MAPPING SPATIO-TEMPORAL CROPLAND CHANGES DUE TO WATER STRESS IN KRISHNA RIVER BASIN USING TEMPORAL SATELLITE DATA

THESIS SUBMITTED

TO

THE ANDHRA UNIVERSITY, VISAKHAPATNAM

FOR THE AWARD OF THE DEGREE OF

DOCTOR OF PHILOSOPHY

By

REDDI. V. RAMANA MURTHY

Under the Guidance of

Research Guide	Co-Guide	Addl. Co-Guide
Dr. E. Ammineedu	**Dr. G. Jai Sankar**	**Dr. Murali Krishna Gumma**
Professor	Professor & Head of the Dept.	Head, Remote Sensing & GIS Lab
Dept. of Geo-Engineering	Dept. of Geo-Engineering	Senior Scientist
College of Engineering(A)	College of Engineering(A)	ISD, ICRISAT
Andhra University	Andhra University	Patancheru
Visakhapatnam	Visakhapatnam	Hyderabad

DEPARTMENT OF GEO-ENGINEERING
COLLEGE OF ENGINEERING (A), ANDHRA UNIVERSITY
VISAKHAPATNAM
2014-20

CHAPTER - 1

INTRODUCTION

1.1 Introduction

Natural hazards namely droughts, floods, cyclones, hailstorms, volcanic eruptions, earth quakes, landslides, forest fire, locust outbreak etc, are common on the earth's surface. Most of them are of climatic origin. Incidence of these hazards causes loss of human life, failure of crops and destruction of ecosystems. Consequently, the social as well as economic conditions of any region is disoriented. Natural hazards cannot be prevented but the loss can be minimized to some extent by taking appropriate disaster mitigation strategies. These strategies can be achieved by developing early warning systems and developing effective communication systems to take immediate action during the incidence of disasters, improving medical services and training to the people individually; how to react when disaster warning announced in a region, on their own without waiting for the help. Thus, disaster management includes warning, prevention, planning, preparedness, monitoring, and assessment and relief activity.

Among all the natural disasters, drought is a weather related disaster. Droughts are generally defined as periods of dryness due to lack of rain, though the concept varies from region to region. Hence it is considered as a relative term. The understanding of drought is different to different people. To the farmer, drought is a period during which his normal farm operations are disturbed. On the other hand, according to soil scientists and ecologists drought incidence depends on the water balance conditions of a particular region. Thornthwaite et al. (1931), an eminent climatologist, explained the drought as a condition in which the amount of water needed for direct evaporation and transpiration is higher than the amount in the soil. The meaning of all these definitions indicate that drought is a meteorological situation of prolonged deviations causing acute water deficits which reflected in identifiable ecological expressions and farming imperatives. It is essential to analyse the droughts of any region critically as they adversely affect the food production and water availability. Unfortunately, prediction of droughts is not yet possible like other natural disasters such as cyclones, hailstorms, tornadoes etc

Studies indicated that drought is not a consequential effect of rainfall shortage alone, but it is also related to the soil and water demand of a place. Thus, to carry out the drought analysis of any region rainfall parameter is not sufficient.

According to Ray K. Linsley et al. (1982), drought do not descend all of a sudden without warning but usually is the culmination of set of weather sequences that require extended periods of time to develop. Thus, droughts like many other natural events may be considered to have an origin, intensification, spread as well as decay. Thornthwaite and Mather observed that drought does not begin when rainfall ceases but rather it initiates when plant roots can no longer obtain moisture from the soil for their requirements. Thornthwaite water balance method was developed from universal hydrological cycle. In this method, the atmospheric demand is compared with atmospheric supply and soil moisture storage. These estimations will provide quantitative information of water deficit and water surplus of a region in a given time. Hence, Thornthwaite's water balance approach is more rational to analyse the droughts since the drought condition is nothing but the deficit of water due to the failure of precipitation to meet the demands of the potential evapotranspiration.

According to Thornthwaite scheme, the earth comprises of 5 major climates namely per humid, humid, sub humid, semi-arid and arid. Among them per humid and humid climates are almost drought free and semi-arid and arid climates are drought prone. Persistence drought conditions of arid climate leads to desertification. Whereas, the sub humid climates possess critical water balances which vary vigorously from time to time and are therefore liable to incidence of droughts of various kinds.

Thornthwaite (1947) recognized three types of droughts as permanent, seasonal and contingent. The permanent droughts associate with driest climates, seasonal droughts accompany the climates which have well defined rainy and dry seasons and contingent droughts prevail in the climates where erratic rain occurs. These contingent droughts are the most characteristic phenomenon of sub humid climates and are of short duration in limited areas.

According to water balance concept drought is a physical disorder of the environment in which amount of water available from precipitation and soil moisture storage is not sufficient to meet the demands of evapotranspiration. In the Thornthwaite’s book – keeping procedure it is possible to compare the water supply by precipitation with water need through potential evapotranspiration, using soil as a moisture reservoir and estimate the water surplus, water deficit and the actual evapotranspiration on a monthly and seasonal basis or even on daily basis. In drought analysis, water deficiency is a significant parameter.

1.2 Drought Categorization

Though water deficiency computed from water balance analysis, which is the root cause of the drought, it is an absolute quantity cannot by itself furnish the idea of the acuteness of water shortage unless it is weighed against the water need. The aridity index, on the other hand, percentage ratio of water deficiency to the water need of the region is most appropriate parameter for the analytical study of drought situations.

Percentage departures of yearly aridity Indices (Ia) from the median value expressed as a percentage for the study period can indicate the diverse drought conditions experienced by the station under study. Yearly departures of these indices of a station from the median when graphically plotted against successive years will provide not only information about the years of drought but also the intensity of the drought situations. Subrahmanyam and Subramaniam (1965) have categorized the droughts according to their intensity by using standard deviation (○) technique. Table 1.1 provides the scheme of drought categorization

Table 1.1 Scheme of drought categorization

Departure of Ia from the median	Drought Category	Symbol
Less than ½ ○	Moderate	M
Between ½ ○ and 1 ○	Large	L
Between 1 ○ and 2 ○	Severe	S
Above 2 ○	Disastrous	D

1.3 Climate and agriculture

Agricultural potential of any region can be achieved with favourable climatic and edaphic factors. Andhra Pradesh is one of the prosperous agricultural regions of India as it has abundant thermal potential to support good crop growth. But the State is not an exception to weather hazards such as floods, droughts, hail storms and cyclones associated with gale winds. Hence, a proper management of crops is essential. Cropping pattern should be planned in accordance with the changing climatic conditions.

The two environmental parameters that are associated with crop prosperity are temperature and rainfall. The low and erratic nature of rainfall is responsible for the low seasonal soil moisture availability in the root zone. If the soil moisture deficit is prevented through irrigation, the reduction in the yield could be eliminated.

Water balance techniques of Thornthwaite (1955) enable to derive agro climatic zonation of cropping patterns based on the moisture adequacy of the region. Water balance estimations include soil moisture status and hence provide a realistic picture for a proper agricultural planning. The book-keeping procedure of water balance enables estimation of actual evapotranspiration (AE), which represents the amount of water that actually is used by the crops from the soil. The percentage ratio of potential evapotranspiration (PE), gives the index of moisture adequacy (Ima). Theima varies with the total availability of moisture and, therefore, is the best index to estimate the agricultural potentiality of the region to grow a variety of crops (Hemamalini, 1996). For an effective crop planning, it is essential to identify ecological zones which will provide maximum productivity of a particular plant species. The "moisture adequacy" is an index parameter which indicates the high or low potentiality of the region in terms of crop cultivation. The percentage values indicate high potentiality of the region. if the Ima percentage is low, it indicates that the particular region is suitable for certain type of crops which require low water supply. Sometimes crop cultivation can be adjusted to rainy season to fulfill the water requirements.

1.4 Agro Climatic Zones

The book-keeping procedure of Thornthwaite, which has a multifold utility in scientific investigations, also helps in demarcating suitable crops for particular climatic conditions. The actual evapotranspiration (AE), which is one of the derived parameters of water balance, represents the amount of water that is actually used by the vegetation and the soil. If AE is expressed as a percentage ratio of Potential evapotranspiration, the derived index is known as moisture adequacy index (Ima).

It varies with the total availability of moisture and therefore is the best index to estimate the agricultural capability of the region. On the other hand, if the value of this parameter is low, the agricultural pattern requires to be modified or growth of crops in those areas will be confined to the rainy season. Thus, Index of moisture adequacy is a useful indicator to assess the suitability of crops in a particular area.

According to the concept of Moisture adequacy (Subrahmanyam et al., 1963), when Ima values are between 60% and 100% paddy cultivation can be carried out even in the absence of supplemental irrigation. On the other hand, in areas where Ima values are 60 to 80 percent, paddy cultivation is uneconomical without supplemental irrigation. However these areas are efficiently suitable for millet cultivation. In the areas where Ima values are between 40 % and 60 %, only millets can be grown successfully, whereas in the areas with 20 % and 40 % Ima the choice of crops is highly limited to drought resistant crops which can withstand water scarce conditions (Table.1.2). Lastly, areas with less than 20 % of Ima are not at all suitable for any type of crop cultivation. However, livestock rearing can be suggested as an alternative to crop cultivation.

Table 1.2 Crop suitability under different Moisture adequacy conditions

Moisture adequacy Index (Ima) %	***Crop Suitability***
Above 80	Efficiently suitable to paddy
60 – 80	Suitable to paddy but yields are low; efficiently suitable to millets
40 – 60	Suitable to millets
20 – 40	Suitable only to drought resistant crops
Below 20	Not suitable to crop agriculture

1.5 Drought Vs. Agriculture

Drought is the single most important weather – related natural disaster. Drought may start any time, last indefinitely and attain many degrees of severity. It affects very large areas for months and years and has a serious impact on regional ecological resources and causes food shortages and starvation of millions of people. Compared to other natural disasters such as earthquakes, cyclone, floods or volcanic eruptions, the nature and impact of drought are more difficult to asses as its effects are pervasive encompassing all the resources in the region.

Based on the nature, droughts can be classified as meteorological, hydrological, soil moisture, agricultural, socio-economic and ecological droughts (Sinha, 2000). According to meteorologists drought is a condition whenever the deficiency of rainfall more than 26 %. (Srinivasulu et al., 2002). The hydrological drought indicated by reduced stream flow and low water levels in reservoirs and tanks. Drying up of water in the surface storage is most common. Inadequate moisture in the soil storage which may not support the cultivation is the soil moisture storage. Whereas, agricultural drought come into existence whenever rainfall and soil moisture are fails to meet the water requirement of the crops.

Indian economy is largely dependent on agriculture as more than 70% of the total population depends on agriculture for their livelihood. Indian agriculture is highly dependent on monsoon rainfall. The erratic nature of monsoon rainfall varies in terms of spatial as well as temporal distribution. As a consequence, drought is a frequent phenomenon over many parts of the country.

Out of net sown area of 140 million hectares about 68% of the area is reported to be vulnerable for drought conditions and about 50% of the drought prone area is classified as severe.

Indian Meteorological Department (IMD) monitors drought condition on a regular basis by correlating daily rainfall collected from the network of weather stations, with field observations of crops and seasonal conditions generated from the State agricultural and Revenue departments.

India has experienced a number of droughts since time immemorial. Drought derails the food production due to crop failure. Kharif crop is a very important crop season in India (June – October). Most of the crop produce comes from this season. The successes of kharif crop depend on the south west monsoon season’s rainfall.

1.6 Role of Remote sensing in monitoring Agriculture

In developing countries like India, the Crop statistics plays a vital role in understanding the crop production and food security. This comes into role because India is a country where majority of the food security depends on monsoon rainfall. It is very difficult to estimate the crop production, types of crop and crop acreage by field surveys and it will take lot of time and human effort. In this case, Monitoring agriculture using remote sensing is best alternate to estimate acreage under the crop, crop yield per unit area and also crop condition assessment. Now a day, the free availability of satellite data helps in large scale of research in agriculture sector.

The forecasting of crop production using remote sensing increases and spread all over the world. Acreage estimation using RS data has been verified in different parts of the world and also number of studies and research have been carried on remote sensing for crop acreage estimation in India Work carried out so far in India has demonstrated that even with single-date satellite data. It is possible to estimate pre-harvest acreages of major crops, particularly in single crop dominated regions, with sufficient accuracy. Many carried various studies on land use statistics through integrated modelling using GIS, integrated approach for estimation of crop acreage using remote sensing data and GIS, field survey for hilly region and spectral data used visual interpretation technique.

Crop yield estimation surveys based on several experiments estimated the accurate average yield for all major crops. Various yield models were developed by different researches like yields and weather, soil or biometrical characters, spectral reflectance and the crop yield. Several studies also measured parameters like vegetation vigour and some agronomic quantities such as leaf area index, wet or dry biomass or grain yield. Several vegetation indices were developed for the identification of different parameters.

The real time forecast of crop production helps in economic system and the development in remote sensing technology had an immense potential to improve the existing pre-harvest forecasting models.

1.7 Crop condition assessment

Monitoring of Crop condition in the early stage is essential for crop monitoring and crop yield prediction as well as the status and trend of their growth. Monitoring the crop condition at early stages of crop growth is very important in acquiring the exact production after harvest time. The real time statistics shows the great influence on the policymaking on the price, circulation and storage (Gumma et al 2019 and 2020).

The field survey statistics are often expensive, with some errors, and cannot provide real-time, and also delay in forecasting of crop condition. Remote sensing based satellites will provide temporally and spatially continuous information of crop. Many studies help in improving the methodology in finding crop rotation, cropping area or crop phenology, cropped/fallow land which is integrated to increase the accuracy of crop condition monitoring. International organizations like USDA of U.S. and VI of EU, as well as FAO, all have their own remote sensing based crop monitoring systems.

1.8 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 et al. (1963) defined "drought as the smallest annual value of daily stream-flow."

(vii) Palmer et al. (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.

1.9 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.

1.9.1 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.

1.9.2 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.

1.9.3 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).

1.9.4 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.

1.10 Impact of Drought

Drought is one of the costliest 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.

1.10.1 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.

1.10.2 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.

1.10.3 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.

1.10.4 Drought severity and duration

Droughts are a recurrent feature of the climate, varying in intensity, duration, and frequency across the climatic spectrum. A drought can have substantial economic, environmental, and social impacts and it produces a large number of impacts that affects the social, environmental, and economical standard of living. The characteristics of droughts are expressed in terms of drought index, intensity-duration- frequency. The relations between drought intensity, duration and frequency can be studied with conceptual models, which deal with meteorological droughts lasting at least one year, with specific applicability to subtropical and mid latitudinal regions. The severity of a drought depends upon its nature (whether agricultural, hydrological, or ecological). The overall impact of a drought event depends on several factors, including severity, frequency, area, and duration. Several drought indices have been defined for the characterization of drought severity over time. The timing of drought is important. Short but intense droughts that occur in the growing season typically have a significant impact on agriculture. Fundamental descriptors of droughts include their intensity and duration. Duration can be defined as the number of consecutive time steps that the time series (of soil moisture or runoff) is below a specified threshold level [intensity as the averaged cumulative departure from the threshold level for that duration, while severity is defined as the product of intensity and duration (cumulative departure from the drought threshold). Because droughts are regional phenomena that can cover large areas for long periods of time, the spatial extent of a drought is an equally important feature. On the other hand, droughts that start in the fall and end in the spring may have minimal impact since they occur in the time of year when the demand for water by both man and the environment are low.

1.10.5 Drought risk evaluation

Risk assessment involves evaluation of the significance of a risk, either quantitatively or qualitatively. Risk assessment/evaluation comprises of three steps:

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

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

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

Drought impacts have not been well quantified economically; officials tend to underestimate the importance of drought and often fail to be proactive in preparing for droughts.

Also society's vulnerability to drought is affected by population growth and shifts, urbanization, technology, demographic characteristics, water use trends, government policy, social behavior and environmental awareness. These factors are continually changing and society's vulnerability to drought may rise or fall in response to these changes. Therefore, assessment of probable risk arising out of this slow disaster would certainly help people adopt corrective measures in time to rule out the social and economic disruption caused.

1.11 Drought scenario – India

Indian economy mainly depends upon the agriculture as nearly 70 % of its population depends directly or indirectly on agriculture based occupation. About two thirds of the land receives uneven distribution rainfall and also less rainfall (less than 1000mm). Drought is frequent phenomenon over many parts of India, out of net sown area nearly 65 percent of the land are vulnerable to drought. Even after post-independence, about one thirds of irrigated area got affected by droughts. Every year, there is some area in India which affected by drought. In India, it is necessary to achieve 350 million metric tons of food production to meet its food security.

The traditional approach to drought as a phenomenon of arid and semi-arid areas is changing in India too. Now, even regions with high rainfall, often face severe water scarcities. Cherrapunji in Meghalaya, one of the world's highest rainfall areas, with over 11,000 mm of rainfall, now faces drought for almost nine months of the year. On the other hand, the western part of Jaisalmer district of Rajasthan, one of the driest parts of the country, is recording around 9 cm of rainfall in a year. Total rainfall increases generally eastwards and with height. Increase in precipitation is high at an elevation of around 1,500 metres in the Himalaya Mountains. With average annual rainfall ranging between 20 cm to over 1000 cm, the primary challenge is to store this precious water for the dry season that may follow. The droughts in Odisha State, which has an average rainfall of 1100 mm, remain a matter for continuing concern. Conditions of water scarcity in the Himalayan region are also not uncommon. Thus, drought is just not the scarcity or lack of rainfall, but an issue related to water resource management. The requirement of over 80-90 % of the drinking water and over 50 % for irrigation is met from groundwater in India. The control of this resource is with the owner of land. Without effective and large scale rainwater harvesting, only limited recharge can take place. An earlier analysis of incidence of droughts over the last two centuries in India does not show any increase in the frequency of drought in the recent years. However, the severity appears to have increased

1.12 Drought Scenario - Globally

All the developing countries are very much depending on the agriculture related business. These countries are almost drought prone. In most of the tropical countries, severe drought occurs for every five years. It depicts that fifty percent of worlds total population are affected by drought and nearly 33 percent of land under desertification.

Drought conditions have been widespread in North Africa, the Mid-East, West Asian countries, India, China and are also known to occur in North Central, and South America. The increased frequency and intensity of extreme weather conditions such as droughts, floods, heat/cold waves, cyclones, delayed or early onset of rains, long dry spells, early withdrawal, during the last two decades, have been attributed to global warming

With more than 300 river basins in India, some being shared by two or more countries, drought conditions will continue to exacerbate international water conflicts. Growing concerns over a potential increase in the frequency and severity of drought, along with the mounting evidence of the expanding vulnerability of countries to drought, underlining the importance of placing greater emphasis on pro-active drought policies and preparedness is a must. In many nations, particularly those characterized by more complex economies, the impact of drought quickly radiates to other sectors, as drought conditions extend for multiple seasons and years. In the United States, droughts have had significant impact on transportation, recreation and tourism, energy sector, forest fires, and the environment, endangering the survival of animal and plant species, and aggravating soil erosion.

1.13 Advantages of MODIS for drought monitoring

MODIS provides a unique opportunity for global assessment and monitoring of vegetation phenology and productivity every eight days at 1 km spatial resolution. The advantage of MODIS data is to develop a prototype for a near real time drought monitoring system at the scale of a country, state, district or pixel with an 8 or 16-day time interval. The results described feed directly into the development of the regional drought monitoring system (Thenkabail, 2004). The objectives of MODIS mission is to improve predictions and characterizations of natural disasters like droughts and as a next generation scientific satellite sensors, MODIS has particular advantages over NOAA AVHRR for land surface temperature detection and biomass estimation. On the other hand, MODIS has more finely defined visible and near infrared bands then NOAA AVHRR and it has one of the most accurate calibration subsystems ever flown on a remote sensing instrument. The calibration allows the raw brightness values to be converted into true percentage reflectance or radiance measurements (Wan, 1999). MODIS has a higher radiometric resolution than other sensors. It uses 12 bits for quantization in all bands as compare to AVHRR's 10 bits. Taking advantage of these characteristics, MODIS is expected to determine land surface temperature accurately and by integrating MODIS thermal infrared data into land surface monitoring can address two main problems in current drought monitoring schemes. First, accurate temperature observations from remotely sensed data can overcome very coarse spatial resolutions of weather stations at relative low costs and secondly it can be an appropriate tool for real time drought monitoring, which has not been successfully accomplished by current remotely acquired measures, such as vegetation indices, due to a lagged vegetation response to drought (Park, 2004). In addition to this the data (version 4) has been validated by NASA for scientific usages meaning that product quality is improved compared to earlier versions. MODIS provides in total 44 standard products to scientists. These products cover the fields of oceanography, biology and atmospheric science.

1.14 NDMA Guidelines

As per the National Disaster Management Guidelines, following are the procedures and definitions.

1.15 Drought Monitoring

Drought in the Indian region is monitored from the progress of the onset and the withdrawal of the southwest monsoon. Weather forecasts is broadly classified into three categories viz.

(1) Short range forecast (validity for less than 3 days),

(2) Medium range forecast (validity from 3-10 days), and

(3) Long range forecast (validity for more than 10 days).

These forecasts are issued by the Indian Meteorological Department through the All India Radio, the Doordarshan and various Newspapers. The National Centre for Medium Range Weather Forecasting in the Department of Science and Technology disseminates weather related information through its network of Agro-Met Advisory Service units located mainly in the State Agricultural universities and ICAR institutes. There is a need for establishing a centralized facility to fully realize the potential of the data base for drought management. Procedures will be streamlined to generate the information in a more objective manner, reducing the subjectivity in the interpretation of the data. The raw data along with their derivatives will be made accessible to the organizations concerned to enable decision making. Detailed project report for Integrated Agriculture Drought Management Information System has been prepared for National Informatics Centre. Maintenance of a substantial segment of such information system, monitoring and dissemination of the information is already in place in Karnataka and Andhra Pradesh.

1.15.1 Early Warning and Forecasting of Drought

With the launch of the Indian Remote Sensing Satellite (IRSS) in 1988 and the follow on IRS series subsequently, the thrust has also been on remote sensing application to key sectors of development such as land and water resources management, coastal and marine resources, forest management, flood and drought disaster management etc. With the active user participation, the satellite application programme has evolved to provide vital inputs to decision making at Central and State level. The satellite derived vegetation index and wetness index information constitute the main indicators for crop condition monitoring. Ministry of Earth Sciences in collaboration with ICAR has set up 89 centres for short and medium range monitoring and forecasting of weather. In order to overcome the limitations of drought monitoring, a project titled ‘National Agricultural Drought Assessment and Monitoring System (NADAMS) sponsored by the Department of Agriculture and Cooperation and the Department of Space (DoS) was taken up by the National Remote Sensing Agency in collaboration with the Indian Meteorological Department (IMD), Central Water Commission (CWC) and concerned State Government agencies. Near real-time assessment of agricultural drought at district level for 9 States and sub district level for 4 States, in terms of prevalence, severity and persistence, during kharif season (June-Nov) and submission of monthly drought reports to the Ministry of Agriculture and State Departments of Agriculture and Relief of different States is the main focus of this project. There is a need to use additional vegetation related parameters (derived from satellite generated products for estimation of agrometeorological parameters such as rainfall, soil moisture and evapo-transpiration. This is important in view of low density of the network of ground-based observations available in the country. There is also a need to develop ways and means to obtain soil moisture data and also the evapo-transpiration rates to forecast accurately the crop health at different phenological stages in a season. Similarly, there is a need to analyse soil samples to measure the moisture level for an assessment of actual crop conditions

1.15.2 Drought Assessment and Risk Analysis

National guidelines on Drought Management will reduce risk by developing better awareness and understanding of the drought and the causes of societal vulnerability. The principles of risk management will be promoted by building greater institutional capacity through the improvement and application of seasonal and shorter-term forecasts, integrated monitoring and drought early warning systems and connected information delivery systems, developing preparedness plans at all levels of governance, adopting mitigation actions and programmes, and creating a safety net of emergency response programmes that ensure timely and targeted relief.

1.16 Indicators

Drought indicators are identified from the types and the impact of drought. The impacts of drought are listed as environmental, economic or social. Among the environmental indicators one could include, rainfall, water level in the reservoirs and other surface storage systems, ground water depth and soil moisture. A robust data base that is comparable over time and progressively captures micro-level details has to be built and constantly updated. For each indicator thresholds need to be fixed contextually, to define intensity of the problem. A normal rainfall succeeding a few years of drought would not wipe out the cumulative effect the earlier droughts. On the social and economic front, data relating to trends in agricultural commodity prices, land distribution, copping pattern, changes in copping calendar, sown area, productivity, livestock density etc. have to be built and updated. When drought begins, the agricultural sector is usually the first to be affected because of its heavy dependence on stored soil water. Soil water will be rapidly depleted during extended dry periods. If precipitation deficiencies continue, then people dependent on other sources of water begin to feel the effects of the shortage.

1.16.1 Agriculture drought

Agriculture is the first sector to be affected by drought. Within the agricultural sector, marginal and small farmers are more vulnerable to drought because of their dependence on rain fed agriculture and related activities. As a consequence, they face much greater relative loss of assets, thus widening disparities between small and large farmers. Also, as unemployment increases purchasing power decreases- credits shrink and the cost of credit increases. Consequently, the vulnerable segments are either forced to migrate, work at lower wages or live in near hunger conditions. Pressure and fear of losing social status due to drought induced poverty forces farmers to take drastic steps like suicides In order to understand the diversity of coping strategies, it is necessary to explore the social, political and institutional factors that provide contexts for these individual perceptions. Perceptions, however, are not static and will shift over time or are expressed differently under altering circumstances. Thus perceptions of drought and the associated risks are crucial to formulate appropriate relief and mitigation policies. Perceptions also shape the responses to drought and the confusion on what drought is, which will cause difficulties in dealing with the hazard. Some of the difficulties are:

(i) Drought is perceived as a slow onset phenomenon because its onset and end are often difficult to identify;

(ii) Drought is generally viewed as a transient phenomenon. As a result, it is usually not taken seriously after the rains occur; it is considered as a calamity and managed as an event.

(iii) The direct impacts of drought such as the withering crops, dry watering points, reduced forage for livestock etc., are obvious. Second and third order effects, such as price rise, increased food imports, surges in rural-urban migration rates, are often not recognized

.

1.16.2 Hydrological Drought

Hydrological drought is associated with the effects of periods of precipitation (including snowfall) shortfalls on surface or subsurface water supply (i.e., stream flow, reservoir and lake levels, ground water). The frequency and severity of hydrological drought is often defined on a watershed or river basin scale. Although all droughts originate with a deficiency of precipitation, hydrologists are more concerned with how this deficiency plays out through the hydrologic system. Hydrological droughts are usually out of phase with or lag the occurrence of meteorological and agricultural droughts. It takes longer for precipitation deficiencies to show up in components of the hydrological system such as soil moisture, stream flow, and ground water and reservoir levels. As a result, these impacts are out of phase with impacts in other economic sectors. For example, a precipitation deficiency may result in a rapid depletion of soil moisture that is almost immediately discernible to agriculturalists, but the impact of this deficiency on reservoir levels may not affect hydroelectric power production or recreational uses for many months. Also, water in hydrologic storage systems (e.g., reservoirs, rivers) is often used for multiple and competing purposes (e.g., flood control, irrigation, recreation, navigation, hydropower, wildlife habitat), further complicating the sequence and quantification of impacts. Competition for water in these storage systems escalates during drought and conflicts between water users increase significantly. Although climate is a primary contributor to hydrological drought, other factors such as changes in land use (e.g., deforestation), land degradation, and the construction of dams all affect the hydrological characteristics of the basin. Because regions are interconnected by hydrologic systems, the impact of meteorological drought may extend well beyond the borders of the precipitation-deficient area. Like an agricultural drought, this can be triggered by more than just a loss of rainfall.

1.16.3 Drought Declaration

Different States adopt different methodologies for drought assessment, preparation of drought memoranda, drought declaration and assessment of magnitude of relief required. The administrative units for drought declaration also differ from State to State; while some States consider 'talukas' as units, some 'mandals' and others 'districts'. The time of declaration also differs from state to state. States making drought declarations in the beginning of the season take into account the impact of subsequent developments. The issues that need to be reflected upon in this context are listed

- Different criteria by different states
- Differences in Time of declaration from state to state
- Early declaration (eg. June/July)
- Improved rainfall situation after declaration in June/July not being accounted for
- Drought declaration at the end of the season – too late for relief works
- Differences in timelines of declaration.

Declaration of drought, traditionally, is recommended after the estimates of crop production are obtained through Annewari/ Paisewari. Generally, those areas where Annewari/ Paisewari is less than 50 percent, the areas is considered to be affected by a drought. Final figures in respect of Kharif crops are available only in December, while those for Rabi crops are available in March. If drought is declared as late as December or January, relief works will start only after such a declaration. It will be too late if the distress signals have appeared in the wake of rainfall deficiency. Also if the drought is declared in January or February, the Central Team would visit much after the crop is harvested and it would not be in a position to assess crop losses. To promote management of relief measures in near real time it is necessary to declare early season drought by end of July, mid-season drought (growing season) by end of September and end season by November. Timely declaration in Phase 1 and 2 facilitates the commencement of interim relief measures such as crop contingency, supply of inputs etc. Currently the crop yield assessment arising out of crop cutting experiments are the basis for the declaration of drought and intervention regarding conversion of term loans by the banks. The crop cutting experiments are conducted by the Department of Economics and Statistics. The number of crop cutting experiments is increasing and it is taking more time to arrive at the decisions relating to declaration of drought and benefits to the affected farmers through change in the loan terms and input subsidies for the subsequent sowing season. It is possible that parts of districts which are declared as drought affected may not be facing drought. As a result some States use Bolcks/Tehsils as unit for declaring drought. Some States such as Rajasthan have used village as unit for declaring drought. This may lead to problems in implementation of drought relief measures vis-a vis neighbouring villages. There is therefore a need to standardise State specific units for declaration of drought to exclude areas not affected by drought and at the same time enable effective targeted relief measures.

1.16.4 Immediate Measures

With a view to ensuring timely declaration of drought, based on objective considerations, the following steps will be taken:

i. The Drought Monitoring Cell (DMC) in the States will receive and collate the weather data from multiple sources across the state like IMD, Irrigation Department, Department of Agriculture, Ground water Department;

ii. Data on water levels in reservoirs/ tanks, ground water etc. will be received weekly from the concerned departments;

iii. This work of collection and collation at district level will be done by the existing departments and the information will be supplied to DDMA and SDMA;

iv. The data received from sub-district level through District and State level will be made available online.

v. The DMC will prepare weekly status of weather and crop condition on the following indicators:

a. Rain fall deviations at taluka/block level;

b. Number and length of the dry spell at taluka/block level;

c. Progression of crop area sown at district/taluka level;

d. Satellite derived indicators such as Normalized Difference Vegetation Index (NDVI), Normalized Difference Water Index (NDWI) and interpreted maps/images provided by NRSC and ISRO;

e. Soil Moisture (computed on the basis of either water balance approach geo spatial indicators);

f. Ground water availability map;

vi. Declaration of drought will be done in a timely manner preferably in three phases

(1) end of July,

(2) end of September and

(3) end of November;

vii. Declaration in each phase will account for the beneficial effects of rainfall from the time of previous declaration and change in the agricultural situation;

viii. Interim relief measures will commence from the middle of the season;

ix. The final relief measures will be implemented after the final declaration at the end of the season;

x. After declaration of the Drought, the SDMA Secretariat will take steps to approach the Centre for financial and other assistance;

xi. The DMC as a part of State Disaster Management Authority will work in close coordination with State Departments of Revenue, Agriculture, Ground water, Irrigation, Science & Technology for pooling the data and expertise;

xii. The network of the Revenue and Agriculture Departments will be effectively used for collecting the information on crop sown areas, rainfall and crop yield data and for integrating then with DMC data base; and Regional climate models which improve the drought prediction and forecasting, to enable forewarning of drought and preparedness and agro advisories to minimize the impact of drought will be developed and disseminated.

1.17 Guidelines of Drought Management

These guidelines will ensure that: -

I All contemporary knowledge, experience and information are taken on board, clear destinations identified and road maps drawn with milestones clearly marked off through a wide consultative process involving all stakeholders

ii. The evolution and practice of standard procedures for declaration of drought including the time of declaration is promoted and the gravity of the risk and the vulnerability of various States are duly understood.

iii. Development of standard procedures for drought vulnerability assessment and generation of vulnerability maps in each state is undertaken.

iv. The critical areas for minimizing loss of lives, livelihood and property are addressed purposefully and systematically.

v. Measures are put in place for drought proofing of chronically drought-prone areas.

vi. The India Drought Management Centre (IDMC) is set up.

vii. Organization and development of a centralized data base at state level and at nation level related to drought intensity assessment, drought declaration, vulnerability assessment and drought management are undertaken on priority. Grievance Management Systems are put in place for ensuring that benefits reach the intended beneficiaries.

viii. Application of ICT is promoted not only to create the databases, but also for effective monitoring the measures being taken. Effective use of e-mail, Video Conferencing, mobile phones for reducing time lag in traditional systems is encouraged.

ix. Remote sensing technology and data warehousing is promoted to study historical and future trends of the drought occurrence and its effects

. x. There is institutional participation and use of collective expertise in the drought intensity assessment/drought declaration/drought vulnerability assessment. Expert advisory systems are set up for providing advice to the affected population to mitigate the effects

xi. A common policy is evolved to dovetail short-term relief measures into long-term interventions being handled in different Ministries/ Departments for comprehensive and allinclusive Drought Management. xii. Global and National best practices in Drought Management are identified and adopted.

1.18 Objectives of The National Guidelines On Drought Management

i. The primary responsibility of managing drought (or any other natural calamity) is that of the respective State Government. The criteria followed for drought declaration and the time when the drought is declared differs across the states. There is no time limit for declaration of drought by the States.

ii. Involvement of various Ministries/Departments/Organisations in one or the other shortterm or long term activities of drought management results in delay in effective and timely coordination. The indicators used and the methodology followed for drought intensity assessment and drought monitoring differ largely from state to state.

iii. Slow setting in of drought makes it difficult to determine the onset and end of drought.

iv. The data required for drought assessment and drought declaration are available but in a scattered manner, with different organizations, in local formats making it cumbersome for quick analysis and decision making.

v. The availability of key data used for drought intensity assessment such as rainfall, crop sown areas, and reservoir levels differs from state to state. The procedures for data collection and data-base maintenance vary across states. This leads to insufficient use of Information and Communication Technology (ICT) tools by various agencies in management of drought.

vi. Lack of check dams in the rainfed areas results in inadequate storage-water in times of need or drought.

vii. Lack of community participation in drought management activities at the village/Tehsil level, and the low levels of involvement of Self Help Groups, NGOs and the corporate sector in drought management reduces the overall value of the effort.

1.19 Crop Insurance

An important instrument to combat the adverse financial impact of droughts on the farmers is agricultural insurance. Though the agricultural insurance schemes have not been very successful, the GoI has taken several initiatives towards increasing its coverage and reach. An All-India Comprehensive Crop Insurance Scheme (CCIS) for major crops was introduced in 1985. It was subsequently replaced by the National Agricultural Insurance Scheme (NAIS) in 1999. The GoI also set up the Agriculture Insurance Company of India (AIC) in 2003 to serve the needs of farmers better and to move towards a sustainable actuarial regime. As the coverage of agricultural insurance in the country increases, insurance schemes for drought protection will become more viable. Insurance products will be developed for different agro-climatic zones providing coverage against drought. The Central/State Governments will promote in these zones, agricultural insurance programmes and ensure that farmers are informed about the availability of insurance products and educate them about the need for managing their yield and income risks through insurance coverage. Therefore:i.

Focus of the Government on crop insurance will continue and role of agriculture insurance company will be widened.

ii. Weather insurance will be promoted for crops not having data base on productivity. Government will set up automated weather stations where necessary.

iii. The scope of the National Agricultural Insurance Scheme (NAIS) will be widened to include pre-sowing and post-harvest losses. vii. Awareness will be enhanced with reference to crop insurance through state departments to improve coverage.

iv. Price fluctuations will be stabilized by strengthening links of farm products with agro-based industries.

v. Price linked insurance products will be promoted to avoid distress sales of farm produce.

vi. The use of satellite derived crop condition images as surrogates to crop yield estimates will be explored to facilitate for settlement of insurance claims.

PMFBY (PRADHAN MANTRI FASAL BIMA YOJANA)

The PMFBY was launched in 2016 and replaces all the prevailing yield insurance schemes in India with an impetus on crop sector. The scheme has extended coverage under localized risks, post-harvest losses etc. and aims at adoption of technology for the purpose of yield estimation.

Coverage of Risks and Exclusions:

Prevented Sowing/ Planting Risk:

Insured area is prevented from sowing/ planting due to deficit rainfall or adverse seasonal conditions

Standing Crop (Sowing to Harvesting):

Comprehensive risk insurance is provided to cover yield losses due to non- preventable risks, viz. Drought, Dry spells, Flood, Inundation, Pests and Diseases, Landslides, Natural Fire and Lightening, Storm, Hailstorm, Cyclone, Typhoon, Tempest, Hurricane and Tornado.

Post-Harvest Losses:

coverage is available only up to a maximum period of two weeks from harvesting for those crops which are allowed to dry in cut and spread condition in the field after harvesting against specific perils of cyclone and cyclonic rains and unseasonal rains.

Localized Calamities:

Loss/ damage resulting from occurrence of identified localized risks of hailstorm, landslide, and Inundation affecting isolated farms in the notified area.

1.20 Importance of drought monitoring and previous studies

The identification of changes of Land use/land cover (LULC) of river basin is one of most important factor for assessment of drought. LULC changes (LULCC) has considerable effects on many processes in basins including soil erosion (Douglas et al., 1983), global warming (Penner et al., 1992) and biodiversity (Chapin et al., 2000), and LULCC leads to cause greater impact on human habitat than climate change (Skole et al., 1994). Land cover helps in environmental monitoring (FAO, 2002). even though the significance of land cover as an environmental variable, the understanding of its dynamics is poor (Foody et al., 2002) or inaccurate.

The Spatial information distribution data of irrigated areas available at the state and national governments have much deviation from the ground level values. The district level crop statistics have been collected by both irrigation and agriculture departments and are published by the state and national governments have differences in the extent of irrigated area reported. The irrigation varies with rainfall which leads to stress during critical crop growth stages. There is inequitable distribution of water due to overuse in high areas and cultivating water-intensive crops such as rice and sugarcane leads to water stress in major command areas of the Krishna Basin. The allocation of water in the river basin and command area should be based on location specific information can help in reducing water stress level for some extent. Monitoring and understanding LULC for every crop year will have high advantage to identify parameters, such as loss of agriculture land, decreasing environmental quality, water resources management etc. Land use data helps in analyzing various environmental processes and problems for sustainable development. Continuous monitoring the land use and land cover changes manually in the command areas can be labour intensive and costly. It is very efficient to use satellite images available in the public domain at coarse and medium spatial resolution (such as AVHRR, MODIS, Landsat and ASTER and also have an continuous monitoring.

Accurate information on the basin-wise extent of cropland have an advantage in food security assessment, water allocation decisions and yield estimation. This information helps decision makers to monitor the dynamic changes in landscapes like agricultural lands, fallow croplands and land cover such as forests, water bodies and wetlands. The land use changes help in socially, economically and ecologically sustainable land use planning. The agriculture and revenue departments of states and country require spatial information up to the village level to make policies for farmers' advantage and adopting best agricultural practices.

World Meteorological Organization (WMO) declared year 2015 as the hottest year on record. There was an extreme weather events such as heat waves, flooding and severe drought with very high temperatures over both land and ocean in 2015.

The major portion of the fresh water available for human habitat is utilized by Irrigation and evapo-transpiration which is about 70-80%. The high water usage in upstream areas leads to scarcity in downstream areas. The Krishna basin has nearly 90% of flat area (below 750m) which resists the flow leads to loss due to evaporation. There is a need of data availability of amount of irrigated land and usage of irrigation for assessment of drought years. To understand the amount of irrigation required for future use, the current extent has to be known. A number of studies have been conducted using advanced tools like remote sensing and GIS to monitor irrigated agriculture. The topic of research is to map drought areas under Krishna river basin using MODIS time-series coarse resolution satellite data due to its daily global coverage, freely available and availability of multi-date data. Thenkabail et al. (2005) generated LULC and irrigated area maps for the Ganges and Indus river basins in the Indian subcontinent using MODIS time series. This study explains all the pre-processing methods required to handle time-series data sets for irrigated area mapping. Kamthonkiat et al. (2005)

established a technique called peak detector algorithm to show the difference between rain-fed and irrigated rice crops in Thailand using a 3-year time series of SPOT VEGETATION 1-km NDVI data to identify cropping intensity. Satakmoto et al. (2006) mapped the spatiotemporal distribution of rice cropping systems of Mekong and Bassac river basins using MODIS. Biggs et al. (2006) used MODIS time series to map surface water irrigation, groundwater irrigation, and rain-fed ecosystems of the Krishna river basin in southern Indian peninsula. This paper has stressed the importance of NDVI time series to identify the drought areas. Using multi-temporal MODIS data, Xiao et al. (2006) mapped rice-growing regions in the south and southeast Asia. This study has established the methodology of deriving drought affected areas using time composite satellite data at the global scale. MODIS data is highly helpful in eliminating cloud cover by compositing the daily data.

The major observation of the literature taken shows that the single-date imagery acquired at the peak of the growing season, is sufficient to identify irrigation. The multi-date data are required to identify different irrigated crop types and the irrigation intensity (Thiruvengadachari, et al., 1981; Rundquist et al., 1989; Thenkabail, et al., 2005, 2006).

Moderate Imaging Spectrometer (MODIS) onboard National Aeronautic and Space Administration’s (NASA’s) Terra satellite imagery became easy to assess LULC dynamics, irrigated areas, and quantitative landscape characteristics (e.g., biomass, leaf area index) in near real time due to its temporal resolution of one day. The advancement of spectral, spatial, radiometric, and temporal resolutions and techniques of cloud/haze removal algorithms, time compositing, and normalization of data into reflectance helps in many qualitative and quantitative applications related to LULC, irrigated area mapping, biomass estimations (Thenkabail et al., 2003 and 2004a), and leaf area index assessments with greater frequency and accuracy.

The methods applied for mapping irrigated areas are well established and validated for time-series coarse spatial resolution data to derive intensity of irrigation and cropping calendar of all the crops under irrigation, and acquiring coarse spatial resolution data has its own advantages such as availability of cloud-free, time series that can be downloaded for free.

The main reason of analyzing changes in agricultural land use is to observe the cropping patterns and cropland changes. These analyses depend on agricultural statistics (e.g., area extent) reported by the district and state or provincial level agricultural and irrigation agencies have some deviations from ground level. Using remote sensing with satellite imagery helps in preparing detailed maps of land use and identifying cropping pattern changes due to variations in rainfall and other parameters. Remote sensing utilizing satellite imagery helps in quantifying irrigation systems, but is less frequently used to identify the irrigated area changes in command areas due to variations in rainfall and water supply. MODIS continuous time series data of the normalized difference vegetation index (NDVI) have been used for mapping land use changes, irrigated areas and used for detecting changes in irrigated areas in major river basins. Water deficit for rainfed crops can also identified based on low rainfall using NDVI imagery during 2013-2014 and 2015-2016. The land use and land cover changes were compared with ground survey data and published statistics. The present study analyzed irrigated areas land use changes in the Krishna Basin and also focused on the areas where significant changes had occurred in the cropping pattern for the drought assessment.

CHAPTER - 2

REVIEW OF LITERATURE

2.1 Introduction

Drought is understood as a most significant natural disaster phenomenon which leads to food, fodder, and water shortages along with destruction of vital ecological system. Drought is a natural hazard with negative effects on society and environment which is intensified by increasing water demand (Mishra & Singh, 2010 Mishra, A. K., & Singh, V. P. (2010). A review of drought concepts. Journal of Hydrology, 391, 202–216.10.1016/j.jhydrol.2010.07.012[Crossref], [Web of Science ®], [Google Scholar]). Drought is a phenomenon associated with the scarcity of water due to delay in rainy season and/or reduction in "Normal" rainfall. Droughts can be experienced anywhere such as areas having little or high rainfall. It brings misery to large sections of the population and habitat. The drought characteristics usually varied significantly amid regions such as the Western Europe, North American Great Plains, southern Africa, Australia, and north-western India (Wilhite & Buchanan-Smith, 2005 Wilhite, D. A., & Buchanan-Smith, M. (2005). Drought as a hazard: Understanding the natural and social context. In D. A. Wilhite (Ed.), Drought and water crisis. Science, technology, and management issues (pp 3–29).London: CRC Press, Taylor and Francis.10.1201/CRCBKSPE [Crossref], [Google Scholar]), Drought is an environmental disaster which has a concern with hydrology, environment, ecology, meteorology, geology, and agricultural scientists. The soil surface as well as ground water resources are affected by drought and can lead to reduced-productivity as well as crop failure, reduction in water supply, declined water quality, reduced power generation, disturbed riparian habitations, suspended entertaining events, and economic as well as social events (Riebsame, Changnon, & Karl, 1991 Riebsame, W. E., Changnon, S. A., & Karl, T. R. (1991).

Drought and natural resource management in the United States: Impacts and implications of the 1987–1989 drought (p. 174). Boulder, CO: The Westview Press. [Google Scholar]). Demand of water have been increasing by many folds to cater a growing population in developing countries and for maintaining living standards as well as for recreation in the developed countries. Rise in conflicts for water sharing has been increased amongst urban population (drinking and domestic use), expansion of agriculture in rural sector (livelihood and food security), generation of power (hydropower and thermal power plants), and industrial sectors (processing and cleaning). The conflicts for water sharing between countries, states, regions, and districts had made people enemy of each other. The situation gets worsened in drought period when limited water resources get depleted faster than rejuvenation. Also water scarcity is also added by factors, such as water contamination, variation of rainfall pattern due to climate change, etc.

Indian economy is largely based on agriculture, as approximately 70% of the total population depends on it for their livelihood. Almost 75–90% of the yearly rainfall of India occurs in four months of the rainy season due to the southwest monsoon. Owing to both spatial and temporal abnormalities in monsoon precipitation, droughts frequently occurs in most part of the country.

2.2 Studies on 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 et al. (1980) introduced “Bhalme and Mooley et al., 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 3.2.

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 capable 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:

$$\mathrm{NDVI} = (\mathrm{NIR} - \mathrm{Red}) / (\mathrm{NIR} + \mathrm{Red})$$

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:

$$\mathrm{VCI}_i = 100 * [(\mathrm{NDVI}_i - \mathrm{NDVI}_{min}) / (\mathrm{NDVI}_{max} - \mathrm{NDVI}_{min})]$$

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 has 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:

$$\text{TVDI} = (Ts - Ts_{min}) / (a + b\text{NDVI} - Ts_{min})$$

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 2.1). The TVDI usage is good enough for application over large areas.

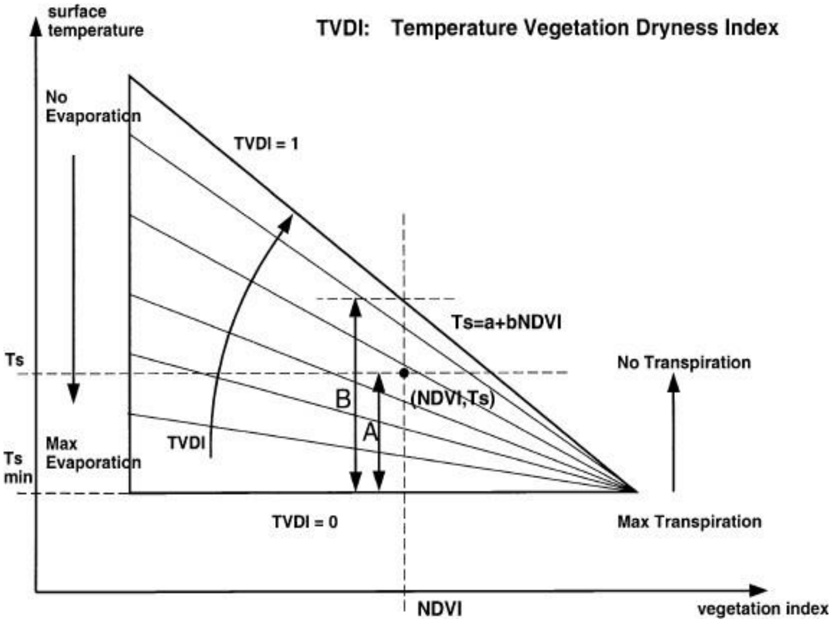


Figure 2.1 Temperature Vegetation Dryness Index
(Source: Sandholt et al., 2002)

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 Drought Studies Using Remote Sensing and GIS

Ajay and Baldev Sahai et al. (1986) have described the role of remote sensing in drought detection and its quantification. Different types of drought have been discussed. It is stated that the steady rise in temperature, absence or the deficiency of rainfall over a fairly long period from the basic characteristic of drought. In addition, the study provides the information on useful spectral bands and indices used for the assessment of drought like NDVI, Stress Degree Day, Temperature Stress Days and Crop Water Stress Index. The study concluded that the problem of drought/crop condition assessment may use a hybrid approach which uses both comparatively high resolution earth resources satellite data together with coarse resolution meteorological satellite data.

Thiruvengadachari and Gopalakrishna et al. (1993) developed an Integrated Data base Environment for Assessment of Drought (IDEA), primarily meant to provide operational assistance to the National Agricultural Drought Assessment and Monitoring System (NADAMS) in the analyses and interpretation of NDVI data derived from the NOAA AVHRR satellite sensor. IDEA has been used to derive two indices namely Seasonal Vegetation Index (SVI) and Peak Vegetation Index (PVI) that are used in tandem to characterize the drought prone taluks of the Karnataka State. A weighting model was used to show relative drought proneness of the Karnataka taluks. The ground variables taken into account were, percentage irrigation support, percentage forested area, percentage rainfed area and normal seasonal rainfall for each taluk.

Bora et al. (1995) studied the integrated resource survey using remote sensing to combat drought in a part of Nagaur district of Rajasthan State, India using False Color Composite (FCC) of IRS-1A LISS-II of October 1988 and January 1989. Based on visual interpretation, it is concluded that remote sensing technique is a useful tool for inventory of resources of any area and the integration of database of resources led to scientific planning and alternate land uses for combating drought menace.

Tripathy et al. (1996) attempted to evaluate the indicators of desertification process in semi-arid lands of Shahapur and Shorapur taluks of Gulbarga district of Karnataka State, India by making use of temporal satellite information (Landsat-4 MSS 1984 & 1985 and IRS-1A LISS-II 1988 & 1991) along with the surface and statistical data with the aid of GIS. A desertification severity map was produced by integrating meteorological, hydrological and biological indicators. The study concludes that the average severity of desertification is moderate and aggravated by human activity.

A study for monitoring the regional drought of South American continent using AVHRR data was carried out by Liu and Kogan (1996). Drought areas are delineated with certain threshold values of NDVI and Vegetation Condition Index (VCI). It has been reported that drought patterns delineated by NDVI and VCI agreed quite well with rainfall anomalies observed from rainfall map. The results showed that NDVI images provided a useful tool to study large scale climatic variability, while VCI images provided a useful tool to analyse the temporal and spatial evolution of regional drought as well as to estimate the crop production qualitatively.

Seiler et al. (1998) carried out a study on AVHRR based Vegetation and Temperature Condition indices for drought detection and impact assessment on agricultural yields in Cordoba province of Argentina. It is concluded that the VCI and TCI are useful to assess the spatial characteristics, the duration and severity of drought, and were in a good agreement with precipitation patterns.

Bayarjargal Yu et al. (2000) carried out a study on drought and vegetation monitoring in the arid and semi-arid regions of the Mongolia using NOAA/AVHRR satellite data. Drought affected regions were detected by calculating the Normalised Difference Vegetation Index (NDVI) and Land Surface Temperature (LST) values of the drought and wet years. Due to moisture stress on the vegetation, NDVI (LST) value recorded in the dry years should be lower (higher) than those values recorded in a normal year. It is concluded that the AVHRR based NDVI and LST can provide valuable information for operational drought detecting and monitoring.

Hostert et al. (2001), made a study on monitoring and assessment of desertification using remote sensing and GIS. The study provides the additional value that can often be added through integrating remote sensing derived information with auxiliary data through GIS approach. The study outlined the importance of integrating socio-economic boundary conditions and anthropogenic influences. The study further highlights the perspectives of future developments and their likely implications on Remote Sensing and GIS based desertification research.

Jayaseelan et al. (2002) has described the recent trends in remote sensing applications to drought assessment and monitoring with a case study on National Agricultural Drought Assessment and Monitoring System (NADAMAS). After the country wide drought in 1987, the emphasis on using space technology for drought monitoring grew and in 1989, NADAMAS was set up at National Remote Sensing Agency (NRSA), India. Organizations involved in the functioning of NADAMS are National Remote Sensing Agency (NRSA), India Meteorological Department (IMD), Central Water Commission (CWC) and State Agricultural Departments. The project covers 14 agriculturally important and drought vulnerable states of the country, which include Tamil Nadu State. NADAMS monitors drought during June to October, the main cropping season in the country.

The NADAMS uses NOAA AVHRR data to monitor country level vegetation dynamics. Bi- weekly NDVI time series is used to monitor the vegetation phenology throughout the season. For regional drought monitoring (State level), NADAMS uses Wide Image Field Sensor (WiFS) data of IRS-1C/1D and IRS-P3.

Singh Ramesh et al. (2003) carried out a study on monitoring drought over India by studying VCI and TCI of NOAA AVHRR data. Time series of satellite data during 1985-1996 over various Indian regions have been used for mapping vegetation cover and classification employing NDVI. The VCI quantifies weather component which varies from 0 to 100, corresponding to changes in vegetation condition from extremely unfavourable to optimal. The study has reported that VCI and TCI can be used for drought detection and mapping. The TCI alone cannot be used alone to predict drought due to stressed vegetation and wetting of land. The VCI coupled with TCI may be employed as a tool to monitor both drought and excessive wetness.

Lei and Peters Albert et al. (2003) presented a study for assessing the vegetation response to drought in Northern Great Plains using AVHRR data during 1989 to 2000. The derived vegetation condition and moisture availability for the grassland crop land in the Northern Great Plains fits very well with the predicted and observed NDVI values in most cases. It is concluded that the NDVI is a good indicator of moisture condition and can be an important data source when used for detecting and monitoring the drought. However, seasonality may be an important factor for decision makers to consider.

Wan et al. (2004) carried out studies for drought monitoring in Southern Great Plains, USA. The NDVI derived from Terra Moderate Resolution Imaging Spectroradiometer (MODIS) of 2001 and Land Surface Temperature (LST) have been used in this study. These two are called Vegetation

Temperature Condition Index (VTCI) which ranges from 0 to 1. The lower the value the higher the occurrence of drought. The study concluded that VTCI is physically interpreted as the ratio of LST differences among the specific NDVI values in an area large enough to provide wide ranges of NDVI and soil moisture at surface layers. Drought monitoring approach by VTCI integrates the remotely sensed land surface reflectance and thermal properties and gives the emphasis on changes in both LST and NDVI over a region. VTCI is time dependant and usually region specific and is useful during plant growing seasons.

Simeonakis and Drake et al. (2004) studied the monitoring desertification and land degradation over sub-Saharan Africa using AVHRR data of 1996. This study emphasized the role of soil erosion that has resulted due to natural processes, such as drought and human activities, such as irrigation, agriculture, deforestation and urbanization. The regional land degradation is assessed by the estimation of vegetation cover which is linearly related with NDVI. Soil erosion, the chief indicator is estimated using a model parameterized over land flow, vegetation cover, the digital soil map and a digital elevation model. The most susceptible degraded land is highlighted by combining the effects of all the four indicators.

Bhuiyan et al. (2004) used multi-sensors data to deduce surface and meteorological parameters (vegetation index, temperature, evapotranspiration) of Aravalli region for the years 1984-2000 together with actual ground data (rainfall, temperature, ground water level) for detailed drought analysis. The Standardised Precipitation Index (SPI) has been used to quantify the precipitation deficit. A standardized Water-level Index (SWI) has been developed to assess groundwater recharge deficit. Vegetation drought index has been calculated using NDVI values obtained from Global Vegetation Index (GVI) of NOAA AVHRR data. Spatial and temporal variations in meteorological, hydrological and vegetative droughts in the Aravalli terrain have been analysed and correlated for monsoon and non-monsoon seasons during the years 1984-2000. Based on the results, it is concluded that, none of the drought indices follow any particular spatial and temporal pattern in this region. The analysis reveals that meteorological, hydrological and vegetative droughts are not linearly inter-related and suggests that combination of various indices offer better understanding and monitoring of drought conditions for hilly and semi-arid terrains such as Aravalli of Western India.

Nageswara Rao et al. (2005) used METEOSAT-5 thermal infrared (TIR) data for assessing the spatial and temporal distribution of rainfall and impact of successive agricultural droughts in the state of Karnataka. It is emphasized that there is a need for an independent system that can provide the severity, duration and aerial extent of drought and its impact on the actual condition of the crops/vegetation so that the authorities concerned can take appropriate relief measures. A comparison of NDVI for the years 2000, 2001 and 2002 has been made. Districts having permanent vegetation, like forests and agricultural land under irrigation did not show much variation between a normal year (2000), drought year (2001) and a severe drought year (2002). It is concluded that the NDVI is a good indicator of agricultural drought but the reduction in green cover due to drought may be inferred and interpreted carefully by comparing the NDVI values of the year under study with a normal year.

Wipop Paengwangthong and Sirirat Sanyong et al. (2006) carried out a study on drought risk area analysis in Bandanlanhoi district, Sukhothai province based on stepwise regression model from spatial data. QUICKBIRD satellite images were used for creation of spatial data. Geographic Information System was applied to simulation spatial data such as rainfall, rainy days, relative humidity, temperature, groundwater potential, distance from water body, elevation and soil drainage data. The model showed that the well soil drainage and rainfall are important parameters for the determination drought risk area. The drought risk area was divided into four classes viz., No risk, low risk, moderate risk and high risk. The study concluded that, though the result was shown quite low accuracy, the technique is good enough for using with GIS.

Rasheed and Venugopal et al. (2009) attempted to map the agro- ecological units for Vellore district of Tamil Nadu and derive the crop-zone map for the four corps namely, paddy, sugarcane, groundnut and millets. The study has demonstrated the application of agro-ecological units for sustainable land use planning of a region. The basic theory of FAO framework for land evaluation was adopted to define the suitability of crops. Land quality details like terrain, soil and climatic characteristics are necessary for evaluating agro-land suitability of crops and for delineating the agro- ecological units. Agro-ecological units' map was generated by overlaying the agro-edaphic and agro-climatic map layers in GIS. The agro-land suitability map was generated by matching the crop requirement details with the land qualities. The results of the suitability evaluation, when compared with the current land use statistics of these crops showed that area cultivated is less than the area suitable for these crops.

2.4 Studies on Multi-Criteria Analysis and GIS

Sandeep Goyal et al. (1999) has made an attempt to use multi criteria evaluation technique to evaluate the interclass and intermap dependencies for groundwater resource evaluation in Rawasen and Pili river watershed, which are tributaries of Ganga. The individual class weights and map scores were determined using Analytical Hierarchy Process (AHP). These weights were applied in linear summation equation to obtain a unified weight map containing due weights of all input variables, which has further reclassified to arrive at groundwater potential zone map.

Mongkolsawat et al. (2000) made an attempt to model the drought risk area with a set of themes using remotely sensed data and GIS for Northeast Thailand. The drought risk area represents the integration of meteorological drought, hydrological drought and physical drought. The matrix overlay operation of the three drought risk layers was performed to yield the resultant polygonal layer. The study indicated that high drought risk areas are found in the Southeast and extended to Northeast of the region. The study confirms that the model developed can greatly enhance drought risk area mapping in the Northeast. In conclusion, the results obtained by the integration of a number of variables concerned provides guidelines for drought mitigation plan and allocates water for rural consumption.

Wendy Proctor et al. (2000) made a study on the practical application of a Multi-criteria Analysis to the integration of various forest values. It is stated that AHP is essentially an interactive one where a decision-maker or group of decision-makers relay their preferences to the analyst and can debate or discuss opinions and outcomes. AHP is based upon the construction of a series of ‘pair-wise comparison’ matrices which compare criteria to one another in order to estimate a ranking or weighting of each of the criteria that describes the importance of each of these criteria in contributing to the overall objective. The results show that the two extreme forest use options – the ‘conservation’ option and the ‘timber industry’ option – are preferred over the more ‘middle ground’ scenarios. The results also show that, overcoming the complex problems involved in achieving Ecologically Sustainable Development, such as those of comparing multiple values and incorporating stakeholder participation into the decision process can be aided by the use of Multi-Criteria Analysis.

Prathumchai et al. (2001) made an attempt to evaluate the criteria for identifying drought risk areas in Lop Buri province, Thailand Geographic Information System and Remote Sensing technology. JERS-1 OPS dry season data was acquired for the years 1995 & 1997, and was processed to detect vegetation condition change in response to drought. Physical and meteorological factors were analyzed and drought risk areas were identified based on the criteria of Ministry of Science, Technology and Environment (MOSTE) of Thailand. NDVI change between a normal year (1995) and drought year (1997) was analyzed for each drought risk area. The results shown that the relationship between drought risk levels and NDVI change, can only be considered significant for the first three drought risk levels (very high, high and moderate). It was found that the value of the NDVI is lower in high drought risk areas, which justifies the modified criteria of MOSTE.

Thirumalaivasan and Karmegam et al. (2001) made an attempt to assess the aquifer vulnerability of Upper Palar Watershed using DRASTIC model. The thematic layers viz., depth to water, recharge, aquifer media, soil media, topography, impact of vadose zone and hydraulic conductivity were used for the assessment of aquifer vurnerability. Analytical Hierarchy Process (AHP) has been used to arrive at the weights of the criteria. An user friendly VB software interfaced with GIS for estimation of weights and ranks of the thematic layers for aquifer vulnerability was developed. Using these ranks and weights the DRASTIC vulnerability index was calculated which was divided into very low, low, moderate and high vulnerability classes.

De Steiguer et al. (2003) attempted a study on Analytic Hierarchy Process (AHP), as a means for Integrated Watershed Management (IWM). It is stated that, IWM situations consist of multiple criteria and alternatives that must be evaluated by a decision maker in order to achieve an objective and AHP provides a systematic method for comparison and weighting of these multiple criteria and alternatives by decision makers. The reasons for choosing AHP method are given as (i) the AHP is a structured decision process, quantitative process which can be documented and replicated, (ii) it is applicable to decision situations involving multi-criteria, (iii) it is applicable to decision situations involving subjective judgment, (iv) it uses both qualitative and quantitative data, (v) it provides measures of consistency of preference, (vi) there is ample documentation of AHP applications in the academic literature, (vii) commercial AHP software is available with technical and educational support and (viii) AHP is suitable for group decision making. The study has reported that AHP is capable of providing numerical weights to options where subjective judgments of either quantitative or qualitative alternatives constitute an important part of the decision making process and the disadvantage is that it is a time consuming and tedious process if there are many levels in the decision hierarchy. It is concluded that the context of the decision and the sophistication of the decision makers is crucial to the use and success of AHP.

Phukon et al. (2004), has carried out a study using multi criteria evaluation in GIS environment for ground water resource mapping in Guwahati city. Using AHP, a paired comparison matrix was prepared for the five criteria (geomorphology, slope, soil, geology and landuse) for Guwahati city and individual class weights and map scores were worked out. The computed values show acceptable level of consistencies. The weights were fed into the multi criteria analysis of SPANS 7.2 software and a groundwater potential map was prepared for the city. It is suggested that artificial seasonal recharge through injection wells might be an effective way of managing the aquifers in the study area.

Aznar Bellver and Caballer Mellado et al. (2005) have applied a multi- criteria methodology to farmland appraisal. The study proposed and developed AHP for its application in farmland appraisal, especially in the situations, where only partial information is available, either due to the inaccessibility of direct quantification of the variables or because the explicative variables used are qualitative. The explanatory variables considered for the farmland appraisal are productivity, soil quality and access. The study concluded that the application of Analytic Hierarchy Process to the field of farmland appraisal is an advancement with respect to previous studies on the application of multi criteria methods in which only quantitative variables have been used.

Shiva Prakash et al. (2005) demonstrated the application of GIS based modeling for drought severity mapping and its management in Gubbi taluk of Karnataka State. IRS LISS III satellite images have been used for identification of landuse / landcover. As the satellite images are available at regular short time intervals; these can be used for the prediction of both rapid and slow events of droughts. It is concluded that the model generated may guide for a quicker approach for identifying prevailing drought-hit villages.

Matrix overlay function in ArcView GIS developed by Khon Kaen University is applied by **Suwanwerakamtorn et al. (2006),** to assess the drought risk areas in the Nam Choen watershed which is in the Northeast of Thailand. Seven parameters considered in accordance to the impacts on drought are rainfall, surface water and irrigation, sub-surface water, stream density, slope, soil drainage and landuse. The intensity of impact is represented by the value assigned to the entries of each matrix. It is concluded that the result obtained from matrix overlay do not give much satisfy for drought risk analysis in the Nam Cheon watershed. The percentage of matching between drought risk level and the level of the shortage water is low.

2.5 Drought assessment - Literature

Drought assessment involves analysis of spatial and temporal water related data. Several methods were developed to assess the drought quantitatively. Basically, droughts are assessed with reference to nature of water deficit, averaging period, truncation level and regionalization approach (Dracup et al., 1980). Over the years, various indices have been developed to detect and monitor droughts. The effects of drought often accumulate slowly over a considerable period of time; they may linger for several years after the drought period ends. As a result, the onset and termination of a drought are difficult to determine precisely and that is why a drought is often referred to as a creeping phenomenon (Mishra et al., 2007).

After the various definitions of drought and their groupings to confine the problem, many researchers have attempted to assess drought severity. These studies are grouped under meteorological, hydrological and agricultural aspects, as classified by the National Commission on Agriculture (1976).

2.5.1 Meteorological Drought Assessment

Meteorological drought, in general, implies the deficiency of rainfall of such magnitude which would seriously affect the normal living of the society. However, many definitions are available based on different truncation levels and base periods to delineate the rainfall deficiency and drought periods.

The widely used methods for meteorological drought assessment are (i) India Meteorological Department (IMD) method (ii) Herbst’s method (iii) Aridity Index and (iv) Palmer’s Drought Severity Index.

The IMD method is a simple and widely used one which will give a preliminary idea about the drought condition of an area. In this method, drought is assessed on the basis of percentage deviation of rainfall from the long term annual mean rainfall. Herbst et al. (1996) developed a technique for evaluating droughts by using monthly precipitation. The technique determines duration and intensity of droughts as well as the month of their onset and termination. Subramanyam (1964) proposed a method of meteorological drought severity assessment based on the concept of Aridity Index (Ia). The aridity index is the ratio between annual water deficiency and annual water need for evapotranspiration expressed as percentage.

Palmer et al. (1965) developed an elaborate and comprehensive technique for computing the severity of drought. The calculations are made here with respect to what are termed by Palmer as CAFEC (Climatically Appropriate For the Existing Conditions) values of the hydro-meteorological factors such as rainfall, evapotranspiration, recharge and runoff. This technique is based on a mass balancing of water and Palmer used the difference between actual precipitation and required precipitation under conditions of average climate in an area to evaluate drought severity in space and time. This technique found its application in many countries.

A great lacuna in Palmer's methodology is that it cannot be applied uniformly over all agro climatic zones. In humid zones, it represents more of agricultural drought whereas in semi-arid and arid zones it represents hydrological drought (Shewale 2001).

Appa Rao et al. (1981) made extensive analysis in classification of drought using the aridity index. Appa Rao (1987) presented meteorological subdivisions of India affected by moderate and severe droughts during the period from 1875 to 1980.

According to the Task Force on Drought Prone Area Programme (DPAP 1973), the areas which received less than 750mm of rainfall per annum are classified as drought prone and those between 750 mm to 800 mm are vulnerable to drought. The Meteorological Department of The Government of India has defined an area as drought hit when annual rainfall is less than 75% of the normal and severe drought when deficiency is above 50%.

McKee et al. (1993) developed the Standardized Precipitation Index (SPI) to quantify the precipitation deficit for multiple time scales, reflecting the impact of precipitation deficiency on the availability of various water supplies.

Kulandaivelu and Jayachandran et al. (1994) reported in Tamil Nadu, 85% of the total area benefits from the northeast monsoon; only 15% benefits from the southeast monsoon and the mean annual rainfall is 945mm, with 45 rainy days. Tamil Nadu has been classified into drought prone area, based on precipitation, potential evaporation and soil type. Nathan (1995) analysed the summer monsoon rainfall (June–September) for 1871–1991, in Tamil Nadu. The analysis shows that the state experienced below-normal rainfall in 30% of these years. The average rainfall of the season is 266 mm and the water demand is 663 mm, which clearly indicates it as a deficit season.

Singh et al. (2000) reported that a drought prone area is one in which the probability of a drought year is greater than 20%. A chronic drought prone area is one in which the probability of a drought year is greater than 40%. A drought year occurs when less than 75% of the “Normal” rainfall is received.

IMD (2002) reported that when the rainfall for the monsoon season of June to September for the country as a whole is within 10% of its long period average, then it is categorized as a normal monsoon. When the monsoon rainfall deficiency exceeds 10%, it is categorized as an all - India drought year. In the year 2002, the Southwest monsoon rainfall for the country as a whole was 19% below normal, making 2002 an all - India drought year.

Sinha Ray and Shewale et al. (2001) reported that the probability of drought exceeds 20% over Gujarat, West Rajasthan and Jammu & Kashmir. The probability of drought occurrence is between 16 to 20% over Haryana, Punjab, Himachal Pradesh, East Rajasthan and Rayalaseema, where as in the hill of West Uttar Pradesh (now Uttarakhand), Marathwada and Telangana, it could be between 11 to 15%. The probability of drought occurrence is 10% or less in rest of India.

2.5.2 Hydrological Drought Assessment

Hydrological drought is understood with respect to low stream flows or water availability. Vast literature is available for the stochastic characterization of droughts using stream-flow data; Gumbel (1959), Chow (1964), Huff (1964), Yevjevich (1967), Downer et al. (1967), Milan and Yevjevich (1970), Joseph (1970), Askew et al. (1971), Dyer (1977), Rodda et al. (1978), Whipple (1996), Zekai Sen (1980) and Chang (1990).

Chow et al. (1964) suggested that analysis of low stream-flow is a suitable way of quantifying droughts. He found that during the periods of deficient precipitation, the deviation from normal conditions is greater for stream-flow than for rainfall. He also suggested that low flow data must be specified in terms of magnitude of flow.

Herbst et al. (1966) developed a method to assess the meteorological drought severity using rainfall data, which was applied by Mohan and Rangacharya (1991) for stream-flow data. The effective available water (Qe) of a particular month is calculated by adding the actual available water (Q) with the excess or deficit of previous month's available water from long term mean monthly available water. While doing this carryover, a weighting factor (W) is included. The frequency and severity of hydrological drought is defined on a watershed or river basin scale. This method provides information on onset, termination and severity of drought.

Yevjevich et al. (1967) proposed a theory of runs which assesses the drought on the basis of deficiency of stream-flow with respect to the long term mean value as the truncation level. The excess or deficit for a month is the difference between the actual stream-flow of a month and the long term mean value for that month. In this method, the stream-flow data is plotted as a continuous time series. The truncation level (long term mean value) will separate the excess and deficit periods. The run length is defined as the distance between two successive points on the truncation line where the series switch from one side to other. The run length between two successive down-cross and up-cross is termed as the duration of drought. The run sum is defined as the sum of the negative deviations, which is the drought severity.

Gumma et. al (2011c, 2015) assessed crop stress areas due to water shortage in rice growing areas using spectral matching techniques, but this was monitored in rice-growing areas.

Dracup et al. (1980) assessed the drought based on the deficiency of stream-flow with the long term median value as the truncation level. The excess or deficit for a month is the difference between the actual stream-flow of a month and the long term median value for that month. The months with deficit values are assessed as hydrologic drought periods. The severity of a drought is the cumulative stream-flow deficits occurring continuously.

2.5.3 Agricultural Drought Assessment

Agricultural drought occurs when soil moisture and rainfall are inadequate during the growing season to support healthy crop growth to maturity and cause extreme crop stress and wilt. Meteorological and Hydrological droughts are concerned with rainall, surface water and groundwater components of the hydrologic cycle, i.e. they are only supply oriented ones, whereas agricultural drought is concerned with the availability of water to meet the crop water requirements.

Many previous works in agricultural drought severity assessment focus their attention mainly on micro-implications of agronomy of crops and not in quantification of water deficiency with respect to agricultural demand (Krishnan (1979), Choudhury (1987), Schmugge et al. (1986), Wang and Choudhury (1985). Stochastic analysis of agricultural droughts was reported by Prajapati et al. (1977).

Rama Prasad et al. (1990) tried to quantify the water deficiency during an agricultural drought and the method considers the soil moisture in the form of an Antecedent Precipitation Index (API). The difference between the actual API on a given time period and the API value necessary (crop water requirement for the time period) to ensure that the crop water demand is fully met is defined as the deficit for the day. The cumulative value of the deficits in a water year is calculated as total deficit. The total deficit for each water year is plotted with the crop yield data and a straight line is fitted. The drought severity classification is made based on the normalized yield values that were noted from the plotted line against the corresponding deficit for each year.

2.6 NDVI - Rainfall relationship as indicator of drought

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

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

A study regarding the modelling of drought risk areas by using remotely sensed was carried out by C.Mongkolsa Wat (et al., 2000) in Northeast Thailand, where drought has the most profound effect on the lives and regional economy. In this paper the severity of drought was considered to be a function of rainfall, hydrology and physical aspect of landscape. Three different types of droughts i.e. meteorological, hydrological and physical drought were analysed after which an overlay matrix operation was performed that yielded the areas which faced drought risk wherein drought risk was classified into four classes. The result obtained was satisfactory confirming that the model developed in this study could help in the mapping of drought risk area in the Northeast Thailand.

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

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

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

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

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

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

Anyamba and Tucker et al. (2005) analysed seasonal and interannual vegetation dynamics in Sahel using NOAA-AVHRR NDVI. The study concentrated only on NDVI patterns in growing season, which was defined by examining the long-term patterns of both rainfall and NDVI. Year to year variability in NDVI patterns was examined by calculating yearly growing season anomalies. The correlation between NDVI and rainfall anomaly time series was found to be positive and significant, indicating the close coupling between rainfall and land surface response patterns over the region.

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

2.7 Rainfall anomaly based drought identification

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

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

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

A large number of papers have analysed the interannual variability of the summer (June - September) mean monsoon rainfall averaged over India (Parthasarthy and Mooley 1978; Shukla 1987; Parthasarthy et al 1994), stating an interannual standard deviation of the mean seasonal rainfall to be 10% of the long-term mean value.

2.8 Spatial and temporal variation of climatic variables and drought analysis

Droughts are regional in nature and often characterized by temporary departures from normal precipitation resulting in severe water shortage (Ganguli and Reddy, 2014). Variability in precipitation imposes a challenge for the sustainable management of water resources. Understanding this variability and the factors influencing this phenomenon is very important for water managers and policy-makers (Loch et al., 2013). The Intergovernmental Panel on Climate Change (IPCC) (2007) reported that significant trends were observed in precipitation in many regions from 1900 to 2005. Precipitation decreased on the Mediterranean coast and in southern Africa and parts of southern Asia, whereas precipitation increased significantly in eastern parts of North and South America, northern Europe and northern and central Asia. Climate change projections for Victoria suggest that, although increases and decreases in rainfall are projected in the future, decreases dominate the overall pattern, especially in the south in winter and spring (Suppiah et al., 2007). Other climatic variables that have an impact on drought are temperature, wind and relative humidity, and they need to be considered when characterizing drought. (Suppiah et al., 2004) reported that there is a considerable spatial variability in temperature in different parts of Victoria. The study predicted that by 2070, the number of days with temperatures greater C will be 17 per year in Melbourne (south Victoria) and as high as 51 days per year°than 35 in Mildura (north-west Victoria). This study also observed that the reduction in relative humidity would be 2% in west/north-west Victoria and 1% in south/south-east Victoria. Due to decreasing rainfall and increasing temperature projected, drought projections for Australia suggest that up to 20% more drought months will occur over most of Australia by 2030, with up to 40% more droughts by 2070 in eastern Australia, and up to 80% more in south-western Australia (Mpelasoka et al., 2008). Overall, it is important to understand the varying characteristics of dryness and wetness for predicting and preventing disasters brought about by extreme events such as drought. For instance, Du et al. (2012) applied the Standardized Precipitation Index (SPI) to analyse dry/wet conditions and for drought/flood monitoring in Hunan Province, China, while in western India, Ganguli and Reddy (2014) carried out a study to detect potential trends in long-term time series of the SPI in order to seek climate change impacts. Monitoring changes in the occurrence and length of dry spells is of obvious importance, since it is directly relevant for food and water supplies. Subash and Ram Mohan (2011) investigated the possible trends in monsoon rainfall and frequency of droughts using the SPI covering a 100-year period (1906-2005) to assess rice-wheat productivity in India. In additon, the detection of changes in climatic variables is significant in planning climate change adaptation measures, hydrologic modelling studies, establishing the validity of the dataset for frequency analysis and infrastructure design. Changes in climatic variables may be in the form of gradual trends over some period in time, a more abrupt change or in a more complex form (Kundzewicz and Robson, 2004). Monitoring and forecasting drought are real challenges in water resources management. However, they are essential as droughts are becoming more common and severe due to the impact of climate change (Meehl et al., 2000; Alexander et al., 2009; Mishra et al., 2009). Analysing historical drought events is essential to determine the potential risk of droughts occurring in the future. Each drought event is unique in its intensity, duration, peak and spatial extent. An event might persist for few months, years, or even more. The frequency of droughts at various levels of severity, duration and peak provides the exposure risk of drought in a region. It is critical to understand the nature of drought risk in order to establish comprehensive and integrated drought management strategies. Appropriate management of droughts requires knowledge of the expected frequency of drought magnitude, which can be achieved by employing probabilistic approaches (Ganguli and Reddy, 2014).

2.9 Water Balance Concept

Water balance of any region can be estimated by comparing rainfall with evapotranspiration on monthly as well as daily basis. This study plays an important role in many fields of Earth Science, especially in agriculture and water resources development (Subramanyam, et al., 1980).

It is simply an estimation of balance of water that occurs in the hydrosphere, lithosphere and the atmosphere with outgoing moisture. The surface of the earth receives water from precipitation and loses the same to the atmosphere through the processes of evaporation and transpiration. The soil structure and texture determines the amount of precipitation retained by it and the surplus water joins the open water bodies as surface and sub- surface runoff. Evaporation from all water bodies and moist land areas and transpiration from vegetation adds moisture to the atmosphere which in due course of time comes back to the lithosphere and hydrosphere as precipitation thus completing the hydrologic cycle. Thus, the circulation of water, the gain and loss in between three realms is known as hydrologic cycle. This cycle is represented by the following equation.

$P = E + \Delta S + G + R$

P = precipitation

E = Evaporation

ΔS = Change in storage and or below the surface of the earth within the region.

G = Sub – surface leakage

R = Run off.

If the study area is large and free from unusual geologic formations, leakage G can be neglected. Thus the hydrologic equation can be reduced to $P = E + \Delta S + R$, which can be used to compute the water balance of any region.

Of all meteorological elements precipitation is most widely measured and its measurement is within acceptable limits of accuracy. For this purpose, the amount of precipitation is obtained from instrumental measurements. The loss of water by evaporation affects the water supply and storage but what is more appropriate and is of greater importance to water balance studies is the total loss of water by the evaporation as well as by transpiration together known as Evapotranspiration. The rate of evapotranspiration depends upon several factors such as soil moisture, nature and properties of soil and vegetation, air temperature, solar radiation, wind, humidity etc. Among the several formulas suggested by many scientists viz., Penman (1956), Ramadas (1957) Budyako (1958), Strahler and Mcllroy (1961), Rijtema (1965), Van Bavel (1966), Tanner and Fusch (1968), Blany and Criddle

(1950), Lowry and Johnson (1941) and Garnier (1972), Thornthwaite's (1948) concept of Potential Evapotranspiration (PE) found to be appropriate. In India, Thornthwaite's method was followed by many scientists; namely Subramanyam (1956a and 1956b), Subramanyam (1961) Sastry (1969), Rama Sastry (1973) Sarma (1974) Bora (1976), Ram Mohan (1978), HemaMalini (1979) and Viswanadham (1981) and still the method is significant in the agroclimatological studies especially in the drought analysis.

2.9.1 Water Balance techniques and methodology

For the water balance analysis, monthly Potential evapotranspiration are compared with monthly rainfall. When the precipitation (P) and Potential Evapotranspiration (PE) of a particular region are equal, there will be no deficiency or surplus of moisture. Low precipitation leads to aridity and high precipitation leads to surplus for wasteful run-off. Precipitation and potential evapotranspiration are often not the same either in amount or in monthly distribution. The distribution of precipitation seldom coincides with the changing demands of water throughout the year.

Hence, for agro-ecoclimatological studies, it is essential to have a thorough understanding of the occurrence and distribution of the water balance parameters such as precipitation, or water supply (P), actual evapotranspiration (AE)(the amount of water that actually evaporates and transpires), potential evapotranspiration (PE) (the maximum amount of water that would evaporate and transpire if the required amount of water is readily available), the water deficiency (WD) (the amount by which water need of the area exceeds AE and the water surplus (WS) (the amount by which P exceeds PE).

Ecologists have confirmed that the rate of plant growth and abundance of vegetation are directly connected to temperature, when the moisture supply is adequate. Insufficient heat is a limiting factor for plant growth just as deficient moisture (Subrahmanyam, 1980). Hence, in water balance studies the knowledge of temperature efficiency (effective temperature for plant growth) and moisture affectivity (amount of moisture available for plant growth) are also important.

To compute water balance, the knowledge of the field capacity of the soil is essential. Field capacity is the maximum amount of moisture that a soil can retain against gravity. If the soil is at its field capacity, the availability of soil moisture is sufficient to support plant growth and development at the optimal level.

The moisture holding capacity of a soil depends on the depth of the soil layer, its type and structure. This can vary from just a few millimeters to well over 400 mm. The roots of the plants compensate for the variable nature of the soil. They are deep rooted in porous sandy soil and shallow rooted in non-porous clay. When the soil moisture content decreases the rate of evapotranspiration slows down and when the field capacity is available the rate of evapotranspiration speeds up.

Water Surplus (WS), indicated by the amount by which precipitation exceeds the potential evapotranspiration after the field capacity is met, finds it way to the open water bodies as the surface or sub-surface run off. Water Deficiency (WD) represents the amount by which the actual and potential evapotranspiration differ and which can give a rough estimate of the supplemental irrigation required for the most effective growth and development of crops. Water deficit occurs when water potential in the rhizosphere is sufficiently negative to reduce water availability to sub-optimal levels of plant growth (Yadav et al, 2001). Potential evapotranspiration (PE) has a double role to play both as a thermal parameter and as moisture parameter and it is this feature which makes Thornthwaite’s (1948) water balance concept and procedure very unique and novel. Hence, water balance parameter provides a comprehensive climatic picture of a region and plays an important role in Hydrology, Agriculture, Forestry, Ecology, etc.

Thornthwaite et al. (1948) has developed a simple book-keeping procedure for making the comparison between the precipitation and potential evapotranspiration on a monthly basis, taking into consideration the role of soil as storage of rainwater which can be used at times of inadequate rainfall.

In the water balance procedure, P is treated as income, PE as expenditure and the amount of moisture stored in the soil as a sort of reserve available for use to a limited extent for purposes of evapotranspiration during rainless periods. While water supply (i.e., P) and the water need (i.e., PE) are the basic elements of the water balance, Actual Evapotranspiration (AE), Water Deficiency (WD) and the Water Surplus (WS) are the derivatives which in turn enable to compute some other components such as Aridity Index (Ia), Humidity Index (Ih) and Moisture Index (Im).

PE of any region can be determined by field measurements with the help of an instrument called Evapotranspirometer. However, in the absence of such an instrument, PE can be estimated empirically since there exists a relation between PE and mean temperature of the region. The formulae for computation of PE is as follows:

$e = 1.6\ (10\ t/I)^{a}$

Where e = ‘unadjusted’ PE in cm

t = mean monthly temperature in ºC

I = annual heat index (This value is the sum of the 12 monthly heat indices, i, when

$I = (t/5)^{1.514}$)

$a = 6.75 \times 10^{-7} 1^{3} - 7.71 \times 10^{-5} 1^{2} + 1.792 \times 10^{-2} 1 + 0.49239$

the value of ‘e’ thus obtained is based on 12-hour day and 30-day month. Hence, it is necessary to adjust it by taking into account the actual number of hours in the day as well as the variation in the number of days in the month from 28 to 31. Using a series of conversion tables and nomograms prepared by Thornthwaite, it is possible to determine the PE of any area, and also adjust the same for the changing number days in a month and for changing length of the day in different seasons.

As a first step, the heat index (I) is computed from the monthly values of (i) corresponding to mean monthly temperature using a series of tables prepared by Thornthwaite and Mather (1955). In the second step, the unadjusted PE is calculated which is further multiplied by a correction factor to derive the adjusted PE in the third step. Precipitation (P) is obtained from the measured values at the observatories. The value of P-PE denotes the deviation of PE from Precipitation. Accumulated Potential Water Loss (Acc. Pot.Wl) is calculated by progressively adding (P-PE) values starting from the first negative value that occurs usually after the rainy season. The first Accumulated Potential Water Loss value is obtained by a successive approximation method using the field capacity table. Variation in soil moisture is obtained from the amount of accumulated potential water loss and the tables of field capacity values. When precipitation (P) exceeds the water need (PE), the soil storage rises till the field capacity is reached. On the other hand, the soil storage depletes when water supply fails to meet the demands of PE. The change in soil storage (ΔST) reflects the amount utilized for evapotranspirational purposes. The actual evapotranspiration is obtained by the sum of P and ΔST (AE = P+ ΔST). The differential amount of PE and AE is the water deficiency (i.e. WD = PE – AE). When AE is equal to PE, water deficiency (WD) will be zero. Water surplus (WS) occurs only when P is greater than PE and the soil moisture is at field capacity.

On account of the wide applicability of the water balance concepts as developed by Thornthwaite (1948), and Thornthwaite and Mather (1955), the same technique has been adopted in the present study.

2.10 Climatic classification

Climatic classification is an intellectual device derived based on the human perception. It deals with grouping of similar climatic characteristics into regions. It comprises with generalization and simplification of large data in to a comprehensive system and orderly arrangement of climates. In other words, classification is a shorthand system that will reduce the complexities and enhance the comprehension. Classification enables to understand the regions of similar characteristics and facilitate mapping of climatic regions. This knowledge is essential in systematic and scientific developmental activities.

In general, most of the world climates are classified into different geographical areas based on the two principal elements namely precipitation and temperature. Several schemes of climatic classification have been previously devised but most of them were descriptive and empirical and had no rationality of development. Koppen’s scheme of climatic classification is based mainly on critical temperature and precipitation for the growth and development of different kinds of vegetation. But, Koppen has not considered the most significant vegetation variables, such as water need in relation to water supply, soil moisture storage or actual evapotranspiration in his classification.

In 1948, Thornthwaite made a great contribution in the field of climatic classification. He proved that by using the water balance parameters, it is possible to specify the climate into Thermal Regime and Moisture Regime i.e. Climatic classification based on the thermal efficiency and moisture efficiency of the region, respectively. Thermal Efficiency (TE) is nothing but annual PE which is a parametric index used to determine the thermal regime since it has been derived from the temperature and the length of the day.

The indices developed from water balance parameters are the prime eco-climatic factors for the luxuriant growth and development of vegetation. It is for this reason that Thornthwaite scheme has been recognized and widely accepted as a rational classification and was considered as a relevant approach from an ecological angle. The characteristic significance of Thornthwaite's scheme is the employment of a single parameter namely the potential evapotranspiration to derive both thermal and moisture regimes of the climates (Subrahmanyam and Sastry, 1969). The academicians namely Subrahmanyam(1956 a and 1956 b), Subrahmanyam, SubbaRao and Subramanian (1965), Carter and Mather (1966), HemaMalini (1979) Viswanadnam (1981) and many others used this procedure for different applications which is evident from several publications by them.

By using the water balance parameters, it is possible to specify the climate into Thermal Regime and Moisture Regime i.e. Climatic classification based on the thermal efficiency and moisture efficiency of the region, respectively.

2.11 Thermal Regime

Thermal regime classification is based on the thermal efficiency of the region. Thermal Efficiency (TE) is nothing but annual PE which is a parametric index used to determine the thermal regime since it has been derived from the temperature and the length of the day. The classification of climate in terms of thermal regime is shown in Table 2.4

Table 2.4 General Scheme of Thermal regime classification

Climatic Type	Thermal Efficiency Index (mm)	Symbol
Megathermal	Above 1140	A'
Mesothermal	997 to 1140	B'_4
Mesothermal	855 to 997	B'_3
Mesothermal	712 to 855	B'_2
Mesothermal	570 to 712	B'_1
Microthermal	427 to 570	C'2
Microthermal	285 to 427	C'_1
Tundra	142 to 285	D'
Frost	Below 142	E'

As mentioned already, the above classification is based on the annual totals of thermal efficiency values. But these values in a region show seasonal changes with the highest concentration during summer. To emphasize these seasonal variations a supplementary classification is added which is based on the summer concentration percentage of thermal efficiency (SCTE % i.e. the ratio of the sum of the thermal efficiencies for the three highest summer months to the annual total. This classification is presented in Table 2.5.

Table 2.5 General Scheme of Thermal regime – sub classification

Climatic Type	SCTE in Percentage	Symbol
Megathermal	Below 48.0	a'
Mesothermal	48.0 to 51.9	b'_4
Mesothermal	51.9 to 56.3	b'_3
Mesothermal	56.3 to 61.6	b'_2
Mesothermal	61.6 to 68.0	b'_1
Microthermal	68.0 to 76.3	c'_2
Microthermal	76.3 to 88.0	c'_1
Tundra	Above 88.0	d'

Based on the annual potential evapotranspiration values of all the representative stations main Thermal regime categories of Srikakulam district were categorized. Similarly, Summer Concentration of thermal Efficiency values for all the stations were computed in order to understand the seasonal variation of thermal potentiality of the region. Based on SCTE percentages, sub classification type of thermal regime of all the stations was made.

2.12 Moisture regime

From the thermal regime analysis is evident that in Srikakulam district thermal efficiency is abundant and more than adequate to support luxuriant vegetation and prosperous crop varieties if water is not a hindrance. Hence it is essential to understand the moisture potential of the region in order to assess the crop capability of the area.

Thornthwaite’s book keeping procedure of water balance also helps to derive zonation of climates based on the hydrological conditions. Thornthwaite’s climatic classification based on moisture effectively formulated during 1948 along with the Thermal regime classification. As water surplus and water deficiency vary seasonally, they play a crucial role in the determination of Index of moisture which is the key to delineate climates of any region. The formula to calculate moisture index is

$Im = Ih - Ia$

Where

Im = Index of moisture

Ih = Index of humidity

Ia = Index of aridity

Index of aridity (Ia) is the percentage ratio of annual water deficiency to the annual water need (PE); the Index of humidity (Ih), on the other hand, it is the percentage ratio of annual water surplus to the annual need (PE).

Table 2.5., indicates the moisture regime classification. The humid types are according to originally proposed by Thornthwaite et al. (1948) and dry types are based on modified classification by Carter and Mather et al. (1966).

CHAPTER - 3

OBJECTIVES AND STUDY AREA

3.1 Objectives

The main objectives of the research are to

1. Deriving a methodology for the drought assessment:

   A methodology was designed by considering different parameters for the assessment of drought.

2. Identification of Irrigated areas for the years 2013-14, 2015-16 using MODIS (MOD13Q1) 250 m resolution data:

   Spatial distribution of the irrigated areas was mapped for normal year and water- deficit year using MODIS (MOD13Q1) 250m resolution

3. Observing the changes of agriculture land use for the study years

   Comparing the spatial distribution of the study years and identifying the drought affected areas

4. Accuracy Assessment using ground survey data and statistics available
5. Assessment of drought areas

   The intensity of the drought was identified spatially considering different parameters

3.2 Study Area

3.2.1 Physical Geography

The Krishna River Basin (Figure 2.1) is the fourth largest perennial river basin in India covering a total geographical area of 258,912 km^2 flowing the states of Karnataka (113,235 km^2), Erstwhile Andhra Pradesh (76,252 km^2) and Maharashtra (69,425 km^2). The Krishna river basin comes under semi-arid southern region. It ranks fourth considering annual discharge, and fifth largest basin in terms of surface area. The basin lies between 73°17′ to 81°9′ east longitudes and 13°10′ to 19°22′ north latitudes. It extends 701 km in terms of length and 672 km in width. The Krishna River rises in the Western Ghats north of Mahabaleshwar, about 64 km from the Arabian sea at an elevation of about 1,337 m from sea level flowing nearly 1,400 km joins the Bay of Bengal at Hamasaladeevi in Andhra Pradesh. The Major Tributaries of Krishna River are joining from left are Bhima, Dindi, Peddavagu, Halia, Musi, Paleru, Munneru and from Right are Venna, Koyna, Panchganga, Dudhg.

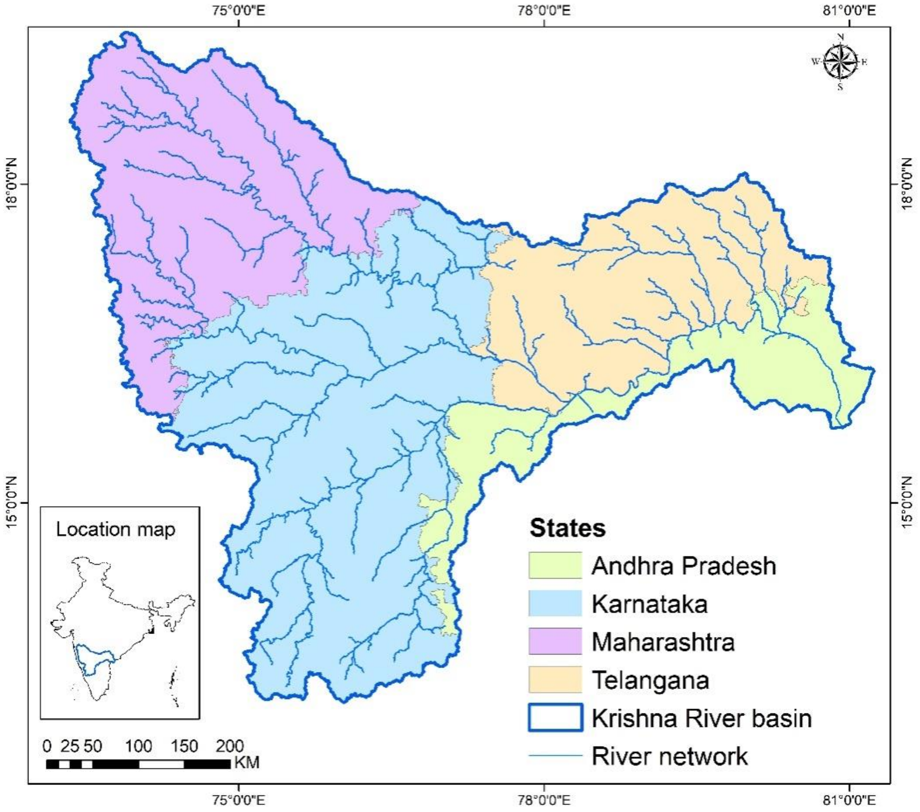


Figure 3.1 Location map of the Krishna River Basin with River network extracted from SRTM 90m DEM (ftp://edcsgs9.cr.usgs.gov/pub/data/srtm/.SRTM_Topo.txt)

Table 3.1 Indian Reserve Banking in terms of Annual discharge.

Rank	Name	Discharge volume (km^3/year)	Drainage Area (km^2)
1	Brahmaputra	586	194,413
2	Ganges	525	861,452
3	Godavari	110.5	312,812
4	Krishna	78.1	258,948
5	Indus (to Pakistani border)	73.3	321,289

Source: Ministry of Water Resources, http://wrmin.nic.in

The Krishna Basin lies on the granitic gneiss of the Indian Shield and the basalts of the Deccan Traps forming red alfisol and black vertisol soils. These rock types forms fractured, hard-rock aquifers with low specific yield and low transmissivity compared to deep alluvial aquifers of the Indo-Gangetic plains.

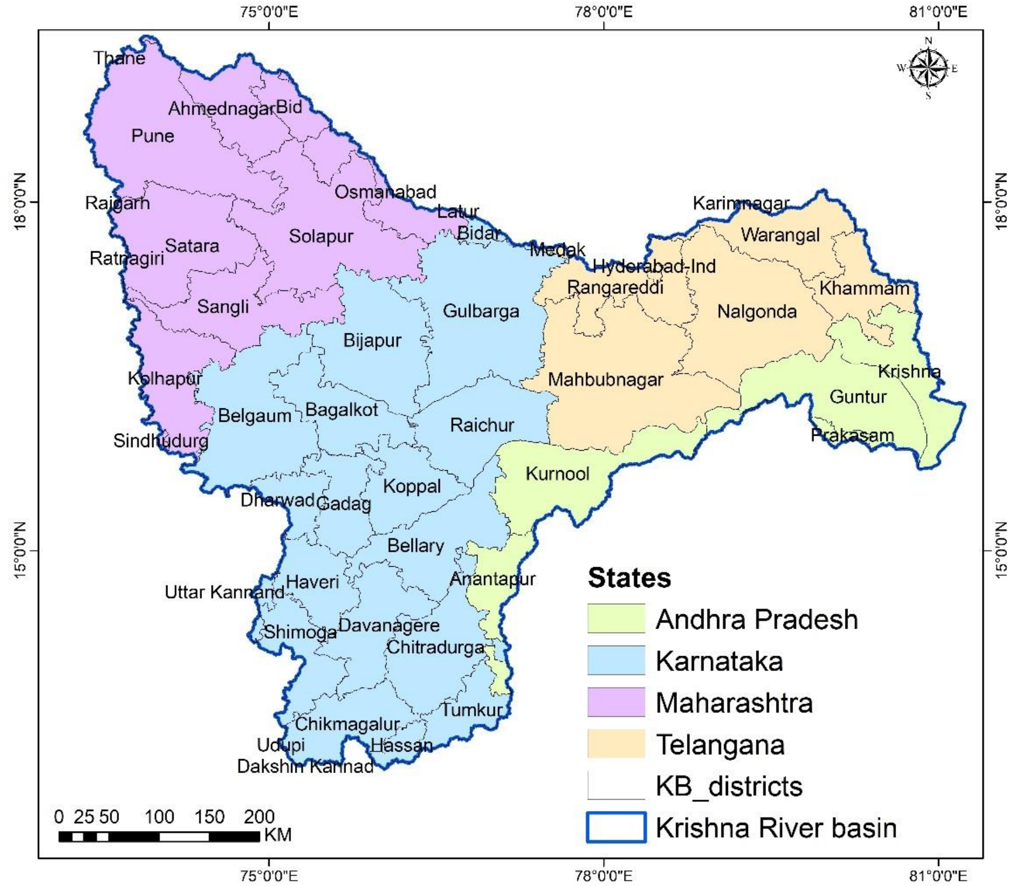


Figure 3.2 Districts in the Krishna River Basin

The climate of the basin is dominantly semiarid, with sub-humid areas in the eastern delta and Western Ghats with annual average precipitation in the basin as 784 mm, of which approximately 90% occurs from June to October during the South-West Monsoon and decreases gradually from 850-1,000 mm in the Krishna Delta to 300-400 in the northwest (Figure 3.3). In the extreme western parts of the basin, the Western Ghats have high annual precipitation (1, 500-2, 500 mm) covering a smaller portion of the basin.

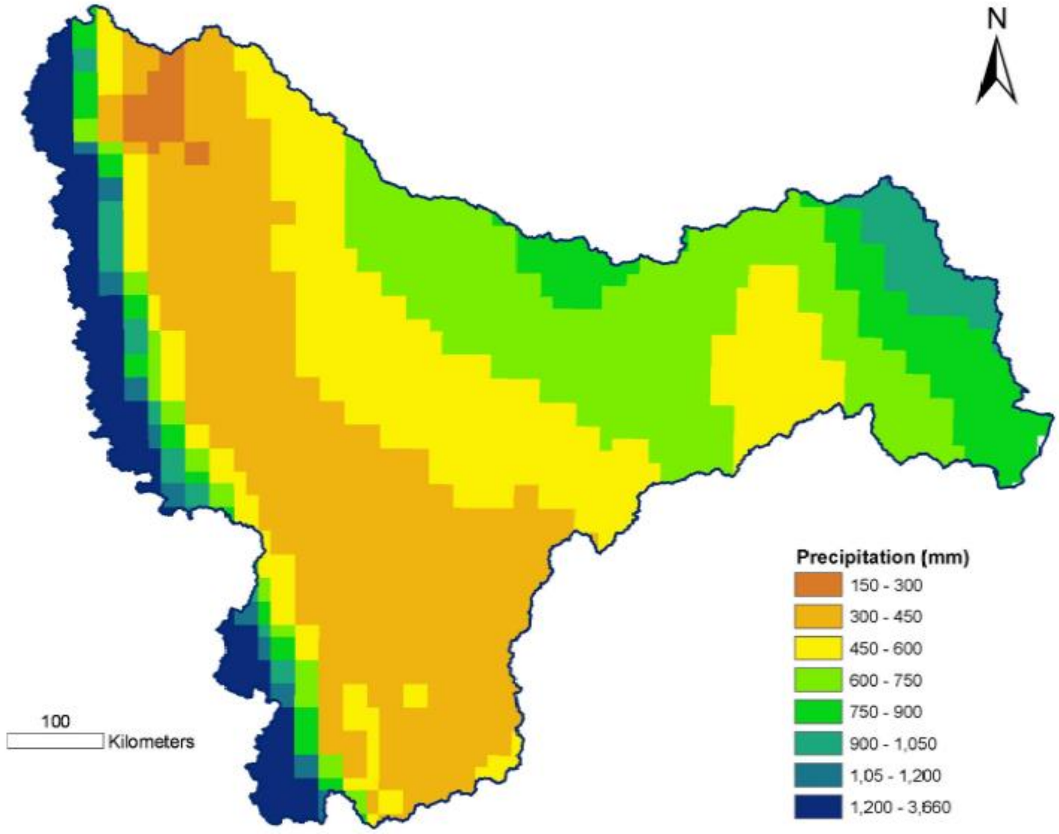


Figure 3.3 Annual average precipitation using Global precipitation data (http://www-cger.nies.go.jp/cger-e/db/info-e/InfoDBWeb/db/gpcc.htm)

In Krishna river basin, Cropping occurs mainly in three seasons:

1. *Kharif* during the monsoon (June to mid-December)
2. *Rabi* in the post-monsoonal dry season, (mid-December to March
3. *A summer season* in April and May

Major crops include double cropping of rice and grains, single cropping of sugarcane, chilly, cotton, fodder grass, and also some crops like corn, sorghum, sunflower, and other grains are slightly irrigated. Other irrigated crops include bananas, vegetables, curry leaves, ginger, turmeric, and teak occupying relatively small fractions of the total area. Some crops like grains (sorghum, millet), pulses (red and green gram, chickpea), and oilseeds (sunflower, groundnut) are rain dependent i.e. rainfed crops.

Irrigation in Krishna river basin is mainly done through major reservoirs-major command areas (>10,000 ha), groundwater and tanks (<10,000 ha). The major reservoirs like the Tungabhadra, Nagarjuna Sagar, Bhima and the Bhadra projects plays a vital role in irrigation and also many smaller reservoirs at the base of the Western Ghats supply water to canal irrigated projects in the upper Krishna. Basin. Major hydroelectric projects producing greater than 240 Mw are shown in below table

Table 3.2 Hydroelectric Projects with rated power

Name of the project	**Rated Power (in MW)**
Almatti Dam	290
Jurala Hydroelectric Project	240
Koyna Hydroelectric Project	1,920
Lower Jurala Hydro Electric Project	240
Mulshi Dam	300
NagarjunaSagar Dam	960
Srisailam Dam	1,670

During first and second five year plan the major national objective was to achieve self-sufficiency in food production and to develop water resources in different river basins across the country. Due to the above decision, the total storage capacity of major reservoirs that are larger than 200 million cubic meters Mm^3in the Krishna Basin has increased to 42,910 Mm^3. There is a high demand in agricultural, domestic and industrial sectors due to increasing population. This leads to conflicts between the states. In order to resolve the conflict among three states, the Krishna Tribunal was formed in 1969 to allocated water based on "equitable apportionment" in 1976.

Major irrigation projects in the basin started with the Krishna Delta Project in Andhra Pradesh in 1852 to irrigate 500,000 acres in the 1920s, reservoirs were built across the tributaries of Krishna river for urban water supply were established near Hyderabad, the regional capital of Telangana.

Table 3.3 Major reservoirs and gross storage capacity in the Krishna Basin

Name	**Year completed**	**Gross Storage Capacity (TMC)**	**State**
Almatti Dam	2005	123.08	Karnataka
NagarjunaSagar Dam	1967	312	Telangana
Srisailam Dam	1981	216	Telangana, Andhra Pradesh
Pulichinthala Project	2013	46	Andhra Pradesh
Jurala Project	1995	12	Telangana
Narayanpura Dam	1982	30.5	Karnataka
Dhom dam	1977	14	Maharashtra
Osman Sagar	1920	11.62	Telangana
Pocharam	1922	1.82	Telangana
Himayatsagar	1927	7.65	Telangana
Bhatagar	1927	24.08	Maharashtra
Tungabhadra	1953	133.3	Karnataka
Musi	1961	5.03	Telangana

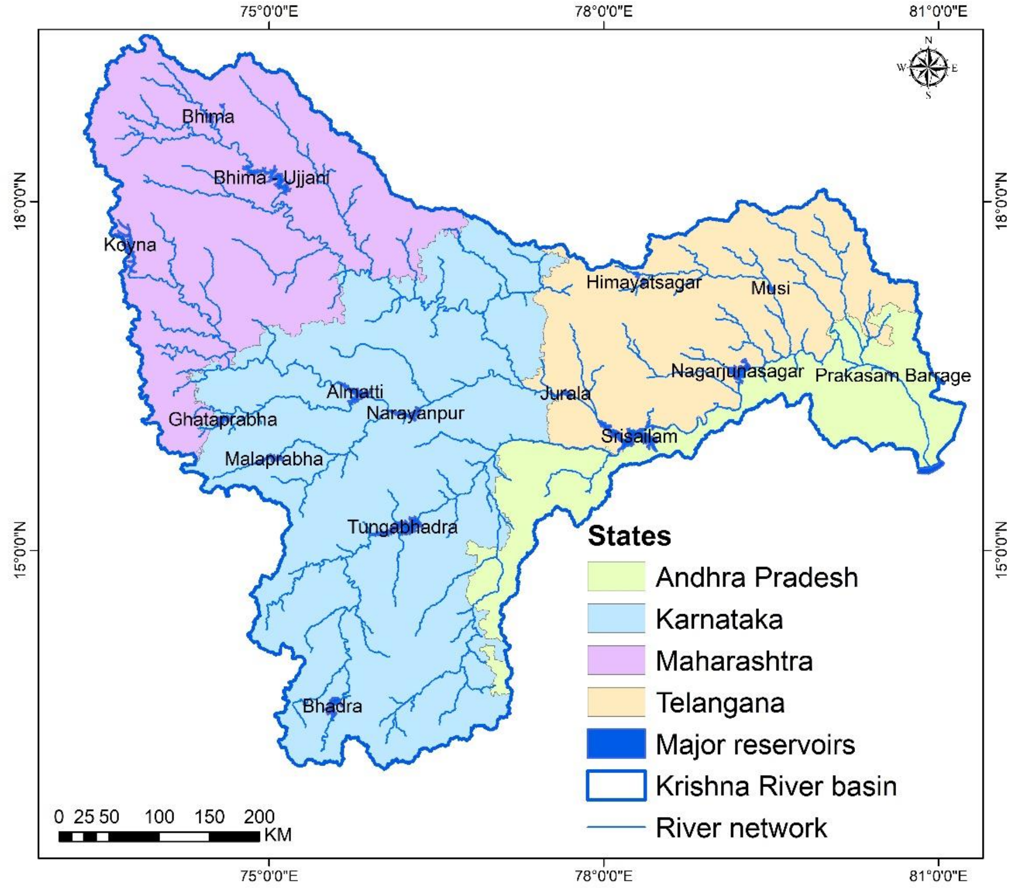


Figure 3.4 Major reservoirs in the Krishna River Basin and river network extract from SRTM DEM, toposheets and remote sensing data

From 1850s, the irrigation strategy in southern India concentrated on "light irrigation" to irrigate dry crops like cotton and sorghum, versus "heavy irrigation" of water-intensive crops like rice and sugarcane (Walach, 1984). The irrigation schemes in the Krishna Basin, including the Tungabhadra, Bhadra, and Nagarjuna Sagar were designed for light irrigation changed to high irrigation planned on heavy clay soils.

In the early 1990s, there was drought which makes the Government of Andhra Pradesh to initiate irrigation reforms to improve water management in the State and transfer of decision-making authority from the State to district and sub-district levels. Decentralizing water resources control to local levels created water user associations (WUAs) and Distributary Committees (Mollinga et al., 2001). Management interventions in irrigation project command areas focus on maintenance and repair of existing irrigation infrastructure. In upland areas, focus on rainwater harvesting, construction of small percolation tanks, contour ditches, and small tanks to catch storm runoff and store it as either surface water or groundwater (Batchelor at al., 2003).

As per Indian water policy, the water allocation in a multipurpose reservoir is critically based on order as domestic, industrial, and agricultural purposes. Agriculture is the subject which will have high impact on agricultural production, and farmers' livelihoods within the irrigated command area during water shortages. The Spatiotemporal analysis of the irrigation project helps in identifying the performance of the irrigation scheme and helps in improving water and land productivity.

3.2.2 Water Management of Krishna River Basin

Water has been managed in the Krishna Basin for centuries by constructing small earthen dams (Shiva, 1991). In the sixteenth century, the Vijayanagar Empire constructed many irrigation canals and small reservoirs (tanks) on the Tungabhadra River in Karnataka.

3.2.3 Krishna Water Allocation among states

Due to high demand of water with growing population leads to conflict between the states. In order to resolve, the Krishna Water Disputes Tribunal was established in1969 to allocate Krishna water among the three states. Even though there is a high demand of water across the states creating surplus demand for water and continuing conflicts between states.

Table 3.4 Water allocation to the three states from the Krishna Basin

State	Percent of basin area	Water Allocation (TMC)
Maharastra	25	560
Karnataka	42	700
Erstwhile- Andhra Pradesh	33	800
Total	100	2060

The Krishna River Management Board (KRMB) has decided to share of Krishna water to Andhra Pradesh and Telangana in the existing ratio 66:34.

3.2.4. Population

According to the 2011 census, the multi state population of the Krishna Basin were about 70 million. The rural population density is highest in the Krishna Delta and out of the 12 major sub-basins, the Musi has the highest population density due to its high urban area i.e. Hyderabad.

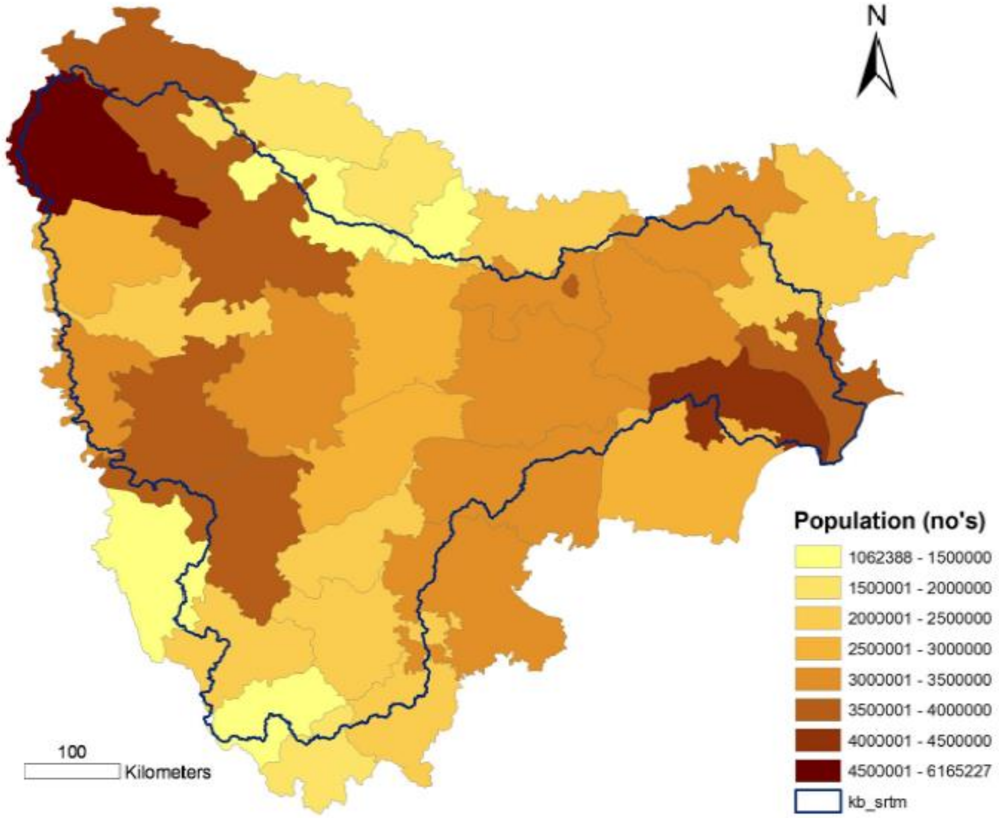


Figure 3.5 District-wise population in the Krishna River Basin (Census, 2000)

CHAPTER - 4

DIGITAL DATA PREPARATION

4.1 Introduction

The 16-day composite images in the MOD13Q1 (MODIS 250m) dataset are available in the public domain and are pre-calibrated (http://modis-sr.1tdri.org/html). The product is an estimate of the surface reflectance for each band at ground level with no atmospheric scattering or absorption. Originally, MODIS data are acquired in 12-bit (0 to 4096 levels), and later is stretched to 16-bit (0 to 65,536 levels). Before processing the datasets, it will go through the Cloud removal approaches and the preparation of mega data files.

4.1.1 Cloud removal algorithm

The location of Krishna Basin is at 18° north latitudes i.e. oscillating Sub-Tropical Convergence Zone had monsoons over the region. Along the year, high change in vegetation cover, rapid changes in dynamics of vegetation, and biomass accumulation during the monsoon season in which cloud cover is also maximal. In order to obtain cloud free time-series images we: (a) obtain all images with < 5% cloud cover and (b) passing through cloud-masking algorithm. Out of the 46 images, there 14 images with 25-40% cloud cover. So, it is required to get cloud free areas to get maximum temporal coverage and monitoring. Cloud removal algorithm go through the cloud algorithm development, testing and implementation.

4.1.2 Minimum reflectivity threshold for cloud removal

In the cloud removal algorithm, the minimum reflectivity of clouds among the MODIS bands (b1 and b2) in which the one with maximum cloud cover is removed. If the reflectance value in b1 is more than 18 or null value, then the values in b1 are replaced with a null value. If the reflectance value in b1 is less than 18 then reflectance values will remain as it is.

4.1.3 Preparation of Mega data sets

The continuous time-series analysis of MODIS data requires the preparation of mega data sets using multiple bands. The 16-day NDVI images were stacked into a 23-band file for each crop year (two images per month) and then the monthly maximum value composites were created using 16-day NDVI MODIS data to minimize cloud effects. The single mega-files help in preparing and analysis of monthly MVC NDVI.

4.2 Secondary Data Sets

4.2.1 SRTM 90m elevation

The Shuttle Radar Topography Mission (SRTM) 90m spatial resolution elevation data used to generate the most complete high-resolution digital topographic database of the earth (SRTM technical guide).. An SRTM elevation data is useful to separate command areas and deltas from non-irrigated and highly elevated areas in the river basin (Figure 4.2).

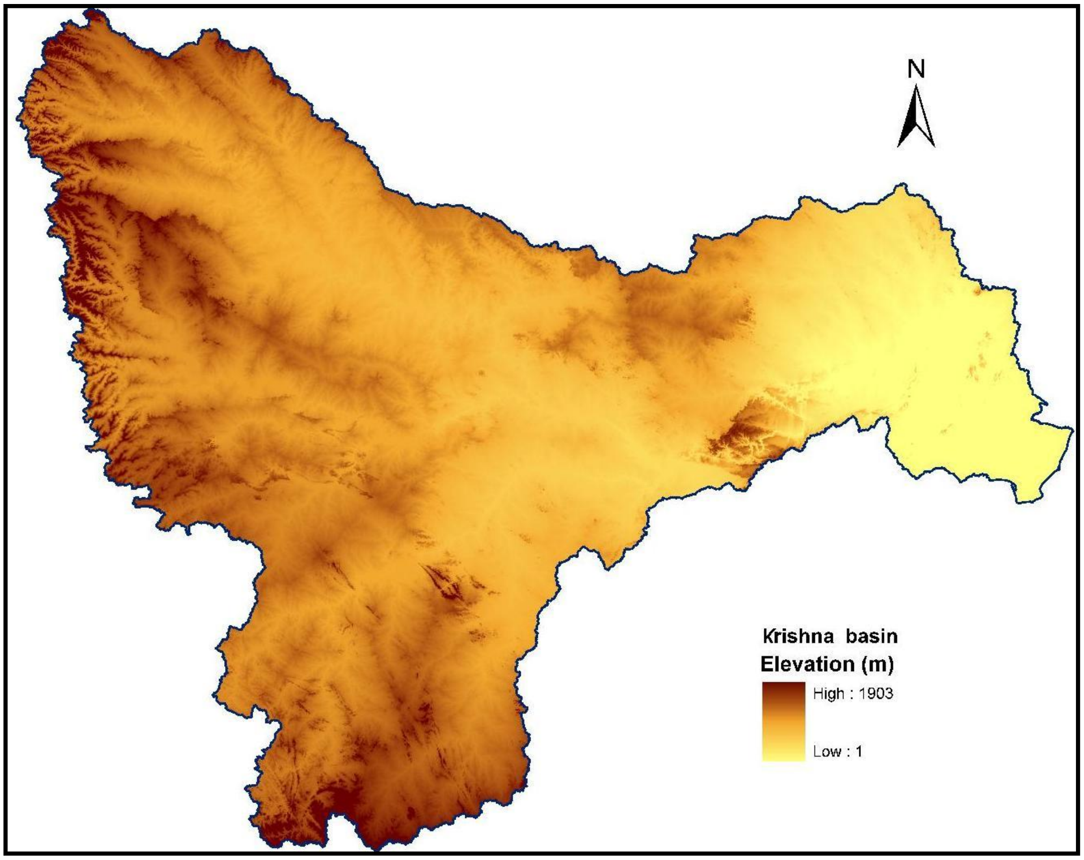


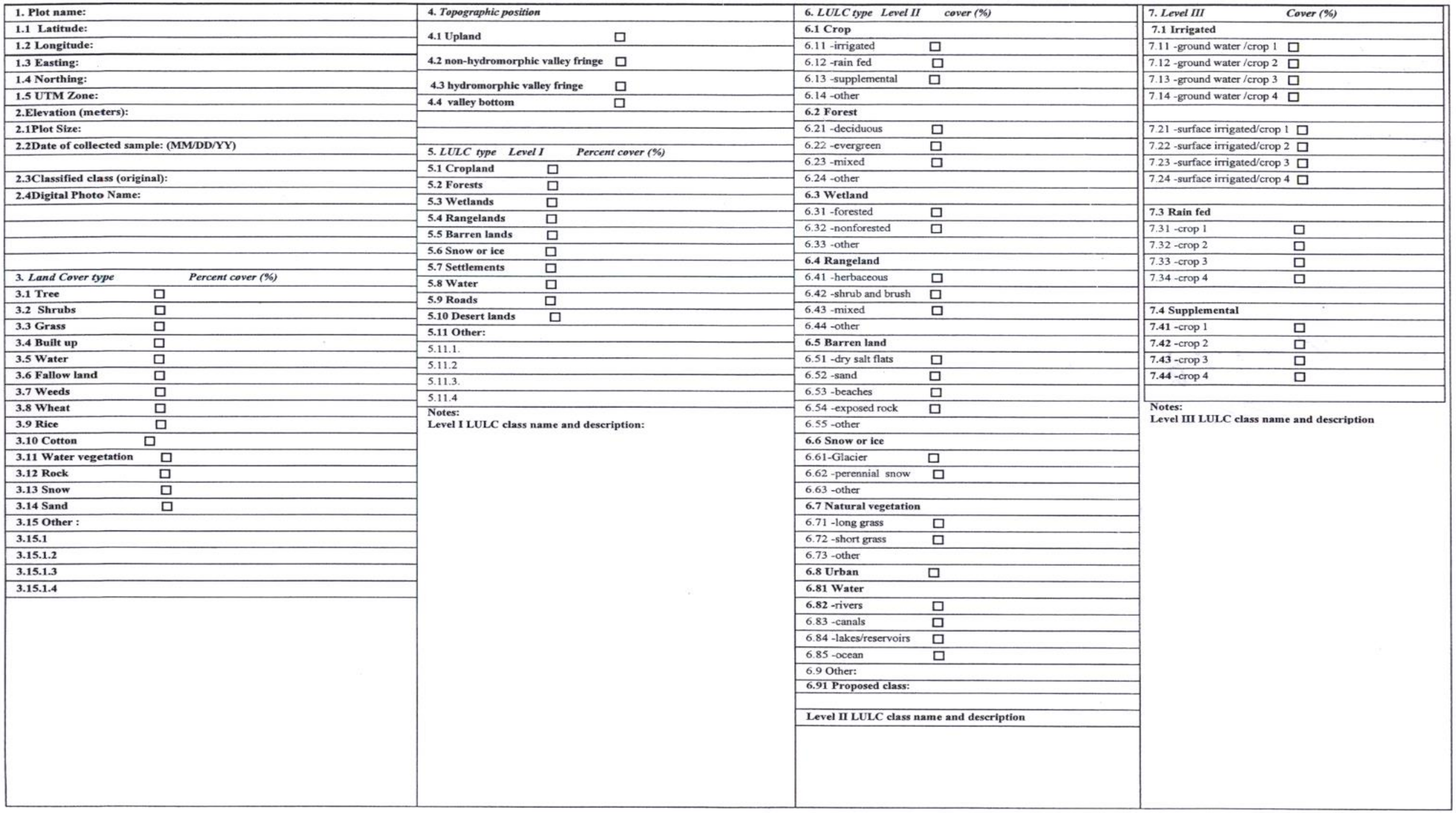
Figure 4.2 Digital Elevation Model (Ayele et al.,) for the Krishna river basin

4.2.2 Ground truth datasets

Ground survey data was collected covering about 7500 km of road travel in the Krishna River Basin during 13-26 September 2013 for 227 sample points out of which 73 were collected for class identification and labelling and the remaining 154 points were used to assess accuracy, 21-30 September 2015 for 243 sample points out of which 81 were used for class identification and labelling and the remaining 162 points were used to assess accuracy and 19-21october 2015 for 47 sample points were used to assess accuracy for the 2015-2016 classification (Figure 5.4). Based on the pre-classified output, using Google Earth imagery and GPS tracking attached to the image processing software collected ground survey data. The detailed information was collected for some point for class identification and labelling. The detail information includes land use categories, land cover percentages, cropping pattern during different seasons (through farmer interviews), crop types, and watering method (irrigated, rainfed). Samples were obtained within large contiguous areas of a particular LULC because of 250 X 250 m size. Available Landsat 8 products were also used as additional ground survey information in identification of LULC class. A stratifiedsystematic sample design was adopted to obtain a various parameter during ground survey and collecting the information using vehicle/on foot. The below form shows the collecting parameters during ground survey. The ground truth form contains parameters like

1. GT Point no, Country, province, District
2. Coordinates (Using GPS), date
3. Crop calendar
4. Crop intensity
5. Topographic position
6. Land use land cover parameters: (% cover): trees, shrubs, grasses, barren land/soil, rock, water, built-up, farmland, and others.
7. Crop parameters
8. General description (land use land cover at particular location)
9. Soil condition (soil moisture, soil type and soil erosion)
10. Cropping pattern (Previous/present including season wise)
11. Crop growth / crop health
12. Agriculture technique (Rainfed, Irrigated, and etc)
13. Irrigation techniques \ watering methods like
    - Shallow tube well irrigated areas during dry season
    - Surface irrigated areas (canal/river)
    - Combined dug well and dug out irrigated areas during dry season
14. Two photos at each location (Figure 6.6)

Ancillary data is non remote sensing data collected during field visit and also related information from other available sources (also called as secondary data) which help in remote sensing analysis including class identification, labelling (ex: source of irrigation, crop information and etc) for accuracy assessment.



1. Plot name:
1.1 Latitude:
1.2 Longitude:
1.3 Easting:
1.4 Northing:
1.5 UTM Zone:
2.Elevation (meters):
2.1Plot Size:
2.2Date of collected sample: (MM/DD/YY)

2.3Classified class (original):
2.4Digital Photo Name:

3. *Land Cover type* ***Percent cover (%)***
3.1 Tree ☐
3.2 Shrubs ☐
3.3 Grass ☐
3.4 Built up ☐
3.5 Water ☐
3.6 Fallow land ☐
3.7 Weeds ☐
3.8 Wheat ☐
3.9 Rice ☐
3.10 Cotton ☐
3.11 Water vegetation ☐
3.12 Rock ☐
3.13 Snow ☐
3.14 Sand ☐
3.15 Other :
3.15.1
3.15.1.2
3.15.1.3
3.15.1.4

4. *Topographic position*
4.1 Upland ☐
4.2 non-hydromorphic valley fringe ☐
4.3 hydromorphic valley fringe ☐
4.4 valley bottom ☐

5. *LULC type Level I* ***Percent cover (%)***
5.1 Cropland ☐
5.2 Forests ☐
5.3 Wetlands ☐
5.4 Rangelands ☐
5.5 Barren lands ☐
5.6 Snow or ice ☐
5.7 Settlements ☐
5.8 Water ☐
5.9 Roads ☐
5.10 Desert lands ☐
5.11 Other:
5.11.1.
5.11.2
5.11.3.
5.11.4
Notes:
Level I LULC class name and description:

6. *LULC type Level II* ***cover (%)***
6.1 Crop
6.11 -irrigated ☐
6.12 -rain fed ☐
6.13 -supplemental ☐
6.14 -other
6.2 Forest
6.21 -deciduous ☐
6.22 -evergreen ☐
6.23 -mixed ☐
6.24 -other
6.3 Wetland
6.31 -forested ☐
6.32 -nonforested ☐
6.33 -other
6.4 Rangeland
6.41 -herbaceous ☐
6.42 -shrub and brush ☐
6.43 -mixed ☐
6.44 -other
6.5 Barren land
6.51 -dry salt flats ☐
6.52 -sand ☐
6.53 -beaches ☐
6.54 -exposed rock ☐
6.55 -other
6.6 Snow or ice
6.61-Glacier ☐
6.62 -perennial snow ☐
6.63 -other
6.7 Natural vegetation
6.71 -long grass ☐
6.72 -short grass ☐
6.73 -other
6.8 Urban ☐
6.81 Water
6.82 -rivers ☐
6.83 -canals ☐
6.84 -lakes/reservoirs ☐
6.85 -ocean ☐
6.9 Other:
6.91 Proposed class:

Level II LULC class name and description

7. *Level III* ***Cover (%)***
7.1 Irrigated
7.11 -ground water /crop 1 ☐
7.12 -ground water /crop 2 ☐
7.13 -ground water /crop 3 ☐
7.14 -ground water /crop 4 ☐

7.21 -surface irrigated/crop 1 ☐
7.22 -surface irrigated/crop 2 ☐
7.23 -surface irrigated/crop 3 ☐
7.24 -surface irrigated/crop 4 ☐

7.3 Rain fed
7.31 -crop 1 ☐
7.32 -crop 2 ☐
7.33 -crop 3 ☐
7.34 -crop 4 ☐

7.4 Supplemental
7.41 -crop 1 ☐
7.42 -crop 2 ☐
7.43 -crop 3 ☐
7.44 -crop 4 ☐

Notes:
Level III LULC class name and description

Figure 4.3 Groundtruth form used during the field visit to record database on physical observation and farmer interviews

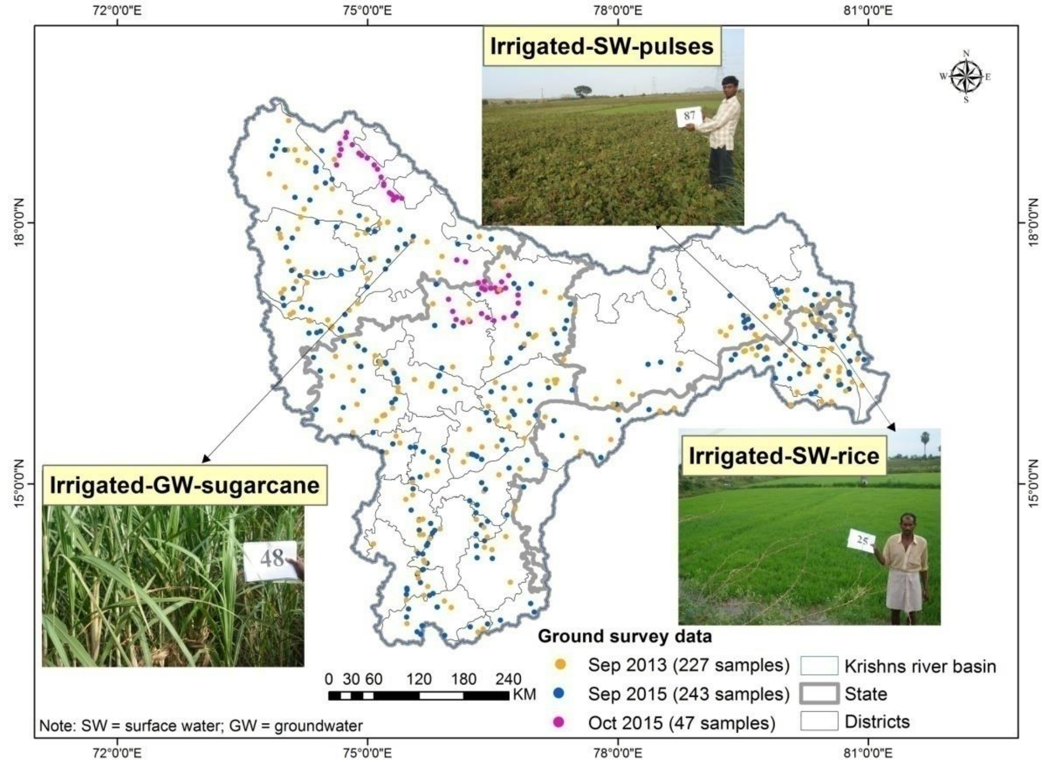


Figure 4.4 Ground survey locations in the Krishna River Basin and representative photographs taken during the survey

4.2.3 National Statistics & Secondary Data

The Statistics related to cultivated area, production, crops and their pricesat the sub-national level (districts) were obtained from India-stat (DIP, 2015). Using Tropical Rainfall Measuring Mission (TRMM), daily rainfall data was collected (TRMM, 2016)and processed as monthly mean rainfall data to compare with 11 years (from 2005 to 2016), spatial resolution is 0.25 degrees X 0.25 degrees. The TRMM estimates are near real-time grids from which average monthly rainfall data during rainy season was extracted for the selected 11 years, including for 2002, 2015 drought year. Due to the lack of official statistics for drought-affected areas, the rainfall data was not used to identify drought areas but as an accumulation of evidence of water stress occurrence.

CHAPTER - 5

CROP STRESS ANALYSIS

The methodology was designed by considering different parameters for the mapping and assessment of cropping patterns in a region with two crop seasons per year. Cropping patterns plays a significant role inmapping spatial and temporal complexity in land use changes due to water stress. The methodology starts with unsupervised classification of NDVI MVCs and follows. In the class identification and labelling process, the 16-day dataset as well as monthly MVCs are being used. The main advantage of this methodology during classification is to obtain the monthly cloud-free or near-cloud-free images with maximum value composites. MODIS 16-day temporal resolution data helps in identification of cropping systems across different cropping patterns and changes (irrigated, rainfed, etc.). Spectral matching techniques were successful in distinguishing cropping patterns such as mild-water stress, moderate water-stress, severe water-stress areas by comparing the spectral signatures. Finally, the Accuracy Assessment has been done after the intensity of the drought was identified spatially considering different parameters.

Methodology

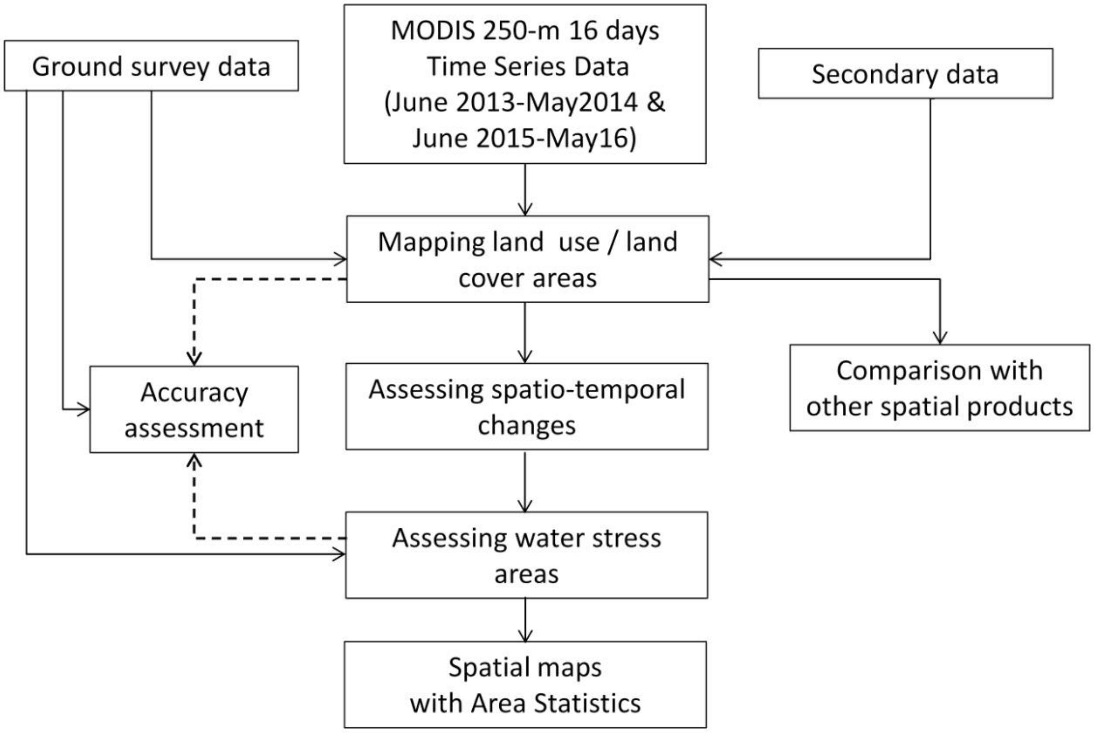


Figure 5.1 Methodology-flow chart of the study

5.1 MODIS data pre-processing

5.1.1 Blue band minimum reflectivity threshold for clouds

India is one of the south Asian country which is subjected to the influences of the oscillating subtropical convergence zone leads to flood mainly in monsoon season i.e. June to September. During this monsoon season of the year, we will observe the significant change in vegetation cover, dynamics of vegetation, and biomass accumulation. Due to high cloud coverage in monsoon season, it is difficult to retain the required number of pixels in the time-series.

In order to rectify the problem of cloud cover up to some extent, the following approach was adopted (Thenkabail et al., 2005): (a) retain all the images with <5 percent cloud cover (b) apply a cloud-masking algorithm to the eliminate areas with cloud cover and retain the rest of the image in an unchanged form (Thenkabail et al., 2005; Gumma et al., 2011a). The cloud-masking algorithm runs with a threshold value of 18% (1800 when MODIS pixel values are scaled to a 0-10000 range) for band 3 and set to make all other bands to null if this is exceeded. A detailed description of cloud removal algorithms for MODIS, available with (Thenkabail et al., 2005; Gumma et al., 2011a).

5.1.2 NDVI and monthly maximum value composite (MVC)

A normalized difference vegetation index (NDVI) was created using surface reflectance values of red and NIR bands (equation 1). For every month, two 16-day composites were available. A total of 23 16-day composites for ever crop year, forms Monthly maximum value composites (MVCs) by combining two 16-day composites for every month from June 2013 through May 2014 and 2015-16 were created in order to minimize cloud effects during the monsoon season in equation 2. The created monthly MVCs were stacked into a 12-band mega-file data cube (MFDC).

$$NDVI = \frac{\lambda_{NIR} - \lambda_{red}}{\lambda_{NIR} + \lambda_{red}} \qquad (1)$$

$$NDVI_{MVC_i} = Max(NDVI_{i1}, NDVI_{i2}) \tag{2}$$

Where, MVC_i is the monthly maximum value composite of the ith month.

i_1, and i_2 are every 16 days' data in a month.

5.1.3 Mega-file data cube composition

The combination of many bands of data of a study area into a single file after cloud removal referred to as mega-file data cube. These mega datacube has no limitation for size or dimension of a mega-file.

5.1.4 Unsupervised classification

Unsupervised classification (Cihlar et al., 1998) was used to classify the image. The unsupervised ISOCLASS cluster algorithm (ISODATA in ERDAS Imagine 2014^{TM}) run on the NDVIMVC file with an inputs of initial 40 classes with a maximum of 40 iterations and convergence threshold of 0.99. Using unsupervised classification, depending upon the inputs, it will classify the nearly homogenous NDVI values as classes. It is recommended to use unsupervised techniques for large areas with unknown range of vegetation types, and identification of homogeneous sites (Cihlar et al., 2000; Biggs et al., 2006; Gumma et al., 2011c). It is very difficult to Identify training sites for small, heterogeneous irrigated areas.

5.1.5 Creation of ideal spectra

Using ground survey data collected for the entire Krishna Basin was used to create Ideal spectral signatures for LULC classes. The precise locations of the ground data were recorded by a Garmin GPS unit with accuracy of 15m. It is good to have at least 50 samples per category (Congalton et al., 1999; Gumma et al.; 2008b) for extraction of ideal spectra from MODIS time series. Ideal spectra names are assigned based on a) type of crops b) dominant crop and c) type of irrigation with their individual spatial distribution. For generating ideal spectra, we used 73 precise locations in 2013-14 and 81 locations in 2015-16 across the study areas to cover major irrigated classes. Based on above locations with their known similar signature plots were correlated based on their similarity and spectral correlation values, ideal spectra were created.

The ideal spectra likely to vary from one location to location because it depends up on the duration of the crop, variety of the seed, the eco-systems and etc. There is also a possibility of matching of ideal spectra's of one crop with another classes: for example the ideal spectra of irrigated-cotton-chilli and irrigated-rice-single crop shows the same plot. Even though, there is difference in magnitude with in irrigated surface water, groundwater and rainfed based crops. The field-plot data shows the crop dominance (mixed crops occupying smaller fractions of the area) than the dominance of any single crop. In such cases, ideal spectral signatures for crop dominance were generated in irrigated and rainfed conditions. The approach involves the selection of classes with similar cropping patterns by characterizing their ideal spectral and grouped based on similarity in their spectral signatures.

Ideal signatures (Figure 5.2 and 5.3) were selected based on single-cropped, double cropped, homogenous areas such as major irrigated crops in the Krishna Basin like rice, sugarcane, cotton, chilli, and maize, and rain-fed crops like bajra, sorghum and sunflower.

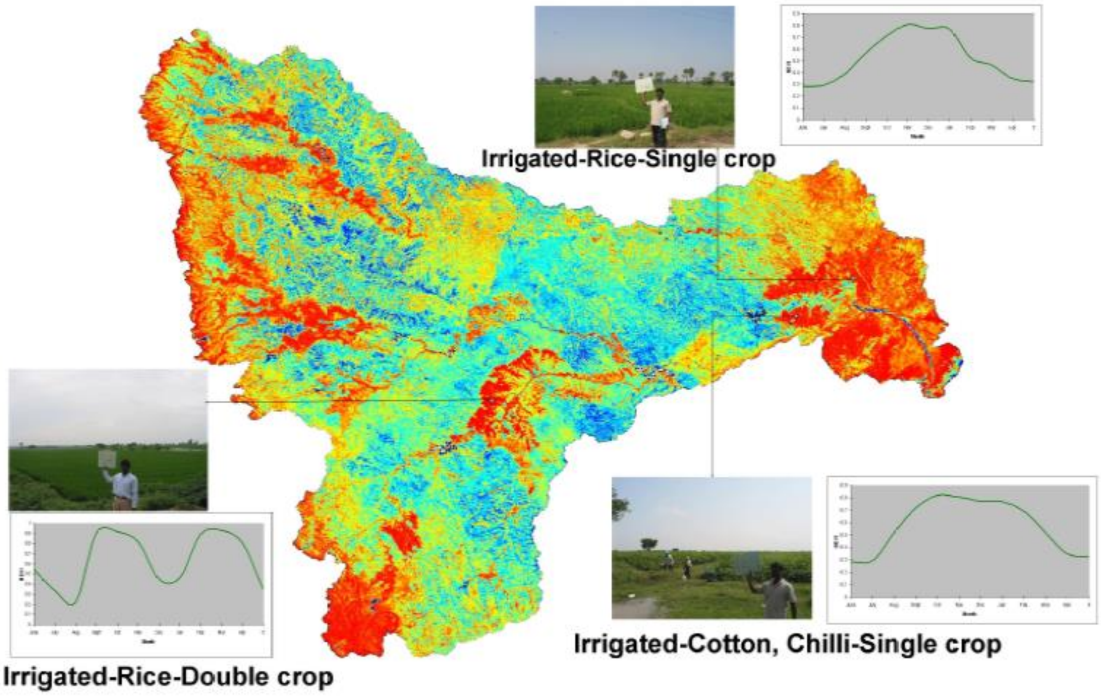


Figure 5.2 Ideal spectral signatures for irrigated classes (MODIS time series)

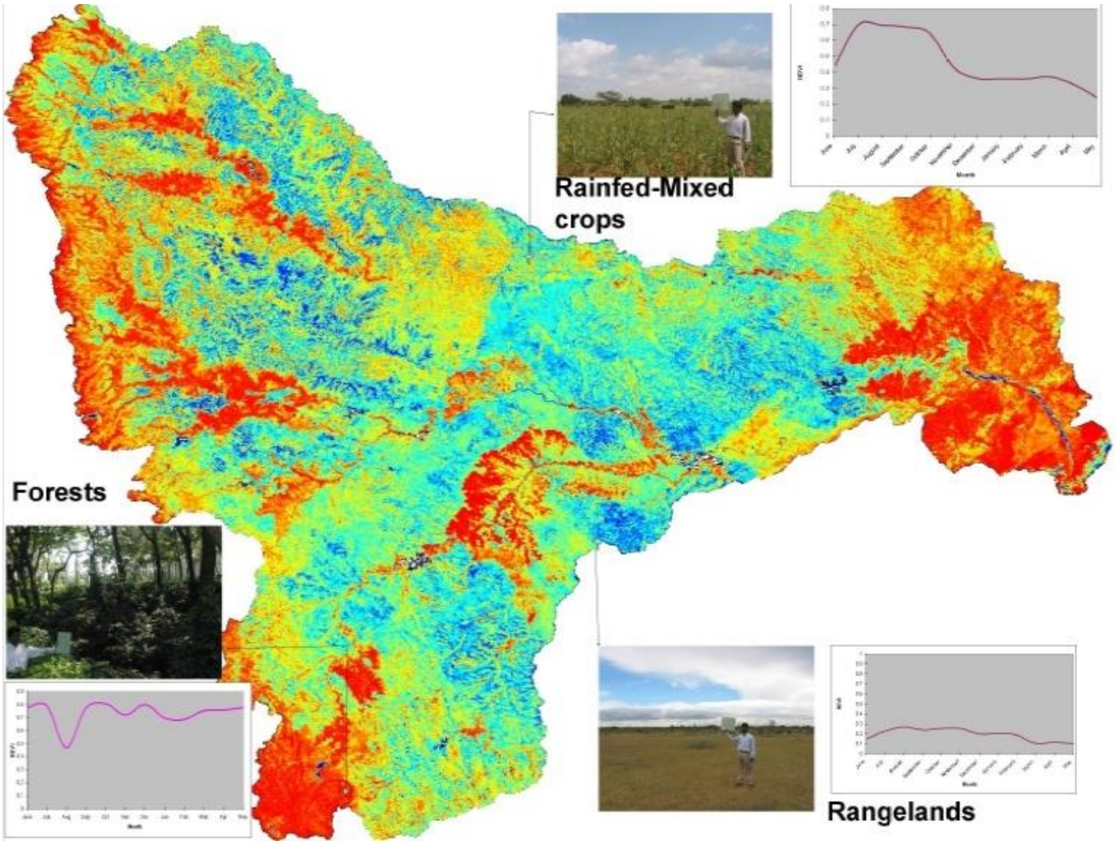


Figure 5.3 Ideal spectral signatures for other classes (MODIS time series)

5.1.6 Generation of class spectra

Using unsupervised ISOCLASS k-means classification (Tou and Gonzalez, 1975; ERDAS, 2006) using the MODIS NDVI MVC 250m mega-file data-cube i.e. the 12 layer NDVI stack is classified using unsupervised classification with 40 classes initially. The obtained signature file is used to plot the signature of each LULC class over time shows the profile of vegetative intensity, which helps in identification of the LULC classes.

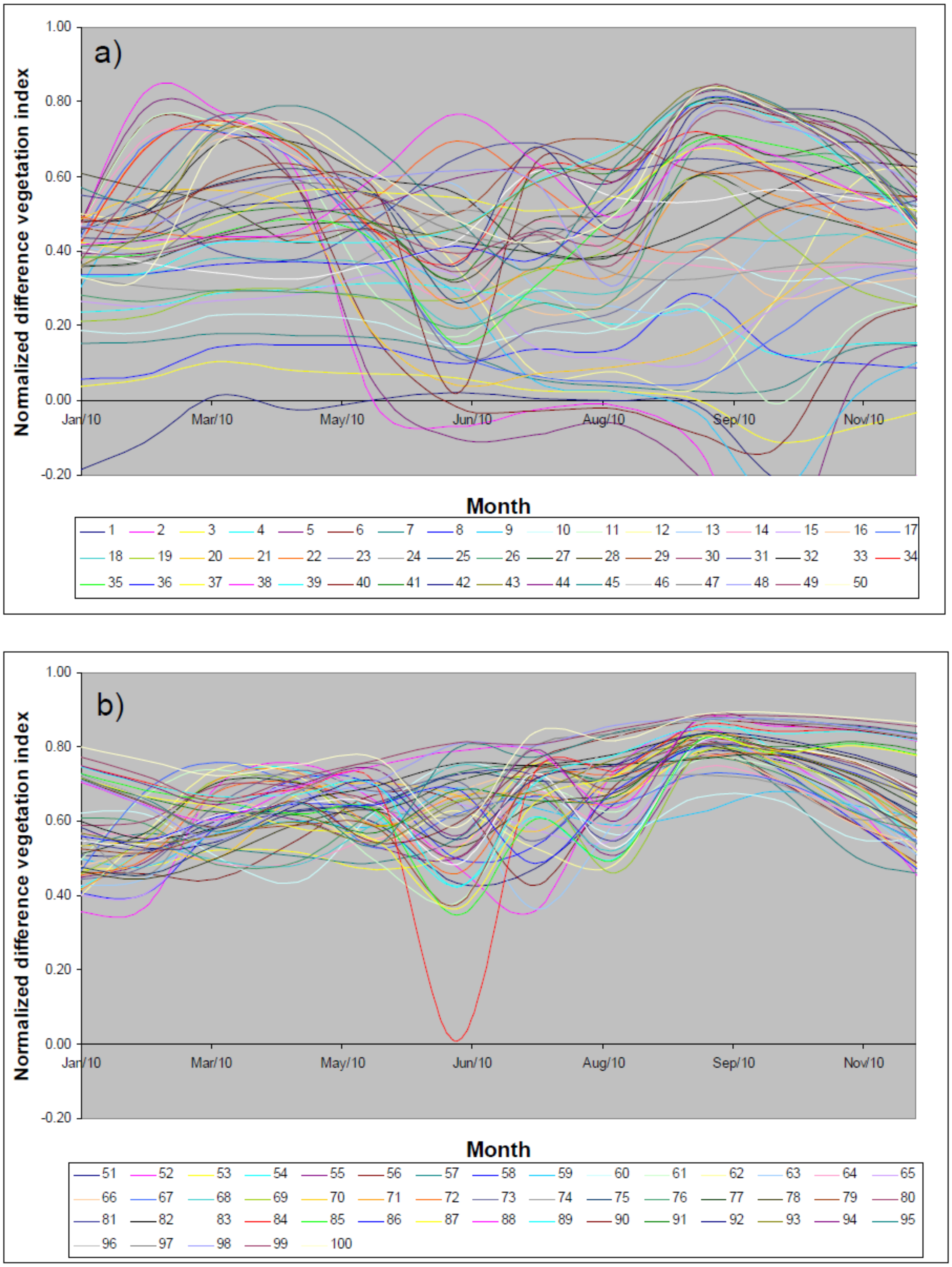


Figure 5.4b Class spectral signatures of unsupervised classes derived using MODIS 250m mega-file data-cube (MFDC) for year 2013 -14: a) 1-50 ISODATA classes and b) 51-100 ISODATA classes

The crop growth along with cropping calendar was derived from these time series curves as explained by Thenkabail et al. (2005) to identify the classes with similar spectral behaviour throughout the cropping year. Same procedure was adopted to identify the entire class and labelling protocol.

5.2 Mapping of Land Use and Land Cover

5.2.1 Class Identification and Labelling Process

Class identification and labelling is a step-by-step process based on NDVI temporal signatures along with ground survey data. The observation of crop growth stages and cropping pattern from temporal signatures mainly

(a) Start of cropping season (e.g., monsoon and winter)

(b) Length of cropping season

(c) Magnitude of crops during different seasons (e.g., water stress and normal years)

(d) End of cropping season

Using spectral matching techniques, (Gumma et al., 2014; Gumma et al., 2016). The obtained class spectra was compared with ideal spectra bank to identify the class by observing the above patterns. The similar NDVI time series and pattern was combined into a single class, if there is significant mixing, e.g., continuous irrigated areas and forest, then the class is masked out and reclassified using the same ISOCLASS algorithm. If the same problem arises, the continuous irrigated areas mixed with forests in the Western Ghats were separated using a 90m digital elevation model (Ayele et al.,) from the shuttle radar topography mission (SRTM) and an elevation threshold of 630m, Landsat imagery and ground survey data through spatial modeling techniques such as overlay matrix, recode and proximity analysis. After the classification, the respective classes were merged into nine required classes.

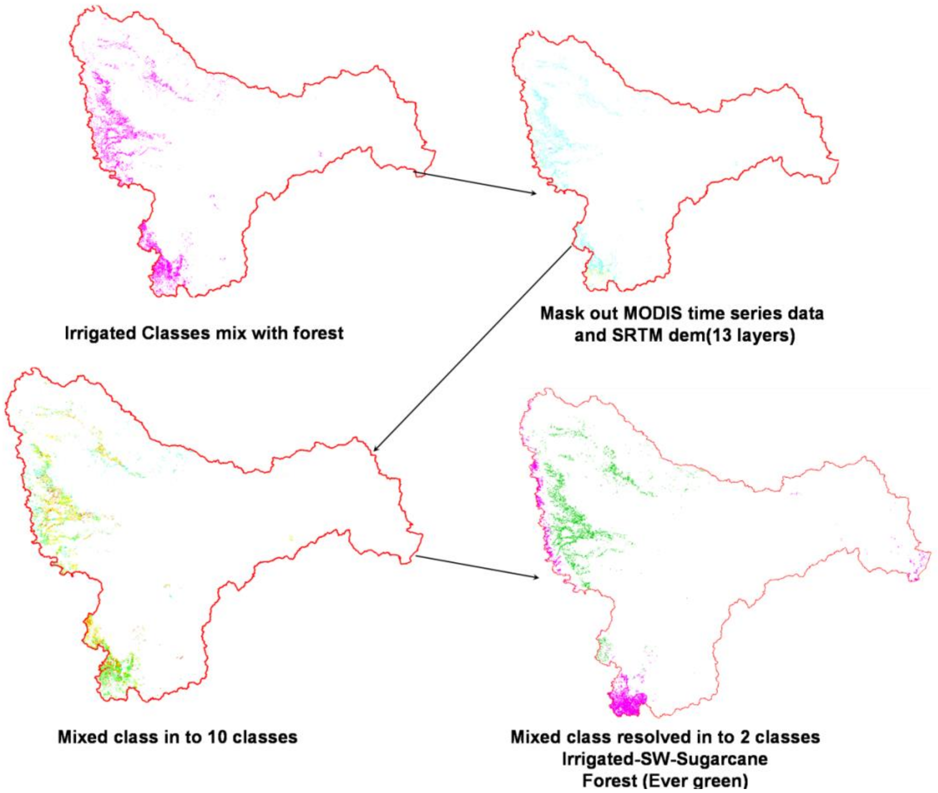


Figure 5.5 Resolving the mixed class (Tomlinson, 2003; Gumma et al., 2011b)

In the present study, the classification was carried on 250 m spatial resolution, where average land holding size is less than a pixel and there is a possibility of falling different LULC classes in one class with 250 m × 250 m pixel (6.25 ha). Full pixel areas are not an accurate representation, in order to increase the accuracy of the classification, cropland fraction was calculated using the methodology described in Sub-pixel areas to separate from different other LULC classes (e.g., grasses, trees, shrubs, etc.).

5.2.2 Ground Survey data

Ground truth data contains the cropland fraction and irrigated area fractions which helps in sub-pixel area (King et al.,2003) calculations, creation of ideal spectra and also in accuracy assessment of identified classes.

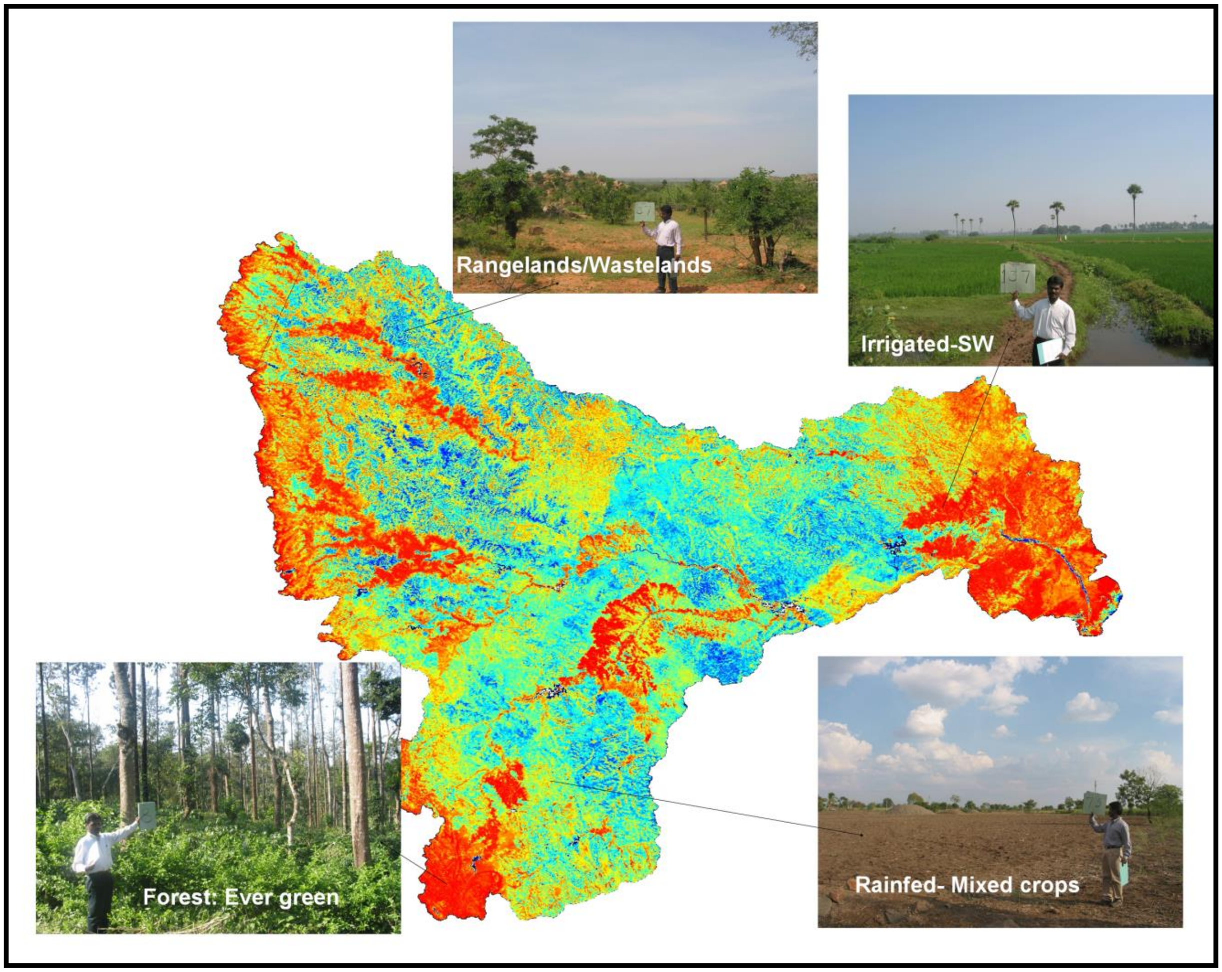
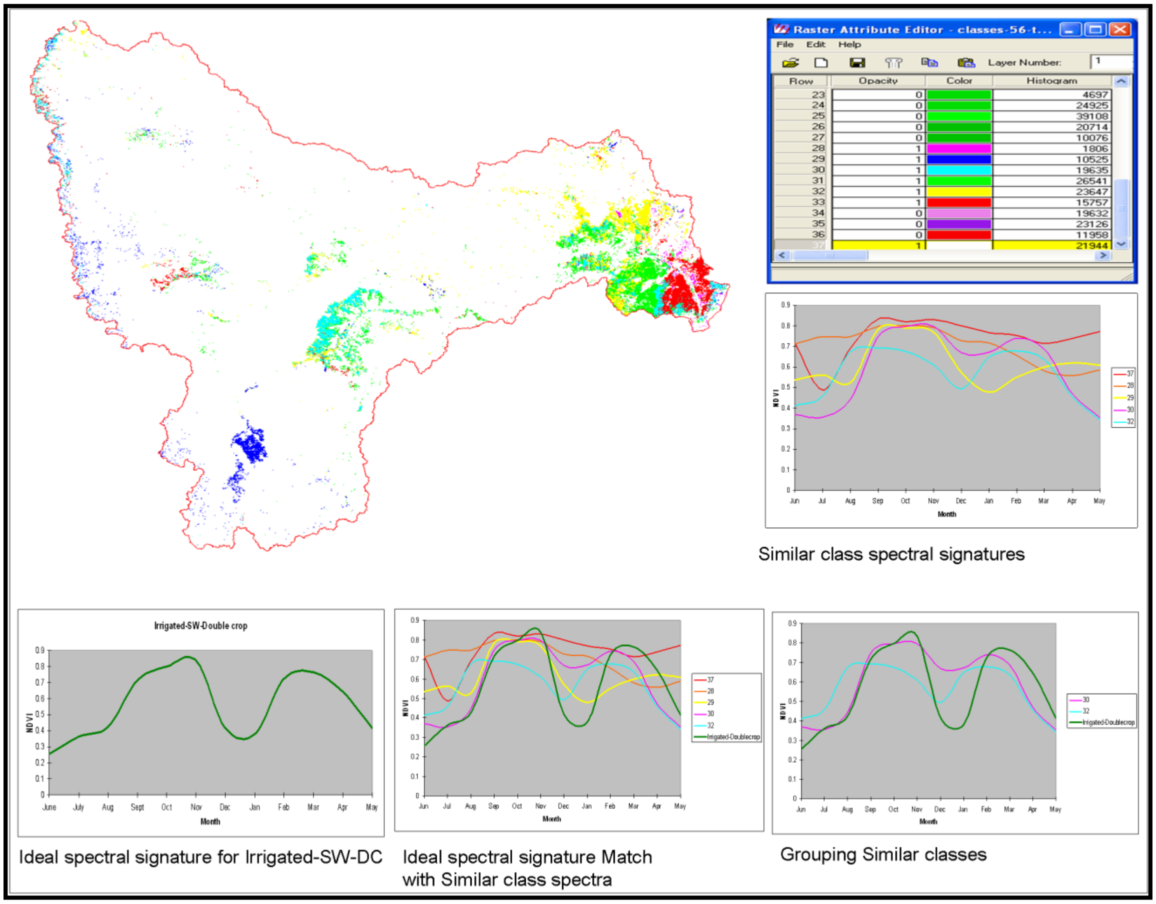


Figure 5.6 Ground survey photographs of LULC

5.2.3 Spectral matching techniques

Spectral signature matching (Van Ittersum et al., 2013) techniques are traditionally developed for hyper-spectral data analysis of minerals (e.g., Homayouni and Roux, 2003; Shippert, 2001; Bing et al.,1998; Farrand and Harsanyi, 1997; Granahan and Sweet, 2001; Thenkabail et al., 2004 c,d). The same principle of spectral matching techniques (SMTs) which was applied for hyper spectral data analysis of minerals, also applied in identification of LULC classes from MODIS time-series (HTS) satellite imagery.

Spectral signature matching (Van Ittersum et al., 2013) techniques categorise the similar classes and compared with the ideal spectral data bank for class identification and labelling process.



Row	Opacity	Color	Histogram
23	0	🟩	4697
24	0	🟩	24925
25	0	🟩	39108
26	0	🟩	20714
27	0	🟩	10076
28	1	🟪	1806
29	1	🟦	10525
30	1	🟦	19635
31	1	🟩	26541
32	1	🟨	23647
33	1	🟥	15757
34	0	🟪	19632
35	0	🟪	23126
36	0	🟥	11958
37	1	⬜	21944

Similar class spectral signatures

Ideal spectral signature for Irrigated-SW-DC

Ideal spectral signature Match with Similar class spectra

Grouping Similar classes

Figure 5.7 Class spectral signatures matching with ideal spectral signatures for grouping and identifying the class (Gumma et al. 2011)

5.2.4 Google Earth data

Google Earth verification is used for class identification and labeling because of high resolution Google Earth (http://earth.google.com/) with spatial resolution of 0.61-4 m helps the user to zoom into specific areas from a base of 30 m resolution data to sub-meter resolution for free and easy access through the Web. Using google earth, the visual interpretation of class is possible by considering shape, size, pattern, and texture. Google earth data was also used for class identification and verification because it helps in identification of the LULC where it is difficult to access during field visits. It does not have an accurate information, but the zoom-in views of high-resolution imagery helps in identifying the rice bunds, irrigation structures (e.g., canals, irrigation channels, open wells) and vegetation conditions. When the identification of the LULC was difficult by Google earth, the usage of the earth data in the analysis was restricted and choose alternate methods. But analysing the previous year's data with the current study year shows the supportive results from the year 2000, the Google earth data shows the high resolution imagery from one to three years old. In this study, Google Earth data were used to identify and label the classes and deriving irrigated area fractions that helped in sub-pixel area (King et al., 2003) calculations and accuracy assessment of irrigated area classes and verifying the classified image by overlaying in Google earth.

5.2.5 Actual or sub-pixel area calculations

The composite MODIS pixels cover an area of (250 X 250 m) i.e. nearly 6.25 hectares, which is larger than average land holding in the study area. In this case, many pixels contain more than one land cover class i.e. mixed classes. The accurate identification of the crop can be obtained only by computing SPAs (equation 3) (Thenkabail et al., 2005; Thenkabail et al., 2009; Gumma et al., 2011b), as

$$SPA_n = FPA_n \times CAF_n \qquad (3)$$

where, SPA_n is the sub-pixel area of class n,

FPA_n is the FPA of class n

CAF_n is the crop area fraction of class n as derived from the field-plot observation data.

The CAF's of individual class were calculated based on a large sample size of points which are spatially well distributed in such class. The CAFs were observed by considering the combination of ground data and very high resolution i.e., Google earth data(less than 5 m) data. The SPA of each class is calculated by multiplying the FPA of such class with the CAF of class. Later, the SPAs of all classes are combined to obtain the actual areas from all the classes.

5.3 Accuracies and errors

Ground survey points which were collected during the study years are used to assess the accuracy of the classification results. The accuracy assessment was carried out using standard procedure includes generation of an error matrix and accuracy measures for each LULC map. Error matrices and Equation (4)'Cohen's kappa coefficient (κ)' are commonly used for accuracy assessment and helpful in building models during prediction of discrete classes. κ can be used as a measure of agreement between model predictions and reality which is computed as:

$$\kappa = \frac{N \sum_{i=1}^{r} x_{ii} - \sum_{i=1}^{r} (x_{i+} \times x_{+i})}{N^2 - \sum_{i=1}^{r} (x_{i+} \times x_{+i})} \qquad (4)$$

where, *N* is the total number of sites in the matrix,

r is the number of rows in the matrix,

x_{ii} is the number in row I and column i,

x_{+I} is the total for row i, and x_{i+} is the total for column i

5.4 Water Stress Mapping and Categorization

Water stress was measured based on NDVI signatures and field survey data. The areas are classified into three categories based on intensity/crop condition.

1. Severe water stress areas - no crop throughout the cropping season due to water shortage.
2. Moderate stress areas - a fraction of the plot was used to grow rice or partial damage had occurred
3. Mild water stress areas - a fraction of the plot was used to grow and the rest was left fallow

The above information was collected from 205 fields out of 584 locations during field survey.

The Farmers' responses which were obtained during ground survey were used along with the NDVI signatures to identify ideal spectral signatures (temporal signatures) for water stress and non-water stress areas. During the ground survey, it was observed that the year 2015-2016 was one of the severe water stress year and large agricultural areas including irrigated command areas were left fallows.

CHAPTER - 6

RESULTS AND DISCUSSION

This section deals with results obtained from classification of LULC areas including major croplands, changes in irrigated area, water stress areas and accuracy assessment based on ground survey data and a comparison of irrigated areas from the present study and national statistics.

6.1 LULC Classification of the Krishna River Basin at using MODIS 250m.

6.1.1 Spatial Distribution of LULC

The spatial distribution and identification of LULC was performed using the 16-day time series NDVI stack and the spectral signatures (temporal signatures) generated from for sampled locations and class signatures obtained using spectral matching techniques. Image is classified into nine LULC classes for the normal year (2013-2014; Figure 6.1 and Table 6.1) and water-deficit years (2015-2016; Figure 6.2 and Table 6.1). The identification of Classes were based on spectral matching techniques along with ground survey data and field observations.

The cropland areas in the Krishna River Basin for 2013-2014 are shown in Table 6.1. The full pixel area of rainfed croplands were 4.8Mha shows the rainfed croplands mixed with other land cover areas i.e., the actual rainfed agriculture area was 4.1Mha, and remaining 0.7Mha was mixed with other LULC classes. The total amount of irrigated area was about 9.5Mha which includes groundwater, tank irrigation, and major canal irrigation during 2013-2014 whereas groundwater irrigated areas alone covered 5.1Mha, mainly located across the Krishna River Basin.

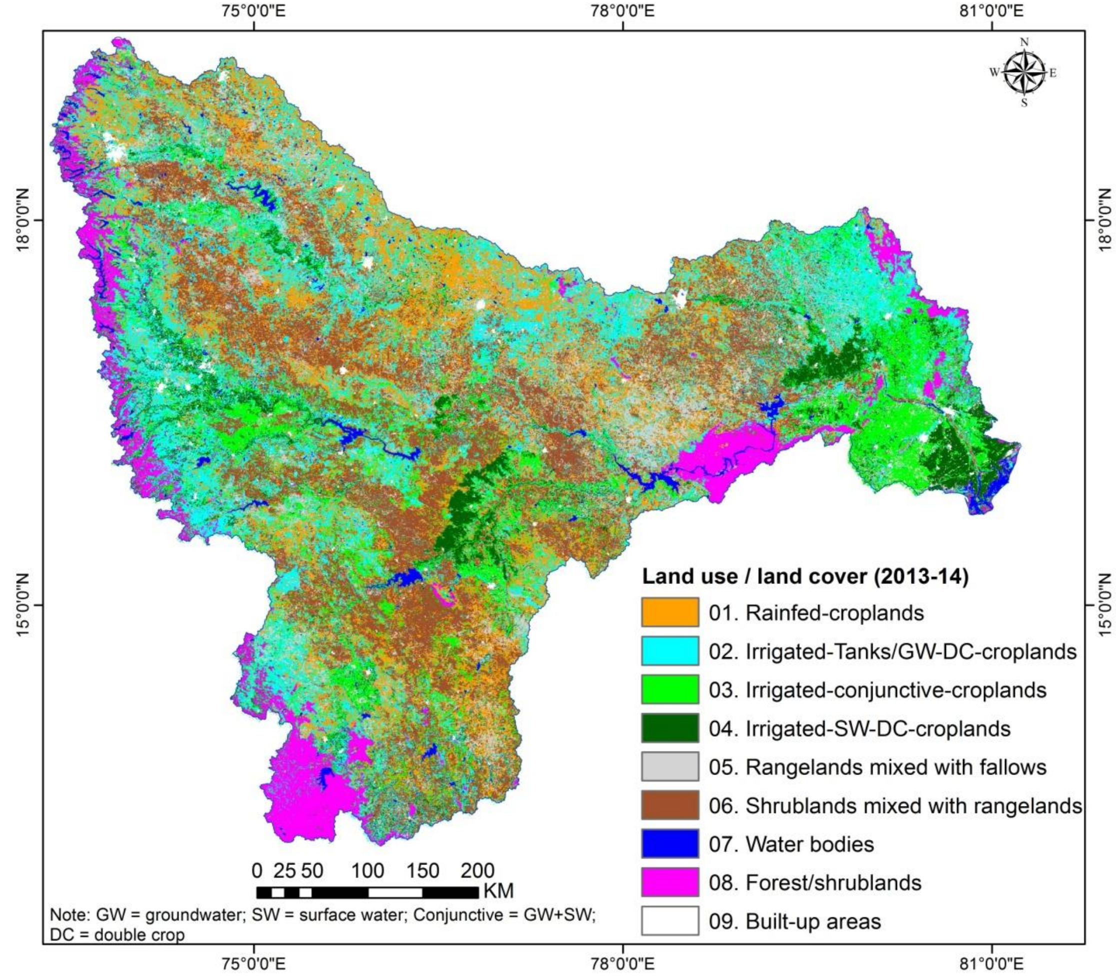
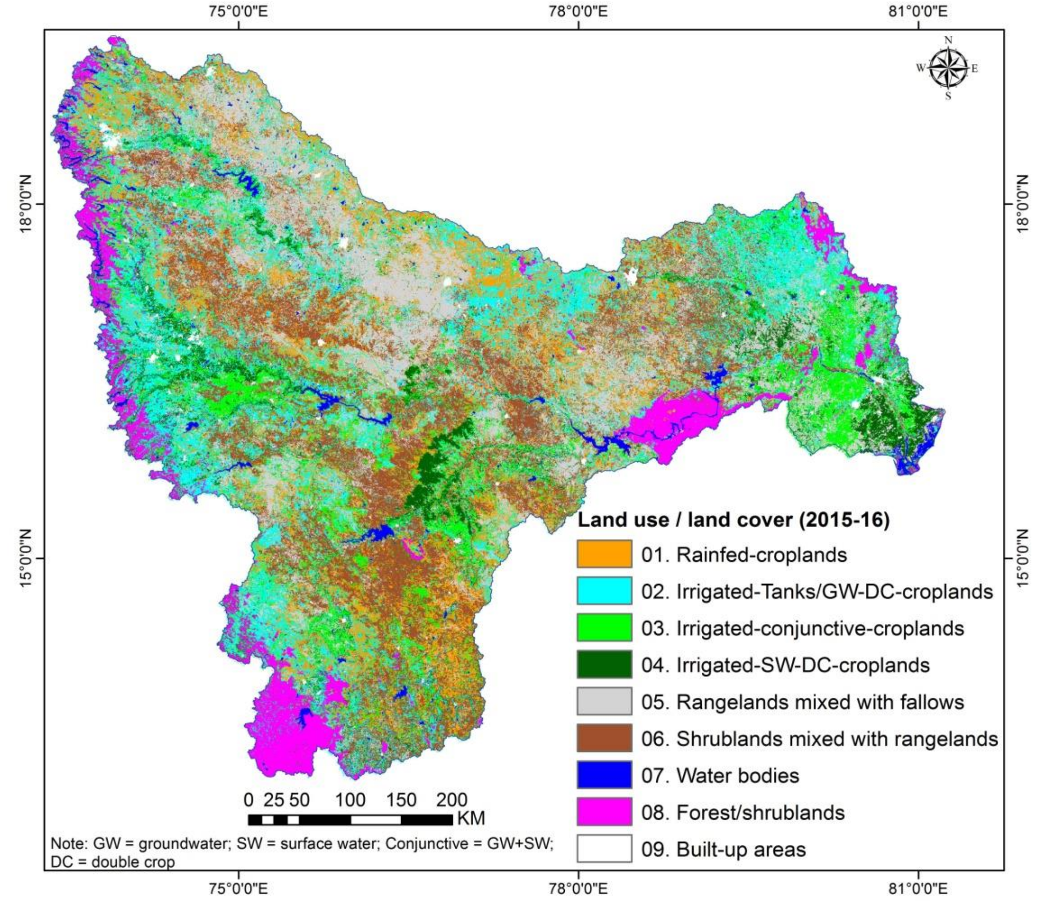


Figure 6.1 Spatial distribution of LULC derived from 2013-2014 MODIS composite

Table 6.1 Areas of Irrigated, Rainfed and other LULC classes.

	Full Pixel Area (FPA) (000′ha)		**Crop Area Fraction (%)**		**Actual Cropland Area (000′ha)**	
	2013-2014	**2015-2016**	**2013-2014**	**2015-2016**	**2013-2014**	**2015-2016**
01. Rainfed croplands	4853.5	3972.9	84.2	70.5	4087.4	2801.7
02.Irrigated-Tanks/GW-DC-croplands	5896.8	5112.9	86.5	76.3	5102.3	3900.5
03. Irrigated-conjunctive-croplands	3196.9	2795.2	89.2	83.6	2852.1	2335.9
04. Irrigated-SW-DC-croplands	1726.5	1477.1	92.6	86.1	1598.7	1271.8
05. Rangelands mixed with fallows	2678.2	5730.9	21.5	12.5	576.9	713.8
06.Shrublands mixed with rangelands	5587.8	4886.8	8.5	9.1	472.6	444.7
07. Water bodies	458.2	440.7	-	-	458.2	440.7
08. Forests/shrublands	1949.1	1940.8	-	-	1949.1	1940.8
09. Built-up areas	305.6	298.5	-	-	305.6	298.5
Net irrigated area	-	-	-	-	9553.1	7508.2
Net agriculture area	-	-	-	-	14,690.0	11,468.5

Note: GW = groundwater; SW = surface water; DC = double crop.



Note: GW = groundwater; SW = surface water; Conjunctive = GW+SW; DC = double crop

Figure 6.2 Spatial distribution of LULC derived from 2015-2016 MODIS composite

The spatial distribution of LULC in the Krishna River Basin for 2015-2016 is shown in Figure 6.2 and areas shown in Table 6.1. Altogether nine classes were identified in which four were croplands and five were other LULC. Rainfed croplands covered 2.8 Mha and the total irrigated area was 7.6 Mha, which included groundwater irrigated, tank irrigated and major canal irrigated areas during 2015-2016 whereas Groundwater irrigated area alone covered 4.0Mha was spatially distributed across the Krishna River Basin.

The results show a significant decrease in total irrigated area (including surface and groundwater areas) in the Krishna Basin between 2013-2014 (9.5Mha) and 2015-2016 (7.6Mha) and also shows decrease in groundwater irrigated area between 2013-2014 (5.1Mha) and 2015-2016 (4.0Mha). Due to less rainfall in 2015-16, there is a significant decrease in the rainfed cropped area between 2013-2014 (4.1Mha) and 2015-2016 (3.1Mha) was observed. Due to lower water storage in the reservoir during 2015-2016, the area irrigated by canals decreased during 2013-2014 (1.6Mha) and 2015-2016 (1.3Mha). Figure 6.3 shows the spatial distribution of crop land changes where crop lands converted to fallows due water stress.

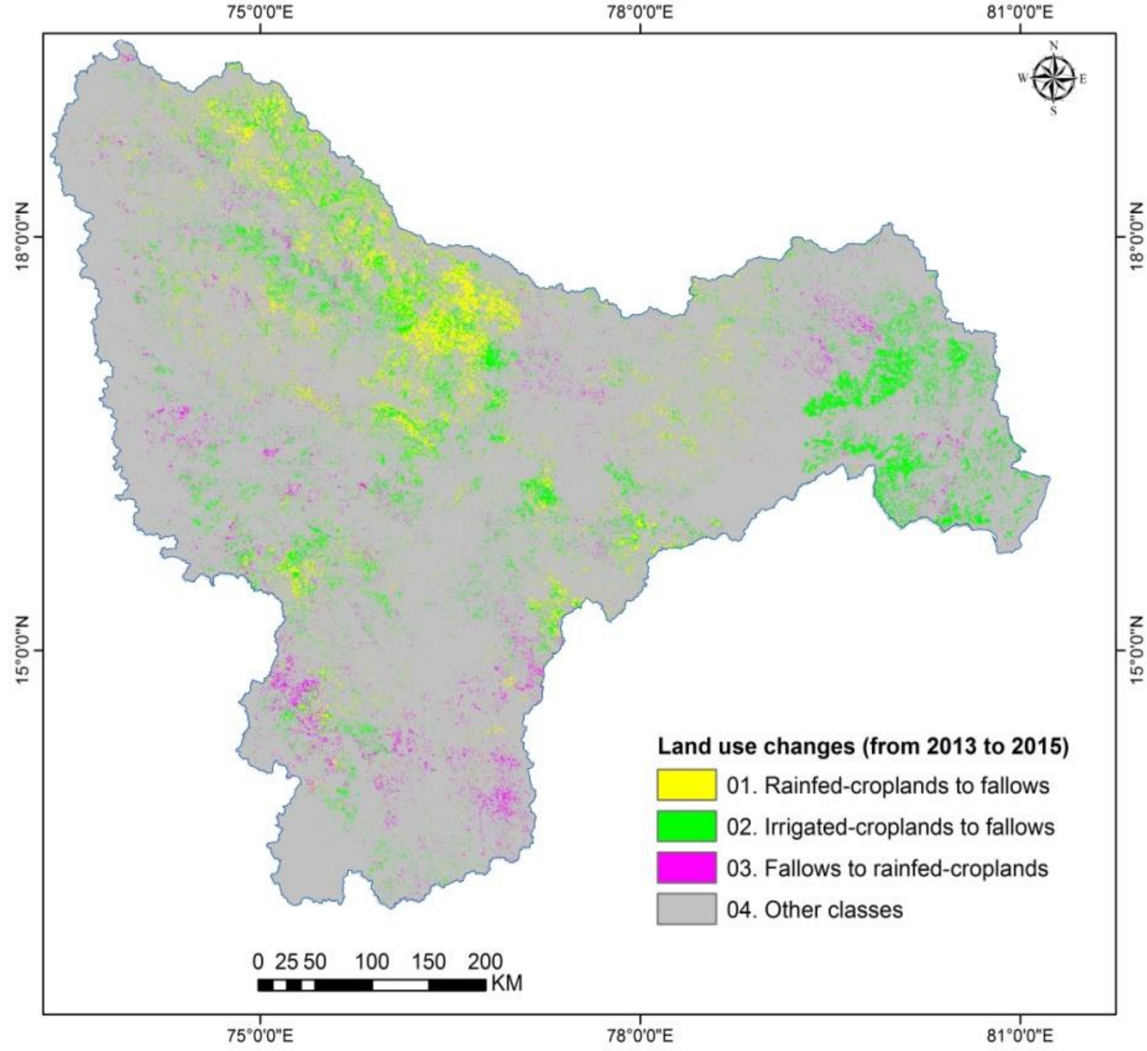


Figure 6.3 Land use changes from 2013-2014 to 2015-2016

6.1.2 Water Scarcity and Cropland Changes

During the water stress year (2015-2016) (Figure 6.3 and Table 6.3) land uses decreased from 14.7 Mha in a normal year (2013-2014) to 11.5 Mha. These arises mainly due to water scarcity in reducing cropping intensity and conversion of crop lands to fallow. Less rainfall was recorded during 2015 year (Figure 6.6). Due to this, Rainfed croplands in the Krishna Basin were reduced to half of the normal year to 2.8 Mha, and also significant reduction in the irrigated croplands. Overall, 7.6 Mha of croplands were affected by water scarcity (rainfed and irrigated croplands), and 7.1 Mha were not affected (Table 6.2).

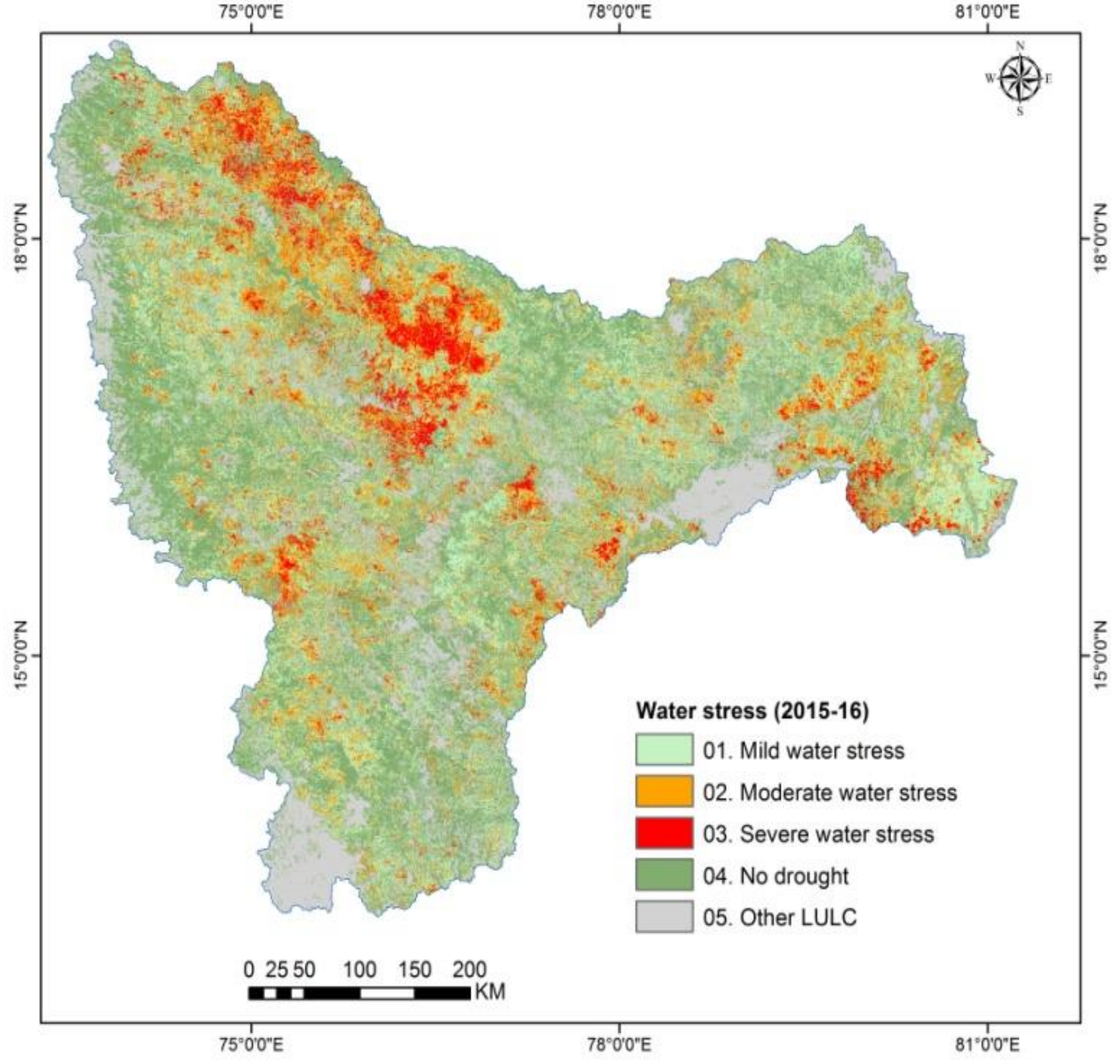


Figure 6.4a: Spatial distribution of water stress during 2015-2016 derived from 2015-2016 MODIS composite

Table 6.2 MODIS-derived water stress areas across the Krishna River Basin. The table shows full-pixel area (FPA), crop area fraction (CAF), and sub-pixel area (SPA) or actual area. SPA = FPA × CAF.

Water Stress Class	Full Pixel Area (FPA) (000′ha)	Cropland Fraction (%)	Actual Cropland Area (000′ha)
01. Mild water stress	5209.8	81.1	4226
02. Moderate water stress	3013.2	78.1	2355
03. Severe water stress	1125.1	88.1	991
04. No water stress	8409.9	84.7	7120
05. Other LULC	9013.2	-	9013
Total water stress area	-	-	7572

The changes in cropping patterns during 2015-2016 was observed (Table 6.3). due to water scarcity, long-duration irrigated crops like sugarcane was converted to crops such as rice and maize (Figure 6.4, class2). The area under double crop (monsoon rice + winter rice) also converted to pulses instead of rice included in the system. There is high shift in irrigated areas, which include groundwater irrigated areas, in 2013-2014were under fallows in 2015-2016. Water scarcity in minor irrigation systems forced farmers to drill bore wells to irrigate or to keep land as fallow.

An unexpected decline in food production affected market leads to high costs and also food insecurity. These results are due to change in climate scenario and growing water efficient crops during a water deficit year. Water scarcity is a frequent reality faced by farmers in the semi-arid tropics, even in the basin command areas which leads to a chain of events affecting crop production, cropping pattern changes and eventually reduced in incomes to farmers. To sustain food security, large river basins like the Krishna should adopt new adaptation strategies such as the use of climate smart varieties and water related management practices along with advanced mechanisms to remunerate the crops during such times.

Table 6.3 Changes in irrigated agricultural cropland from 2013-2014 (normal year) to 2015-2016 (water-deficit year) as a response to water stress, where FPA = full-pixel area; CAF = crop area fraction; SPA= and sub-pixel area or actual area. SPA = FPA × CAF.

Water Stress Class		**01. Mild Water Stress**	**02. Moderate Water Stress**	**03. Severe Water Stress**
Full pixel area (FPA) (000′ha)	01. Rainfed-croplands	1327	1030	482
	02. Irrigated-Tanks/GW-DC-croplands	1968	1092	355
	03.Irrigated-conjunctive-croplands	1160	580	183
	04.Irrigated-SW-DC-croplands	755	310	105
Cropland Fraction (%)		**81.1**	**78.1**	**88.1**
Actual Cropland area (000′ha)	01. Rainfed-croplands	1076	805	425
	02. Irrigated-Tanks/GW-DC-croplands	1596	854	313
	03.Irrigated-conjunctive-croplands	941	454	161
	04.Irrigated-SW-DC-croplands	612	242	93

Note: GW = groundwater; SW = surface water; and DC = double crop.

6.1.3 Temporal changes of water stress in cropland areas

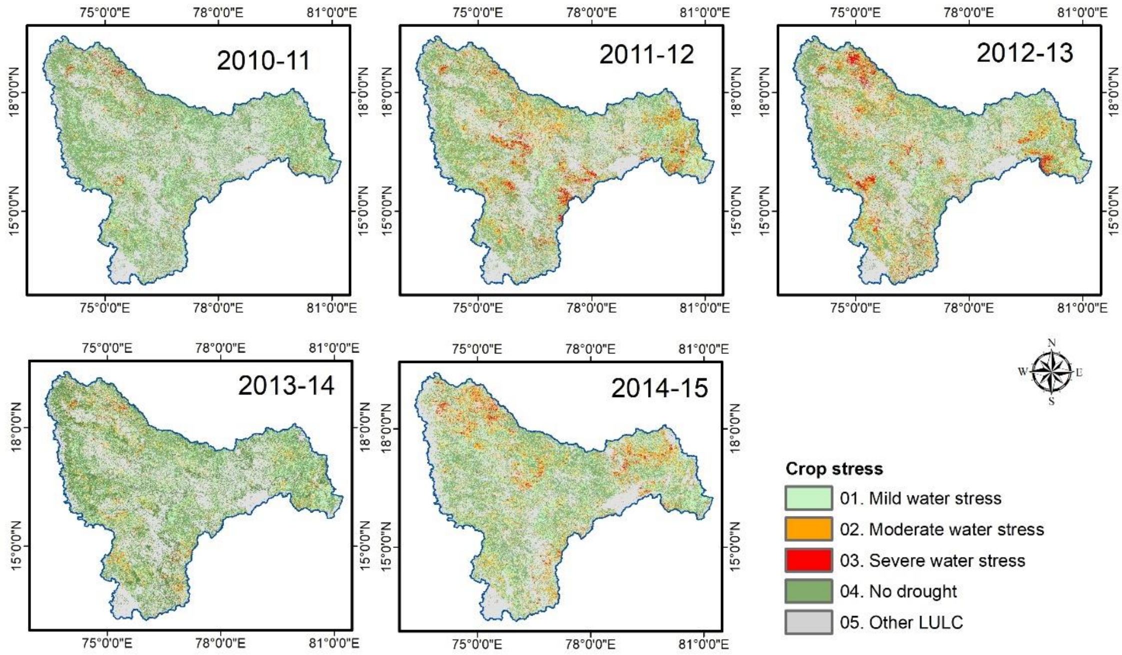


Figure 6.4b: Temporal changes of water stress from 2011 to 2015

Temporal variations of water stress in cropland areas in Krishna river basin over 5 years starting from 2010-11 to 2014-15 are shown in Figure 6.4b and Table 6.4. The water stress was mapped from 2010-11 onwards using known spectral signatures. The area under severe water stress and moderate stress was large in 2011, 2012 and 2015 years due to low rainfall recorded. The table 6.4 below shows the full pixel areas, due to non-availability of ground data, the crop area fraction was not multiplied to get sub pixel areas. The above map Figure 6.4b was not validated as ground data was not available, but same methodology was used while developing the maps considering spectral signatures of known crops.

Table 6.4 MODIS-derived water stress areas across the Krishna River Basin over 5 years starting from 2010-11 to 2014-15. The table shows sub-pixel area (SPA) or actual area. SPA = FPA × CAF.

	Area ('000 ha)				
Water stress	**2011**	**2012**	**2013**	**2014**	**2015**
Mild water stress	7112.4	7145.8	6665.5	6783.6	6488.9
Moderate water stress	3698.3	3894.2	1665.2	2489.2	3750.9
Severe water stress	964.0	1057.6	259.3	510.2	1329.1
No water stress	5500.2	5177.3	8684.9	7491.8	5706.0

6.2 Accuracy Assessment and Comparison with Other Published Data Sets

A quantitative accuracy assessment is to examine whether a known LULC was identified as the same LULC or not using error matrix. The ground survey data was collected during the kharif season for the crop years 2013-2014 and 2014-2015 throughout the Krishna Basin. Classification accuracy was performed on three classified products (LULC maps of 2013-2014 and 2015-2016) using 363 points that were not used in the classification.

Tables 6.4 to 6.6 show the error matrices of each classified product of year 2013-14 and 2015-16. In LULC 2013-2014, the first class i.e. 01. Rainfed croplands have matched 10 ground survey reference points with 14 rainfed croplands and remaining three points matched with 02. Irrigated-tanks/GW-croplands and one point matched with other LULC class. The same assessment was carried out for all the classes shown in Table 6.4. For all the six classes, 125 points are matched with 152 points with the same class of reference data. Table 6.4 shows the accuracy for the final six classes of 2013-2014 was 82.4% with a Kappa value of 0.78. Table 6.5 shows the accuracy for the year 2015-2016 with 162 sample points, of which 138 matched correctly with the present classification with an overall accuracy of 85% and a kappa value of 0.82.

The district-wise statistics collected from the Directorate of Economics and Statistics (DES), Andhra Pradesh and Telangana, Directorate of Economics and Statistics, Karnataka; and the Department of Agriculture, Maharashtra were compared with the final MODIS-derived cropland areas statistics of the Krishna Basin. This data contains district-wise area covered in the Krishna Basin to study the comparison with the MODIS derived data. The majority of the district level statistics from DES matched with the MODIS derived statistics varies between −35% and +35% (Figure 5.5) and R^2 value was 0.8686. Figure 6.6 shows the decrease in rainfall percentage from 17 years to 2015 rainfall for monsoon and post-monsoon seasons (from June to November). The basin level inflows/outflows are also a good indicator of water availability during crop production.

Figure 6.7 clearly indicates that during 2015-2016 due to low rainfall, the inflows into and outflows from the sub-basins were at a very low level.

Table 6.4 Accuracy assessments done using error matrix for LULC classes of 2013-2014

LULC		**Reference Data**						**Reference Totals**	**Classified Totals**	**Number Correct**	**Producers Accuracy**	**Users Accuracy**	**Kappa**
		01.	**02.**	**03.**	**04.**	**05.**	**06.**						
MODIS-derived classification	01. Rainfed croplands	10	3	0	0	0	1	15	14	10	67%	71%	68%
	02.Irrigated-Tanks/GW-DC-croplands	1	23	3	1	1	0	31	29	23	74%	79%	74%
	03. Irrigated-conjunctive-croplands	1	2	28	1	0	0	35	32	28	80%	88%	84%
	04. Irrigated-SW-DC-croplands	0	0	1	19	0	0	23	20	19	83%	95%	94%
	05. Rangelands mixed with fallows	2	1	2	1	10	0	12	16	10	83%	63%	59%
	06. Other LULC	1	2	1	1	1	35	36	41	35	97%	85%	81%
	Total	15	31	35	23	12	36	152	152	125			
	Overall Classification Accuracy = 82.24%								Overall Kappa Statistics = 0.7811				

Table 6.5 Accuracy assessments done using error matrix for LULC classes of 2015-2016

LULC		**Reference Data**						**Reference Totals**	**Classified Totals**	**Number Correct**	**Producers Accuracy**	**Users Accuracy**	**Kappa**
		01.	**02.**	**03.**	**04.**	**05.**	**06.**						
MODIS-derived classification	01. Rainfed croplands	19	0	0	0	1	0	28	20	19	68%	95%	94%
	02.Irrigated-Tanks/GW-DC-croplands	2	22	0	0	1	0	26	25	22	85%	88%	86%
	03.Irrigated-conjunctive-croplands	0	0	29	0	1	1	30	31	29	97%	94%	92%
	04. Irrigated-SW-DC-croplands	0	0	0	25	0	0	31	25	25	81%	100%	100%
	05.Rangelands mixed with fallows	4	1	1	6	20	0	23	32	20	87%	63%	56%
	06. Other LULC	3	3	0	0	0	23	24	29	23	96%	79%	76%
	Total	28	26	30	31	23	24	162	162	138			
	Overall Classification Accuracy = 85.19%								Overall Kappa Statistics = 0.8224				

Table 6.6 Accuracy assessments done using error matrix for water stress classes of 2015-2016

LULC		**Reference Data**					**Reference Totals**	**Classified Totals**	**Number Correct**	**Producers Accuracy**	**Users Accuracy**	**Kappa**
		01.	**02.**	**03.**	**04.**	**05.**						
MODIS-derived classification	01. Mild water stress	31	3	3	20	0	39	57	31	79%	54%	44%
	02. Moderate water stress	7	18	5	2	0	21	32	18	86%	56%	51%
	03. Severe water stress	0	0	46	0	0	54	46	46	85%	100%	100%
	04. No water stress	1	0	0	57	1	83	59	57	69%	95%	92%
	05. Other LULC	0	0	0	4	10	11	14	10	91%	71%	70%
	Total	39	21	54	83	11	208	209	162			
	Overall Classification Accuracy =77.51%							Overall Kappa Statistics = 0.7038				

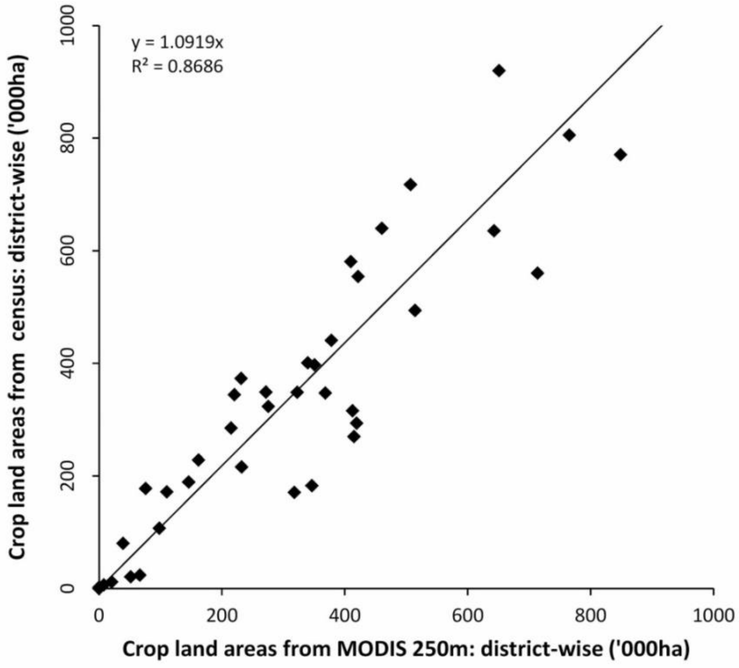


Figure 6.5 A comparison of district-wise cropland area from the MODIS classification and national statistics

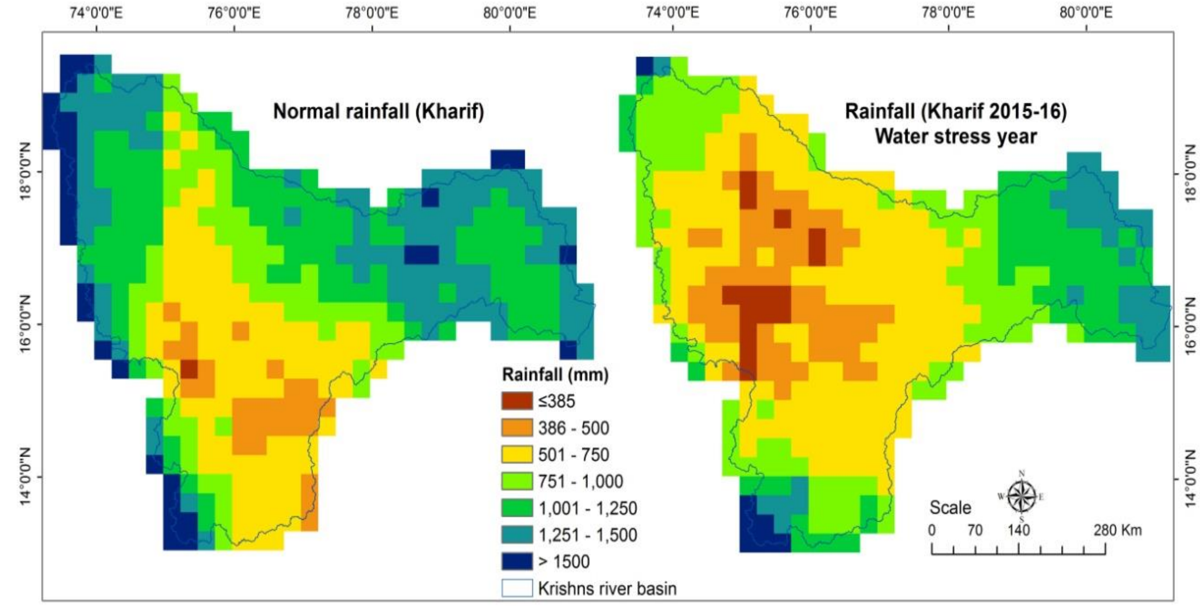


Figure 6.6 Decrease in rainfall percentage from 2013 to 2015 using the Tropical Rainfall Measuring Mission (TRMM) 0.25 degree rainfall grid

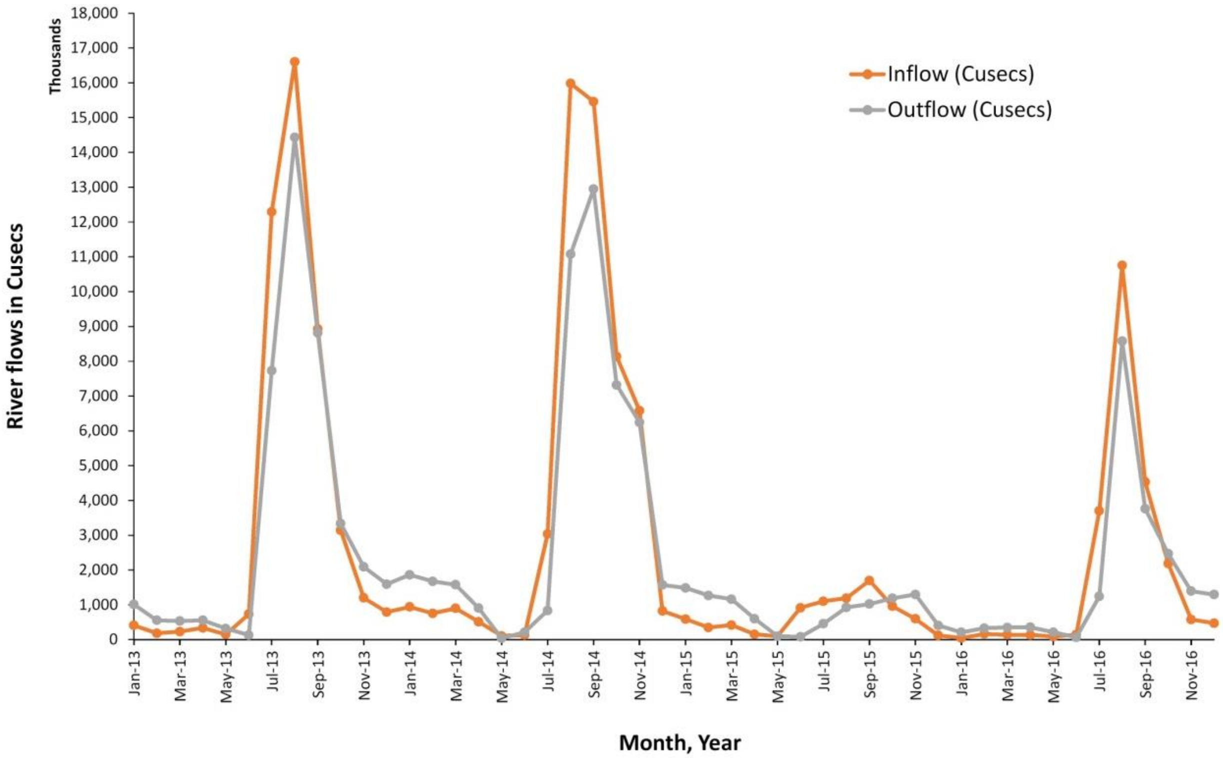


Figure 6.7 Inflow and outflow the Krishna Basin between 2013 and 2016

CHAPTER - 7

SUMMARY AND CONCLUSIONS

7.1 Summary

This study identified the changes in irrigated areas including other cropland areas and also drought assessment in a Krishna river basin due to water scarcity. A baseline irrigated area map of the study area was produced for 2013-2014 with an estimation of cropland area. Using thefield-plot information and sub-national statistics obtained from the Ministry of Agriculture, accuracy assessment was done by correlating the MODIS-derived land use/land cover areas. MODIS imagery plays a vital role in this type of study, where time series (composites of every 16 days) imagery not only helps in identifying a land use type but also monitors the dynamics of such land use mainly in identification of crop and its growing period. It has an advantage of minimizing the cloud by creating maximum value composite. The spectral matching technique used in identifying a specific land use where the spectral profile follows the phenology.

This study applied spectral matching techniques for mapping irrigated areas using AVHRR time-series imagery along with intensive field-plot information. The purpose of this study is to map changes in cropping patterns in a region with two crop seasons per year. It is a significant new information of mapping spatial and temporal complexity in land use changes due to water stress. The methodology starts with unsupervised classification of NDVI MVCs and follows. In the class identification and labelling process, the 16-day dataset as well as monthly MVCs are used. The main advantage of this approach during classification is to obtain the monthly cloud-free or near-cloud-free images with maximum value composites. MODIS 16-day temporal resolution data helps in identification of cropping systems across different cropping pattern and changes (irrigated, rainfed, etc.). Spectral matching techniques were successful in distinguishing cropping patterns such as mild-water stress, moderate water-stress, severe water-stress areas by comparing the spectral signatures.

Chapter 1 deals with the introduction related to the study like Role of Remote sensing in monitoring Agriculture and the described the advantages of using remote sensing in monitoring, crop condition assessment, Drought definitions in view of different authors, Types of Drought and Impact of Drought on society. The Drought Scenario and its effects throughout globe and India. This section also studied about Importance of drought monitoring and previous studies.

Chapter 2 illustrates the objectives of the study and also described the entire study area in terms of its geographical features, climate and population. It's also mentioned the Krishna river canals, distributaries, and hydro power plants on the dams of Krishna river. The brief structure of the Krishna river basin is also illustrated here. The water disputes, water management, water sharing between the different states and their percentage of shares discussed in this section.

Chapter 3 deals with the literature supporting the current study. This sections includes the literature of drought, drought assessment using the remote sensing, GIS and multi variants. This also deals with the different drought indices used by different authors to monitor or to calculate drought and its related study.

Chapter 4 contains the datasets used for the study and its pre-processing techniques to get accurate data like minimizing cloud removal algorithms etc. This also included the materials like SRTM data for finding slope, ground survey data for classification as well as accuracy assessment and national statistics.

Chapter 5 deals with the drought prone areas analysis of the study which explains the assessment of irrigated areas, water stress prone areas. The study follows this procedures like mapping, classification, identification of the classes through datasets. Comparison of different datasets and procedure of finding the drought areas was explained in this section. Later on accuracy assessment was done on the classified image.

Chapter 6 shows the results of the chapter 5 and explains the results with their corresponding values. It's also shows the classified images of the study areas in their study areas, accuracy assessment values. The drought areas map also showed here with their respective values.

7.2 Conclusions

The study showed the significant changes in agricultural land use as a result of water stress during 2015-2016 compared to 2013-14. Rainfed and irrigated areas for study years 2013-14, 2015-16 were mapped with classification accuracy between 77-85% using MODIS 250 m time series images and spectral matching techniques (SMTs). The MODIS-based irrigated cropland statistics for the districts obtained for study years were highly correlated (R^2value of 0.86) with the figures reported by the Directorate of Economics and Statistics. Though the current study focused on a large river basin like Krishna river, these methods and approaches are also appropriate for large areas, such as countries and continents.

The spatial distribution and identification of LULC was performed using the 16-day time series NDVI stack and the spectral signatures (temporal signatures) generated from for sampled locations and class signatures obtained using spectral matching techniques. Image is classified into nine LULC classes for the normal year (2013-2014) and water-deficit year (2015-2016). The identification of Classes were based on spectral matching techniques along with ground survey data and field observations.

A quantitative accuracy assessment is to examine whether a known LULC was identified as the same LULC or not using error matrix. The ground survey data was collected during the kharif season for the crop years 2013-2014 and 2014-2015 throughout the Krishna Basin. Classification accuracy was performed on three classified products (LULC maps of 2013-2014 and 2015-2016) using 363 points that were not used in the classification.

During the water stress year (2015-2016) land uses decreased from 14.7 Mha in a normal year (2013-2014) to 11.5 Mha. These arises mainly due to water scarcity in reducing cropping intensity and conversion of crop lands to fallow. Rainfed croplands in the Krishna Basin were reduced to half of the normal year to 2.8 Mha during water stress year, and also significant reduction in the irrigated croplands. Overall, 7.6 Mha of croplands were affected by water scarcity (rainfed and irrigated croplands), and 7.1 Mha were not affected.

An unexpected decline in food production affected market leads to high costs and also food insecurity. These results are due to change in climate scenario and growing water efficient crops during a water deficit year. Water scarcity is a frequent reality faced by farmers in the semi-arid tropics, even in the basin command areas which leads to a chain of events affecting crop production, cropping pattern changes and eventually reduced in incomes to farmers. To sustain food security, large river basins like the Krishna should adopt new adaptation strategies such as the use of climate smart varieties and water related management practices along with advanced mechanisms to remunerate the crops during such times.

The basin-level water inflow and outflow estimates are highly useful in understanding the water balance in the basin. It also presents a realistic picture of the effects of water scarcity during a low rainfall year on crop production and food security of the population in the basin. The result of this research recognizes the value of using MODIS time series 250 m data and advanced methods such as spectral matching techniques to study changes in the agricultural cropland in large river basins. It also contributes considerable amount to the knowledge base of earth observation groups involved in monitoring irrigated areas.

Overall, the thesis provides a comprehensive strategy on the methods and approaches of mapping irrigated areas and also drought assessment using MODIS 250m resolution data.

REFERENCES

A.Anyamba and C.J.Tucker (2005). "Analysis of Sahelian Vegetation Dynamics using NOAA- AVHRR NDVI data from1981-2003." Journal of Arid Environments.

Abderrahman, W. A., Bader, T. A., 1992. Remote sensing application to the management of agricultural drainage water in severely arid region: A case study. Remote Sensing of Environment 42 (3): 239-246.

Achard, F. and Estreguil, C., 1995, Forest classification of Southeast Asia using NOAA AVHRR data. Remote Sensing of Environment 54: 198-208.

Agarwal, S., Joshi, P.K, Shukla, Y., and Roy, P.S. (2003). SPOT vegetation multi temporal data for classifying vegetation in south central Asia. Current Science84 (11): 1440-1448 (10 June 2003).

Alexandridis, T., Asi S. and Ali, S. 1999. Water performance indicators using satellite imagery for the Fordwah Eastern Sadiqia (South) irrigation and drainage project. Report no. R-87, International Water Management Institute, Lahore, Pakistan: 16p.

Apparao, V. (1957).Bhadrachala Ramadas. unpublished paper.

Ayele, G.T., Demessie, S.S., Mengistu, K.T., Tilahun, S.A., Melesse, A.M., 2016. Multitemporal land use/land cover change detection for the Batena Watershed, Rift Valley Lakes Basin, Ethiopia. Landscape Dynamics, Soils and Hydrological Processes in Varied Climates. Springer, pp. 51-72.

Ayoade, J. O. (1983). The impact of urban physical development on the environment: a case study of Ibadan. Nigerian Institute of Social and Economic Research.

Bartholome, E., & Belward, A.S. (2005). GLC2000: A new approach to global land cover mapping from Earth observation data. International Journal of Remote Sensing 26(9): 1959-1977.

Bastiaanssen, W. G. M., Molden, D. J. Thiruvengadachari, S. Smit, A. A. M. F. R. Mutuwatte, L., and Jayasinghe. G. 1999. Remote sensing and hydrologic models for performance assessment in Sirsa Irrigation Circle, India. Research Report 27.Colombo, Sri Lanka: International Water Management Institute.

Batchelor, C. H.; M. S. Rama Mohan Rao and S. Manohar Rao. 2003. Watershed development: A solution to water shortages in semi-arid India or part of the problem? Land Use and Water Resources Research 3: 1-10.

Batra, R., &Sinha, I. (2000).Consumer-level factors moderating the success of private label brands. Journal of retailing, 76(2), 175-191.

Bector, C. R., & Chandra, S. (2005). Fuzzy mathematical programming and fuzzy matrix games (Vol. 169). Berlin: Springer.

Belward, A.S., and Bartholome, E. (2003), GLC2000: a new approach to global land cover mapping from earth observation data. International Journal of remote sensing 26 (9): 1959-1977 (10 May 2005).

Biggs, T., Thenkabail, P.S., Gumma, M.K, Gangadhara Rao, P., and Turral, H., 2006. Vegetation Phenology and Irrigated Area Mapping Using Combined MODIS Time-series, Ground Surveys, and Agricultural Census Data in Krishna River Basin, India. International Journal of Remote Sensing 27(19):4245-4266.

Bing, Z., L. Jiangu, W. Xiangjun, and W. Changshan, 1998. Study on the classification of hyperspectral data in urban area. SPIE 3502.0277-786x/98.

Blaney, H. F., & Criddle, W. D. (1950). Determining water needs from climatological data. USDA Soil Conservation Service. SOS–TP, USA, 8-9.

Boken, V. K., Hoogenboom, G., Kogan, F.N., Hook, J.E., Thomas, D.L., and Harrison, K.A. (2004).Potential of using NOAA-AVHRR data for estimating irrigared area to help solve an inter-state water dispute. International Journal of Remote Sensing 25 (12) 2277-2286 (2004).

Bora Jr, F. W., Pleasure, D. E., & Didizian, N. A. (1976).A study of nerve regeneration and neuroma formation after nerve suture by various techniques. The Journal of hand surgery, 1(2), 138-143.

Bourke, P. A. (1968). The use of the potato crop in pre-famine Ireland. Journal of the Statistical and Social Inquiry Society of Ireland, 12(6), 72-96.

Budyko, M. I. (1958). The heat balance of the earth's surface, US Dept. of Commerce. Weather Bureau, Washington, DC, USA.

C. Warren Thornthwaite, F. Kenneth Hare, The Loss of Water to the Air, Agricultural Meteorology pp 163-180.

C. Warren Thornthwaite, The Climates of North America: According to a New Classification, Geographical Review, Vol. 21, No. 4 (Oct., 1931), pp. 633-655

Carter, D. B., & Mather, J. R. (1966). Climatic classification for environmental biology.CW Thornthwaite Associates, Laboratory of Climatology.

CBIP (Central Board of Irrigation and Power). (1994). Central Board of Irrigation and Power irrigated area map of India for 1994.New Delhi, India: CBIP.

Chapin, F.S.III, A. D. Mcguire, J. Randerson, R. Pielke Sr., D. Baldocchi, S. E. Hobbie, N. Roulet, W. Eugster, E. Kasischke, E. B. Rastetter, S. A. Zimov, S. W. Running (2000) Arctic and boreal ecosystems of western North America as components of the climate system. Global Change Biology 6 (s1): 211-223.

Cihlar, J., 2000, Land cover mapping of large areas from satellites: status and research priorities. International Journal of Remote Sensing 21: 1093-1114.

Cihlar, J., Xiao, Q., Beaubien, J., Fung, K. and Latifovic, R., 1998, Classification by progressive generalization: a new automated methodology for remote sensing multichannel data. International Journal of Remote Sensing 19: 2685-2704.

Congalton, R. G., and Green, K., 1999.Assessing the accuracy of remotely sensed data: principles and practices. New York: Lewis.

Crist, E.P. and Cicone, R.C., 1984. A physically-based transformation of the Thematic Mapper data - the Tessled Cap. IEEE Transactions on Geoscience and Remote Sensing GE-23:256-263

Das, B., Saha, N., &Hazra, D. K. (2000). Ionic association and conductances of some symmetrical tetraalkylammonium salts in methanol, acetonitrile, and methanol (1)+ acetonitrile (2) mixtures at 298.15 K. Journal of Chemical & Engineering Data, 45(2), 353-357.

DeFries, R., Hansen, M., Townsend, J. G. R., and Sohlberg, R. (1998). Global land cover classifications at 8 km resolution: the use of training data derived from Landsat imagery in decision tree classifiers. International Journal of Remote Sensing 19: 3141-3168.

DeFries, R., Hansen, M., Townshend, J.R.G., Janetos, A.C., and Loveland, T.R. (2000). A new global 1 km data set of percent tree cover derived from remote sensing. Global Change Biology 6: 247-255.

Deosthali, V., &Akmanchi, A. N. (2006). Yield estimation of summer crops grown in a mixed cropping area, a spectral growth curve profile approach. Journal of the Indian Society of Remote Sensing, 34(3), 279-288.

DIP, 2015. Agriculture Statistics, Datanet India Pvt. Ltd. http://www.odishastat.com/agriculture/. (accessed on 15 Jan2015).

Douglas, I. 1983. Observation and simulation of dew in rural and urban environments. Physical Geography 9:146-149.

Draeger, W.C. (1977). Monitoring irrigated land acreage using LANDSAT imagery: An application example. ERIM Proc. of the 11th Intern. Symposium on Remote Sensing of Environment, Vol. 1 p. 515-524 (SEE N78-14464 05-43); United States; 1977.

E. J. Gumbel, The Return Period of Flood Flows, The Annals of Mathematical Statistics, Vol. 12, No. 2 (Jun., 1941), pp. 163-190.

Eidenshink, J.C., Faundeen, J.L. (1994). The 1 km AVHRR global land data set: first stages implementation. International Journal of Remote Sensing 15: 3443-3462.

Ellaiah, P., Adinarayana, K., Bhavani, Y., Padmaja, P., &Srinivasulu, B. (2002). Optimization of process parameters for glucoamylase production under solid state fermentation by a newly isolated Aspergillus species. Process Biochemistry, 38(4), 615-620.

ETM+ i. FAO (Food and Agriculture Organization). 2002. FAOSTAT agriculture data.

FAO/UNEP, 1999, Terminology for integrated resources planning and management. Rome, Italy and Nairobi, Kenya: Food and Agriculture Organization/United Nations Environmental Programme.

Farrand W.H. and Harsanyi J.C., 1997. Mapping the distribution of mine tailings in the Coeur d’AleneRiverValley, Idaho, through the use of a constrained energy minimization technique. Remote Sensing of Environment 59: 64-76.

Fleig, A. J., D. F. Heath, K. F. Klenk, N. Oslik, K. D. Lee, H. Park, P. K. Bartia, and D. Gordon., 1983. User's Guide for the Solar Backscattered Ultraviolet (SBUV) and the Total Ozone Mapping Spectrometer (TOMS) RUT-S and RUT-T Data Sets: October 31, 1978 to November 1980. NASA Reference Publication 1112.

Foody, M., Boyd, D. S., and Curran, P. J., 1996. Relations between tropical forest biophysical properties and data acquired in AVHRR channels 1± 5. International Journal of Remote Sensing17: 1341± 1355.

Foody, G. (2002). Status of land cover classification accuracy assessment. Remote Sensing of Environment 80: 185-201.

Friedl, M.A., Woodcock, C., Gopal, S., Muchoney, D., Strahler, A.H. and Barker-Schaaf, C., 2000, A note on procedures used for accuracy assessment in land cover maps derived from AVHRR data. International Journal of Remote Sensing 21, doi 10.1080/014311600210434.

Frolking, S., Qiu, J.B., S., Xiao, X., Liu, J., Zhuang, Y., Li, C. and Qin, X., 2002. Combining remote sensing and ground census data to develop new maps of the distribution of rice agriculture in China. Global Biogeochemical Cycles 16 (38-31), doi 10.1029/2001GB001425.

Gopal, S. and Woodcock, C., 1994.Theory and methods for accuracy assessment of thematic maps using fuzzy sets. Photogrammetric Engineering and Remote Sensing 60: 181-188.

Gordon. D. (1984). User's Guide for the Solar Backscattered Ultraviolet (SBUV) and the Total Ozone Mapping Spectrometer (TOMS) RUT-S and RUT-T Data Sets: October 31, 1978 to November 1980. NASA Reference Publication 1112.

Government of India, 2001.Report on Census of Minor Irrigation Schemes - 1993-94. (Delhi: Ministry of Water Resources, Minor Irrigation Division).

Goward, D. G., Turner, S., Dye, D. G., and Liang, J. (1994), University of Maryland improved Global Vegetation Index. Int. J. Remote Sensing 15(17):3365-3395.

Granahan J.C. and Sweet J.N, 2001. An Evaluation of Atmospheric Correction Techniques Using The Spectral Similarity Scale. IEEE 2001. International Geosciences and Remote Sensing Symposium 5: 2022-2024 (2001).

Gumma M.K., Thenkabail P.S., Nelson A. Mapping Irrigated Areas Using MODIS 250 Meter Time-Series Data: A Study on Krishna River Basin (India). Water. 2011; 3(1):113-131.

Gumma, M.K, Thenkabail, P.S., N.C.Gautam, Gangadhara Rao, P. and Velpuri, M. 2008a.Irrigated area mapping using AVHRR, MODIS, and LANDSAT ETM+ data for the Krishna River basin, India. International Journal of Technology of Spectrum 12 (1):1-11 (March 2008).

Gumma, M.K., Thenkabail, P.S., Hideto, F., Nelson, A., Dheeravath, V., Busia, D., Rala, A., 2011a. Mapping Irrigated Areas of Ghana Using Fusion of 30 m and 250 m Resolution Remote-Sensing Data. Remote Sensing 3, 816-835.

Gumma, M.K., Thenkabail, P.S., Maunahan, A., Islam, S., Nelson, A., 2014. Mapping seasonal rice cropland extent and area in the high cropping intensity environment of Bangladesh using MODIS 500m data for the year 2010. ISPRS Journal of Photogrammetry and Remote Sensing 91, 98-113.

Gumma, M.K., Thenkabail, P.S., Muralikrishna, I.V., Velpuri, M.N., Gangadhararao, P.T., Dheeravath, V., Biradar, C.M., Acharya Nalan, S., Gaur, A., 2011b. Changes in agricultural cropland areas between a water-surplus year and a water-deficit year impacting food security, determined using MODIS 250 m time-series data and spectral matching techniques, in the Krishna River basin (India). International Journal of Remote Sensing 32, 3495-3520.

Gumma, M.K., Thenkabail, P.S., Nelson, A., 2011c. Mapping Irrigated Areas Using MODIS 250 Meter Time-Series Data: A Study on Krishna River Basin (India). Water 3, 113-131.

Gumma, M.K., Thenkabail, P.S., Teluguntla, P., Rao, M.N., Mohammed, I.A., Whitbread, A.M., 2016. Mapping rice-fallow cropland areas for short-season grain legumes intensification in South Asia using MODIS 250 m time-series data. International Journal of Digital Earth 9, 981-1003.

Gumma, M.K., Gauchan, D, Andrew, N., Pandey, S. and Rala, A. (2011c). Temporal changes in rice-growing area and their impact on livelihood over a decade: a case study of Nepal. Agriculture, Ecosystems & Environment.142 (3-4), 382-392.

Gumma, M.K, Mohanty, S, Andrew, N, Rala, A, Irshad, A.M, Das, S.R. (2015) Remote sensing based change analysis of rice environments in Odisha, India. Journal of Environmental Management. 148(2015):31-41.

Gumma, M.K., Tsusaka, T.W., Mohammed, I., Chavula, G., Ganga Rao, N.V.P.R., Okori, P., Ojiewo, C.O., Varshney, R., Siambi, M., & Whitbread, A. (2019). Monitoring Changes in the Cultivation of Pigeonpea and Groundnut in Malawi Using Time Series Satellite Imagery for Sustainable Food Systems. Remote Sensing, 11, 1475

Gumma, M.K., Thenkabail, P., Teluguntla, P., Oliphant, A., Xiong, J., Giri, C., Pyla, V., Dixit, S., Whitbread, M. A., (2020) Agriculture cropland extent and area of South Asia derived using Landsat satellite 30-m time-series big-data using Random Forest Machine Learning Algorithms on the Google Earth Engine Cloud. GIScience & Remote Sensing. 57 (3), 302-322. DOI:10.1080/15481603.2019.1690780.

Hayes, M. J., M. D. Svoboda, et al. (1999). "Monitoring the 1996 drought using the Standardized Precipitation Index." BAMS Vol.80: pp.429-438.

HemaMalini, B. (1996). Impact of human induced environmental change in the incidence of malaria in Visakhapatnam city. Disasters, Environment and development', RB Singh (Ed.), published by Oxford and IBH Co., Pvt. Ltd, 395-406.

Herrmann, S. M., A. Anyamba, et al., "Exploring Relationships between Rainfall and Vegetation Dynamics in the Sahel Using Coarse Resolution Satellite Data."

Holben, B.N. and Shimabukuro, Y.E., 1993. Linear mixing model applied to coarse spatial resolution data from multispectral satellite sensors. International Journal of Remote Sensing 14: 2231-2240.

Holben, B.N., 1986. Characteristics of maximum-value composite images from temporal AVHRR data. International Journal of Remote Sensing 7: 1417-1434.

Homayouni, S., & Roux, M. (2003).Material Mapping from Hyperspectral Images using Spectral Matching in Urban Area. Submitted to IEEE Workshop in honor of Prof. Landgrebe, Washington, D.C., USA Oct. 2004

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

Huete. A., Justice.C., and Liu.H. 1994. Development of Vegetation and Soil Indices for MODIS-EOS. Remote Sensing Environment 49: 224-234.

J. Qu, "Towards a Compendium on National Drought Policy", Proceedings of an Expert Meeting on the Preparation of a Compendium on National Drought Policy, 2011.

Jeyaseelan, S., Chu, H. W., Young, S. K., &Worthen, G. S. (2004). Transcriptional profiling of lipopolysaccharide-induced acute lung injury. Infection and immunity, 72(12), 7247-7256.

Job, J. C., Garnier, P. E., Chaussain, J. L., & Milhaud, G. (1972). Elevation of serum gonadotropins (LH and FSH) after releasing hormone (LH-RH) injection in normal children and in patients with disorders of puberty. The Journal of Clinical Endocrinology & Metabolism, 35(3), 473-476.

Johnson, M. J. (1941). Isolation and properties of a pure yeast polypeptidase. Journal of Biological Chemistry, 137(2), 575-586.

K.Prathumchai, K. Honda, et al. (2001). Drought Risk Evaluation using Remote Sensing and GIS: A case study in Lop Buri Province. 22nd Asian Conference on Remote Sensing.

Kates, M., &Sastry, P. S. (1969). [36] Phospholipase D: EC 3.1. 4.4 Phosphatidyleholinephosphatidohydrolase. In Methods in Enzymology (Vol. 14, pp. 197-203).Academic Press.

Keene, K.M., and Conley, C.D. (1980). Measurement of irrigated acreage in Western Kansas from LANDSAT images. Environmental Geology, Earth and Environmental Science 3 (2): 107-116 (March 1980).

Kerber, A.G., and J.B.Schytt. 1986. Utility of AVHRR channels 3 and 4 in land-cover mapping. Photogrammetric Engineering and Remotesensing 52:1877-1883.

Kidwell, K. 1991. NOAA Polar Orbiter Data User's Guide. NCDC/SDSD. Washington, D.C.: National Climatic Data Center.

King, M.D., Closs, J., Spangler, S. and Greenstone, R. (King et al.) 2003, EOS Data Products Handbook Version 1, (Greenbelt, Maryland: NASA Goddard Space Flight Center).

Kogan, F.N., & Zhu, X. (2001). Evolution of long-term errors in NDVI time-series: 1985-1999. Advances in Space Research 28 (1): 149-154.

Komuscu, A. U. (1999). "Using the SPI to analyze spatial and temporal pattern of drought in Turkey." Drought Network News Vol.11: pp.7-13.

Latifovic, R. and Olthof, I., 2004. Accuracy assessment using sub-pixel fractional error matrices of global land cover products derived from satellite data. Remote Sensing of Environment 90: 153-165,doi:110.1016/j.rse.2003.1011.1016.

Lieca. 2007. Earth Resources Data Analysis System (ERDAS Imagine8.x) Lieca Geosystems A.G. Heinrich-Wild-Strasse, CH-9435 Heerbrugg, Switzerland.

Loveland, T. R., Zhu, Z., Ohlen, D. O., Brown, J. F., Redd, B. C., and Yang, L. (1999). An analysis of the IGBP global land-cover characterization process. Photogrammetric Engineering and Remote Sensing 65 (9): 1021-1031.

Loveland, T.R., Reed, B.C., Brown, J.F., Ohlen, D.O., Zhu, J, Yang, L., and Merchant, J.W. (2000). Development of a Global Land Cover Characteristics Database and IGBP DISCover from 1-km AVHRR Data. International Journal of Remote Sensing 21 (6/7): 1303-1330.

Mathur, G., & Ram, H. M. (1978).Significance of Petal Colour in Thrips-pollinated Lentanacamara L. Annals of Botany, 42(182), 1473-1476.

Mathur, P. B., &Subramanyam, H. (1956).Effect of a fungicidal wax coating on the storage behaviour of mangoes. Journal of the Science of Food and Agriculture, 7(10), 673-676.

Mishra, A. K., & Singh, V. P. (2010). A review of drought concepts. Journal of Hydrology, 391, 202-216.10.1016/j.jhydrol.2010.07.012

Mollinga, P. P.; R. Doraiswamy and K. Engbersen. 2001. Participatory irrigation management in Andhra Pradesh, India. International Journal of Water 1: 71-90.

Mongkolsawat, P.Thirangoon, et al. (2000). An Evaluation of Drought Risk Area in Northeast Thailand using Remotely Sensed Data and GIS. GIS Development. 2005.

Murthy, C.S., Raju, P.V., Jonna, S., Hakeem, K. A., and Thiruvengadachari, S. (1998). Satellite derived crop calendar for canal operation schedule in Bhadraproject command area, India. International Journal of Remote sensing 19 (15): 2865-2876 (1998).

National Geophysical Data Center.(1994). 5 Minute Gridded World Elevation. NGDC Data Announcement DA 93-MGG-01.Boulder.

Navalgund, R. R., &Sahai, B. (1985, February).Remote sensing applications in agriculture-Indian experience and plans.In Proceedings of 4th Asian Agricultural Symposium. Feb (pp. 329-343).

Nemani. R, Running, S.W. 1998.Estimation of Regional Surface Resistance to Evapotranspiration from NDVI and Thermal-IR AVHRR Data. Journal of Applied Meteorology 276-284.

Penman, H. L. (1956).Estimating evaporation. Eos, Transactions American Geophysical Union, 37(1), 43-50.

Penner, J. E., Atherton, C. A. & Graedel, T. 1992.inProc. 1st Int. Global Atmospheric Biospheric Chemistry (ed. Prinn, R. G.) (OHOLO Conf. Ser., Plenum, New York, 1992).

Peuquet, D.J., & Marble, D.F. (1990). Introductory readings in geographic information systems. New York: Taylor and Francis. 381p.

Quarmby, N.A., Townshend, J.R.G., Settle, J.J., White, K.H., Milnes, M., Hindle, T.L. and Silleos, N., 1992, Linear mixture modelling applied to AVHRR data for crop area estimation. International Journal of Remote Sensing 13: 415-425.

Ramankutty, N. and Foley, J.A., 1998, Characterizing patterns of global land use: an analysis of global croplands data. Global Biogeochemical Cycles 12: 667-685.

Rao, C. R. N. (1993a). Nonlinearity corrections for the thermal infrared channels of the Advanced Very High Resolution Radiometer: Assessment and recommendations. NOAA Technical Report NESDIS-69. NOAA/NESDIS. Washington, D.C.

Rao, C. R. N. (1993b). Degradation of the visible and near-infrared channels of the Advanced Very High Resolution Radiometer on the NOAAP9 spacecraft: Assessment and recommendations for corrections. NOAA Technical Report NESDIS-70. NOAA/NESDIS. Washington, D.C.

Ray K. Linsley, Social and Political Aspects of Drought The Robert E. Horton Lecture, presented at the 62nd Annual Meeting of the AMS, San Antonio, Tex., 14 January 1982

Riebsame, W. E., Changnon, S. A., & Karl, T. R. (1991). Drought and natural resource management in the United States: Impacts and implications of the 1987-1989 drought (p. 174). Boulder, CO: Westview Press.

Rijtema, P. E. (1965). An analysis of actual evapotranspiration(Doctoral dissertation, Pudoc).

Roberts, D.A., Numata, I., Holmes, K., Batista, G., Krug, T., Monteiro, A., Powell, B. and Chadwick, O.A., 2002, Large area mapping of land-cover change in Rondônia using multi-temporal spectral mixture analysis and decision tree classifiers. Journal of Geophysical Research 107: 8073, JD000374.

Rundquist, D.C., Richardo, H., Carlson, M.P., and Cook, A. (1989).The Nebraska center-pivot inventory - An example of operational satellite remote sensing on a long term basis. Photogrammetric Engineering and Remote Sensing. 55: 587-590.

Rundquist, D.C.; Richardo, H.; Carlson, M.P.; Cook, A. The nebraska center-pivot inventory—An example of operational satellite remote sensing on a long term basis. Photogramm. Eng. Remote Sens. 1989, 55, 587–590.

Sabitha, G., Reddy, G. K. K., Reddy, K. B., Reddy, N. M., &Yadav, J. S. (2004). A new, efficient and environmentally benign protocol for the synthesis of 1, 5-benzodiazepines using cerium (III) chloride/sodium iodide supported on silica gel. Advanced Synthesis & Catalysis, 346(8), 921-923.

Sabziparvar, A. and Tabari, H. “Regional Estimation of Reference Evapotranspiration in Arid and Semiarid Regions.” ASCE Journal of Irrigation and Drainage Engineering, Volume 136, pp.724-731,2010.

Sakthivadivel, R., S. Thiruvengadachari, Upali Amerasinghe, W. G. M. Bastiaanssen, and David Molden.(1999). Performance evaluation of the Bhakra irrigation system, India, using remote sensing and GIS techniques. Research Report 28.Colombo, Sri Lanka: International Water Management Institute.

Sarma, R. H., Lee, C. H., Evans, F. E., Yathindra, N., &Sundaralingam, M. (1974). Probing the interrelation between the glycosyl torsion, sugar pucker, and the backbone conformation in C (8) substituted adenine nucleotides by proton and proton-phosphorus-31 fast Fourier transfer nuclear magnetic resonance methods and conformational energy calculations. Journal of the American Chemical Society, 96(23), 7337-7348.

Sastry, B. R. (1973). Stereoisomerism and drug action in the nervous system. Annual review of pharmacology, 13(1), 253-267.

Satakmoto, T., Nguyen, N.V., Ohno, H., Ishitsuka, N., and Yokozawa, M. (2006).Spatio-temporal distribution of rice phenology and cropping systems in the Mekong Delta with special reference to the seasonal water flow of the Mekong and Bassac rivers. Remote Sensing of Environment 100: 1-16(2006).

Seiler, R.A., Kogan, F. and Sullivan. J. “AVHRR based Vegetation and Temperature Condition Indices for Drought Detection in Argentina”, Advance Space Research, Vol. 21, No. 3, pp.481-484, 1998.

Sen, T. K., Nayak, D. C., Dubey, P. N., Chamuah, G. S., &Sehgal, J. (1997). Chemical and electrochemical characterization of some acid soils of Assam. Journal of the Indian Society of Soil Science, 45(2), 245-249.

Shewale M.P. (2001), ‘Drought Studies in the India Meteorological Department, IMD, Pune, India.

Shimabukuro, Y.E. and Smith, J.A., 1991. The least-squares mixing models to generate fraction images derived from remote sensing multispectral data. IEEE Transactions on Geoscience and Remote Sensing 29: 16-20.

Shippert, P. (2001). Spectral and hyper spectral analysis with ENVI. ASPRS ENVI user's group notes. April 22-28, Annual meeting of the American Society of Photogrammetry and Remote Sensing, St. Louis, Missouri, USA

Shiva, V. 1991.Large dams and conflicts in the Krishna Basin. In Ecology and the Politics of Survival--Conflicts over Natural Resources in India. Tokyo. United Nations University Press.

Siebert, S., Döll, P., Hoogeveen, J., 2002.Global map of irrigated areas version 2.1.Center for Environmental Systems Research, University of Kassel, Germany, and FAO, Rome, Italy. Online documentation and download of 5 min map of irrigated area version

Siebert, S., Hoogeveen, J., & Frenken, K. (2006).Irrigation in Africa, Europe, and Latin America. Update of the Digital Global Map of Irrigation Areas to Version 4.Frankfurt Hydrology Paper 05.Germany: University of Frankfurt (main) and Rome, Italy: FAO.

Singh and Kriplani "Monsoon rainfall at preferred frequencies and the triplex behaviour of the Indian Summer Monsoon". Meteorology and Atmospheric Physics, Vol. 37, No. 4, pp. 219 - 236,1987.

Singh Ramesh, P., Roy Sudipa and Kogan R. "Vegetation and temperature condition indices from NOAA AVHRR data for drought monitoring over India", International Journal of Remote Sensing, Vol. 24, No. 22, pp. 4393 - 4402,2003.

Singh, R. and Irmak, A. “Estimation of Crop Coefficients Using Satellite Remote Sensing.”, ASCE Journal of Irrigation and Drainage Engineering, Volume 135, pp.597-608,2009.

Sinha Ray K.C. and Shewale M.P.(2001), ‘Probability of Occurrence of Drought in Various Subdivisions of India’, Mausam, India Meteorologic Department, India.

Sinha Ray, K.C. “Role of Drought Early Warning Systems for Sustainable Agricultural Research in India”, India Meteorological Department, Pune, India, 2000.

Sivakumar, M.V.K., Raymond P. Motha, Donald A. Wilhite andJohn

Skole, David, W.H. Chomentowski, William A. Salas, and Antonio D. Nobre. 1994. "Physical and Human Dimensions of Deforestation in Amazonia." BioScience 44:314-322.

Slatyer, R. O., &McIlroy, I. C. (1961).Evaporation and the principle of its measurement. Practical Meteorology.

Smith G.I. “Climate Variation and Its Effects on our Land and Water”, US Geological Survey Circular, No. 776-B,1978.

Smith, K., &Lavis, M. E. (1975). Environmental influences on the temperature of a small upland stream. Oikos, 228-236.

Smith, P.M., Kalluri, S.N.V. Prince, S.D., & DeFries, R.S. (1997). The NOAA/NASA Pathfinder AVHRR 8-km land data set. Photogrammetric Engineering and Remote Sensing 63:12-31

Stephen H Schneider, 1996, Encyclopedia of Climate and Weather.

Subrahmanyam, M. G., & Thomadakis, S. B. (1980).Systematic Risk and the Theory of the Firm. The Quarterly Journal of Economics, 94(3), 437-451.

Subrahmanyam, V. P. (1982). Water balance and its applications: with special reference to India (No. 173). Andhra University Press.

Subrahmanyam, V. P., & HemaMalini, B. (1979).Delimitation of drought-prone areas techniques and methodology. In Proceedings of the all India symposium on drought prone areas of India, Rayalaseema Geographical Society, SV University, Tirupati, India (pp. 31-36).

Subrahmanyam, V. P., &Sastry, C. V. S. (1969).Climatic analogues for the dry regions of India. Tropical ecology.

Subrahmanyam, V. P., SubbaRao, B., &Subramanyam, A. R. (1965).Koppen and Thornthwaite climatic classification as applied to India. Ann. Arid Zone, 49, 46-55.

Subramaniam, M. K., &Subramanyam, S. (1961). Superposable Pictures of Chromosome Structure of Allium CEPA in Feulgen and Haematoxylin SQUASHES. Current Science, 30(5), 172-174.

Subramanyam V.P. "Climatic Water Balance of Indian Arid Zones", Proceedings of Symposium on Indian Arid Zone, Jodhpur, pp. 405-411, 1964.

Sullivan, CA and Meigh, JR, "Targeting Attention on Local Vulnerabilities using an Integrated Index Approach: the Example of the Climate Vulnerability Index', Water Science & Technology, vol. 51, no. 5, pp. 69-78,2005.

Symeonakis, E. and Drake, N. "Monitoring Desertification and Land Degradation over Sub-Saharan Africa" International Journal of Remote Sensing, Vol. 25, No. 3, pp. 573 - 592,2004.

Tannehill, I.R. "Drought: Its Causes and Effects" Princeton University Press,1947.

Tanner, C. B., & Fuchs, M. (1968). Evaporation from unsaturated surfaces: a generalized combination method. Journal of Geophysical Research, 73(4), 1299-1304.

Thenkabail P.S., Nolte, C., and Lyon, J.G. 2000. Remote sensing and GIS modelling for selection of benchmark research area in the inland valley agro ecosystems of West and Central Africa. Photogrammetric Engineering and Remote Sensing, Africa Applications Special Issue 66(6):755-768.

Thenkabail S. Prasad 1999. Characterisation of the Alternative to slash-and-burn benchmark research area representing the Congolese rainforests of Africa using near-real-time SPOT HRV data. The International Journal of Remote Sensing 20(5):839-877.

Thenkabail, P.S., Biradar, C.M., Noojipady, P., Dheeravath, V., Li, Y., Velpuri, M., Gumma, M., Gangalakunta, O.R.P., Turral, H., Cai, X., Vithanage, J., Schull, M.A., Dutta, R., 2009. Global irrigated area map (GIAM), derived from remote sensing, for the end of the last millennium. International Journal of Remote Sensing 30, 3679-3733.

Thenkabail, P.S., Biradar, C.M., Turral, H., Noojipady, P., Li, Y.J., Vithanage, J., Dheeravath, V., Velpuri, M., Schull, M., Cai, X., and Dutta, R. (2006). An Irrigated area map of the world (1999) derived from remote sensing. Research report. 105, Colombo, Sri Lanka: International Water Management Institute.

Thenkabail, P.S., Enclona, E.A., Ashton, M.S., and Van Der Meer, V. 2004b.Accuracy Assessments of Hyperspectral Waveband Performance for Vegetation Analysis Applications. Remote Sensing of Environment 91:2-3: 354-376.

Thenkabail, P.S., Enclona, E.A., Ashton, M.S., and Van Der Meer, V. 2004d. Accuracy Assessments of Hyper spectral Waveband Performance for Vegetation Analysis Applications. Remote Sensing of Environment 91:2-3:354:376.

Thenkabail, P.S., Enclona, E.A., Ashton, M.S., Legg, C., Jean De Dieu, M., 2004a.Hyperion, IKONOS, ALI, and ETM+ sensors in the study of African rainforests. Remote Sensing of Environment 90:23-43.

Thenkabail, P.S., Gangadhara Rao, P., Biggs, T., Krishna, M., and Turral, H., 2007. Spectral Matching Techniques to Determine Historical Land use/Land cover (LULC) and Irrigated Areas using Time-series AVHRR Pathfinder Datasets in the Krishna River Basin, India. Photogrammetric Engineering and Remote Sensing.

Thenkabail, P.S., Hall, J., Lin, T., Ashton, M.S., Harris, D., Enclona, E.A. 2003. Detecting floristic structure and pattern across topographic and moisture gradients in a mixed species Central African forest using IKONOS and Landsat-7

Thenkabail, P.S., Schull, M., &Turral, H. (2005).Ganges and Indus River Basin Land Use/Land Cover (LULC) and Irrigated Area Mapping using Continuous Streams of MODIS Data. Remote Sensing of Environment 95(3): 317-341.

Thenkabail, P.S., Schull, M., Turral, H., 2005. Ganges and Indus river basin land use/land cover (LULC) and irrigated area mapping using continuous streams of MODIS data. Remote Sensing of Environment 95, 317-341.

Thiruvengadachari, S. (1981). Satellite sensing of irrigation pattern in semiarid areas: An Indian study. Photogrammetric Engineering and Remote Sensing47:1493-1499.

Thiruvengadachari, S. “National Agricultural Drought Assessment and Monitoring System in India: The Satellite Contribution’, in Proc. 39th IAF Congress, Bangalore, India, pp. 35 - 49,1988.

Thiruvengadachari, S. 1981. Satellite sensing of irrigation pattern in semiarid areas: An Indian study. Photogrammetric Engineering and Remote Sensing 47:1493-1499.

Thiruvengadachari, S. and Gopalkrishna, H.R. “And Integrated PC environment for assessment of drought”, International Journal of Remote Sensing, Vol. 14, No. 17, pp. 3201 - 3208,1993.

Thiruvengadachari, S. Satellite sensing of irrigation pattern in semiarid areas: An Indian study. Photogramm. Eng. Remote Sens. 1981, 47, 1493–1499.

Thiruvengadachari, S., and R. Sakthivadivel. (1997). Satellite remote sensing for assessment of irrigation system performance: A case study in India. Research Report 9.Colombo, Sri Lanka: International Irrigation Management Institute.

Thiruvengadachari, S., Prasad T.S. and Harikishnan J. ‘Satellite Monitoring of Agricultural Drought in Anantapur District in Andhra Pradesh State’, Drought Mission Team, Department of Space, Govt. of India, 1987.

Thornthwaite, C. W. (1940). Atmospheric moisture in relation to ecological problems. Ecology, 21(1), 17-28.

Thornthwaite, C. W. (1948). An approach toward a rational classification of climate (Vol. 66, No. 1, p. 77).LWW.

Thornthwaite, C. W., & Mather, J. R. (1955).Publications in climatology. The water balance, 8, 1-104.

Todisco, F., Vergni, L., and Mannocchi, F., “Operative Approach to Agricultural Drought Risk Management”, Journal of Irrigation and Drain Engineering, Vol.135, No.5, pp.654-664,2009.

Tomlin, D. 1990. Geographic information systems and cartographic modelling (hardcover). Prentice HallCollege Div., 575p.

Tomlinson, R. 2003. Thinking about geographic information systems planning for managers. ESRI Press. 283p.

Tou, J.T and Gonzalez, R.C. 1975. Pattern recognition principles.Reading, Massachusetts: Addison-Wesley Publishing Company.

Tripathy G.K., Ghosh, T.K. and Shah, S.D. “Monitoring of Desertification Process in Karnataka State of India using Multi- temporal Remote Sensing and Ancillary Information using GIS”, International Journal of Remote Sensing, Vol. 17, No. 12, pp. 2243 - 2257,1996.

TRMM, 2016. Tropical Rainfall Measuring Mission. http://trmm.gsfc.nasa.gov/ (accessed on 10 Jan 2016).

Uphoff, N., “Demonstrated Benefits from Social Capital: The Productivity of Farmer Organizations in Gal Oya, Sri Lanka.”,1998.

Van Bavel, C. H. M. (1966). Potential evaporation: the combination concept and its experimental verification. Water Resources Research, 2(3), 455-467.

Van Ittersum, M.K., Cassman, K.G., Grassini, P., Wolf, J., Tittonell, P., Hochman, Z., 2013. Yield gap analysis with local to global relevance—a review. Field Crops Research 143, 4-17.

Vermote, E. F., El Saleous, N. Z., and Justice, C. O. (2002). Atmospheric correction of MODIS data in the visible to middle infrared: First results. Remote Sensing of Environment 83: 97-111.

Vidal, A. & Perrier, A. 1990. Irrigation monitoring by following the water balance from NOAA-AVHRR thermal infrared data, IEEE Transactions on Geoscience and Remote Sensing 28: 949-954.

Viswanadham, R. K., Sun, T. S., Drake, E. F., & Peck, J. A. (1981).Quantitative fractography of WC-Co cermets by Auger spectroscopy. Journal of Materials Science, 16(4), 1029-1038.

Vitkevich, V. V., Alekseev, Y. I., Zhuravlev, V. F., &Shitov, Y. P. (1969). Pulsar PP 0943. Nature, 224(5214), 49.

Walach, B. 1984.Irrigation developments in the Krishna Basin since 1947.Geographical Review 74:127-144.

Wan, Z., Wang, P. and Li, X. "Using MODIS Land Surface Temperature and NDVI Products for Monitoring Drought in the Southern Great Plains, USA", International Journal of Remote Sensing, Vol. 25, No. 1, pp. 61 - 72,2004.

WEN, C.G, and R. TATEISHI, 2001, second degree grid land cover classification of Asia. International Journal of Remote Sening 22 (18): 3845-3854.

Whyte, W. F., Participatory Action Research, Newbury Park, Sage Publications, 1991.

Wilhelmi, O.V and Wilhite, D.A. "Assessing Vulnerability to Agricultural Drought : A Nebraska Case Study", Natural Hazards, Volume: 25, Issue: 13029, pp 37-58,2002.

Wilhite, D. A., & Buchanan-Smith, M. (2005). Drought as hazard: Understanding the natural and social context. In D. A. Wilhite (Ed.), Drought and water crisis. Science, technology, and management issues (pp 3-29).London: CRC Press, Taylor and Francis.10.1201/CRCBKSPE [Crossref], [Google Scholar]

Wilhite, D.A. "State Level Drought Planning in the United States: Factors Influencing Plan Development.", Journal of Water International, Vol. 19, pp.75-79, 1994.

Wilhite. D.A. “Drought Planning and State Government”, Bulletin of American Meteorological Society, Vol. 72, No. 10, pp. 1531 - 1536, 1991.

William, J.W., “Managing Water for Drought”, U.S. Army Corps of Engineers, Water Resources Support Center,1994.

Wipop, P and Sirirat, S. “Application of Satellite Data and GIS for Drought Risk Area Analysis”, Proceedings of 27th Asian Conference on Remote Sensing (ACRS), Ulaanbaatar, Mongolia,2006.

Wu, J., He, B.,Lu, A., Zhou, L., Liu, M. and Zhao, L. “Quantitative Assessment and Spatial Characteristics Analysis of Agricultural Drought Vulnerability in China”, Natural Hazards, Volume: 56, Issue: 3, pp 785-801,2011.

Xiao, X., Boles, S., Frolking, S., Li, C., Babu, J, Y., Salas, W., and Moore B. (2006).Mapping paddy rice agriculture in South and Southeast Asia using multi-temporal MODIS images. Remote Sensing of Environment 100: 95-113.

Zuqiang Zhang, “Drought Plans in China”, Expert Meeting on the Preparation of a Compendium on National Drought Policy, National Climate Center, China Meteorological Administration, 2011.

Appendix:

Other secondary data sets:

Landsat 8:

A 9-class map (Figure X1) is generated, which shows clear spectral separability on spectral signatures. The total geographical area of the Krishna Basin is 258,912 km^2, with a high percentage of irrigated area identified (Figure X1). We observe from the biomass fluctuation curve that class 4 showing high NDVI for long duration represents sugarcane crop. For class 5 it is clearly seen that two peaks representing (kharif, rabi) are found to be irrigated with double cropping area. The biomass fluctuation curve for class 9 shows a clear increase in the NDVI values in the rainy season (July-September) and a decreasing trend later, which indicates a rain-fed area. Rain-fed agriculture with supplemental irrigation and late sown areas identified with class 1 also show a peak in the rainy season but shifted to September and higher NDVI than the rain-fed areas.

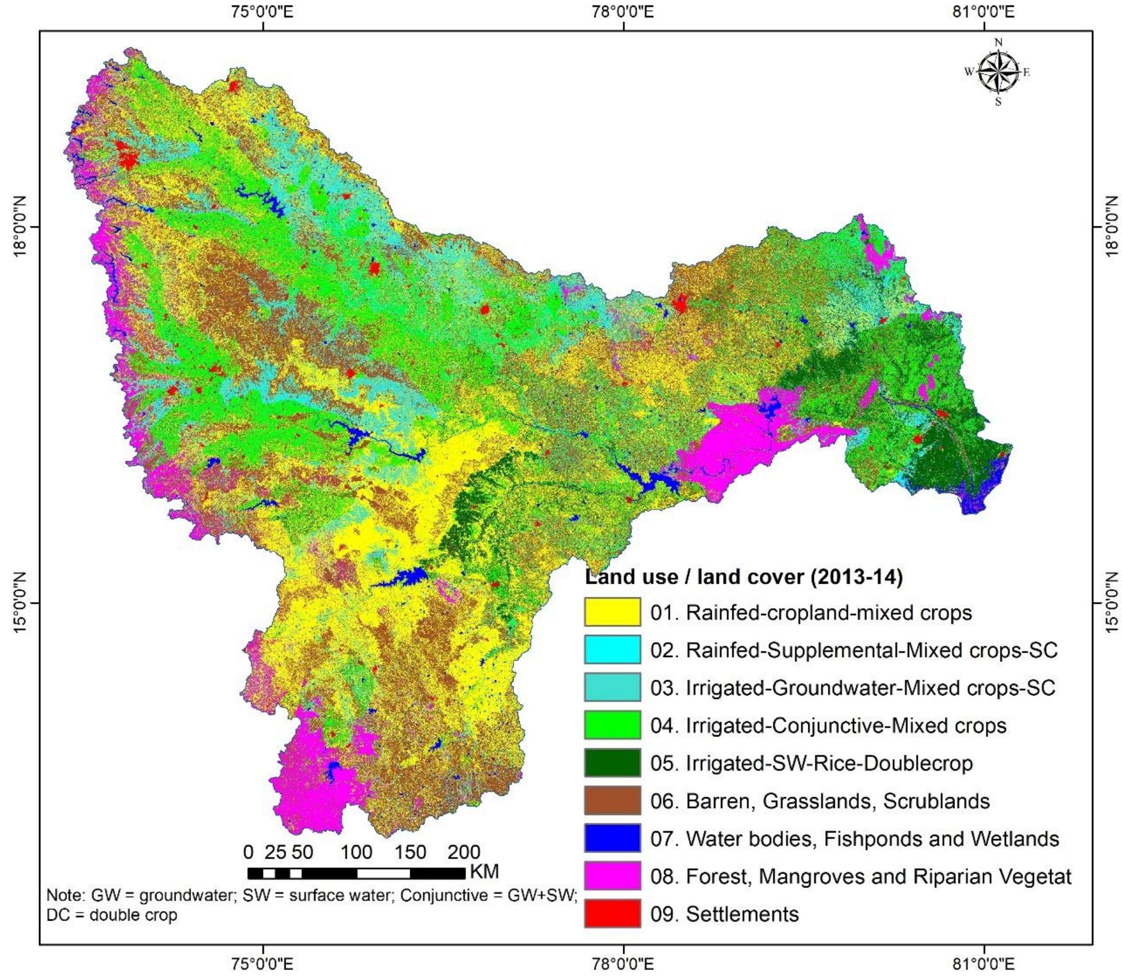


Figure X1: The 9 LULC and irrigated area classes in the Krishna River Basin. 37 classes were mapped using 12 band MODIS MVC data sets.

Other Global products:

A number of other secondary data sets were used to identify and/or verify class labels. These include LULC maps produced by other sources. For example, global LULC map is produced by the global land cover for the entire world by an international partnership of 30 research groups coordinated by the European Commission’s Joint Research Centre

(Bartholome and Belward, 2005). The LULC map for the Krishna River Basin is extracted from the South Asia subset of the GLC2000 generated by then Indian partner. This is a generic 45 class LULC map derived using SPOT VEGETATION at 500 m resolution. Classes 33 and 34 of this map correspond to irrigated areas (Agarwal et al., 2003). These classes are used to compare the irrigated classes identified by this study. A second data set is USGS seasonal LULC data set for year 1992-93 (Loveland et al., 2000).

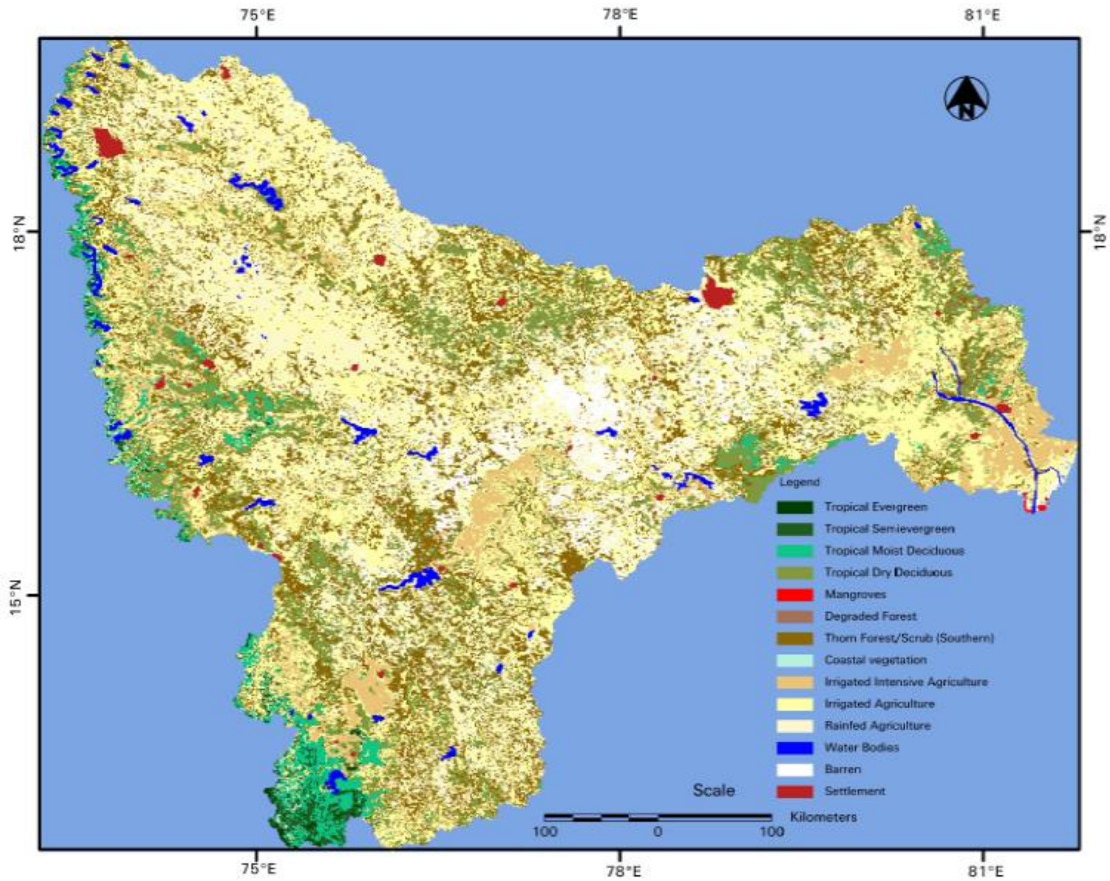


Figure X2: Global Land Cover 2000 (SPOT-4 Vegetation-s1); this data set is used for comparison (http://www.gvm.sai.jrc.it/glc2000/Products/).

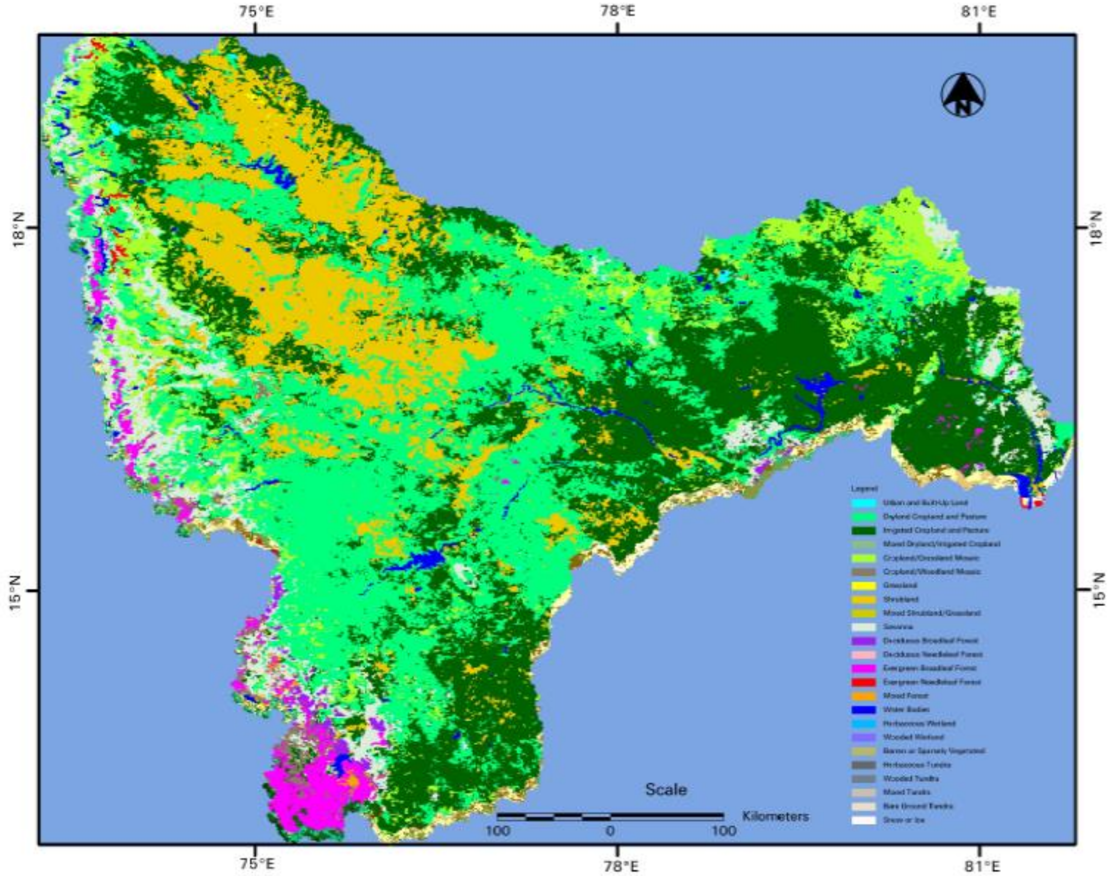


Figure X3: USGS seasonal LULC 1992 (AVHRR data); this data set is used for comparison (http://edcdaac.usgs.gov/glcc/globe_int.html).