MONITORING PRE-MONSOON DROUGHT IN BANGLADESH USING REMOTE SENSING TECHNIQUE

SITI AISHAH BINTI MANSOR

UNIVERSITI TEKNOLOGI MALAYSIA

MONITORING PRE-MONSOON DROUGHT IN BANGLADESH USING REMOTE SENSING TECHNIQUE

SITI AISHAH BINTI MANSOR

A thesis submitted in fulfillment of the
requirements for the award of the degree of
Master of Philosophy

Faculty of Geoinformation and Real Estate
Universiti Teknologi Malaysia

MARCH 2018

Alhamdulillah Syukur ke hadrat ALLAH dengan limpah kurnianya aku masih bernafas untuk detik ini dan mampu menyiapkan thesis ini dengan jayanya

Aku dedikasikan thesis ini khas untuk Mak,

Jamaliah Binti Manab
15/08/1955 ~ 10/1/2016

Sebagai tanda terima kasih atas segala jasa dan pengorbanannya.

Semoga ALLAH membalas kebaikan Mak hingga ke akhirnya

Al-Fatihah

"..Whenever you want to give up, just remember why you started..."

ACKNOWLEDGEMENT

All praises to ALLAH S.W.T for giving me courage and determination as well as guidance in this research study, despite all difficulties. I would like to take this opportunity to express my gratefulness to the people who have given me help and support during the process of the study and finishing my master thesis.

Thank you from the bottom of my heart to my supervisor, Dr Latifur Rahman Sarker and Assoc. Prof Dr Baharin Ahmad for all their helpful instruction, guidance and encouragement from time to time for keeping me on the right track of my work. Their endless patience and guidance for helping me to learn and developing my skill during my master journey.

To my beloved family and friend for their undying support, their unwavering belief that I can achieve so much. Unfortunately, I cannot thank everyone by name because it would take a lifetime but, I just want you all to know that you count so much. Had it not been for all your prayers and benedictions; were it not for your sincere love and help, I would never have completed this thesis. So thank you all.

May ALLAH bless all of you for the contribution that you made.

ABSTRACT

Drought has been a prevalent concern in Bangladesh over the past few decades, and the findings of several studies have indicated that Bangladesh has a high risk of drought, in association with a significant increasing trend of temperature. However, little attention has so far been given in Bangladesh to the mitigation and monitoring of drought, although few studies have been conducted for drought assessment based on either rainfall and temperature or a drought index based on rainfall, such as the Standardized Precipitation Index (SPI). The objective of this study is to assess drought conditions in Bangladesh using long-term satellite data from January to May (2001-2014). Temperature-Vegetation Dryness Index (TVDI) is a drought index based on remote sensing data that exploits the relationship between Normalized Difference Vegetation Index (NDVI) and Land Surface Temperature (LST) for estimating soil moisture condition has been used. A systematic approach was adopted in the methodology for considerations to; i) identify the spatial and temporal variation of drought using TVDI, ii) examine the relationship between TVDI and other climatology as well as environmental variables (such as soil moisture, LST, NDVI, rainfall, and Land Use Land Cover (LULC)), and iii) compare TVDI result with field investigation. Results indicate that drought is a concerning problem in Bangladesh and drought conditions varies spatially and temporally. It is clearly observed from the TVDI results that the problem of drought was not prominent in January and February (2001-2014) due to low temperatures. But the effect of drought was considerably high for the rest of the three months, of March, April and May (2001-2014) due to high temperature. However, there were still severe drought conditions have been observed in several small parts of the study areas where no additional water supply were available during that time, except rainfall. Nevertheless, a large part of the study area was still unaffected by the drought even during very hot weather condition due to massive irrigation which has been ascertained during the field investigations. Among the investigated parameters, very closed agreements were found between TVDI and LST as well as NDVI and LULC, although relationships between TVDI and rest of the parameters were not well-defined. This study also found that the TVDI result is in a good agreement with the field investigation. Most importantly, the correlation between TVDI and field investigation clearly indicates the important of this TVDI for the investigation of drought in a complex environment in Bangladesh, where drought estimation using only meteorological data (rainfall and temperature) is ineffective due to anthropogenic and environmental factors which modified the soil moisture condition across the ground very severely. Finally, this study highlights the potential of drought monitoring using remote sensing technique especially on the use of TVDI in Bangladesh due to lack of meteorological data.

ABSTRAK

Kemarau telah menjadi kebimbangan lazim di Bangladesh sejak beberapa dekad yang lalu dan penemuan beberapa kajian telah menunjukkan bahawa Bangladesh mempunyai risiko kemarau yang tinggi berkaitan dengan peningkatan ketara corak peningkatan suhu. Namun, hanya sedikit perhatian telah diberikan untuk mengatasi dan memantau kemarau di Bangladesh walaupun beberapa kajian penilaian kemarau telah dijalankan sama ada berdasarkan hujan dan suhu atau indeks kemarau berdasarkan hujan seperti indeks hujan seragam (SPI). Objektif kajian ini adalah untuk menilai keadaan kemarau di Bangladesh menggunakan data satelit jangka panjang dari Januari hingga Mei (2001-2014). Indeks kekeringan suhu tumbuhan (TVDI), iaitu suatu indeks kemarau berdasarkan data penderiaan jauh yang mengeksploitasi hubungan antara indeks perbezaan tumbuh-tumbuhan (NDVI) dan suhu permukaan tanah (LST) untuk menganggarkan keadaan kelembapan tanah telah digunakan. Pendekatan sistematik telah dipertimbangkan untuk diguna pakai di dalam metodologi iaitu untuk i) mengenal pasti perubahan ruang dan masa kemarau menggunakan TVDI, ii) memeriksa hubungan antara TVDI dan pemboleh ubah secara klimatologi dan alam sekitar yang lain (seperti kelembapan tanah, LST, NDVI, hujan dan kawasan litupan dan guna tanah (LULC), dan iii) membuat perbandingan hasil TVDI dengan siasatan lapangan. Keputusan menunjukkan bahawa kemarau mendapat perhatian di Bangladesh dan keadaan kemarau adalah pelbagai dari segi ruang dan masa. Adalah jelas diperhatikan daripada keputusan TVDI menunjukkan masalah kemarau tidak ketara dalam bulan Januari dan Februari (2001-2014) kerana suhu rendah. Tetapi kesan keadaan kemarau adalah agak tinggi sepanjang tiga bulan yang lain iaitu Mac, April dan Mei (2001-2014) disebabkan suhu tinggi. Namun, masih ada kesan kemarau teruk yang hanya dilihat pada beberapa bahagian kecil dalam kawasan kajian di mana tiada bekalan air tambahan boleh didapati pada masa ini kecuali air hujan. Walau bagaimanapun, sebahagian besar kawasan kajian masih tidak terjejas oleh kemarau walaupun keadaan cuaca yang sangat panas disebabkan sistem saliran secara besar-besaran di sesetengah kawasan yang dikenalpasti sewaktu siasatan lapangan. Di antara pembolehubah yang dikaji, terdapat kesamaan yang sangat dekat di antara TVDI dengan LST dan NDVI dengan LULC, walaupun hubungan antara TVDI dan pembolehubah yang lain tidak dapat dijelaskan dengan tepat. Kajian ini juga mendapati keputusan TVDI mempunyai hubungan yang rapat dengan siasatan lapangan. Yang paling penting, korelasi di antara TVDI dan siasatan lapangan jelas menunjukkan kebolehgunaan TVDI dalam siasatan keadaan kemarau di persekitaran yang kompleks di Bangladesh, di mana anggaran kemarau yang hanya menggunakan data meteorologi (hujan dan suhu) adalah tidak berkesan kerana faktor antropogenik dan alam sekitar yang mengubah keadaan kelembapan tanah di seluruh permukaan dengan amat teruk. Akhir sekali, kajian ini menekankan potensi teknik pemantauan kemarau menggunakan penderiaan jarak jauh terutamanya TVDI di Bangladesh kerana data meteorologinya adalah sangat kurang.

TABLE OF CONTENT

LIST OF TABLE

LIST OF FIGURE

LIST OF ABBREVIATIONS

GRFP	Ganges River Floodplain
HBT	High Barind Tract
HYV	High Yielding Variety
LULC	Land Use Land Cover
LST	Land Surface Temperature
MODIS	Moderate Resolution Imaging Spectroradiometer
NDVI	Normalized Difference Vegetation Index
PCI	Precipitation Condition Index
PDSI	Palmer Drought Severity Index
RMSE	Root Mean Square Error
SDCI	Synthesized Drought Condition Index
SDI	Synthesised Drought Index
SPI	Standardized Precipitation Index
TCI	Temperature Condition Index
TRMM	Tropical Rainfall Measuring Mission
TVDI	Temperature Vegetation Dryness Index
VCI	Vegetation Condition Index
VTCI	Vegetation Temperature Condition Index
NASA	National Aeronautics and Space Administration
PR	Precipitation Radar
TMI	TRMM Microwave Imager
VIRS	Visible And Infrared Radiometer System

CHAPTER 1

INTRODUCTION

1.1 Background of Study

Drought is recognized as a complex natural disaster that has severe effects on agriculture, human life, flora fauna and the economy. This disaster differs from other hazards (Wilhite, 2000) including the difficulty to i) determine the onset and the end of a drought (Tannehill, 1947), ii) define drought precisely (Gibbs, 1975; Dracup *et al.*, 1980), iii) manage drought affected areas due to large geographical extent, iv) perceive the effect of complex human activities that can directly trigger a drought, v) access the impact of different types of droughts, and vi) understand the changeable inter-relationships among different types of drought in time and space.

A widely diverse view of the definition of drought has been utilized among scientist's due to drought's functional and conceptual differences (Yevjevich, 1967; Wilhite and Glantz, 1985). Nevertheless, drought can generally be defined as a prolonged period of precipitation deficiency that results in a significant hydrological imbalance, often causing damage to crops, and loss of crop yield. Notable several other definitions of drought have also been reported by several organizations and scientists (WMO, 1986; UN Secretariat General, 1994; Schneider, 1996). However, droughts are generally classified into four categories (Wilhite and Glantz, 1985), which include: i) meteorological drought; a lack of precipitation, ii) hydrological drought; a period soil moisture deficit, iii) agricultural drought; a continuous from hydrologic drought and effect to crop production, and iv) socio-economic drought;

shortages for economic good due to limited water supply. It gives an impact towards the crop production that affects the large areas (Lobell and Field, 2007).

In the recent years, there have been many large-scale droughts affecting sizable areas in all over the parts of the world (Woods and Woods, 2007; IPCC Special Report, 2012) that can be linked to significant economic loss, limited food supply and, in some cases, starvation for millions of people. The adverse effect of drought is normally increased, if drought is observed in an agrarian and densely populated country (Miyan, 2015) such as Bangladesh where about 84% of the 145 million (currently 160 million) people are depended on a wide range of agricultural activities (Rahman, 2004). The findings from several studies on climate change indicated that the risk of drought in Bangladesh found to be very high in association with a significant increasing trend of temperature (Karmakar and Shrestha, 2000; Debsarma, 2003; Mia, 2003; Karmakar, 2003) due to global warming (IPCC, 2007) which are thought to eventually increase natural hazards such as drought.

In the recent years, there have been many initiatives in observing large scale drought over the entire continent that led to the bad impact to economy, ecological destroyed and also give an effect to food shortages which causes millions of people died due to starvation (Kogan, 2001). These scenarios have led to the awareness to the importance of drought monitoring (Downing and Baker, 2000). Therefore, many drought indices have been developed using climate data and used in different context for drought characterization and monitoring around the world. Drought indices are quantitative measures that characterized levels of drought by assimilating data based on meteorological parameter from one or several indicators, into a single value. These indices can indicate the nature of drought by reflecting different events and conditions based on climate dryness anomalies (Zargar *et al.,* 2011). But several limitations of climate data based drought index have been highlighted in the previous studies especially its dependency on interpolation technique and unavailability of adequate climate data particularly in developing countries (Mendelsohn *et al.,* 2007; Rhee *et al.,* 2010; Dutta *et al.,* 2015).

Different satellite sensor has been used to develop a number of drought indices. They are typically based on satellite derived vegetation indices (VIs), Land Surface Temperature (LST) and empirical methods using a certain combination of LST versus VIs (Ghulam *et al.,* 2007). However, the performance of the drought indices is varied based on the characteristics of the study sites under investigation. Nevertheless, it is quite clear from the literature that Normalized Difference Vegetation Index (NDVI) is the most widely used index for drought monitoring (Bayarjargal *et al.,* 2006; Vicente- Serrano *et al.,* 2006; Murali Krishna *et al.,* 2009) due to its ability for observing droughts in long term series of data (Ghulam *et al.,* 2007). Several studies found significant correlations between NDVI and precipitation (Unganai and Kogan, 1998; Yang *et al.,* 1998; Peters *et al.,* 2002). Although the NDVI has been found to be an effective indicator for drought characterization (Ji and Peters, 2003; Tadesse *et al.,* 2005), studies found that NDVI has a delayed response to precipitation or soil moisture deficit, and thus that the initial deficiency in soil moisture is not apparent in the NDVI signals (Rundquist and Harrington, 2000; Swain *et al.,* 2011). The lapse of time between the occurrence of a drought and the NDVI change is one of the limitations of NDVI based methods for real time monitoring of drought conditions (Ghulam *et al.,* 2007).

In contrast, Land Surface Temperature (LST) is more sensitive to initial water stress (Wan *et al.,* 2004). LST has been used in estimating surface soil moisture (McVicar and Jupp, 1998) and evapotranspiration (Granger, 2000; Anderson *et al.,* 2007). Several indices have been developed using satellite-derived LST observations such as Temperature Condition Index (TCI) (Unganai and Kogan, 1998) for drought monitoring (Singh *et al.,* 2003). Furthermore, studies found that the Vegetation Health Index (VHI) (Kogan, 1997, 2004), an additive combination of Vegetation Condition Index (VCI) and Temperature Condition Index (TCI), has a better capability to assess the stress of vegetation related to both water and temperature than VCI and TCI separately. Although VHI has been successfully applied globally for drought assessment in parts of Asia, Africa, Europe, and the America. However, Karnieli *et al.,* (2006) stated that this VHI index were limited indicated that this index should be used in caution especially in humid regions of high-latitude, where vegetation growth is primarily limited by lower temperatures.

However, the relationship between LST and NDVI has been investigated by several researchers (Moran *et al.*, 1995; Goetz 1997; Nemani and Running, 1997). These studies found that thermal and the visible/near infrared wavelengths can provide complementary information related on vegetation stress and soil moisture based on the combination of LST and NDVI. Temperature Vegetation Dryness Index (TVDI) is one of the index that derived from the combination of LST and NDVI (Sandholt *et al.,* 2002). A number of studies have employed TVDI for monitoring vegetation stress, surface moisture condition and drought considering the simplicity and effectiveness of this method (Son *et al.*, 2012; Huang *et al.*, 2013; Dhorde and Patel, 2016).

Therefore, it is comprehensible from the above background and existing literatures that drought is one of the most complex and the least understood natural disaster (He *et al.,* 2013). The impact of the drought has become a serious matter nowadays due to the population increase, environmental degradation, industrial development and fragmented government authority in the water and natural resources management (Rezayi *et al.,* 2011). As a result, any contribution for understanding and predicting drought conditions will be a step toward minimizing the impacts of drought. Numerous indices are available for drought monitoring based on both meteorological and remote sensing (satellite based) data, however, selection of drought indices need to be done based on the field condition and availability of data, since not all indices are equally effective for drought detection or monitoring in all field situations.

1.2 Problem Statement

Bangladesh is one of the drought prone countries in the world. This country has already suffered by several severe drought events in the past (Paul, 1995). For example, drought in 1973 was one of the most severe on record and was responsible for a local famine in northern Bangladesh in 1974. Several studies stated that drought has been observed in Bangladesh an average once in 2.5 years (Adnan, 1993; Shahid and Behrawan, 2008) although severity and duration varied in time and space.

Droughts mostly occur in Bangladesh during the pre-monsoon (January-May) and post-monsoon (October-December) seasons (Banglapedia, 2006), affecting all three rice varieties regionally grown (Aman, Aus and Boro) as well as other crops grown in different seasons (Tanner *et al.,* 2007). Pre-monsoon season is the warmest season in Bangladesh due to the scarcity of rainfall and high temperature (Banglapedia, 2006). In the past, during this season, Aus (local rich variety), Jute and few other crops were cultivated over large areas in Bangladesh depending on very little rainfall. Therefore, slightly decrease in rainfall and increase in temperature had a devastating impact on agriculture productions.

In recent decades, the scenario of pre-monsoon season in several parts of Bangladesh has been altered completely due to intensive irrigation using the easily available underground water for the cultivation of High Yield Varity (HYV) Boro rice (Miyan, 2015). Approximately 88% of the potentially available agriculture is under the cultivation of Boro rice during this time (Tanner *et al.,* 2007; Wahid *et al.,* 2007; Shahid and Behrawan, 2008). Significant water supply (240 mm/month) is required for Boro rice cultivation but average monthly rainfall for January, February, March, and April is only 5mm, 10mm, 30mm, and 85mm respectively. This huge gap between required and observable soil moisture is compensated by the massive extraction of a slowly declining ground water supply (GOB, 2002). However, three factors have created a complex scenario of the drought in this period at present: i) increasing trend of temperature; ii) intensive irrigation; and iii) depletion of underground water. As a result, three circumstances can be seen i.e. i) meteorological drought which perhaps exist due to high temperature and low rainfall, ii) agriculture drought may or may not able to activate owing to irrigation, and iii) future threat to irrigation practice due to regular depletion of underground water. This situation emphasizes an urgent need for a detailed investigation of the recent drought scenario in Bangladesh considering the future potential risks of this irrigated agriculture practice.

Several studies have been conducted to assess the drought and its spatial and temporal variation focusing on several parts of the country (Shahid and Behrawan, 2008; Habiba *et al.,* 2011; Dash *et al.,* 2012; Alamgir *et al.,* 2015). However, the problems associated with the most previously conducted studies are that drought assessment was conducted based on either rainfall/temperature or a drought index based on rainfall such as standardized precipitation index (SPI; McKee *et al.*, 1993, 1995). Consequently, the impact of human induced activity particularly irrigation on drought is mostly absent from their outcomes. Additionally, previous studies are also influenced by several notable limitations of climate data as well as the SPI method itself which include; i) dependency on distribution and density of weather stations across the landscape (Brown *et al.*, 2008; Rhee *et al.*, 2010) as well as spatial interpolation techniques (Brown *et al.*, 2002; Mendelsohn *et al.*, 2007; Rhee *et al.*, 2010), ii) lack of sufficient and reliable climate data particularly in developing countries (Dutta *et al.*, 2015), and iii) inability to consider environmental factors which can influence droughts. Therefore, drought detection was not accomplished successfully through the effort of the previously conducted studies because of the complex situation in Bangladesh where climate variables (temperature and rainfall) and human induced activity (irrigation) are interacting with each other for modifying drought intensity.

In contrast, during the past several decades, remotely sensed data have been used in plant biophysical and climate change related studies, including drought monitoring (Ji and Peters, 2003; Bayarjargal *et al.*, 2006) since this data can be used to assess ground soil moisture condition (whether it is due to climatic factors, environmental factors or human induced activities) by generating several useful indices using different spectral bands. Moreover, remote sensing satellite provides a spatially contiguous and temporally repetitive view of the earth surface which is very useful for drought monitoring (Du *et al.*, 2013). Indeed, several drought indices based on satellite data have been developed and many studies have also been carried out successfully for the monitoring of drought around the world using a wide range of simple to complex drought indices derived from different kind of satellite data (Tadesse *et al.*, 2005; Mallick *et al.*, 2009; Rhee *et al.*, 2010; Son *et al.*, 2012; Wang *et al.*, 2014). Unfortunately, very little effort has been made to characterize drought in Bangladesh using satellite derived drought indices (Murad and Islam, 2011) although a robust technique for drought monitoring is necessary which can comprehend not only the rainfall but also other factors that affecting the drought across the landscape under investigation.

Therefore, this study is going to take an opportunity to study drought in Bangladesh and its spatial and temporal variation using long-term satellite data. This study investigates the present drought scenario of a Bangladesh area using a remote sensing based drought index TVDI considering its ability to incorporate both LST and NDVI in an effective way. TVDI was conceptually and computationally straightforward methodology, simple data requirement (only satellite-derived information) and already demonstrated the potential for drought monitoring in various geographical regions (Qi *et al.*, 2003; Son *et al.*, 2012). However, in this study, drought assessment will be carried out during pre-monsoon season (January, February, March, April and May) from 2001 to 2014 taking into account the availability of all necessary data. This study provides a new insight in recent change of droughts in Bangladesh which in turn will help policy makers in taking the necessary steps for preventing future drought hazards and making drought mitigation planning.

1.3 Aim and Objective

1.3.1 Aim of Study

The overall objective of this study is to examine the potential of remote sensing technique for monitoring long term drought in Bangladesh.

1.3.2 Objectives of Study

1. To identify the spatial and temporal variation of drought during pre-monsoon by using Temperature Vegetation Dryness Index (TVDI),

2. To examine the relationship between TVDI and other climatologically and environmental variables (such as soil moisture, LST, NDVI, rainfall, and land use/land cover), and

3. To compare the TVDI result with field observation.

1.3.3 Research Question

1. How much drought phenomena changed spatially and temporarily in Bangladesh during the last decade?

2. How is the relationship between the TVDI and the other meteorological parameter?

3. What is the main reason behind the different situation of drought condition in Bangladesh in these five different months?

1.4 Scope of Study

1. This study uses MODIS Terra for LST and NDVI determination. MODIS has been selected in this study because of the long-term data availability (since 2000), better spatial coverage (i.e. 250m, 500m and 1km) and higher temporal resolution (1 to 2 days).

2. The other satellite data that were used are Tropical Rainfall Measuring Mission (TRMM) used for precipitation measurement and ESA CCI Soil Moisture data for the soil moisture measurement in the study area. These two additional data were selected due to the availability of data for the overall period of the study

3. Other than the satellite data, this study were also meteorological data such as temperature and precipitation from different meteorological stations. This data that covers from year 1950 up to 2014 were obtained from the Bangladesh Meteorological Station (BMD). This data is freely available for end users and very simple to be used for analysis purposes.

4. This study was carried out in focusing on total Bangladesh, since there is an occurrence of drought once in every 2.5 years (Adnan, 1993; Hossain, 1990; Murad and Islam, 2011).

1.5 Significance of Study

Generally, due to global warming, species and habitat of flora and fauna have been declined and chances for ecosystem to adapt the changes naturally have been diminished. The variability in climate system will influence imperative divisions in Bangladesh. Additionally, increasing of temperature would increase evaporation and transpiration, hence, it could lead to the risk of the increasing hydrological and agricultural drought as the temperature rises. Therefore, it is necessary to understand the trend of water-related disaster such as drought with respect recent variable climate and land use/land cover scenario. Drought causes the agricultural planning in Bangladesh to be distracted and alters the future food security production.

During monsoon, the available rainfall may fulfil the crop water demand, but during the dry season the evapotranspiration exceeds the amount of rainfall by an amount of more than 0.5 times the rainfall. Therefore, water deficit exists in the dry months of the year, as the demand is higher than the total rainfall (Paul, 1995). Thus, the groundwater is used as one of the alternative sources for soil moisture supply for agricultural activities in dry season in several parts of this country (Habiba *et al.*, 2010). This ground water-based intensive irrigation for practice helps to reduce the severity of soil moisture deficit but continuous high pumping of groundwater leads to the overexploitation and groundwater depletion (Bangladesh Bureau of Statistics (BBS), 2005).

A potential threat of drought is expected in Bangladesh since global temperature is increasing, evapotranspiration is exceeding the amount of rainfall in pre-monsoon, and underground water is declining very rapidly. Therefore, it is necessary to develop an efficient drought monitoring system for Bangladesh using freely available satellite data with usable spatial and temporal resolution since only climate data (such as rainfall) is unable to detect drought in Bangladesh effectively. However, very little effort has been made so far using satellite data and effective drought index for the detection of drought in Bangladesh due to several reasons. Therefore, it is expected that the outcome of the study will provide useful information in relation to drought, its recent trend, and spatial as well as temporal distribution in Bangladesh. This long-term observation (more than a decade) can benefit different stakeholders such as farmers, government and planner to understand the drought problem more accurately. Government can use this method to develop a systematic drought monitoring system over this region. Additionally, scientist who is interested to study drought in this region may also be benefitted as this study provides a comprehensive outcome about the detection of drought using satellite and its relationship with several environmental and climatic parameters as well as field data.

1.6 Study Area

Bangladesh is located on the northern coast of the Bay of Bengal, surrounded by India with small common border with Myanmar in the Southeast (Figure 1.1). Climatically, Bangladesh region is located at Tropic of Cancer, so it has tropical monsoon climate that can be categorized by heavy seasonal rainfall, high temperature and high humidity. Three distinct seasons can be recognized in the area from climatic point of view: (1) the pre-monsoon dry winter season from December to February, (2) the pre-monsoon hot summer season from March to May, and (3) the rainy monsoon season which lasts from June to October (Shahid and Hazarika, 2010). January is known as the coolest month with temperature averaging near 26°C and April with the warmest with temperature from 32°C to 36°C.

Climatically, the study area belongs to dry humid zone with annual average rainfall vary between 1,400 and 1,650 mm, among which almost 83% rainfall occur in monsoon (June to October). Rainfall in the area varies widely from year to year. For example, the rainfall recorded at Rajshahi in 1997 was 2,062 mm, but in 1992 it was 798 mm only. Average temperature in the region ranges from 25◦C to 35◦C in the hottest season and 9◦C to 15◦C in the coolest season. In summer, some of the hottest days experience a temperature of about 42◦C or even more. In winter it falls to about 5◦C. So the region experiences extremes that are clearly in contrast to the climatic condition of the rest of the country (Banglapedia, 2003).

Bangladesh is subject to devastating cyclones, originating from the Bay of Bengal, in the periods of April to May and September to November. Other natural calamities such as floods, drought, tornadoes and tidal bores affect the country almost every year. Bangladesh experiences drought severity when the rainfall distribution is normally low, which can affect crop production and vegetation growth. Water deficit has become a major problem in Bangladesh during the post to pre-monsoon season (November to March). The inland and coastal zone in southwest region is connected to Ganges River which suffers from water shortages during dry season and also problem related to arsenic contamination.

Drought plays an important role for agricultural productivity in several physiographic areas in Bangladesh such as Piedmont regions, level and high Barind Tracts areas and Madhupur Tract areas during the winter season. This causes a big challenge to agriculture labourers and others considering the fact that country's main economic activity is agriculture, which is overwhelmingly, dependent on timely onset, duration, and distribution of the rainfall (Gebrehiwot *et al.*, 2010). Drought usually occur in Kharif (March to June) which is also called pre-monsoon, and Rabi (October to February) that is also called post-monsoon season, and affect the agricultural product such as Aman, Aus and Boro rice cultivation.

Figure 1.1 Map of Bangladesh

1.7 Chapter Organization

There are six chapters in this thesis which are i) introduction of the study, ii) literature review, iii) methodology, iv) result and analysis, v) discussion, vi) conclusion and recommendation.

Chapter one describes the background of research based on topics related to this study. This chapter include with problem statement, aim and objective, scope of study, significance of study and study area.

Chapter two briefly describes the drought and its definition, theory and concepts of drought indices including meteorological and satellite data based drought indices. This chapter also describes the concept of remote sensing for drought monitoring, their capabilities, satellite application, the advantages and disadvantages of remote sensing data based drought estimation technique. Moreover, the indices that are suitable for drought monitoring in this study were also introduced in this chapter based on existing published literature including journal articles, thesis and worldwide web.

Chapter three describes the research methodology where all the processing steps are explained in detailed. The result and the analysis of the study are presented in chapter four. Results of this study are presented with help of diagrams and explanation in order to enable reader to have better understanding about this research. The analysis of the study is illustrated by the qualitative and quantitative assessment techniques.

A brief discussion about this study is presented in Chapter five. In this chapter an assessment was made to investigate whether the overall research objective of this study has been achieved or not. This chapter also summarizes the outcome this research with respect to other published research works.

The last chapter in this study is chapter six where an overall conclusion of the study is presented. This chapter also summarizes the research findings with respect to research limitations. Several recommendations are also made in this chapter for the improvement of the future research.

REFERENCES

Adnan, S. (1993) Living Without Floods: Lessons from the Drought of 1992. Research and Advisory Services, Dhaka.

Alamgir, M., Shahid, S., Hazarika, M. K., Nashrrullah, S., Harun, S. B., & Shamsudin, S. (2015). Analysis of meteorological drought pattern during different climatic and cropping seasons in Bangladesh. *JAWRA Journal of the American Water Resources Association*, *51*, 794-806.

Alley, W.M., (1984). The Palmer Drought Severity Index: limitations and assumptions. *Journal of Applied Meteorology*. 27 (7), 1100–1109.

Almazroui, M. (2011). Sensitivity of a regional climate model on the simulation of high intensity rainfall events over the Arabian Peninsula and around Jeddah (Saudi Arabia). *Theoretical and Applied Climatology*, *104*(1-2), 261-276.

Anderson, M. C., Norman, J. M., Mecikalski, J. R., Otkin, J. A., & Kustas, W. P. (2007). A climatological study of evapotranspiration and moisture stress across the continental United States based on thermal remote sensing: 2. Surface moisture climatology. *Journal of Geophysical Research: Atmospheres*, *112*, D11.

Andreadis, K. M., Clark, E. A., Wood, A. W., Hamlet, A. F., & Lettenmaier, D. P. (2005). Twentieth-century drought in the conterminous United States.*Journal of Hydrometeorology*, *6*(6), 985-1001.

Bajgiran, P. R., Darvishsefat, A. A., Khalili, A., & Makhdoum, M. F. (2008). UsingAVHRR-based vegetation indices for drought monitoring in the Northwest of Iran. *Journal of Arid Environments*, *72*(6), 1086-1096.

Bangladesh Bureau of Statistics (BBS). (2005). Compendium of environment statistics of Bangladesh. Dhaka: Ministry of Planning, Government of Bangladesh.

Banglapedia (2003). Banglapedia: National encyclopedia of Bangladesh. In: Islam S (ed) Asiatic society of Bangladesh, Dhaka.

Banglapedia (2006). Drought in Bangladesh. (Available at: http://banglapedia.search.com.bd/HT/D_0284.htm).

Bayarjargal, Y., Karnieli, A., Bayasgalan, M., Khudulmur, S., Gandush, C., & Tucker, C. J. (2006). A comparative study of NOAA–AVHRR derived drought indices using change vector analysis. *Remote Sensing of Environment*, *105*, 9-22.

Berliner, P., Oosterhuis, D. M., & Green, G. C. (1984). Evaluation of the infrared thermometer as a crop stress detector. *Agricultural and Forest Meteorology*, *31*(3), 219-230.

Brown, J. F., Reed, B. C., Hyes, M. J., Wilhite, A. D., and Hubbard, K., (2002) A Prototype Drought Monitoring System Integrating Climate and Satellite Data, Percora 15/Land Satellite Information IV/ ISPRS Commission I/FIEOS 2002.

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

Cai, G., Du, M., and Liu, Y. (2011). Regional drought monitoring and analyzing using MODIS data — A case study in Yunnan Province. In Computer and Computing Technologies in Agriculture IV. Edited by D. Li, Yande Liu, and Y. Chen. Springer, Boston. pp. 243–251.

Chen, C.F., Son, N.T., Chang, L.Y., Chen, C.C., (2011). Monitoring of soil moisture variability in relation to rice cropping systems in the Vietnamese Mekong Delta using MODIS data. *Applied Geography*. 31, 463–475.

Cheng, C. H., Lehmann, J., Thies, J. E., & Burton, S. D. (2008). Stability of black carbon in soils across a climatic gradient. *Journal of Geophysical Research: Biogeosciences (2005–2012)*, *113*(G2).

Choi, M., Jacobs, J.M.,Anderson, M.C., Bosch, D.D., (2013). Evaluation of droughtindices via remotely sensed data with hydrological variables. *Journal of Hydrology*. 476, 265–273.

Dai, A., Trenberth, K. E., & Qian, T. (2004). A global dataset of Palmer Drought Severity Index for 1870-2002: Relationship with soil moisture and effects of surface warming. *Journal of Hydrometeorology*, *5*(6), 1117-1130.

Dash, B. K., Rafiuddin, M., Khanam, F., & Islam, M. N. (2012). Characteristics of meteorological drought in Bangladesh. *Natural hazards*, *64*, 1461-1474.

Debsarma, S.K. (2003). Intra-annual and inter-annual variation of rainfall over different regions of Bangladesh. *Proceedings of SAARC Seminar on Climate Variability in the South Asian Region and its Impacts*, *SMRC*, *December 20-24, 2002*, *Dhaka, Bangladesh Dhaka*, *SAARC Meteorological Research Centre*.

Dhorde, A. G., & Patel, N. R. (2016). Spatio-temporal variation in terminal drought over western India using dryness index derived from long-term MODIS data. *Ecological Informatics*, *32*, 28-38.

Downing, T.E., Baker, K., (2000). Drought discourse and vulnerability. In: Wilhite, D.A. (Ed.), Drought: A Global Assessment. Routledge, London, UK, pp. 213–230.

Dracup, J. A., Lee, K. S., & Paulson, E. G. (1980). On the statistical characteristics of drought events. *Water Resources Research*, *16*, 289-296.

Du, L., Tian, Q., Yu, T., Meng, Q., Jancso, T., Udvardy, P., & Huang, Y. (2013). A comprehensive drought monitoring method integrating MODIS and TRMM data. *International Journal of Applied Earth Observation and Geoinformation*, *23*, 245-253.

Dutta, D., Kundu, A., Patel, N. R., Saha, S. K., & Siddiqui, A. R. (2015). Assessment of agricultural drought in Rajasthan (India) using remote sensing derived Vegetation Condition Index (VCI) and Standardized Precipitation Index (SPI). *The Egyptian Journal of Remote Sensing and Space Science*, *18*(1), 53-63.

Ezzine, H., Bouziane, A., & Ouazar, D. (2014). Seasonal comparisons of meteorological and agricultural drought indices in Morocco using open short time-series data. *International Journal of Applied Earth Observation and Geoinformation*, *26*, 36-48.

Gebrehiwot, T., van der Veen, A., & Maathuis, B. (2011). Spatial and temporal assessment of drought in the Northern highlands of Ethiopia. *International Journal of Applied Earth Observation and Geoinformation*, *13*(3), 309-321.

Ghulam, A., Qin, Q., Teyip, T., & Li, Z. L. (2007). Modified perpendicular drought index (MPDI): a real-time drought monitoring method. *ISPRS Journal of Photogrammetry and Remote Sensing*, *62*, 150-164.

Gibbs J, Maher J (1967) Rainfall deciles as drought indicators. Bureau of Meteorology Bulletin No. 48, Commonwealth of Australia, Melbourne

Gibbs, W. J. (1975). Drought-its definition, delineation and effects. In *Drought. Lectures presented at the twenty-sixth session of the WMO Executive Committee.* (pp. 1-39). WMO.

Goetz, S. J. (1997). Multi-sensor analysis of NDVI, surface temperature and biophysical variables at a mixed grassland site. *International Journal of Remote Sensing*, *18*, 71-94.

González, J., & Valdés, J. B. (2006). New drought frequency index: Definition and comparative performance analysis. *Water Resources Research*, *42*(11).

Government of Bangladesh (2002). Second National Report on Implementation of United Nations Convention to Combat Desertification. Bangladesh. *Government of Bangladesh (GOB) Report*, Ministry of Environment and Forests, Dhaka, April, 2002.

Granger, R. J. (2000). Satellite-derived estimates of evapotranspiration in the Gediz basin. *Journal of Hydrology*, *229*, 70-76.

Gumbel, E. J. (1963). Statistical forecast of droughts. *Hydrological Sciences Journal*, *8*, 5-23.

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

Guttman, N.B., (1997). Comparing the Palmer Drought Index and the Standardized Precipitation Index. Journal of American Water Resource Association. 34 (1), 113–121.

Habiba, U., Shaw, R., & Takeuchi, Y. (2011). Drought risk reduction through a socioeconomic, institutional and physical approach in the northwestern region of Bangladesh. *Environmental Hazard*, *10*, 121-138.

Habiba, U., Takeuchi, Y., & Shaw, R. (2010). Chapter 3 Overview of drought risk reduction approaches in Bangladesh. *Climate Change Adaptation and Disaster Risk Reduction: An Asian Perspective (Community, Environment and Disaster Risk Management, Volume 5) Emerald Group Publishing Limited*, *5*, 37-58.

Hayes, M. J., Svoboda, M. D., Wilhite, D. A., & Vanyarkho, O. V. (1999). Monitoring the 1996 drought using the standardized precipitation index. *Bulletin of the American Meteorological Society*, *80*(3), 429-438.

Heim, R.R., (2002). A review of twentieth-century drought indices used in United States. Bulletin of the American Meteorological Society 83 (8), 1149-1166.

Hoffmann, W. A., & Jackson, R. B. (2000). Vegetation–climate feedbacks in the conversion of tropical savanna to grassland. *Journal of Climate*, *13*(9), 1593-1602.

Holmes, T. R. H., De Jeu, R. A. M., Owe, M., & Dolman, A. J. (2009). Land surface temperature from Ka band (37 GHz) passive microwave observations.*Journal of Geophysical Research: Atmospheres (1984–2012)*, *114*(D4).

Huang, Y., Tian, Q., Du, L., & Sun, S., (2013). Analysis of spatial temporal variation of agricultural drought and its response to ENSO over the past 30 years in the Huang-Huai-Hai Region, China. *Terrestrial Atmospheric and Oceanic Sciences*, *24*, 745–759.

Idso, S. B., Reginato, R. J., Jackson, R. D., & Pinter Jr, P. J. (1981). Measuring yield-reducing plant water potential depressions in wheat by infrared thermometry. *Irrigation Science*, *2*(4), 205-212.

IPCC (2007). Climate change 2007: The physical science basis. Fourth assessment report of the Intergovernmental Panel on Climate Change (IPCC) [Solomon, S. D., Qin, M., Manning, Z., Chen, M., Marquis, K. B., Averyt, M. T., & Miller, H. L. (Eds.)]. Cambridge University Press, Cambridge, United Kingdom.

IPCC Special Report (2012). Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation: Special Report of the Intergovernmental Panel on Climate Change, IPCC Working Group II. Cambridge University Press (978-1-107-025006-6).

Islam MN, Das S, Ahasan MN, Rahman MM, Hasanat MSA, Devkota LP, Baidya SK, Budhathoki KP (2009) Drought diagnosis and monitoring over Bangladesh and Nepal. SMRC report no. 26, SAARC, Meteorological Research Centre, Dhaka, Bangladesh, p 50.

Islam, M. N., & Uyeda, H. (2007). Use of TRMM in determining the climatic characteristics of rainfall over Bangladesh. *Remote Sensing of Environment*,*108*(3), 264-276.

Jain, S. K., Keshri, R., Goswami, A., Sarkar, A., & Chaudhry, A. (2009). Identification of drought-vulnerable areas using NOAA AVHRR data.*International Journal of Remote Sensing*, *30*(10), 2653-2668.

Janácek, J. (1994).: Drought assessment, management and planning: theory and case studies. Biologia Plantarum 36, 628.

Ji, L., Peters, A.J., (2003). Assessing vegetation response to drought in the northern Great Plains using vegetation and drought indices. *Remote Sensing of Environment*, *87*, 85–98.

Kallis, G. (2008). Droughts. *Annual Review of Environment and Resources*, *33*.

Karamouz, M., Rasouli, K., & Nazif, S. (2009). Development of a hybrid index for drought prediction: case study. *Journal of Hydrologic Engineering*, *14*(6), 617-627.

Karim, Z., Ibrahim, A., Iqbal, A., & Ahmed, M. (1990). Drought in Bangladesh agriculture and irrigation schedules for major crops. *Bangladesh Agricultural Research Center (BARC) Publication*, (34).

Karmakar, S. & Shrestha, M. L. (2000). “Recent climate change in Bangladesh”, SMRC No.4, SMRC, Dhaka.

Karmakar, S. (2003). Trends in the annual frequency of cyclonic disturbances and storms in the Bay of Bengal. *Proceedings of SAARC Seminar on Climate Variability in the South Asian Region and its Impacts, SMRC, December 20-24, 2002, Dhaka, Bangladesh. Dhaka, SAARC Meteorological Research Centre.*

Karnieli, A., Agam, N., Pinker, R. T., Anderson, M., Imhoff, M. L., Gutman, G. G., ... & Goldberg, A. (2010). Use of NDVI and land surface temperature for drought assessment: Merits and limitations. *Journal of climate*, *23*(3), 618-633.

Karnieli, A., Bayasgalan, M., Bayarjargal, Y., Agam, N., Khudulmur, S., & Tucker, C. J. (2006). Comments on the use of the vegetation health index over Mongolia. *International Journal of Remote Sensing*, *27*(10), 2017-2024.

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

Kogan, F. N. (2001). Operational space technology for global vegetation assessment. *Bulletin of the American Meteorological Society*, *82*(9), 1949-1964.

Kogan, F., Stark, R., Gitelson, A., Jargalsaikhan, L., Dugrajav, C., & Tsooj, S. (2004). Derivation of pasture biomass in Mongolia from AVHRR-based vegetation health indices. *International Journal of Remote Sensing*, *25*, 2889-2896.

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

Lambin, E. F., & Strahlers, A. H. (1994). Change-vector analysis in multitemporal space: a tool to detect and categorize land-cover change processes using high temporal-resolution satellite data. *Remote sensing of environment*, *48*(2), 231-244.

Li, Y., Ye, W., Wang, M., & Yan, X. (2009). Climate change and drought: a risk assessment of crop-yield impacts. *Climate research*, *39*, 31-46.

Liu, W. T., & Juárez, R. N. (2001). ENSO drought onset prediction in northeast Brazil using NDVI. *International Journal of Remote Sensing*, *22*(17), 3483-3501.

Lobell, D. B., & Field, C. B. (2007). Global scale climate–crop yield relationships and the impacts of recent warming. *Environmental research letters*, *2*(1), 014002.

Loukas, A., Mylopoulos, N., & Vasiliades, L. (2007). A modeling system for the evaluation of water resources management strategies in Thessaly, Greece. *Water Resources Management*, *21*(10), 1673-1702.

Mallick, K., Bhattacharya, B.K., Patel, N.K., (2009). Estimating volumetric surface moisture content for cropped soils using a soil wetness index based on surface temperature and NDVI. Agricultural and Forest Meteorology. 149, 1327–1342.

Matalas, N. C. (1963). *Probability distribution of low flows*. Washington DC: US Government Printing Office.

McKee, T. B., Doesken, N. J., & Kleist, J. (1993). The relationship of drought frequency and duration to time scales. *Proceedings of the 8th Conference on Applied Climatology (Vol. 17, No. 22, pp. 179-183). Boston, MA, USA: American Meteorological Society.*

McKee, T. B., Doesken, N. J., & Kleist, J. (1995). Drought monitoring with multiple time scales. *Proceedings of the 9th Conference on Applied Climatology (pp. 233-236). Dallas, Boston, MA: American Meteorological Society.*

McMahon, T. A., & Arenas, A. D. (Eds.). (1982). *Methods of computation of low streamflow*. Paris: UNESCO.

McVicar, T. R., & Bierwirth, P. N. (2001). Rapidly assessing the 1997 drought in Papua New Guinea using composite AVHRR imagery. *International Journal of Remote Sensing*, *22*, 2109-2128.

McVicar, T. R., & Jupp, D. L. (1998). The current and potential operational uses of remote sensing to aid decisions on drought exceptional circumstances in Australia: a review. *Agricultural systems*, *57*(3), 399-468.

Mendelsohn, R., Kurukulasuriya, P., Basist, A., Kogan, F., & Williams, C. (2007). Climate analysis with satellite versus weather station data. *Climatic Change*, *81*, 71-83.

Mendicino, G., Senatore, A., & Versace, P. (2008). A Groundwater Resource Index (GRI) for drought monitoring and forecasting in a mediterranean climate. *Journal of Hydrology*, *357*(3), 282-302.

Mia, N. M. (2003). Variations of temperature of Bangladesh. *Proceedings of SAARC seminars on climate variability in the South Asian region and its impacts, SMRC, Dhaka*.

Mishra, A. K., & Singh, V. P. (2010). A review of drought concepts. *Journal of Hydrology*, *391*(1), 202-216.

Miyan, M. A. (2015). Droughts in Asian least developed countries: vulnerability and sustainability. *Weather and Climate Extremes*, *7*, 8-23.

Moffitt, C. B., Hossain, F., Adler, R. F., Yilmaz, K. K., & Pierce, H. F. (2011). Validation of a TRMM-based global Flood Detection System in Bangladesh.*International Journal of Applied Earth Observation and Geoinformation*, *13*(2), 165-177.

Moran, M. S., Clarke, T. R., Inoue, Y., & Vidal, A. (1994). Estimating crop water deficit using the relation between surface-air temperature and spectral vegetation index. *Remote Sensing of Environment*, *49*, 246-263.

Mottram, R., De Jager, J. M., & Duckworth, J. R. (1983). Evaluation of a water stress index for maize using an infra-red thermometer. *Gewasproduksie= Crop production*.

Mozafari, G.A., Khosravi, Y., Abbasi, E., Tavakoli, F., (2011). Assessment of geostatistical methods for spatial analysis of SPI and EDI Drought Indices. *World Applied Sciences Journal*, 15 (4), 474–482.

Murad, H., & Islam, A. S. (2011). Drought Assessment using remote sensing and GIS in Northwest region of Bangladesh. In *proceedings of 3rd International Conference on Water and Flood Management*.

Murali Krishna, T., Ravikumar, G., Krishnaveni,M., (2009). Remote sensing based agricultural drought assessment in Palar Basin of Tamil Nadu State, India. *J. Indian Soc. Remote Sens*. 37, 9–20.

Nemani, R., & Running, S. (1997). Land cover characterization using multitemporal red, near-IR, and thermal-IR data from NOAA/AVHRR. *Ecological Applications*, *7*, 79-90.

Niemeyer, S. (2008). New drought indices. *Water Management*, *80*, 267-274.

Obasi, G. O. P. (1994). WMO's role in the international decade for natural disaster reduction. *Bulletin of the American Meteorological Society*, *75*(9), 1655-1661.

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

Paul, B. K. (1995). Farmers' and public responses to the 1994-95 Drought in Bangladesh: A case study.

Peters, A. J., Walter-Shea, E. A., Ji, L., Vina, A., Hayes, M., & Svoboda, M. D. (2002). Drought monitoring with NDVI-based standardized vegetation index. *Photogrammetric Engineering and Remote Sensing*, *68*, 71-75.

Pinter, L., Kálmán, L., & Palfi, G. (1979). Determination of drought resistance in maize (zea-mays-l) by proline test. *Maydica*, *24*(3), 155-159.

Prihodko, L., and Goward, S.N. (1997). Estimation of air temperature from remotely sensed surface observations. Remote Sens. Environ. 60 (3): 335–346. doi:10.1016/S0034-4257(96)00216-7.

Prince, S. D. (1991). A model of regional primary production for use with coarse resolution satellite data. *International Journal of Remote Sensing*, *12*(6), 1313-1330.

Qi, S. H., Wang, C. Y., & Niu, Z. (2003). Evaluating Soil Moisture Status in China Using the Temperature/Vegetation Dryness Index (TVDI). *Journal of Remote Sensing-Beijing*, *7*, 420-427.

Quiring, S. M., & Ganesh, S. (2010). Evaluating the utility of the Vegetation Condition Index (VCI) for monitoring meteorological drought in Texas.*Agricultural and Forest Meteorology*, *150*(3), 330-339.

Rahimzadeh Bajgiran, P., Darvishsefat, A.A., Khalili, A., Makhdoum, M.F., (2008). Using AVHRR-based vegetation indices for drought monitoring in the Northwest of Iran. *Journal of Arid Environments* 72, 1086–1096.

Rahman, A. Z. (2004). Correlations between green revolution and population growth: revisited in the context of Bangladesh and India. *Asian Aff*, *26*, 41-60.

Rajib, M. A., Mortuza, M. R., Selmi, S., Ankur, A. K., & Rahman, M. M. (2011). Spatial Drought Distribution in the Northwestern Part of Bangladesh. In*Proceedings of the Asian Conference on Sustainability, Energy and the Environment* (pp. 568-575).

Rezayi, R., Hosseini, M., & Safa, L. (2011). Studding and identifying the economic, social, environmental, and ecological impacts of drought in Zanjan township. In *The first national conference of drought and climate change* (pp. 686-693).

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

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. Westview Press, Boulder, CO.

Rojas, O., Vrieling, A., & Rembold, F. (2011). Assessing drought probability for agricultural areas in Africa with coarse resolution remote sensing imagery. *Remote Sensing of Environment*, *115*(2), 343-352.

Rundquist, B. C., Harrington Jr, J. A., & Goodin, D. G. (2000). Mesoscale satellite bioclimatology. *The Professional Geographer*, *52*, 331-344.

Salazar, L., Kogan, F., Roytman, L., (2008). Using vegetation health indices and partial least squares method for estimation of corn yield. *International Journal of Remote Sensing*. 29 (1), 175–189.

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

Schneider, S.H. (Ed.), (1996). *Encyclopaedia of Climate and Weather*. Oxford University Press, New York.

Shahid, S., & Behrawan, H. (2008). Drought risk assessment in the western part of Bangladesh. *Natural Hazards*, *46*, 391-413.

Shahid, S., & Hazarika, M. K. (2010). Groundwater drought in the northwestern districts of Bangladesh. *Water resources management*, *24*(10), 1989-2006.

Sheffield, J., & Wood, E. F. (2007). Characteristics of global and regional drought, 1950–2000: Analysis of soil moisture data from off-line simulation of the terrestrial hydrologic cycle. *Journal of Geophysical Research: Atmospheres (1984–2012)*, *112*(D17).

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

Sivakumar, M., Motha, R., Wilhite, D., & Wood, D. (2010). Agricultural Drought indices proceedings of an expert meeting. 2–4 June 2010, Murcia, Spain. *World Meteorological Organization, Geneva, Switzerland*.

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

Steinemann, A.C., Hayes, M.J., and Cavalcanti, L. (2005). Drought indicators and triggers. Drought and water crises: Science, technology, and management issues. CRC Press, Boca Raton, FL. pp. 71–92.

Swain, S., Wardlow, B. D., Narumalani, S., Tadesse, T., & Callahan, K. (2011). Assessment of vegetation response to drought in Nebraska using Terra-MODIS land surface temperature and normalized difference vegetation index. *GIScience & Remote Sensing*, *48*, 432-455.

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

Tannehill, I. R. (1947). Drought, its causes and effects. *Soil Science*, *64*, 83.

Tanner, T. M., Hassan, A., Islam, K. N., Conway, D., Mechler, R., Ahmed, A. U., & Alam, M. (2007). ORCHID: piloting climate risk screening in DFID Bangladesh. *Rapport d'étude. Institut des études de développement, Université du Sussex, Brighton*.

Thornthwaite, C. W., & Mather, J. R. (1955). The water balance. Centerton: Drexel Institute of Technology, 1955. 104 p. *Publications in climatology*, *8*(1).

UN Secretariat General (1994). United Nations Convention to Combat Drought and Desertification in Countries Experiencing Serious Droughts and/or Desertification, *Particularly in Africa*.

Unganai, L. S., & Kogan, F. N., (1998). Drought monitoring and corn yield estimation in Southern Africa from AVHRR data. *Remote Sensing of Environment. 63*, 219–232.

Ustin, S. L., Roberts, D. A., Gamon, J. A., Asner, G. P., & Green, R. O. (2004). Using imaging spectroscopy to study ecosystem processes and properties. *BioScience*, *54*(6), 523-534.

Vasiliades, L., Loukas, A., & Liberis, N. (2011). A water balance derived drought index for Pinios River Basin, Greece. *Water resources management*,*25*(4), 1087-1101.

Vicente-Serrano, S. M., Beguería, S., & López-Moreno, J. I. (2010). A multiscalar drought index sensitive to global warming: the standardized precipitation evapotranspiration index. *Journal of Climate, 23*, 1696-1718.

Wahid, S. M., Babel, M. S., Gupta, A. D., & Clemente, R. S. (2007). Spatial assessment of groundwater use potential for irrigation in Teesta Barrage Project in Bangladesh. *Hydrogeology Journal*, *15*, 365-382.

Wan, Z., & Dozier, J. (1996). A generalized split-window algorithm for retrieving land-surface temperature from space. *Geoscience and Remote Sensing, IEEE Transactions on*, *34*(4), 892-905.

Wan, Z., & Li, Z. L. (1997). A physics-based algorithm for retrieving land-surface emissivity and temperature from EOS/MODIS data. *Geoscience and Remote Sensing, IEEE Transactions on*, *35*(4), 980-996.

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

Wang, P.X., Li, X.W., Gong, J.Y., & Song, C.H. (2001). Vegetation temperature condition index and its application for drought monitoring. Proceedings of International Geoscience and Remote Sensing Symposium. Sydney, Australia, 141-143.

Wang, S. Y., Hipps, L., Gillies, R. R., & Yoon, J. H. (2014). Probable causes of the abnormal ridge accompanying the 2013–2014 California drought: ENSO precursor and anthropogenic warming footprint. *Geophysical Research Letters*, *41*(9), 3220-3226.

Wang, W. S., Pan, Y. J., Zhao, X. Q., Dwivedi, D., Zhu, L. H., Ali, J., ... & Li, Z. K. (2010). Drought-induced site-specific DNA methylation and its association with drought tolerance in rice (Oryza sativa L.). *Journal of experimental botany*, *62*(6), 1951-1960.

Wilhite, D. A. (Ed.). (2005). *Drought and water crises: science, technology, and management issues*. CRC Press.

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

Wilhite, D. A., (2000), "Preparing for Drought: A Methodology," in Drought: A Global Assessment, Wilhite, D. A. (Ed.), London, UK: Routledge, Natural Hazards and Disaster Series, 2:89–104.

Woods, M. B., & Woods, M (2007). In Droughts, Learner Publications Minneapolis MN 55401 USA, 23–34.

World Meteorological Organization (1986). Report on Drought and Countries Affected by Drought During 1974–1985, *World Meteorological Organization. WMO*, Geneva, 118.

World Meteorological Organization. 2000–2009, the warmest decade. Press release no. 869, December8,2009.http://www.wmo.int/pages/mediacentre/press_releasesb/pr_869_en.html

World Meteorological Organization. 2000–2009, the warmest decade. Press release no. 869, December8,2009.http://www.wmo.int/pages/mediacentre/press_releasesb/pr_869_en.html

Wright, B. D., & Hewitt, J. A. (1994). All-risk crop insurance: lessons from theory and experience. In *Economics of agricultural crop insurance: theory and evidence* (pp. 73-112). Springer Netherlands.

Wu, J.; Zhou, L.; Liu, M.; Zhang, J.; Leng, S.; Diao, C. (2012). Establishing and assessing the Integrated Surface Drought Index (ISDI) for agricultural drought monitoring in mid-eastern China. *Int. J. Appl. Earth Obs. Geoinf*., 23, 397–410.

Yang, L., Wylie, B. K., Tieszen, L. L., & Reed, B. C. (1998). An analysis of relationships among climate forcing and time-integrated NDVI of grasslands over the US northern and central Great Plains. *Remote Sensing of Environment*, *65*, 25-37.

Yevjevich, V. M. (1967). An objective approach to definitions and investigations of continental hydrologic droughts. *Hydrology papers (Colorado State University); no. 23*.

Zargar, A., Sadiq, R., Naser, B., & Khan, F. I. (2011). A review of drought indices. *Environmental Reviews*, *19*(NA), 333-349.

Zhang, A., & Jia, G. (2013). Monitoring meteorological drought in semiarid regions using multi-sensor microwave remote sensing data. *Remote Sensing of Environment*, *134*, 12-23.

Zhou, G., Wei, X., Wu, Y., Liu, S., Huang, Y., Yan, J., ... & Wang, C. (2011). Quantifying the hydrological responses to climate change in an intact forested small watershed in Southern China. *Global Change Biology*, *17*(12), 3736-3746.

Zhou, L., Tucker, C. J., Kaufmann, R. K., Slayback, D., Shabanov, N. V., & Myneni, R. B. (2001). Variations in northern vegetation activity inferred from satellite data of vegetation index during 1981 to 1999. *Journal of Geophysical Research: Atmospheres*, *106*(D17), 20069-20083.