Flood Inundation Mapping Using Remote Sensing and GIS Techniques: A Case Study of Sokoto plain, Nigeria.

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Declaration

I hereby declare that the following thesis is a product of my own research. All information contained within this document is original work and to the best of my knowledge has not featured in any other published and unpublished literature, except where due reference has been given in the text.

Oluwadamilare Olawale Ajayi

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June 2016.

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List of Acronyms

AHP- Analytical Hierarchy Process

AU- African Union

AVHRR- Advanced Very High-Resolution Radiometer

DEM- Digital Elevation Model

DRR- Disaster Risk Reduction

DTM- Digital Terrain Model

EC- European Council

EOS- Earth Observation System

EME- Electro Magnetic Energy

ETM- Enhanced Thematic Mapper

FAO- Food and Agriculture Organization of the United Nations

GIS- Geographic Information Systems

GPW- Gridded Population of the World

JERS-1- Japan Earth Resources Satellite

LGA- Local Government Area

LIDAR- Light Detection Ranging

LSWI- Land Surface Water Index

MAUP- Modifiable Areal Unit Problem

MCE- Multi-Criteria Evaluation

ML- Maximum Likelihood

MNDWI- Modified Normalized Difference Water Index

MODIS- Moderate Resolution Imaging Spectro-radiometer

MSF- Medecins Sans Frontieres

NASA- National Aeronautics and Space Administration

NBS- National Bureau of Statistics

NEMA- National Emergency Management Agency Nigeria

NEPAD- New Partnership for Africa's Development

NDVI- Normalized Difference Vegetation Index

NDWI- Normalized Difference Water Index

NIR- Near Infrared

NOAA- National Oceanic and Atmospheric Administration

NRCS- Nigerian Red Cross Society

ORNL- Oak Ridge National Laboratories

RS- Remote Sensing

RADAR- Radio detection and Ranging

SAR- Synthetic Radar Aperture

SEMA- Sokoto Emergency Management Agency

SPOT- Satellites Pour l'Observation de la Terre

SWIR- Shortwave Infrared

TIN- Triangulated Irregular Network

TM- Thematic Mapper

UNFCCC- United Nations Framework Convention on Climate Change

UNISDR- United Nations International Strategy for Disaster Reduction

UNICEF- United Nations International Children's Emergency Fund

WHO- World Health Organization

Abstract

Flooding is one of the most frequent and devastating natural disasters and can often result in severe damage to agricultural products, commercial infrastructure, personal property and loss of human lives. Accurate delineation of flooded waters is an important research issue in determining both economic and personal risk. Determining the spatial extent and temporal pattern of flood inundation events has largely been achieved using remotely sensed imagery due to its synoptic and repeatable abilities. Along with Geographical Information Science (GIS) techniques, these technologies help facilitate the development of rapidly accessible inundation and vulnerability maps that will help prioritize mitigation efforts. This is particularly important in developing countries such as Nigeria where population growth is rapid and flood management resources are scarce. Specifically, this study focuses on the Sokoto-Rima river system in Sokoto State, Nigeria. The river system is key to the local agrarian economy and is subject to frequent flood events that have impacted upon agrarian systems and displaced thousands of people in recent years.

Central to this study is the use of the Moderate Resolution Imaging Spectroradiometer (MODIS), which offers frequent synoptic coverage at a national scale and is freely available. Multitemporal MODIS imagery is used here to measure flood frequency and extent through the Modified Normalised Difference Water Index (MNDWI) for selected flood periods 2003, 2010, 2012 and 2015. LandScan GRID population data from Oaks Ridge National Laboratory (ORNL) and the projected population data derived from the most recent Nigerian census data 2006 is used to estimate population vulnerable to flood inundation.

The delineation of inundated areas from non-inundated areas was undertaken using a threshold technique of the Modified normalized difference water index (MNDWI). The frequency and maximum spatial extent of floods, generated by comparing the four periods of flood extents, was informative and identified populations and Local government areas (LGAs) vulnerable to flooding. In a developing country where spatial information and infrastructure is limited, we report a simple, cost effective, and successful approach to detecting and mapping floods in the Sokoto region. Considering that MODIS data products are freely available and have broad national coverage that allow frequent observations, the results demonstrate a cost effective method of detecting and quantifying the extent of floods in Sokoto, Nigeria.

Keywords

RS, GIS, Flood, MODIS, NDVI, NDWI, MNDWI, LandScan, Sokoto.

CHAPTER 1

1.1 Background of study

Floods are considered to be the most persistent and devastating natural hazard around the globe (Berz et al, 2001; Sanyal and Lu, 2004) impacting on average 99million people each year between 2000 and 2008 (WHO, 2010). The incidence of flood events has become more frequent and severe around the world, a situation that has been attributed to climate change and sea level rise (Clark, 1998). Consequently, it is understood that risk associated with flooding will not subside in the future, where frequency and intensity of flooding is likely to increase and will undermine numerous areas across the globe (McCarthy, 2001; Jonkman, 2005). Today, the frequency and extent of so called '1-in-100 year' floods are occurring on an annual basis, which particularly effects developing nations (Klijn, 2009; Wisner et al, 2004). This is largely as a result of poor infrastructure and housing facilities, inadequate warning systems, low income and preparedness (Wisner et al, 2004). This is particularly true for Nigeria, the focus country of this study.

Although storm severity in Nigeria generally cannot be compared to those that occur in some developed countries (e.g. Hurricane Sandy or Hurricane Katrina), the aftermath of flooding in Nigeria can be severe and is now of great concern to people and a challenging issue for governments (Emuh, 2008; Egbinola, Olaniran and Amanambu, 2014). The present trend and future scenarios of flooding demand accurate temporal and spatial information on their potential risks and hazards, particularly in developing countries like Nigeria.

The advancements in the fields of Geographical information science (GIS) and remote sensing (RS) over the last two decades have largely, facilitated the operation of flood risk assessment and mapping. RS and GIS now play a major role in the management of natural hazards, such as flooding, as their occurrence and impact is spatially inherent (Coppock, 1995). First order flood risk management typically involves the generation of flood hazard maps showing areas prone to flooding based on historical flood data. However, in developing nations, historical data that accurately identifies flood extents and frequency can be poorly recorded and subjective, leading to inaccuracies in flood risk zoning and compromising mitigation efforts. Spatial technologes and infrastructure can play an important role in helping to acquire reliable, accurate and repeatably obtained spatial information on flood events. Moreover, spatial technology like GIS not only provide a way of visualizing the spatial distribution of flood events, but also allows the potential to further analyse and estimate likely damages caused by flooding (Clark, 1998; Haussmann and Weber, 1998).

Likewise, Joyce et al. (2009) suggests that RS is an essential tool in every stage of managing disasters; giving quick-response teams valuable near real-time information used in assessment and recovery efforts. While Joyce et al. (2009) notes some challenges that need to be overcome in connecting and obtaining information quickly, RS has proved to be a principal tool in the assessment, mapping and management of natural disasters. Moreover, the integration of both GIS and RS typically extends on the potential limitations of a single technology, that when combined enables greater capacity to obtain timely spatial information and improved capacity for flood risk assessment, identification and monitoring flood disaster (Pradhan, Pirasteh and Shafie, 2009; Pradhan and Shafie, 2009). Combined GIS and RS methods also help us to understand the causes of flooding by providing objective information on the spatio-temporal dynamics and evolution of flooding in specific areas (Smith, 1997; Brakenbridge et al, 2003; Brakenbridge et al, 2007). Importantly, space-borne sensors like the Moderate Resolution Imaging Spectroradiometer (MODIS) provide broad scale reliable and repeatable global coverage of moderate-to-large flood events over inaccessible areas or places where there are limited means of local flood monitoring information (Brakenbridge, 2006; Birkett et al, 2002).

1.2 Problem definition

Natural disasters such as floods have constituted a major problem in many developed and developing countries. It has been recognised that flood events are one of the main factors that keep Africa’s growing populace of city inhabitants from escaping poverty and hinders the United Nations 2020 goal of accomplishing notable change in the lives of the populace living in the regions of the African continent (Douglas et al, 2008). This is because most of the African cities do not have the infrastructure to withstand severe weather conditions and the means and equipment to monitor them. Poor flood mitigation planning in African cities, building along floodplains, and dam failures, coupled with other inappropriate environmental practices, contribute towards putting the African population at a higher risk.

In Nigeria, nearly 90 percent of natural hazard causing damages are because of flood events (Adeoye, Ayanlade, and Babatimehin, 2009). Flood events in the country have become a typical and recurrent event, having devastating effects on human livelihoods and infrastructural development. Unfortunately, the effect is felt more by some people than others in a way that recuperation is unlikely to be accomplished without external help (Blaikie et al, 1994). The nation's cities have, at different times, been affected by severe flooding, particularly in the densely populated urban areas like Port-Harcourt, Lagos, Aba, Kano, Ibadan, and Sokoto, resulting in loss of life and destruction of properties (Emuh, 2008; Mordi, 2011; Amaize, 2011).

The Sokoto region in Nigeria is one of the major floodplain areas in Nigeria. The plains are seasonally flooded by the Sokoto-Rima River and rainwater run-off during the rainy season. The land area in this location is near flat, making drainage of water on the terrain slow, permitting retention of flooded waters that disperse over large areas during large rain events. The Sokoto plains, in addition to its natural environment and processes, offers important economic benefits such as local large-scale irrigation farming, agriculture, animal grazing, small-scale fishing and flood recession agriculture (Mohammed, 2002). To support these activities and for flood mitigation, the Bakolori and Goronyo dams were built in 1978 and 1984 respectively. The Bakolori dam was built on the River Sokoto, a major water supply tributary of the River Rima, which in turn feeds the Niger River and supplies the Bakolori irrigation project (Mohammed, 2002). The Goronyo dam was constructed on the Rima River to control flooding and to release water in the dry season to the area and the neighbouring state, Kebbi state, for irrigation purposes (Akane and Jurgen, 2005). Unfortunately, both dams have fallen into disrepair where repeated severe flood events have led to major siltation with the dams, significantly reducing their water holding capacity, along with the collapse of the main wall on both dams. Consequently, the Sokoto plains are now once again subject to considerable flooding resulting in the loss of properties and lives (Akane and Jurgen, 2005). This has been exacerbated by changing rainfall regimes in the region to less frequent but more intense rainfall events. This has resulted in the further reduction and loss of activities such as flood recession grazing, agricultural lands, fishing activities, biodiversity and reduction in vegetation succession (Ekpoh and Ekpenyong, 2011). In particular, the floods of 2009, 2012, 2013 and 2015, all of which affected large areas of the state including the Sokoto plains, serve as clear evidence of their destructive nature and their adverse effect on agricultural products, livestock, property as well as human lives.

Despite this, *"floods are acknowledged to be among the most manageable of disasters"* (Keys, Angus and Benning, 1996). Several studies have been carried out on flooding in Nigeria, looking at their impact and plans for their abatement across many areas of the country (Ayoade and Akintola, 1980; Akintola 1994; Adeloye and Rustum 2011; Ologunorisa, 2009; Ishaya, Ifatimehin and Abaje, 2009; Egbinola, Olaniran and Amanambu, 2014). However, despite the well-established value of GIS and RS as a critical decision support tool for flood hazard, risk mapping and management, only a few studies incorporating these technologies have been carried out in Nigeria (Ikusemoran, Anthony, and Maryah, 2013; Muhammad and Iyortim, 2013; Ojigi, Adbulbakiri and Aderoju, 2013; Nwilo, Olayinka and Ayila, 2012). Of these studies, none have focused on the Sokoto region; the primary focus of this current study. This is unfortunate because it has increasingly been acknowledged by Egbinola, Olaniran and Amanambu, (2014); Abah, (2013) and Isma'il and Saanyol, (2013) that areas like the floodplains of Sokoto region, which experiences repeated perennial flooding due to its location, topography and recent heavy rainfall, should benefit from these RS and GIS decision support tools.

Like other flood-prone areas in Nigeria, a review of the flood events in Sokoto State shows that flood management and flooding has become one of the primary concerns of people and government decision makers (Amunobi, 2013). With the frequency in flooding likely to increase because of environmental changes (Bhuiyan and Dutta, 2012; Karamouz et al, 2011), there is a growing demand for accurate flood maps for managing disaster risk. Therefore, this study seeks to obtain baseline information on the temporal dynamics of flooding, their extent, and potential risk to human life in the Sokoto Sate region. Information about flooding underscores and justifies the need for this study, in order to help our understanding of flood events in this region that may assist mitigation efforts with the objective of minimising their destructive power.

GIS and RS have been mainstream decision support tools used to acquire, store, and analyse environmental information for the past two decades (Lillesand and Kiefer, 2004). These technologies have had a profound impact on progressing research techniques and outcomes in geography over this period. These innovations have been utilized for managing numerous flood prone and floodplain areas around the world. Specifically, therefore, this study investigates a RS approach to detecting and mapping temporal flood extents using existing image analysis methods along the Sokoto-Rima river system in Sokoto State, Nigeria. GIS is then used to estimate the population living within flood-affected areas in order to develop flood risk and inundation maps for Sokoto region of Nigeria. Notably, developing countries like Nigeria have poor spatial data infrastructure and resources to acquire high precision information. These countries often rely on global data sets to supplement local spatial information that is scarce or incomplete. Consequently, MODIS imagery and LandScan GRID population data are used to conduct this research where no other means of doing so is available. However, these data sets are of high quality, providing reliable consistent and repeatable information in the face of limited local data. MODIS data provides a daily global coverage of land surface information, while the LandScan GRID population data *"is the finest resolution global population distribution available representing ambient population"* (ORNL, 2016) that aims to account for people's mobility.

1.3 Research questions

Specifically, this research sets out to answer the following questions:

1. What is the most suitable image analysis method to delineate flooded areas along the Sokoto-Rima river system?
2. What are the various geospatial techniques available for delineating flooded areas and their extent?
3. What is the extent of flooded areas in each of the LGAs along the Sokoto-Rima river system?
4. Where and how many people are at risk from flooding?
5. How suitable is MODIS imagery in delineating flooded areas along the Sokoto-Rima river system?
6. How suitable is LandScan population data in identifying people at risk from flooding?

1.4 Research aims and objectives

From the research questions posed, the primary aim of this study is to develop a better understanding of the temporal flood extents and the people at risk from flooding along the Sokoto-Rima river system in Nigeria in order to prioritise mitigation efforts for disaster risk reduction in this area.

To this end, the study explores the use of remote sensing (RS) and geographical information science (GIS) technology through freely available MODIS imagery and LandScan GRID population data in estimating population risk to flood events where the specific objectives of the study are:

1. To investigate whether the temporal and spatial resolution of MODIS imagery can suitably reveal all recorded severe flood events over the selected periods.

2. Investigate a suitable image analysis technique that will adequately map the distribution and quantify flooded areas for each of the recorded flood events.

3. To develop frequency of inundation and spatial distribution maps of these flood events.

4. To assess the suitability of the LandScan GRID population data to reveal real population concentrations against normalised population counts recorded at the LGA level from the most recent Nigerian census, conducted in 2006.

5. To investigate the spatial relationship between flooded areas and population concentrations to identify the number of people that are vulnerable to flood events using GIS.

6. To evaluate flood risk mapping results against historical records of people affected by these flood events.

1.5 Scope of study and anticipated outcomes

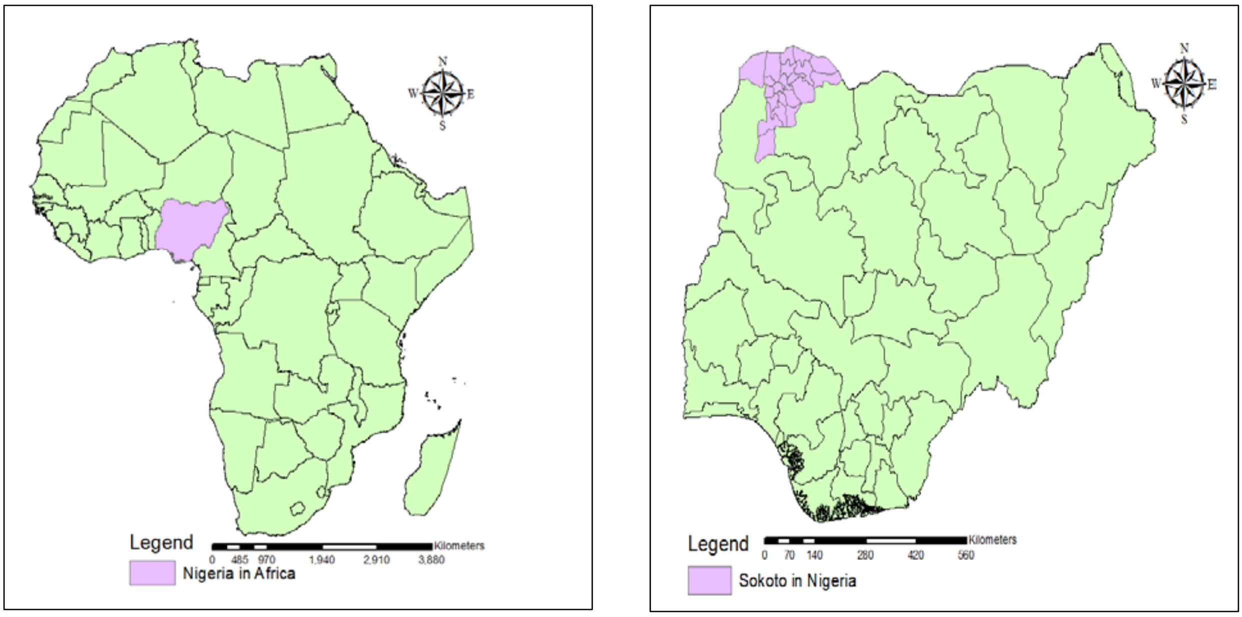
This study examines the use of Moderate Resolution Imaging Spectro-radiometer (MODIS) data and the LandScan GRID population data to map inundation and estimate the number of people at risk/vulnerable in Sokoto, Nigeria. Some of the terms and concepts associated with flood mapping and disaster risk management will be discussed along with the applications of remote sensing (RS) and Geographical information system (GIS) in monitoring and mapping flood events. The focus of this study is to detect the flood, identify the areas at risk, estimate the total number of people vulnerable using the LandScan GRID population data (2014) and create a flood inundation map showing the areas vulnerable to flooding.

This research will be an addition to the studies of flood hazards/risk/vulnerability mapping in Nigeria. This study, contributes towards reducing the impacts of floods in Sokoto, Nigeria because it will serve as input for the integration of flood risks management strategies and spatial planning in the area. The flood inundation maps can further be utilized for easy and quick identification of areas of potential flood hazard to minimize losses. In addition, this methodology can be used as a tool by the authorities concerned to control and apply management and land zoning, reduce flood hazards, protect the environment, provide insurance and plan development.

1.6 Study area

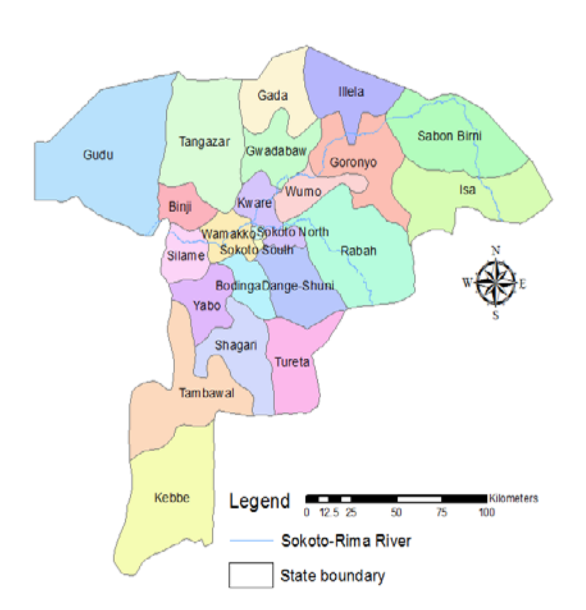
1.6.1 Location

The study area for this research is Sokoto located in the North-western region of Nigeria. The state is located at latitude 13° 03’ 39” N and Longitude 5° 14’ 20” E, and was established in 1976 (Figure 1). The state was one of the largest in Nigeria before two other states Zamfara and Kebbi were carved out of Sokoto State in the early and mid-90s. The state covers a land area of approximately 33,777km^2 and shares its borders with the Niger Republic to the north, Benin-republic to the west and Niger State to the southeast. With a population of more than 4.3 million, Sokoto-city, which is the modern day capital of the state, remains the most densely settled part of the state.



a) Nigeria in Africa

b) Sokoto state in Nigeria



c) Sokoto State LGAs d) Map showing River Sokoto and its tributaries.

Figure 1.1 (a-c) - Nested map series showing Africa, Nigeria, Sokoto and the LGAs (Source: GIS-DIVA vector dataset).

Figure 1.1 (d) Map of Nigeria showing the River Sokoto and its tributaries (Wikipedia, 2016).

1.6.2 Relief and drainage

The Sokoto area is situated within the Iullemeden basin, which is surrounded by the Precambrian basement complex (Greigert, 1961). The area is covered by a progression of sedimentary rocks that has been deposited over the basement complex. These rock sediments were laid down under different environmental settings varying from continental to marine events. The relief of area is generally a lowland with an average height of 300m above sea level, known as the Sokoto plains. Davis (1982) described this relief as a monotony of lowland disrupted by mesas and escarpments and these escarpments, along with the hills, ascend to around 488m.

The area is drained by the River Sokoto-Rima and its tributaries, most of which rise in the South-eastern area of the state and in Kaduna the neighbouring State. Two of the tributaries flow in a northerly direction to join Rima while the two other tributaries, flow westwards to join the main River Sokoto.

1.6.3 Climate and vegetation

The climate of the area is tropical continental and is dominated by two opposing air masses; tropical continental and tropical maritime. The tropical continental air mass (dry) blows from the Sahara Desert while the tropical maritime (moist) blows from the Atlantic Ocean. The first predominates during the dry season while the other predominates during the rainy season. The annual rainfall is between 500mm and 1300mm and the majority of this falls between the month of June and September, which is when most of the flooding occurs. Moreover, the state is characterised by two extreme temperatures relative to its tropical position: the cold and hot seasons. There is the prevalence of Harmattan between the months of November and February, which is characterised by dust-laden winds and very cold temperatures.

The study area falls inside the Sudan Savannah zone and the vegetation in this area is characterised by scatters of acacia and thorny species. The courses along the river are also lined with Dum palms, which are interspersed with herbaceous cover of annual grasses.

1.6.4 Geology and soil

As noted earlier, the study area lies within the Iullemeden basin, which is surrounded by the Precambrian basement complex. Minerals such as limestone, gold, marble, clay, kaolin, feldspar, gypsum and lignite can be found in the area. Soils in this study area are sandy topsoil with clayey subsoil, with alluvial soils predominating along the flood plains of the river valleys. Along the border to the north with the Niger Republic, Aeolian deposits of variable depth cover the undulating plains. The topography of the area comprises of a floodplain with rich alluvial soils that are appropriate for the cultivation of a variety of crops. There are also ranges and isolated hills scattered across the area (Ekpoh and Ekpenyong, 2011).

1.6.5 Brief historical account of floods in Sokoto

The Sokoto state is located in a floodplain and flood records extend back as far as 1978 (Adams, 1992). Occurrences of floods in this area of the nation in recent times have been of great concern and a challenge to the government, researchers, and people. There have been journalistic and non-quantitative reports of flooding for different locations in the country including Sokoto Sate. However, they are superficial, subjective and lack directions for policy makers and professionals (Aderogba, 2012).

During the last decade in Nigeria, flooding has been on the increase as a result of climate change coupled with intensive human activities. The 2009 floods in Nigeria affected 150,000 people and displaced tens of thousands across the Northern states including Sokoto state (NEMA, 2009). The substantial downpour in the northern part of the country and neighbouring country Niger Republic during the months of August and September 2010 also brought about extreme flooding in Sokoto State (Figure 1.2-1.4). The flood situation in the state during this period was compounded by the overflow of the Rima River and the breakdown of Goronyo Dam amid the first week of September 2010. Numerous houses were submerged and hectares of farmland including domesticated animals and crops were washed away by floodwater that claimed over 40 lives and displaced a huge number of families in 50 communities of 11 Local Governments areas out of the 23 that made up the Study area (People's daily online, 2010).

According to the Nigerian Red Cross Society (NRCS) after an in-depth assessment of the 2012 flood, with support from the International Federation, 10,214 farms were destroyed, 1,524 water wells contaminated by floodwater, while 1,786 toilet facilities were damaged and 2,972 families were displaced by the flood (NRCS, 2011). The floods also damaged some public infrastructure including schools, roads, bridges and the Usmanu Dan Fodio University, Sokoto State. After the rainfall ceased and floodwaters receded, access to some of the affected areas was still a major problem due to the collapse of bridges and the difficult terrain. Egbinola, Olaniran and Amanambu (2014) described the 2012 flooding as the worst in more than 40years where, 33 out of the 36 states in the country were affected and an estimation of about 7million individuals were affected by the floods. This, led to about 363 deaths and more than 600,000 houses damaged or destroyed with the internal displacement of 2,157,419 people (Egbinola, Olaniran and Amanambu, 2014). The recent severe flooding in September 2015 began with heavy rainfall that resulted in an increase, overflow and release of excess water from the Goronyo Dam by the River Sokoto, which led to an evacuation of no fewer than 10,000 people from the 20 flood-prone communities in the Sokoto region (Figure 1.5) (Premium times, 2016).

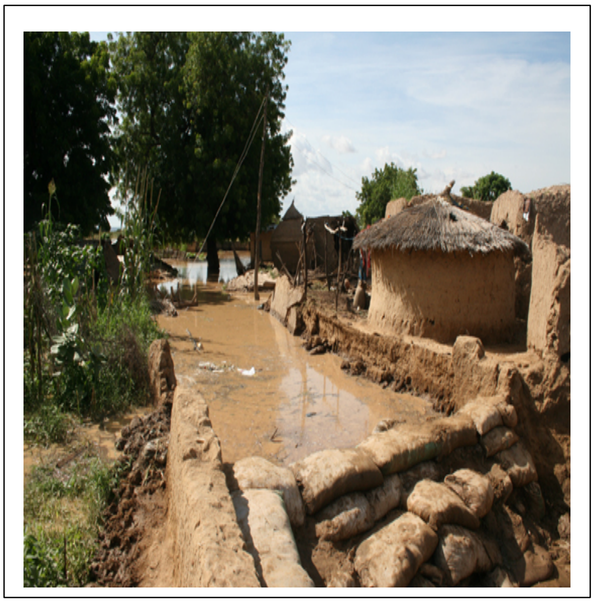


Figure 1.2

Figure 1.3

Figure 1.4

Figure 1.5

Figure 1.2-1.4 Flooding in Sokoto state, Northern Nigeria, September 2010. (Source: Chris Houston/MedecinsSansFrontieres **(**MSF)

Figure 1.5 Submerged houses by the August 2015 flood in Sokoto state, Northern Nigeria. (Source: Nigerian eye new).

These specific flood events underpin this study where it is hoped to quantify the extent of these flood events for the purpose of understanding and mitigation for risk reduction. This will help further to contribute towards reducing the impacts of floods in Sokoto, Nigeria because it will serve as input for the integration of flood risks management strategies and spatial planning in the area. The flood inundation maps can further be utilized for easy and quick identification of areas of potential flood hazard to minimize losses.

1.7 Thesis structure

Chapter 2 of this thesis will review the different definitions of flood; discuss the principle types of flood, causes of flood and the hazards usually associated with flood events. This will be followed by a look at flood mapping and a review of the different terms and concept used in disaster risk management. Chapter 2 will conclude with a review of RS and GIS applications for monitoring and mapping flood inundation and how some of these techniques have been used and sometimes combined in mapping flood hazard, risk and inundation.

Chapter 3 focuses on the methods used in carrying out this research. Specifically, it will present data sources used for mapping inundation and estimating the population at risk; how the data was processed and the methods used in order to detect and map the frequency of flooding and its impact on populous places.

Chapter 4 presents the results of this study along with a discussion on the information derived from the flood analysis. The extent of inundation and the population at risk will be explained.

Chapter 5 concludes the thesis with the research findings, outcomes, limitations and recommendations for future studies.

Chapter 2

2.1 Flood management

2.1.1 Definition of flood

Flood remains the most frequently reported, and costliest disaster around the globe, constituting over forty percent of natural global catastrophe (Tapsell and Tunstall, 2008). It is for sure the most well-known of all the natural hazards which frequently claims over 20,000 lives every year and has impacts on about seventy-five million people around the world (Smith, 2006).

Flooding, though a common event all over the world, is more widespread and has weighted impact in developing countries like Nigeria (Andjelkovic, 2001). This event has emerged to be one of the main issues of concern in the development of the country as the frequencies of such events and the magnitude of the misfortunes as far as lives and properties are concerned are becoming frightening (Oyebande, 1983; Emuh, 2008).

The definitions used to describe flooding are many and may mean something different to different researchers with respect to the context and location in which it is used (Brooks, Adger, and Kelly, 2005; Brooks, 2003). Nicholls (2002), in defining floods, described it as a process whereby water brought into a drainage channel is more than it can convey. The abundant water flows over the banks and spreads out to the surrounding areas, creating the condition where we have a flood.

According to Burt et al, (2002), flood can be said to be an unusual water accumulation above the ground, which is created as a result of heavy rainfall, rapid runoff from concrete surfaces or high tides. Natural floodplains happen to be a characteristics feature of some rivers. The most severe floods happen along coastal areas. In these regions, substantial precipitation and poor soil combine to bring about flooding.

Smith and Ward (1998) demonstrates that there are a number of components utilised to depict the nature of flooding and its extent. For example, its range of coverage, the speed of flow, the volume of water released by time and duration. However, these factors are generally influenced by the amount of rainfall, soil type, the period of year, geomorphic characteristics as well as slope of terrain. In general, the reasons for increasing flood events in many parts of the world are as a result of climate change, increasing population, changes in land-use pattern and land subsidence (Smith and Ward, 1998; Bhuiyan and Dutta, 2012; Karamouz et al, 2011). Issues linked to flooding and populace vulnerability have considerably increased in last few decades as a result of a number of factors including urbanization in the areas liable to flood, increase in the density of the households, sub-standard constructions and settlement pattern and changes in the land-use pattern (Pelling, 2003). In addition, the dangers of floodwaters are associated with various factors such as rate of rising waters and recurrence, load of sediment, water depth, velocity and duration (Klijn, 2009).

2.1.2 The principal types of floods

There are different nomenclatures given to describe types of flood events and they can be described or characterised according to the source of water, the geography of the area receiving it, the river course and velocity, or the cause. The major different types of flood include; fluvial floods, urban floods, coastal floods, and pluvial floods.

Coastal floods are brought about by extreme storm events bringing severe onshore coastal winds and vast waves typically coupled with high tides that floods estuaries and coastal zones with ocean water (Klijn, 2009; Wright et al, 2008; EC, 2007). Usually, large areas are affected and means of living and human lives can be lost in the process. Forecasts of a coastal storm can normally be between a couple of hours to days ahead (Klijn, 2009) while the conceivable rise in the level of the sea can happen between four to eight hours after the storm surge has begun (Wright et al, 2008). Flooding along the coast is usually followed by huge, battering waves and floating debris that lead to erosion of the beach and large-scale destruction to infrastructure along the coastline (Wright et al, 2008).

River floods, on the other hand, are caused as a result of long periods of precipitation in the catchment zone that lead to an increasing level of water that eventually overflows the banks of the river (Wright et al, 2008; EC, 2007). This type of flood starts slowly and is typically confined to floodplains (Wright et al, 2008; Wisner et al, 2004). They are often known by their slow speed that effect largely inundated zones that can bring about many damages but few fatalities (Klijn, 2009).

Flash floods occur in hilly areas, in the upper level of the basin of a river during extreme rainfall (Wright et al, 2008; Klijn, 2009). Even though this type of flood occurs under the subdivision of river flooding (Wisner et al, 2004; Wright et al, 2008), they are regularly considered as another type of flood because of the extreme damage and high fatalities they can bring about. Klijn (2009) refers to this type of flood as “small-scale killers” as these floods are the small types that can happen regularly. The high speed and load of debris of this type of flood (Wright et al, 2008) and the trouble in anticipating them (Klijn, 2009) make early warning and evacuation a big problem.

The Ponding or Pluvial flood types occur when water from precipitation begins to accumulate in low-lying areas with soil types that are clayey in nature (Klijn, 2009). This type of flood starts slowly and can be predicted days ahead, though they can bring about major damage, particularly in urban zones, however not often with fatalities (Klijn, 2009).

Lastly, urban flood types can result from flash floods, river floods or coastal flooding. Urban flooding often results from a lack of good drainage, impervious surfaces, coupled with high rainfall. Most urban areas have paved surfaces with little soil and poor drainage systems, which do not allow the amount of rain that is falling to drain away. In developing countries in particular, where there are little or no drainage/stormwater systems, water disperses quickly over impervious surfaces and is deposited in another place leading to a flood. The condition is known for its repetitive and systemic effect it has on the area, regardless of whether they are close to or located in a floodplain or water body (Klijn, 2009).

2.1.3 Causes of flood

Floods usually are most commonly caused by excessively prolonged and/or heavy rainfall when the natural watercourse does not have the ability to convey surplus water. However, there are also other ways in which floods can occur apart from heavy or prolonged rainfall, which can be ascribed to other natural hazards or human-caused hazards like dam failure or storm surge associated with a tropical cyclone or high tides coinciding with higher than ordinary river levels (Wisner et al, 2004; EC, 2007). Ojo (2011) identifies that floods in developing countries are often caused by economic pressures from developers, lack of institutional capacity at the municipal level, poor or lack of standard drainage system on roads, unrealistic regulations, unregulated developments, and the ineffectiveness of planning regulation by permitting development on flood plains.

Climate change is a significant driver of flooding and it is a problem that is identified with the physical, social, economic and cultural environment of any country. This is a key component of the environment that mould and re-mould different individual activities in a particular environment. The United Nations Framework Convention on Climate Change (UNFCCC) defines climate change *"as a change of climate which is attributable directly or indirectly to human activity that alters the composition of the global atmosphere and which is in addition to natural climate variability observed over comparable time periods"* (UN-ISDR, 2009a). Human activities such as burning of fossil fuels, industrialization, deforestation, technology development, natural factors such as solar radiation, agricultural activities and urbanization are significant causes of climate change (Mshelia, 2005). This change in the climate is making weather less predictable, particularly in the developing countries such as Nigeria where means and equipment to manage and predict weather conditions are not sufficient (Nwafor, 2007). This unpredictability of precipitation during the rainy season has brought about untold hardship in many regions across the country.

2.1.4 Hazards associated with flooding

Notably, flood events do not necessarily constitute a hazard where it is a necessary requirement of some natural ecosystems and where regular "controlled" flood events necessitate irrigation for crops. However, flooding can become a hazard when it is uncontrolled and where there is the potential for negative impacts on infrastructure and human lives. This is more evident in coastal and floodplain areas where the desire to live in areas susceptible to flooding out ways the perceived risk.

Flood effects can be grouped into primary, secondary and tertiary or long-term effects (Klijn, 2009; EC, 2007). Primary flood effects are those that happen as a result of direct contact with flooded water, such as injuries and loss of life, secondary flood effects are those associated with health implications and disruption of services. Tertiary flood effects are those long-term effects such as economic loss due to disruption to food production and tourism or restoration of ecosystems and infrastructure due to realignment of river channels. All through the last century, flood events have been one of the costliest disasters in terms of both human casualties and property damage. Pelling et al, (2004) estimated that over one hundred and ninety-six million individuals in more than ninety nations are vulnerable to flooding calamity each year. Floods have effects on both individuals and communities and have environmental, economic and social consequences. The impacts of floods can also be both positive and negative, and they vary greatly depending on the flood extent and the location of the flood, and the vulnerability and value of the built and natural environments they affect. However, the negative effect of flooding is usually more than the positive.

As indicated earlier, a rise in the occurrence of flooding and its effects can be attributed to the impact of climate change and the propensity of people to dwell in areas that are liable to flood (Klijn, 2009; Wisner et al, 2004). In spite of the risk, people living in areas prone to flooding often do so as a matter of ignorance or by choice. However, many people living in flood-affected areas or move back into areas where severe flooding has occurred, do so as they have little choice. This is particularly true in developing countries where flood plains are often crucial to their means of living. They move back to these areas (Wright et al, 2008; Wisner et al, 2004) where the soils are rich in nutrients and where the river provides water for aquaculture and irrigation of crops like the Sokoto plains where agriculture is their main practice and source of income.

Archived and reported severe flood events/disasters in Nigeria afford good insights into flood-related issues and the potential extent of flood risk in the country. For example, during the 2012 flood event, 33 out of the 36 states in the country was affected and an estimation of about 7million individuals were affected by the floods, leading to about 363 deaths and more than 600,000 houses damaged or destroyed leading to the internal displacement of 2,157,419 people (Egbinola, Olaniran and Amanambu, 2014). This is the worst the country experienced for more than 40 years. The 2012 flood event lasted seven days and during this period, Sokoto State witnessed a full season of flooding as a result of the dam breakage on Rima River, which resulted in no fewer than 50 villages been ravaged by floods, displacement of more than 130,000 people in nine councils and the death of eight people. Out of the 50 villages in this location, 20 were completely submerged, while major roads and bridges were destroyed (UNICEF, 2013).

2.1.5 Understanding the areas liable to flooding

The regions along a river that are liable to flood disaster can be separated into distinctive zones, specifically the floodway, floodplain, and flood line. The first is recognised by high stream speeds, the presence of flowing debris with possible erosion and deep water levels. Any development apart from infrastructure that is critical like bridges should never be allowed in this area (Wright et al, 2008; UN-ISDR, 2004). The other, floodplain represents all the zones encompassing the channel of the river that can be immersed amid the event of a flood (Wright et al, 2008). There exists no determinable limit for a floodplain as there is no restriction on the size of a flood. As the elevation of a point on the floodplain increases, the likelihood of immersion reduces (Alexander, 2001). A flood line, however, is just a line that characterizes a range whereby no development ought to occur, as it is a sign of the flood water level with a predefined yearly exceedance likelihood (Alexander, 2001).

2.1.6 Flood mapping in floodplains

In numerous floodplain environments, maintenance occurs naturally by natural flooding regimes (Junk, 2002) fed by rainfall and river waters (Barber et al, 1996). Natural floods are very important in this type of ecosystem. This natural flooding period helps to maintain the soil fertility in natural and agricultural floodplain areas by transportation of sediments and nutrients. However, understanding the frequency, extent and changes that are likely to occur because of flooding in a particular floodplain is important because it enables better planning and timing of urgent and non-urgent restoration and mitigation efforts.

To enable more strategic management of flooding in floodplain areas, there is a need for information that is regularly collected and up-to-date that informs decision makers about the characteristics of natural flood regimes. This should include both non-spatial and spatial information. Multitemporal flood maps are invaluable in this regard (Michael, 2007). Flood mapping have been undertaken using different techniques (Sandholt et al, 2003, Wang, 2006) which include the utilization of airborne remote sensing (RS), hydrodynamic models, and ground survey. However, because of the difficulties in accessing and acquiring information over many, widely dispersed floodplain areas that can be hundreds of square kilometres in size, these techniques are time-consuming and expensive. Utilizing these methods is often then limited to smaller regional areas. Satellite RS presents the most reliable way for mapping large, inaccessible floodplains like the Sokoto plains. Microwave and/or optical sensors on board satellites gives a synoptic view over vast areas (Toyra et al, 2002). A good example is a study by Rachael et al, (2015) that used Landsat TM imagery to map inundation in the heterogeneous floodplain wetlands of the Macquarie Marshes, Australia. The marshes which covers an area of 19,850 hectares in South-east Australia, is one of the largest semi-permanent freshwater wetlands in the area.

2.2 The concept of disaster risk management

It is important to understand common concepts utilised in disaster risk management in view of the fact that this study forms a component of a progression towards minimising risk. Different terms and definitions are additionally included for a more comprehensive overview. Disaster Risk Reduction (DRR) underpins the motivation for this study and this defined as the structured growth and application of strategies, practices, and policies to reduce vulnerabilities and disaster risks in every part of a community, to avoid or to reduce the harmful effects of hazards (UN-ISDR, 2004). As earlier, pointed out in the first chapter, natural disasters, and floods specifically have become recurrent and this is likely to continue in the future because of climate change. It might hence, not be attainable to mitigate all floods and their associated risk. What is important though is to attempt to comprehensively understand flood risk and related impacts in the context of DRR. This is made possible by obtaining baseline information through the development of flood risk, inundation and hazard maps, which can be utilized to outline proper measures to control and reduce the impacts of flooding and to strengthen and shape the ability by which people can adapt (AU and NEPAD, 2004). Notably, flood risk/vulnerability maps are those maps showing the projected damage or losses experienced by flooding, whereas flood hazard maps are those showing the inundation area (Tsakiris, Nalbantis and Pistrika, 2009; EC, 2007).

2.2.1 Defining natural hazards and disaster

Natural hazards refer to those natural phenomena or processes that occur in the biosphere, such as geological, hydrological or climatological processes (UN-ISDR, 2007) that can bring about harm, loss of life, loss of livelihoods, damage to properties, environmental degradation, or socio-economic disruption (UN-ISDR, 2009a). The degree of these types of hazards can be affected by human-caused activities, for example, environmental degradation and urbanization (The World Bank, 2010).

The word Disaster is derived from the combination of two French words "des' and 'aster' "Desastre" meaning 'bad'. A disaster is a serious problem that disrupts the way a society or community functions bringing about widespread economic, human, or material losses that surpass the capacity of the affected society or community to adapt, utilizing its own resources (UN-ISDR, 2009a). Disasters are regularly confused with events that are abrupt and unexpected; however, disasters can develop over a long period, such as drought (UN-ISDR, 2009b; Amin and Goldstein, 2008). The interaction between hazards and disasters must be given great consideration and that it should be noted that not every hazard leads to a disaster. If a hazard destroys lives and source of living of a society to such a degree that they are not able to adapt, then that hazard has turned into a disaster (Venton and Hansford, 2006; Amin and Goldstein, 2008). Thus, a disaster takes place when a hazard is significant enough to affect people that are vulnerable and results in disruption, casualties, and damage.

2.2.2 Defining vulnerability and capacity to cope

Vulnerability refers to the extent to which a structure, community, environment, individual, system or unit can be adversely affected by a hazard (UN-ISDR, 2007). Physical, economic, social and environmental processes (Venton and Hansford, 2006; UN-ISDR, 2009a) dictate the conditions that intensify the vulnerability of a group of people. Venton and Hansford (2006) defined vulnerability as the state of being able to sufficiently predict, withstand and recuperate from the impacts of a hazard. The extent by which a hazard will affect a number of people in a particular place will not merely lie in its physical parts of the vulnerability but also on the socio-economic conditions. A better comprehension of ways of coping can, therefore, throw light on who and what are at risk from the flood, and how it develops into risks and its effect.

Capacity to cope on the other hand can be defined as the capacity of a community to utilize the available resources to them to minimize the adverse impacts of a hazard (UN-ISDR, 2009a; Wisner et al, 2004). These resources can incorporate social and physical means that give way to safety and means of livelihood (Wisner et al. 2004). The management of these available resources is a continual operation that takes place after, during and before a hazard (UN-ISDR, 2009a). Hazards, as we know, are always prevalent, but it only becomes a disaster when there is a greater vulnerability and less of a capacity to cope.

2.2.3 Defining flood hazard

The word hazard has its origin in French word ‘hasard’ and in Arabic ‘az-Zahr’ meaning ‘chance’. Hazard as defined by the UN-ISDR (2009a) as a potentially damaging phenomenon, physical event or human activity or condition that may bring about harm, loss of lives, loss of livelihoods and properties, environmental damage or disrupt the social and economic sector. Hazards can be grouped into two different categories namely artificial and natural. While the artificial hazards are those due to the negligence of humans like pollution, dam failure, and poor waste disposals etc. natural hazards are those caused typically as a result of natural phenomenon like tsunamis, cyclones, earthquakes, flooding etc. (UN-ISDR, 2009a). Flood hazard, therefore, is defined as the exposure to flooding and depends on flood extents and magnitudes like the depth of the flood, duration, and velocity.

2.2.4 Defining flood risk

Often when people talk about risk, they actually mean hazard. However, risk is defined as the likelihood of expected losses or harmful outcomes such as personal injuries, deaths, means of livelihood and economic loss as a result of the interaction between human-induced or natural hazards and associated vulnerable conditions (UN-ISDR, 2004). Like studies undertaken by Kron (2005) and Karim, Mimura and Nobuoka, (2005) who both defined flood risk as a result of flood vulnerability and hazard. Risk is described “*generally as the uncertain product of a hazard and its potential loss”* (Kron, 2005; Crichton, 2002). It has been defined as an extent of the overall adverse effects of flooding (Dang, Babel and Luong, 2010). It includes the notion of risk to life, the trouble and chance of removing people and their belongings amid a flood, production loss and possible damage to buildings, social disruptions, and destruction to public properties. Importantly, since people have the ability to react and shield themselves from the impacts of hazards, the capacity to cope is incorporated into the notion of risk (Baas et al, 2008).

2.3 Review of GIS and remote sensing in flood management

As noted earlier, floods have been acknowledged to be among the most manageable of disasters (Keys, Angus and Benning, 1996). Geographical information system (GIS) along with Remote sensing (RS) technology has been shown to be an important tool for flood monitoring and mapping in recent years (Lillesand and Kiefer, 2004). The focus of these decision support tools revolves around the preparation of flood maps (risk/hazard) for vulnerable areas and the delineation of flood zones.

A GIS is an information system designed to acquire, store, process and display spatial or geographical referenced data (Goodchild, 2006). Coppock (1995) notes that GIS has a key part to play in flood mapping and other disaster management scenarios because natural disasters are multidimensional and the spatial component is intrinsic. A key point of using GIS in flood management is not just because of its visualization capabilities of flooding, but it also provides spatial analysis tools to help estimate possible damage and risk to vulnerable areas. RS, on the other hand, is the primary way in which information on flood extent and frequency is derived. Satellite images acquired during, before and after a flood event can give valuable information about the occurrence of flooding, their intensity and progress. These images can also provide information on delineating the river course, its spill channels, embankments and spurs affected by flooding that allow appropriate mitigation and flood relief measures to be planned and executed on time.

2.3.1 GIS applications for monitoring and mapping floods

Accurate floodplain mapping is one of the most valuable tools for avoiding severe losses from floods (social and economic). Geographical information system (GIS) is a tool that can be utilized in each progression of the assessment of flood risk for modelling, management of data, and prediction (Goodchild, 2006; Maidment, Robayo and Merwade 2005). Currently, GIS is being utilized as a major tool for preparing flood hazard maps in many flood prone and floodplain areas. Azagra-Camino (1999) used GIS to model the extent of potential flood areas concentrating on a small study zone making use of a more exact terrain model developed from a Triangulated Irregular Network (TIN). The TIN was created from stereo aerial photographs, which brought about a highly precise landscape illustration of the area of study. Azagra-

Camino (1999) was then able to develop a topographic digital elevation model (DEM) from the TIN and derived channel and stream geometry for utilization in a flood model. The flood visualization results gave highly precise two-dimensional (2D) and three-dimensional (3D) flood hazard maps. Yalcin, (2002) utilised multi-criteria evaluation (MCE) technique to examine and discover the vulnerable flood zones in northern Turkey. In this study, GIS was incorporated with MCE. The study used seven criteria which were developed into spatial data layers using GIS software. A criteria ranking method was used to order the importance of each layer/criteria where a Boolean approach, and pairwise techniques were utilized to make a composite map of the flood vulnerable areas. Based on this technique, three separate results were produced and differences between the three were analysed. Their study provided and showed useful ways to examine alternatives and evaluate criteria to reduce uncertainty for the decision solution. Lawal (2012) also used a multi-criteria evaluation method alongside Analytical Hierarchy Process (AHP) within a GIS to assess flood susceptible zones. The outcome of the assessment indicated zones that are susceptible to flooding which also helped in the effective decision-making and development of control policies. The decisions and control policies indicated that structural measures alone could not withstand the current flood phenomenon common in most parts of the world today; therefore, the requirement for a sustainable method to control flood is unavoidable. Importantly, since about 80 percent of data used by decision makers is connected geographically (Malczewski, 1999), GIS provides the ability to model these spatial relationships for better decision making.

Dutta, Herath and Musiake, (2003) also utilised a mathematical model for assessing the estimate of losses caused as a result of flooding in Japan. The model created is a combined flood misfortune distributed estimation model and a physically based hydrological distributed model. They showed how the model requires multi-temporal spatial data such as Satellites Pour l'Observation de la Terre (SPOT) and Landsat satellite data to obtain comprehensive land cover information and to delineate the urban flood zone. The study showed how the spatial model output was equivalent to actual damages observed. The model was likewise demonstrated to perform better in assessing the damage caused by flooding in an urban area compared to the damage in rural areas. This study also showed that the process of using data from different sensors is not straightforward and often requires iterative experiments to arrive at an optimal result.

Sanyal and Lu (2004) also utilized GIS for evaluation of flood damage in the monsoon Asia by designing a Flood Hazard Map where its key function was to support proper planning of land use in flood-prone zones. It produced readily available, easily read flood hazard maps and charts, which assist the managers and planners in determining zones that are at risk and set up their efforts of alleviation/reaction.

Hardmeyer and Spencer (2007) used GIS to develop flood hazard maps in Rhode Island indicating zones where the flood is likely to occur and reoccur in an urban area on the island. They report that the GIS map was extremely valuable to town planners and other administrators in viewing the potential flood zones and the likely damages that could occur. This would allow them to recognize priority zones, therefore, improving flood relief arrangement and communication of the data to the general population and different stakeholders.

Fox et al., (2008) in North Carolina, USA used a 3D ArcGIS visualization method to evaluate flood problem in this area. The visualization methodology was exceptionally valuable and helped in the recognition of flood areas for successful decision-making. This study has additionally demonstrated that GIS information can easily aid in risk aversion, through mapping of land cover, dangerous zones, drainage patterns and through spatial modelling.

Furthermore, Konadu and Fosu (2009) in their study in the city of Accra, Ghana utilized a vector based GIS and Digital elevation model (DEM) to outline watershed limits and foresee regions of possible overflow during a flood event. In their GIS study, raster-based analysis was conducted to create information on the direction of flow, stream segmentation and other processes. These data were valuable in building a vector representation of the drainage lines in the catchment area. The extent of the flood was simulated based on the inferred drainage lines, ability to hold precipitation run-off and their depth. Zones that could face possible flooding where indicated using the flood level contours obtained from the selected flood water levels.

A study carried out Samarasinghe et al, (2010) in Kalu-Ganga River, Sri Lanka is also an illustration in which these earth observing methods have effectively been utilized in analysing flood risk and mapping. In their study, two images obtained amid the dry season and during flooding were analysed to determine flood range. Their outcomes show that flood range derived from the information were similar to those collected when one of the flood inundation models was utilized and based on this, they were able to ascertain their model. The study additionally utilized GIS information and capacities for flood imitation and risk mapping. They were able to do this in a GIS environment by overlaying vulnerability and flood hazard values with the polygon map of the region, Samarasinghe et al, (2010) were able to map out high, medium and low flood risk areas.

Also in India, Sanyal and Lu (2004) utilized Landsat Enhanced Thematic Mapper Plus (ETM^+) and SAR images to segregate zones of flooded and non-flooded areas. The study pinpoint some major issues experienced in extracting information accurately from the affected flood areas on SAR images. A common problem associated with the relation between roughness of the terrain and surface water and the radar wavelength. In addition, dense forest cover acts as an obstacle to accurately identifying flooded areas from this imagery. In some African settlements that are rural in nature and often surrounded by trees, it will be very difficult to detect flooding within this type of settlement as a result of this.

Notably, almost all of the studies described above were largely facilitated by the acquisition and use of relatively high-resolution and high precision data recorded at a local or regional scale. In some developing countries, like Nigeria, the availability of such high precision information is limited or non-existent, as a result of inadequate spatial infrastructure which hinder the progress of such studies.

2.3.2 Remote sensing applications for monitoring and mapping floods

Floods can be monitored and mapped with remote sensing (RS) data acquired via satellites and aircraft, or even from ground-based platforms. An advantage of satellite RS is its capacity to capture events on the Earth's surface at or close to the time of their occurrence, including its ability to monitor the progress of events through time (Michael, 2007). Moreover, satellite data allows the monitoring of flooding over large regions.

Generally, to map flood areas, two RS data sets are required: one dataset containing information collected before the flood event and the other acquired amid the flood occurrence (Wang, Colby, and Mulcahy, 2002). The first image data acquired is normally used as a reference, mapping all features in flood plain areas, while the second is typically acquired during the flood event in order to delineate flood boundaries and map inundation areas.

The type of sensor and data processing methods that exist to extract information from imagery about floods are many. Sensors on board satellites that record flood events may operate in different regions of the Electromagnetic Spectrum (EMS) (visible, near infrared, thermal and microwave regions). This is possible using either Radio Detection and Ranging (RADAR) or optical RS systems. RADAR is an active remote sensing system that records the backscatter of transmitted radio waves from Earth surface features. RADAR is an invaluable RS technology that can record information during unfavourable climatic conditions amid flood events where cloud cover prevents the use of standard optical systems. The long microwave/radio wavelengths transmit and penetrate through atmospheric constituents including the condensed water vapour that form clouds. However, both sensor types make satellite observation one of the most dependable techniques to study the area.

2.3.3 Microwave remote sensing for monitoring and mapping floods

The surface of the Earth can be imaged using space borne Radio Detection and Ranging (RADAR) sensors in all weather conditions, day or night. "*Active microwave sensors, like Synthetic Aperture Radar (SAR), provide their own illumination and record the amount of incident energy returned from the imaged surface*" (Townsend, 2002). SAR can penetrate open forest cover, aquatic plants, and cloud cover to detect standing water (Horritt, Mason, and Luckman, 2001; Brivio et al., 2002; Townsend, 2002; Lawrence et al, 2005). The ability to penetrate clouds with RADAR systems is a key benefit for monitoring flood events since they usually happen amid times of extended precipitation (Townsend and Walsh, 1998; Kiage et al, 2005; Stevens, 2013). However, the interpretation SAR imagery is less straightforward than when using visible/near infrared imagery. Floods are typically revealed in RADAR imagery as dark areas due to the low backscatter return from smooth surfaces, such as water. Water also has a unique dielectric property. As a result, water in this type of condition returns low RADAR signals and is shown with low backscatter on RADAR image data. On the other hand, partly inundated vegetation appears brighter on RADAR images differentiating them from other features (Michael, 2007). It is feasible to utilize these attributes of inundated vegetation and water for mapping wetland floods (Jensen, 2000).

Consequently, numerous studies have been conducted effectively using RADAR data. For example, Henry et al, (2006) utilised advanced multi-polarized SAR data for mapping flood after the heavy rainfall over the central European alpine basin, which caused a devastating flood on the Elbe River in 2002. In addition, Honda, Francis and Sah, (1997) also carried out a study *"Flood Monitoring in Central Plane of Thailand Using JERS-1 SAR Data"* for the central plane of Thailand. In another study, Townsend, (2002) in the forests of the Roanoke River floodplain in North Carolina analysed some Radarsat scenes imaged from September 22, 1996 and February 28, 1998 in delineating flood inundation. These studies demonstrate that images acquired from SAR have the capacity and ability to monitor and map flood events. Notably, Townsend and Walsh (1998) used SAR imagery to map flood extents within the lower Roanoke River floodplain in North Carolina and compared these results with a higher resolution Digital Elevation Model (DEM)-based GIS flood cover model. The results show that both the DEM/GIS flood cover model and the RS SAR images gave a comparable delineation of the flood event. However, the main drawback of the use of this method is that it is very dependent of the accuracy of the DEM. In the absence of highly accurate DEMs required for mapping floods in relatively flat areas, multi-date SAR and/or optical RS serves as an alternative, provided these instruments have an adequate temporal resolution to capture the flood event.

In the study by Townsend and Walsh (1998) within the lower Roanoke River floodplain, North Carolina. The DEM was utilised to generate GIS models representing potential flood cover and wetness. They also used SAR imagery obtained from satellites to derive possible flood areas. Their outcomes show that both the GIS model and RS SAR images obtained gave a comparable result of the flood event. However, the main drawback of the use of this method is that it is very dependent of the accuracy of the DEM. In the absence of highly accurate DEMs required for mapping floods in relatively flat areas, multi-date SAR and or optical RS serves as an alternative, provided these instruments have an adequate temporal resolution to capture the flood event.

Stereo pairs of RADAR images can also be used to create very accurate Digital Terrain Models (DTM) through stereo interferometry. The DTM and/or DEMs are the core spatial data set used to develop hydrological models for flood hazard assessment where they are used to define water catchment area, watercourse delineation, accumulation points, stream flows and thus can predict the spatial distribution and frequency of flood events. Similarly, light detection and ranging (LiDAR) imagery is now being used to produce a high-density last return point surface from which a highly accurate DTM is produced. The mapping of geomorphological features using LiDAR imagery and subsequent modelling of water flow through a landscape have been demonstrated by Jones et al, (2007) and by Marks and Bates, (2000). In addition, LiDAR imaging can also be used to detect flood depth (Schumann et al, 2008). However, one of the primary limitations of LiDAR data is its limited availability and high cost.

RS data, particularly SAR data, represents a good alternative for mapping the total flood extent of these floodplains, because of its ability to provide timely and continuous information, since they can be acquired during both day and night and are less affected by atmospheric conditions than optical data. However, the presence of emergent vegetation, waves, and rapidly moving water can lead to roughness on the surface of open water bodies and thus a higher backscatter return, making them hard to differentiate from other land surface types that are not flooded (Smith, 1997). A good example is a study by Sanyal and Lu (2004) who used SAR images to segregate zones of flooded and non-flooded areas in India, along with Landsat Enhanced Thematic Mapper Plus (ETM+) imagery. The study highlighted common issues encountered in accurately extracting information from flood-affected areas from the SAR imagery. Further limitations to this are that the data are expensive (freely unavailable) and it has a long revisit time, which is often unsuitable in delineating flood extent at the peak of the event or monitoring flood progression. Moreover, SAR data are liable to speckle or "salt and pepper" noise, *"a multiplicative random type of noise that considerably minimizes the interpretability of the images and limits classification methods where these images need to be filtered in a way to increase the signal-to-noise ratio"* (Brivio et al, 2002).

2.3.4 Optical remote sensing for monitoring and mapping floods

Optical remote sensing (RS) is generally utilised to monitor floods in both the urban and natural environments (Townsend and Walsh, 1998; Birkett, 2000; Shaikh, Green and Cross, 2001). These passive sensors record naturally reflected or emitted electromagnetic energy (EME) from different Earth surface features. Land cover types, including water bodies, are differentiated and identified by their spectral properties, as a result of their specific physiological and chemical composition. Where trees, floating vegetation and clouds do not cover the surface of the water, high-resolution visible, near infrared (NIR) and shortwave infrared (SWIR) sensors gives a better delineation of flooded areas. NIR and SWIR images are particularly valuable because these wavelengths are strongly absorbed by water, yet strongly reflected by land, which provides good contrast between these broad land cover types (Shoji et al 1999; Birkett, 2000; Jensen, 2000). A number of optical sensors have been utilised for decades for successfully mapping floods (Michael, 2007). RS sensors such as Moderate Resolution Imaging Spectro-radiometer (MODIS), Satellites Pour L'Observation De La Terre (SPOT), Landsat, and Advanced Very High Resolution Radiometer (AVHRR) have all been utilized for mapping flood effectively (Sheng, Gong and Xiao, 2001; Toyra et al, 2002; Sandholt et al, 2003; Shamsedddin et al., 2006).

Numerous authors have delineated floods utilizing the visible and NIR bands with a high level of accuracy. For example, Sheng, Gong and Xiao, (2001) utilised density slicing of the NIR band of the AVHRR for flood delineation. Sandholt et al, (2003) also utilised the visible and NIR bands to map floods in the River valley of Senegal using Landsat Thematic Mapper (TM) data and the maximum likelihood (ML) classification method. Brakenbridge (2006) used MODIS data band 1 (Red) and band 6 (SWIR) for major flood detection, measurement and mapping in Europe and the United States. Townsend and Walsh (1998), Shoji et al, (1999), Domenikiotis, Loukas and Dalezios, (2003) and Tan et al, (2004) used the Normalised Difference Vegetation Index (NDVI) computed from the Red and NIR bands of NOAA/AVHRR and Landsat TM to identify floods (Equation 1). Importantly, other water indices will be discussed in the next sub-section.

Consequently, the achievable accuracies when utilizing optical data for mapping flood events is a component of numerous factors including those specified previously. This type of data is further impacted by numerous atmospheric effects, which may need to be corrected, particularly when conducting multi-temporal studies. The unfavourable weather conditions that often occur during flood events limit the use of optical sensors for flood mapping due to clouds that obscure the scene (Jensen, 2000). This is the main reason why microwave sensors have been explored for their ability to map surface water (Stevens, 2013).

2.3.5 Spectral indices techniques for delineation of flood extent and water bodies.

There is a range of image analysis techniques specifically designed to map standing water, including the single band density slicing (Frazier and Page, 2000), supervised and unsupervised classification (Sheng, Shah and Smith, 2008; Huang, Chen and Wu, 2014), and spectral water indices and band ratios (Li et al, 2013; Jiang et al, 2014; Yao et al, 2015). Of these water body-mapping techniques, spectral water index methods are reliable, user friendly, efficient and cost effective in terms of computation (Ryu, Won and Min, 2002). In the past few decades, different water indices have been proposed. The two most commonly used water indices include the Normalized Difference Water Index (NDWI) proposed by McFeeters (1996) and the Modified Normalized Difference Water Index (MNDWI) proposed by Xu (2006). Earlier indices include the Normalized Difference Water Vegetation Index (NDVI) proposed by Rouse et al, (1974).

Table 2.1 Two derived most commonly used water indices that can be used to detect the spatial and temporal distribution of flood on MODIS data.

No.	Indices	Equation
1.	Normalized difference water index (NDWI)	$NDWI = \frac{P(green)-P(nir)}{P(green)+P(nir)}$...(McFeeters, 1996)
2.	Modified normalized difference water index (MNDWI)	$MNDWI = \frac{P(green)-P(swir)}{P(green)+P(swir)}$…(Xu, 2006)

Where;

Pgreen = reflectance in Green wavelengths (545-565nm, MODIS band 4)

Pnir = reflectance in NIR wavelengths (841-876nm, MODIS band 2)

Pswir = reflectance in SWIR wavelengths (1628-1652nm, MODIS band 6)

2.3.5.1 The normalised difference vegetation index

The NDVI has been used to recognise and map surface waters (Rogers and Kearny, 2004). The NDVI is a normalised ration between the Red versus the NIR wavelength (Equation 1) producing and index range between -1 and +1 where values above a specified index threshold value (typically around 0.2) denote vegetated areas. Values closer to one (1) represent actively growing green vegetation, while values less than Zero (0) indicate non-vegetated areas including water. The NDVI was first used by Rouse et al, (1974) to normalise the variations in reflectance as a result of changes in the solar zenith angle while studying vegetation systems across the Great plains in Central USA. While the NDVI has been used for mapping standing water, its main use is to map variations in vegetation radiative response. Consequently, improvements to this model saw the development of more dedicated water index models including the Normalised Difference Water Index (NDWI) by McFeeters' (1996) and Modified Normalised Difference Water Index (MNDWI) by Xu (2006).

$$NDVI = \frac{P(nir) - P(red)}{P(nir) + P(red)} \qquad \text{Equation 1}$$

Where;

Pred = reflectance in RED wavelengths (621-670nm, MODIS band 1)

Pnir = reflectance in NIR wavelengths (841-876nm, MODIS band 2)

2.3.5.2 The normalised difference water index

The NDWI proposed by McFeeters (1996) is a widely used index in identifying water-related surfaces. It uses the same normalised formula as the NDVI but substitutes the Red band with the Green wavelength band to produce values between -1 and +1 (Equation 2). The NIR wavelength used in the NDWI highly contrasts vegetation cover from moisture content in the soil, which allows discrimination of water features from vegetated features. An alternative NDWI proposed by Gao (1996) ($NDWI_{GAO}$), substitutes the Green and the NIR bands with NIR and SWIR respectively to produce a normalised ratio index designed to monitor changes in the water content of leaves (Equation 3).

The higher values of McFeeters (1996) NDWI indicate an increased contrast between water and non-water features by reducing the low reflectance values of water in the NIR band while maximizing the higher reflectance value of water in the Green band (McFeeters, 1996). Therefore, making vegetation and soil have negative values while the water features have a positive value (McFeeters, 1996). Index results depict vegetation and soil with mostly negative index values, while water features have mostly positive values (McFeeters, 1996). To isolate and extract water areas alone, the key is to determine a threshold index value in which water can be separated from other land features. Various studies have been done that uses the NDWI and the spectroscopic characterisation of the NIR band to detect water content in different areas

(McFeeters, 2006; Tong et al, 2004; Rogers and Kearney, 2004). Notably, the NDWI does suffer from false positive values in the presence of shadow and dark vegetation where water signatures exhibit similar signatures. Moreover, the NDWI has difficulties in separating water features from built-up urban features as many urban features usually have positive values mixed with water features. The MNDWI was proposed by Xu, (2006) to overcome these limitations of the NDWI index.

$$NDWI\text{McFeeters} = \frac{P(green)-P(nir)}{P(green)+P(nir)}$$ ....Equation 2

$$NDWI\text{GAO} = \frac{P(nir)-P(swir)}{P(nir)+P(swir)}$$ ....Equation 3

Where;

Pgreen = reflectance in Green wavelengths (545-565nm, MODIS band 4)

Pswir = reflectance in SWIR wavelengths (1628-1652nm, MODIS band 6)

Pnir = reflectance in NIR wavelengths **(**841-876nm, MODIS band 2)

2.3.5.3 The modified normalised difference water index

The MNDWI modifies McFeeters' NDWI where the Near infrared (NIR) band is substituted for the Shortwave Infrared (SWIR) band to better delineate water features (Equation 4). According to Xu (2006), the MNDWI is less susceptible to shadow noise and is more suitable in delineating water bodies in the presence of built-up land areas where the introduction of the SWIR band helps to effectively reduce built-up land noise over the NDWI. The selection of wavelength bands for the MNDWI takes advantage of the high SWIR reflectance of soil to contrast the low reflectance of SWIR by water features (including vegetation) and making use of the Green wavelength to maximize the reflectance of water features (Xu, 2006).

It has been argued though that the use of the Green wavelength can bias water index results by the higher green reflectance from vegetation than surrounding non-water features, such as soils and bare ground (Takeuchi and Yasuoka 2004; Brakenbridge 2006). To compensate, a variant of the MNDWI is proposed by Takeuchi and Yasuoka (2004) where the Green band is substituted for the Red wavelength band and is used with the Moderate Resolution Imaging Spectro-radiometer (MODIS) optical sensor (Equation 5). This MNDWI has been found to be sensitive to surface water in the presence of mixed cells (pixels) of both dry land and wetland areas and reduces the influence of the reflectance of green vegetation. Another alternative example is given by Brakenbridge (2006), who used MODIS data band 1 (Red) and band 6 (SWIR) for major detection, measurement and mapping of floods in Europe and the United States. However, in areas where the background soil colour is dominated by red soils, this variant of the MNDWI is biased by the high reflectance in the Red wavelength band where the original MNDWI by Xu (2006), which uses the Green band, becomes a more suitable substitute (Mizuouchi et al, 2014) if the later does not perform well. Further attempts to normalise for both the Green and Red reflectance bias has been conducted by Mizuouchi et al, (2014). Where water features rely on detecting differences between visible and SWIR wavelength reflectance, Mizuouchi et al, (2014) developed an MNDWI that uses the average of all three visible wavelengths 'colours' instead of using only Green or Red (Equation 6). Their study showed that this MNDWI was able to mitigate the effects of the red soils, while it "somewhat mitigated" the effects of the green vegetation compared with the MNDWI of Xu (2006), arguing that their water index is better in avoiding the bias of background colours. Notably though, numerous studies have demonstrated that the MNDWI developed by Xu (2006) is suitable in enhancing water information and can extract water bodies with greater accuracy than NDWI (Ji, Zhang and Wylie, 2009; Li et al, 2013; Xu, 2006; Singh et al, 2015).

The primary challenge usually involved in the use of each of this spectral water index technique is to identify a suitable index threshold value that can adequately differentiate non-water from water features, particularly in the context of flooded waters. Despite the spectral contrast between water and non-water areas, each of these water indices perform inconstantly with varying levels of water turbidity and suspended sediment load, typically present during flood events where water is highly contaminated with soils and debris. These contaminants significantly reduce the spectral contrast between water and non-water areas making it difficult to identify a single index threshold value that will separate the two. Once a threshold is determined though, pixels pertaining to water can be separated from the non-water features and a thematic map layer produced to show the extent of standing water.

$$MNDWI = \frac{P(green) - P(swir)}{P(green) + P(swir)}$$ ……………………………………………… Equation 4

$$MNDWI = \frac{P(red) - P(swir)}{P(red) + P(swir)} \text{ .... Equation 5}$$

$$MNDWI = \frac{P(red+green+blue) - 3swir}{P(red+green+blue) + 3swir} \text{ .... Equation 6}$$

Where;

Pgreen = reflectance in Green wavelengths (545-565nm, MODIS band 4)

Pswir = reflectance in SWIR wavelengths (1628-1652nm, MODIS band 6)

Pred = reflectance in RED wavelengths (621-670nm, MODIS band 1)

Pblue = reflectance in Blue wavelengths (459-479nm, MODIS band 3)

2.3.6 Satellite remote sensing MODIS data

The utilisation of spatial data within a GIS platform captured by Earth observing systems (EOS) technology has become a reliable, integrated and well-developed approach to disaster and risk management (Islam and Sado, 2000; Sanyal and Lu, 2006; Yang and Rystedt, 2002; Bapalu and Sinha, 2003). The principal data used in this research is the Moderate Resolution Imaging Spectro-radiometer (MODIS) imagery acquired on board NASA's Terra and Aqua satellites, which acquires 36 spectral bands that expands between the visible to the thermal infrared wavelengths (Running et al, 2011). MODIS bands 1 through to 7 are designed specifically for RS of Earth surface features at a spatial resolution of 250m and 500m for bands 1-2 and bands 3-7 respectively (Running et al, 2011).

The MODIS instrument operates on both the Aqua and Terra satellite spacecraft and can obtain global coverage of the Earth every one to two days with a swath width of 2,330km (cross track) by 10km (along track at nadir) (NASA, 2015). Aqua orbits the Earth south to north crossing over the equator in the afternoon while the Terra satellite, on the other hand, is timed in such a way that it passes over the equator north to south in the morning. The broad swath width (2,330km) of the MODIS instrument enables data to be captured with a very high temporal cycle, which is one of this instruments primary advantages (Marsalek et al, 2004). While it is an optical sensor subject to atmosphertic attenuation (cloud), its very high repeat cycle enables near realtime information capture (NASA, 2015), along with the ability to stich together many images acquired over several days as a single composite image to minimise the effects of cloud cover. The MODIS composite data product is thus well suited for mapping river/floodplain flood events, as apposed to flash foods, where river/floodplain flooding is slow and extends over vast areas where the landscape is relatively flat.

The high temporal imaging capability of MODIS makes it very useful in analysing natural hazards such as floods and more broadly is a popular and dependable data source for disaster management and assessment (Brakenbridge et al, 2003). Specifically, it has been widely used for vulnerability analysis, flood assessment, mapping, mitigation, and warning (Brakenbridge et al, 2003; Islam, Bala and Haque, 2009; Zheng et al, 2008; Chen et al, 2012). Brakenbridge et al, 2003 showed that MODIS data can be utilised to recognise areas that are flooded from non-flooded areas, even with its broad/coarse spatial resolution. This can be very crucial in regions where no other methods of mapping and monitoring floods are available.

The primary limitation of MODIS imagery is its coarse spatial resolution. Unlike satellite sensors such as Landsat, which has a spatial resolution of 30m, the 250m and 500m spatial resolution of MODIS imagery makes it suitable only for mapping large-scale homogeneous phenomenon. Hence, despite its coarse resolution, MODIS is well suited to mapping broad-scale floodplain flooding. Notably, while Landsat imagery is also freely available and has a much higher spatial resolution, its temporal acquisition cycle is only every 16 days. Even large-scale flood events may defy detection when using Landsat imagery as these flood events can come and go before the satellite's return visit; even then, clouds may obscure the scene and a further 16 days must past before reimaging. Importantly, the high temporal cycle of MODIS enables a higher likelihood of flood capture and allows for the development of a composite image to help mitigate contamination by clouds. All this makes MODIS imagery a suitable data source for delineation and mapping of inundated areas in this type of environment where no other means is available. Table 2.2 shows the sensor characteristics of MODIS for reflectance bands (1-7).

Table 2.2 Wavelengths and names of reflectance bands (1-7) in MODIS.

Band	Common name	Wavelength (nm)	Reflectance mid-point (nm)	Spatial resolution (m)
Band 1	Red	620-670	~650	250
Band 2	Near infrared (NIR)	841-876	~860	250
Band 3	Blue	459-479	~470	500
Band 4	Green	545-565	~550	500
Band 5	Mid-Infrared (MIR)	1230-1250	~1240	500
Band 6	Shortwave Infrared (SWIR) 1	1628-1652	~1640	500
Band 7	Shortwave Infrared (SWIR) 2	2105-2155	~2125	500

In concluding this chapter, previous studies show the importance of using RS and GIS in assessing, monitoring and mapping flooding. In particular, MODIS data, because of its high temporal imaging capability used to mitigate the influence of clouds makes it a very useful alternative to Radio Detection and Ranging (RADAR) imagery for analysing natural hazards such as floods. Moreover, optical sensors like MODIS enable the development and use of dedicated spectral water indices to differentiate water from non-water features. Specifically, the MNDWI proposed by Xu (2006) provides significant benefits over the NDWI by providing higher contrast between water and other built-up features (Ji, Zhang and Wylie, 2009). Notably, variants of MNDWI by Takeuchi and Yasuoka (2004) and Mizuouchi et al, (2014) also show benefits over the standard NDWI. The next chapter describes the data and methods used in the analyses of the data over Sokoto State, Nigeria with the aim of investigating their suitability by way of detecting and mapping flood inundation to aid in mitigation effect.

Chapter 3

Research methods

This chapter focuses on the methods used in carrying out this research. Specifically, it will present data sources used for mapping inundation and estimating the population at risk; how the data was processed and the methods used in order to detect and map the frequency of flooding and its impact on populous places.

3.1 Main Data and pre-processing

3.1.1 MODIS MOD09A1 and MYD09A1

The principal data used in this research is the Moderate Resolution Imaging Spectroradiometer (MODIS) imagery acquired on board NASA's Terra and Aqua satellites. The MODIS image data used is designated MYD09A1 (Aqua) and MOD09A1 (Terra) with differences in their orbital acquisition bringing about various viewing and cloud-cover conditions. During an eight-day period, the level three 8-day composite surface reflectance products, delivered in the sinusoidal projection (for both MYD09A1 and MOD09A1), contain the best observations as chosen on the basis of the absence of clouds and aerosol loading at 500m, low view angle, and high observation coverage (USGS, 2016). The frequent acquisition of MODIS imagery allows effective monitoring of the regular changes in water bodies and their extent.

This study investigates four major flood events in the Sokoto state region, which occurred on or close to October 8, 2003; October 16, 2010; September 21, 2012; and September 22, 2015. The closest pre-flood cloud-free MODIS imagery and the first useful (during) flood images were acquired from NASA which can be downloaded from NASA, (2016). These images were first used to visually investigate the area before and during each flood event to determine their suitability for further image analysis. Figures 3.1 through 3.4 show the MODIS imagery over Sokoto state study area before and during each flood event under investigation. The light blue areas depicted in each image is standing water/inundated areas, with the Goronyo dam evident in the upper north east of each image. Following this initial visual investigation, each image was used as input to several flood mapping models to delineate standing water and its extent, as detailed in Section 3.2 and 3.3 below.

Table 3.1 Satellite data used.

No.	Dates of Flood	Before Flood	Data	Composition	Resolution
1.	8 OCT 2003	18 JUNE 2003	MODIS TERRA	8-day	250-500m
2.	16 OCT 2010	2 JUNE 2010	MODIS AQUA	8-day	250-500m
3.	21 SEPT 2012	24 MAY 2012	MODIS AQUA	8-day	250-500m
4.	22 SEPT 2015	4 JULY 2015	MODIS TERRA	8-day	250-500m

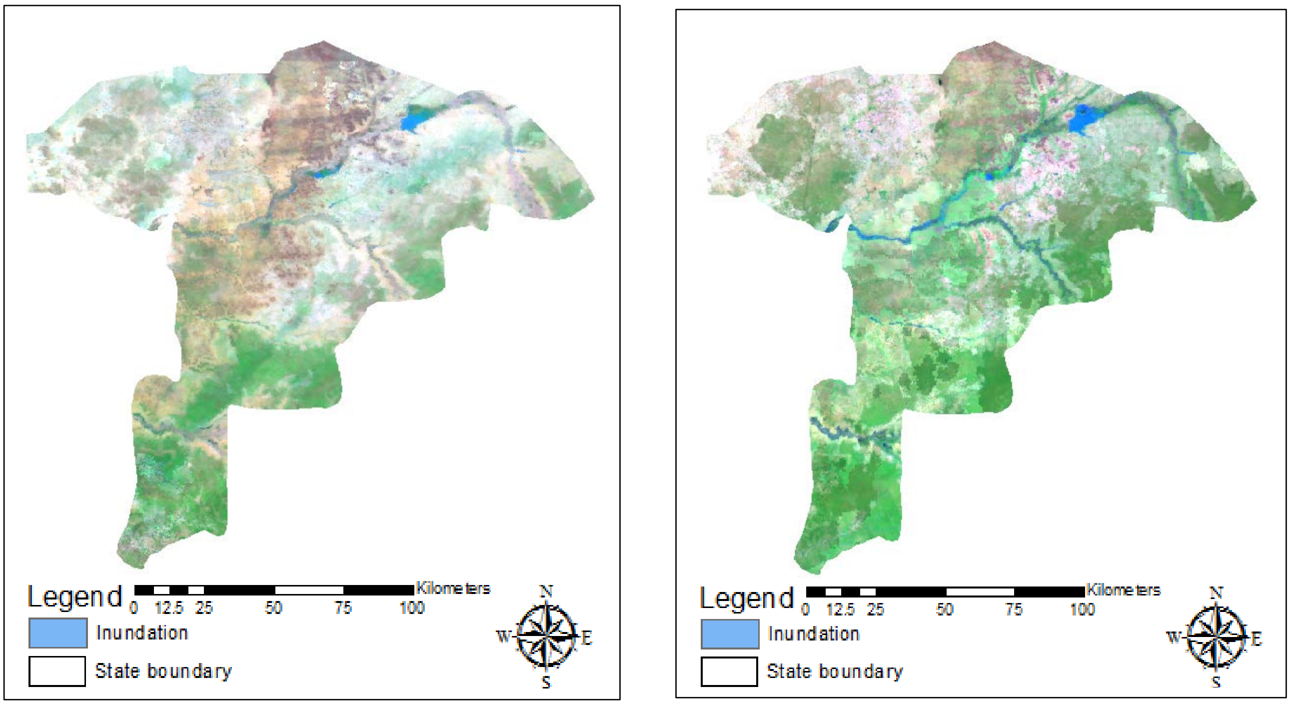


Figure 3.1 (a) MODIS Non-flood image June 18, 2003 (b) MODIS Flood image Oct 8 2003

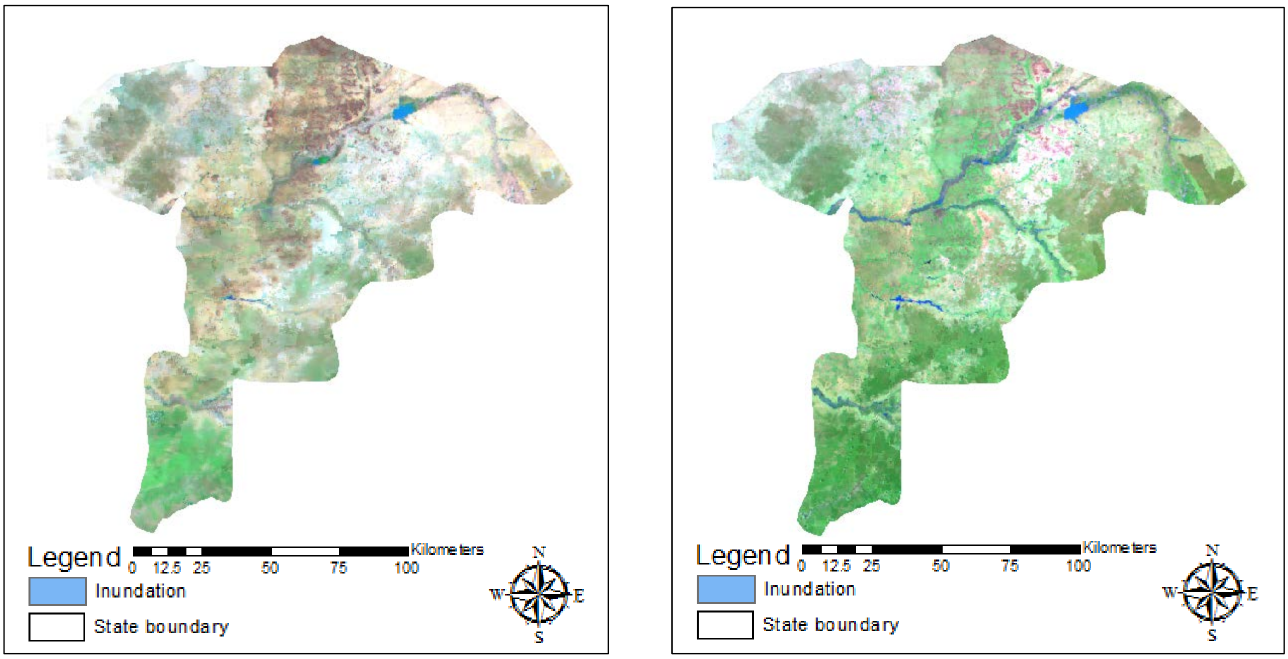


Figure 3.2 (a) MODIS Non-flood image June 2, 2010 (b) MODIS Flood image Oct 16 2010

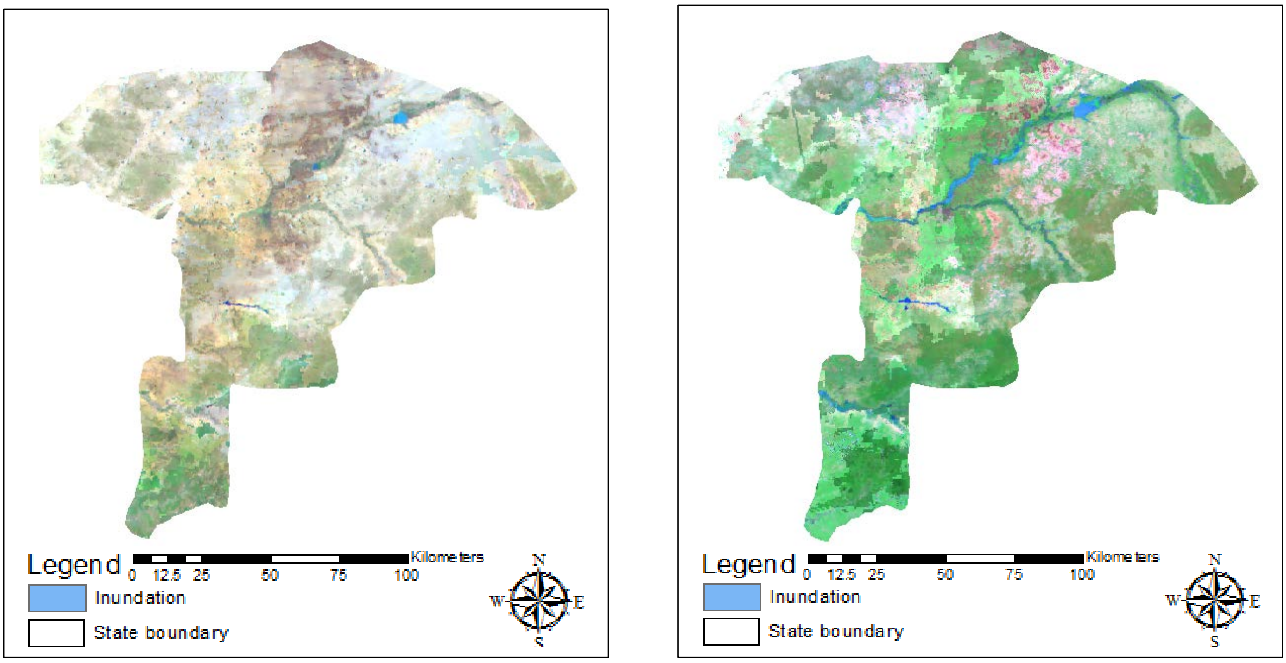


Figure 3.3 (a) MODIS Non-flood Image May 24, 2012 (b) MODIS Flood Image Sept 21 2012

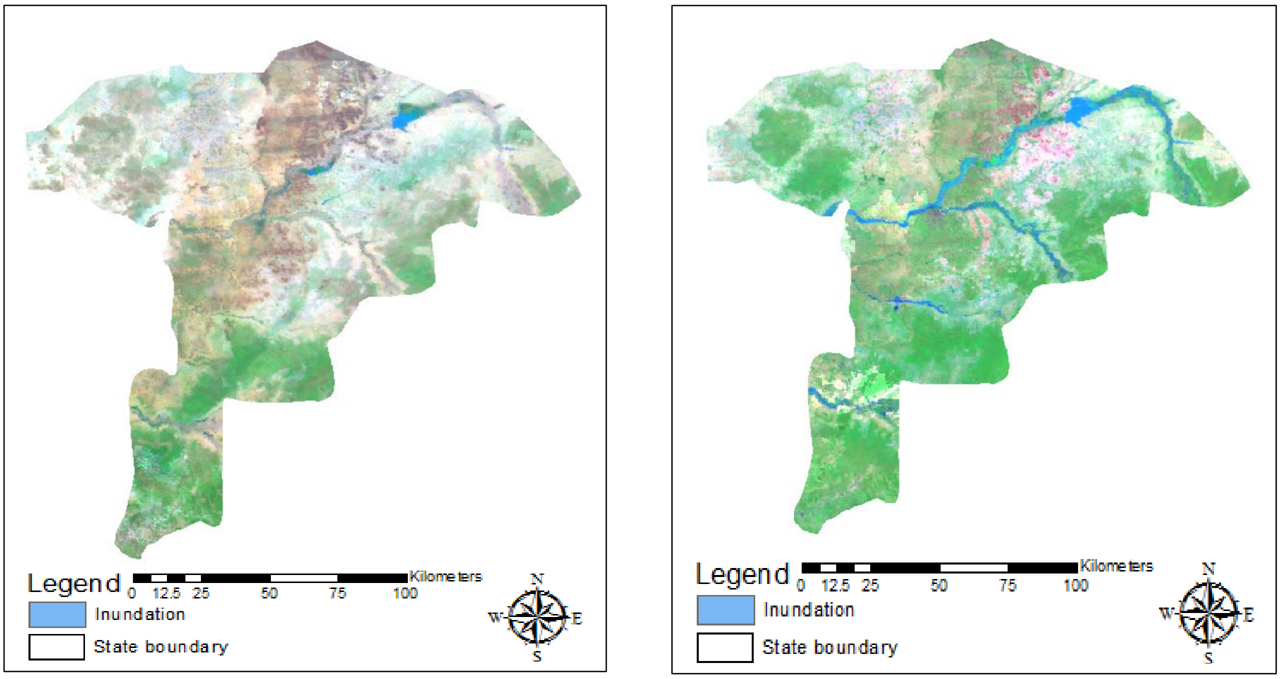


Figure 3.4 (a) MODIS Non-flood Image July 4, 2015 (b) MODIS Flood Image Sept 22 2015

Figure 3.1–3.4 Images showing the pre-flood and during/closest flood event over Sokoto State.

3.1.2 LandScan population data

Despite the review provided in the preceding chapter on flood risk, there is no scientific consensus on the appropriate ways to measure population at risk (Andresen and Jenion, 2010). However, while crude, clearly understanding the spatial distribution of the population within, or proximal to, areas subject to flooding provides important information about personal risk to life, livelihoods and infrastructure. However, the Nigerian population census data lacks locational specificity and is aggregated and uniformly distributed to the considerably large Local Government Area (LGA) level. Consequently, the 2014 ambient global population dataset from LandScan obtained from Oaks Ridge National Laboratory (ORNL) was used as an alternative data set to estimate the population at risk from flooding over the study area. Unlike the traditional Nigerian census data that ties the location of people to just their homes before aggregation to the LGA level, the LandScan data aims to account for people's mobility and provide more locational specificity. This data aims to map the presence of people everywhere, for instance, on roads, in schools, or on farms rather than in their homes only. It was developed as a part of the ORNL global population project (Dobson et al, 2000). It is based on the information from night-time light sources, census data, elevation distribution, and AVHRR land-cover by allocating a certain number of people to each 1 by 1 km cell based on the relative likelihood of population occurrence on the factors mentioned (Dobson et al, 2000). "*It is the finest resolution global population distribution data available and represents an ambient populace*" (ORNL, 2016). The advantages of LandScan, as compared with others like the Gridded population of the world (GPW), "*include its better output resolution of 30 arc-seconds, as opposed to 2.5 arc-minutes, and the use of an extensive model to predict population distribution within administrative units*" (FAO, 2016). The data is also available free of charge by continent.

In addition to this data, the Census data for 2006 in Nigeria was acquired in text form from National population commission, Nigeria (NPC, 2006). This data along with the administrative boundaries of Nigeria acquired from DIVA-GIS.org was used to input the population figures for each LGA by creating a field in its attribute table in the ArcGIS (version 10.2) environment. The LandScan GRID data was used to analyse the number of people at risk from flooding in each of the LGAs and the state in total. Projected 2014 population estimates calculated from the 2006 Nigerian census was compared with the LandScan GRID population data over the same region for 2014 to help validate and build confidence in the risk estimates. Projected 2014 population estimates were determined using the population growth rate of 2.7% by the united nations (UNdata, 2016) to derive the population figures.

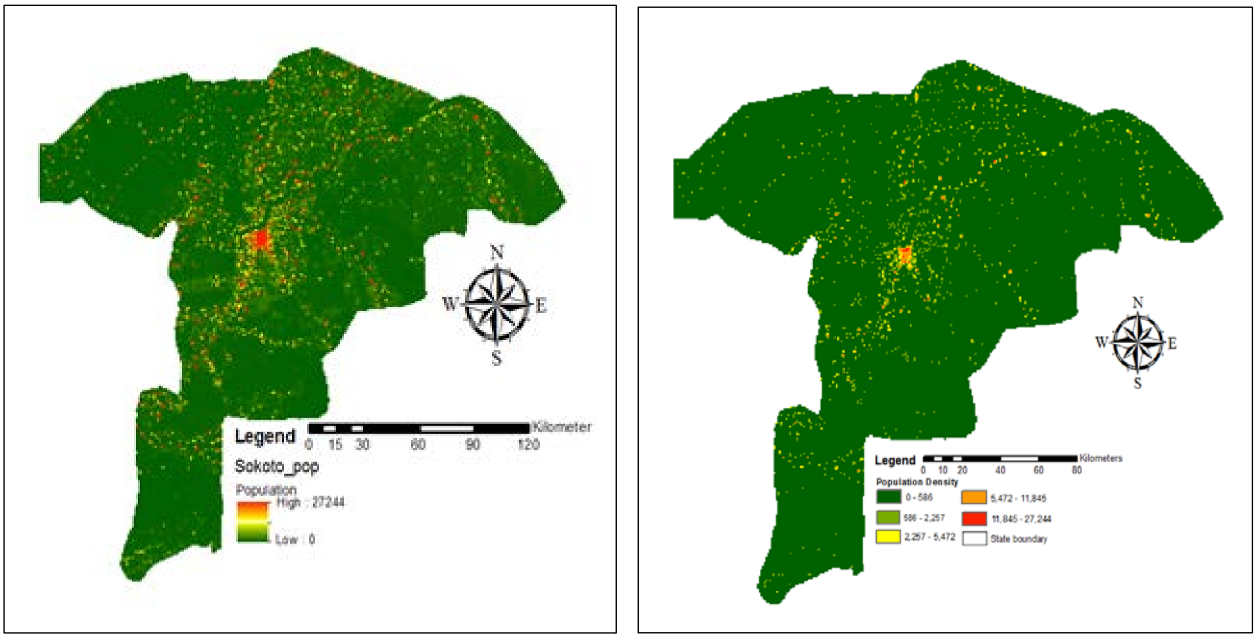


Figure 3.5 Map Showing the LandScan GRID population counts and density data of the Study area (Source: ORNL, 2014).

3.2 Delineating water features using the normalized difference water index

Importantly, during the time of each of the Sokoto floods, considerable vegetation cover dominated the landscape. Consequently, heavy vegetation cover may bias the use of the Green wavelength band and thus as proposed by Takeuchi and Yasuoka, (2004) and Brakenbridge, (2006), substituting the Green with the Red may reduce the influence of the green vegetation in mapping more clearly flooded waters. The Normalized Difference Water Index (NDWI) was first used with the Green wavelength but it produced a considerably noisy image. As a result, the Green visible band was substituted for the Red wavelength band in the NDWI calculation (Equation 7).

Using the October 8, 2003 and October 16, 2010 MODIS flood images; the NDWI was computed using the Red (Red- MODIS band 1) and the SWIR (SWIR- MODIS band 6) wavelengths. Where the SWIR band is subtracted from the Red band before being normalised (ratio) by the sum of the two bands as shown in (Equation 7). The calculation was built within ERDAS IMAGINE's Spatial Modeller (Version 15) where an overview of the method can be seen in Figure 3.6.

$$NDWI = \frac{P(red)-P(swir)}{P(red)+P(swir)}$$ ....Equation 7

Where;

Red= reflectance in RED wavelengths, 621-670nm (MODIS band 1)

SWIR= reflectance in SWIR wavelengths 1628-1652nm (MODIS band 6)

The results of the NDWI produce an index of values ranging between -1 and +1 where a pixel value closer to 1 indicates that the area of a single pixel consists largely of water (see Figure 4.1, Chapter 4). To isolate those pixels that contain water and thus separate water from non-water features, an optimal threshold value of the water index is required. In order to achieve this, an initial threshold value of zero was used. When comparing the zero value threshold applied to the NDWI results with the Red and SWIR bands of MODIS imagery, most obvious flooded areas contained positive NDWI values, while soil and vegetated surfaces contained negative or zero values. However, quite a few land features (non-water features) including urban features contained some positive NDWI values such that they could not be differentiated from water (see Figure 4.1, Chapter 4). This led to the use of the MNDWI in search of improving water delineation.

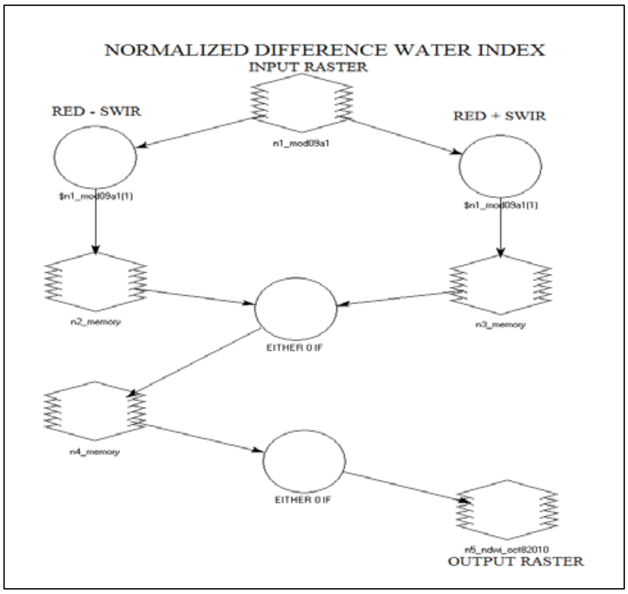


Figure 3.6 Methodology for NDWI calculation.

3.3 Delineating water features using the modified normalized difference water index

The MNDWI is used here to address the limitation of the NDWI where urban features also contained positive values along with water features. The MNDWI index was proposed by Xu, (2006) to correct this problem by suppressing land features while water features are enhanced. The MNDWI serves as the main technique used to map water from non-water features in this study where an overview of the method is shown in Figure 3.7. The MNDWI was applied to the same four MODIS flood images of October 8, 2003, October 16, 2010, September 21, 2012 and September 22, 2015. The Green (Green- MODIS band 4) and the SWIR (SWIR- MODIS band 6) wavelength bands were used where the SWIR band is subtracted from the green band before being normalised (ratio) by the sum of the two bands as in Equation 4. Notably, the Green wavelength band in the MNDWI was not substituted for the Red band in this case as the standard MNDWI of Xu (2006), with the inclusion of the MIR wavelength, produced a considerably less noisy image and confidently delineated water from non-water features. The calculation was once again built within ERDAS IMAGINE’s Spatial Modeller (Version 15) where an overview of the method can be seen in Figure 3.7.

$$MNDWI = \frac{P(green) - P(swir)}{P(green) + P(swir)} \text{..} \text{Equation 4}$$

Where;

Green= reflectance in Green wavelengths, 545-565nm (MODIS band 4)

SWIR= reflectance in SWIR wavelengths, 1628-1652nm (MODIS band 6)

Like the NDWI, the MNDWI also produces an index of values ranging between -1 and +1 where water features are denoted by higher positive values. An index threshold value of zero was used once again to distinguish non-water from water features in the MNDWI images. The MNDWI produced considerably better results in delineating water features than that of the NDWI and are presented in Chapter 4, which confirms its suitability in this landscape.

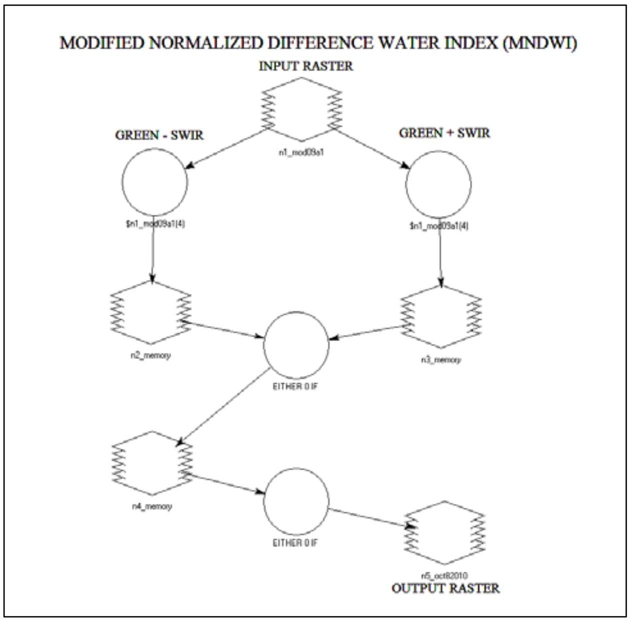


Figure 3.7 Methodology for MNDWI calculation.

3.4 Mapping flood inundation extent and frequency

The MNDWI was confirmed to map water features more accurately and consistently than that of the NDWI. Subsequently, the MNDWI was applied to all MODIS images to detect flood inundation extent for the four major flood events. Importantly, considerable investigation was conducted comparing pre-flood MODIS imagery with MNDWI results to determine an index threshold value that appropriately delineated water from non-water areas. A value of ‘0’ was concluded to be the most suitable for the Sokoto landscape. The MNDWI for each date was then recoded into binary thematic layers with values ‘1’ and ‘0’ for flooded and non-flooded areas respectively. Each thematic map shows the full extent of flood inundation for each period and is presented in Chapter 4, Figures 4.4. ArcGIS Spatial Analyst Tools (version 10.2) was then used to combine all flood inundation periods together to reveal a combined flood extent map, presented in Chapter 4, Figure 4.5. The Spatial Analyst Tools were used again to overlay and sum each of the flood inundation areas for each period together to produce a single spatial frequency layer in Chapter 4, Figure 4.6 that shows the number of times an area, defined by the spatial resolution of the MODIS imagery, was inundated by water for the four chosen times. Finally, four flood inundation extents for each year were mapped and one combined inundation map showing the largest inundation for the four periods.

3.5 Flood risk/vulnerability

In assessing the distribution of the population vulnerable to flood hazard, the flood inundation maps were combined with LandScan demographic data using spatial overlay analysis in ArcGIS (version 10.2). The LandScan population data, aggregated to l km raster (GRID) cells, was first converted into vector format and reprojected to the same coordinate system as the flood extent raster layers. Each of the flood extent layers, including the combined flood layer, were also converted to vector polygon layers.

The combined flood extent layer was then overlayed to intersect with the LandScan population grid of vector cells. This process computes the geographic intersection between two input layers where the newly created layer carries the attributes of both the LandScan population distribution data and the flood inundation area information. Subsequently, a summation of the total population within flood affected areas was calculated and is presented in Table 4.3 of the results section. Figure 4.7 is also presented in Chapter 4 showing graphically the population distribution within the flood affected areas. A more detailed risk assessment focused on calculating the population at risk within each LGA where flood mitigation efforts are typically managed at this administrative level. To do so, the LGA administrative boundaries were used to intersect with the combined LandScan and flood extent layer from which a ‘population at-risk’ count could be calculated for each LGA. The results are presented in Table 4.4 in Chapter 4.

Chapter 4

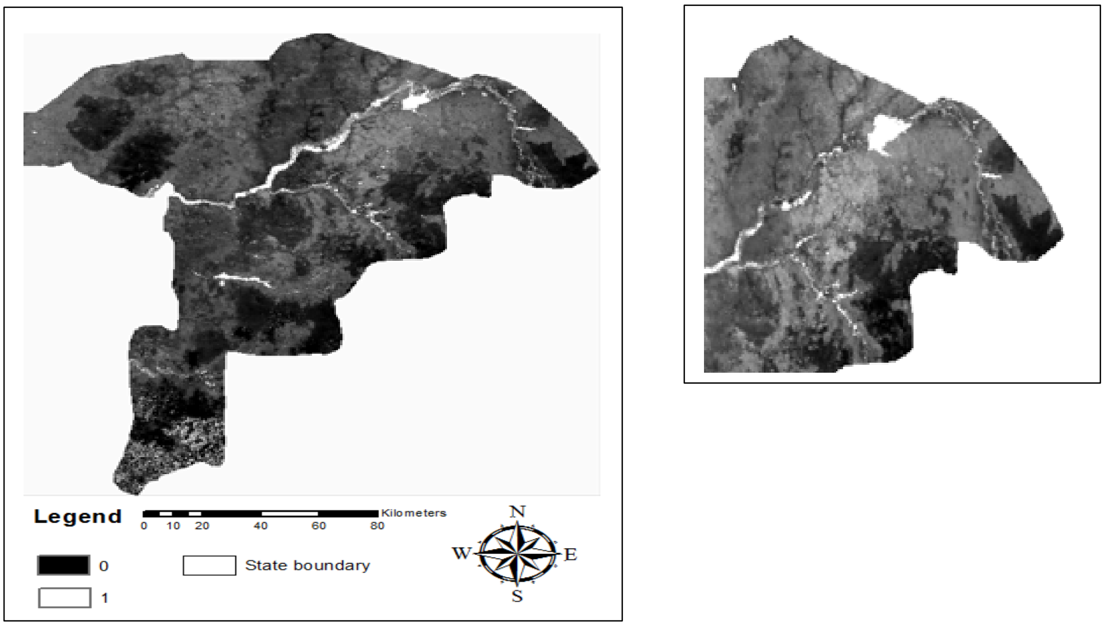
Results and Discussion

This chapter will first present the results of the water indices used to map flood inundation extent and frequency across the Sokoto State using the methods outlined in Chapter 3. This will be followed by a discussion of these specific flood events before results are presented that outline those populations at-risk from flooding in each Local Government Area (LGA). The chapter concludes with a discussion on the risk assessment results, suitability of Moderate Resolution Imaging Spectro-radiometer (MODIS) imagery and LandScan GRID population data for mapping flood inundation, estimating the number of people vulnerable and mitigation management approaches.

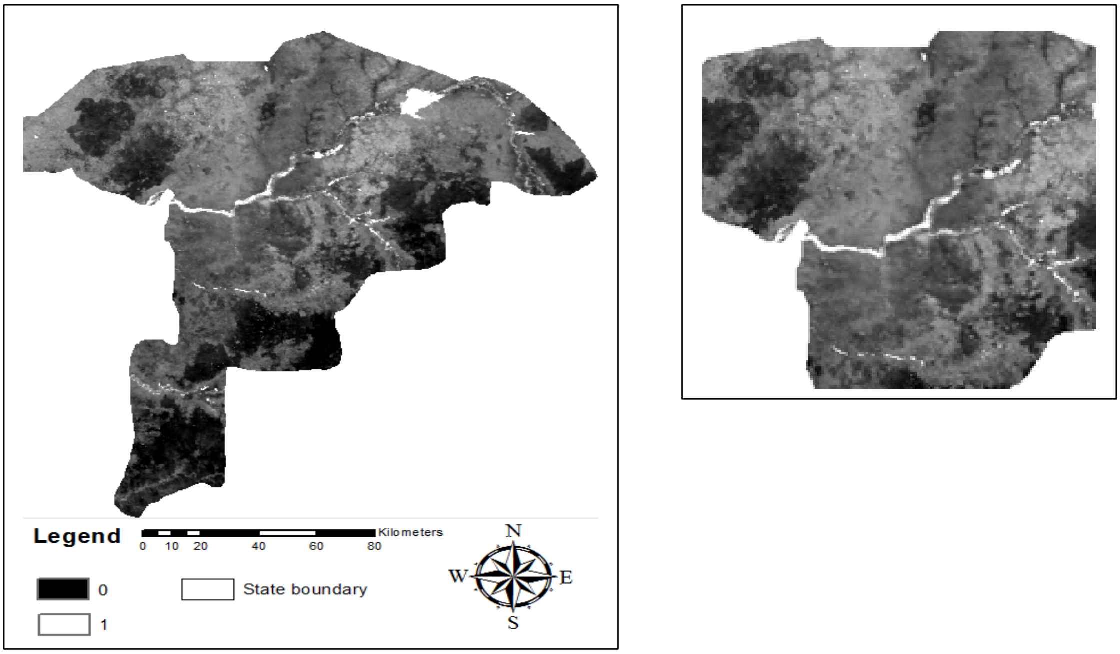
4.1 Mapping flood inundation extent using the normalised difference water index

The Normalised Difference Water Index (NDWI) was first tested and applied to the MODIS flood image acquired on October 8, 2003 and October 16, 2010, where subsequent comparisons between the original MODIS image and NDWI allowed judgement of an index threshold estimate that suitably separated water from non-water areas. However, it was found that some clearly delineated standing water areas shared the same/similar positive index values as urban areas, and thus water features could not be confidently separated, as shown in Figure 4.1 where the white areas show locations that are flooded by water and the black/grey areas show land area that have mixture of floodwaters and land not flooded.

As identified by Xu (2006), the NDWI has been found to be susceptible to misclassification of water features with shadowing and built-up areas, and this was certainly found to be the case here when using the NDWI when applied to the first two MODIS flood images, as illustrated in figure 4.1 where there is a mismatch between the inundated areas (white areas) and the land areas not inundated in the MODIS image scene. Therefore, the MNDWI proposed by Xu (1996) was investigated as a potential alternative to improve floodwater mapping results.



a) October 16, 2010



b) October 8, 2003

Figure 4.1 Map showing the NDWI results

4.2 Mapping flood inundation extent using the modified normalised difference water index

Following the MNDWI procedure outlined in Chapter 3, after a suitable index threshold was determined through the evaluation of the original MODIS flood image, floodwaters were more confidently separated from non-water features using this method, as shown in Figure 4.2. Figure 4.2 shows how the MNDWI enhances the open water features and inundated area while efficiently suppressing and even removing built-up land noise as well as vegetation and soil noise in the Sokoto area. The results shown in Figure 4.3 confirms the suitability of the MNDWI over this landscape where it was subsequently applied to each of the MODIS image flood dates as shown in Figure 4.3.

Notably, the inclusion of the MIR wavelength band in the MNDWI calculation seems to mitigate any bias from the green wavelength where considerable green vegetation is present in the scene by increasing the contrast between the two wavelengths compared with the NIR wavelength alone. This has helped delineate more clearly standing water from non-water features despite variation in green reflectance across the landscape.

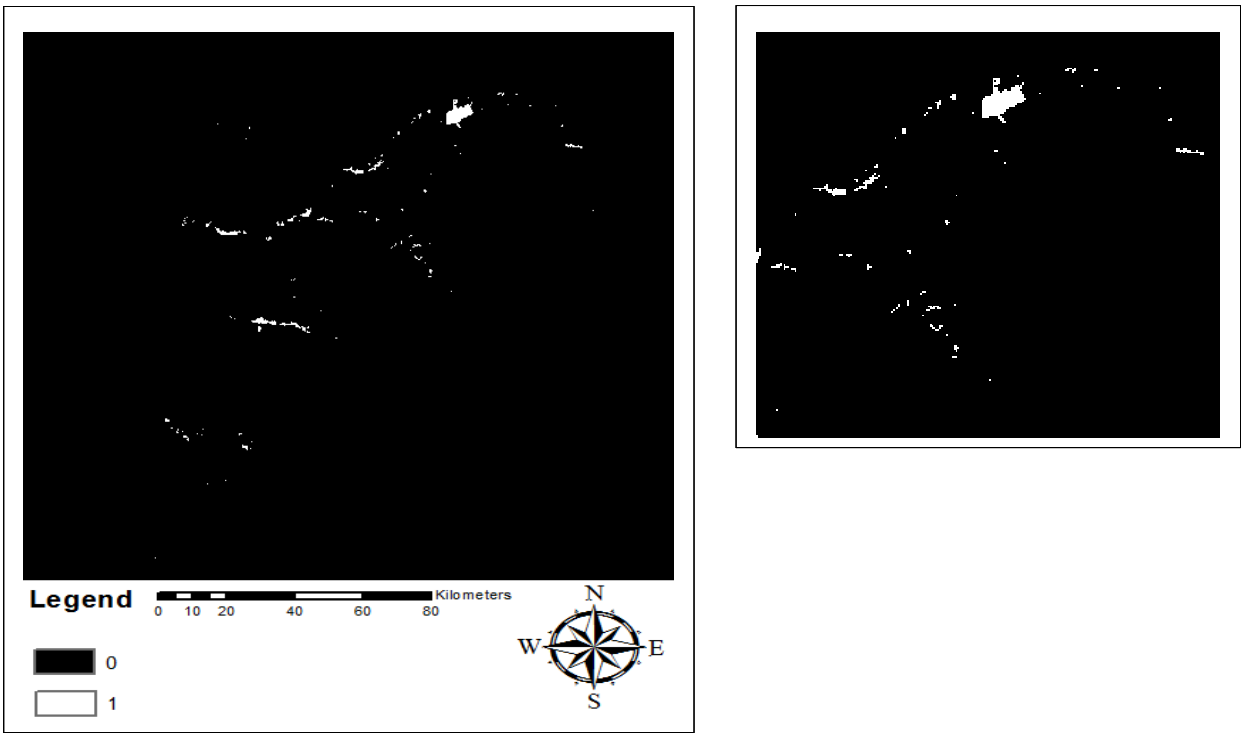
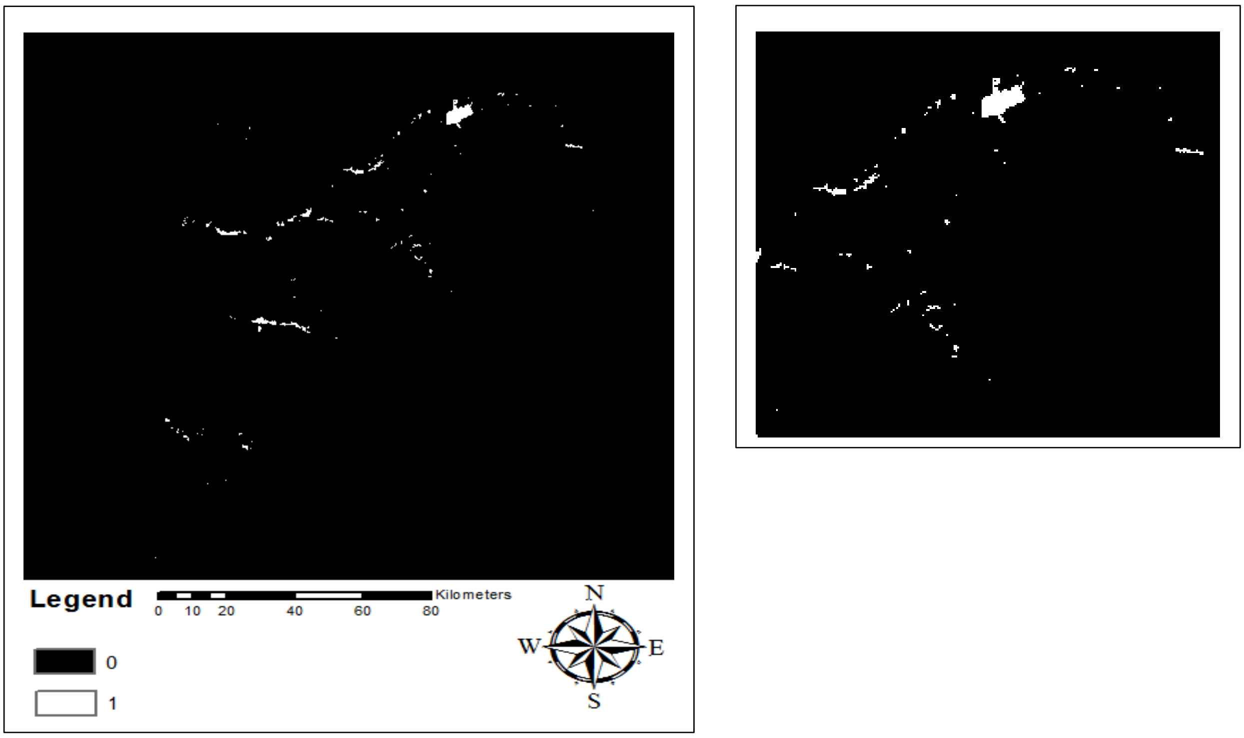
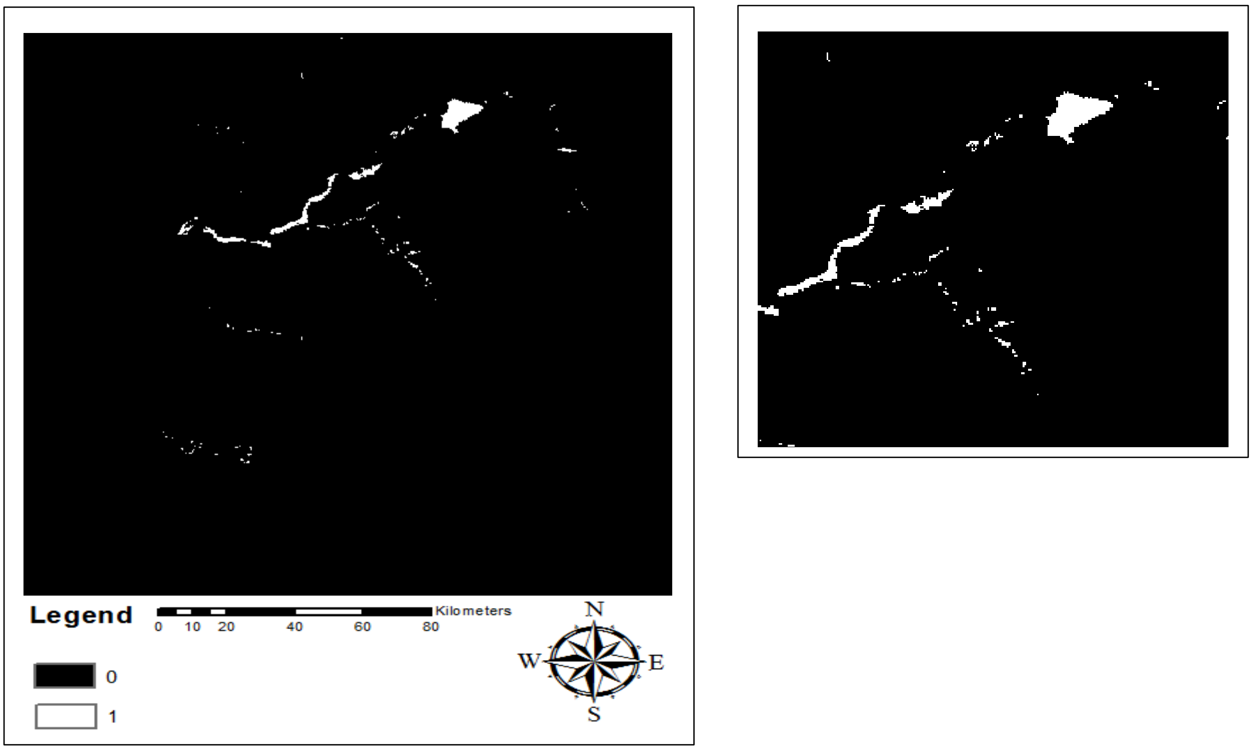


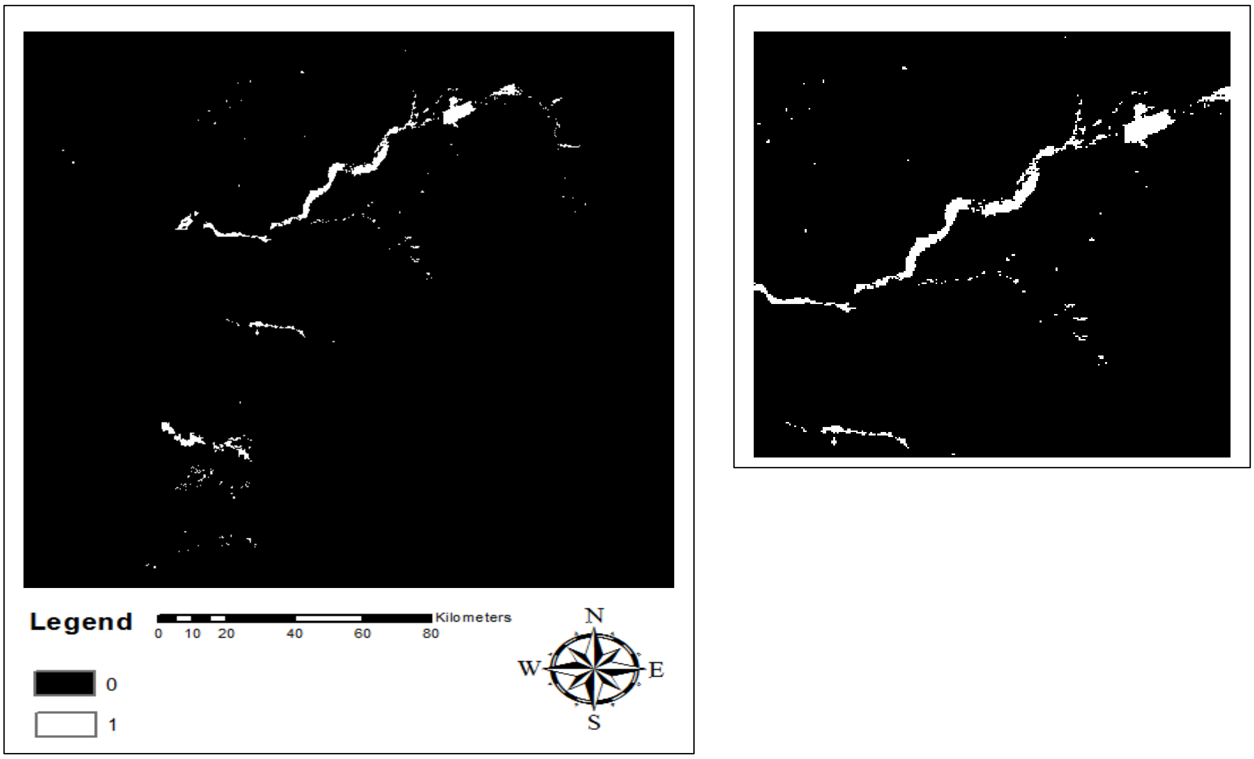
Figure 4.2 Map showing MNDWI result (October 16, 2010)



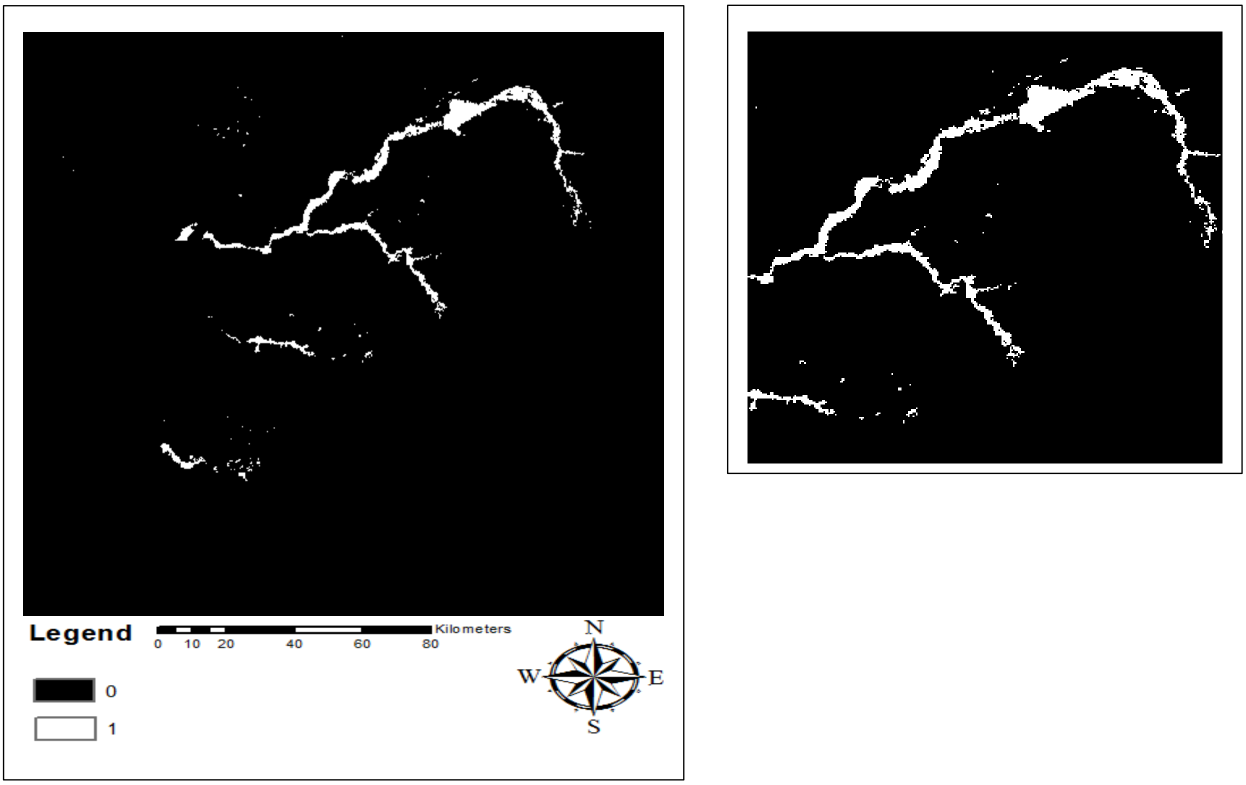
a) October 16, 2010



b) October 8, 2003



c) September 21, 2012



d) September 22, 2015

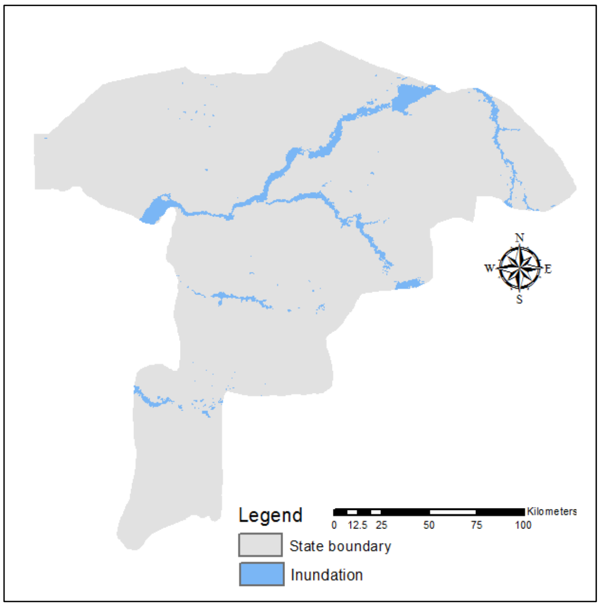
Figure 4.3 Map showing the MNDWI results for the four periods

ArcGIS was then used to recode each output MNDWI raster grids to constraining layers of flooded ('1') and non-flooded ('0') areas and coloured before summing each layer together to create a final combined flood extent map presented in Figure 4.5. This map shows all areas vulnerable to flooding throughout the study period. Table 4.1 lists the flood extent areas from largest to smallest, while Figure 4.4 shows the spatial extent of each flood event separately. The maps clearly show that the 2015 flood event was the most extensive with an inundated area of 1464.82km^2. This was a result of the high rainfall during this period, which led to the collapse and subsequent overflow of the Goronyo dam wall in the State.

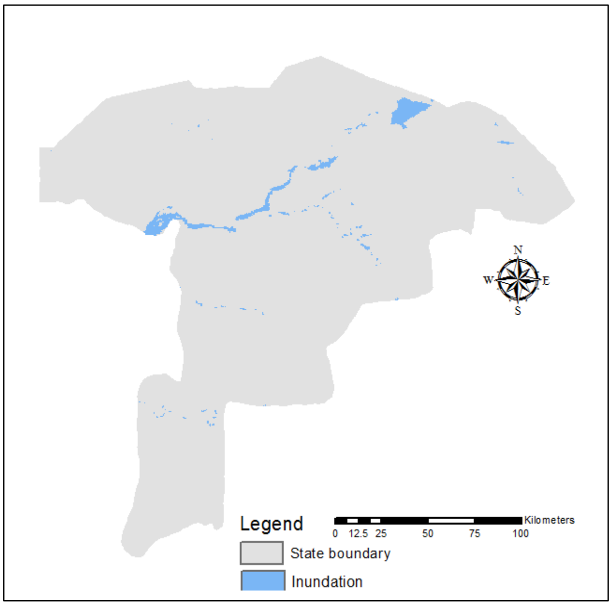
According to the Nigerian meteorological centre, rainfall for the State between the month of July and September 2015 was between 388mm to 2962mm, which was much higher than the monthly average of 161mm, in the area (Climate-data, 2016). The impact assessment undertaken by the NEMA (2015) of the 2015 flood showed that this event led to the displacement of over 100,000 people and destruction of farmlands, agricultural produce with no fewer than 7,577 farmers and 2,500 hectares of agricultural land destroyed, which was widely reported in newspapers (Channels, 2015; Vanguard, 2015). However, despite the damage and destruction this flood had caused, people still moved back to these flood prone areas because of its usefulness of the area in terms of their main agricultural practice, means of livelihood and economy (Our world, 2014; Premium times, 2016; The Guardian, 2016).

Table 4.1. MODIS data dates used and the area (km^2) inundated.

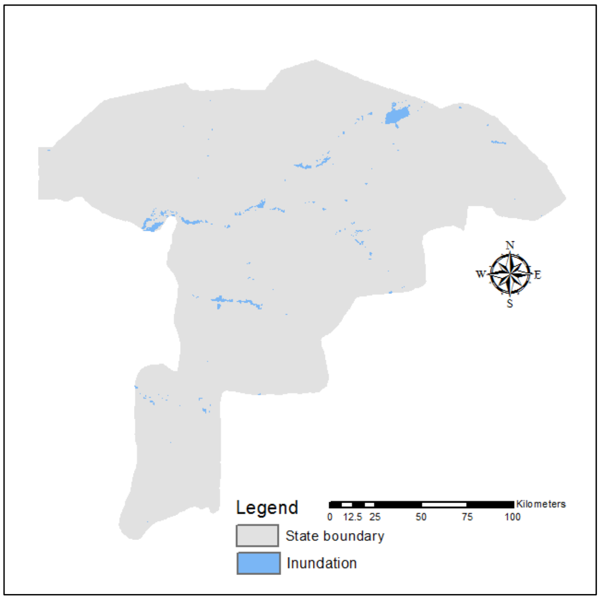
No.	**MODIS data flood dates**	**Inundated area (km^2)**
1.	September 22, 2015	1464.82
2.	September 21, 2012	819.09
3.	October 8, 2003	561.95
4.	October 8, 2003	317.25



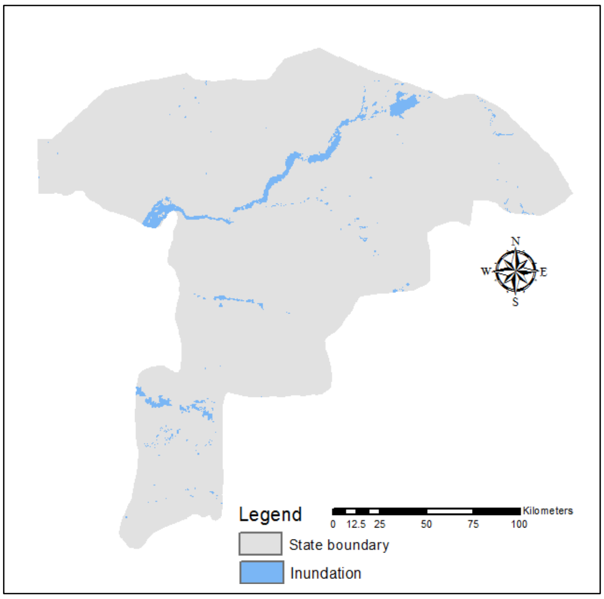
a) September 22, 2015 flood



b) October 08, 2003 flood



c) October 16, 2010 flood



(d) September 21, 2012 flood

Figure 4.4 Map showing the inundated areas for each period.

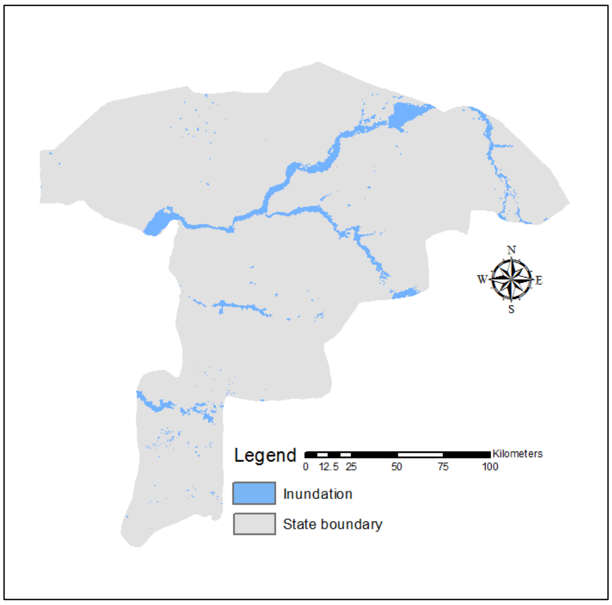


Fig 4.5. Map showing the combined final flood inundation extent (largest inundated area)

4.3 Flood frequency map

The map shown in Figure 4.6 was derived using the Spatial Analyst toolset in the ArcGIS environment (10.2) by overlaying and summing each of the inundation periods together. This effectively labelled each image pixel with a frequency value of the number of times it was inundated by water for the four flood periods. This was subsequently overlayed with the Local Government Areas (LGAs). Consequently, areas (groups of pixels) labelled 1 through 4 indicate the frequency of inundation for the selected time period.

Importantly, areas with the highest frequency of inundation with a value of '4' should be marked as the most vulnerable areas, while areas that were inundated only once should be marked as least vulnerable. The total combined flooded area for all four flood periods is 1,509.9km^2, with the total area for each inundation period presented in Table 4.2. Areas that were inundated four times out of the 4 flood events are dispalyed in red and totaled 441.6km^2. Note these area includes all river channels and permanent water bodies. Areas inundated three out of the 4 flood events are displayed in yellow and totaled 248.56km^2. Areas inundated twice out of the 4 flood events are dispalyed as dark blue and totaled 145.35km^2, while areas inundated only once out of the 4 flood events are displayed in light blue and extended over 674.42km^2 (44.7% of the combined flooded area).

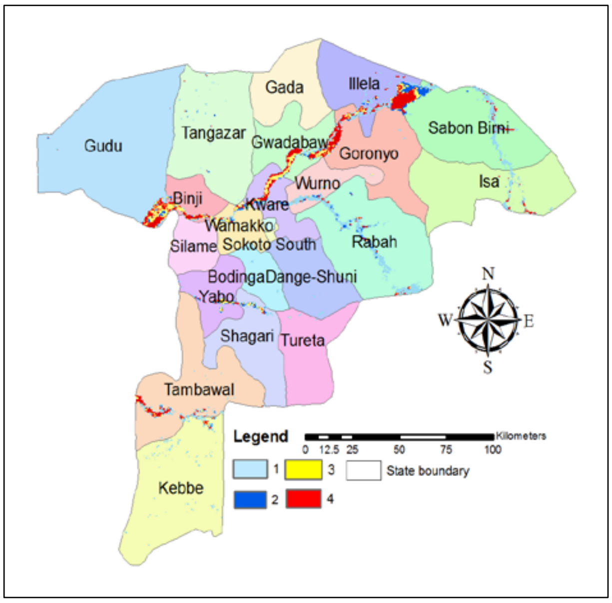


Figure 4.6 Map showing the frequency of inundation with the inundation times.

Table 4.2. Frequency of inundation and the total area of inundation (km^2).

No.	Inundation times	Inundated area (km^2)	Total %
1.	1	674.42	44.7
2.	2	145.32	9.6
3.	3	248.56	16.5
4.	4	441.60	29.2
	Total	1509.9	100

4.4 Risk/vulnerability

The creation of a risk/vulnerability map in this study is demographically driven and based on population data. The population vulnerable was estimated using the LandScan GRID population data from Oaks Ridge National Laboratory (ORNL). Combining the inundation map with the population data, the spatial distribution of people vulnerable to the total flood was derived. The total population vulnerable to flood been 1,053,172 out of the total population of 4,338,418.

At the LGA level, the results show that people that are close to the floodplain and river area like the Goronyo, Illela, Kware, Gwadabawa, Rabah, Binji, Yabo are much more vulnerable to flood. For instance, in Yabo, Gwadabawa, and Kware LGAs, there are 129,737, 134,086 and 106,889 people estimated that could be affected respectively which includes 39.1, 106.1,

$105.78km^2$ of land vulnerable to flooding respectively. Because these LGAs are located close to the floodplains and river area and with high population, they are likely to be more vulnerable to flood hazard. This is in line with the report by Channels which states that Gwadabawa, Wurno, and Goronyo LGA in the state was heavily affected by the 2015 flood after a heavy rainfall that lasted more than a week (Channels, 2015). In addition, according to the various news report, it was also reported that the LGAs of Gwadabawa, Wurno, Goronyo Rabah, Kware, Binji, Kebbe, Wammako in the Sokoto area are always the most affected by flood disaster, which is in line with this study's result (Premium times, 2016; The Guardian, 2016; Today, 2016; Channels, 2015; Vanguard, 2015). These areas are close to the river and floodplain region and as a result of the agrarian nature of the people, most people use the river and surrounding floodplain area for growing agricultural products and rearing animals.

To be able to develop a realistic risk minimization and preparedness methodology, there is a need for emergency response managers to estimate the number of visitors, farmers, employees and resident who could potentially be exposed to possible hazards. This is the reason for the use of the ambient population data (LandScan), which endeavours to measure the actual distribution of people present (rather than living) in a geographical location. Moreover, the LandScan population data is aggregated to 1km grid cells as opposed to the much coarser aggregation of the Nigerian census data to the much larger LGA level. The use of population data aggregated to the LGA level alone would make it very difficult to identify varying concentrations of people within these LGAs necessary to determine more accurately those who are at risk from flooding. In support of the independent 2014 LandScan population data and in recognition of the 'official' 2006 Sokoto Sate population count obtained from the last Nigerian census, the latter was projected to a 2014 population estimate for comparison and support of the LandScan population data. Using the varying annual population growth rate estimate for Nigeria (as a surrogate for Sokoto State) between the years 2006 and 2014 from the United States Census Bureau's International Statistics (data), the projected 2014 population estimate is 4, 582,255. Comparison with the LandScan population count shows a relative difference of only 243,807**,** a percentage difference of 5.5 people between the two demographic data sets, which further supports the use of the LandScan data but with the significant benefit of locational specificity.

The result in this study, therefore, indicate that the method and data used is effective and can be applied to identify the areas that are vulnerable to flooding where flooding is on a large scale. This is particularly true for the Sokoto State where large rainfall events that cause severe flooding extends over very large areas (many hundreds of kilometres) where the land is very flat. In this case, uncontrolled water is often not channelled or confined to the floodplain areas and will overflow and disperse over very large areas. The reason for the high number of vulnerable people in Sokoto State is that the majority of people live along and close to the floodplains and rivers where these areas serve as a major source of income to the local community. Agriculture is the main source of livelihood for the people in this area, most people engage in large scale farming, flood recession agriculture and animal rearing which contributes to the economy of the state.

As indicated in Chapter 2, developing countries like Nigeria have poor spatial data infrastructure and resources to acquire and manage high precision information acquired over vast areas. These countries often rely on global data sets to supplement local spatial information that is scarce or incomplete. Using these data sets of the Sokoto State region, the extent of severe flooding and the population at-risk can be estimated to help support and prioritise flood mitigation efforts.

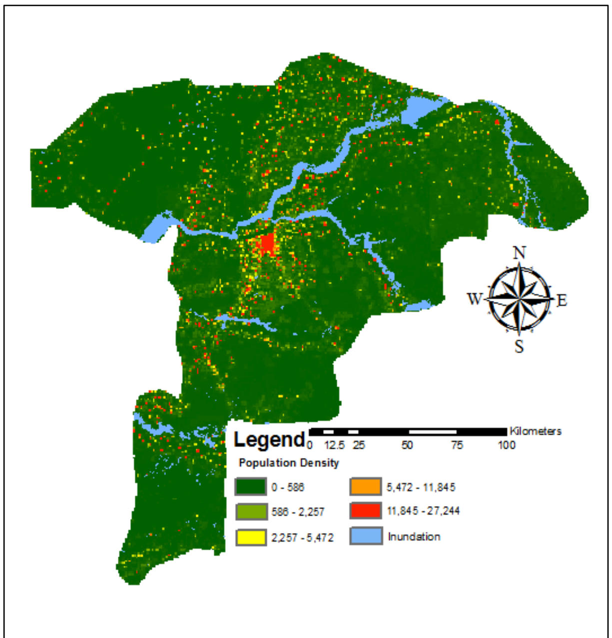


Figure 4.7 Map showing the population distribution within the affected flood areas

Table 4.3 Total population within flood affected areas

No.	State	Population vulnerable
1.	Sokoto	1,053,172

Table 4.4 The LGAs land area (km^2), the total area inundated (km^2) and the population vulnerable.

No.	LGA	Land-area (km^2)	Area-inundated (Km^2)	LandScan 2014 population	Population vulnerable
1.	Binji	526.00	69.542	131,958	60,313
2.	Bodinga	553.179	4.508	201,986	12,457
3.	Dannge-Shuni	1194.494	5.716	221,127	1,284
4.	Gada	1190.464	0.147	276,735	-
5.	Goronyo	1647.867	126.129	209,802	71,356
6.	Gudu	3990.259	118.616	123, 084	70,352
7.	Gwadabawa	1006.775	106.101	259,253	129,737
8.	Illela	1295.346	168.383	177,817	85,650
9.	Isa	2080.139	52.234	177,952	58,715
10.	Kebbe	2747.769	60.135	150,838	27,486
11.	Kware	700.556	105.783	161,768	134,086
12.	Rabah	2648.705	196.957	176,836	109,787
13.	Sabon-Birni	2238.677	188.359	235,154	82,679
14.	Shagari	1292.438	32.782	183,591	20,785
15.	Silame	608.762	2.706	132,286	984
16.	Sokoto North	39.457	-	260,697	-
17.	Sokoto South	30.250	-	225,371	-
18.	Tambuwal	2199.529	98.512	253,602	16,732
19.	Tangaza	2452.411	15.086	142,455	15,636
20.	Tureta	1289.281	2.565	96,099	261
21.	Wamakko	569.730	50.969	206,931	10,191
22.	Wurno	640.348	65.574	190,088	50,995
23.	Yabo	826.108	39.098	142,988	106,889
	Total	31,768.584	1509.902	4,338, 418	1,053,172

Table 4.5 The LGAs, 2006-population census, projected 2014 population from the 2006 census and the 2014 LandScan population figures.

No.	LGA	2006 population	2014 projected population	LandScan 2014 population
1.	Binji	104,274	142,560	131,958
2.	Bodinga	174,302	212,588	201,986
3.	Dannge-Shuni	193,443	231,729	221,127
4.	Gada	249,051	287,337	276,735
5.	Goronyo	182,118	220,404	209,802
6.	Gudu	95,400	133,686	123, 084
7.	Gwadabawa	231,569	269,855	259,253
8.	Illela	150,133	188,419	177,817
9.	Isa	150,268	188,554	177,952
10.	Kebbe	123,154	161,440	150,838
11.	Kware	134,084	172,370	161,768
12.	Rabah	149,152	187,438	176,836
13.	Sabon-Birni	207,470	245,756	235,154
14.	Shagari	155,907	194,193	183,591
15.	Silame	104,601	142,887	132,286
16.	Sokoto North	233,012	271,298	260,697
17.	Sokoto South	197,686	235,972	225,371
18.	Tambuwal	225,917	264,203	253,602
19.	Tangaza	114,770	153,056	142,455
20.	Tureta	68,414	106,700	96,099
21.	Wamakko	179,246	217,532	206,931
22.	Wurno	162,403	200,689	190,088
23.	Yabo	115,302	153,589	142,988
	Total	3,702,676	4, 582,255	4,338, 418

Table 4.6 The land area (km^2), the total area inundated (km^2) and the percentage of area inundated per LGA.

No.	LGA	Land Area (km^2)	Area Inundated (km^2)	Area Inundated (%)
1.	Binji	526.00	69.542	4.6
2.	Bodinga	553.179	4.508	0.3
3.	Dannge-Shuni	1194.494	5.716	0.4
4.	Gada	1190.464	0.147	0.0
5.	Goronyo	1647.867	126.129	8.4
6.	Gudu	3990.259	118.616	7.9
7.	Gwadabawa	1006.775	106.101	7.0
8.	Illela	1295.346	168.383	11.2
9.	Isa	2080.139	52.234	3.5
10.	Kebbe	2747.769	60.135	4
11.	Kware	700.556	105.783	7
12.	Rabah	2648.705	196.957	13
13.	Sabon-Birni	2238.677	188.359	12.4
14.	Shagari	1292.438	32.782	2.2
15.	Silame	608.762	2.706	0.2
16.	Sokoto North	39.457	-	0.0
17.	Sokoto South	30.250	-	0.0
18.	Tambuwal	2199.529	98.512	6.5
19.	Tangaza	2452.411	15.086	1
20.	Tureta	1289.281	2.565	0.2
21.	Wamakko	569.730	50.969	3.4
22.	Wurno	640.348	65.574	4.3
23.	Yabo	826.108	39.098	2.5
	Total	31,768.584	1509.902	100

4.5 Mitigation management

The motivation for this study and the results presented above can be used to help support flood mitigation efforts. Flood mitigation can be defined as those measures that are taken before the flood disaster occurs to minimize or eliminate the impacts and risk of flooding through proactive measures. In order to support these measures, base-line information about where flood hazard and risk occurs must be established. Mitigation of flood hazards or risk can be attempted in two ways, including a structural approach or non-structural approach and/or the combination of both approaches to decrease the vulnerability to flooding (NTG, 2016). The structural approach also known as the engineering approach seeks to prevent the advance of floodwaters, usually through an engineered measure such as building of a levee, retention ponds, dam or floodwall. These structures can be built alongside the channel or a river or even the floodplain to provide an outlet for the water during flood events or trapping the water for some period of time before releasing it at a controlled rate to prevent flooding downstream (CDEMA, 2010).

Non-structural mitigation measures are efforts that can be done to manage the use of the flood prone and flood plain areas to reduce the likely damage caused by flooding that can normally be expected to occur. This can be done after a better understanding of the behaviour of the river, the areas liable to flooding and probability of flooding. These can be regulatory approaches that people or government agencies can undertake to minimise the vulnerability to flooding. Some examples of non-structural measures that can be taken in this case are zonation of the floodplain by passing laws that restrict habitation and construction in the floodplain areas. These areas can be zoned for strictly agriculture and recreational uses whereby lives and properties are not at risk when these flood events occur. In addition, structures that are high enough off the ground and that withstand the velocity of the flood should only be allowed within the floodplain and flood prone areas to reduce the risk of flood destroying and washing away buildings and critical infrastructure.

Integration of engineering and regulatory measures can be effective. For example, governments can purchase and remove buildings that are close to the river and flood plain areas including building of dams and levees away from the river allowing natural movement and storage of floodwaters. This area can then be protected and used to restrict access to the river and floodplain areas. This combination of non-structural and structural approaches will help reduce losses as a result of flooding, help preserve and maintain the natural floodplain and riparian ecosystem of the area.

An overall flood control management plan to manage recurrent disasters associated with flooding in this region will require continued monitoring of persistent flood event to gain a better understanding of areas and people who are vulnerable. Remote sensing and GIS technologies are well placed to provide such information in support of both mitigation and emergency measures to minimise and overcome the damage caused by a flood disaster.

Chapter 5

Conclusion

5.1 Research findings

The primary aim of this study is to develop a better understanding of the temporal flood extents and the people at risk from flooding in Sokoto State in Nigeria, with the intention of obtaining base-line information that will help prioritise flood mitigation efforts for disaster risk reduction. In doing so, inundation maps for the four major flood events of October 8, 2003, October 16, 2010, September 21, 2012, and September 22, 2015 were derived using remote sensing (RS) techniques. Subsequently, LandScan GRID population data was used to identify people most vulnerable to these flood events. Importantly, this study introduces a simple but efficient and cost effective method for the analysis of flood inundation mapping extent and frequency using imagery acquired from the Moderate Resolution Imaging Spectroradiometer (MODIS). The use of MODIS data and the Modified Normalised Difference Water Index (MNDWI) technique for discriminating between water and non-water features can be used to identify and map the areal extent of inundation in developing countries like Nigeria where no other means to acquire, monitor and map floods is available on a large scale. This study has demonstrated that the unique capability of satellite imagery like that provided by the MODIS coupled with the MNDWI technique can be used in detecting inundation areas and their extent to create inundation maps particularly useful in a developing country like Nigeria. Moreover, as this area in Nigeria is one of the major floodplains in the country, it is suggested that this technique of mapping flood inundation has the potential to be applied to other areas in Nigeria, other countries in Africa and/or developing countries around the world; where no better means of acquiring data and mapping natural hazards is available.

It is no doubt that Nigeria, like many other countries in the world, is affected by flooding and different factors are responsible for this. The result of this study show that over a million people are vulnerable to flood occurrences in this area and that the majority of these people live along the floodplain and river areas. This is in line with NEMA (2012, 2015), which states that the majority of the populace live close to the floodplain and river systems because of the benefit they derive from these areas and that people are not discouraged by the negative impact that might result during flood events. It was confirmed that risk/vulnerability mapping is very important for the development of planning in the State.

This result also shows that the LandScan GRID data used with the MODIS inundation mapping produced a reasonable estimate of the population vulnerable to flooding in Sokoto, Nigeria. Importantly, the projected 2014 population data derived from the last official Nigerian census in 2006 was used to test the validity of the 2014 LandScan population data with only a 5.5% error margin. While the next Nigerian census is scheduled for later this year (2016), population data will once again be aggregated to the LGA level as its smallest administrative unit. This unfortunately prevents locational specificity of the presence and density of people living in specific areas, which is necessary for disaster management efforts. Consequently, alternative demographic information like that of LandScan will continue to play an important role in providing more precise information on the spatial distribution of people and place.

This study has investigated, through its literature review and implementation of its methods, a number of geospatial techniques for delineating flooded areas. Specifically, the MNDWI derived using MODIS imagery has shown to be a useful combination in delineating inundated areas in this landscape after severe broad-scale flooding. At this scale, LandScan population data has also been shown to provide valuable information by quantifying the number of people at-risk in these areas through simple GIS analysis techniques. The combination of GIS and remote-sensing has been proven to be of great importance for mapping and management of flood risk due to different resolutions, such as the spatial, temporal, and structure of data. In doing so, this study has successfully answered the research questions posed in this thesis; the results of which can be used as valuable base-line information for flood mitigation programs and management.

5.2 Outcomes

Sokoto state, Nigeria is used here as a focus study area due to its vulnerability to severe flood events as a result of high rainfall, flat land, its lack of flood control and infrastructure and history of large-scale flooding. This study concentrated on developing a flood detection method for flood inundation hazard and risk mapping by utilizing simple but effective remote sensing and GIS methods and freely available global data sets, in the absence of more detailed ‘on-ground’ higher resolution information, with considerable success.

Overall, while this study does not provide absolute locational specificity of people at risk, it does provide valuable broad-scale information about where the larger population is at risk from flooding. This can help to focus resources based on national or state level assessment. In this context, the flood inundation hazard and risk maps provide valuable state-wide baseline information. While the limitations of this study will be discussed in the next section, the outcomes of such hazard and risk mapping and the methods used may:

- Serve as input for the integration of flood risk management strategies and spatial planning in the area.

-Provide the concerned authorities with a method that can be used as a legal tool to control and apply management and land zoning, protect the environment, decrease flood hazards, provide insurance and plan development.

- Increase the awareness in the use of RS and GIS technology and geo-processing methods that provide that facilitate mapping the extent of flooding and estimating the spatial distribution of population vulnerable to this flood hazard in the state and country.

- The flood inundation maps can further be utilized for quick identification of locations of potential flood hazard to reduce the losses involved.

- Be useful and beneficial in evaluating and assessing wide range of disaster through the use of different spatial functionalities, like the vector and raster analysis, topographic operations and intersect operations which can assist in anticipating management and relief of natural disasters including flooding.

5.3 Limitations

While this study has demonstrated a successful approach to estimating populations at risk from flooding using the MNDWI technique on MODIS imagery and LandScan population data, detailed below are some of the challenges encountered.

5.3.1 Selection of satellite data

The choice of imagery is a critical but generally underestimated requirement in flood mapping. Various sensors on-board Earth observation satellites (EOS) provide resolution characteristics suitable for mapping inundated areas as a result of flooding. However, each system has its advantages and disadvantages in terms of its spatial, spectral, and temporal characteristics. While the goal is to provide the highest possible accuracy on flood hazard extent, and thus locational specificity of people at risk, this may not be possible. For example, initial investigation was made into the use of freely available Landsat imagery that would provide 30m spatial resolution. However, due to the reduced temporal cycle (16 days) and considerable cloud that was present during all four major flood events, these events remained undetected or were obscured by clouds making Landsat imagery unsuitable. Nevertheless, high-resolution sensors should not be dismissed altogether. For example, SPOT-6/7 imagery provides a multispectral spatial resolution of 6m but with a substantially improved revisit time due to its off-nadir viewing capabilities and the use of two orbiting satellites. While a 45 degree viewing angle is possible, the more geometrically stable <20 degree viewing angle reduces revisit times to every 4 days with both SPOT-6 and 7 image acquisitions and a further reduction to 2-day revisit time with <30 degree viewing angle with both SPOT-6 and 7 acquisitions. Notably, the SPOT imagery is not freely available but could be purchased as part of an organisation's spatial information capture program that would serve to derive a range of data products, including environmental mapping and monitoring, land cover mapping, land cover land use change (LCLUC) and baseline and/or near real-time information for disaster management.

5.3.2 Water mapping models and integration with population data

Alternative water mapping models have been widely discussed in this thesis. It should be noted though that one technique found to be suitable in its ability to map water in one environment may not be suitable in another. Experimentation will need to be conducted commencing with an understanding of the characteristics of the study area and its landscape composition in order to target a suitable water mapping algorithm. While this study proposes that the water mapping approach used here can be applied to other areas in Africa, the specific water model will need to be carefully investigated. This also extends to a suitable threshold value used to separate water from non-water areas. Specifically, water indices perform inconsistently with varying levels of water turbidity and suspended sediment load, typically present during flood events where water is highly contaminated with soils and debris. These contaminants significantly reduce the spectral contrast between water and non-water areas making it difficult to identify a single index value threshold that separate the two.

It should also be noted that the intersection between the delineated water boundaries derived from the MODIS imagery and the LandScan GRID population data might introduce errors by overestimating the population at risk. The disadvantage of the intersect/overlay method with the gridded population data is that the total population in a grid is classified as being vulnerable whether or not the total grid area is actually inundated. This is primarily due to the coarse resolution $1km^2$ LandScan grid size where the overlay method only needs any portion of the population grid cell to intersect with the water boundary and the total population for that grid cell is counted as at-risk. This approach, and the use of coarse resolution data, may lead to an over-estimation of the population at risk/vulnerable in the study area.

5.3.3 Population data

The ambient population is the total number of people likely to be present in a location as opposed to just people residing there, with the counts for each cell ($1km^2$) being based on probability coefficients (Dobson et al, 2000). The coefficients based on land cover, road proximity, night-time light and slope are verified to be accurate to within ten percent of the given values. However, with a $1km^2$ cell size, this dataset is believed to be too coarse for local planning. Also, with this data, positional or attribute errors and inconsistencies are to be expected in large dissimilar spatial data (ORNL, 2016).

A further limitation of the data is that for each country, the model used to arrive at the population count does not take into consideration the spatial continuity of the road networks between them, bringing about uneven changes in the density of counts at country boundaries, which might affect the estimation of the population vulnerable to flooding. Likewise, the underlying models for deriving this data have not been published, so the assumptions utilized by LandScan to distribute populace numbers to pixels are not known, which affects our understanding of how the population distribution is derived. Despite this, projected 2014 population counts derived from the official 2006 Nigerian census closely aligned with population estimates derived from the LandScan population dataset, which instilled confidence in the use of the LandScan data product.

5.3.4 The modifiable areal unit problem

The modifiable areal unit problem (MAUP) is one of the most obstinate issues in spatial analysis where spatial data collected from point locations is aggregated to arbitrary boundaries (Wong and Amrhein, 1996). Spatial data classified or tabulated at different spatial scales or distinctive zonal systems for the same locale will not give consistent analysis results. For example, the population count given to a specific 1km grid cell will be influenced by the position of the grid location over the study area, where the assumption of uniformity (aggregation) applies in each grid cell. While the grid cell positions are fixed they are arbitrarily placed and a shift in the grid cell positions (a different origin perhaps) will alter the population count in each grid cell, which in turn will affect the total summation of population counts when intersected with the flood extent layer. This is also true if the grid cell size was aggregated to a smaller or larger grid cell size. Consequently, while these global data sets provide valuable information and every effort is made to minimise error in the risk calculation, their arbitrary aggregation to 1km grid cells will introduce error into the final calculation of people at risk. While absolute counts of people at risk from flooding are sought from this analysis, the relative number of people at risk across the study area is likely to be more robust than absolute counts.

5.3.5 Cloud problems associated with the data

The MODIS data utilised in this study is of a coarser spatial resolution (250-1000m) and the suitability of this data was much dependent on the requirements by the user. Despite the fact that the MODIS sensors images at a sub-daily interval, cloud was still a major issue, especially during the peak periods of the flood. Most of the images free of cloud of the flood events were only available several days after the peak of the flood, which led to the development of flood hazard maps based on image data acquired when the flood level was reduced. However, despite all the limitations, when data free of cloud cover is available, MODIS can show a large flood's movement through time and it is valuable for providing flood extent maps during or after a flood incident. In terms of this, the SAR data with a better resolution and cloud penetrating capabilities is also recommended for further flood hazard studies in the Country, which may provide a better mapping result, but subject to the limitations discussed in Chapter 2.

5.4 Recommendations for future research

The main aim of this research is to identify flooded areas, create a flood inundation hazard map of the Sokoto region and give an estimation of the number of people vulnerable to flooding, which has not been without its challenges. Based on the findings of this study, the following recommendations are made in support of minimising the impacts of flood disaster in the state.

- The integration of other floodwater detection techniques with the use of an accurate DEM that will help in identifying flood areas more accurately than the single use of the MNDWI. Combining high-resolution DEM, for example LiDAR, with moderate to high resolution imagery, including radar data in inundation characterization will be the future focus of on-going study.

- Linking hydrological data with the frequency and inundation extent maps to aid in better understanding of the spatial and temporal patterns of flood inundation. This will, enhance the knowledge of the characteristics (hydrological) of the floodplain ecosystem.

- The combination of the RS data and topographic analysis, which will help illustrate the interaction between floodplain environments and flood processes.

- An automated way of analysing and mapping the terrain of Sokoto State to be able to generate a database and a plan for monitoring and managing flood disaster monitoring in the area.

- Public enlightenment and awareness on areas vulnerable to flooding, which can be done in their own local dialect through schools, newspapers or television channels the majority of people have access to.

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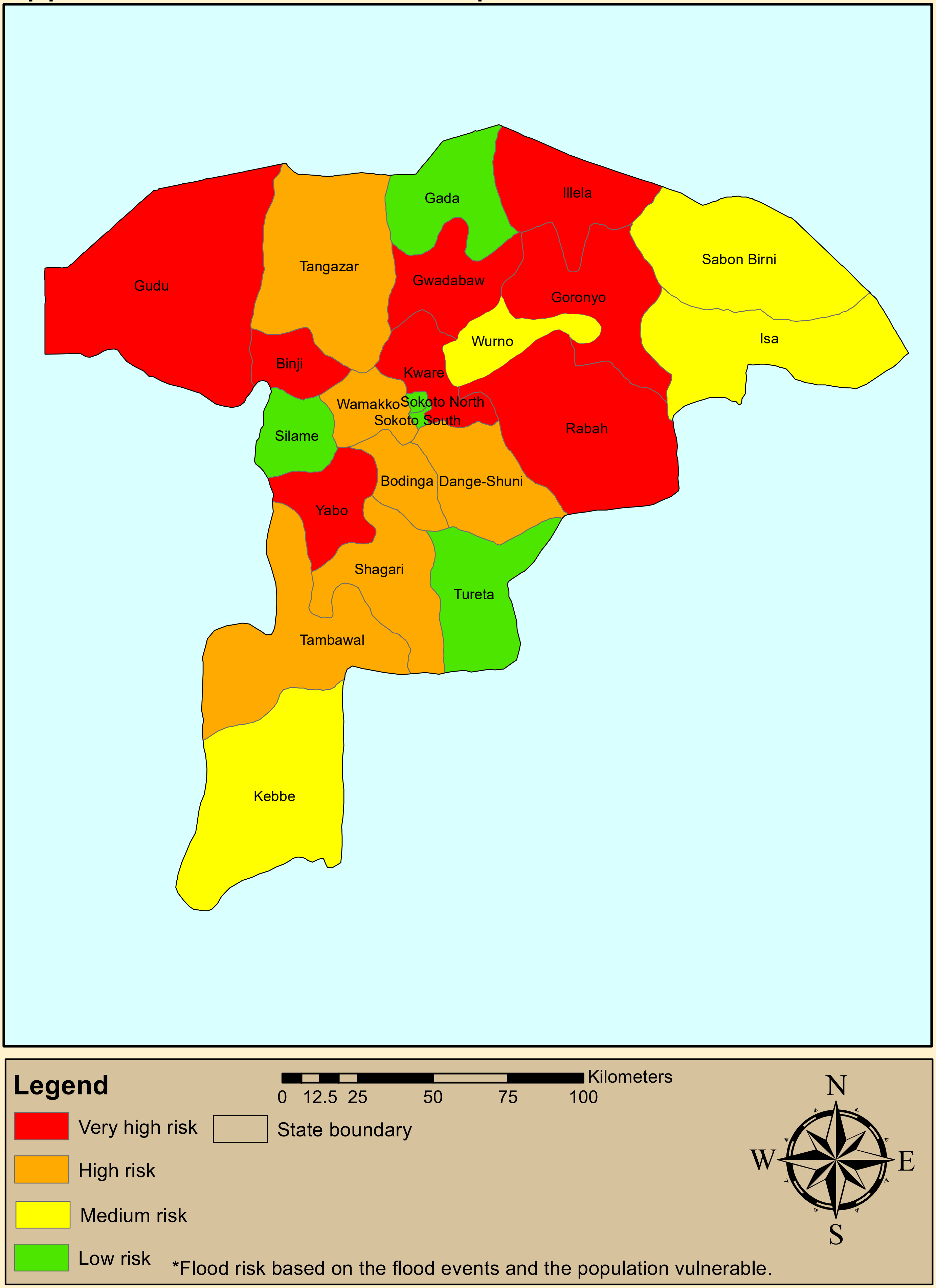
Appendix 1 Flood Risk Map of Sokoto State.



Appendix 2 Flood risk Map based on Frequency of Inundation.