all India drought. *Journal of Agrometeorology*, 6 (1), 47-54.

Guttman, N.B. (1999). Accepting the standardized precipitation index: a calculation algorithm. *Journal of The American Water Resources Association*, 35 (2), 311- 322.

Heim, R. R. (2002). A review of twentieth-century drought indices used in theUnited States. *Bulletin of the American Meteorological Society*, 84, 1149−1165.

Hermance, J.F., Jacob, R.W., Bradley, B.A., & Mustard, J.F. (2007). Extracting phenological signals from multiyear AVHRR NDVI time series: framework for applying high-order annual splines with roughness damping. *IEEE Transactions on Geoscience and Remote Sensing*, 45 (10), 3264-3276.

Hisdal, H., & Tallaksen, L.M. (2003). Estimation of regional meteorological and hydrological drought characteristics: a case study for Denmark. *Journal of Hydrology*, 281, 230–247.

Huete, A., Didan, K., Miura, T., Rodriguez, E.P., Gao, X., & Ferreira, L.G. (2002). Overview of the radiometric and biophysical performance of the MODIS vegetation indices. *Remote Sensing of Environment*, 83, 195–213.

Hughes, B.L., & Saunders, M.A. (2002). A drought climatology for Europe. *International Journal of Climatology*, 22, 1571–1592.

In D. A. Wilhite, & D. A. Wood (Eds.). Early warning systems for drought preparedness and drought management. *Geneva: World Meteorological Organization*, 75−87.

Jiang, L., & Islam S. (2003). An intercomparison of regional latent heat flux estimation using remote sensing data. *International Journal of Remote Sensing*, 24 (11), 2221–2236.

John F., Robert W. J., Bethany A. B., & John F. M. (2007). Extracting phenological signals from multiyear AVHRR NDVI time series: Framework for applying high-order annual splines with roughness damping. *IEEE Transactions on Geoscience and Remote Sensing*, 45 (10), 3264-3276.

Kaheil, Yasir H., Gill, M. Kashif, McKee, Mac, Bastidas, Luis A., & Rosero, E. (2008). Downscaling and assimilation of surface soil moisture using ground truth measurements. *IEEE Transactions on Geoscience and Remote Sensing*, 46 (5).

Kim Do-Woo, Byun, Hi-Ryong, & Choi, Ki-Seon (2009). Evaluation, modification, and application of the Effective Drought Index to 200-year drought climatology of Seoul, Korea. *Journal of Hydrology*, 378, 1–12.

Kim, Jongyoun, & Hogue, Terri S. (2012). Improving spatial soil moisture representation through integration of AMSR-E and MODIS products. *IEEE Transactions on Geoscience and Remote Sensing*, 50 (2), 446-460.

Kogan, F.N. (1990). Remote sensing of weather impacts on vegetation in non-homogeneous areas. *International Journal of Remote Sensing*, 11, 1405–1419.

Kogan, F.N. (1995). Droughts of the late 1980s in the United States as derived from NOAA polar-orbiting satellite data. *Bulletin of the American Meteorological*, 76 (5), 655–668.

Kogan, F.N. (1997). Global drought watch from space. *Bulletin of the American Meteorological Society*,78 (4), 621–636.

Lee, R., Yu, F., Price, K. P., Ellis J., & Shi, P. (2002). Evaluating vegetation phenological patterns in Inner Mongolia using NDVI time-series analysis. *International Journal of Remote Sensing*, 23 (12), 2505–2512.

Linsely Jr., R.K., Kohler, M.A., & Paulhus, J.L.H. (1959). Applied Hydrology. *McGraw Hill, New York*.

McGuire, A., & Palmer, W.C. (1957). The 1957 drought in The Eastern United States", Monthly Weather Review. *American Meteorological Society*, 305 – 314.

McKee, T. B., Doesken, N. J., & Kleist, J. (1995). Drought monitoring with multiple time scales. *Proceedings of the Ninth Conference on Applied Climatology*, 233–236.

Merlin, O., Bitar, A. Al, Walker, J. P., & Kerr, Y. H. (2009). A sequential model for disaggregating near-surface soil moisture observations using multiresolution thermal sensors. *Remote Sensing of Environment*, 113 (10), 2275–2284.

Merlin, O., Bitar, A. Al, Walker, J. P., & Kerr, Y. H. (2010). An improved algorithm for disaggregating microwave-derived soil moisture based on red, near-infrared and thermal-infrared data. *Remote Sensing of Environment*, 114 (10), 2305–2316.

Meyer, S. J., Hubbard, K. G., & Wilhite, D. A. (1993). A crop-specific drought index for corn: I. Model development and validation. *Agronomy Journal*, 86, 388–395.

Mishra, A.K., & Singh, V.P. (2010). A review of drought concepts. *Journal of Hydrology*, 391, 202–216.

Morid , Saeid, Smakhtin, Vladimir, & Bagherzadeh, K. (2007). Drought forecasting using artificial neural networks and time series of drought indices. *International Journal of Climatology*. 27, 2103–2111.

Morid, Saeid, Smakhtin Vladimir, & Moghaddasi, Mahnosh (2006). Comparison of seven meteorological indices for drought monitoring in Iran. *International Journal of Climatology*, 26, 971–985.

Narasimhan, B., & Srinivasan, R. (2005). Development and evaluation of Soil Moisture Deficit Index (SMDI) and Evapotranspiration Deficit Index (ETDI) for agricultural drought monitoring. *Agricultural and Forest Meteorology*, 133, 69–88.

National Rainfed Area Authority (2008). Report on drought mitigation strategy for Bundelkhand region of Uttar Pradesh and Madhya Pradesh.

Ozdogan, M., & Gutman, G. (2008). A new methodology to map irrigated areas using multi-temporal MODIS and ancillary data: An application example in the continental US. *Remote Sensing of Environment*, 112, 3520–3537.

Palmer, W.C. (1965). Meteorological drought. *U.S. Weather Bureau Research Paper*, 45, 58.

Pandey, R.P., Dash B.B., Mishra, S.K., & Singh R. (2008). Study of indices for drought characterization in KBK districts in Orissa (India). *Hydrological Processes.*, 22, 1895–1907.

Pashiardis, S., & Michaelides, S. (2008). Implementation of Standardized Precipitation Index (SPI) and Reconnaissance Drought Index (RDI) for regional drought assessment: A case study for Cyprus. *European Water Resources Association, European Water*, 23/24, 57-65.

Peters, A. J., WalterShea, Elizabeth A., JI, Lel, Vliia, Andres, Hayes, Mlchael, & Svoboda, M.D. (2002), Drought monitoring with NDVI-based Standardized Vegetation Index. *Photogrammetric Engineering & Remote Sensing*, 68 (1), 71-75.

Piles, M., Camps, A., Vall.llossera, M., Corbella, I., Panciera, R., R¨udiger, C., Kerr, Y., & Walker, J. (2011). Downscaling SMOS-derived soil moisture using MODIS Visible/ Infrared data. *IEEE Transactions on Geoscience and Remote Sensing*, 49, in press.

Prasad, A.K., Singh, R.P., Tare,V. & Kafatos, M. (2007), Use of vegetation index and meteorological index for the prediction of crop yield in India. *International Journal of Remote Sensing,* 28 (23), 5207-5235.

Quiring, Steven M., & Ganesh, S. (2010). Evaluating the utility of the Vegetation Condition Index (VCI) for monitoring meteorological drought in Texas. *Agricultural and Forest Meteorology,* 150, 330–339.

Rhee, Jinyoung, Im, Jungho, & Carbone, G. J. (2010). Monitoring agricultural drought for arid and humid regions using multi-sensor remote sensing data. *Remote Sensing of Environment*, 114, 2875–2887.

Rojas, O., Vrieling, A., & Rembold, F. (2011). Assessing drought probability for agricultural areas in Africa with coarse resolution remote sensing imagery. *Remote Sensing of Environment*, 115, 343–352.

Rooy, M. P. van (1965). A rainfall anomaly index independent of time and space. *Notos*, 14, 43.

Sandholt, I., Rasmussen, K., & Andersen, J. (2002). A simple interpretation of the surface temperature/vegetation index space for assessment of surface moisture status. *Remote Sensing of Environment*, 79, 213-224.

Shafer, B.A., & Dezman, L.E. (1982). Development of a Surface Water Supply Index (SWSI) to assess the severity of drought conditions in snowpack runoff areas. *In: Proceedings of the Western Snow Conference, Reno, NV,* 19-23, 164-175.

Singh, R.P., Roy, S., & Kogan, F. (2003). Vegetation and temperature condition indices from NOAA AVHRR data for drought monitoring over India. *International Journal of Remote Sensing*, 24, 4393–4402.

Smakhtin, V.U., & Hughes, D.A. (2007). Automated estimation and analyses of meteorological drought characteristics from monthly rainfall data. *Environmental Modelling & Software*, 22, 880-890.

Son, N.T., Chen, C.F., Chen, C.R., Chang, L.Y., & Minh, V.Q. (2012). Monitoring agricultural drought in the Lower Mekong Basin using MODIS NDVI and land surface temperature data. *International Journal of Applied Earth Observation and Geoinformation*, 18, 417–427.

Stockli, R., & Vidale P. L. (2004). European plant phenology and climate as seen in a 20-year AVHRR land-surface parameter dataset. *International Journal of Remote Sensing*, 25 (17), 3303–3330.

Tadesse, T., Brown, J.F., & Hayes, M.J. (2005). A new approach for predicting drought-related vegetation stress: Integrating satellite, climate, and biophysical data over the U.S. central plains. *ISPRS Journal of Photogrammetry & Remote Sensing,* 59, 244–253.

Tallaksen, L., & Lanen, van (2004). Hydrological drought, processes and estimation methods for streamflow and groundwater. *Developments in Water Science, Elsevier, Amsterdam*, 48, 579.

Tao, J., Zhongfa, Z., & Shui, C. (2011). Drought monitoring and analysing on typical Karst ecological fragile area based on GIS. *Procedia Environmental Sciences*, 10, 2091–2096.

Thenkabail, P.S., Dheeravath, V., Biradar, C.M., Gangalakunta, O.R.P., Noojipady, P., Gurappa, C., Velpuri, M., Gumma, M., & Li, Y. (2009). Irrigated area maps and statistics of India using remote sensing and national statistics. *Remote Sensing*, 1, 50–67.

Tsakiris, G., & Vangelis, H. (2005). Establishing a drought index incorporating evapotranspiration. *European Water Resources Association*, *European Water*, 9/11, 3-11.

Tucker, C. J. (1979). Red and photographic infrared linear combinations for monitoring vegetation. *Remote Sensing of Environment*, 8 (2), 127–150.

Tucker, C. J., & Choudhury, B.J. (1987). Satellite remote sensing of drought conditions. *Remote Sensing of Environment*, 43, 243-251

Usman, Muhammad T., Archer Emma, Johnston Peter, & Tadross, M. (2005). A Conceptual Framework for enhancing the utility of rainfall hazard forecasts for agriculture in marginal environments. *Natural Hazards*, 34, 111–129.

Wan, Z., Wang, P., & Li, X. (2004). Using MODIS land surface temperature and Normalized Difference Vegetation Index products for monitoring drought in the Southern Great Plains, USA. *International Journal of Remote Sensing*, 25, 61–72.

Wang, Lingli, & Qu, J. J. (2007). NMDI: A normalized multi-band drought index for monitoring soil and vegetation moisture with satellite remote sensing. *Geophysical Research Letters*, 34.

Watson, R.T., Intergovernmental Panel on Climate Change, Working Group II (1997). The regional impacts of climate change: an assessment of vulnerability: summary for policymakers. *Intergovernmental Panel on Climate Change*.

Weghorst, K. (1996). The reclamation drought index: Guidelines and practical applications. *Bureau of Reclamation, Denver (CO)*, 6.

Wilhite, D.A. (2002). Preparing for drought: a methodology. In:Wilhite, D.A. (Ed.), Drought: A Global Assessment. *Hazards and Disaster Series*, Routledge, New York, 2, 89 – 104.

Wilhite, D.A., & Glantz, M.H. (1985). Understanding the drought phenomenon: The role of definitions. *Water International*, 10, 111-120.

APPENDIX

APPENDIX – I

Rainfall deficit periods and Meteorological drought periods observed from 1975 to 2010, during Rabi seasons for 42460.

Season	Seasonal rainfall (mm)	Rainfall deficit from the mean seasonal rainfall	Meteorological drought as per IMD
1975-1976	52.1	deficit	normal season
1976-1977	42.6	deficit	normal season
1977-1978	54.4	normal	normal season
1978-1979	146.5	normal	normal season
1979-1980	76.3	normal	normal season
1984-1985	6.2	deficit	normal season
1987-1988	116.8	normal	normal season
1988-1989	44	deficit	normal season
1989-1990	39.6	deficit	normal season
1990-1991	32.9	deficit	normal season
1991-1992	20.8	deficit	normal season
1992-1993	151.6	normal	normal season
1993-1994	22.6	deficit	normal season
1994-1995	43.4	deficit	normal season
1998-1999	7.7	deficit	normal season
1999-2000	22	deficit	normal season
2000-2001	35.3	deficit	normal season
2001-2002	48.2	deficit	normal season
2002-2003	57.2	normal	normal season
2004-2005	46.2	deficit	normal season
2006-2007	33.2	deficit	normal season
Mean Seasonal rainfall **52.3 mm**			

APPENDIX – II

Rainfall deficit periods and Meteorological drought periods observed from 1975 to 2010, during Rabi seasons for 42463.

Season	Seasonal rainfall (mm)	Rainfall deficit from the mean seasonal rainfall	Meteorological drought as per IMD
1975-1976	73.9	deficit	normal season
1976-1977	53.9	deficit	normal season
1977-1978	60.1	deficit	normal season
1978-1979	66.7	deficit	normal season
1979-1980	66.8	deficit	normal season
1980-1981	26	deficit	normal season
1981-1982	102.8	normal	normal season
1982-1983	112.8	normal	normal season
1983-1984	70.2	deficit	normal season
1985-1986	412.5	normal	normal season
1986-1987	65.9	deficit	normal season
1987-1988	95.9	normal	normal season
1988-1989	98.4	normal	normal season
1990-1991	65.4	deficit	normal season
1993-1994	34.6	deficit	normal season
1994-1995	44.3	deficit	normal season
1995-1996	93.1	normal	normal season
1998-1999	25.9	deficit	normal season
1999-2000	12.1	deficit	normal season
2000-2001	47.3	deficit	normal season
2001-2002	75.2	normal	normal season
2002-2003	49.9	deficit	normal season
2003-2004	46.7	deficit	normal season
2004-2005	65.2	deficit	normal season
2005-2006	37.8	deficit	normal season
2006-2007	47.3	deficit	normal season
2007-2008	18.9	deficit	normal season
2008-2009	38.6	deficit	normal season
2009-2010	139.5	normal	normal season
Mean Seasonal rainfall is **74.1 mm**			

APPENDIX – III

Rainfall deficit periods and Meteorological drought periods observed from 1975 to 2010, during Rabi seasons for 42469.

Season	Seasonal rainfall (mm)	Rainfall deficit from the mean seasonal rainfall	Meteorological drought as per IMD
1982-1983	130.4	normal	normal season
1984-1985	31	deficit	normal season
1985-1986	227.9	normal	normal season
1986-1987	52.8	deficit	normal season
1987-1988	107.4	normal	normal season
1988-1989	35	deficit	normal season
1989-1990	50.7	deficit	normal season
1990-1991	3	deficit	normal season
1992-1993	13.8	deficit	normal season
1993-1994	8.4	deficit	normal season
1994-1995	8.9	deficit	normal season
1995-1996	14.7	deficit	normal season
1996-1997	124.3	normal	normal season
1997-1998	143.8	normal	normal season
1998-1999	24.8	deficit	normal season
1999-2000	15.2	deficit	normal season
2000-2001	5.6	deficit	normal season
2001-2002	25.8	deficit	normal season
2002-2003	18.7	deficit	normal season
2003-2004	47.1	deficit	normal season
2005-2006	48.8	deficit	normal season
2006-2007	105.7	normal	normal season
2007-2008	12	deficit	normal season
2009-2010	27	deficit	normal season
Mean Seasonal rainfall is **53.5 mm**			

APPENDIX – IV

Rainfall deficit periods and Meteorological drought periods observed from 1975 to 2010, during Rabi seasons for 42473.

Season	Seasonal rainfall (mm)	Rainfall deficit from the mean seasonal rainfall	Meteorological drought as per IMD
1975-1976	110.6	normal	normal season
1976-1977	21.8	deficit	normal season
1977-1978	73.4	deficit	normal season
1978-1979	67.9	deficit	normal season
1979-1980	91.3	normal	normal season
1981-1982	109.1	normal	normal season
1982-1983	90.1	normal	normal season
1983-1984	236.6	normal	normal season
1984-1985	23.3	deficit	normal season
1985-1986	241.9	normal	normal season
1986-1987	122.2	normal	normal season
1988-1989	82.5	deficit	normal season
1989-1990	37.8	deficit	normal season
1990-1991	99.9	normal	normal season
1992-1993	105.8	normal	normal season
1993-1994	75.6	deficit	normal season
1994-1995	71	deficit	normal season
1995-1996	131.7	normal	normal season
1996-1997	88.4	normal	normal season
1999-2000	50	deficit	normal season
2000-2001	43.8	deficit	normal season
2001-2002	52.1	deficit	normal season
2002-2003	71	deficit	normal season
2003-2004	27.6	deficit	normal season
2004-2005	96.2	normal	normal season
2005-2006	49.6	deficit	normal season
2006-2007	124.4	normal	normal season
2007-2008	2	deficit	normal season
Mean Seasonal rainfall is **85.6 mm**			

APPENDIX – V

Rainfall deficit periods and Meteorological drought periods observed from 1975 to 2010, during Rabi seasons for 42562.

Season	Seasonal rainfall (mm)	Rainfall deficit from the mean seasonal rainfall	Meteorological drought as per IMD
1975-1976	143.9	normal	normal season
1976-1977	34.2	deficit	normal season
1977-1978	88.7	normal	normal season
1978-1979	170.2	normal	normal season
1979-1980	213.7	normal	normal season
1980-1981	37.9	deficit	normal season
1981-1982	119.4	normal	normal season
1982-1983	147	normal	normal season
1983-1984	104.8	normal	normal season
1984-1985	10	deficit	normal season
1986-1987	115.8	normal	normal season
1987-1988	162.4	normal	normal season
1989-1990	29	deficit	normal season
1990-1991	22.6	deficit	normal season
1991-1992	5	deficit	normal season
2002-2003	30.2	deficit	normal season
2003-2004	26.5	deficit	normal season
2004-2005	65.9	deficit	normal season
2005-2006	80	deficit	normal season
2006-2007	77.8	deficit	normal season
Mean Seasonal rainfall is **84.25 mm**			

APPENDIX – VI

Rainfall deficit periods and Meteorological drought periods observed from 1975 to 2010, during Rabi seasons for 42570.

Season	Seasonal rainfall (mm)	Rainfall deficit from the mean seasonal rainfall	Meteorological drought as per IMD
1975-1976	65	deficit	normal season
1976-1977	53.2	deficit	normal season
1977-1978	196	normal	normal season
1978-1979	193.6	normal	normal season
1979-1980	125.2	normal	normal season
1981-1982	152.1	normal	normal season
1983-1984	216.8	normal	normal season
1984-1985	25.8	deficit	normal season
1986-1987	167.8	normal	normal season
1987-1988	143	normal	normal season
1988-1989	28.7	deficit	normal season
1989-1990	55.9	deficit	normal season
1990-1991	44.5	deficit	normal season
1991-1992	19.5	deficit	normal season
1993-1994	59.6	deficit	normal season
1994-1995	106.2	normal	normal season
1995-1996	84.7	deficit	normal season
1999-2000	0	deficit	normal season
2000-2001	6	deficit	normal season
2001-2002	183.2	normal	normal season
2003-2004	81.8	deficit	normal season
2004-2005	80.3	deficit	normal season
2005-2006	61.2	deficit	normal season
2006-2007	67	deficit	normal season
Mean Seasonal rainfall is **92.4 mm**			

APPENDIX –VII

Rainfall deficit periods and Meteorological drought periods observed from 1975 to 2010, during Rabi seasons for 42673.

Season	Seasonal rain (mm)	Rainfall deficit from the mean seasonal rainfall	Meteorological drought as per IMD
1977-1978	222.7	normal	normal season
1978-1979	192.1	normal	normal season
1979-1980	216.6	normal	normal season
1980-1981	43.8	deficit	normal season
1981-1982	199.5	normal	normal season
1982-1983	107.1	deficit	normal season
1983-1984	203.4	normal	normal season
1984-1985	28.4	deficit	normal season
1985-1986	245.6	normal	normal season
1986-1987	148.8	normal	normal season
1987-1988	42.6	deficit	normal season
1988-1989	52.2	deficit	normal season
1989-1990	49.6	deficit	normal season
1990-1991	82.8	deficit	normal season
1991-1992	12.8	deficit	normal season
1992-1993	47	deficit	normal season
1993-1994	129.6	normal	normal season
1994-1995	118.5	normal	normal season
1995-1996	133.5	normal	normal season
1996-1997	45	deficit	normal season
1997-1998	316.1	normal	normal season
1998-1999	182.4	normal	normal season
1999-2000	100.4	deficit	normal season
2000-2001	56.2	deficit	normal season
2001-2002	102.5	deficit	normal season
2002-2003	168.2	normal	normal season
2003-2004	64.8	deficit	normal season
2004-2005	64.4	deficit	normal season
2007-2008	17.6	deficit	normal season
2008-2009	40.6	deficit	normal season
2009-2010	235.7	normal	normal season
Mean Seasonal rainfall is **118.4 mm**			

APPENDIX – VIII

Mean of effective precipitation (X*p*)and standard deviation of difference between observed effective precipitation and X*p* (Y*p*), for the *p*th Julian day.

Julian day (p)	Northern Plains				Central Highlands			
	Irrigated		Rain-fed		Irrigated		Rain-fed	
	Xp	Yp	Xp	Yp	Xp	Yp	Xp	Yp
1	0.68	1.77	0.83	2.13	0.80	1.97	0.37	0.85
2	0.71	0.93	0.94	1.18	0.93	1.12	0.65	0.52
3	0.36	0.40	0.52	0.53	0.64	0.57	0.57	0.49
4	0.15	0.20	0.19	0.20	0.28	0.33	0.28	0.30
5	0.03	0.07	0.04	0.05	0.08	0.11	0.08	0.12
6	0.01	0.03	0.01	0.02	0.01	0.04	0.01	0.04
7	0.18	0.55	0.42	1.34	0.40	1.27	1.24	3.90
8	0.08	0.25	0.19	0.61	0.18	0.58	0.56	1.77
9	0.10	0.28	0.17	0.48	0.19	0.55	0.24	0.62
10	0.29	0.92	0.47	0.00	0.66	2.09	0.87	2.75
11	1.22	3.85	1.16	3.64	1.10	3.47	1.05	3.29
12	1.36	4.28	1.80	5.66	2.22	6.99	2.66	8.37
13	0.57	1.80	0.76	2.39	0.94	2.96	1.13	3.56
14	1.13	2.94	1.52	3.89	1.52	3.59	0.94	2.02
15	0.45	1.32	0.59	1.74	0.54	1.52	0.25	0.64
16	0.18	0.53	0.23	0.70	0.22	0.61	0.10	0.26
17	0.05	0.01	0.12	0.03	0.09	0.03	0.25	0.07
18	0.35	1.01	0.50	1.34	0.50	1.42	0.72	1.79
19	0.16	0.46	0.22	0.61	0.00	0.64	0.32	0.00
20	0.06	0.18	0.08	0.24	0.08	0.26	0.11	0.33
21	0.27	0.85	0.56	1.77	1.50	4.52	1.07	3.35
22	0.47	1.23	0.55	1.56	0.80	2.34	0.66	1.86
23	1.23	3.31	0.96	2.16	0.78	1.56	0.91	2.09
24	2.02	6.15	2.13	6.45	2.46	7.46	1.84	5.57
25	1.12	3.45	1.12	3.42	1.36	4.18	1.01	3.13
26	0.39	1.22	0.40	1.27	0.52	1.65	0.37	1.16
27	0.05	0.15	0.03	0.11	0.05	0.15	0.04	0.12
28	0.11	0.33	0.14	0.45	0.09	0.29	0.03	0.10
29	0.21	0.46	0.23	0.50	0.16	0.32	0.19	0.36
30	0.37	0.89	0.53	1.39	0.53	1.42	0.43	1.00
31	0.18	0.43	0.30	0.74	0.30	0.72	0.41	0.74
32	0.37	0.56	0.58	0.93	0.83	1.48	0.70	1.28
33	1.16	2.91	1.33	3.06	1.03	2.10	0.92	1.82
34	1.40	4.08	2.16	6.29	2.86	8.41	4.69	14.23
35	0.61	1.87	0.98	2.99	1.35	4.20	2.19	6.80

Julian day (p)	Northern Plains				Central Highlands			
	Irrigated		Rain-fed		Irrigated		Rain-fed	
	Xp	Yp	Xp	Yp	Xp	Yp	Xp	Yp
36	0.87	2.74	1.81	5.70	2.62	8.23	4.85	15.26
37	0.38	1.17	0.82	2.53	1.31	4.01	2.13	6.40
38	0.15	0.47	0.33	1.02	0.53	1.63	0.86	2.57
39	0.02	0.04	0.05	0.09	0.12	0.25	0.10	0.19
40	0.00	0.01	0.01	0.03	0.03	0.09	0.02	0.07
41	0.53	1.20	0.57	1.38	0.95	2.63	0.63	1.78
42	1.65	3.37	1.81	3.89	3.26	7.45	2.50	5.71
43	5.78	12.75	6.60	14.74	6.91	14.41	6.25	13.01
44	8.75	14.09	9.06	14.54	9.54	15.81	7.54	13.59
45	3.85	6.22	4.01	6.43	4.27	7.02	3.37	5.97
46	2.48	4.89	2.40	4.64	2.14	3.75	1.53	2.68
47	0.71	1.88	0.66	1.79	0.46	1.31	0.35	0.91
48	0.38	0.74	0.39	0.69	0.25	0.46	0.15	0.31
49	0.06	0.02	0.08	0.02	0.04	0.01	0.02	0.01
50	0.31	0.84	0.28	0.68	0.40	0.98	0.52	1.32
51	2.49	7.78	2.85	8.90	2.91	9.02	3.11	9.59
52	1.38	4.21	1.50	4.61	1.38	4.22	1.46	4.47
53	0.55	1.66	0.59	1.83	0.53	1.63	0.55	1.71
54	0.06	0.15	0.07	0.19	0.09	0.24	0.10	0.26
55	0.18	0.54	0.18	0.53	0.14	0.34	0.10	0.25
56	0.24	0.54	0.19	0.43	0.11	0.23	0.10	0.20
57	0.88	2.68	1.10	3.35	1.17	3.61	0.85	2.63
58	0.38	1.21	0.48	1.52	0.52	1.64	0.38	1.19
59	0.14	0.45	0.18	0.58	0.20	0.64	0.15	0.47
60	0.00	0.01	0.00	0.01	0.00	0.01	0.00	0.01
61	0.69	2.18	0.68	2.14	0.37	1.15	0.20	0.64
62	0.63	1.66	0.73	1.77	1.00	2.17	0.79	1.70
63	0.40	0.97	0.41	0.93	0.60	1.38	0.49	1.11
64	0.14	0.35	0.18	0.44	0.27	0.69	0.35	0.94
65	0.51	1.02	0.50	0.77	0.55	0.99	0.69	1.10
66	0.25	0.52	0.24	0.39	0.25	0.44	0.31	0.49
67	1.99	5.98	1.24	3.37	0.96	2.26	1.12	2.67
68	1.50	4.38	1.59	4.25	2.29	5.61	2.87	7.45
69	2.21	5.39	2.61	6.17	3.31	7.86	3.98	8.88
70	3.97	9.48	4.23	10.01	4.45	10.38	4.64	11.38

Julian day (p)	Northern Plains				Central Highlands			
	Irrigated		Rain-fed		Irrigated		Rain-fed	
	Xp	Yp	Xp	Yp	Xp	Yp	Xp	Yp
71	3.31	7.60	3.09	6.95	3.32	7.78	3.23	7.83
72	1.59	3.81	1.45	3.42	1.66	4.13	1.69	4.38
73	0.43	1.10	0.36	0.91	0.46	1.21	0.49	1.29
74	1.00	2.97	0.82	2.38	0.34	0.84	0.38	0.86
75	1.93	4.32	1.71	3.74	1.04	2.18	1.46	2.86
76	0.96	2.16	0.91	1.98	0.59	1.18	0.76	1.39
77	0.32	0.87	0.32	0.81	0.22	0.49	0.29	0.57
78	0.02	0.05	0.03	0.07	0.02	0.05	0.02	0.04
79	1.07	3.38	1.09	3.43	0.61	1.93	0.30	0.94
80	0.65	2.04	0.64	2.03	0.36	1.13	0.17	0.55
81	0.27	0.84	0.27	0.84	0.15	0.47	0.07	0.23
82	0.03	0.09	0.03	0.09	0.01	0.05	0.01	0.02
83	0.00	0.01	0.00	0.01	0.00	0.01	0.00	0.01
84	0.17	0.53	0.35	1.06	0.69	2.10	0.52	1.55
85	0.09	0.25	0.18	0.52	0.33	0.97	0.28	0.78
86	0.04	0.10	0.07	0.21	0.13	0.39	0.11	0.32
87	0.00	0.00	0.00	0.01	0.00	0.01	0.01	0.02
88	0.00	0.01	0.00	0.01	0.00	0.01	0.00	0.01
89	0.13	0.04	0.10	0.03	0.03	0.01	0.03	0.01
90	0.06	0.02	0.05	0.01	0.01	0.00	0.01	0.00
91	0.02	0.01	0.02	0.01	0.01	0.00	0.01	0.00
92	0.00	0.01	0.00	0.01	0.00	0.01	0.00	0.01
93	0.06	0.18	0.13	0.42	0.12	0.39	0.30	0.94
94	0.03	0.08	0.06	0.19	0.06	0.18	0.14	0.43
95	0.12	0.07	0.13	0.15	0.06	0.13	0.12	0.30
96	0.25	0.61	0.24	0.54	0.16	0.40	0.27	0.62
97	0.35	0.35	0.35	0.51	0.44	1.01	0.41	0.88
98	0.39	0.57	0.47	0.78	0.49	0.91	0.47	0.91
99	0.51	1.24	0.48	1.06	0.42	0.90	0.41	0.77
100	0.74	1.75	0.98	2.38	1.14	3.12	1.37	3.91
101	0.52	1.01	0.70	1.34	0.67	1.49	0.66	1.71
102	0.19	0.38	0.28	0.53	0.26	0.58	0.25	0.66
103	0.04	0.12	0.05	0.17	0.03	0.10	0.01	0.04
104	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
105	0.36	0.10	0.50	0.14	0.30	0.09	0.10	0.03

Julian day (p)	Northern Plains				Central Highlands			
	Irrigated		Rain-fed		Irrigated		Rain-fed	
	Xp	Yp	Xp	Yp	Xp	Yp	Xp	Yp
106	0.45	0.35	0.55	0.46	0.50	0.84	0.30	0.64
107	0.22	0.16	0.26	0.21	0.22	0.38	0.14	0.29
108	0.50	0.81	0.88	1.84	1.58	4.38	1.39	4.07
109	2.19	1.84	2.20	2.00	1.88	3.35	2.20	3.19
110	1.07	0.83	1.15	0.89	0.94	1.43	1.29	1.39
111	0.57	0.32	0.55	0.28	0.33	0.28	0.53	0.35
112	0.09	0.03	0.10	0.04	0.05	0.03	0.10	0.08
113	0.03	0.01	0.03	0.02	0.01	0.01	0.02	0.03
114	0.01	0.02	0.02	0.06	0.02	0.05	0.05	0.17
115	0.08	0.24	0.06	0.17	0.04	0.10	0.05	0.14
116	0.40	0.76	0.35	0.78	0.36	0.97	0.28	0.72
117	0.66	1.33	0.54	1.16	0.34	0.82	0.36	0.93
118	0.30	0.62	0.26	0.54	0.21	0.50	0.33	0.76
119	0.10	0.21	0.10	0.20	0.08	0.16	0.16	0.33
120	0.04	0.12	0.09	0.26	0.21	0.64	0.18	0.53
121	0.02	0.05	0.04	0.11	0.09	0.27	0.07	0.20
122	0.07	0.03	0.10	0.05	0.09	0.11	0.04	0.08
123	0.77	2.11	0.54	1.21	0.43	0.96	0.26	0.64
124	0.59	1.21	0.53	1.03	0.45	0.82	0.78	1.57
125	1.26	2.77	1.32	3.25	0.76	1.71	0.67	1.23
126	0.57	1.41	0.60	1.59	0.33	0.82	0.29	0.58
127	0.21	0.57	0.22	0.63	0.11	0.32	0.07	0.18
128	0.00	0.01	0.00	0.01	0.00	0.01	0.00	0.01

273	1.91	4.41	2.44	5.48	2.43	5.11	3.20	6.54
274	3.15	6.57	4.74	9.27	8.23	16.41	9.58	22.78
275	1.38	2.80	2.07	3.98	3.64	7.21	4.18	10.01
276	2.07	1.01	2.92	1.48	4.22	2.81	4.00	3.83
277	4.08	4.44	4.48	4.38	5.85	4.54	6.03	4.61
278	10.03	21.27	9.52	18.75	9.83	16.78	10.04	14.52
279	8.15	20.44	8.36	20.86	8.50	20.33	8.83	19.56
280	6.43	18.55	7.52	21.89	8.47	24.72	9.58	27.55
281	3.32	9.88	3.64	11.09	3.92	12.08	4.25	13.06
282	3.27	6.45	2.71	5.25	2.15	4.37	1.98	4.48
283	1.54	3.16	1.26	2.34	1.16	1.84	1.25	1.95
284	0.68	1.32	0.71	1.03	0.78	1.07	0.90	1.04

Julian day (p)	Northern Plains				Central Highlands			
	Irrigated		Rain-fed		Irrigated		Rain-fed	
	Xp	Yp	Xp	Yp	Xp	Yp	Xp	Yp
285	0.19	0.29	0.29	0.41	0.40	0.52	0.53	0.44
286	0.29	0.75	0.43	1.13	0.41	1.00	0.27	0.37
287	5.34	15.83	6.32	18.98	5.62	17.00	4.94	15.13
288	2.42	7.19	2.86	8.63	2.54	7.73	2.23	6.88
289	1.10	2.87	1.37	3.47	1.35	3.23	1.36	3.09
290	0.07	0.22	0.11	0.35	0.16	0.51	0.22	0.68
291	1.35	4.15	2.83	8.73	6.38	19.84	6.98	21.66
292	1.05	3.31	2.30	7.23	5.41	17.02	5.26	16.55
293	0.52	1.42	1.03	3.06	2.38	7.23	2.31	6.97
294	0.99	2.39	0.96	2.03	1.37	3.11	1.13	2.36
295	1.35	3.67	0.98	2.53	1.08	3.05	1.32	3.87
296	0.58	1.61	0.42	1.11	0.46	1.32	0.57	1.71
297	1.84	5.23	1.29	3.70	0.75	1.99	0.72	1.76
298	0.76	2.39	0.54	1.69	0.28	0.89	0.25	0.78
299	0.30	0.96	0.21	0.68	0.11	0.36	0.10	0.31
300	0.25	0.80	0.21	0.66	0.06	0.19	0.07	0.22
301	0.12	0.36	0.10	0.30	0.03	0.09	0.03	0.10
302	0.05	0.14	0.04	0.12	0.01	0.03	0.01	0.04
303	0.00	0.01	0.00	0.01	0.00	0.01	0.00	0.01
304	0.00	0.01	0.00	0.01	0.00	0.01	0.00	0.01
305	0.00	0.01	0.00	0.01	0.00	0.01	0.00	0.01
306	0.00	0.01	0.00	0.01	0.00	0.01	0.00	0.01
307	0.00	0.01	0.00	0.01	0.00	0.01	0.00	0.01
308	0.62	1.95	0.66	2.08	0.73	2.29	0.62	1.96
309	0.28	0.89	0.30	0.95	0.33	1.04	0.28	0.89
310	0.11	0.36	0.12	0.38	0.13	0.42	0.11	0.36
311	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
312	0.07	0.02	0.10	0.03	0.06	0.02	0.02	0.01
313	0.07	0.02	0.09	0.03	0.16	0.04	0.31	0.09
314	0.07	0.02	0.09	0.03	0.20	0.06	0.44	0.13
315	0.34	0.99	0.28	0.78	0.19	0.34	0.28	0.30
316	0.17	0.46	0.17	0.44	0.19	0.43	0.17	0.29
317	1.38	3.65	1.76	4.50	1.88	4.86	2.11	5.21
318	1.31	3.54	1.46	3.59	1.48	3.49	1.50	3.40
319	3.19	9.66	4.41	13.17	5.63	16.88	7.03	20.77

Julian day (p)	Northern Plains				Central Highlands			
	Irrigated		Rain-fed		Irrigated		Rain-fed	
	Xp	Yp	Xp	Yp	Xp	Yp	Xp	Yp
320	1.38	4.03	1.95	5.57	2.62	7.28	3.63	9.13
321	0.68	1.88	1.04	2.76	1.35	3.55	1.96	4.46
322	1.97	6.10	3.10	9.51	3.96	12.17	4.95	14.78
323	1.70	4.05	1.84	4.50	2.10	5.57	2.38	6.71
324	1.56	4.16	1.20	2.76	1.18	2.73	1.12	2.84
325	1.75	3.99	1.63	3.73	1.18	2.82	0.58	1.27
326	1.50	3.85	1.38	3.65	0.85	2.31	0.48	1.25
327	0.58	1.62	0.55	1.58	0.34	0.98	0.19	0.54
328	0.14	0.46	0.12	0.39	0.06	0.20	0.04	0.14
329	0.09	0.28	0.07	0.22	0.03	0.09	0.02	0.08
330	0.04	0.13	0.03	0.10	0.01	0.04	0.01	0.04
331	0.55	1.73	0.46	1.45	0.23	0.71	0.16	0.50
332	0.34	1.07	0.31	0.97	0.24	0.76	0.16	0.51
333	1.56	4.90	2.13	6.69	2.21	6.94	1.41	4.45
334	0.66	2.08	0.93	2.92	0.98	3.09	0.62	1.96
335	0.26	0.81	0.36	1.14	0.38	1.20	0.24	0.76
336	0.00	0.01	0.00	0.01	0.00	0.01	0.00	0.01
337	0.00	0.01	0.00	0.01	0.00	0.01	0.00	0.01
338	1.55	3.77	1.35	3.01	1.34	3.12	1.74	3.73
339	0.71	1.71	0.61	1.37	0.61	1.42	0.79	1.69
340	0.28	0.69	0.25	0.55	0.24	0.57	0.32	0.68
341	0.00	0.01	0.00	0.01	0.00	0.01	0.00	0.01
342	0.00	0.01	0.00	0.01	0.00	0.01	0.00	0.01
343	0.06	0.20	0.04	0.14	0.02	0.06	0.02	0.07
344	0.07	0.20	0.10	0.28	0.08	0.24	0.07	0.20
345	0.03	0.09	0.04	0.13	0.04	0.11	0.03	0.09
346	0.01	0.03	0.01	0.05	0.01	0.04	0.01	0.04
347	0.00	0.01	0.00	0.01	0.00	0.01	0.00	0.01
348	0.00	0.01	0.00	0.01	0.00	0.01	0.00	0.01
349	0.00	0.01	0.00	0.01	0.00	0.01	0.00	0.01
350	0.00	0.01	0.00	0.01	0.00	0.01	0.00	0.01
351	0.00	0.01	0.00	0.01	0.00	0.01	0.00	0.01
352	0.82	2.59	0.93	2.93	1.22	3.83	1.92	6.05
353	0.39	1.23	0.45	1.42	0.59	1.85	0.93	2.93
354	0.16	0.50	0.18	0.57	0.24	0.75	0.37	1.18

Julian day (p)	Northern Plains				Central Highlands			
	Irrigated		Rain-fed		Irrigated		Rain-fed	
	Xp	Yp	Xp	Yp	Xp	Yp	Xp	Yp
355	0.00	0.01	0.00	0.02	0.01	0.02	0.00	0.03
356	0.00	0.01	0.00	0.01	0.00	0.01	0.00	0.01
357	0.34	1.07	0.49	1.53	0.30	0.96	0.16	0.52
358	0.92	2.88	0.81	2.55	0.48	1.50	0.35	1.11
359	0.49	1.31	0.19	1.15	0.37	0.85	0.00	0.63
360	0.21	0.48	0.18	0.39	0.14	0.32	0.11	0.25
361	0.03	0.10	0.03	0.09	0.03	0.10	0.02	0.07
362	1.69	5.30	1.39	4.37	0.63	1.97	0.52	1.64
363	1.49	4.69	1.58	4.96	1.18	3.71	1.33	4.20
364	0.64	2.00	0.68	2.15	0.52	1.64	0.59	1.87
365	0.13	0.42	0.17	0.54	0.16	0.51	0.20	0.63

APPENDIX – IX

Mean of Soil Moisture in Irrigated and Rain-fed Agriculture in Different Agro Climatic Zones of Bundelkhand region

Northern Plains				**Central Highlands**			
Irrigated		**Rain-fed**		**Irrigated**		**Rain-fed**	
Period Starting day	Mean SM (m^3/ $m^{3)}$	Period Starting day	Mean SM (m^3/ $m^{3)}$	Period Starting day	Mean SM (m^3/ $m^{3)}$	Period Starting day	Mean SM (m^3/ $m^{3)}$
1	0.189	1	0.181	1	0.214	1	0.190
17	0.196	17	0.187	17	0.202	17	0.202
33	0.190	33	0.183	33	0.195	33	0.183
49	0.171	49	0.168	49	0.177	49	0.172
65	0.132	65	0.122	65	0.142	65	0.139
81	0.101	81	0.093	81	0.118	81	0.112
97	0.103	97	0.095	97	0.122	97	0.118
113	0.088	113	0.085	113	0.112	113	0.101
273	0.200	273	0.178	273	0.214	273	0.203
289	0.173	289	0.159	289	0.180	289	0.176
305	0.161	305	0.151	305	0.168	305	0.163
321	0.173	321	0.165	321	0.182	321	0.180
337	0.227	337	0.224	337	0.235	337	0.231
353	0.177	353	0.167	353	0.189	353	0.187

APPENDIX – X

Mean of NDVI in Irrigated and Rain-fed Agriculture in Different Agro Climatic Zones of Bundelkhand region

Northern Plains				**Central Highlands**			
Irrigated		**Rain-fed**		**Irrigated**		**Rain-fed**	
Period Starting day	Mean NDVI	Period Starting day	Mean NDVI	Period Starting day	Mean NDVI	Period Starting day	Mean NDVI
1	0.61	1	0.54	1	0.57	1	0.53
17	0.62	17	0.55	17	0.60	17	0.54
33	0.59	33	0.52	33	0.57	33	0.49
49	0.53	49	0.47	49	0.52	49	0.44
65	0.42	65	0.39	65	0.42	65	0.36
81	0.30	81	0.30	81	0.30	81	0.29
97	0.24	97	0.25	97	0.25	97	0.26
113	0.23	113	0.24	113	0.24	113	0.25
273	0.44	273	0.56	273	0.55	273	0.62
289	0.38	289	0.49	289	0.46	289	0.52
305	0.37	305	0.44	305	0.40	305	0.47
321	0.40	321	0.44	321	0.41	321	0.46
337	0.49	337	0.47	337	0.46	337	0.49
353	0.56	353	0.51	353	0.53	353	0.52