Government of the People's Republic of Bangladesh
Department of Disaster Management
Ministry of Disaster Management and Relief

MULTI HAZARD
RISK AND
VULNERABILITY
ASSESSMENT,
MODELING AND MAPPING

FINAL REPORT OF MULTI HAZARD RISK AND VULNERABILITY ASSESSMENT, MODELING AND MAPPING IN BANGLADESH

VOLUME I: HYDRO-METEOROLOGICAL HAZARD ASSESSMENT

FLOOD, STORM SURGE, LANDSLIDE AND DROUGHT

Government of the People's Republic of Bangladesh

Report on Multi-Hazard, Risk and Vulnerability Assessment, Modelling and Mapping in Bangladesh

Volume I: Hydro-meteorological Hazard Assessment

(Flood, Storm Surge, Landslide and Drought)

Department of Disaster Management
Ministry of Disaster Management and Relief

Message from Secretary, MoDMR

Government of the Peoples' Republic of Bangladesh had initiated the 'Emergency 2007 Cyclone Recovery and Restoration Project (ECRRP)' under DDM, LGED & BWDB with the assistance of the World Bank for Disaster Risk Mitigation and Reduction. Multi-hazard Risk and Vulnerability Assessment, Modeling and Mapping (MRVAM) is one of the initiatives under ECRRP, D1(DDM component) to assess risk and vulnerability of 8(eight) major hazards like Flood, Cyclone induced Storm Surge, Landslide, Drought, Earthquake, Tsunami, Technological & Health hazards. Component D1 is designed to contribute towards 'building long-term preparedness by strengthening disaster risk management' through strengthening and enhancement of long-term disaster risk mitigation and reduction ability of the DDM. This study is very important, due to the geographical location and topographical features of Bangladesh, exposed the country to almost all kinds of natural disasters and a large-scale disaster in Bangladesh has been observed at a frequency of 5-6 years.

I am very happy to know that ECRRP-D1 project is going to publish comprehensive Report on MRVAM with the help of ADPC, Thailand and IWM, Bangladesh. This study will supplement the efforts of the government to incorporate disaster risk reduction issues in all development programmes to build a safe and disaster resilience nation, referring to the SOD-2010, Disaster Management Act-2012, Disaster Management Policy-2015, and National Disaster Management Plan 2010-15. Alongside by the government, all including non- governmental organizations (NGOs) and civil society should come forward to build an effective disaster management infrastructure to reduce the post-disaster losses. District and local level officials who are frequently involved with the disaster damage assessment, management, preparedness and risk & vulnerability reduction activities will be benefitted by using these national level risk assessment map and database from this project.

Md. Shah Kamal
Secretary
Ministry of Disaster Management and Relief

Message from DG, DDM

Bangladesh has made a strong commitment to implement Hyogo Framework for Action (HFA) during 2005-2015 for critical guidance in efforts to reduce disaster risk and the Multi-Hazard Risk and Vulnerability Assessment, Modeling and Mapping (MRVAM) project initiated under 'Emergency 2007 Cyclone Recovery and Restoration Project (ECRRP)' as D1 component has advanced Bangladesh's progress in Priority Action 2: Identify, assess and monitor disaster risks and enhance early warning. In continuation of this, outcome of this project "Multi-Hazard Risk Assessment at national level" is in line with Priority 1: 'Understanding disaster risk' of Sendai Framework for Disaster Risk Reduction 2015-2030, adopted in the 3rd World Conference on Disaster Risk Reduction, held from 14 to 18 March 2015 in Sendai, Miyagi, Japan.

The findings of MRVAM project has create the basis for "building long term preparedness through strengthening disaster risk management capacity in the country as well as for enhancement of long term disaster risk mitigation and reduction ability of the Department of Disaster Management (DDM)". On the other hand, MRVAM project outcome has created awareness among the district and upazila level officials and will help in contributing towards incorporating appropriate risk-reduction strategies and prioritizing them into the country's development planning process.

In addition to this, the findings of this study 'risk information of population, housing and livelihood at upazila level' will allow decision makers to prioritize risk mitigation investments and measures to strengthen the emergency preparedness and response mechanisms for reducing the losses and damages due to future disaster events.

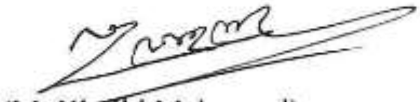
(Md. Reaz Ahmed)
Director General (Additional Secretary)
Department of Disaster Management

Message from PD, ECRRP-D1, DDM

Multi-Hazard Risk and Vulnerability Assessment, Modeling and Mapping (MRVAM) project implemented as a part of sub-component D1.2 'Emergency 2007 Cyclone Recovery and Restoration Project (ECRRP)', by Department of Disaster Management (DDM) is an efforts towards 'building long-term preparedness through strengthened disaster risk management', through the strengthening and enhancement of the long-term disaster risk mitigation and reduction ability of the DDM.

This project has developed enormous quantity of database representing multi-hazards of Flood, Cyclone induced Storm Surge, Landslides, Drought, Earthquake, Tsunami, Technological and Health along with national level database representing population, housing, livelihood, critical facilities, infrastructure which can be used at Union / Upazila level for development planning process.

DDM has established Multi-Hazard Risk and Vulnerability Assessment (MRVA) Cell, in which geo-database of hazard, exposure and risk assessment at upazila level developed in this project and hosted in the state of the hardware & software facilities. I take this opportunity to state that, this will enhance the capacity of the department to monitor the hazard, exposure and risk assessment, in this way, all the government agencies, professionals and researchers will be benefitted in contributing towards disaster risk reduction in Bangladesh.



(M. Khalid Mahmood)
Joint Secretary and Director (Planning & Development)
Project Director, ECRRP-D1
Department of Disaster Management

Preface

A category IV cyclone *SIDR* struck in the south west coast of Bangladesh on November 15, 2007 evening and moved inland, destroying infrastructure, causing numerous deaths, disrupting economic activities, and affecting social conditions. As most all of Bangladesh is considered as a Delta just above sea level, tidal surge of 15-20 feet and gail-force winds of approximately 150 mph creates havoc in most of the area. The aim of the assessment was to identify priority areas to support the Government of Bangladesh in cyclone recovery efforts as well as to recommend priority interventions for a long-term disaster management strategy. The preparation of Multi-Hazard Risk and Vulnerability Assessment, Modelling and Mapping (MRVAM) project has identified the damage needs and quantified financial and technical requirements and established MRVA Cell in DDM, that will facilitate formulating comprehensive early recovery actions, medium-term recovery and reconstruction plans and a long-term disaster risk management and reduction strategy. The main objective to establish MRVA Cell is to strengthen and enhance country capacity in carrying out systematic multi-hazard risk assessments and consolidating and maintaining hazard risk information at central (national) and disaggregated (district) levels. This will contribute towards the realization of the specific priority attached in the country's disaster management strategy of 'defining and redefining the risk environment' of the country. The Asian Disaster Preparedness Center (ADPC), Thailand, in partnership with the Institute of Water Modeling (IWM), the Norwegian Geotechnical Institute (NGI), the Asian Institute of Technology (AIT), and the Faculty of Geo-Information Science and Earth Observation of the University of Twente (ITC), the Netherlands have been worked together to deliver consulting services on the Multi-Hazard Risk and Vulnerability Assessment, Modeling and Mapping in Bangladesh and finally have prepared the Volume I: Hydro-meteorological Hazard Assessment (Flood, Storm Surge, Landslide, Drought), Volume II: Geological and Environmental Hazard Assessment (Earthquake, Tsunami, Technological, Health), Volume III: Elements at risk, Volume IV: Vulnerability and Risk Assessment (Flood, Storm Surge, Landslide, Drought), Volume V: Vulnerability and Risk Assessment (Earthquake, Tsunami, Technological, Health), Volume VI: Summary and Recommendations.

For flood hazard and vulnerability assessment, Flood Modeling used in this study is MIKE11 Hydrodynamic Model developed by DHI, coupled with Geographic Information System (GIS) to capture the hydraulic response of Bangladesh Rivers, in-depth Flood analysis and its floodplains in extreme flooding conditions. Then a frequency analysis was carried out in the river network at 7617 grid points in order to obtain return period-wise flood levels for 25 year, 50 year, 100 year and 150 years. The model used in MRVAM project for Cyclone induced Storm Surge is called Bay of Bengal Model (BoBM). The model is developed using a MIKE21 FM modelling system, which is a numerical modelling system for the simulation of water levels and flows in estuaries, bays and coastal areas. Storm Surge hazard depth was divided into seven different depth categories in order to find the extent of surge inundation and prepare inundation maps for all return periods: 25, 50 and 100 years for the entire coastal region. The depth categories are <1 m, 1-1.5 m, 1.5-2 m, 2-3 m, 3-4 m, 4-5 m, >5 m. Earthquake hazard maps were developed using the historical data and existing geological setting for 50 year, 100 year, 200 year, 500 year and 1000 years return periods at the sites of investigation derived and interpolated to develop earthquake hazard maps representing spatial variation of Peak Ground Acceleration (PGA) Map in Bangladesh.

Simultaneously, to model the tsunamigenic conditions and the possible hazard maps due to Tsunami, have been generated for 50, 100, 200, 500 and 1000 years return period and the SPI (Standardized Precipitation Index)-Return period plots used to calculate the severity of Drought with different return periods such as the SPI values for 10, 50 and 100 years return period.

The purpose of this Multi-Hazard Risk and Vulnerability Assessment (MRVA) Modelling and Mapping study is to develop a hazard and vulnerability framework using the progression of vulnerability model to identify the root causes (problems) and the underlying pressures within coastal belt as well as whole Bangladesh. The information provided in this study was intended to assist in identifying hazards and vulnerabilities thereby building a disaster resilient Districts and Upazilas by sharing local hazards and also establishing community structures. Combining the results of the theoretical framework and research findings with the argument constructed in these Volumes I-VI about the disaster risk reduction and mitigation; it was found that it is possible to reduce hazard risks, and vulnerability to disasters, through the application of the latest GIS & RS tools and Hydrodynamic modeling and the participation of the grass-root level community in disaster risk management activities.

It is a great pleasure to successfully launch this Scientific MRVA National Document, signifying the needs and opportunities for the protection of the coastal environment as well as overall most vulnerable districts of Bangladesh and associated lives and livelihoods. The Department of Disaster Management (DDM), Ministry of Disaster Management and Relief would like to thank all those involved in the preparation and finalization of this document and would like to believe that materialization of these policies and programmes will improve overall catastrophic environment of the country as a whole and coastal environment in particular.

We would like to express our in-depth gratitude to the prominent experts of Technical Advisory Committee (TAC), the well-known and reverend group of professionals of the Country, specially, Dr. A. S. M. Maksud Kamal, Convener-TAC and Dean, Faculty of Earth and Environmental Sciences, Dhaka University; Dr. Umme Kulsum Navera, Professor, Department of Water Resources Engineering, BUET; Dr. Md. Atiqur Rahman, Joint Secretary (Admin.), Ministry of Disaster Management and Relief (MoDMR), Mr. M. A. Rouf Hawlader, Director, Survey of Bangladesh; Mr. Shamsuddin Ahmed, Director in Charge, Bangladesh Meteorological Department (BMD), Mr. Md. Shahidul Islam, GIS Analyst, CDMP-II; Mr. Mir Ahmed, Member Secretary-TAC & Director-MIM, DDM; Mr. M. Khalid Mahmood, Director (Planning & Development) & PD-ECRRP-D1, DDM; and Mr. Reaz Ahmed, Director General and MRVAM Advisor, DDM & last of all, those associated with MRVA Cell; under whose overall guidance and supervision, these MRVA Volumes were duly checked and scientifically verified, who had worked relentlessly for years to generate scientific information required for these risk and vulnerability assessments. A special appreciation to the World Bank, ERD and PCMU – Planning Commission Team, whose financial and project extension support from the beginning helped us to reach its ultimate destination.

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List of Abbreviations

ADPC	Asian Disaster Preparedness Center
AIT	Asian Institute of Technology
ARCGIS	ARC Geographic Information System
BBS	Bangladesh Bureau of Statistics
BMD	Bangladesh Meteorological Department
BNBC	Bangladesh National Building Code
BoBM	Bay of Bengal Model
BTM	Bangladesh Transverse Mercator
BWDB	Bangladesh Water Development Board
BUET	Bangladesh University of Engineering and Technology
CDMP	Comprehensive Disaster Management Programme
CEIP	Coastal Embankment Rehabilitation Project
CERP	Coastal Embankment Rehabilitation Project
CPP	Cyclone Preparedness Program
CSPS	Cyclone Centre Preparatory Study
DDM	Department of Disaster Management
DDMC	District Disaster Management Committee
DEM	Digital Elevation Model
DGHS	Directorate General of Health Services
DHI	Danish Hydraulic Institute
DMB	Disaster Management Bureau
DNA	Damage Loss and Needs Assessment
DoE	Department of Environment
DRR	Disaster Risk Reduction
DRM	Disaster Risk Management
ECRRP	Emergency Cyclone Recovery and Restoration Project
EDP	Estuary Development Program
EM-DAT	Emergency Event Database
ENSO	El Nin˜o Southern Oscillation
FFWC	Flood Forecasting and Warning Center
FSCD	Fire Service and Civil Defence
GBM	Ganges Brahmaputra Meghna
GCPP	Global Precipitation Climatology Centre
GDP	Gross Domestic Product
GIS	Geographic Information System
GSB	Geological Survey of Bangladesh
GTM	Global Tide Model
HFA	Hyogo Framework for Action
GDEM	Global Digital Elevation Model
GDP	Gross Domestic Product
IPCC	Intergovernmental Panel on Climate Change
IPSWAM	Integrated Planning for Sustainable Water Management
ITC	Faculty of Geo-Information Science and Earth Observation of the University of Twente
IWM	Institute of Water Modeling
IDW	Inverse Distance Weighted

KAFCO	Karnaphuli Fertilizer Company Limited
LSZ	Landslide Susceptibility Zonation
LGED	Local Government Engineering Department
MPO	Master Plan Organization
MoDMR	Ministry of Disaster Management and Relief
MoHFW	Ministry of Health and Family Welfare
MIS	Management Information System
MRVA	Multi-Hazard Risk and Vulnerability Assessment
MRVAM	Multi-Hazard Risk and Vulnerability Assessment Modelling and Mapping
MSL	Mean Sea Level
NAO	North Atlantic Oscillation
NDVI	Normalized Difference Vegetation Index
NGI	Norwegian Geotechnical Institute
NOAA	National Oceanic and Atmospheric Administration
NPDM	National Plan for Disaster Management
PDSI	Palmer Drought Severity Index
PGA	Peak Ground Acceleration
PDO	Project Development Objective
PWD	Public Works Department
RegCM	Regional Climate Model
SOD	Standing Orders on Disaster
SPI	Standardized Precipitation Index
ToR	Terms of Reference
UDD	Urban Development Directorate
UNDP	United Nations Development Programme
UNISDR	United Nations International Strategy for Disaster Reduction
UNO	Upazila (Sub-district) Nirbahi (executive) Officer
USGS	United States Geological Survey
UZDMC	Upazila Disaster Management Committee
WARPO	Water Resource Planning Organization
WHO	World Health Organization

Multi-Hazard Risk and Vulnerability Assessment (MRVA) Report

Volume I: Hydro-meteorological Hazard Assessment

Chapter 1: Introduction

Bangladesh has made a strong commitment to implementing the Hyogo Framework for Action (HFA) and, in that context, the “Project on Multi-Hazard Risk and Vulnerability Assessment Modeling and Mapping for Bangladesh” will advance Bangladesh’s progress in Priority Action Area 2: “Identify, assess and monitor disaster risks and enhance early warning”. This includes ensuring that “national and local risk assessments based on hazards data and vulnerability information are available and include risk assessments for key sectors. “Bangladesh is considered to be a disaster “hot-spot”, facing multiple hazards that threaten lives, property and economic development (UNISDR, 2008).

1.1 Background

A 15-year long term strategic plan of action for strengthened disaster risk reduction and mitigation was developed by the Cyclone Sidr Joint Damage, Loss and Needs Assessment (JDLNA) team. D1 is a component of the World Bank-financed Emergency Cyclone Recovery and Restoration Project (ECRRP), under implementation by the Department of Disaster Management (DDM) (earlier DMB). This directly supports the startup implementation of activities envisaged under three of the five strategic pillars of JDLNA's long term program on strengthening disaster risk mitigation (DRM) in Bangladesh. Whereas the ECRRP provided an overall credit of USD 109 million to the Government of Bangladesh (GoB), over a four-year implementation period between December 2008 and December 2012, the total amount available under component D1 is USD 8 million. Component D1 aims to contribute towards the project development objective (PDO) of “building long-term preparedness through strengthened disaster risk management”, through the strengthening and enhancement of long-term disaster risk mitigation and reduction ability of the DDM. Among other things, this has entail the creation of two dedicated cells in the DDM: 1) Multi-Hazard Risk and Vulnerability Assessment (MRVA), and 2) Damage Loss and Needs Assessment (DNA).

The strategic areas of the JDLNA directly supported under component D1 include: 1) risk identification and assessment; 2) strengthening and enhancing emergency preparedness; and 3) institutional capacity building related to DRM. These entail structural and non-structural interventions both generally at the national level and those specifically targeting 12 severely affected districts and upazilas from Cyclone Sidr. Component D1 includes the following three subcomponents:

- Subcomponent D 1.1: Capacity Building of the Department of Disaster Management
- Subcomponent D 1.2: Support Towards Detailed National-level Multi-Hazard Risk and Vulnerability Assessment, Modeling and Mapping

- Subcomponent D 1.3: Strengthening and Enhancing Emergency Preparedness in 12 Severely Cyclone Affected Districts and Upazilas

This project is part of the subcomponent D 1.2.

1.2 Purpose of Hazard and Risk Mapping at the National Level

The project on Multi-Hazard Risk and Vulnerability Assessment Modeling and Mapping will have an impact far beyond what its detailed scope might suggest. On a macro level, this project aims to be the catalyst for DRR practice in Bangladesh, helping to achieve the Government’s ambitious goal of bringing its policies, institutions, and capabilities for disaster preparation, mitigation, and response up to world-class standards. In a very real sense, it is a pilot effort for activities to be financed by various donor agencies in order to expand efforts further at all levels. Therefore, it absolutely must establish a solid base and ensure that Bangladesh will have the expertise to take maximum advantage of the present and future interventions. At the same time, on a more micro level, outputs of the project are aimed to increase the capacity of Districts, City Corporations, Paurashava, Upazila etc., and individual citizens, including the most vulnerable individuals and groups among them, to deal with all aspects of emergencies. It further aims to help save lives and property, and increase the sense of security for people throughout the country.

1.3 Challenges in Executing the Project

The current study aims to cover the entire country in terms of geographical coverage. However, the risk and vulnerability is based on specific hazards, considering the regions affected by the hazards respectively. Since the study completed a detailed assessment of different hazard specific risks, it required an intensive database on different population, housing, livelihood, critical facilities and infrastructure etc. at all levels starting from Union, upazila and city, up to the district level. Currently, the detailed datasets on population and housing are available at union/upazila/district levels from the Bangladesh census data of 2011, whereas livelihood, critical facilities and infrastructure data was available at upazila level from the Local Government Engineering Department (LGED). Although this data set is not up to date, there are no other data sets available from respective line departments. Hence, same data has been combined in order to develop datasets at the district level, and is used in this study for the vulnerability and risk assessment. Under these circumstances, it is emphasized that, updating of this data, or the development of a new dataset, is the collective responsibility of all the concerned line departments at different levels. Further, it is also a collective responsibility to support DDM in updating the risk profile of Bangladesh, using the methodology developed and transferred through this study. However, it has been a major challenge for DDM to convince different agencies and organizations at national and local levels to participate during post implementation of this project.

1.4 Project, Implementation Organizations and Partners

Many national and international institutions and organisations supported the ADPC team during the execution of this project. They are described below.

- The Asian Disaster Preparedness Center (ADPC), in partnership with the Institute of Water Modeling (IWM), the Norwegian Geotechnical Institute (NGI), the Asian Institute of Technology (AIT), and the Faculty of Geo-Information Science and Earth Observation of the University of Twente (ITC), will work together to deliver consulting services to conduct a project on Multi Hazard Risk and Vulnerability Assessment, Modeling and Mapping in Bangladesh. The ADPC team worked in close association with the Department of Disaster Management (DDM) (earlier DMB) and other related technical departments in Bangladesh such as Bangladesh Bureau of Statistics (BBS), Directorate General Health Services (DGHS), Geological Survey of Bangladesh (GSB), Local Government Engineering Department (LGED), and Water Resources Planning Organization (WARPO). Close linkages with government agencies has ensured secondary data collection, hazard specific information exchange and sharing of any other data relevant to the study.
- The project covered various technical and management activities including review of past and ongoing studies, activities related to various hydro-meteorological, geological, health, and technological hazards, establish hazard assessment methodology, vulnerability assessment, exposure and risk assessment for various sectors. The major outcome has shown the way to identify institutional gaps, prioritizing the disaster risk reduction, options for institutional measures etc.
- This study provided an opportunity to share existing information, data and resources in developing comprehensive hazard assessment. The DDM and focal agencies for various hazard assessments received the opportunity to interact with international research and development agencies, working in hazard and disaster management.

1.5 Project Objectives

The main objectives of this study are as follows:

- Identify all hazard prone areas of Bangladesh specifically district, City Corporation, municipality, upazila and unions covering geological, hydro-meteorological and technological hazards;
- Assess the exposure of people, property, infrastructure and economic activities to the above mentioned hazards;
- Assess the full range of vulnerabilities of the exposed elements experienced throughout the country with reference to the above hazards; and
- Influence sectoral development strategies towards recognizing the highly dynamic form of vulnerabilities and factoring an understanding into institutional, legislative and organizational systems for preparedness, planning and mitigation.

1.6 Scope of the Assignment

The terms of reference note that "various geological and hydrological risk assessment studies have been undertaken in the country mapping vulnerabilities at the district, city and upazila levels." To date, however, there is no effort in conducting unifying comprehensive risk assessment for quantifying the country's risks in terms of economic losses along with social impacts.

The Government often faces difficulties with the task to prepare and manage hazards at various levels starting at the union level, up to the national level. Therefore, it is important for the local authority or city managers to deal with proper disaster management mechanisms.

This study aims to deal with the hazards that are currently making the communities, settlements, and infrastructures vulnerable. Hazards such as cyclones, floods, earthquakes, landslides, river bank erosion, tsunamis, droughts etc. will be brought into consideration in order to understand the risk and vulnerability at various levels starting from the upazila level, up to the national level. Currently there are few studies on hazard and vulnerability that focus on a specific hazard in a particular city or region. Therefore, it is difficult to understand the true risk and vulnerability of a city/division in terms of multi-hazards. Moreover, since there is lack of a proper study, it is beyond the control of the city/national disaster managers to prepare properly and consider the hazards that prevail in a particular area.

This study focuses on several important issues when exploring multi-hazard risk assessment and mapping, and will cover the important issues, namely: *identification of major hazards, evaluation of existing studies and gap analysis, demarcating the exposures, vulnerability, risk assessment and detailed mapping, and web portal development.* This study also intends to develop a national level database focusing the continuation of hazard and vulnerability assessment at different level of the country. In addition, the capacity of local professionals will be enhanced through different trainings as scheduled under this study. The results of this study may serve as a guide for the policy/decision makers and other stakeholders in formulating/reviewing policies on how to prepare for disasters at different levels of the country.

1.7 Stakeholders Contacted in the Project

There are a number of stakeholders related to the project implementation. The stakeholders include the direct implementer, associate implementer and direct and indirect beneficiaries of the project. Department of Disaster Management (DDM) of the Ministry of Disaster Management and Relief (MoDMR) of the Government of Bangladesh are the main implementers of the project, with funding support from the World Bank. The project is implemented with technical assistance from the Asian Disaster Preparedness Center (ADPC), Bangkok, the Institute of Water Modeling (IWM), Bangladesh and the Norwegian Geotechnical Institute (NGI), ITC, Asian Institute of Technology (AIT) through a sub-consultancy.

The major beneficiaries are national, regional and local authorities. At the national level, beneficiaries include the Department of Disaster Management (DDM), Bangladesh Water Development Board (BWDB), Flood Forecasting and Warning Centre (FFWC), Directorate General Health Services (DGHS), Armed Forces Division (AFD), Fire Service and Civil Defence. At the regional level, divisional and district administration, development agencies, national and international NGOs are the beneficiaries, and at local level, the Local Government Institutions such as Municipalities, City Corporations, and Development Authorities are the beneficiaries. Since these departments are responsible for dealing with disaster management and preparedness directly, the outcome of the project is a useful resource for their activities. The other beneficiaries are the departments as mentioned in the Standing Orders on Disaster (SOD) developed by the Government of Bangladesh.

1.8 Methodology

The methodology adopted in this project is summarized in Figure 1.1. The hazards identified for assessment as per the Terms of Reference (ToR) are as follows:

- Flood
- Storm surge
- Earthquake
- Tsunami
- Landslide
- Drought
- Technological
- Health

The elements at risk considered in this project for exposure, vulnerability and risk assessment are as follows:

- Population – Gender, Age, Ethnicity, Employment, Education, Disability, Poverty
- Housing – Housing Types (Pucka, Semi-Pucka, Kutcha, Jhupri)
- Livelihoods - Agriculture, Industries
- Critical Facilities – Healthcare, Educational Institutions, First Responders (Fire and Police stations), Cyclone Shelters
- Infrastructure – Road, Bridge, Railway, Air, Sea and River Ports, Power Stations

Using the individual hazard assessment maps developed for the eight hazards in GIS environment and GIS database developed at the country level, the above elements at risk are combined to assess the exposure. Using the exposure data, vulnerability assessment is carried out by the damage curves developed exclusively for Bangladesh for the first time at the national level. Using the hazard and vulnerability assessment, individual risk of the elements at risk is assessed. The hazard specific risk is combined into a multi-hazard risk assessment to identify the most hazardous prone district/upazila/union in the country.

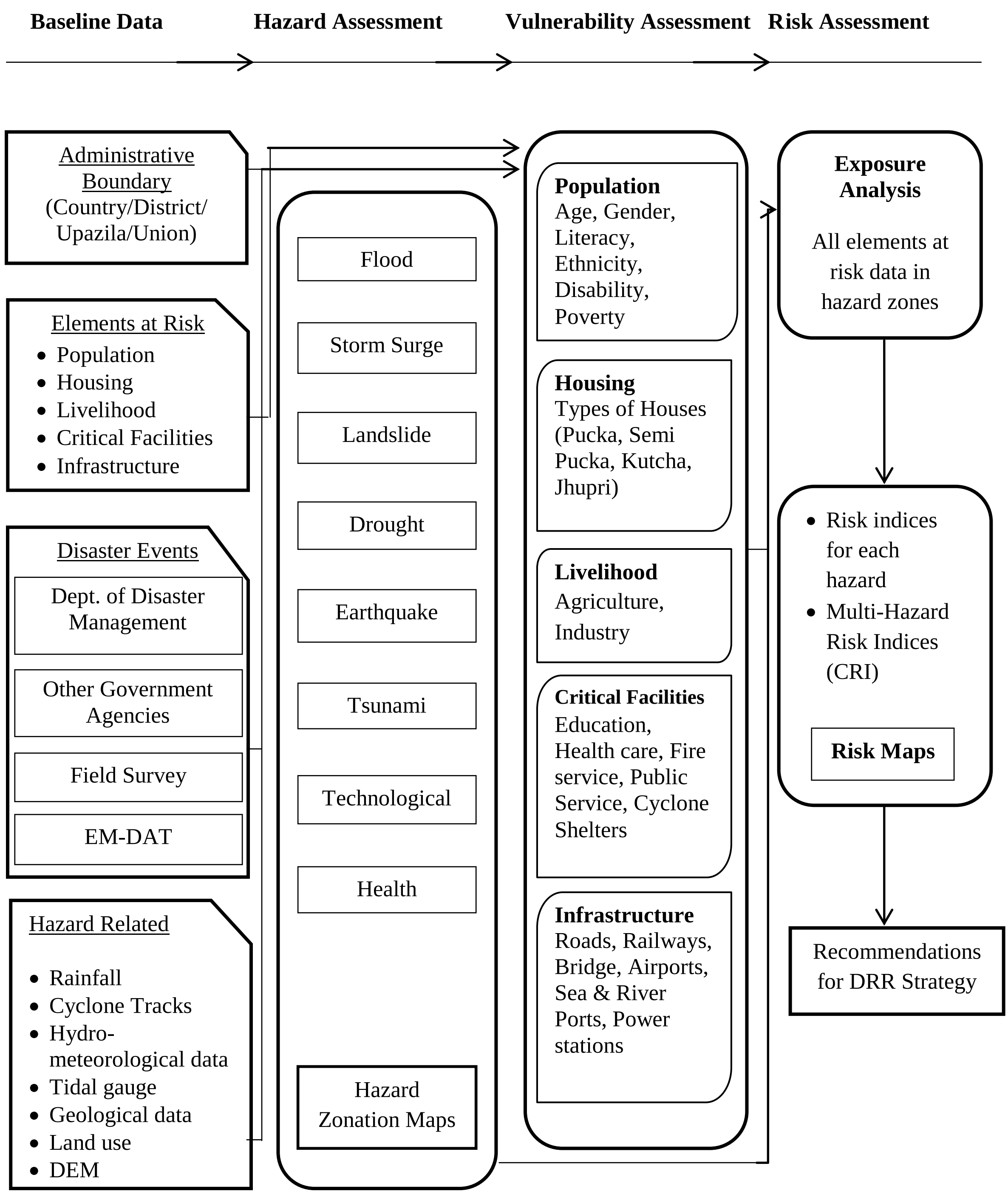


Figure 1.1: Methodology of MRVAM Project

1.9 Project Outcome

The study results are useful for assisting decision makers to prioritize risk mitigation investments and measures for strengthening the emergency preparedness and response mechanisms to floods, cyclones, storm surges, earthquakes, tsunamis, landslides, droughts, technological and health hazards identified in the study.

- Comprehensive multi-hazard risk assessment maps will be helpful for the government for disaster preparedness, identifying the districts, upzilas and unions in prioritizing for assistance required for improving disaster management and recovery.
- The findings of this study created the basis for "building long term preparedness through strengthening disaster risk management capacity in the country as well as for enhancement of long term disaster risk mitigation and reduction ability of the DDM".
- The findings can be used by decision makers to prioritize risk mitigation investments and measures to take proper initiatives and strengthen the emergency preparedness as specified in Standing Orders on Disaster (SOD) and National Plan for Disaster Management (NPDM, 2010-2015) and also response mechanisms for reducing the losses and damages due to future disaster events by incorporating appropriate risk-reduction strategies.
- Responsibilities given to the respective agencies for reducing the risk at respective levels and fields specified in SOD can be fulfilled using the assessment methodology adopted in this study, which is a guide to prepare their own assessments.
- The methodology and tools used in this study are flexible for updating the vulnerability and risk scenarios by the local agencies through the Multi-Hazard Risk and Vulnerability Assessment (MRVA) cell, where a strong database developed in this study will be hosted, which is the basis for modern disaster management initiatives in Bangladesh.

1.10 Structure of this Report

This report is organized in six volumes.

Volume I: Hydro-meteorological Hazard Assessment (Flood, Storm Surge, Landslide, Drought)
Volume II: Geological and Environmental Hazard Assessment (Earthquake, Tsunami, Technological, Health)
Volume III: Elements at risk
Volume IV: Vulnerability and Risk Assessment (Flood, Storm Surge, Landslide, Drought)
Volume V: Vulnerability and Risk Assessment (Earthquake, Tsunami, Technological, Health)
Volume VI: Summary and Recommendations

Chapter 2: Baseline Data and Information

2.1 Administrative Division and Geography of Bangladesh

Bangladesh is divided into eight administrative divisions, each named after their respective divisional headquarters: Barisal, Chittagong, Dhaka, Khulna, Mymensingh, Rajshahi, Rangpur and Sylhet. Divisions are subdivided into districts (zila). There are 64 districts in Bangladesh, each further subdivided into upazila (sub-districts) or thana.

The area within each police station, except for those in metropolitan areas, is divided into several unions, with each union consisting of multiple villages. In the metropolitan areas, police stations are divided into wards, which are further divided into mahallas.

The union boundary map of Bangladesh was purchased from WARPO, which was made in 1991. Bangladesh Bureau of Statistics (BBS), Ministry of Planning, People's Republic of Bangladesh has revised the union/upazila level maps based on the 2011 census. New Geo-codes up to the upazila (BBS, 2012) level are given in Annexure-I. The union/upazila maps purchased are revised based on the 2011 census districts maps. The summary of administrative categories is given in Table 2.1.

Table 2.1: Details of Administrative Divisions in Bangladesh

Division	Districts	Upazilas	Unions	Paurashavas	City Corporations
Barisal	6	40	349	24	1
Chittagong	11	111	947	59	1
Dhaka	13	129	879	60	4
Khulna	10	64	569	36	1
Mymensingh	4	34	377	25	
Rajshahi	8	70	569	60	1
Rangpur	8	58	539	28	1
Sylhet	4	38	333	19	1
Country Total	64	544	4562	311	11

Source: BBS, 2012

2.2 Natural Disaster Profile and Disaster Trends in Bangladesh

Bangladesh is a country prone to a number of natural disasters. A number of disasters such as cyclones, floods, droughts, earthquakes etc. affect the country almost every year, resulting in casualties, infrastructure damage and economic losses. According to world risk report of 2013 (World Risk Report, 2013), Bangladesh is ranked fifth in the world based on world risk index. According to UNISDR (UNISDR, 2012), approximately 2.93% people in Bangladesh are exposed to cyclone, 0.40% to drought, 12.15% to flood, 0.84% to earthquake and 1.06% to tsunami.

The total land area is 147,570 sq.km (BBS, 2012) and consists mostly of low and flat land, with some hilly areas in the northeast and southeast. A network of more than 230 major rivers and their tributaries crisscrosses the country. With an average elevation of four to five meters above mean sea level (MSL), nearly a third of the country is susceptible to tidal inundation and nearly 70% of the country is flooded during heavy monsoons (Strategic Program for Climate Resilience, 2010).

Figure 2.1: Administrative Map of Bangladesh

Source: WARPO, 2013 and BBS, 2012

About 10% of the country is only one meter above the mean sea level, and one-third is under tidal excursions. Bangladesh has a population of about 150 million and Gross Domestic Product (GDP) of USD 67.7 billion per annum (World Bank, 2014) with over 1,000 people per km^2, the country has one of the highest population densities in the world.

2.2.1 Flood

Floods are annual phenomena with the most severe occurring during the months of July and August. Regular river floods affect 20% of the country increasing up to 68% in extreme years. The floods of 1988, 1998 and 2004 were particularly catastrophic, resulting in large-scale destruction and loss of lives. Approximately 37%, 43%, 52% and 68% of the country is inundated with floods of return periods of 10, 20, 50 and 100 years respectively (MPO, 1986). In this study, the percentage of the country inundated due to floods (excluding eastern hilly area, Hatia, Sandwip and estuary areas around them) for return periods of 25, 50, 100 and 150 years is 57.1%, 61.1%, 80.6% and 81.2% respectively. This indicates that the area subjected to flooding has increased from 52% to 61.1% for 50 years and 68% to 80.6% for the 100-year return period. Four types of flooding occur in Bangladesh, including normal and flash floods, as well as storm surges in coastal areas.

Bangladesh is located in a low-lying delta, formed by the dense network of the distributaries of the mighty Ganges, the Brahmaputra and the Meghna, between the Himalayas and the Bay of Bengal. The total land area is 147,570 km^2 and consists mostly of low and flat land, with some hilly areas in the northeast and southeast (BBS, 2015). A network of more than 230 major rivers and their tributaries crisscross the country, which makes 80% of the country is flood plain and 75% of the country is at less than 10m above the mean sea level (Adaptive Learning Mechanism, 2015). Flooding normally occurs during the monsoon season from June to September. Every year, nearly 26,000 km^2 (around 18% of the country) is flooded. Floods has caused devastation in Bangladesh throughout its history. For example, the flood of 1988 resulted in 60% of the country being under flood water for more than a month, while the flood in 1998 caused 75% of the country's area to be under water. There were also severe floods in 1966, 1987 and 2007. A more detailed report on Flood Hazard Assessment is given in Section 3.2.

2.2.2 Storm Surge

Tropical cyclones from the Bay of Bengal accompanied by storm surges are one of the major hazards in Bangladesh. The country is one of the worst sufferers of all cyclonic casualties in the world. The high number of casualties is due to the fact that cyclones are always associated with storm surges. Storm surge heights in excess of 9 m is not uncommon in this region. For example, the 1876 cyclone had a surge height of 13.6 m and in 1970 the height was 9.11 m (WARPO, 2005). In fact, the 1970 cyclone is the deadliest cyclone that has hit the Bangladesh coastline. With a wind-speed of about 224 km per hour, and associated storm surge of 6.1 to 9.11 m, it was responsible for the death of about 300,000 people. Historical cyclone track data (Table 2.2 and Figure 2.2) is analyzed in this study, to develop a cyclone induced storm surge hazard map. More details are provided in Section 3.3.

Table 2.2: Historical Cyclone Track data

Sl. No.	Cyclone event	Date of Occurrence	Nature of the Phenomena	approximate loss/damage
1	1960	10-11, October1960	Severe cyclonic storm, W=129 km/h, S=6.6m and T=1.5m near Noakhali	3,000 people killed, 62,725 houses destroyed. Crops on 94,000 acres (380 km^2) of land were destroyed.
2	1961	6-9, May 1961	Severe cyclonic storm, W=145 km/h, S=4.5m and T=1.2m at Galachipa.	11,468 people killed in Char Alexander and rail road damaged near Noakhali
3	1963	28-29 May 1963,	Severe cyclonic storm, W=201 km/h, S=5m and T=0.3m at Chittagong.	11,520 people killed
4	1965	10-12, May 1965	Severe cyclonic storm, W=161 km/h, S=4.0m and T=1.2m at Barisal and Bakerganj.	19,270 people killed
5	1965	May 31 to June, 11965	Tide plus surge was 7.1m at Companyganj. At Chittagong 1.6m surge on tide.	12,000 people killed
6	1966	1, October 1966	Severe cyclonic storm, W=145 km/h, tide plus surge was 6-7m at Sandwip, Bakerganj.	850 people killed
7	1970	12-13, November 1970	Severe cyclonic storm, W=222 km/h, S=5.5m and T=2.1m. Chittagong.	500,000 lives lost and innumerable animals were killed, widespread damage to crops and properties
8	1974	24-28, November 1974	Severe cyclonic storm, W=161 km/h, S=3.1m and T=0.2m. Cox's Bazar and Chittagong.	200 people killed, 1000 cattle lost and 2,300 houses perished
9	1983	9, November 1983	Severe cyclonic storm, W=136 km/h, S=2.5m. Chittagong, Cox's Bazar	300 fishermen with 50 boats missing; 2000 houses, 22 institutions destroyed
10	1985	24-25, May, 1985	Severe cyclonic storm, W=154 km/h S=3.2m and T=1.8m. Chittagong, Cox's Bazar.	11,069 people killed, 94,379 houses damaged, 64 km road and 390 km embankment damaged
11	1986	9, November 1986	Cyclonic storm, W=110 km/h.	14 lives lost and huge damage to crops and properties

Sl. No.	Cyclone event	Date of Occurrence	Nature of the Phenomena	approximate loss/damage
12	1988	29, November 1988	Severe cyclonic storm, W=160 km/h, S=3.5m T=1.5m	5,708 people killed and 6,000 missing; 65,000 cattle were lost
13	1991	29, April 1991	Most severe cyclonic storm, W = 235 km/h, S=5.8m T=1.7m.	loss of property was estimated at about BDT 60 billion, 150,000 people killed, 70,000 cattle killed, crops were damaged
14	1995	21–25, November 1995	Severe cyclonic storm. W = 210 km/h.	650 people killed, 17,000 cattle perished.
15	1997	16–19, May 1997	Severe cyclonic storm, W = 225 km/hour, S = 3.05 m.	126 people killed
16	1997	25–27, September 1997	Severe cyclonic storm. W= ~ 150 km/hour, S = 1.83 to 3.05 m.	
17	1998	16–20, May 1998	Severe cyclonic storm. W = 150 km/hour, S = 1.83 to 2.44 m.	
18	2007 (Sidr)	15, November 2007	Very Severe Cyclonic Storm W = 248 km/hour, S = 3 -5 m	over 2,000 deaths and severe damage
19	2009 (Aila)	17, April 2009	Cyclonic Storm W = 112 km/hour, S = 3 m	about 150 persons killed, 2 lac houses and 3 lac acres of cultivated land and crops losses
20	2013 (Biyaru)	16, May 2013	Cyclonic Storm. Patuakhali W=95 km/hour, S = 1.1 m	17 people killed and more than 26,500 houses were destroyed

W= Wind Speed, S= Surge height, T= Tidal height

Source: IWM and BCAS, 2013

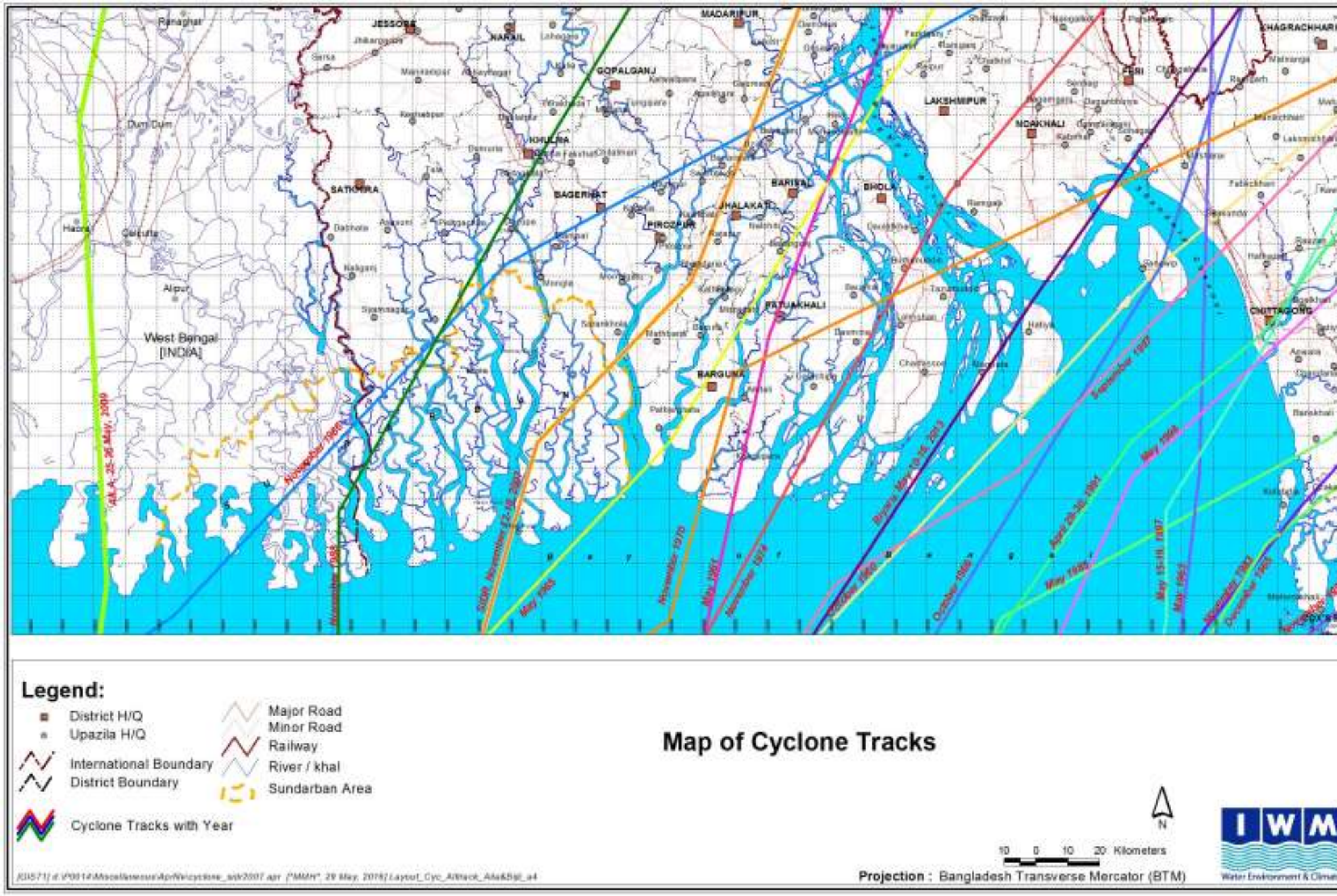


Figure 2.2: Historical Cyclone Track Map of Bangladesh

Source: IWM and BCAS, 2013

2.2.3 Landslide

Landslides have become a recent phenomenon due to rapid hill cutting in the south-eastern part of the country. In most of the cases, these landslides are rain inductive and cause damage to life and property in its vicinity. A major landslide occurred in July 1997 at Charaipada of Bandarban. The total area affected was about 90,000 m^2. In 1999, two large landslides, one in Bandarban and the other one in Chittagong, occurred on 11 and 13 August respectively, claiming the lives of 17 people. Out of the 17 fatalities, ten were in Chittagong and the rest were in Bandarban district. In a tragic event on 11 June 2007, the landslide killed over 100 people in Chittagong and affected 1,926 families. The direct losses due to the event was estimated at USD 13.2 million, while indirect losses were much more because the country's largest port was closed and the city's industries came to a standstill following the event (SAARC, 2007). The landslide in June 2010 in Cox's Bazar and Bandarban damaged a number of settlements with a number of casualties.

In the past, landslides were not considered a major hazard in Bangladesh. However, recently landslides have emerged as a major hazard, particularly after the Chittagong Landslide 2007. Due to heavy rainfall on 10-11 June 2007, landslides and collapsed walls caused widespread damages in six areas of Chittagong city and in different upazilas of the district. A total of 50 mm of rainfall was recorded from 12:00 AM on 10 June 2007 to 6:00 AM on 11 June 2007, and 315 mm of rainfall was recorded from 6:00 AM to 2:00 PM on 11 June 2007. More than 120 people have been reported dead due to the Chittagong landslide.

Landslides are a complex-disaster phenomenon that can be caused by earthquakes, volcanic eruptions, heavy rainfall (typhoons, hurricanes), sustained rainfall, heavy snowmelt, unregulated anthropogenic developments, mining, and other factors. In Bangladesh, landslides are mostly triggered by heavy rainfall. However, underlying causes of landslide include deforestation, hill cutting, unregulated development work, etc. Moreover, poverty and landlessness force poor people to live in the risky hill-slopes.

Most recent landslides due to heavy rainfall and hilly flash flow were reported on 27 June, 2012 in Chittagong, Cox's Bazar and Bandarban districts, which resulted in a death toll of 122 (Chittagong - 37, Cox's Bazar - 47 and Bandarban - 38) due to flash floods and landslides. In this study, the factors influencing the landslides were considered based on the past history and landslide hazard assessment maps were developed. More details are provided in Section 3.4.

2.2.4 Drought

Bangladesh faces unpredictable drought hazards in the dry monsoon due to inadequate and uneven rainfall. It varies from place to place, however, the north-western region suffers most from the drought. As much as 17% of the Aman crops, the main paddy crops in the wet season, may be lost in a typical year due to drought.

In 1866, a severe drought in Bogra effected rice production in the district. Sundarban was badly affected during long drought in 1872. Between 1949 and 1991, droughts occurred in Bangladesh 24 times. Very severe droughts hit the country in 1951, 1957, 1958, 1961, 1972, 1973, 1975, 1979, 1981, 1982, 1984 and 1989. Past droughts have typically affected about 47% area of the country and 53% of the population (WARPO, 2005).

In 1973, one of the most severe droughts in the present century hit the country, which was responsible for the 1974 famine in the northern part of the country. The 1975 drought affected 47% of the entire country and caused sufferings to about 53% of the total population. During 1978-1979, severe drought caused widespread damage to crops, reducing rice production by about 2 million tons and directly affected about 42% of the cultivated land and 44% of the population. It was one of the most severe droughts in recent times. In this study, meteorological drought is assessed using popular indices developed using available rainfall data in Bangladesh. More details are provided in Section 3.5.

2.2.5 Earthquake

The Great India earthquake in 1897, with a magnitude of 8.7, caused serious damage to masonry buildings in Sylhet town where the death toll rose to 545. The origin of the earthquake was north of Bangladesh, in India, and the shaking was felt up to Burma at 1,000 miles from the origin. The casualties from this earthquake were not much since there was limited number of masonry buildings in that period. On 18 July in 1918, an earthquake hit Srimangal with a magnitude of 7.6 and intense damage occurred in Srimangal. Another earthquake in 1930 with a magnitude of 7.1 and the epicenter at Dhubri, Assam caused major damage in the eastern parts of Rangpur district.

Bangladesh and the north eastern Indian states have long been one of the most seismically active regions of the world, and has experienced numerous large earthquakes over the past 200 years. Numerous seismic-tectonic studies have been undertaken on the area comprising the Indo-Burman ranges and their western extension and in the northern India. Major active fault zones of the country have been delineated through geological trenching and dating methods. A list of reference of this is provided in Haque (1990), using data from various sources. A seismic zoning map of Bangladesh has been proposed in 1979 by Geological Survey of Bangladesh (GSB), dividing the country into three seismic zones. This was accompanied by an outline of a code for earthquake resistant design. Later, an updated seismic zoning map and detailed seismic design provisions have been incorporated in the Bangladesh National Building Code (BNBC, 1993). A seismicity map of Bangladesh and its adjoining areas has also been prepared by BMD and GSB.

The record of approximately 150 years shows that Bangladesh and the surrounding regions have experienced seven major earthquakes (with Mb = 7). In the recent past, a number of tremors of moderate to severe intensity took place in and around Bangladesh. The Sylhet Earthquake (Mb = 5.6) of May 8, 1997, the Bandarban Earthquake (Mb = 6.0) of November 21, 1997, the Moheshkhali Earthquake (Mb = 5.1) of July 22, 1999, and the Barkal (Rangamati) Earthquake (Mb=5.5) of July 27, 2003 may be cited as examples (Choudhury, 2005). Mega thrust seismic sources (geological setting) and also historical earthquake phenomena in and around Bangladesh is shown in Figure 2.3. A more detailed report on earthquake hazard assessment is described in Volume II of this report.

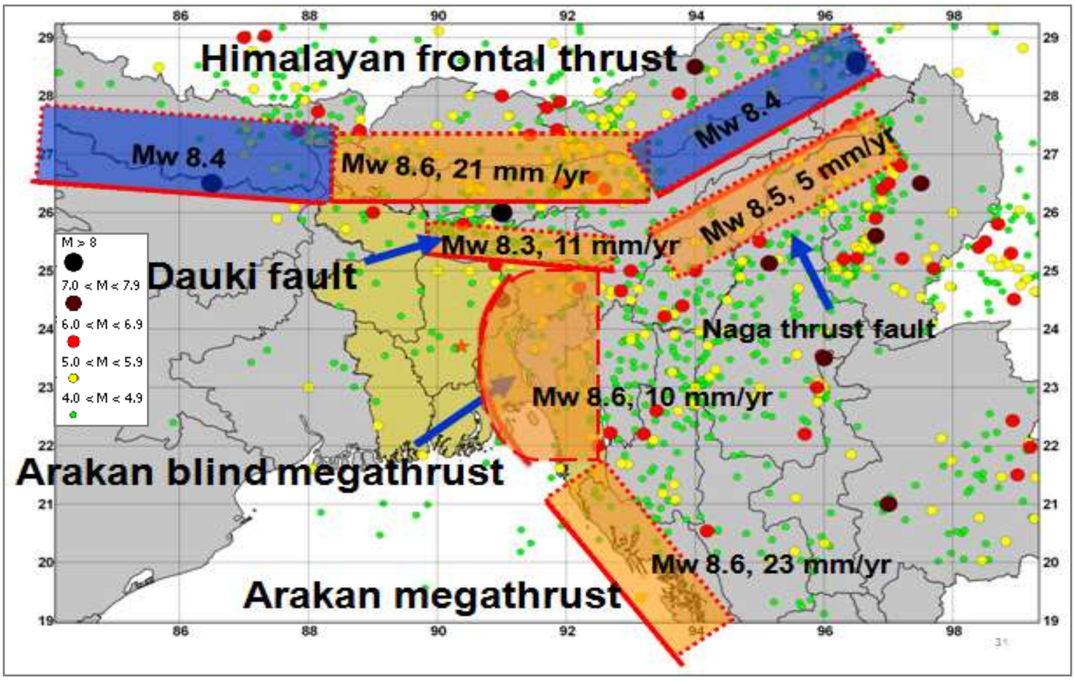


Figure 2.3: Mega thrust seismic sources and historical earthquake phenomena in and around Bangladesh

Source: CDMP-II, MoDMR, 2014

2.2.6 Tsunami

Before the Asia Tsunami 2004, few Bangladeshis ever thought that Bangladesh was vulnerable to tsunami hazards. However, the 2004 Asia Tsunami raised questions around why Bangladesh was not hit by the tsunami. Bangladeshi scientists put together the following reasons:

- Long distance from the epicenter
- Long Continental Shelf (about 200 km) at the front of Ganges- Brahmaputra active Delta System
- Thick sedimentation in Bengal fan
- High density of seawater in Bay of Bengal around/along the coast (suspended load)
- Anti-clockwise oceanic current at Bay of Bengal (winter season)

Considering the state of tsunami vulnerability and potential seismic sources, the Geological Survey of Bangladesh has divided the Bangladesh coastal belt into three zones:

a) Tsunami Vulnerable Zone- I (Chittagong-Teknaf coastline): Most vulnerable. The intra-deltaic coastline is very close to the tectonic interface of Indian and Burmese plates. The active Andaman-Nicobar fault system is often capable of generating tsunami waves.

b) Tsunami Vulnerable Zone- II (Sundarban-Barisal coastline): Moderately vulnerable. This old deltaic belt is extremely vulnerable to local tsunamis due to presence of Swatch of No Ground.

c) Tsunami Vulnerable Zone- III (Barisal-Sandwip estuarine coastline): Low vulnerability. The estuarine coastal belt considered to be less vulnerable due to the presence of numerous islets and shoals in the upper regime of the continental shelf.

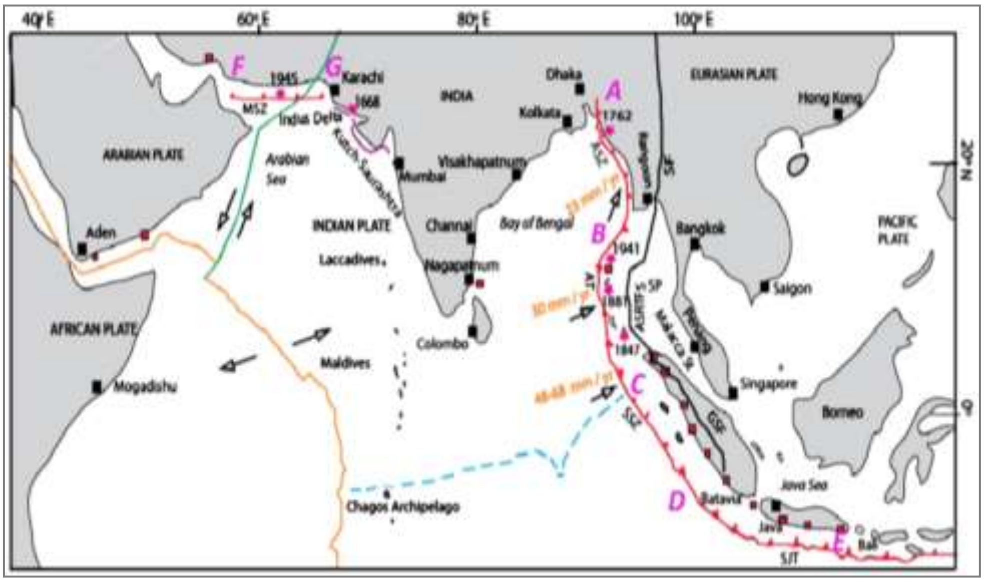


Figure 2.4: Existing Subduction Zones in Bay of Bengal/Indian Ocean Region

Source: modified after Alam et al., 2012

Bangladesh requires a detailed study to scientifically assess the tsunami vulnerability. In this study advanced numerical modeling is carried out, using the existing subduction zones in the Bay of Bengal/Indian Ocean Region (Figure 2.4) for assessing the effect of possible inundation due tsunami for different return periods. These results will help decision makers to develop a tsunami warning system and mass awareness in the coastal districts where these is a possibility inundation due to tsunami. More details are given in Volume II of this report.

2.2.7 Technological

Industrialization in Bangladesh has been growing very rapidly during the last few decades and it has been greatly contributed to the development of the country. The industrial sectors contribute to 28.6% of the country's total GDP in 2011 (Paul et al., 2013). Textiles and clothing, leathers, pharmaceuticals and chemical industries are the main sectors that play a major role in the country's economic growth and provide a significant contribution to employment in Bangladesh. Although the industrial sectors have been making a very important contribution to the economic growth of Bangladesh, these industries have also caused increasingly serious health, safety, and environmental problems to a great extent. Technological disasters caused by chemical, mechanical, civil, electrical or other process failures in an industrial plant due to accident, negligence or incompetence. Common technological hazards in Bangladesh are accidents in garment industries, pollution caused by tannery industries and ship breaking industries, and chemical accidents.

Information on chemical-based industries owned by the government have been provided for this project by the Bangladesh Ministry of Industries. Dhaka and Chittagong are the center of industry in Bangladesh. Possible ammonia release from the chemical-based industries owned by the government are analyzed in this study using a semi-quantitative approach of Seveso Directive and a quantitative method of ALOHA was applied on industrial plants that have enough data. More details are given in Volume II of this report.

2.2.8 Health

Bangladesh is already vulnerable to outbreaks of infectious, water borne and other types of diseases (World Bank, 2000). Due to high population density, pollution and the environment, Bangladesh is highly conducive to emerging diseases. The Directorate General of Health Services (DGHS), under the Ministry of Health and Family Welfare (MoHFW), Government of Bangladesh in partnership with the World Health Organization compiles and manages an epidemic surveillance system for the country. DGHS has developed a management information system (MIS) for maintaining the health database in the country. Communicable disease control continues to remain a public-health priority nationally. Communicable diseases of public-health importance have been identified for health hazard assessment in this study. More details are given in Section 3.6.

2.3 Sources of Project Related Data

The data required for this study has been collected from several government sources. Data collected for elements at risk is briefly described in this section. In addition to this data, many other data were also collected for a hazard assessment. All the details of the data collected is provided in Table 2.2. Additional details of the elements at risk data is given in Volume III of this report

2.3.1 Population

Population data is very important for assessing the people at risk due to any natural hazard. This data is collected from Bangladesh Bureau of Statistics (BBS, 2012), which published census 2011 data. Population data collected at union/upazila/district levels used in this study mainly consists of population based on gender, age, literacy, employment, ethnicity and disability. Poverty data is not available in such detail; however, available data is collected at the upazila level.

2.3.2 Housing

In Bangladesh, existing household types are categorized into four types (Pucca, Semi-Pucca, Kutcha and Jhupri) at the national level in the national census of 2011. This data is published at union/upazila/district as a part of census data of 2011 by BBS (BBS, 2012).

2.3.3 Livelihood

Livelihood data collected includes agriculture area and type of industries. Crop area data is extracted from the land use map of Bangladesh collected from the Water Resources Planning Organization (WARPO). Types of Industries data is collected from the Local Government Engineering Department (LGED).

2.3.4 Critical Facilities

Critical facilities considered in this study are hospitals, educational institutions, warehouses, bank buildings, police stations, fire stations and cyclone shelters. Hospital data is collected from the Directorate General of Health Services (DGHS). All other data is collected form LGED and updated suitably with data from relevant departments.

2.3.5 Infrastructure

Infrastructure data collected includes different types of road, bridge, airports, ports, railway, telecommunication, power and embankments. All this data is collected from LGED and updated suitably with data from relevant departments.

A summary table indicating the details of the data collected is given in Table 2.3.

Table 2.3: Details of data collected in this study

S. No.	Description of the data	Data type	Source of data	Remarks
1	District Boundary	GIS Layer (Shapefile)	LGED, 2013	
2	Upazila Boundary	GIS Layer (Shapefile)	LGED, 2013	
3	Union Boundary	GIS Layer (Shapefile)	LGED, 2013	
4	Road Network	GIS Layer (Shapefile)	LGED, 2013	
5	Railway Network	GIS Layer (Shapefile)	LGED, 2013	
6	Healthcare Facilities	GIS Layer (Shapefile)	DGHS , 2014	Hospital/Family Welfare Centre
7	Educational Institution	GIS Layer (Shapefile)	LGED, 2013	Schools/Colleges
8	Fire Stations	GIS Layer (Shapefile)	FSCD, 2014	
9	Population	PDF File	BBS 2012	
10	Housing	GIS Layer (Shapefile)	BBS, 2012	
11	Ports	GIS Layer (Shapefile)	LGED, 2013 Google Map	Air/River/Sea Ports
12	River Network	GIS Layer (Shapefile)	WARPO. 2013	
13	Landuse	GIS Layer (Shapefile)	WARPO, 2013	
14	Daily Rainfall	Text File	BMD, 2013	
15	Geology	Paper Map	GSB, 2013	
16	Digital Elevation Model	Grid File	WARPO, 2013 ASTER DEM	
17	Bathymetric Data	Paper Map, Grid File	Bangladesh Navy, 2013 GEBCO	
18	Coastal DEM	Grid File	IWM, 2013	
19	Wind Speed	Text File	BMD, 2013	
20	Industrial Location and Chemical Storage Information	Paper Document	Ministry of Industries, 2014	
21	Disease Information	Excel Database	DGHS, 2014	
22	Poverty information	Poverty Report	BBS, 2010	

Chapter 3: Hazard Assessment

3.1 Background

Hazard assessment is the first step towards risk assessment. Hazard assessment includes the severity, frequency, geographical extent of influence and any warning signs it provides. In this study eight hazards are considered based on the ToR including flood, storm surge, landslide, drought, earthquake, tsunami, technological and health. More details of the hazard assessment for flood, storm surge, landslide, and drought are given in this report, and earthquake, tsunami, technological and health is given in Volume II of this report. These hazards are given the subsequent sections.

3.1.1 Characteristics of Hazard Assessment

The Hazard Assessment consists of determining the following:

- When and where hazardous processes have occurred in the past
- The severity of the physical effects of past hazardous processes (magnitude)
- The frequency of occurrence of hazardous processes
- The likely effects of a process of a given magnitude if it were to occur now
- Making all this information available in a form useful to planners and public officials responsible for making decisions in event of a disaster.

3.1.2 Scope of Hazard Assessment in this Project

The identified hazards in this project, namely flood, cyclone induced storm surge, earthquake, tsunami, landslide, drought, technological and health, have been assessed keeping in view the above-mentioned aspects. Some hazards, such as earthquakes and tsunamis, are indirectly affecting Bangladesh due the geographical and geological setting of neighboring countries such as India and Myanmar. Such aspects are also considered in these hazard assessments. Technological hazards are assessed based on the available data from industries provided by Ministry of Industries and the chemical, which can cause damage to population and property in the neighborhood. Health hazard assessment is limited to the number of people affected due to most of the communicable diseases and also arsenicosis at the district level only, due to data limitation. More details of hazard assessment for floods, cyclone storm surges, landslides, and drought hazards are given in this report in subsequent sections.

3.2 Flood

The geographical location of Bangladesh causes it to be flood-prone. It is bound by the Himalayan Range across India, Nepal, Bhutan and China towards the north, there are some other hill ranges to the northeast, east, southern parts of the country, and it is bound by the Bay of Bengal, specifically the Indian Ocean. The Ganges-Brahmaputra-Meghna basin, which passes through Bangladesh and joins the Bay of Bengal, is the second largest basin in the world after the Amazon. The world's highest rainfall area is Cherapunji in Assam, India, which is just north of northwestern Bangladesh.

Although there are a number of causes of flooding, such as huge rainfall in and around Bangladesh, snow-melt in the Himalayan region, deforestation in upstream countries, low and land relief (low land slope), the main source of flood water is the precipitation. Every year from June to October, the monsoon winds from the Bay of Bengal is blown from the south and southwest over Bangladesh, where it cools in the Himalayan region, and huge rainfall occurs. Hence, the main cause of floods in Bangladesh is the monsoon rainfall occurring over the said countries and in Bangladesh. Around 80 percent of the total yearly rainfall in Bangladesh occurs in five months from June to October. Though Bangladesh experiences some levels of floods every year, there were some major floods in recent history as occurred in 1987, 1988, 1998, 2004, and 2007. The one in 1998 led to an estimated two-thirds of the country inundated with floodwater.

Due to its fertile land, the country is mainly agriculture based. Therefore, some level of flooding is beneficial to agriculture and tolerable to people. However, excess flooding in terms of depth of flooding is devastating to life and property of the people in the country. Excessive flooding come can become a hazard. In order to save life and property of people, it is necessary to take preventive, curative and resilient measures, and hence flood hazard assessment is necessary. In this study, according to the ToR, flood depth maps are prepared for 25-, 50-, 100- and 150-year return periods.

3.2.1 Data Used

From model simulation to map preparation, many types of data are needed, such as time series data of water levels, water discharge, river alignment, cross sections, rainfall, and evapo-transpiration. As an example, data used in the South West Region Model is given in the Table 3.1.

Table 3.1: Detailed elements and data used in the South West Region Model

Source: BWDB, 2012 and IWM, 2012

Region Model	Area (km^2)	No. of Catchment		Rivers and Branches		No. of Cross sections used	No. of Hydrometric and Hydro-meteorological Stations					No. of Boundary	
		inside	India	No.s	Length (km); Major River		WL	Q	RF	GWL	EVP	U/S	D/S
SWRM	37330	44		90	5600; Lower Meghna, Arialkhan, Kobadak, Passur	2500	74	3	63	38	9	29	11

Digital Elevation Model

A digital elevation model (DEM) is a computerized virtual representation of a continuous surface of the earth in a specified area. This terrain analysis is typically implemented within a geographic information system (GIS). In preparing maps, IWM used a 300m grid national DEM. The southern extent of it is around Chandpur district headquarters. Map areas beyond the south of Chandpur coastal DEM of up to 50 m was used. The digital elevation model is shown in Figure 3.1.

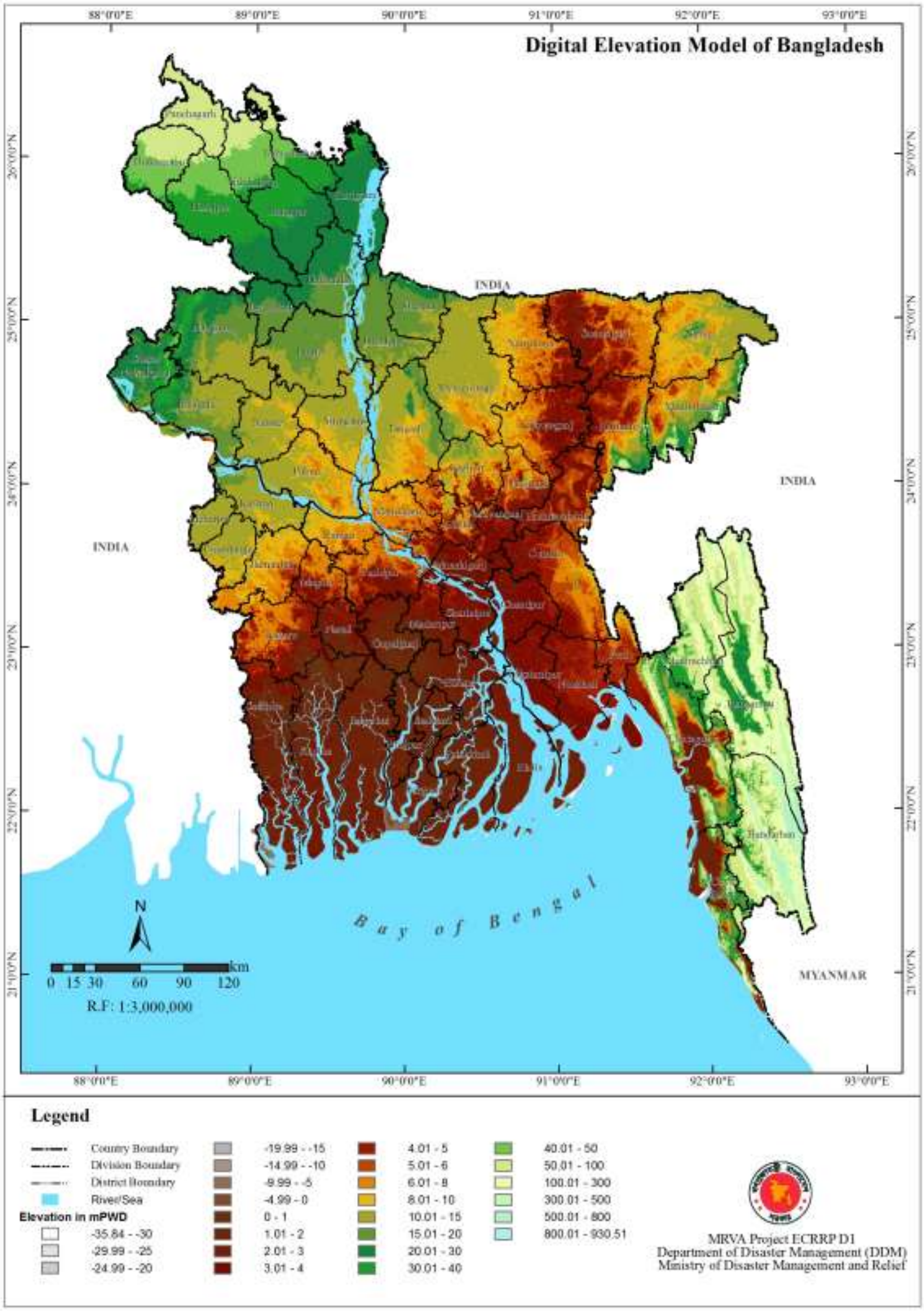


Figure 3.1: Digital Elevation Model of Bangladesh

Source: IWM, 2012

3.2.2 Methodology

The methodology adopted in this flood hazard study is shown in Figure 3.2. Flood modeling used in this study is MIKE11 (DHI, 2004). The MIKE11 flood modeling system consists of two modules: hydrological and hydrodynamic. Hydrological module uses rainfall and evaporation data and performs rainfall-runoff modeling, whose output is the input for the hydrodynamic module. The Hydrodynamic module computes water flows and water levels in the river network. Historical boundary data flood simulations for 26 years (1986 to 2011) was used to compute water levels in the river network at 7617 model grid points. Then a frequency analysis was carried out at these grid points in order to obtain return period-wise flood levels for 25-, 50-, 100- and 150-years. These flood levels are used in ARC GIS software to develop flood hazard maps with the help of a digital elevation model (Section 3.2.1.1) using the following equation:

Flood depth (m) = Flood level (mPWD) – Land level (mPWD)

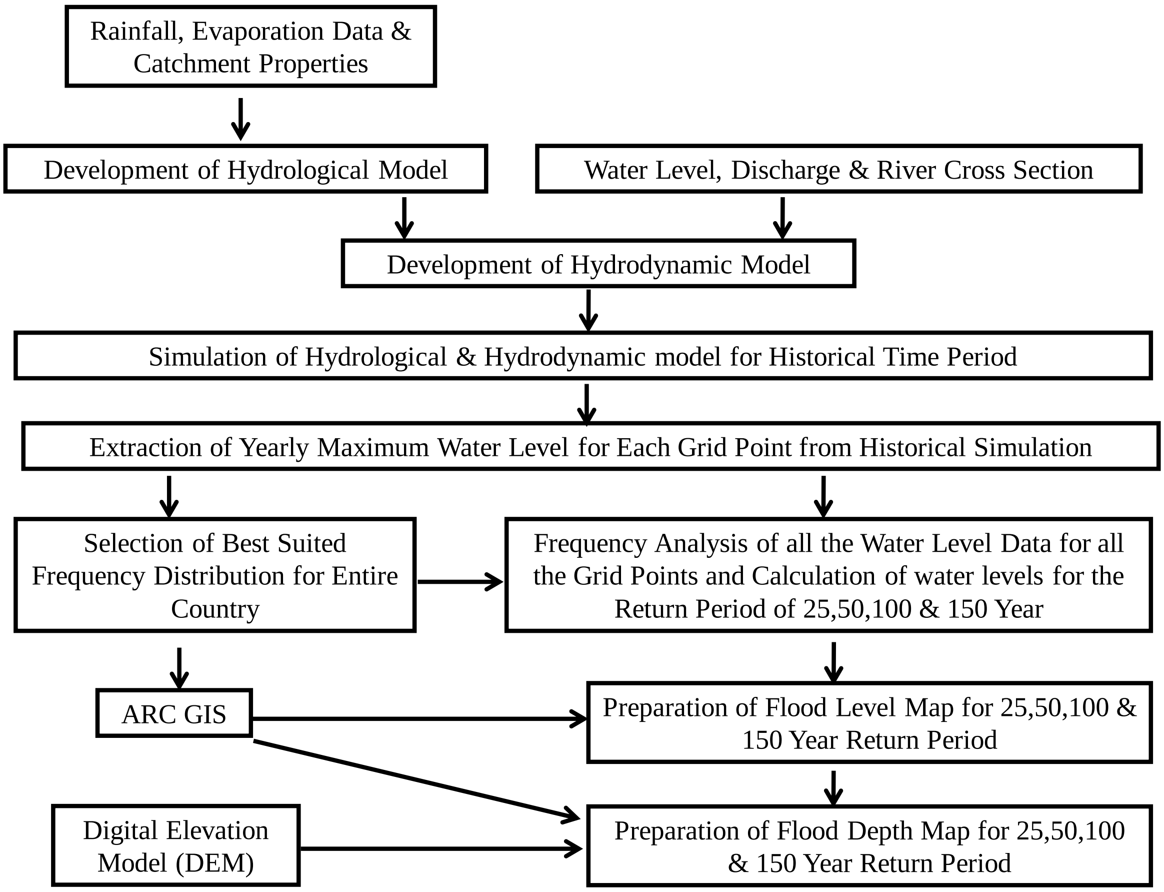


Figure 3.2: Methodology of the Flood Hazard Assessment

Flood simulation is carried out using the existing five hydrological region models: North West Region Model, North Central Region Model, North East Region Model, South West Region Model, and South East Region Model.

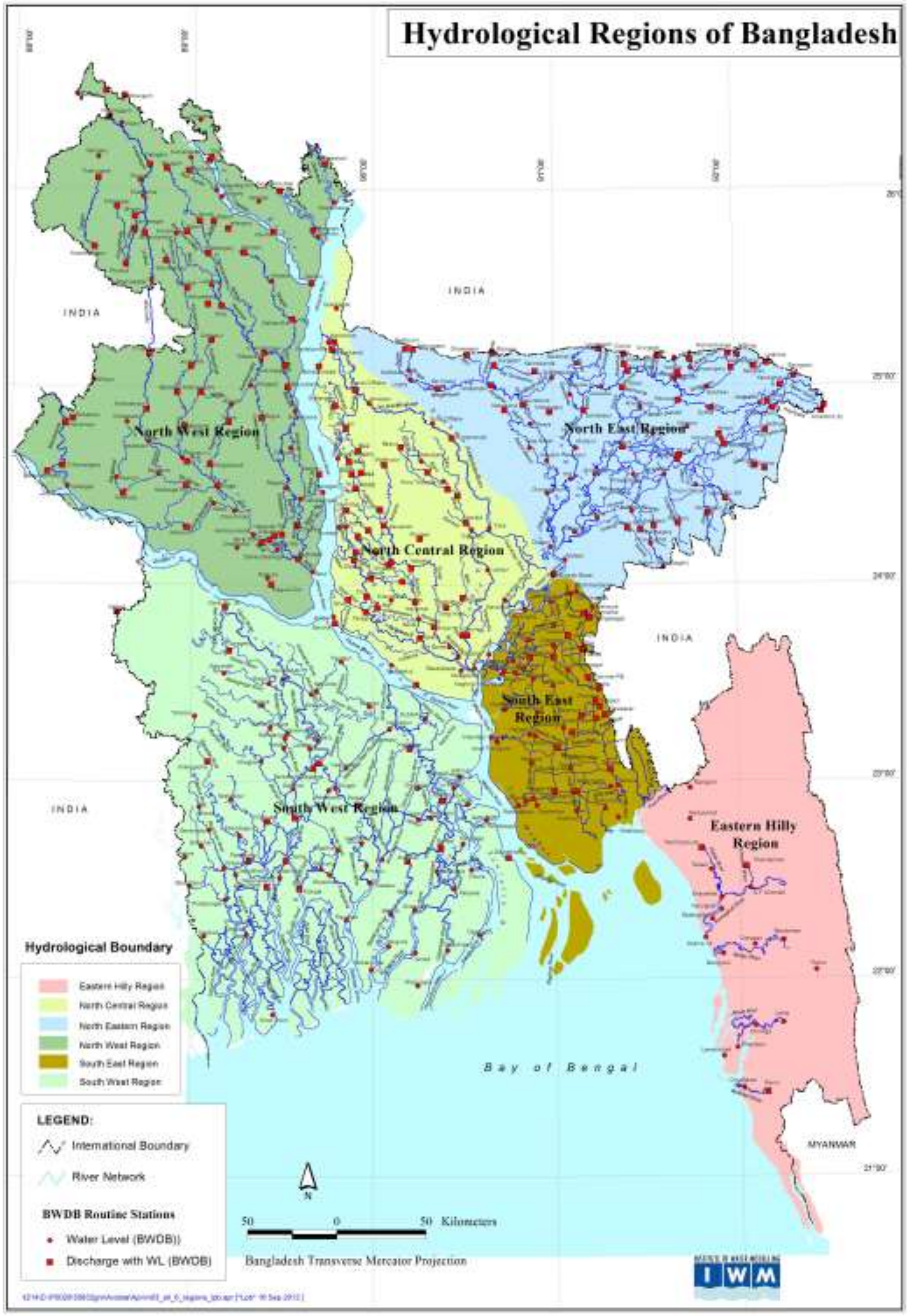


Figure 3.3: Hydrological Regions of Bangladesh

Source: IWM, 2012 and CDMP-II, 2013

Steps in Flood Hazard Assessment and preparation of Return-Period-Wise Flood Maps:

Step-1: <u>Data Collection</u>: This is the first and the most essential part of the study as all the models and analysis are completely depends on data availability and their quality. All the required data on rainfall, water level and flow were collected under this study to validate the model results and data analysis.

Step-2: <u>Model Validation:</u> All the regional models (Figure 3.2) were simulated with available data of past hydrological year to validate the model results whether those models were acceptable or not for further simulation.

Step-3: <u>Simulation of Models for 26 years:</u> The main objective of this study is to assess the return-period-wise flood map for Bangladesh. The frequency analysis is the only way to calculate the return-period-wise flood depth. However, to calculate the return-period- wise flood depth, a historical data series is needed. There are a number of water level measuring stations in Bangladesh, but these are not sufficient to produce a better spatial distribution of water level. To overcome this problem, regional flood models were used under this study. All the regional models (five regional models) were then simulated for 26 years to produce time series water level data at 7617 grid points on the major and minor rivers of the country. Historical water level of 26 years for those 7617 grid points were then extracted (Figure 3.4) from models results and used for frequency analysis.

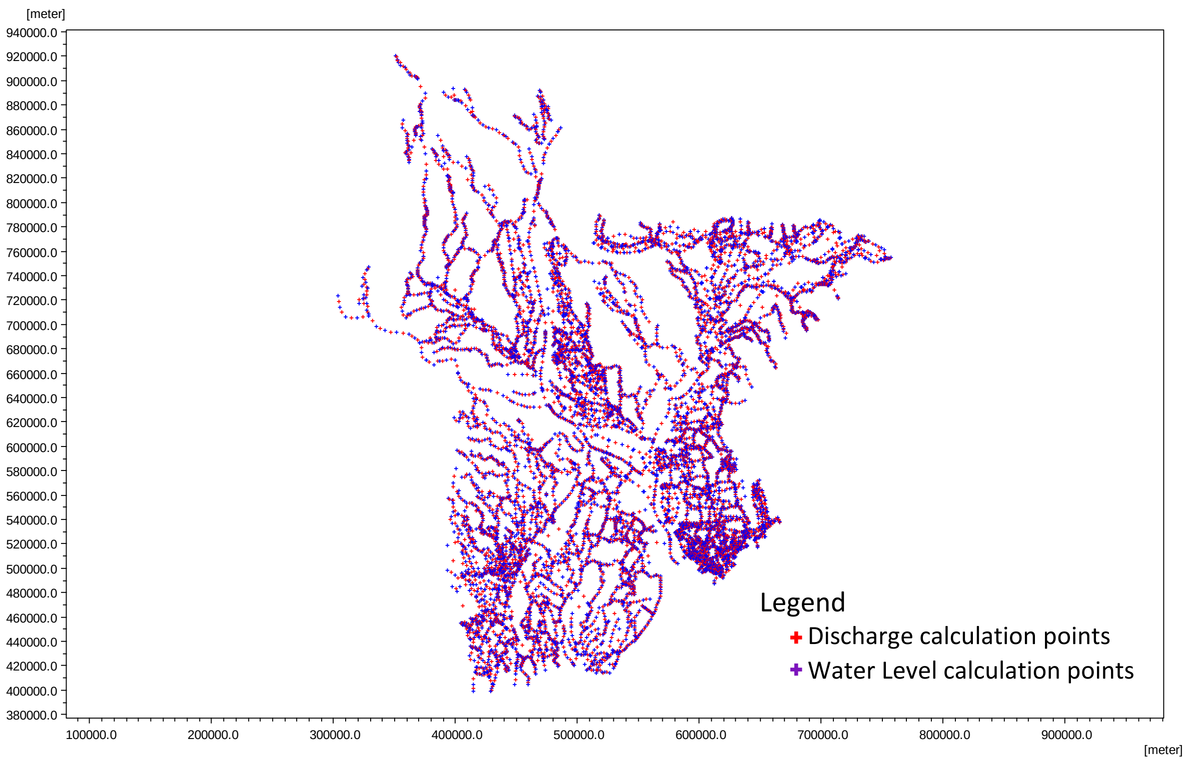


Figure 3.4: Distribution of 7617 grid points in the major rivers of Bangladesh

Source: IWM, 2012

Step-4: **Frequency Analysis of Simulated Water Level Data:** The historical time series water level data were collected from the simulated results and were analyzed to calculate the annual maximum for 26 years for 7617 points. Firstly, 6 points were selected at different regions from three major rivers (Figure 3.5) so that it represents the entire country. The data was then analyzed to select the suitable frequency distribution for the whole country, except non flood-prone areas in the eastern hilly region.

After selecting the suitable frequency distribution, it (the selected frequency distribution) was then applied for 7617 points and generated return period wise depths for those 7617 points. The location of all the points is furnished in Figure 3.6.

Step-5: **Preparation of Inundation Depth Maps Using Data from Frequency Analysis:** Return period wise water level were then collected from frequency analysis and produced water level maps of 300m resolution grid for 25-, 50-, 100- and 150-year return periods using GIS tools. A flood level map for a 100-year return period was prepared.

At the same time, another shape file of Digital Elevation Model (DEM) was collected for the whole country of 300m resolution (Figure 3.1). Each water level shape file was then subtracted from the DEM shape file to produce flood depth maps for a specific return period. Finally, flood depth maps for 25-, 50-, 100- and 150-year return periods were produced, which are shown in Figures 3.7, 3.8, 3.9 and 3.10.

Mike 21 is a two-dimension model, which is use for,

- Design of data assessment for coastal and offshore structures
- Optimisation of port layouts and coastal protection measures
- Cooling water, desalination and recirculation analysis
- Optimisation of coastal outfalls
- Environmental impact assessment of marine infrastructures
- Ecological modelling including optimisation of aquaculture systems
- Optimisation of renewable energy systems
- Water forecast for safe marine operatioand navigation
- Coastal flooding and storm surge warnings
- Inland flooding and overland flow modelling

MIKE 21 comprises of simulation engines, such as Single Grid (which is a classic rectilinear model that is easy to set up and with easy input / output exchange), Multiple Grids (which is a dynamically nested rectilinear model with the ability to focus the grid resolution), Flexible Mesh (which allows maximum flexibility for adapting grid resolution of the model domain). The data requirements for using these engines is high resolution digital elevation model (such as DEM from LIDAR) and in Bangladesh context such DEM is not available, hence could not use MIKE 21 model in this study for riverine (inland and overland) flow modelling.

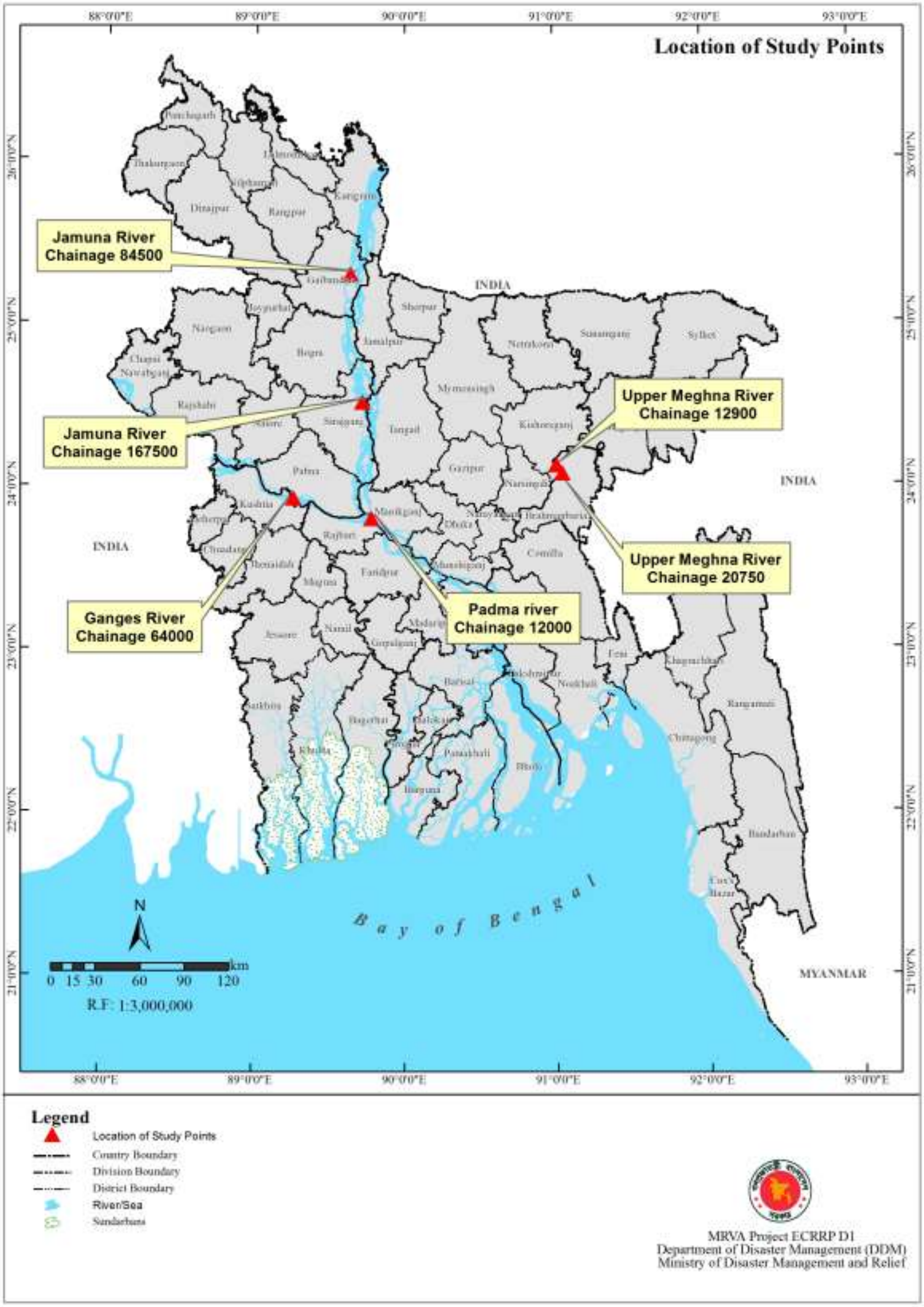


Figure 3.5: Location of study points to select the best suited frequency distribution

Source: BWDB, 2012

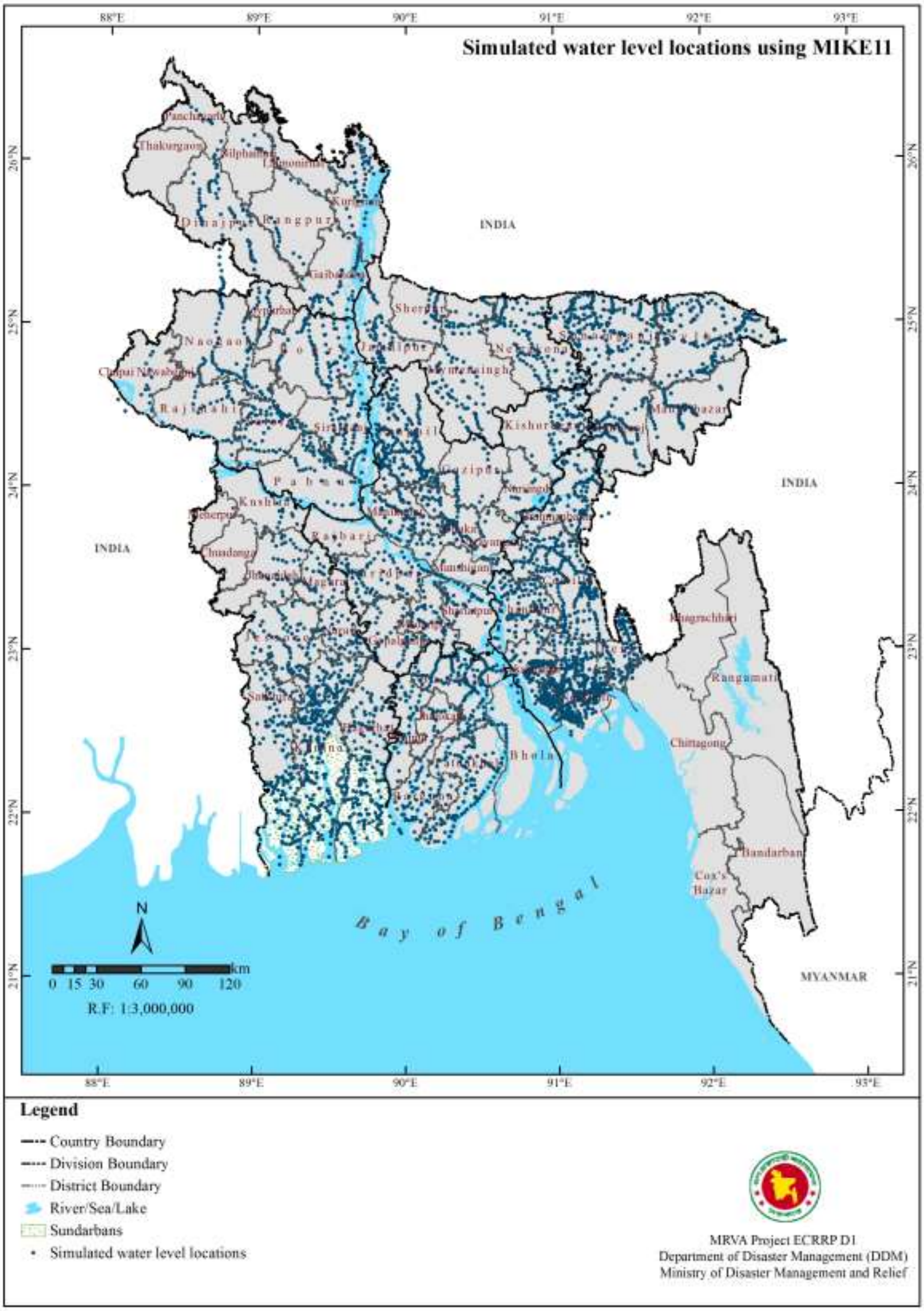


Figure 3.6: Location of Water Levels in the rivers for 100 year return period

Source: IWM, 2013

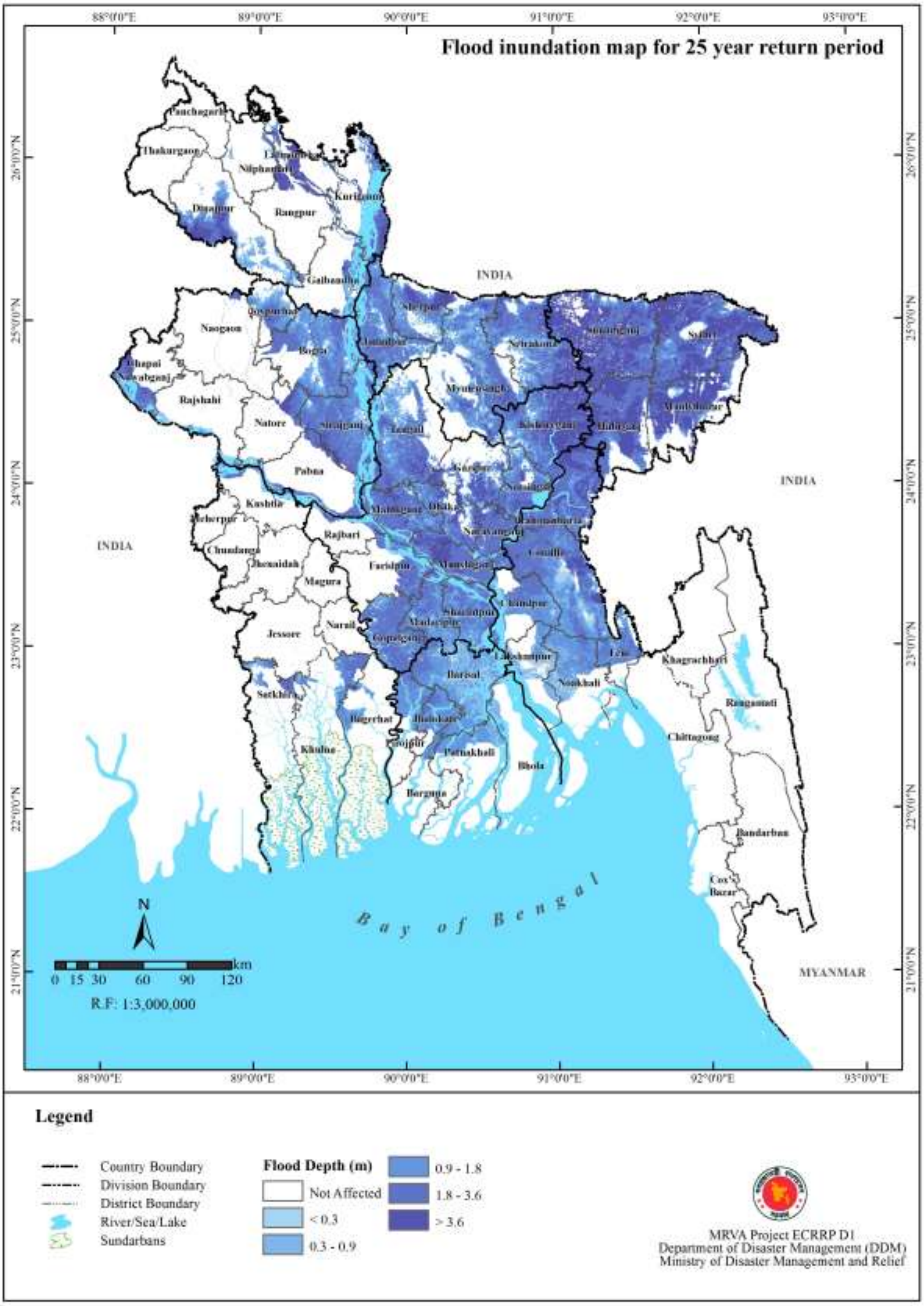


Figure 3.7: Flood inundation map for 25-year return period

Source: IWM, 2013

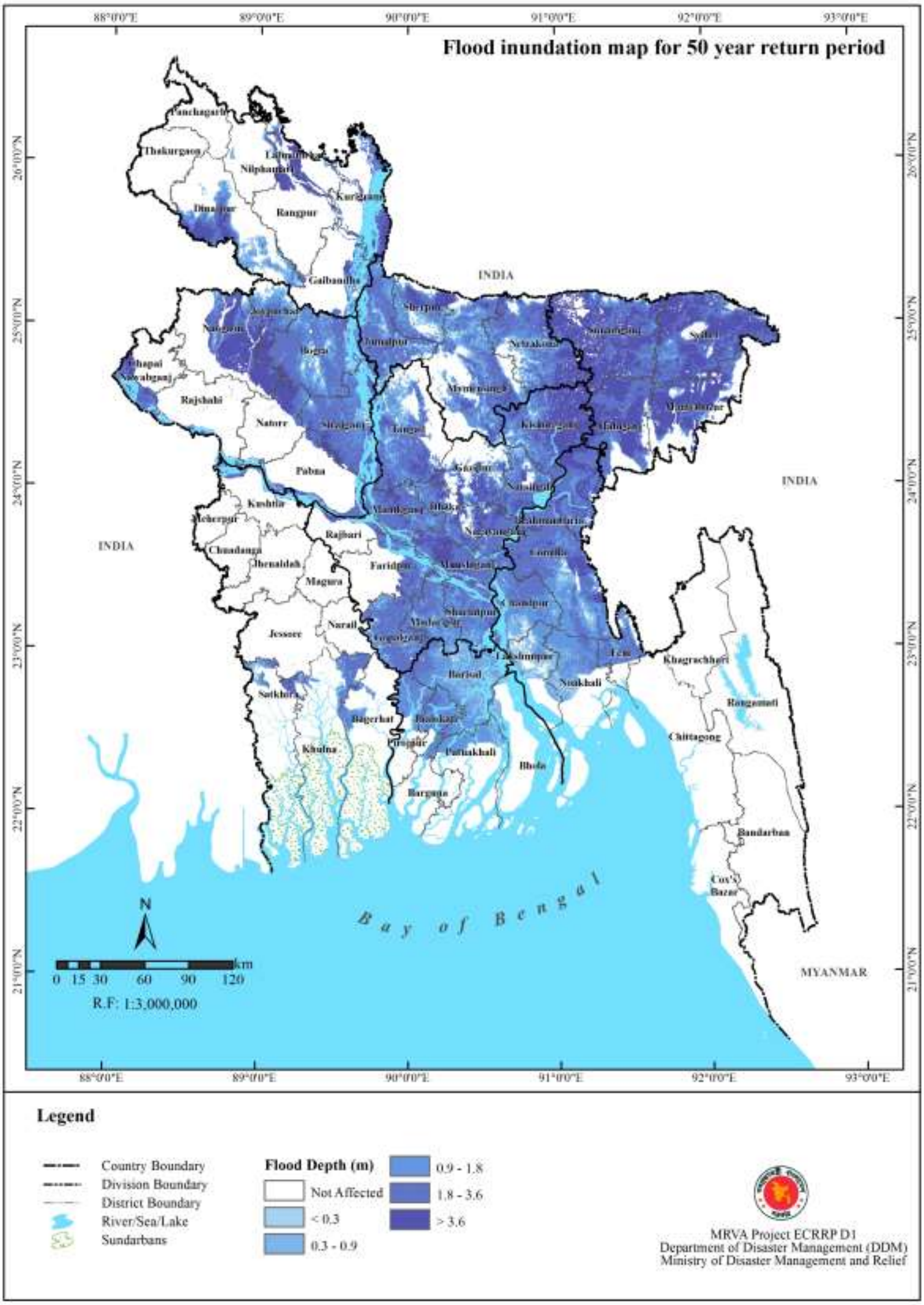


Figure 3.8: Flood inundation map for 50-year return period

Source: IWM, 2013

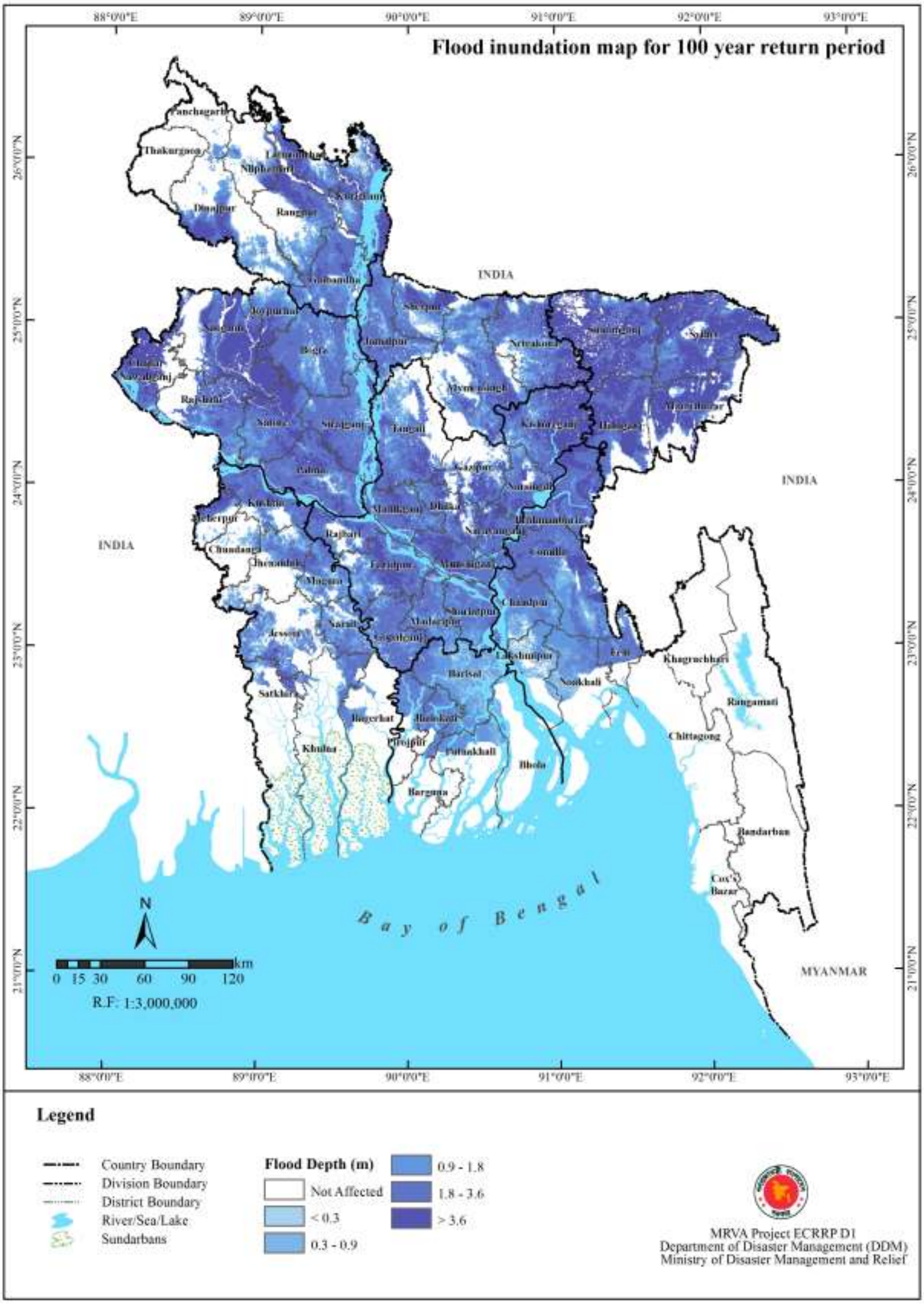


Figure 3.9: Flood inundation map for 100-year return period

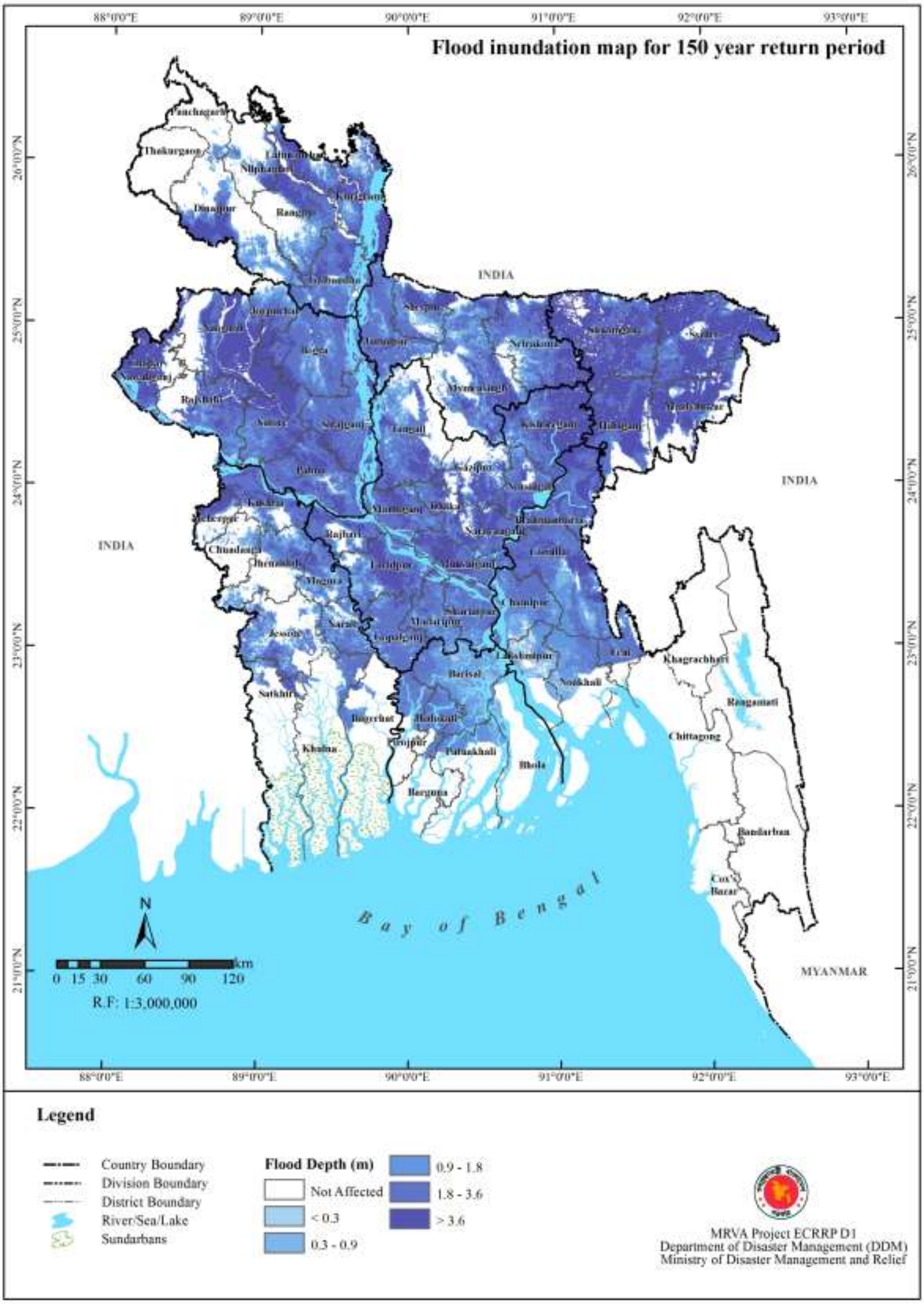


Figure 3.10: Flood inundation map for 150-year return period

Source: IWM, 2013

3.2.3 Analysis of Hazard Assessment

The flood hazard maps of 25, 50, 100 and 150 year return period were analyzed. Flood inundation area (Km^2) and percentage for 25 and 50 year return period is given in table 3.2 and for 100 and 150 years in table 3.3.

Table 3.2: Inundated Area (Km^2) and Percentage in depth categories for 25 and 50 years return period

S.No.	Flood Depth (m)	25 year Return Period		50 year Return Period	
		Inundated area (Km^2)	Percentage of the area (%)	Inundated area (Km^2)	Percentage of the area (%)
1	>3.6	10240.47	10.55	13473.63	13.88
2	1.8 – 3.6	23147.64	23.84	25313.58	26.08
3	0.9 – 1.8	14203.17	14.63	13305.15	13.71
4	0.3 – 0.9	5955.66	6.14	5502.69	5.67
5	0.0001 - 0.3	1860.93	1.92	1774.53	1.83
6	No Flood	41667.84	42.92	37706.13	38.84

Table 3.3: Percentage of inundated area in different depth categories in different divisions

S.No.	Flood Depth (m)	100 year Return Period		150 year Return Period	
		Inundated area (Km^2)	Percentage of the area (%)	Inundated area (Km^2)	Percentage of the area (%)
1	>3.6	18801.9	19.37	23159.97	23.86
2	1.8 – 3.6	33991.11	35.02	33111.81	34.11
3	0.9 – 1.8	15918.84	16.40	14076.36	14.50
4	0.3 – 0.9	7045.47	7.26	6261.3	6.45
5	0.0001 - 0.3	2443.5	2.52	2176.56	2.24
6	No Flood	18874.89	19.44	18289.71	18.84

Table 3.4 indicates the percentage of inundation area in different flood depth categories in different divisions for 100 year return period.

Table 3.4: Percentage of inundated area in different depth categories in different divisions

Division	Flood depth (m) vs percentage of inundation area					Not Affected
	< 0.3	0.3 - 0.9	0.9 - 1.8	1.8 - 3.6	> 3.6	
Barisal	1.5	8.6	26.4	30.9	31.0	69.0
Chittagong	4.5	8.3	16.5	26.4	28.3	71.7
Dhaka	23.7	6.0	17.2	36.3	11.6	5.28
Mymensingh	42.9	43.6	45.8	48.0	48.2	51.8
Khulna	24.7	11.3	22.9	30.0	8.0	3.00
Rajshahi	59.8	63.2	72.1	88.4	91.1	8.9
Rangpur	74.2	76.9	80.4	87.9	92.5	7.5
Sylhet	14.5	16.4	21.7	54.7	96.4	3.6
Country Total	**31.7**	**35.5**	**44.9**	**60.2**	**69.0**	**31.0**

3.2.4 Map Content

Flood hazard maps consist of flood depth in meters. The flood depth is categorized based on the classification adopted by the Master Plan Organization (MPO, 1986). Flood depth categories adopted in this study are given in Table 3.5.

Table 3.5: Flood depth categories based on inundation depth

Flood Depth (m)	**Flood Categories**	**Symbology used in maps**
No Flood	Not affected (NA)	
0 – 0.3	Very Shallow (VS)	
0.3 – 0.9	Shallow (S)	
0.9 – 1.8	Medium (M)	
1.8 – 3.6	Deep (D)	
> 3.6	Very Deep (VD)	

3.2.5 Application of Maps

Some important uses of flood maps are as follows:

- Assessing elements at risk in flood hazard with some specific flood height in an area;
- Comparing flood hazard of different places by assessing spatial variation in flood hazard in the area covered by the map;
- Estimating population exposed to flood hazard in some locality;
- Estimating other elements at risks (communication network, homesteads, buildings, crops, livestock etc.) in some locality;
- Urban and rural planners can use in planning and design of infrastructures, buildings, homesteads – particularly communication network, flood shelters;
- Assessing crop damage;
- Selecting suitable crop patterns with respect to flood types;
- Helping build community awareness in preparation against flood hazard; and
- Helping select more vulnerable areas to flood hazard, and hence help in disaster preparedness.

3.2.6 Special Remarks

Although Flood maps were available from different sources such as Bangladesh Water Development Board (BWDB) and Flood Forecasting and Warning Centre (FFWC) based on individual events and also maps indicating the general flood affected areas, systematic scientific analysis of return period based flood maps were developed for the first time in Bangladesh. The methodology adopted described earlier will explain the complexity involved in development of these maps, which can be utilized by the decision makers for developmental planning activities in the country.

3.2.7 Limitations of Flood Maps

In this MRVA project, flood maps have been prepared with return periods of 25-, 50-, 100- and 150-years, covering all of Bangladesh, with the exception of the south-east hilly region. These maps are intended to be used for disaster risk management purposes by the Government and all parties involved in DRM when such return-period-wise maps appear to be useful. However, there are some limitations that need to be considered while using the maps for practical purposes in disaster risk management.

Limitation arising from DEM

The main limitations arise from using the national digital elevation model. As mentioned in Section 3.2.1.1, the digital elevation model that was used in flood models and preparing flood maps, was developed using the land topography data surveyed during fifties and sixties in the last century by Survey of Bangladesh. It is an undeniable fact that since then, land topography has undergone significant changes due to huge changes in land use patterns, caused by a massive population increase, development pressure on cropland and flood plains, changes of water bodies, forests, changes of landmass due to erosion, accretion etc. This sets a major limitation in calculating the reasonably accurate flood height.

Limitation Arising from the Flood Model: MIKE11

As mentioned in Section 3.2, simulating the MIKE11 flood modeling system has been employed and flood maps have been prepared using five region models. Though detailed river networks and sufficient hydrological boundary conditions have been used in model development and flood simulations, and flood levels were computed at 7617 grid points (Section 3.2.2) along the river network that were used in return-period-wise flood level computations, there are still shortfalls. Since it is one-dimensional in nature, the MIKE11 flood model does not have provisions for lateral flow of water. Computations of flood levels at places between river networks were done by interpolation of water level values at rivers. Therefore, the model may over estimate flood levels at some places between river networks (particularly for big landmasses/crop fields/beel between river networks), and hence more flood heights on maps.

Limitation Arising from the Level of Details of Region Model

As mentioned in Section 3.2.2, all regional flood models were developed and updated with sufficient details of river networks existing all over the region and simulated providing region level boundary conditions. In the MRVA project, output maps would be upazila/union wise. It is to be remembered while using these maps by the relevant parties involved in disaster risk management, that these were not prepared considering/using any upazila/union scale models based on the level of details rivers/channels network and land topography of the upazila/union.

3.2.8 Recommendations

Flood hazard assessments were carried out in flood prone areas for the entire nation for 25-, 50-, 100-, 150-year return periods using secondary data. These flood hazard maps consist of detailed inundation patters, which can be used at district/upazila/union levels by policy makers, planners, decision makers and all relevant stake holders for better planning and implementation of an effective system of flood management.

3.3 Cyclone induced Storm Surge

The geographic location of Bangladesh on the globe and climatological settings make the country one of the most disaster prone countries in the world. Among the most disaster-prone 173 nations in the world, according to World Risk Report 2012, Bangladesh is in the fifth position. Since 1980, there have been 200 disaster occurrences in Bangladesh, which snatched 200,000 lives, as well as livestock and other animals, and caused USD 17 billion in damage. The entire southern boundary of Bangladesh is exposed to the Bay of Bengal, namely the Indian Ocean. Though this sea-resource has definitely immense economic importance, however, at the same time it is a curse. Nearly every year, whether it is less severe or devastating, cyclones hit the coast of Bangladesh and cause a heavy toll to lives and properties. Of the hazards that regularly occur in Bangladesh, the deadliest is the cyclone, particularly with respect to loss of lives. Cyclones come suddenly, and act furiously. There is little time to take preparations. Due to the economic importance of the coastal area, rapid population growth, and development pressure, there are numerous poor people living in coastal areas, with a constant fear of cyclone hazards. Thus, living with hazards is a compromise and reality, but a safe living is expected by the people when the world is in a 21st century in the age of science and technology.

It is proven that disaster risk reduction can save lives and properties. The cyclone that hit Bakerganj district in 1876 claimed 200,000 lives, and the one in 1970 that hit greater Barisal claimed 300,000 lives. However, one with almost the same severity in terms of wind speed hit in 2007, cyclone Sidr, claimed only 3,400 lives (as per government statistics). It has been possible to reduce the impacts of hazards due to increased education, awareness, facilities and progress of disaster risk management in the country. Around the Nicobar and Andaman Island in the Indian Ocean, these places are hot spots where tropical disturbances develop, and they often turn to cyclones of various severities and hit Bangladesh in April-May and October-November. After identification of any hazard, in order to manage its risk, assessment of the hazard in such a way that can be effective in all stages of disaster management is a must. The effect of cyclones come in two forms, one is a due to a severe whirlwind that causes houses and buildings to fall or break, and leads to uprooted trees, electric lines etc. This whirlwind again in the sea leads to heavy waves that surges on the coast and enters into the estuaries and rivers and then over land to affecting people and properties. Cyclones are hazards that cannot be stopped. However, taking risk reduction measures can lessen their impact. Therefore, it is necessary and important to assess the magnitude of hazards. However, this study only addressed the storm surge hazard assessment.

Storm surge hazard assessment means finding storm surge height at a specific location to make storm surge inundation depth maps for the entire coastal area for practical use by relevant stakeholders. The storm surge inundation depth value can be calculated by subtracting the existing bed level from model simulated surge level. Therefore, it follows the following relation.

Storm surge height (m) = Cyclone-induced storm surge levels (mPWD) – land levels at respective location (mPWD)

Now in assessing storm-surge height the job is that how cyclone-induced storm surge levels and land levels at respective location are found. Here is the role of modern-day powerful computer models. Mathematical models, capable of producing/computing storm surge levels by simulating historical cyclone data, can assess surge levels with respect to some datum (m PWD). Such models are called storm surge models. The Institute of Water Modelling (IWM) has been maintaining a storm surge model called the Bay of Bengal Model (BoBM) for the last 22 years. Again, models capable of storing terrain data and presenting continuous land surface are called the digital elevation model (DEM). IWM also has DEM called IWM Coastal DEM. Hence, by employing such both models, storm surge hazards are assessed by using the above mentioned relationship. This assessed hazard is used in preparing hazard map by GIS software. ArcGIS has been used in preparing storm surge inundation maps.

According to the ToR of this project, storm surge inundation maps have been prepared for 25-, 50- and 100-year return periods.

All types of required data, methods and steps needed for inundation map preparation, descriptions of numerical models, digital elevation model, statistical distribution used for frequency analysis, preparation of maps by using GIS software are described in subsequent sections.

3.3.1 Data Used

3.3.1.1 *Bathymetry* Data

Model bathymetry is a measure of bottom surface of water areas under the model extent expressed in terms of elevations with respect to an accepted datum. For the Bay of Bengal model (BoB) model, bathymetry is expressed in metres with respect to PWD datum. The model bathymetry has two broad areas: water areas under the model extent in Bay of Bengal and estuaries and tidally influenced areas in the rivers. The main source of the model bathymetric data of the Bay of Bengal is the ETOPO2 of National Geophysical Data Centre under NOAA, U.S. Ministry of Commerce and C-Map of Hydrographic Office of UK (Figure 3.11). Many rivers and estuaries were surveyed in some study of national water resources projects, such as Meghna Estuary Studies (Figure 3.12). Data obtained from such surveys were used in bathymetry preparation. Data sources for bathymetry preparation are given in Table 3.6.

Table 3.6: Data sources for generating the bathymetry for the model

Water Body (Rivers, Estuary, Sea)	**Source of Data**
Bay of Bengal	ETOPO2 (Global Gridded 2-minute Database), National Geophysical Data Center, NOAA, U.S. Dept. of Commerce; C-Map of Hydrographic Office of UK
Part of Meghna Estuary	Land Reclamation Study, 2007, BWDB
Meghna Estuary around Nijhum Dwiip	Nijhum Dwip Cross Dam Study, 2006, BWDB
Karnaphuli River	Karnaphuli Fertilizer Company Limited (KAFCO), 2007,
Pussur and Sibsa Rivers	Mongla Port Authority, 2004
Internal rivers in South West Region	Integrated Planning for Sustainable Water Management (IPSWAM), 2008
Meghna Estuary (from Chandpur down to Bay)	MES I (FAP 5B) survey (1997) +and MES II survey (1998, 1999), BWDB

3.3.1.2 Meteorological Data Necessary to Develop Cyclone Model

In generating a cyclone model, the following meteorological data/information are necessary:

- Radius of maximum winds, Rm,;
- Maximum wind speed, Vm;
- Pressure drop (ΔP); and
- Cyclone track forward speed Vf and direction.

The pressure drop (ΔP) is defined by the following parameters:

- Central pressure, Pc
- Neutral pressure, Pn

All this information regarding all the past cyclones as collected from the Bangladesh Meteorological Department (BMD).

In developing a cyclone model for this study, 19 major cyclones were used that hit the Bangladesh coast from the year 1960. The tracks of those cyclones are seen in Figure 3.15. BMD classified tropical disturbances into eight categories depending on wind speed (Table 3.7). Following the classification of BMD, here the word ‘major’ refers to cyclone categories of severe cyclonic storms and above (severity in terms of wind speed were 89 kmph and above).

Table 3.7: Classification of tropical disturbances by BMD

S. No.	Disturbances	Wind Speed (kmph)
1	Low pressure area	> 31
2	Well marked low	31-40
3	Depression	41-51
4	Deep Depression	52-61
5	Cyclonic storm	62-88
6	Severe cyclonic storm	89-117
7	Severe cyclonic storm with a core of hurricane winds	118-219
8	Super cyclone	=> 200

3.3.1.3 Hydrological Data Necessary for Bay of Bengal Model

Hydrological data such as water level and flow data were collected from different secondary sources such as the Bangladesh Water Development (BWDB), Bangladesh Inland Water Transport Authority (BIWTA), Institute of Water Modelling (IWM), Global Tide Model (GTM) etc. All these data were used to develop boundary condition of the model and model calibration and validation.

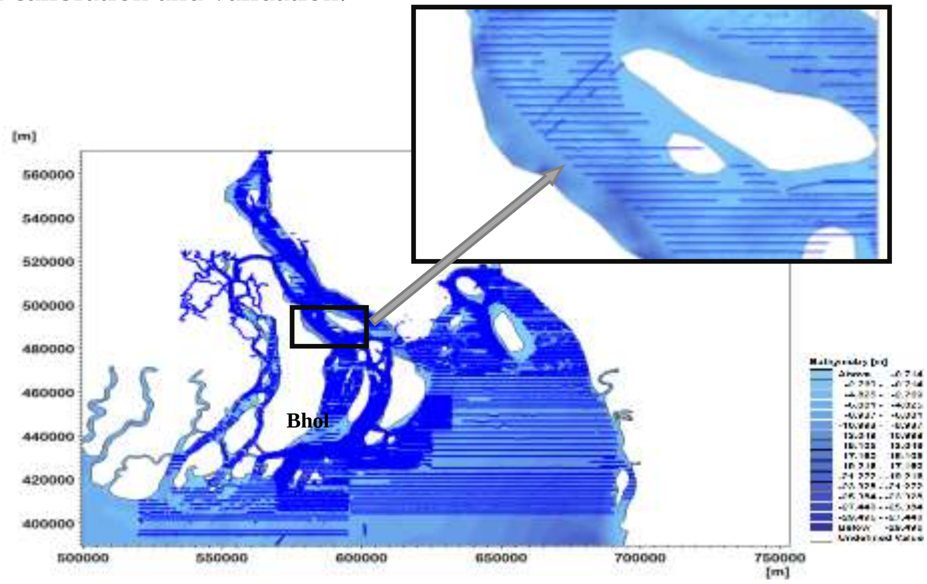


Figure 3.11: Data density during the survey under MES-I in Meghna Estuary

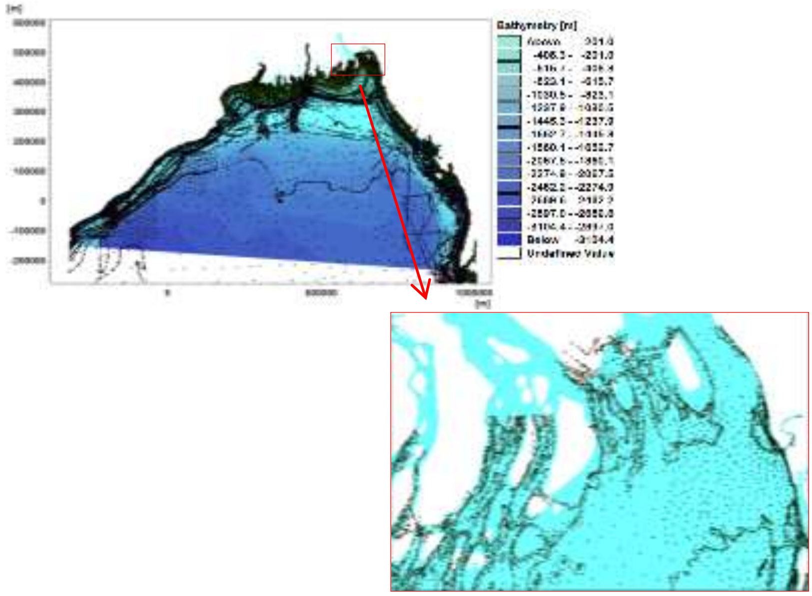


Figure 3.12: Data density from C-Map in the Bay of Bengal

3.3.1.4 Digital Elevation Model

The coastal digital elevation model that is currently being used for modeling purposes at the Institute of Water Modelling was built on FAP19 National DEM with 300m grid cell size, which was originally developed from FAP19 DEM with 500 m grid cell size (see flood hazard assessment in section 3.2). No doubt, the finer the grid size the more useful in assessing flood hazard caused by storm surges in the coastal region of Bangladesh. Topographic survey by FINNMAP was done in 1991 over the entire coastal region. By utilizing this data mainly, and some data from other sources, in 2009 IWM updated the coastal region (the lower part of Chandpur) of the national DEM, which is called IWM Coastal DEM and is currently being used at MRVAM project at IWM.

The task of development of the coastal DEM involves three elements of activities.

- Generating a partial coastline
- Preparing input data
- Generating the coastal DEM

Due to continuous dynamic coastal morphological and sedimentological processes, the coastline is dynamic. The FINNMAP data at 1991 appeared to be old to describe the coastline in 2009. Hence, this initiative needed estimation of coastline from other sources of data. IWM used data from seven different available satellite images to estimate the coastline. For example, images from Google Earth in 2006-07 were used to delineate the coastline beside Sunderban Reserved Forest; Landsat TM in 2007 were used to delineate the coastline from Ramgati to Sitakund including Shandwip, upper part of Monpura and Hatia. Before identifying the coastline to be used in the DEM, images were geo-corrected in reference to available ground control points. Image processing software, ERDAS Imagine and Image Analyst Extension of Arc View GIS, were used in geo-rectification. After this, an on-screen digitization was performed to capture the coastline.

The data used in developing the coastal DEM are given in Table 3.8.

Table 3.8: Data used in developing coastal DEM

Data Source	Time of Data Capture	Area Covered
FINNMAP Land Survey	1991	All over coastal areas
Khulna Jessore Drainage Rehabilitation Project (KJDRP), surveyed by IWM	1997	KJDRP area except Beel Kapalia and Beel Khuksia
Beel Kapalia, surveyed by IWM	March 2008	Beel Kapalia (inside KJDRP)
Beel Khuksia, surveyed by IWM	February 2004	Beel Khuksia (inside KJDRP)

Note: The area of the coastal DEM is larger than the survey coverage by FINNMAP. As such, for the areas outside FINMAAP and KJDRP but inside the coastal DEM FAP19 National DEM data (300 m grid) were used.

In preparing FINNMAP and KJDRP data, spot heights on embankments or elevated roads were not considered. However, points on homesteads were entered into interpolation. FINNMAP data were merged on BTM projection and PWD datum. Likewise, KJDRP data were converted to ArcView shape files in BTM and PWD. Afterwards, both data merged into one theme and shape file. This combined data was then merged with FAP19 DEM data. Hence, now all three data are combined and the result is a set of points that were used in final interpolation in generating the desired coastal DEM.

Some specifications of the coastal DEM are as follows:

- Mercator projection: BTM
- Datum: PWD
- Northern boundary: 568605 Northing
- Southern boundary: 275306 Northing
- Eastern boundary: 747314 Easting
- Western boundary: 380914 Easting
- Grid cell size: 50 m
- Digital format: ASCII, ArcGIS GRID

The coastal DEM that has thus been developed is shown in Figure 3.13.

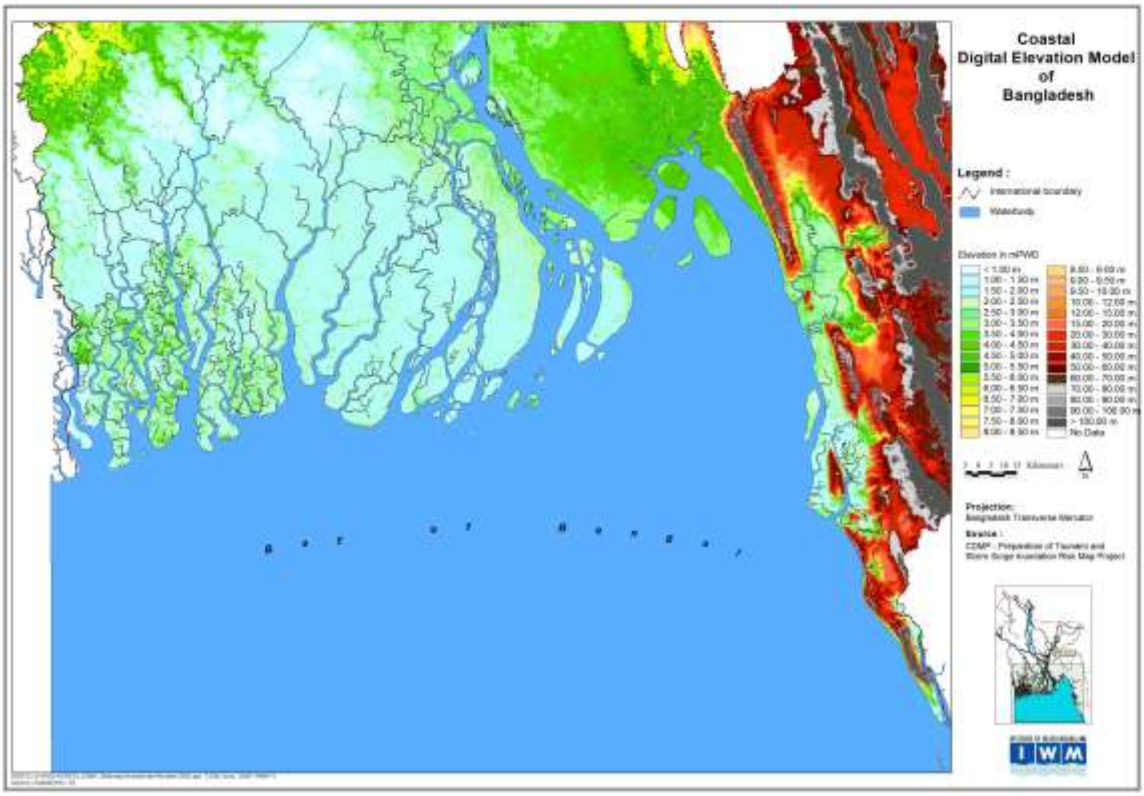


Figure 3.13: The coastal Digital Elevation Model

Source: CDMP-II, 2013

3.3.2 Methodology

The points on the Bangladesh coast where historical major cyclones hit and traversing passage (track of cyclone) in the period from year 1960 to 2009 are shown in Figure 2.2 (page 12). It is evident from the figure that the Chittagong coast is more vulnerable than any other part of our coastal area because most cyclones hit the coast near Chittagong in the last 50 years.

Mathematical modeling systems (the Bay of Bengal Model at IWM) computing storm surge elevations has two model elements: cyclone model and hydrodynamic model. The cyclone model creates cyclone (wind and pressure field) that induces storm surges. In producing the cyclone the model, meteorological data such as the cyclone track, air pressure, wind speed, wind radius etc. are used. The hydrodynamic model in its simulation uses data like water level, water flow and riverbed level and produces spatial and temporal distribution of water level and flow. These two models together construct storm surge model, which can produce surge levels for the whole model domain. Data of surge levels thus obtained from many historical cyclones have been used in frequency analysis to obtain surge levels of return periods of interest – 25, 50 and 100 years. Then surge heights have been obtained from such surge levels by subtracting land levels by using digital elevation model. Arc GIS was then used to produce surge height maps. Hence, surge maps have been prepared for practical use in hazard management. Methods and steps in assessing storm surge hazard and preparing maps are given in Figure 3.14.

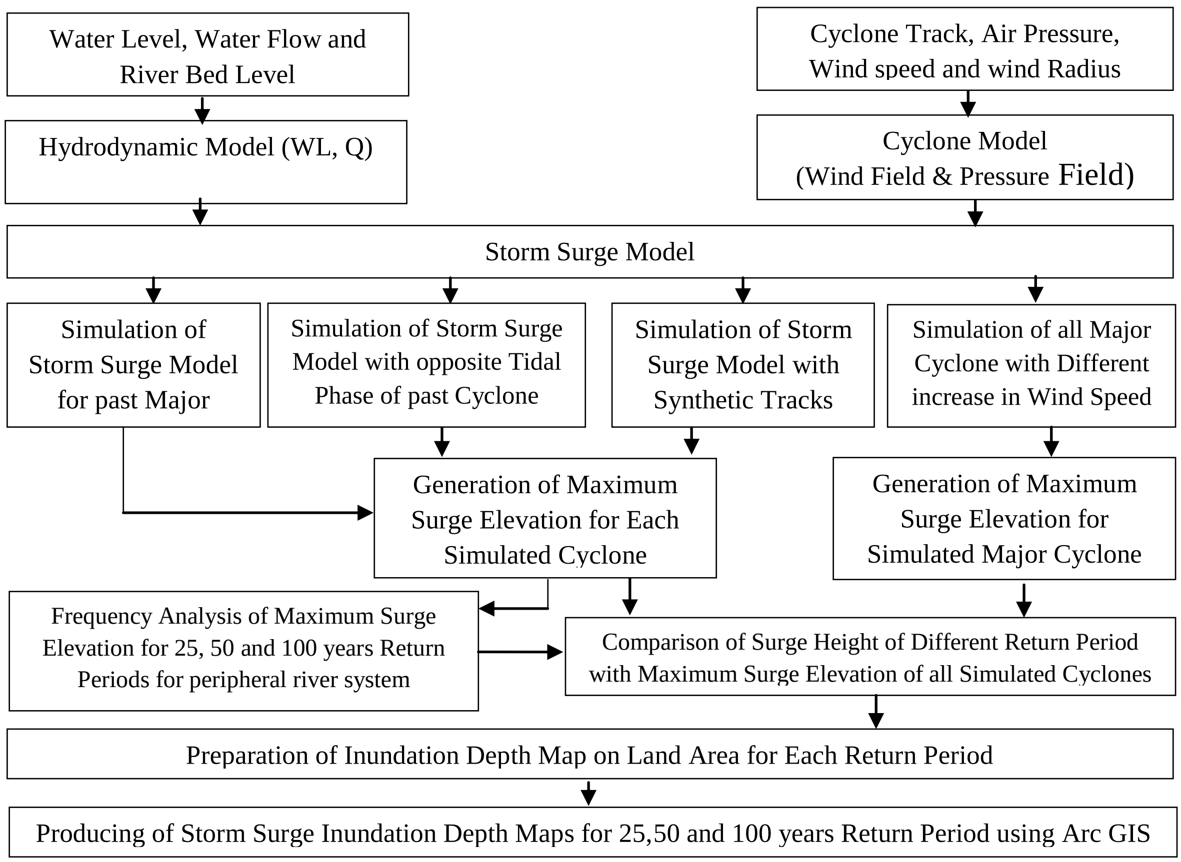


Figure 3.14: Methods and steps in producing cyclone-induced inundation depth maps

The detailed steps are as follows:

Step 1: Collection of data on water level, flow, cyclone track, river and seabed level, wind speed, pressure field and wind radius from different secondary sources. For example, historical hydrological data from BWDB (water level, river water discharge, rainfall), historical cyclone data (pressure and wind speed) from BMD, river and seabed level previous survey data in the past projects and international sources (see Table 3.6)

Step 2: MIKE FM model was used by IWM for Bay of Bengal Hydrodynamic model and then validated against water level and discharge at different location of Meghan Estuary

Step 3: The cyclone model was developed by incorporating wind speed, wind direction and pressure field collected from the Bangladesh Meteorological Department (BMD). Lastly, the combination of Hydrodynamic and Cyclone model produced the Storm Surge Model from which surge level or inundation depth in the coastal area was calculated.

Step 4: After that the storm surge model was simulated for 19 major cyclones that hit the Bangladesh coast during the period of 1960-2009. The model was also simulated for the same cyclone with opposite tidal phase and for ten synthetic tracks. Altogether 48 different cyclones were simulated using the Bay of Bengal Storm Surge Model, which produced surge levels for the entire coastal area for these 48 cyclones. It means that every grid of the storm surge model has 48 different surge levels from these 48 simulations.

Step 5: Then, a frequency analysis was carried out using those simulated results where each grid has 48 different surge levels and it was carried out only for river portion of the model (land part was excluded). The exponential distribution was used to carry out the frequency analysis and surge levels for 25-, 50- and 100-year return periods, where each grid point in the river part of the model was calculated.

Step 6: A comparison technique was used to get the surge level in the land part of the coastal area. The value of return period (any of 25, 50 or 100) for a specific river was then compared with the simulated 48 results and selected the best-fitted result for that return period and for that specific river. This result file was then used to get the surge level in the land part corresponding to that river. In this way the surge level was calculated for the entire coastal area and for different return periods.

Step 7: The surface elevation over the land is subtracted from bathymetry to get the storm surge height over the land and finally the maps were produced.

3.3.2.1 Model Used for Cyclone and Storm Surge Simulations (Bay of Bengal Model)

The model that IWM uses in MRVA project is called Bay of Bengal Model (BoBM). The model is developed using a MIKE21 FM modelling system, which is a numerical modelling system for the simulation of water levels and flows in estuaries, bays and coastal areas. It simulates unsteady two dimensional flows in one layer fluids and has been applied in many studies in the coastal areas of Bangladesh for addressing the issues of tidal flow, storm surge, coastal flooding, sea level rise impacts, land reclamation, land erosion, navigation, etc.

Updating of Bay of Bengal Model

The first version of the model was applied in Cyclone Protection Project (CPP) in 1991. It was further updated under the *Cyclone Centre Preparatory Study (CSPS)* in 1998. It was again updated under *Second Coastal Embankment Rehabilitation Project* (2^{nd} CERP) in 2000. After that, it was updated under the study *Updating of Hydrodynamic and Morphological Models to Investigate Land Accretion and Erosion in the Estuary Development Program (EDP) Area* with the bathymetry data of 2009. In fact, IWM regularly updates the model, and it has been updated with the information up to 2012.

3.3.2.2 Bathymetry and Spatial Boundary of Bay of Bengal Model

Two open boundaries are defined in the model. One in the north in the Lower Meghna river at Chandpur, and another one in the open sea in the Southern Bay of Bengal located along the line around 16° north latitude. Hence, it covers entire coastal area of Bangladesh and a large part of the Bay of Bengal. The Bay of Bengal is quite deep and the maximum depth along the southern open boundary is more than 2000m. In the river boundary flow data is considered, and the southern boundary is generated from the global tide model. All elevations (bathymetry, water level, land level) are expressed with reference to PWD datum. The model extent and bathymetry of BoBM is seen in figure 3.15.

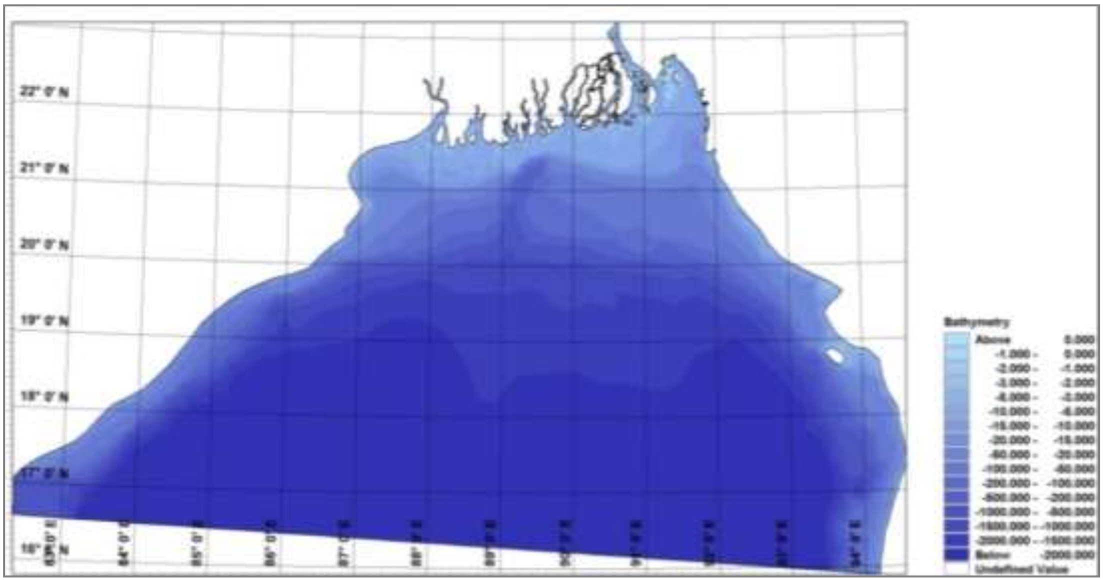


Figure 3.15: Model extent and bathymetry of the Bay of Bengal Model

3.3.2.3 Computational Grids of Bay of Bengal Model

The computational scheme in the model domain of the Bay of Bengal Model is done by MIKE FM (Flexible Mesh) module. It is a triangular gridding system, capable of producing triangular grids the model can delineate more correctly any kind of bank line. As a result, coastline and bathymetry can be gridded more accurately. IWM have used this FM gridding for the MRVAM project. Computational grids of BoBM are shown in Figure 3.16. In Figure 3.16, it is seen that the more towards the coast, the finer the grid size. Each grid point surge elevation has been computed.

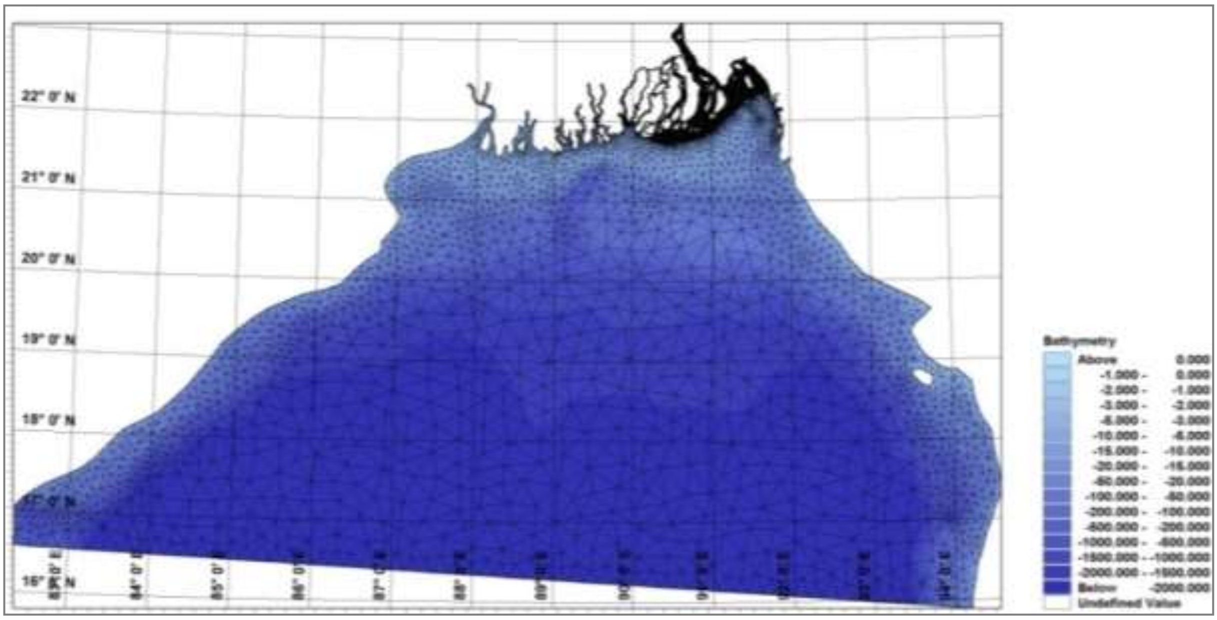


Figure 3.16: Computational grids of the Bay of Bengal Model

3.3.2.4 Validation of Bay of Bengal Model

It was evaluated whether the calibrated model could provide satisfactory results with other sets of real or predicted data. When satisfactory results are obtained from validations runs, the developed model is considered to be ready for practical purpose simulation. The models have been validated at locations in Cox's Bazar, Hironpoint, Kutubdia and Sandwip. In this case, validation was completed by means of predicted tide and simulated tide. The results of validation of the model are provided in Figure 3.17. Model results have shown a very good match with the predicted values.

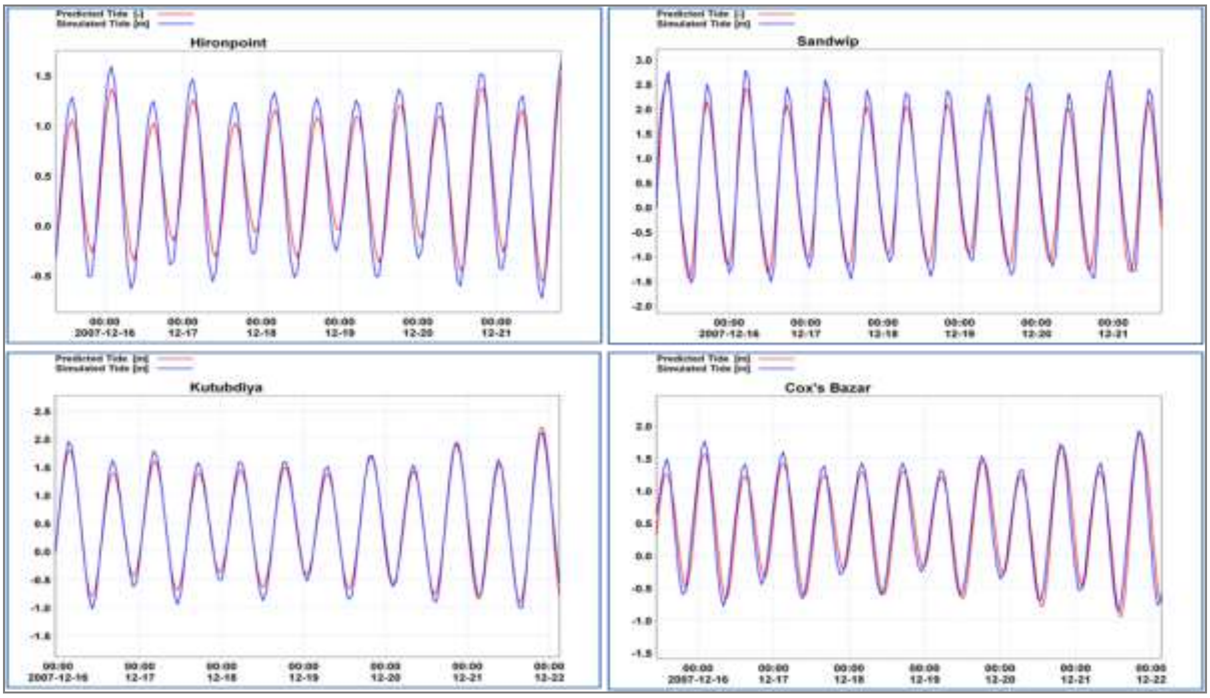


Figure 3.17: Bathymetry of the model was validated at Cox's Bazar, Hironpoint, Kutubdia and Sandwip

3.3.2.5 Simulation of Bay of Bengal Model for the Project Purpose and Extracting Results

A calibrated and validated model was used in simulating cyclone and cyclone-induced storm surges. Surges induced in the sea propagate through estuaries and rivers and inundates coastal areas. The storm surge model computes water levels at all the grid points in the model domain. These water levels are the storm surge levels. As an example, simulation of cyclone Sidr by means of the BoBM is seen in Figure 3.18. The simulation of cyclone Sidr was also used in climate change conditions and a Surge Induced Inundation Map was developed (as suggested by TAC) and is attached in Annexure – 3. In this study, the Holland Single Vortex theory was used to calculate the wind and pressure field in the cyclone module. The reason behind selecting the single vortex formulation is explained in Section 3.3.2.6.

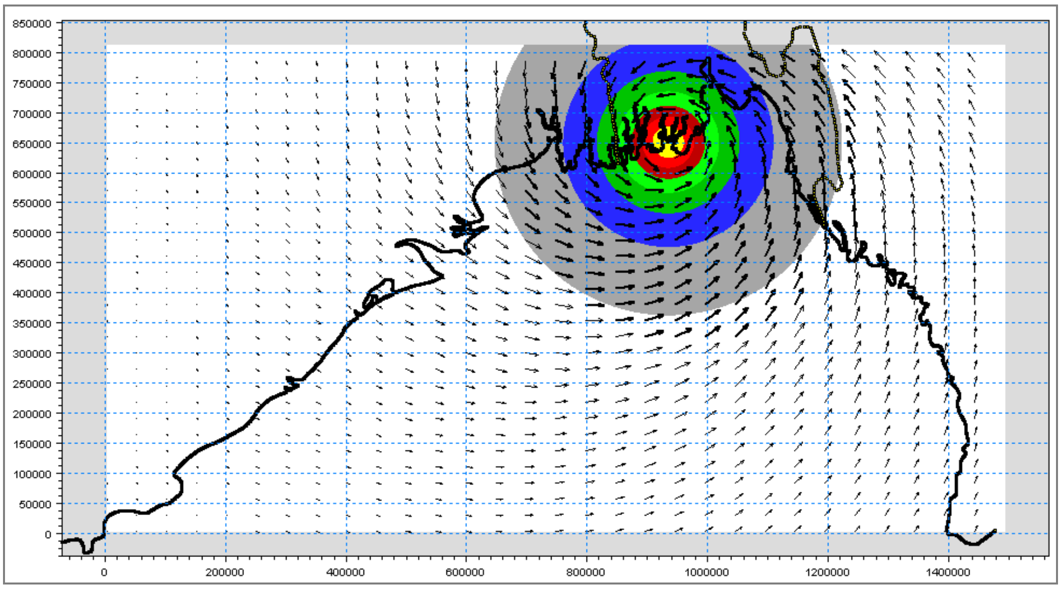


Figure 3.18: Simulated pressure and wind field in case of cyclone SIDR

The storm surge model was then simulated for four different categories. The categories are as follows:

Category-1: Under this category all the past severe cyclones were simulated with actual parameters. There were 19 severe cyclones that hit Bangladesh in the last 50 years (up to 2009). All these severe cyclones were simulated under this study. The list of the past severe cyclones is presented in Table 3.9.

Table 3.9: Occurrence of historical major cyclones that hit Bangladesh coast

Sl. No.	Cyclone event	Occurred during HT/LT*
1	1960	LT
2	1961	LT
3	1963	HT
4	1965	LT
5	1965	HT
6	1966	LT
7	1970	HT
8	1974	LT
9	1983	LT
10	1985	HT
11	1986	HT
12	1988	LT
13	1991	HT
14	1995	HT
15	1997	LT
16	1997	HT
17	1998	LT
18	2007	LT
19	2009	LT

* HT= High Tide, LT= Low Tide

Category-2: All the above-mentioned cyclones either occurred in high tide or the low tide. However, this type cyclone may have occurred in the opposite tidal phase. Considering this possibility, all major cyclones were also simulated with the opposite tidal phase. This means that if one cyclone hit the coast at high tide, the cyclone was simulated in low tide conditions.

Category-3: It is evident from the tracks of past severe cyclones that all of these cover a big part of the coastal area but there are some regions where no cyclone hit in the past. However, these regions can be affected any time by cyclonic storm surge because the cyclone track is completely uncertain. That is why these regions were considered under this study and five different tracks with opposite tidal phase were simulated through these regions.

All these three categories are used to calculate the surge levels for different return periods. The results of each simulated cyclone event (surge levels) in all grid points have been extracted. The maximum surge levels from each simulation at grid points in estuarine and riverine area in the coastal region have been considered for frequency analysis in order to get return period-wise storm surge levels.

Category-4: Under this category, the storm surge model was simulated for different increases in wind speed for all the past severe cyclones. These simulations were carried out during the preparation of inundation depth map for different return periods. This is done since the main objective of this study is to prepare inundation depth maps for different return periods such as 25, 50 and 100 years. However, all the past major cyclones may not produce inundation depths for all the return periods. Sometimes return periods show higher inundation depths than any of the past cyclones. In that case, wind speed was increased to achieve that surge level for that specified return period.

3.3.2.6 Reason behind Selecting Holland Single Vortex Formulation

Better Over Schloemer's Relation

In equations for finding the pressure profile and wind gradient at a certain radius, Schloemer (1954) is used for scale parameters: A and B, where in physical sense A is a radial scaling parameter on the radius of maximum wind and B is shape of the hurricane profile, in such a way that $A=R_w$ (R_w is radius of maximum wind) and B=1 as a universal relation. Schloermer's relation had been in use by many for more than two decades in engineering and storm surge modelling. Holland (1980) through analysis of data on Hurricanes hit in Australia (Tracy and Kerry) and other climatological data found that setting B=1 significantly underestimates the maximum wind speed of most hurricanes. He made improvements to the equations by introducing a parameter (that means normalising the pressure at a certain radius; where the parameter is a quotient of the difference in pressure between the pressure at certain radius and central pressure and that between neutral pressure and central pressure). He applied the normalised model in the said cyclones and nine cyclones blown over Florida and concluded that the scaling parameter B works well with value between 1 and 2.5 in reproducing hurricanes, and should work well in modelling cyclones with reliable winds observations.

Better Over Modified Rankine Vortex

The Modified Rankine vortex formula could make good approximation of the wind profile of a hurricane. However, the vortex formula involves a radius of maximum wind speed and it has a very clear bearing since there are two vortex formulae – one for inside the radius of maximum wind and the other one for the outside of it. Hence, little error in estimating radius of maximum wind results in a large error in estimating maximum wind speed. Application of equation developed by Holland (1980) as discussed above, can make good approximation to the wind profile of a cyclone.

Better Over Young and Sobey

In describing the wind field of cyclone, rotational wind gradient speed at a radius from the centre of the cyclone of Young and Sobey (1981) has two forms – one for within the area of radius of maximum wind speed and the other is for the outside. It involves the terms – radius, radius of maximum wind speed, maximum wind speed. However, it did not consider any scale parameter to describe the cyclone.

MIKE cyclone modelling previously used Young and Sobey (1981) equations. From 2009 DHI started using Holland single vortex formulations (cyclone having single eye) in modelling cyclones. As mentioned earlier, Holland equations, apart from the usual climate variables describing cyclones, do incorporate shape parameters in describing cyclones. The Cyclone Wind Generation Tool contained in MIKE21 used the equation for standard value for shape parameter B as suggested by Harper et al. (2001), Phadke et al. (2003) and Harper and Holland (1999) as $B=2-(p_c-900)/160$, where p_c is the pressure at the centre of the cyclone. DHI tested that using Holland equation simulates well than with Young and Sobey's and advises its clients to use Holland's (personal communication). IWM used Holland equation in simulating cyclones in MRVA project. For further details, please refer to the scientific documentation of MIKE 21.

Two different simulations were also carried out to assess the suitability of Young and Sobey and Holland Single Vortex Theory. Figure 3.19 shows the predicted surge level at Hiron Point and Khepupara for the both the theory along with observed surge level. It is evident from the figure that Holland Single Vortex gives quite reasonable results vs. Young and Sobey.

Stations	Cyclone Event	Maximum Observed WL (mPWD)	Simulated by Young & Sobey (mPWD)	Simulated by Holland Single Vortex (mPWD)
Khepupara	November 1988	3.02	3.5	3.15
Hiron Point	November 2007	2.15	2.31	2.18

Figure 3.19: Comparison between Young and Sobey and Holland Single Vortex theory

3.3.2.7 Frequency Analysis of Storm Surges in Estuaries and Rivers and Computing Return Period-wise Flood Levels on Landmasses

As mentioned earlier, in this MRVA project, mapping of storm surge hazard was to be carried out with return period-wise surge levels for return periods 25, 50 and 100 years. Therefore, it was necessary to carry out a frequency analysis for these return periods by means of a suitable statistical distribution for surge levels. It was found in a number of past coastal projects done by IWM that, in analyzing variable of maximum simulated surge levels, exponential distribution appeared to be the well-suited distribution. For example, this statistical method was used in the *Second Coastal Embankment Rehabilitation Project* (IWM-DHI, 2001) and *Hydraulic and Morphological Modelling Study to Aid Technical Feasibility Studies and Detailed Design for Coastal Embankment Improvement Project* (CEIP) (IWM, 2013). It was also mentioned in the inception report. In the CEIP (IWM, 2013) study, a professional team comprises of Institute of Water Modelling (IWM), Bangladesh University of Engineering and Technology (BUET), Danish Hydraulic Institute (DHI) and Dr. Ranjit Galappatti from Sri Lanka carried out detail analysis to select the best suited distribution for storm surge level in the coastal area of Bangladesh. After several simulations of storm surge model and analysis of six potential distributions, the team determined that the Exponential Distribution is the best suited one for this study.

The probability function of exponential distribution is:

$$\Pr(SL>SL_T)=\exp\left(-\frac{SL_T-\xi}{\alpha}\right)=\frac{1}{\lambda T} \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (1)$$

This can be rewritten to:

$$SL_T=\xi+\alpha.\ln(\lambda T)=\text{a}.\ln\left(\frac{1}{T}\right)=\text{b} \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (2)$$

Where, SL_T (m) is surge level with return period T (years), α (m) and ξ (m) are scale and location parameter, respectively, and λ (year^{-1}) is frequency. The parameters a(m) and b(m) are introduced to simplify the use.

The coastal region in Bangladesh is not a natural state in that a storm surge passing through estuaries and river networks can enter freely onto landmass, because there are 149 polders covering the whole coastal region. On the other hand, the model did not consider any breaching of embankment of any polder. Rather, it considered overtopping of embankment by surge water. As mentioned earlier, frequency analysis was completed with surge levels at grid points in estuaries and a river network meaning around the water bodies of the landmass. However, storm surge maps have to be prepared for landmasses only for the entire coastal area. The inundation depth on the land mass was then prepared based on the return period wise surge level in the nearby river system. We already have results from 48 simulations hat were used to prepare the inundation depth in the landmass. Firstly, the surge level of any return period for a specific location of a river near land mass was selected. Then the selected surge level was compared with all the results for best match at that specific location. After selection of result file, the inundation depth on nearby landmass of that specific river for that return period was taken for inundation depth map. If the best match failed to identify, then new simulations were carried out as a trial and error basis to get the best match.

3.3.2.8 Preparation of Storm Surge Inundation Depth Maps

In the MRVA project, for the purpose of disaster risk reduction management arising out cyclone-induced storm surge inundation depth maps are to be prepared. A storm surge inundation depth map is a map showing water depth at a location in an area during cyclonic storm surge. Inundation depth maps were produced for all the simulations that were carried out under four different categories. All these categories are described Section 3.3.2.5.

3.3.2.9 Preparation of Storm Surge Inundation Depth Maps for 25-, 50- and 100-year Return Periods

It is a big challenge to produce return period wise inundation depth maps for an entire coastal area. It is a rule of thumb to have around 50 percent of data to calculate any return period value, for instance 50 datasets re needed to produce a 100-year return period value. However, it is found that 0 to 7 data values were available on the landmass from 48 simulated results. That is why it was not possible to get the desired return period wise data with these small data sets. To avoid this difficulty, a frequency analysis was carried out only on the peripheral river system around the land part because in the peripheral river there are 48 data values available. Then, these return period wise values were compared with all the simulated values to find the best-suited match. After getting this best suited match, it was then used to get surge level in the land area corresponding to that peripheral river (Section 3.3.2.7). The same procedure was carried out for the entire coastal area, and finally surge level maps of 25-, 50- and 100-year return periods were prepared. By subtracting the DEM from these surge levels, inundation depth maps for the entire coastal area for return period of 25, 50 and 100 years were achieved. Figure 3.20 demonstrates computation of surge height from surge levels and land levels.

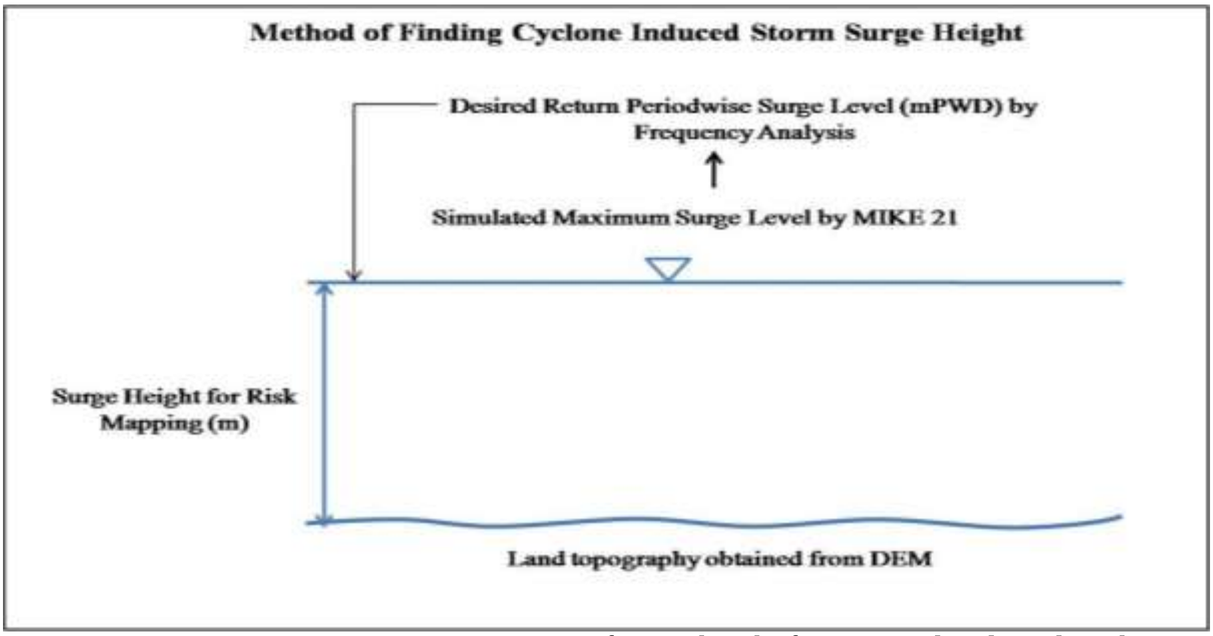


Figure 3.20: Demonstrating computation of surge height from surge levels and earth surface levels

3.3.3 Analysis of Hazard Assessment

Storm surge hazard depth was divided into seven different depth categories in order to find the extent of surge inundation and prepare inundation maps for all return periods: 25, 50 and 100 years for the entire coastal region (Figure 3.22, 3.23 and 3.24). The depth categories are <1 m, 1-1.5 m, 1.5-2 m, 2-3 m, 3-4 m, 4-5 m, >5 m. A district-wise analysis of surge hazard (depth category-wise) for a 50-year return period is given in Table 3.11. Likewise, the division-wise analysis is given in Table 3.10. In this analysis within a district, the river area was excluded from the district area. As obvious from the table headings, the rest area is involved in the hazard analysis. The rest area is of two kinds: surge affected and not-affected. For example, for Bagerhat district, 3498.17 km^2 is the area after excluding the river area. Further, 486.71 km^2 is an area below 1 m surge level, and 13.91 percent is the area out of 3498.17 km^2. The table for the division (Table 3.10) is prepared from the results of table for district-wise analysis. Figure 3.21 shows a bar graph of inundation depth for divisions.

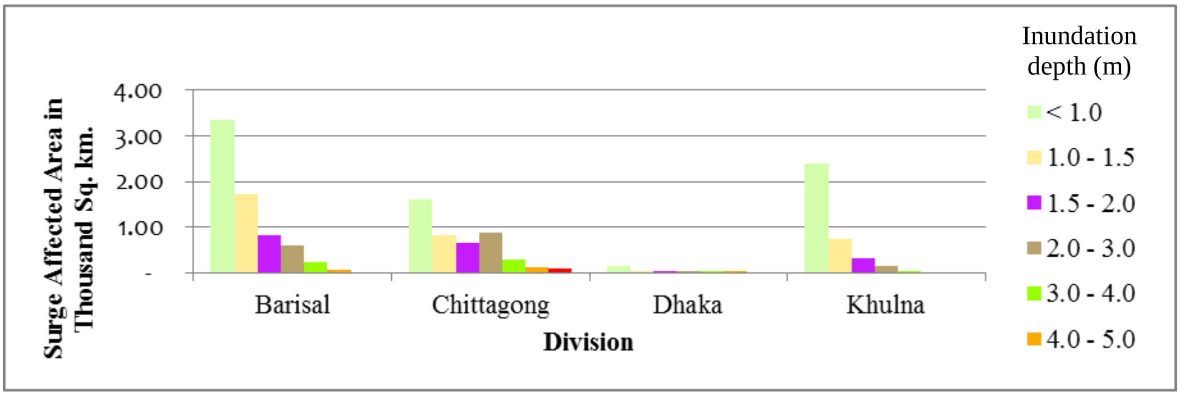


Figure 3.21: Division wise storm surge inundation depth and area of inundation

Table 3.10: Percentage of affected area due to cyclone induced storm surge (50-year) in divisions

Division / Depth	Storm surge Depth Vs. percentage of storm surge affected area							Not Affected area
	< 1.0 m	1.0 - 1.5 m	1.5 - 2.0 m	2.0 - 3.0 m	3.0 - 4.0 m	4.0 - 5.0 m	> 5.0 m	
Barisal	25.37	38.29	44.49	48.98	50.66	51.06	51.05	48.95
Chittagong	4.75	7.17	9.1	11.7	12.53	12.89	13.2	86.78
Dhaka	0.45	0.61	0.71	0.8	0.81	0.82	0.82	99.18
Khulna	10.79	14.15	15.63	16.33	16.4	16.4	16.39	83.61

Table 3.11: Area affected (km^2) due to cyclone induced storm surge (50-year) in districts

District	Storm surge Depth and Area affected (km^2)							Not Affected Area (km^2)
	< 1.0 m	1.0 - 1.5 m	1.5 - 2.0 m	2.0 - 3.0 m	3.0 - 4.0 m	4.0 - 5.0 m	> 5.0 m	
Barguna	631.8	874.9	935.6	955.9	959.5	959.6	959.6	698.6
Barisal	639.2	1128.2	1314.3	1443.3	1479.4	1483.3	1483.3	1,035.0
Bhola	455.1	585.9	743.6	1032.3	1150	1195.7	1195.7	979.5
Jhalokati	431.3	565.2	578	587.6	587.6	587.6	587.6	119.2
Patuakhali	566.6	1060.3	1368.3	1516.9	1582.3	1586.2	1586.2	1,057.4
Pirojpur	648.7	878.2	974.1	982.7	984.1	984.1	984.1	291.0
Chandpur	39.1	54.5	65.4	94.9	107.1	110.5	110.5	1,305.5
Chittagong	443.3	799.7	1078.8	1313.8	1388.9	1423.3	1481.8	3,269.4
Cox's Bazar	371.9	482.4	516.3	524.6	524.9	524.9	524.9	1,877.1
Feni	142.7	177.8	202.1	252	264.8	269.3	279.8	685.1
Lakshmipur	225.4	314.5	373.9	415.9	439.2	453.6	453.7	672.1

District	Storm surge Depth and Area affected (km^2)							Not Affected Area (km^2)
	< 1.0 m	1.0 - 1.5 m	1.5 - 2.0 m	2.0 - 3.0 m	3.0 - 4.0 m	4.0 - 5.0 m	> 5.0 m	
Noakhali	461.2	718.1	1009.8	1614.6	1795.9	1871.1	1914.5	1,293.9
Gopalganj	47.7	48.3	48.7	48.7	48.7	48.7	48.7	1,420.1
Madaripur	0.3	0.3	0.3	0.3	0.3	0.3	0.3	1,125.4
Shariatpur	85.1	131.1	158.6	184.9	188.4	191.3	191.3	912.0
Bagerhat	1,189.2	1536.7	1624	1670.2	1674	1674	1674	1,992.1
Khulna	573.8	839	988.5	1054.8	1063	1063	1063	2,750.0
Narail	0.2	0.2	0.2	0.2	0.2	0.2	0.2	967.7
Satkhira	639.5	780.2	875.4	916.9	919.5	919.5	919.5	2,382.8

Note: Other districts are not affected by Cyclone induced storm surge.

3.3.4 Map Content

The cyclone storm surge hazard map consists of inundation depth (m) due to storm surge. Storm surge height categories adopted in this study are given in Table 3.12.

Table 3.12: Cyclone-induced storm surge inundation depth categories

Inundation depth categories due to storm surge (m)	Storm surge Categories	Symbol used in maps
No Inundation	Not affected	
< 1.0 m	Very shallow	
1.0 - 1.5	Shallow	
1.5 - 2.0	Medium	
2.0 - 3.0	High	
3.0 - 4.0	Very high	
4.0 - 5.0	Extremely high	
> 5.0	Extremely very high	

Cyclone storm surge hazard maps covering entire coastal area for 25-, 50- and 100-year return periods are shown in Figures 3.22, 3.22 and 3.24 respectively.

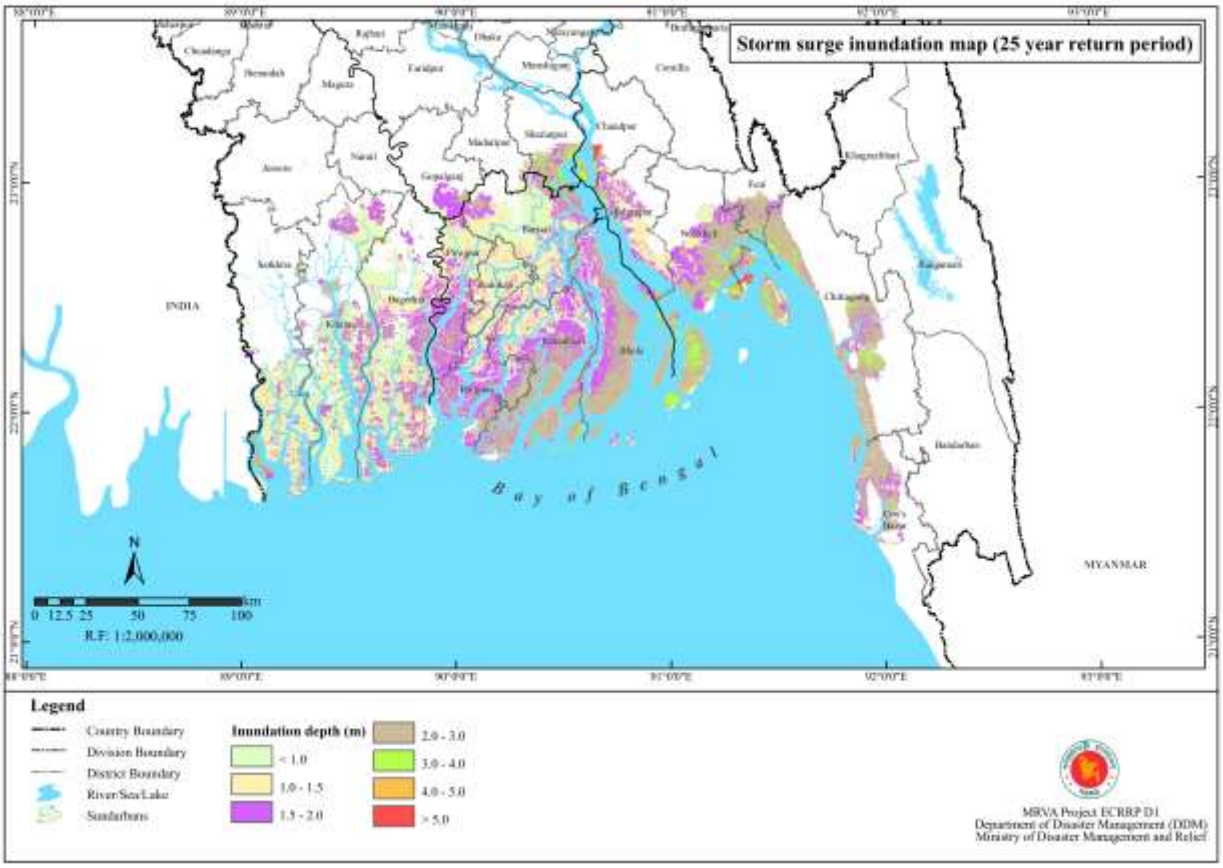


Figure 3.22: Storm surge inundation map of entire coastal area for 25-year return period

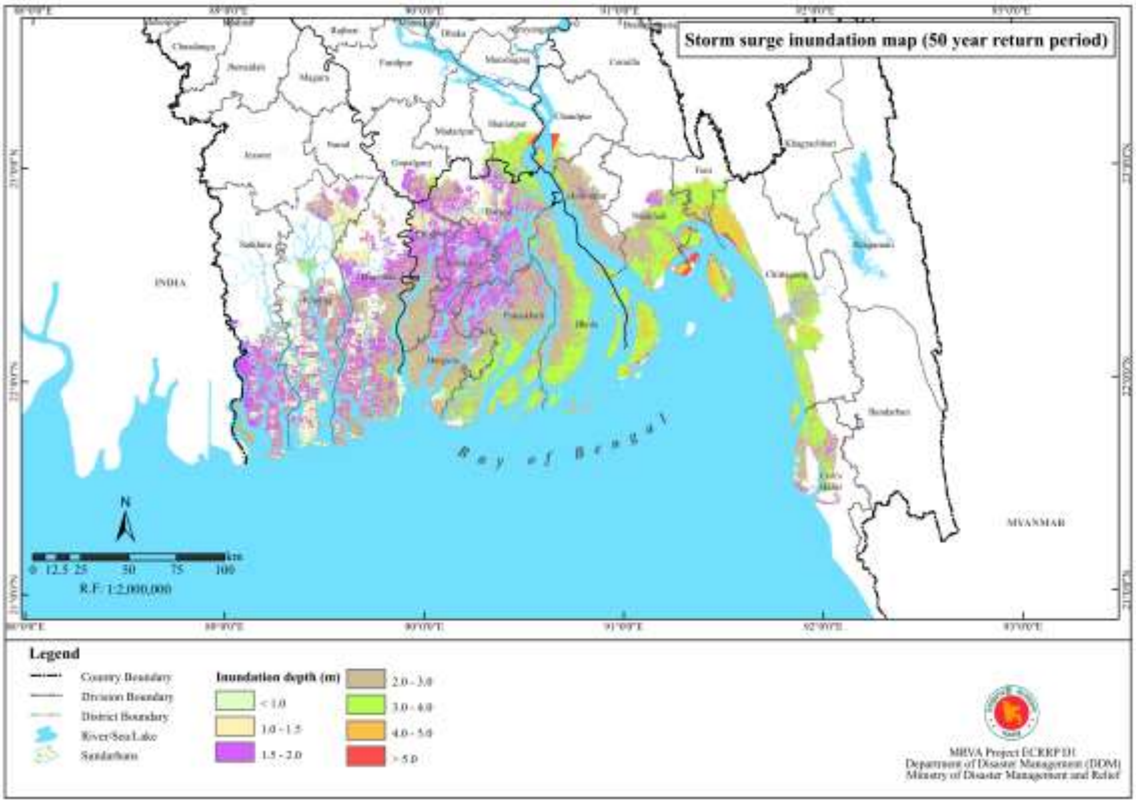


Figure 3.23: Storm surge inundation map of entire coastal area for 50-year return period

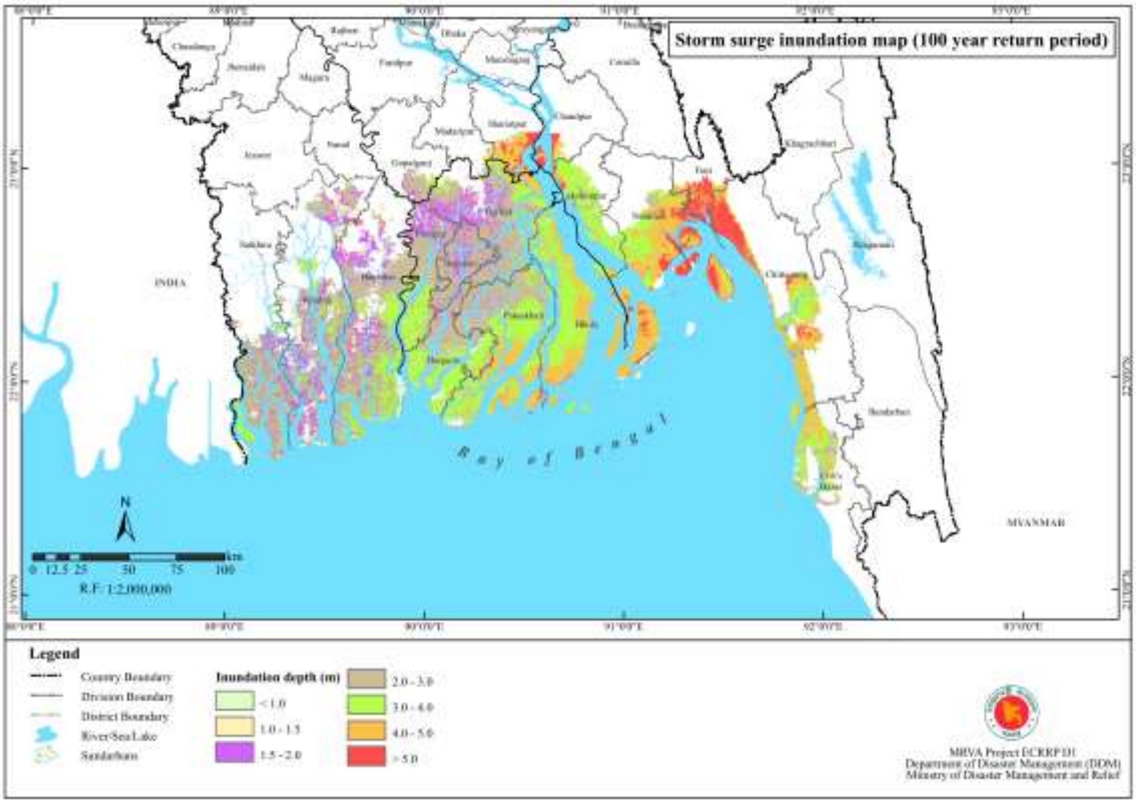


Figure 3.24: Storm surge inundation map of entire coastal area for 100-year return period

3.3.5 Application of Maps

The application of maps will depend on the need of the user specific to the purpose of the need, and area of interest. However, some salient and important uses of storm surge map are as follows:

- Assessing exposure of elements at risk in storm surge hazard with some specific surge height in an area;
- Comparing storm surge hazards of different places by assessing spatial variation in surge height in the area covered by the map;
- Estimating population exposed to storm surge hazard of some depth category in some locality;
- Help in assessing scenarios at the time of cyclone preparedness to make plan of actions for evacuating, rescue etc. and estimating amount of relief;
- Estimating other elements at risk (communication network, homesteads, buildings, crops, livestock etc.) in a particular locality;
- Urban and rural planners can use in planning and design of infrastructures, buildings, homesteads – particularly communication network;
- Selecting, planning and designing of cyclone shelters, killas etc. For example, Section 3.3 of Cyclone Shelters Construction, Maintenance and Management Policy 2011 demands hazard map in determining floor level;
- Assessing crop damage;
- Help in building community awareness in all kinds and stages of cyclone preparedness;
- Help in selecting more vulnerable areas to flood hazards, and hence help in disaster preparedness;
- Help in planning and designing of polders, water flow regulating structures etc.; and
- Help in selecting the site of key point installations.

3.3.6 Special Remarks

In the past, storm surge maps were prepared in different studies, but they were all event based meaning surge map of a historical event (for example Sidr). Return period-wise maps for a couple of return periods including quite high return periods are developed for the first time in order to be used in disaster management purposes. This could be useful to the decision makers for developmental planning and disaster management as well.

3.3.7 Recommendations

Cyclone-induced surge hazard assessment were carried out for the entire coastal areas of Bangladesh for 25-, 50-, and 100-year return periods using the secondary data. These storm surge hazard maps consist of detailed inundation patterns, which can be used at district/upazila/union levels by policy makers, planners, decision makers and all relevant stake holders for better planning and implementation of an effective system of disaster management relating to cyclone induced storm surge hazard.

3.4 Landslide

Bangladesh is highly vulnerable to several natural disasters and every year natural calamities upset human's lives and livelihoods in parts of the country. Along with hydro-meteorological disasters such as floods, cyclones and droughts, occurrence of landslides also occur due to high rainfall intensity during the recent years in the hill track region of Bangladesh. Landslides are one of the most widespread and damaging natural disasters in the hilly regions of Bangladesh. The study of landslides has drawn global attention, mainly due to increasing awareness of its socio-economic impacts as well as increasing pressure of urbanization on the mountain environment (Aleotti and Chowdhury, 1999; Champati Ray and Lakhera, 2004). Landslides cause loss of life, property, and damage to natural resources, developmental projects and essential commodities, etc. Identifying places of landslide occurrence over a region or division of land surface into near-homogeneous zones is known as Landslide Susceptibility Zonation (LSZ) Mapping, which will minimize the loss of life and property. The aim of LSZ is to identify places of landslide occurrence over a region on the basis of conditional and internal causative factors. This set of causative factors can formally be defined and then ranked according to the degrees of actual or potential hazard due to landslides.

Exposed soft sedimentary rocks in the vast tract of mountainous and hilly terrains (18 percent of the total area of the country) and interventions of human activities across the slopes caused fatal landslides triggered by the torrential monsoon rainfall. The hilly terrain in the southeastern part of the country has the long history of slope instability. Since 1980, major urban growth has taken place through rural-urban migration in different cities of Bangladesh including hill track region (Islam, 1994). Since 1997, landslides have caused depth of approximately 235 persons around Chittagong town and other urban areas (Technical Report, 2008). Considering the potential landslide hazards due to rainfall and earthquake, an attempt has been made in this study to assess the landslide hazard assessment due to rainfall and earthquake.

Major processes that cause landslides in Bangladesh are:

a) Removal of lateral support:
   i. Erosion by rivers;
   ii. Previous slope movements such as slumps that create new slopes; and
   iii. Human modifications of slopes such as cuts, pits, and canals.
b) Addition of weight to the slope:
   i. Accumulation of rain water;
   ii. Increase in vegetation;
   iii. Construction on fill;
   iv. Weight of buildings and other structures; and
   v. Weight of water from leaking pipelines, sewers, canals, and reservoirs.
c) Earthquakes

d) Removal of underlying support:

   i. Undercutting by rivers and waves; and
   ii. Swelling of clays.

e) Anthropogenic activities as jhum cultivation

Keeping the past landslide occurrences in Bangladesh in mind, methodology and a necessary database was developed in this study.

3.4.1 Data Used

As explained earlier, the main conditional factors considered for susceptibility mapping are lithology, land use and land cover, and slope.

Lithology: Geology map (USGS and GSB, 2001) was developed by United States Geological Survey (USGS) and Geological Survey of Bangladesh, which consists of about 27 geological units, as given in Table 3.13. The areal extent and percentage of each geological unit is given in table 3.13. The geological map of Bangladesh is shown in Figure 3.25.

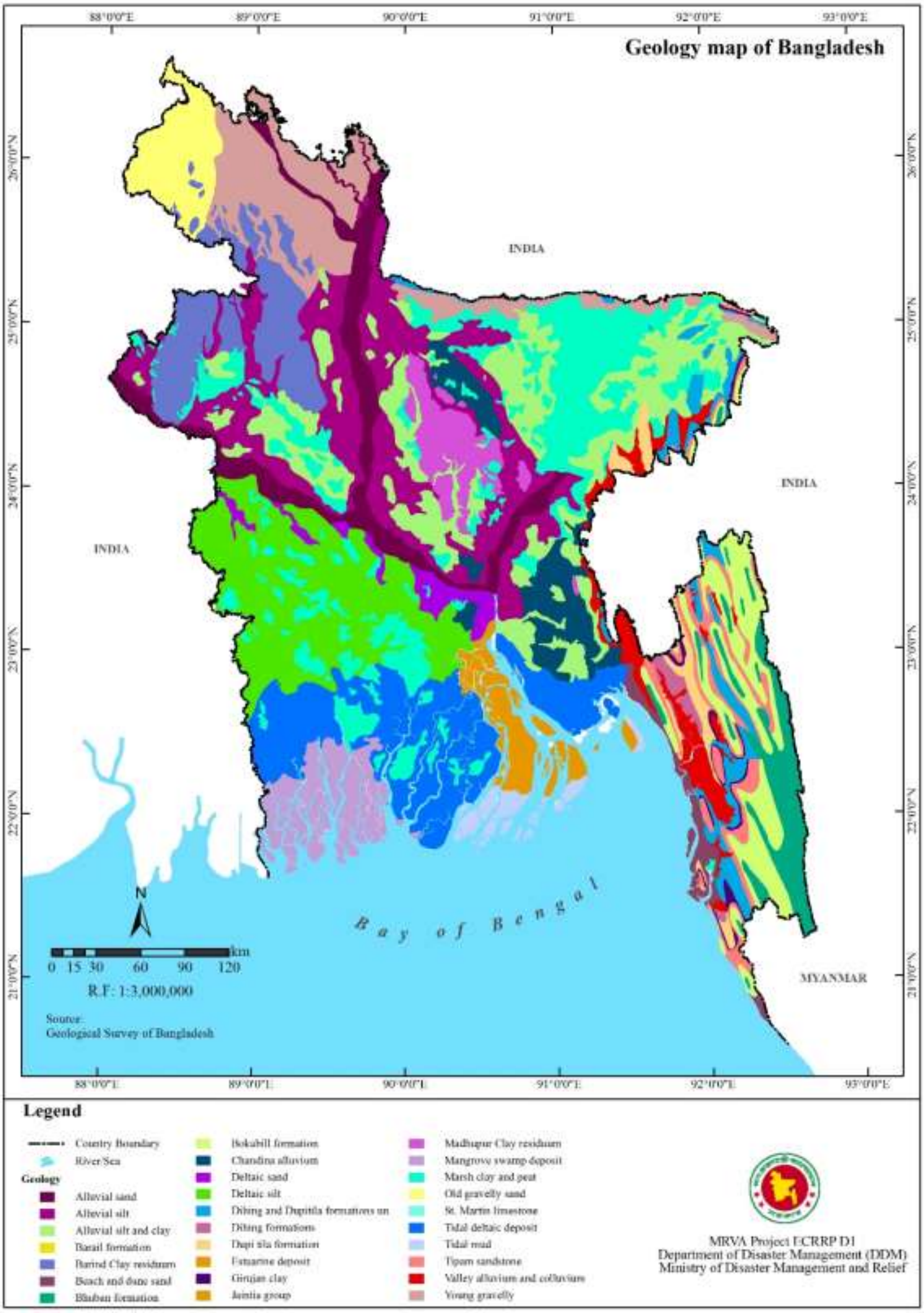


Figure 3.25: Geology map of Bangladesh

Source: GSB and USGS, 2001

Table 3.13: Description of Geological units existing in Bangladesh (area, percentage)

Geologic Time	Group	Formation	Unit	Area (Km^2)	Percentage
Holocene or Recent		Alluvium	Chandina alluvium	4642.3	3.31
			Old gravelly sand	5110.0	3.64
			Young gravelly sand	10381.4	7.39
			Alluvial silt and clay	14157.1	10.08
			Alluvial sand	3522.3	2.51
			Alluvial silt	15520.7	11.05
			Valley alluvium and colluvium	3514.6	2.50
			Beach and dune sand	1393.0	0.99
			Estuarine deposits	2436.0	1.73
			Tidal mud	1212.7	0.86
			Deltaic sand	1703.9	1.21
			Deltaic silt	13870.0	9.87
			Mangrove swamp deposit	4608.9	3.28
			Tidal deltaic deposits	10179.8	7.25
			Marsh clay and peat	16191.9	11.53
Pleistocene		St. Marin limestone		2.9	0.00
		Barind clay residuum		7568.4	5.39
		Madhupur clay residuum		3566.7	2.54
		Dihing Formation		661.8	0.47
Plio-Pleistocene		DupiTila Formation		5276.4	3.79
Pliocene	Tipam group	Girujan Clay		564.6	0.40
		Tipam Formation		3326.3	2.37
Miocene	Surma group	BokaBil Formation		6128.8	4.36
		Bhuban Formation		4144.9	2.95
Eocene	Jaintia Group	Tura- Sylhet- Kopili formations		99.8	0.07

Source: USGS and GSB, 2001

Brief Description of Geological Units

Most parts of Bangladesh are covered by thick layers of sediments of one of the largest delta complexes in the world, formed by the Ganges (Padma) and the Brahmaputra

(Jamuna) rivers (Norman, 1992). The delta was formed by the deposits of eroded material from the eastern Himalayas and the Indo–Burman Ranges, and carried by these river systems.

Several stratigraphic formations exist in Bangladesh. However, the units that have the most influence for landslide hazard are described here (Banglapedia, Wikiepedia).

Dihing Formation: The formation consists of yellow and grey, medium-grained, occasionally pebbly sandstone and clayey sandstone with interbeds of mottled clay. The rocks are poorly consolidated, for the most part. The unit lies uncomfortably between Dupi Tila and Alluvium. In some places, the unit is reported to contain white clay at the base.

DupiTila Formation: The Dupi Tila Formation consists mostly of loosely consolidated medium- to coarse-grained sandstone with minor amounts of shale–clay. That is overlain by recent alluvium of sand, silt and clay. The Dupi Tila Sandstone uncomfortably overlies the Tipam Group; in the Sylhet Trough it comprises a sandy lower unit and an argillaceous upper unit. The lower unit is composed of medium- to coarse-grained, cross-bedded sandstone with pebbles of sedimentary and crystalline rocks. The upper unit – which has not been identified elsewhere in Bangladesh – consists of fine- to medium-grained siltstone with intercalations of mottled clay horizons.

Tipam group

Girujan Clay and Tipam Formation: Subsidence rates in the Sylhet Trough increased three to eight times when the Tipam Sandstone and Dupi Tila Formation were deposited. The Surma Group is uncomfortably overlain by Tipam Group, which consists of Tipam Sandstone and Girujan Clay. Tipam Sandstone consists of yellowish-brown to orange, coarse-grained, cross-bedded, sand and sandstone. Tipam Sandstone is thickest in the Sylhet Trough. Girujan clay is brown, blue, purple and gray mottled clay is also thickest in the Sylhet Trough.

Sands of the Tipam Group and the Dupi Tila Sandstone contain abundant argillitic and low- to medium-grade metamorphic lithic fragments and feldspar grains, suggesting continued orogenic unroofing. These younger sands are rich in potassium feldspar relative to plagioclase phospherous-rich Bhuban and Boka Bil sandstones, suggesting a granitic source, probably the Miocene leucogranites of the High Himalayan crystalline terrane.

The Tipam Sandstone has two layers of gravel within the sandstone layers. It is yellow-brown to orange, medium- to coarse-grained, massive and cross-bedded. The sandstone has pebbles and coal fragments.

Surma Group

The Surma Group consists of the Bhuban Formation and overlying Boka Bil Formation. These formations are thick in the eastern fold belts and the deeper part of basin; the equivalent unit in the Indian platform – the Jamalganj Formation.

BokaBil Formation: The Boka Bil Formation consists of both a top and bottom layer of bedded and rippled mudstone. The second-lowest layer of calcareous concretions, with the next layer of siltstone and fine- to medium-grained sandstone.

The middle part of the Boka Bil forms natural gas reservoirs in the Bengal Basin. The top of the Boka Bil is popularly known as the Upper Marine Shale, marking the last marine transgression in the Surma Group.

Strata of the Boka Bil Formation show a similar geographic trend in deposition of coarsest and thickest sediment; the major depocenter had shifted northward relative to that of the Bhuban Formation. The lowest sand-shale ratio for the Boka Bil Formation is in the extreme northeastern corner of Bangladesh. Sand content in depocenters of the Boka Bil Formation is generally higher than that in the Bhuban Formation.

Bhuban Formation: Potential source rocks in the exposed part include the marine shales and carbonaceous shales of the Bhuban and Boka Bil formations.

The lower Bhuban Formation consists of light-grey to light-yellow siltstone sandwiched between a layer of fine-grained sandstone and a layer of bluish-grey mudstone. The middle Bhuban Formation consists of four layers of sandy mudstone, separated by layers of blue to yellowish-grey silty mudstone. The upper Bhuban Formation consists of several layers of light-grey to light-yellow bedded siltstone, fine-grained sandstone and bluish-grey sandy mud.

Bhuban Formation sediments accumulated in a large, elongate trough. The grain size and sand thickness both decrease away from the trough; the trough meanders westward from the northeastern Bengal Basin and curves southward toward the Bay of Bengal and the Bengal Fan. This sediment lobe can be traced down to southern Bangladesh. A second lobe distributed sediment southward through the Chittagong Hills of southeastern Bangladesh, where sand contents and thicknesses are high relative to the surrounding regions.

The other location in which the Bhuban Formation has a comparably high sand content is in the hinge zone more than 200 km (120 mi) west. In the hinge zone the sand percentage in the Bhuban Formation (25 percent) is over twice that of the Boka Bil Formation (11 percent). Shale thickness decreases from the Bhuban to the Boka Bil Formation in the southeastern area.

Land Use and Land Cover: Human activities that are directly related to land, making use of its resources or having an impact upon it. Land cover is the physical attributes of the land, while land use is a pattern of human activities undertaken within a socio-economic context. Natural land cover is changed by use of man in meeting cultivation, homestead or other demands.

Physiographically, Bangladesh may be divided into three major units: hills of the north, northeast and southeast covering about 12 percent of the total area; Pleistocene terraces stretching over only 8 percent area and floodplains accounting for 80 percent of the total area. Of the three determinants, land levels in relation to flood depth are of major importance for land use. Even occupation types in the rural areas are dependent on flooding characteristics - depth, duration and timing. There are regional variations in the distribution of different land types and land use pattern.

Land use pattern in Bangladesh is determined by physiography, climate and land levels in relation to flooding. In this context, land includes all land and water within the national boundaries of the country. Water bodies within land areas are therefore considered to be a part of land. The use of land is of paramount importance in a country that is thickly populated and still very reliant on primary production.

The land use and land cover map is collected from Water Resources Planning Organization (WARPO) and is re-arranged based on the levels. Broadly, there are four levels on the types of land use and land cover that exists in Bangladesh. Agriculture is 77.4 percent, forest is 15.87 percent, water (including rivers) is about 6.41 percent and 0.34 percent is settlement of major cities. Since agriculture is the main land use, it is sub-divided based on the seasonal use for crops such as Aus, Boro and Aman. The areal extent of the land use and land cover is given in Table 3.14. The land use and land cover map is given in Figure 3.27.

Table 3.14: Distribution of land use categories in Bangladesh (area, percentage and weight)

	Land Use and Land Cover Type		Area (km^2)	Percentage
Sl.No.	**Level - I**	**Level – II**		
1	Agriculture	Boro-Fallow-T.Aman	20162.7	13.87
2	Agriculture	Boro-Fallow-Fallow	19118.8	13.15
3	Agriculture	Rabi crop-mixed B.Aus & Aman	14562.7	10.02
4	Agriculture	Fallow-Fallow-T.Aman	13185.8	9.07
5	Agriculture	Rabi crop-B.aus-T.Aman	12644.1	8.70
6	Agriculture	Rabi crop-B.aus-Fallow	9932.4	6.83
7	Agriculture	Fallow-T.aus-T.Aman	6755.7	4.65
8	Agriculture	Rabi crop-Di.aus-T.Aman	5125.4	3.53
9	Agriculture	Fallow-B.aus-T.Aman	5016.1	3.45
10	Agriculture	Fallow-B.Aman	1650.9	1.14
11	Agriculture	Sugarcane	1570.9	1.08
12	Agriculture	Fallow-Shrimp-T.Aman	1385.5	0.95
13	Agriculture	Tea	1010.2	0.70
14	Agriculture	Betelvine & Vegetables	136.4	0.09
15	Agriculture	Fallow (Waterlogged)	116.8	0.08
16	Agriculture	Fallow-Mixed B.aus & Aman	82.9	0.06
17	Forest	Mixed Thickets & Forest	11248.8	7.74
18	Forest	Mixed Evergreen & Deciduous	5276.4	3.63
19	Forest	Natural Mangrove	4271.9	2.94
20	Forest	Planted Mangrove	813.7	0.56
21	Forest	Deciduous (Sal)	789.1	0.54

	Land Use and Land Cover Type		Area (km^2)	Percentage
Sl.No.	**Level - I**	**Level – II**		
22	Forest	Orchard	666.7	0.46
23	Water	River	7990.7	5.50
24	Water	Water body	544.1	0.37
25	Water	Mud Flat Total	370.2	0.25
26	Water	Fallow-Shrimp/Salt bed-Fallow	296.1	0.20
27	Water	Beach	120.7	0.08
28	Settlement	Urban – Flat	443.9	0.003
29	Settlement	Urban - Hilly	45.7	0.0003
		Grand Total	**145335.3**	**100.0**

Source: WARPO, 2012.

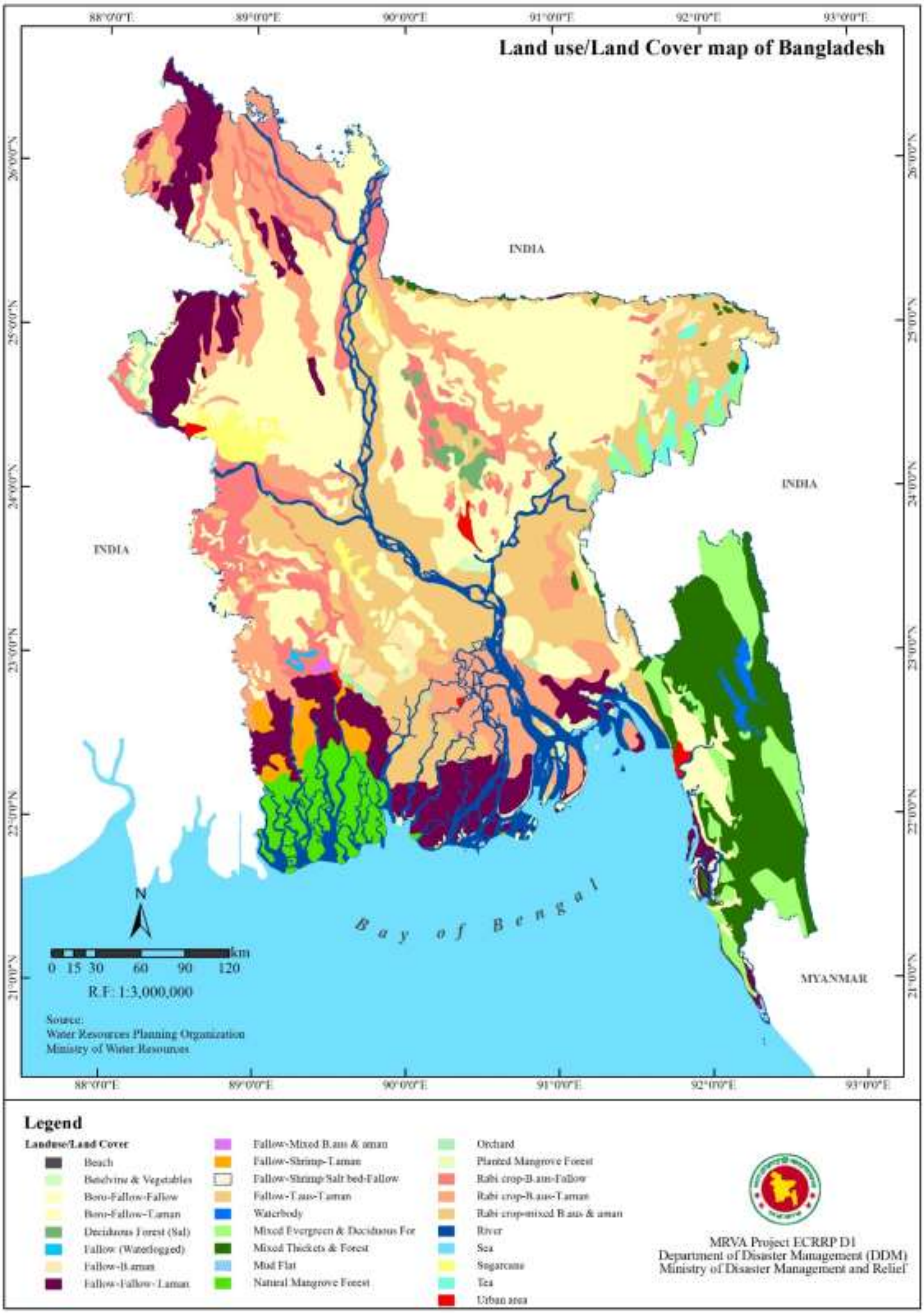


Figure 3.26: Land use/land cover map of Bangladesh

Source: WARPO, 2012.

Slope Map: The influence of slope steepness on landslide occurrence is the easiest factor to understand. Generally, steeper slopes have a greater chance of land sliding (see Figure 3.27). This does not prevent failures from occurring on gentler slopes. Other factors may make a gentle slope especially sensitive to failure, and thus in this situation could be determined to have a relatively high hazard potential.

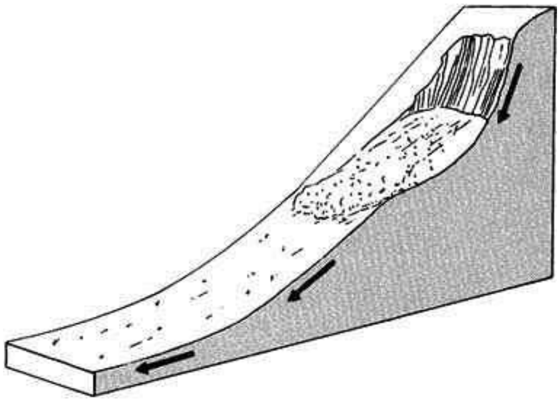


Figure 3.27: Slope steepness associated with landslide activity

Source: Organization of American States, 2002

For example, high ground water conditions occurring in sandy soils may liquefy during an earthquake. This can cause a landslide on a slope as gentle as 5 to 10 percent. Conversely, the steepest slopes may not always be the most hazardous. Steep slopes are less likely to develop a thick cover of superficial material conducive to certain types of landslides. Slope steepness can be mapped using generally available topographic maps or digital elevation model (DEM), which represents the average elevation of the ground surface at a spatial resolution or sample distance.

In this study, slope map is prepared using ASTER Global Digital Elevation Model (ASTER GDEM) (http://www.jspacesystems.or.jp/ersdac/GDEM/E/4.html). It is generated from data collected from the Advanced Space borne Thermal Emission and Reflection Radiometer (ASTER) stereo satellite data. The methodology used to produce the ASTER GDEM involved automated processing of the ASTER scenes, including stereo-correlation to produce individual scene-based ASTER DEMs, cloud masking to remove cloudy pixels, stacking all cloud-screened DEMs, removing residual bad values and outliers, averaging selected data to create final pixel values, and then correcting residual anomalies before partitioning the data into 1°by 1° tiles.

Bangladesh lies between 20°34´ to 26°38´ north latitude and 88°01´ to 92°41´ east longitude. In view of this, 35 ASTER GDEM tiles of 1°by 1° tiles (20° to 26° and 88° 92°) are downloaded and combined to make DEM for Bangladesh. The spatial resolution of ASTER GDEM is 1 arc-second (30 m) grid. At country level, this is best spatial resolution available. Other national level DEM available from FMAP is at 300 m is not suitable for landslide susceptibility assessments.

Slope map (in degrees) is derived using the ASTER GDEM and Slope function in ARC GIS software. The range of slope in Bangladesh is varying from 0 to 68.33 degrees. The slope map of Bangladesh is shown in Figure 3.28.

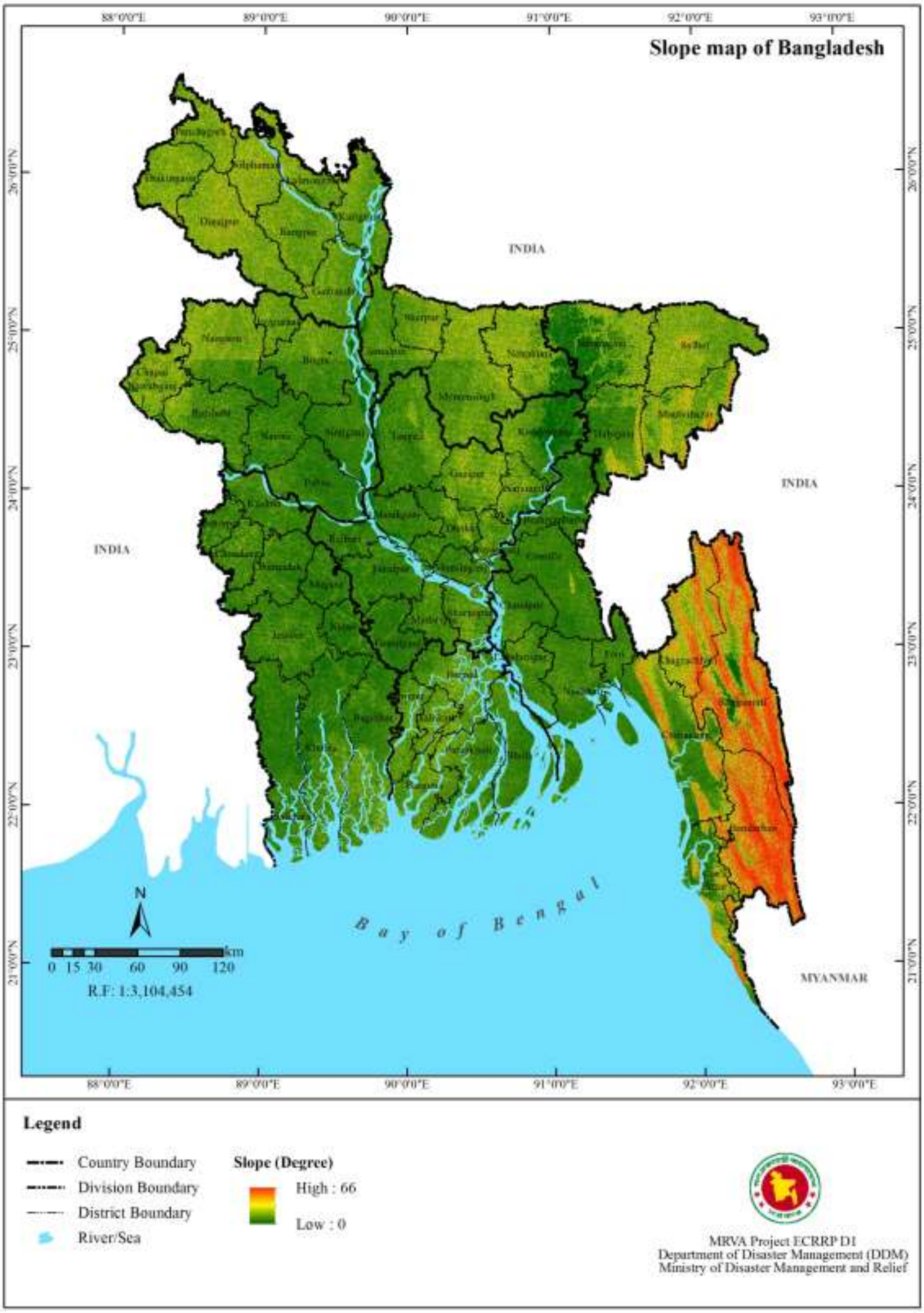


Figure 3.28: Slope map of Bangladesh derived using ASTER DEM

The pixel size of ASTER DEM is 30 meters, to carryout landslide susceptibility assessment at the national level, slope values are to be reclassified based on the most significant slope ranges. Several researchers have used different slope ranges to classify the slope map for use in landslide susceptibility assessment. Summary of slope ranges referred in this study are given in Table 3.15, which indicates the slope ranges are to used based on the local terrain conditions. Based on the local conditions and historical landslide analysis (Amanullah and Mamunul, 2008, Hamidur and Younus, 1995, CDMP, 2011), the slope ranges considered for this study are indicated in Table 3.15.

Table 3.15: Slope ranges (in degrees) used by researchers for landslide susceptibility studies

ADPC (2012a)	**ADPC (2012b)**	**NBRO (1995)**	**Chau et.al. (2004)**	**Khatsu (2005)**	**Nadim (2006)**	**Das (2011)**	**Lee (2002)**	**Suggested in this study**
				Slope ranges in degrees				
0 – 15	0 – 1	0 – 11	0 -15	0-15	0–1	1 - 15	0 – 10	1 – 5
15 – 30	1 – 6	11 – 17	15–18	15-25	1–8	15 – 25	11 - 20	5 – 10
30 - 45	6 – 12	17 – 31	18–22	25-35	8–16	25 – 35	21 – 30	10 – 15
45 – 60	12 – 18	31 – 40	22–27	35-45	16–32	35 – 45	31 – 40	15 – 20
>60	18 – 24	>40	27–30	>45	>32	45 – 60	41 – 50	20 – 30
	24 – 40		30–34			>60	51 – 60	30 - 45
	40 - 45		34–39				61 – 70	45 – 60
	45 - 90							60 – 68.3

The slope map of Bangladesh is reclassified into various slope classes based on the slope ranges (Table 3.15), which influence landslides in Bangladesh. The slope map with new slope classes is shown in Figure 3.29.

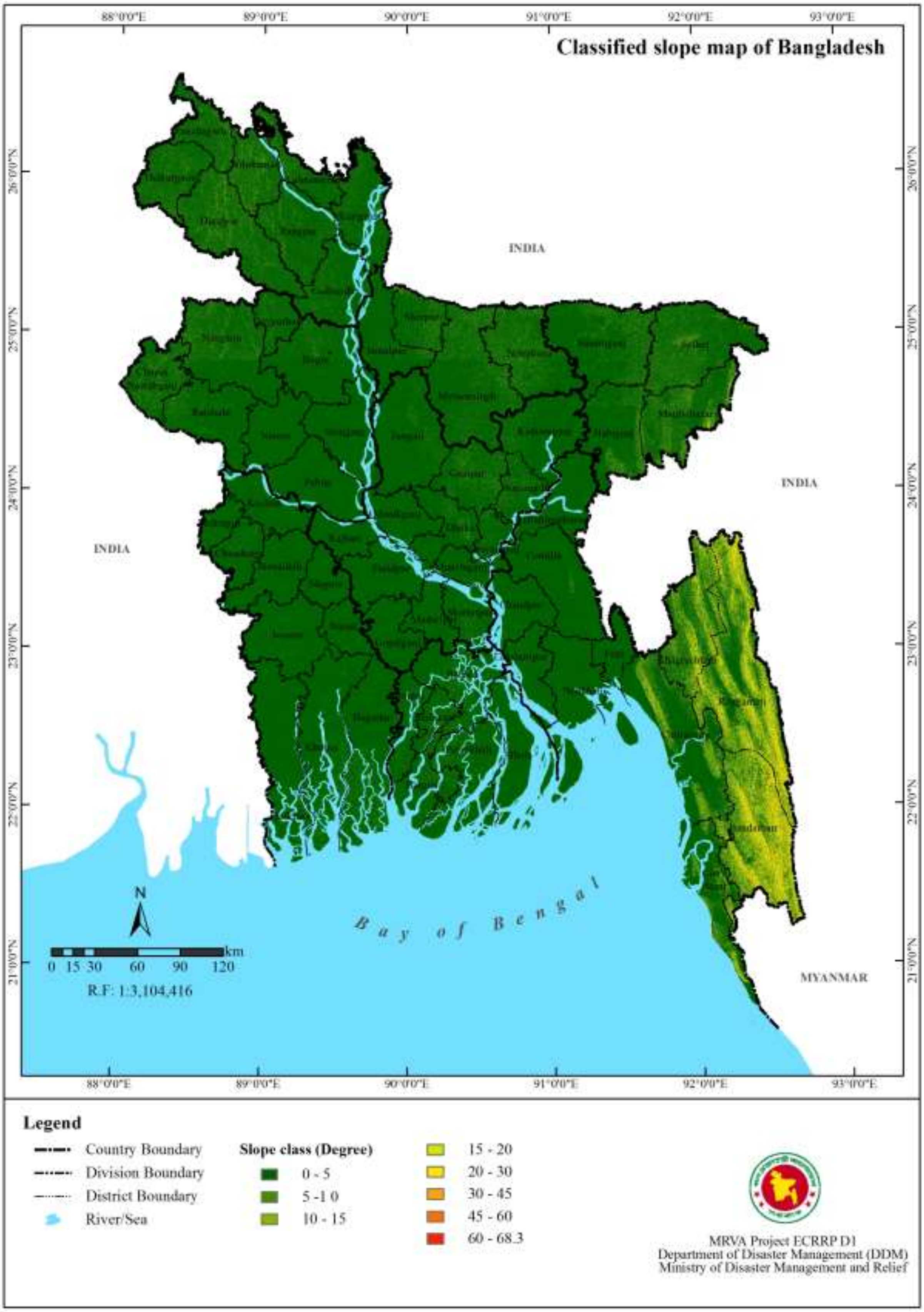


Figure 3.29: Classified slope map of Bangladesh

Aspect Map: Aspect is the compass direction that a slope faces. The aspect of a slope can make very significant influence on its local climate (microclimate). Aspect can have a strong influence on rainfall. Aspect plays important role in occurrence of rainfall pattern in the (anticline) hill-track region of Bangladesh. Because the direction of wind during monsoon (May to October) is from south-west towards north-east. The aspect which is towards south-west and north-east will receive highest rainfall, as these surface are receive the wind.

Aspect is derived using ASTER DEM. The aspect map consist of compass direction with 0^o representing North, 90^o representing East, 180^o representing South, 270^o representing West and 360o representing again North. The aspect (0^o to 360^o) is classified into 8 categories representing eight 8 directions. They are North-North West, North West-West, South West-West, South-South West, South-South East, South East East, North East East, North North East. The distribution of aspect classes is given in table 3.16 and aspect classified map is shown in figure 3.30. This map is used along with rainfall map for calculating effective rainfall map.

Table 3.16: Distribution of aspect classes in Bangladesh (area and percentage)

S.No.	Aspect Class (degree range)	Area (Km^2)	Percentage
1	NNW (360 - 315)	19270.2	13.3
2	NWW (315 - 270)	17838.1	12.3
3	SWW (270 - 225)	17927.3	12.3
4	SSW (225 - 180)	18161.2	12.5
5	SSE (180 - 135)	18193.1	12.5
6	SEE (135 - 90)	17887.2	12.3
7	NEE (90 - 45)	17938.0	12.3
8	NNE (45 - 0)	18120.1	12.5

Figure 3.30: Classified aspect map of Bangladesh

Causative Factors

As explained in methodology, the causative factors for landslides in Bangladesh are rainfall and earthquake.

Rainfall

Rainfall data is available from 35 stations in Bangladesh, ranging from years 1948 to 2013. Using the available rainfall data, the average monthly rainfall of June, July, August, September, October and annual rainfall is derived and shown in Table 3.17.

Table 3.17: Long-term monthly average rainfall (mm) in landslide prone areas of Bangladesh

Station	Monthly and Annual Rainfall (mm)					
	Jun	Jul	Aug	Sep	Oct	Annual
Sylhet	769	789	600	525	211	4077
Chittagong	646	673	472	294	263	2920
Rangamati	482	560	438	293	167	2565
Cox's Bazar	805	869	643	379	199	3471
Teknaf	942	1058	895	433	241	4025

Source: BMD, 2013

The range of annual rainfall is 1488 to 4077 mm among all the 35 stations. A rainfall map representing the annual rainfall prepared in GIS and is interpolated using inverse distance weighted (IDW) interpolation method to make a spatial map. A more popular method of krigging could not be used due to sparse distance between the metrological stations to develop spatial rainfall map at a resolution of 30 m, which is shown in Figure 3.31.

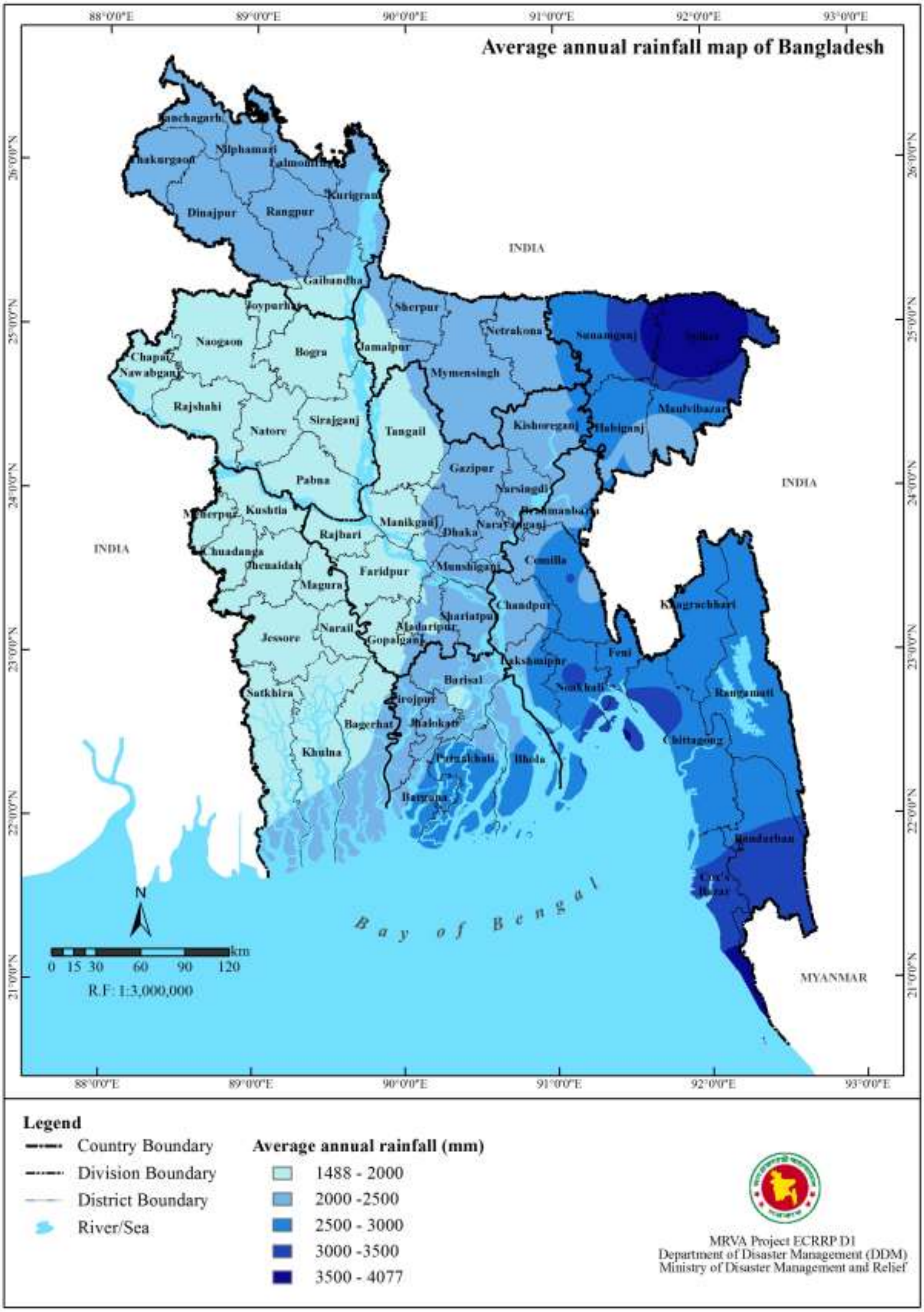


Figure 3.31: Average annual rainfall map of Bangladesh

Source: BMD, 2013

Earthquake

There is no historical evidence of earthquakes causing landslides in Bangladesh, since earthquakes have occurred in neighboring countries such as India and Myanmar. There is a long history of earthquakes, though severe earthquakes are very few. Detailed earthquake hazard maps were developed (see Volume II of this report for more details), using the historical data and existing geological setting for 50-, 100-, 200-, 500- and 1000-year return periods, which represent variation of Peak Ground acceleration (PGA map) in Bangladesh. Among these PGA maps, the 50-year return period map as used as a causative factor for landslide susceptibility assessment, shown in Figure 3.33. The range of PGA is 0.01 to 0.35 m/sec^2.

Figure 3.32: PGA map for 50-year return period

Source: CDMP-II, MoDMR, 2014

3.4.2 Methodology

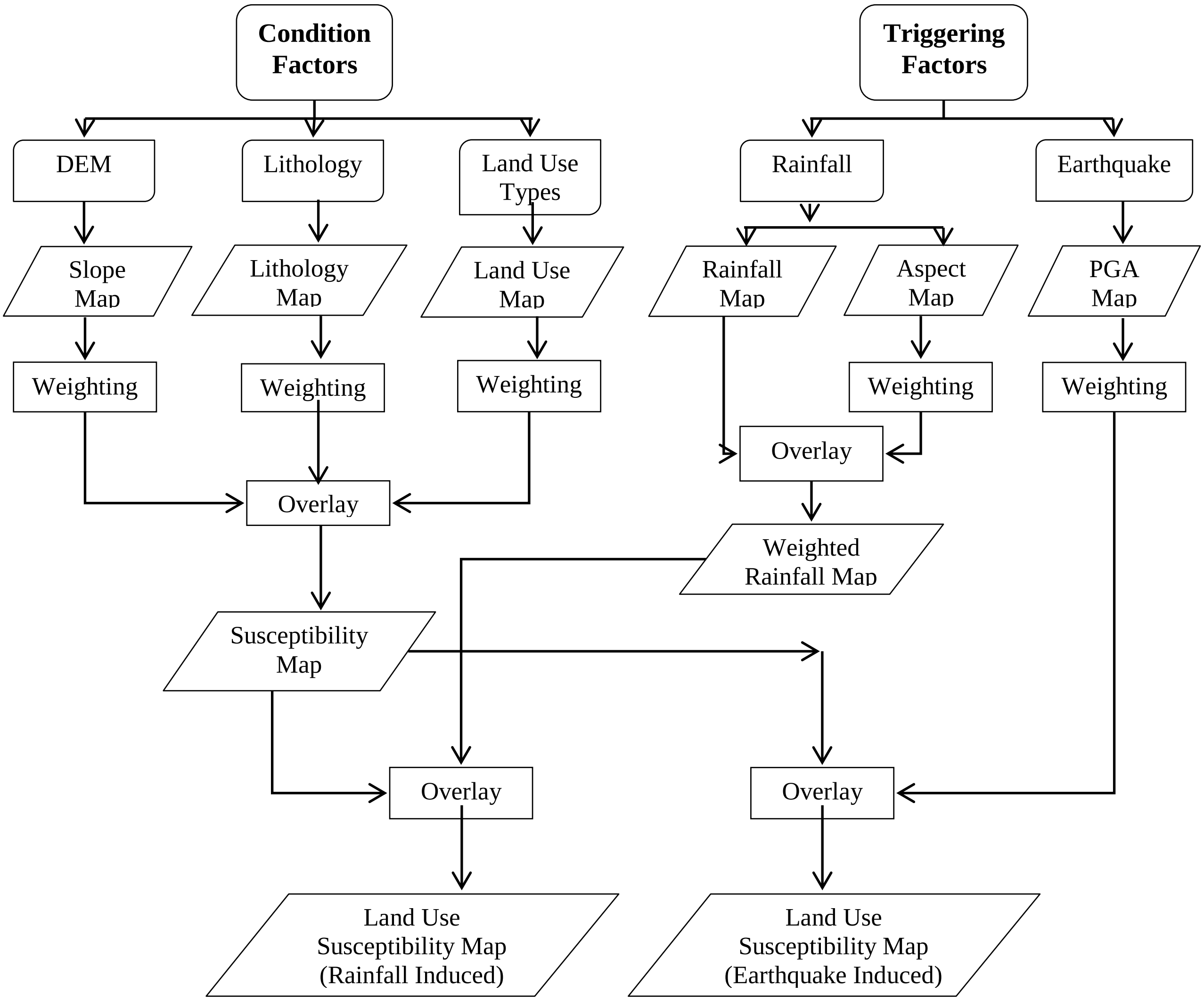
The main conditional factors that were considered for susceptibility mapping were:

- Lithology
- Land use and land cover
- Slope
- Aspect (for rainfall only)

The two causative factors that were considered were:

- Rainfall
- Earthquake (Peak Ground Acceleration)

The methodology adopted in this study is shown in Figure 3.33.



Source: Expert Group Consultation

Figure 3.33: Landslide Hazard Methodology

Weighing of Conditional and Causative Factors

As explained earlier, this set of conditional and causative factors were ranked according to the degrees of actual or potential hazard due to landslides.

Conditional Factors

Lithology: The geological formations that induce landslides are Dihing, DupiTila, Tipam, BokaBil, Bhuban formations and Girujan Clay. Based on the expert judgment these formations are given weights, which are given in Table 3.18.

Table 3.18: Geological units that can induce landslides and their weights

Geologic Time	Group	Formation	Weight (scale of 1 to 10)
Pleistocene		Dihing Formation	9
Plio-Pleistocene		Dupitila Formation	9
Pliocene	Tipam group	Girujan Clay	7
		Tipam Formation	9
Miocene	Surma group	BokaBil Formation	8
		Bhuban Formation	6
Plio-Pleistocene		Dupitila Formation	9

Note: Most of the landslides occur within the hilly region. The exposed rocks along the road section, faults and joint on the slope in these hills are most susceptible to landslides. Considering the geological units, Dihing, Girujan Clay, Dupitila, Tipam, Bhuban and Bokabil formations are mostly landslide prone in Bangladesh.

Source: Expert Group Consultation

Land Use and Land Cover: Land use and land cover plays an important role in reducing or causing landslides triggered by rainfall, especially land use and land cover existing in the hill track region in Bangladesh, which is severely landslide prone. They are given weights based on expert judgment. In addition to this, beaches in high slopes near Cox's Bazar and Teknaf are also prone to landslide susceptibility, hence weight was assigned. Table 3.19 indicates the land and land cover and weights assigned in a scale of 1 to 10.

Table 3.19: Land use and land cover units that can induce landslides and their weights

Land Use and Land Cover Type			Weight (in Scale 1 to 10)
Sl .No.	**Level - I**	**Level - II**	
1	Agriculture	Tea	3
2	Forest	Mixed Thickets & Forest	3
3	Water	Beach	3
4	Settlement	Urban - Hilly	8

Source: Expert Group Consultation

Slope: As explained earlier, the slope ranges that were used in this study are assigned weights based on past studies carried out in this region and also expert judgment. The weights assigned are given in Table 3.20. The slope angle in the range of 30 to 45 degrees is most susceptible to landslides.

Table 3.20: Slope classes and the weights

Sl. No.	Slope Class (degrees)	Weight (scale of 1 to 10)
1	0 - 5	1
2	5 – 10	2
3	10 – 15	3
4	15 – 20	4
5	20 - 30	8
6	30 - 45	9
7	45 - 60	7
8	60 - 90	6

Source: Expert Group Consultation

All the conditional factor maps are combined in GIS to derive a landslide susceptibility map. The landslide susceptibility map is shown in Figure 3.34. This map is used with causative factors of rainfall and earthquake, to derive a landslide hazard map.

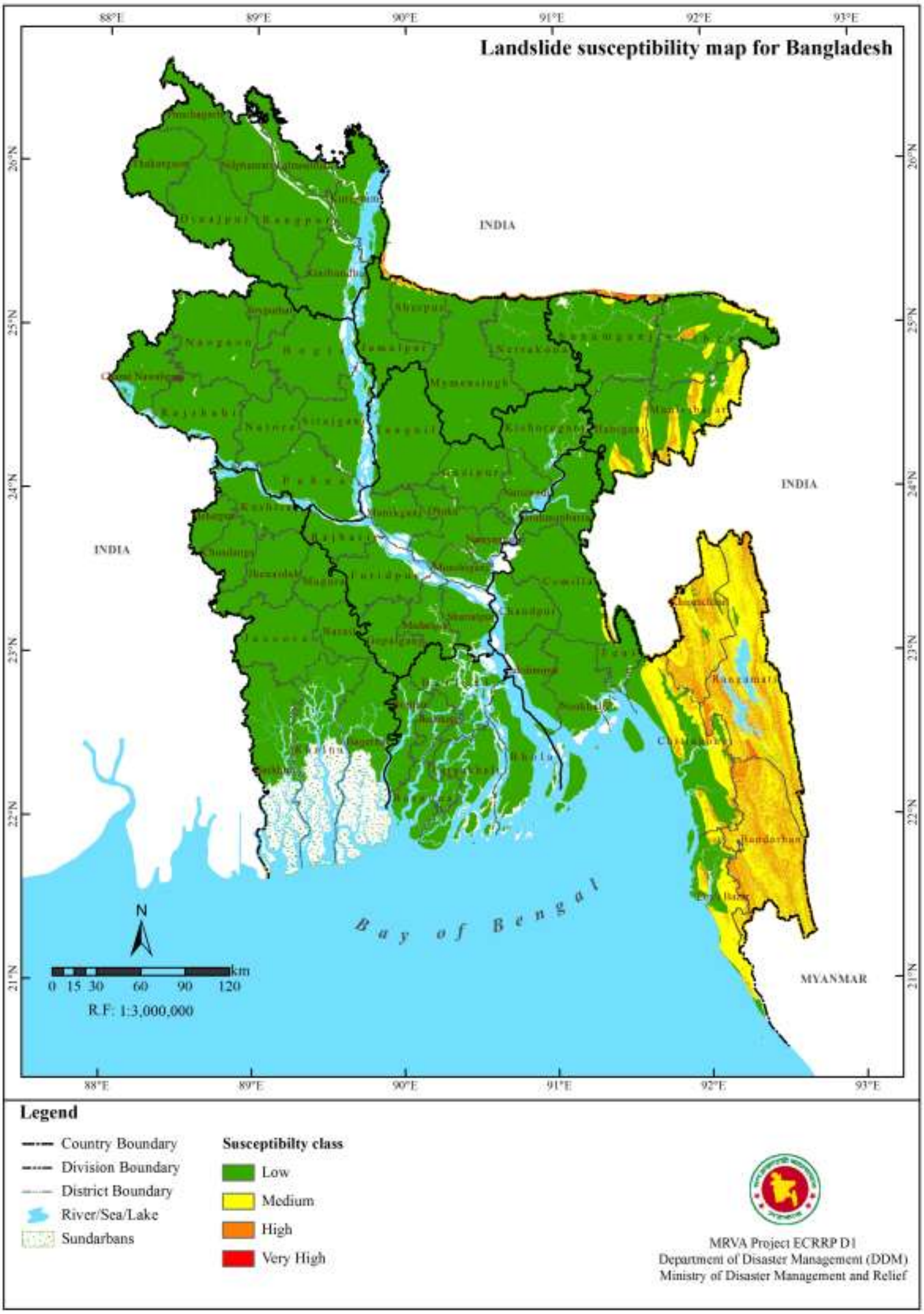


Figure 3.34: Landslide susceptibility map of Bangladesh

Aspect: As explained earlier, an aspect map was considered for calculating weighted rainfall based on aspect in the Hill track and Sylhet region. The weights for the aspect are given in Table 3.21. The aspect class North-North East and South-South East will influence the rainfall most in this region.

Table 3.21: Aspect class and the weights

Sl. No.	Aspect Class (degree range)	Weight (scale of 1 to 10)
1	NNW (360 - 315)	7
2	NWW (315 - 270)	8
3	SWW (270 - 225)	8
4	SSW (225 - 180)	9
5	SSE (180 - 135)	7
6	SEE (135 - 90)	8
7	NEE (90 - 45)	8
8	NNE (45 - 0)	9

Source: Expert Group Consultation

Causative Factors

Rainfall (based on aspect)

The average annual rainfall map (Figure 3.32), aspect map (Figure 3.31) and aspect weight table (Table 3.21) ere combined to derive aspect weighted average annual rainfall map. The range of aspect weighted average annual rainfall is given weights based on the most influencing amount rainfall which can cause landslides is given in Table 3.22. Using Table 3.22, an aspect weighted average annual rainfall map was generated and is shown in Figure 3.35.

Table 3.22: Weighted rainfall range and weights used in this study

Sl. No.	Average Annual rainfall (mm) range	Weight (scale of 1 to 10)
1	1041 - 1500	4
2	1500 - 2000	5
3	2000 - 2500	6
4	2500 - 3000	7
5	3000 - 3500	8
6	3500 - 3670	9

Source: Expert Group Consultation

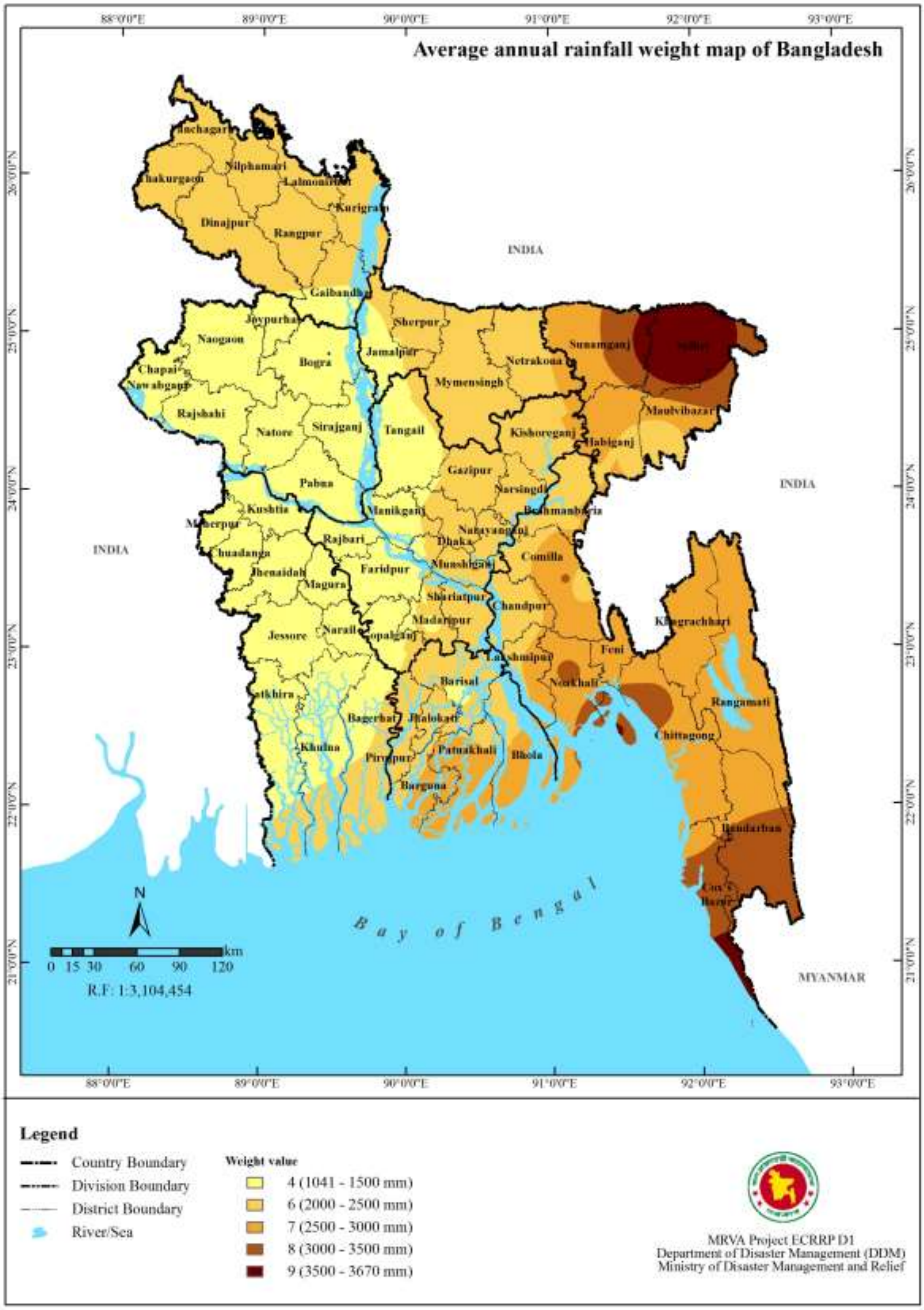


Figure 3.35: Average annual rainfall weight map of Bangladesh

Earthquake: The Peak Ground Acceleration (PGA) range has been classified into six classes based on a range of 0.05 and the weights are assigned according to the influence of earthquake intensity to cause landslides. The higher the PGA is, the higher the weight. Weights used for range of PGA are given in Table 3.23.

Table 3.23: PGA weight table

PGA range (m/s^2)	**Weight**
0.01 - 0.05	2
0.05 - 0.10	4
0.10 - 0.15	5
0.15 - 0.20	7
0.20 - 0.25	8
0.25 - 0.3	9

Source: Expert Group Consultation

The weight map of earthquake intensity is shown in Figure 3.36.

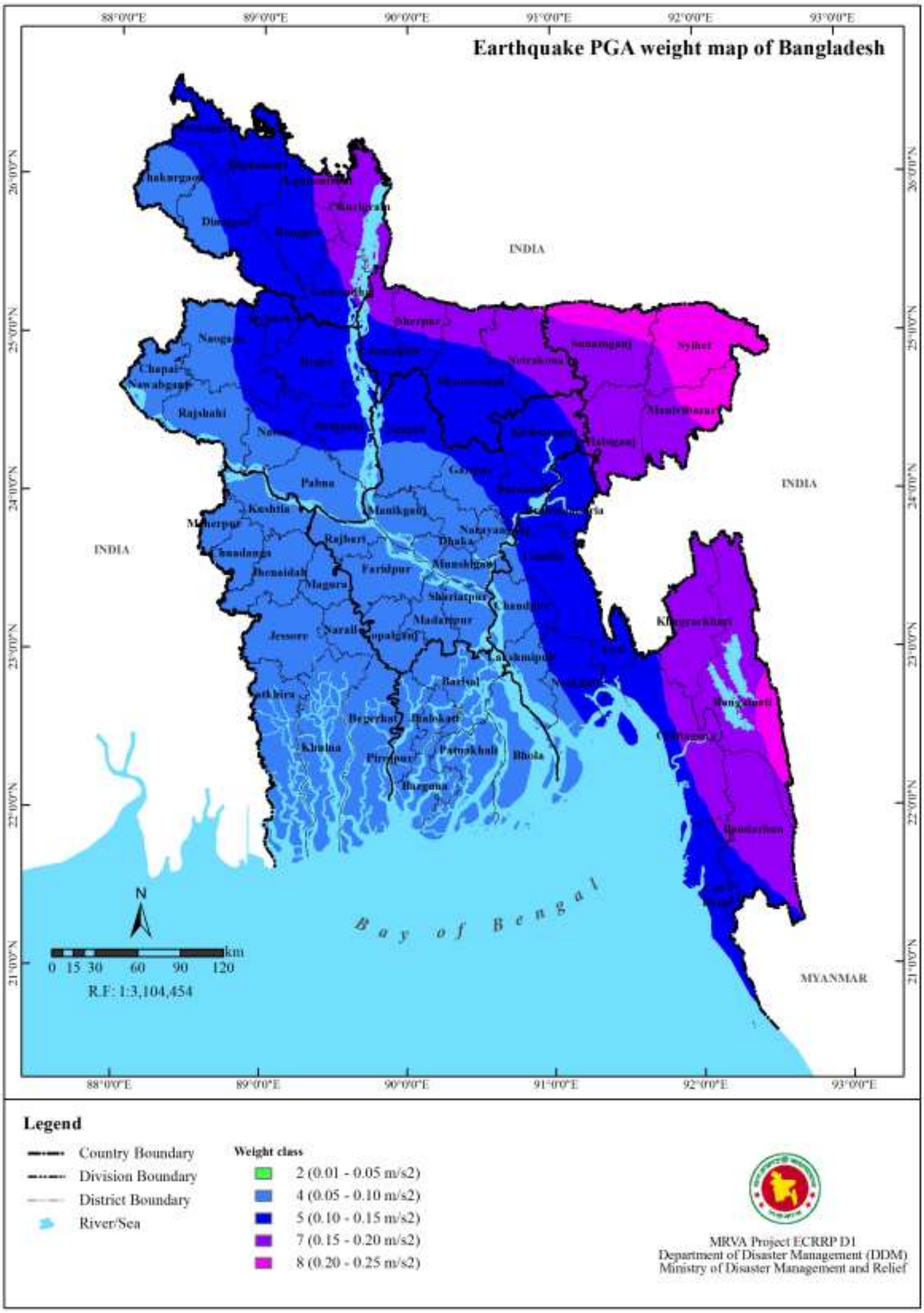


Figure 3.36: Earthquake PGA weight map of Bangladesh

3.4.3 Analysis of Hazard Assessment

The landslide susceptibility maps developed in this study were rainfall and earthquake triggered. The analysis of these maps is presented in this section.

Rainfall Induced Landslide Susceptibility

The weighted rainfall map was combined with the susceptibility map (Figure 3.34) to generate a landslide susceptibility map due to rainfall, which is classified into low, moderate, high and very high categories. The distribution (area and percentage) of rainfall induced landslide susceptibility categories in Bangladesh is given in Table 3.24.

Table 3.24: Area and percentage of rainfall induced landslide susceptibility categories

Rainfall induced landslide category	Area (km^2)	Percentage
Low	121729.8	83.8
Moderate	11652.1	8.0
High	10902.2	7.5
Very High	1051.2	0.7
Total	145335.3	100.0

The distribution of percentage of rainfall induced landslide prone area within the districts is given in Table 3.25.

Table 3.25: Percentage of rainfall induced landslide susceptibility categories in the districts

District	Percentage of Rainfall induced Landslide susceptibility category			
	Low	Moderate	High	Very High
Sylhet	43.09	45.80	8.64	2.46
Sunamganj	93.13	6.24	0.62	0.01
Maulvibazar	49.00	31.99	18.15	0.86
Habiganj	82.38	14.02	3.60	0.00
Bandarban	0.06	24.47	65.03	10.44
Chittagong	53.03	26.76	19.63	0.58
Comilla	97.65	1.97	0.39	0.00
Cox's Bazar	33.77	25.10	38.90	2.23
Khagrachhari	4.35	40.38	53.64	1.63
Rangamati	3.35	51.45	42.74	2.46
Jamalpur	99.19	0.78	0.03	0.00
Netrakona	99.05	0.74	0.21	0.01
Sherpur	93.01	6.86	0.13	0.00

Earthquake Induced Landslide Susceptibility

The weighted earthquake map is combined with the susceptibility map (Figure 3.35) to generate a landslide susceptibility map due to earthquake, which is classified into low, moderate, high and very high categories. The distribution (area and percentage) of earthquake induced landslide susceptibility categories in Bangladesh is given in Table 3.26 and Figure 3.37.

Table 3.26: Area and percentage of earthquake induced landslide susceptibility categories

Earthquake induced landslide category	Area (km^2)	Percentage
Low	119454.8	82.2
Moderate	9194.4	6.3
High	13746.1	9.5
Very High	2940.0	2.0
Total	145335.3	100

The distribution of percentage of earthquake induced landslide prone area within the districts is given in Table 3.27.

Table 3.27: Percentage of earthquake induced landslide susceptibility categories in the districts

District	Percentage of Earthquake induced Landslide susceptibility category			
	Low	**Moderate**	**High**	**Very High**
Sylhet	12.90	73.72	10.06	3.33
Maulvibazar	31.32	20.11	39.38	9.20
Sunamganj	67.73	30.80	1.39	0.08
Habiganj	81.00	1.38	17.47	0.15
Bandarban	2.48	21.10	58.83	17.59
Chittagong	57.20	20.19	22.09	0.53
Comilla	97.90	2.10	0.00	0.00
Cox's Bazar	55.74	42.78	1.45	0.02
Rangamati	0.47	13.90	67.49	18.14
Khagrachhari	1.16	8.48	84.81	5.55
Jamalpur	98.94	0.19	0.84	0.04
Netrakona	97.16	1.89	0.65	0.30

3.4.4 Map Content

Landslide susceptibility maps due to rainfall (Figure 3.37) and earthquake (Figure 3.44) shows spatial distribution of landslide susceptibility zones, which are low, moderate, high and very high. The district boundary of Bangladesh is added as overlay layers for more detailed spatial distribution. The symbology used in representing this in maps is given table 3.28.

Table 3.28: Landslide susceptibility categories and their representation in maps

Landslide susceptibility category	Symbology used in maps
Low	
Moderate	
High	
Very high	

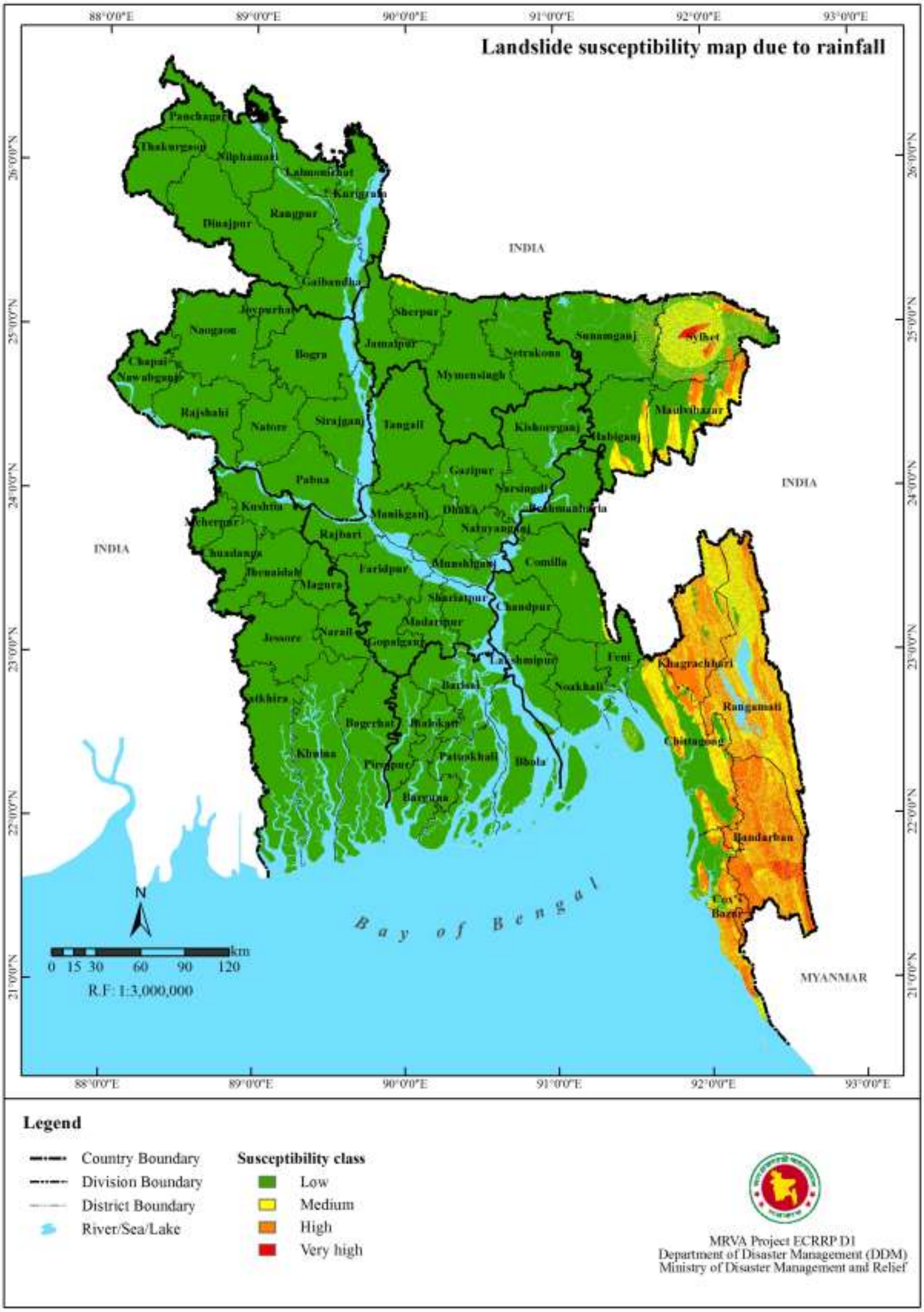


Figure 3.37: Landslide susceptibility map due to rainfall

Earthquake Induced

Earthquake induced landslide susceptibility map is shown in Figure 3.38.

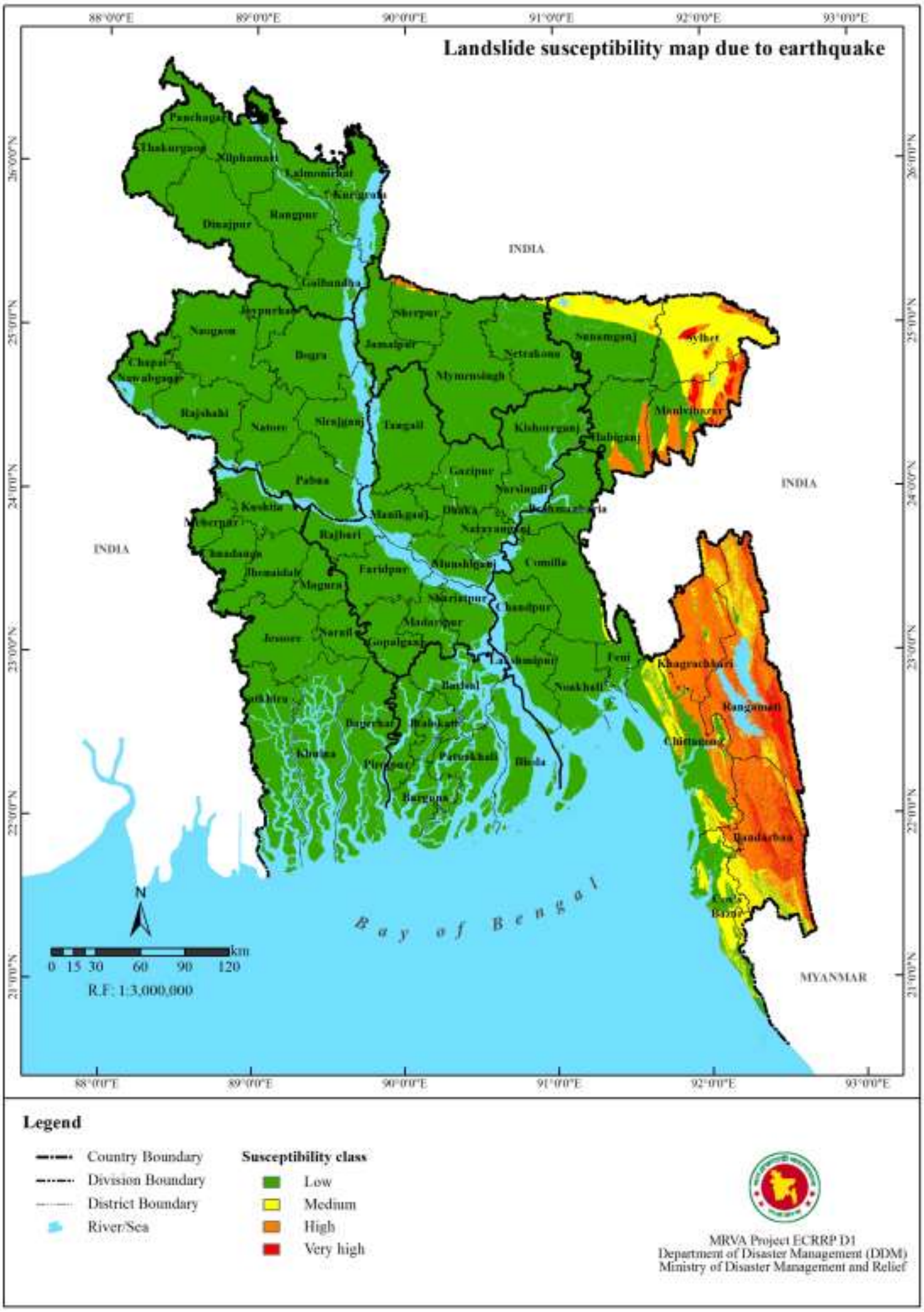


Figure 3.38: Landslide susceptibility map due to earthquake

3.4.5 Application of Maps

- The landslide susceptibility maps will help the planning and development agencies for physical and social development in landslide prone areas.
- The maps will be especially helpful to the Road Transport and Highway Division, Ministry of Road Transport and Bridges for planning and development of roads in landslide prone districts and regions.
- The study reveals that landslide occurrences in hill track region and Sylhet area during the monsoon season.

3.4.6 Special Remarks

- These landslide susceptibility maps can be used for development of landslide inventory, which does not exist at the national level. This will help in planning developmental works at the local level.

3.4.7 Recommendations

- Parameters (weights) related to factors affecting landslide susceptibility in Bangladesh are derived based on suggestions of landslide experts and also literature from neighboring India and Myanmar. Researchers from universities can verify these weights during landslide events in the future.
- Landslide inventory can be developed in high and very high susceptibility zones, which will help in detailed planning for urban/rural and transportation infrastructure.
- Since landslide occurrence is closely related with rainfall quantity in specific rainfall periods, the threshold of rainfall for rainfall-triggered landslides can be a vital help in disaster risk management.

3.5 Drought

Bangladesh is one of the most disaster-prone countries in the world. High spatial and temporal variability of climate, extreme weather events, high growth rate and population density, high incidence of poverty and social inequity, low literacy rate, poor institutional capacity, inadequate financial resources, and insufficient infrastructure have made Bangladesh highly vulnerable to disasters (Shahid, 2010). Drought is one of the most frequent natural disasters in Bangladesh. Since its independence in 1971, Bangladesh has suffered from nine droughts of major magnitude (Paul, 1998). Despite the recurrent and devastating nature of droughts in Bangladesh, it has attracted far less scientific attention than floods or cyclones (Alexander, 1995; Brammer, 1987). However, losses from drought are likely to be more severe than from floods in Bangladesh. An analysis of the relative effects of flood and drought on rice production between 1969–70 and 1983–84 indicates that drought is more devastating than floods to aggregate production (World Bank Bangladesh, 2000). The drought of 1994–95 led to a decrease in rice and wheat production of 3.5×10^6 ton (Rahman and Biswas, 1995). This necessitated the import of some 140,000 tons of food grain between July 1994 and March 1995. An additional 200,000 tons of rice was imported to offset the shortage in national stocks and meet the national demand on an emergency basis (Biswas, 1995).

Due to the land use changes within the country and in neighbouring countries, Bangladesh has already shown an increased frequency of droughts in recent years (National Drought Mitigation Center, 2006). It is anticipated that climate change due to global warming will further aggravate the situation in near future. Concern among scientists has grown on changes of precipitation and frequent occurrence of droughts in Bangladesh. Therefore, drought hazards, vulnerability and risk assessment is essential for implementing mitigation to reduce drought impacts in Bangladesh.

Forecasting of when a drought is likely to begin or to come to an end is extremely difficult or impossible (Cordery and McCall, 2000). Though important progress is being made in relation to the possibilities of using the El Nin˜o Southern Oscillation (ENSO) and the North Atlantic Oscillation (NAO) as forecasting tools (Vogt and Somma, 2000), but it is still very far from reality. Therefore, characterisation of droughts through drought indices is generally used to support drought monitoring and mitigation. Droughts can be defined and analyzed from either conceptual or operational points of view. Conceptual definitions help understand the meaning of drought and its effects. On the other hand, operational definitions help identify the drought's time span, frequency, and degree of severity. In a comprehensive study, droughts should be analyzed from both conceptual and operational points of view. There are various types of droughts, such as meteorological droughts, hydrological droughts, agricultural droughts, socio-economical droughts, etc. The present study concentrates only on meteorological droughts to analyze the drought hazard and risk in Bangladesh.

Numerous indices have been developed to identify the severity of drought conditions (Wilhite and Glantz, 1987). Standardized Precipitation Index (SPI) is one such method developed by Mckee et al. (1993), which quantifies the precipitation deficit for multiple time steps, and therefore facilitates the temporal analysis of droughts. It has been found that SPI is better able to show how drought in one region compares to drought in another region. It has also been reported that SPI provides a better spatial standardization than the other indices (Guttman, 1998; Lloyd-Hughes and Saunders, 2002). Therefore, SPI is used to study the spatial and temporal characteristics of meteorological droughts in Bangladesh.

Drought is a dynamic phenomenon that changes over time and space. Therefore, complete analysis of drought requires study of its spatial and temporal extents. GIS provides tools for spatial and temporal analysis of drought and has been used in this study to map drought hazards during different climatic and crop growing seasons in Bangladesh. In this study, the spatial and temporal characteristics of drought in Bangladesh were analyzed for meteorological drought. Therefore, the term *drought* in the analysis throughout the report refers to the *meteorological drought*.

Drought in Bangladesh:

Droughts are recurrent phenomena in Bangladesh. Bangladesh experienced droughts in the years of 1963, 1966, 1968, 1973, 1977, 1979, 1982, 1989, 1992 and 1994–1995, 1999, and 2006. The droughts in 1973 were in part responsible for the famine in northwest Bangladesh in 1974. The 1978-1979 drought was one of the most severe resulting in widespread damage to crops (rice production was reduced by about 2 million tons) and directly affected about 42 percent of the cultivated land. Rice production losses due to drought in 1982 were about 50 percent more than losses due to floods that same year. The drought of 1994–1995 led to a decrease in rice and wheat production of 3.5×10^6 ton. Losses in 1997 were about 1 million tons and valued at around USD 500 million.

Water requirement in Bangladesh has continued to increase in all sectors. Specially, water demand for irrigation has increased rapidly due to agricultural expansion and increased cropping intensity. The climate in Bangladesh has also changed significantly in recent years. The daily average temperature has increased in all parts of the country. This has caused an increase of water demand in different sectors throughout Bangladesh. Therefore, a small deficit of rainfall often causes severe water crisis in many parts of the country.

Previous Studies of Drought in Bangladesh:

A number of studies have been carried out on the impacts of droughts on agriculture (Karim et al., 1990; Jabber, 1990; Jabber et al., 1982; Saleh et al., 2000; Mazid et al., 2005), food production (Ahmed and Bernard, 1989; Ericksen et al., 1993), land degradation (Rasheed, 1998; Karim and Iqbal, 2001; Government of Bangladesh, 2005), economy (Erickson et al., 1993; World Bank, 2000) and society (Erickson et al., 1993; Paul, 1998) in Bangladesh. The first agricultural drought risk map of Bangladesh was prepared by Karim et al. (1990) by considering the cumulative effect of dry days, higher temperatures during pre-monsoon period and soil moisture availability. WARPO-EGIC (1996) prepared maps of winter and pre-monsoon drought prone areas of Bangladesh using the agroecological zones database and land resources inventory map at 1:1,000,000 scale. Karim and Iqbal (2001) reviewed the concept of WARPO-EGIC (1996) and produced three different drought risk maps for winter, pre-monsoon and monsoon seasons. They defined drought risk classes as slight, moderate, severe and very severe related to the yield losses of 15-20 percent, 20-35 percent, 35-45 percent, and 45-70 percent respectively for different crops. Shahid (2008) analyzed the spatial and temporal characteristics of droughts in the western part of Bangladesh. He used standardized precipitation index to compute the severity of droughts from rainfall data recorded at 12 rainfall gauges for the period of 1961–1999. The obtained results showed that the northwestern and central western parts of Bangladesh are most vulnerable to droughts. Critical analysis of rainfall carried out by Shahid (2008) showed that a minimum of 182 mm pre-monsoon rainfall is required for non-drought conditions in most vulnerable areas. Shahid and Behrawan (2008) used a conceptual framework for mapping geographic distribution of human vulnerability to droughts in Bangladesh. They emphasized the combined role of hazard and vulnerability in defining drought risk. Standardized precipitation index method in a GIS environment was used to map the spatial extents of drought hazards in different time steps. The key social and physical factors that define drought vulnerability in the context of Bangladesh were identified to prepare composite drought vulnerability map. They computed risk as the product of the hazard and vulnerability, and reported that droughts pose highest risk to the northern and northwestern districts of Bangladesh. Shahid and Hazarika (2010) conducted a study on groundwater drought in the northwestern districts of Bangladesh and reported that prolonged absence of groundwater within the operating range of shallow tube-wells during dry season is a common problem in the northwestern districts of Bangladesh. Dash et al. (2012) diagnosed meteorological drought events occur in Bangladesh by using monthly rainfall and mean air temperature from the surface observations and Regional Climate Model (RegCM) by calculating Standardized Precipitation Index (SPI) and Palmer Drought Severity Index (PDSI) for the period of 1961-1990. They reported that the frequency of moderate drought is higher for all over the country. Habiba et al. (2011) measured the existing level of drought resilience with indicators related to Socio-economic, Institutional and Physical (SIP) conditions in two of the most drought-prone districts, namely Rajshahi and Chapai-Nawabganj. They indicated that some of the critical areas that need improvement include education and awareness, conflict resolution on water usage, policy enhancement, coordination among different stakeholders and proper land-use pattern. Habiba et al. (2011) assessed farmer's perception and awareness, impacts and adaptation measures of farmers towards drought. The results revealed that farmers in both areas perceived a changed climate in recent years. They not only identified that drought is the most prevalent disaster in the study area because of rainfall and temperature variation, but also groundwater depletion, lack of canal and river dragging, increased population, deforestation, etc. accelerate drought in this area. As a consequence of drought, agriculture as well as farmers' social life and health are threatened the most. Habiba and Shaw (2013) assessed drought resilience through the SIP approach at the institutional level and also measured drought resilience at farmer's level. This study also tries to develop drought adaptation action policies for increasing farmers' resilience towards drought. At individual and family level, results reveal that crop diversification, mango cultivation and extension worker's role could significantly increase farmers' resilience.

Climate of Bangladesh:

Geographically, Bangladesh extends from 20°34'N to 26°38'N latitude and from 88°01'E to 92°41'E longitude. Climatically, the country belongs to the tropical region where monsoon weather prevails throughout the year in most part of the country. Four distinct seasons can be recognized in Bangladesh from a climatic point of view: (i) the dry winter season from November to February, (ii) the pre-monsoon hot summer season from March to May, (iii) the rainy monsoon season from June to October, and (iv) the post-monsoon season from October to November (Rashid, 1991).

Precipitation climatology over Bangladesh or the mean of annual precipitation for the period 1958–2009 is shown in Figure 3.31 (page 72). Rainfall in Bangladesh varies from 1598 mm in the west to 4197 mm in the east. The gradient of rainfall from west to east is approximately 7 mm km^{-1}. The monthly distribution of rainfall over the country is shown by a graph in Figure 3.39. The left vertical axis of the graph represents rainfall in mm and the right vertical axis represents the rainfall as a percentage of annual total rainfall. The graph shows that the rainfall is highly seasonal in Bangladesh; more than 78 percent of rainfall occurs during monsoon. Spatial distribution of monsoon rainfall over Bangladesh is shown in Figure 3.40.

The main mechanism of the rainfall in Bangladesh during the summer monsoon season is caused by tropical depressions known as monsoon depression in the Bay of Bengal (Ahmed and Kim, 2003). The monsoon depressions move from the Bay of Bengal toward the monsoon trough, and produce enormous amounts of rainfall. Therefore, most of the rainfall in Bangladesh occurs in monsoon. The monsoon depressions enter Bangladesh from the Bay of Bengal with south-to-north trajectory and then turn toward the northwest and west being deflected by the Meghalaya Plateau. As these depressions move farther and farther inland, their moisture content decreases, resulting in decreasing rainfall toward the northwest and west of Bangladesh (Ahmed and Kim, 2003). On the other hand, the additional uplifting effect of the Meghalaya plateau increased the rainfall in northeast of Bangladesh.

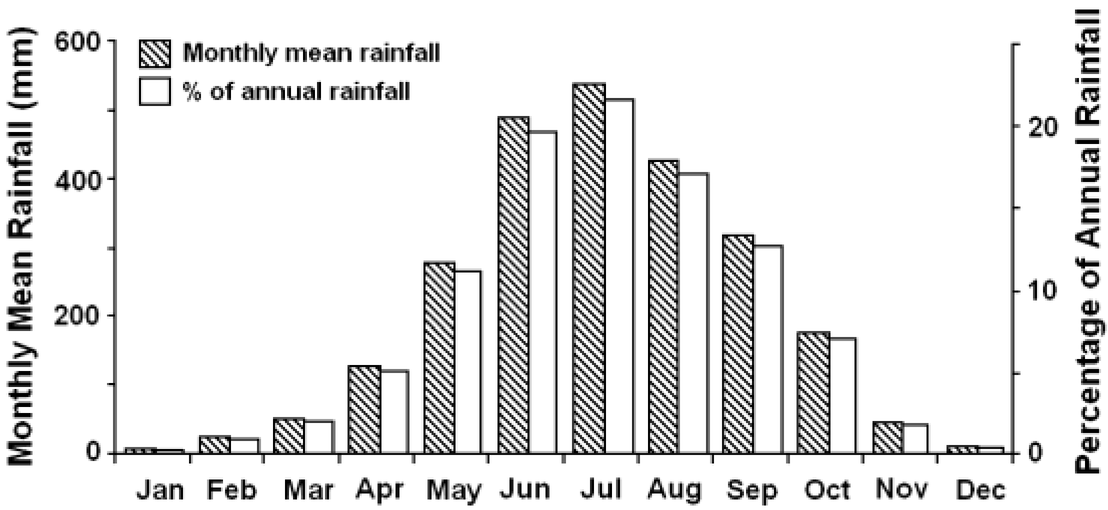


Figure 3.39: Monthly distribution of rainfall in Bangladesh

The average temperature of the country ranges from 17°C to 20.6°C during winter and 26.9°C to 31.1°C during summer. In summer, some hottest days experience the temperature of about 45°C or even more in the Northwest region. Again in the winter the temperature even falls at 7°C in some places. So the Northwest region experiences the two extremities that are in clear contrast with the climatic conditions of the rest of the country. The average relative humidity for the whole year ranges from 78.1 percent to 70.5 percent, with a maximum in September and a minimum in March.

A dryness study of Bangladesh was carried out by Shahid et al. (2008) by using De Martonne aridity index and Thornthwaite precipitation effectiveness index methods. Twenty years of climatic data (1980-1999) available in 50 meteorological stations situated in and around Bangladesh were used for the study. Both De Martonne aridity index map and Thornthwaite precipitation effectiveness index map revealed that the western side of Bangladesh belongs to sub-humid, the central part belongs to humid and a small part is northeastern side belongs to wet class. Least index values obtained by De Martonne and Thornthwaite method were 20.89 and 64.04 respectively in the central-western and northwestern side of Bangladesh. As the dryness index values in the region is close to that of dry zone, the climate of these regions of Bangladesh can be classified said as very close to dry. The total annual evapotranspiration in some areas of the western part of Bangladesh is also lower than or equal to the annual rainfall.

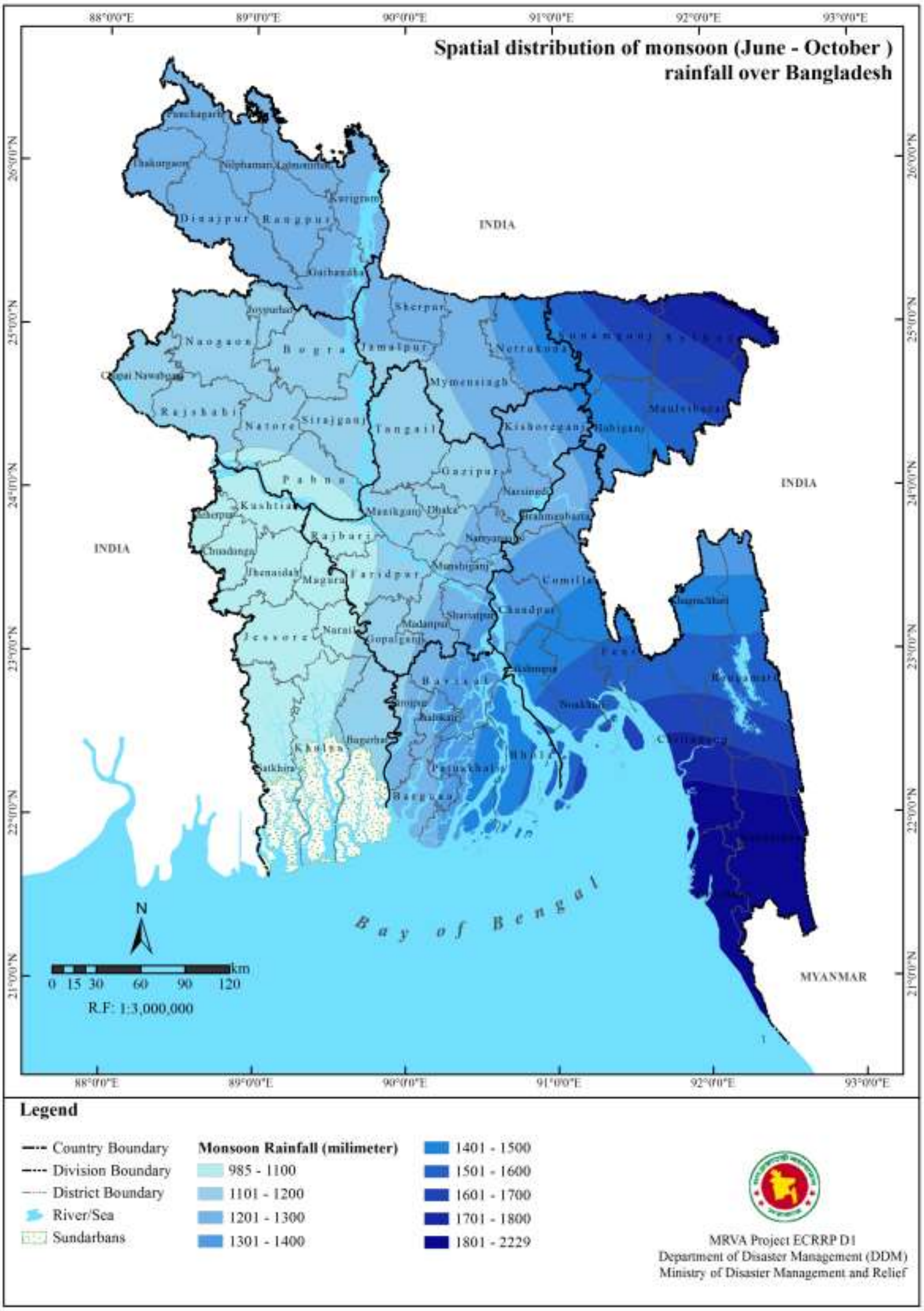


Figure 3.40: Spatial distribution of monsoon (June to October) rainfall over Bangladesh

Source: BMD, 2013

Cropping Seasons of Bangladesh:

The crop-growing period in Bangladesh is divided into two main seasons, Kharif and Rabi. The Kharif season extends from May through October, while the Rabi season starts from November and continues up to April. In addition to these two main seasons, another transition season called Pre-Kharif has been identified. This season starts from March and ends in May. The major characteristics of the cropping seasons of Bangladesh are described below:

Pre-Kharif Season is characterized by unreliable rainfall and varies in timing, frequency and intensity from year to year, and provides only an intermittent supply of moisture for crops. During this transition period, soils intermittently become moist and dry. Common crops of Pre-Kharif season are jute, broadcast aman, aus, groundnut, amaranths, teasle gourd, etc.

Kharif Season starts from May when the moisture supply from rainfall plus soil storage is enough to support rainfed or un-irrigated Kharif crops. The crops most extensively cultivated during the Kharif season are jute, aus, broadcast aman, transplant aman, sesame, different kinds of summer vegetables, ginger, turmeric, pepper, green chilli, different kinds of aroids, cotton, mungbean, black gram, etc. Most Kharif crops are subject to drought and flood in areas without water control.

Rabi Season starts at the end of the humid period and lasts to the pre-Kharif season. Most common Rabi or winter crops are wheat, maize, mustard, groundnut, sesame, tobacco, potato, sweet potato, sugarcane, lentil, chickpea, grass pea etc. The crop calendar of Bangladesh is shown in Figure 3.41.

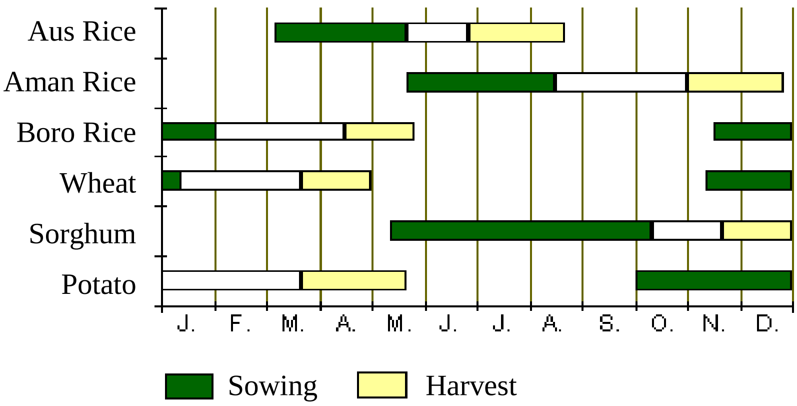


Figure 3.41: Crop calendar of Bangladesh

Source: FAO, 1999.

Objectives:

The major objective is to conduct a comprehensive study to understand the spatial and temporal characteristics of drought of Bangladesh to support mitigation of drought impacts. The specific objectives are:

1. To understand the spatial characteristics of droughts in different cropping seasons such as Kharif, pre-Kharif and Rabi seasons;
2. To study the return periods of droughts with various severity during different cropping seasons;
3. To understand the spatial characteristics of droughts in different climatic seasons such as monsoon, pre-monsoon and winter seasons;
4. To study the return periods of droughts with various severity during different climatic seasons;
5. To identify the drought prone areas of Bangladesh;
6. To combine elements at risk data, to assess the exposure and risk.

3.5.1 Data used

There are thirty-five (35) rainfall-recording stations in Bangladesh operated by the Bangladesh Meteorological Department. The list of stations with available data periods are given in Table 3.29. Among 35 stations, 30 stations were installed before 1980 and have rainfall records of more than 30 years. Stations Ambagan (Chittagong), Mongla, Chuadanga, Syadpur and Tangail were installed after 1980 and have rainfall records of less than 30 years. At least 30 years rainfall data is required for the reliable calculation of SPI index. Therefore, rainfall records from those five stations are not included in the present study. Kutubdia station was installed in 1977, but it was non-operational during 1981-1984. This has made the data length of the station less than thirty years. Therefore, rainfall records from this station were also discarded for this study. Rainfall data from the remaining 29 stations was used in the present study. Location of rainfall stations used in the present study is shown in Figure 3.42.

Data quality control is a necessary step before the calculation of drought index because erroneous outliers can seriously impact the index calculation (You et al., 2008). A number of checks are carried out for quality controls of data such as precipitation values below 0 mm, winter rainfall higher than 100 mm, etc. In some cases data were validated by the rainfall records of nearby stations. Histograms of the data are also created which reveal problems that show up when looking at the data set as a whole (Aguilar et al., 2005).

Several strategies have been described in the literature to detect non-homogeneities in the data series (Peterson et al., 1998). In this study, both the subjective double mass curve method and the objective student T test were applied to the annual precipitation time series data of 35 stations for the period shown in Table 3.29. The double mass curve (Kohler, 1949) is a plot of the deviation from a station's accumulated values versus the average accumulation of the base group. Non-linearity or bends plots can be an indicator of changed conditions (Su et al., 2006). Results of the double mass curves of all stations are almost a straight line as displayed an example in Figure 3.43 for Dhaka station. No breakpoints are detected in the time series of precipitation.

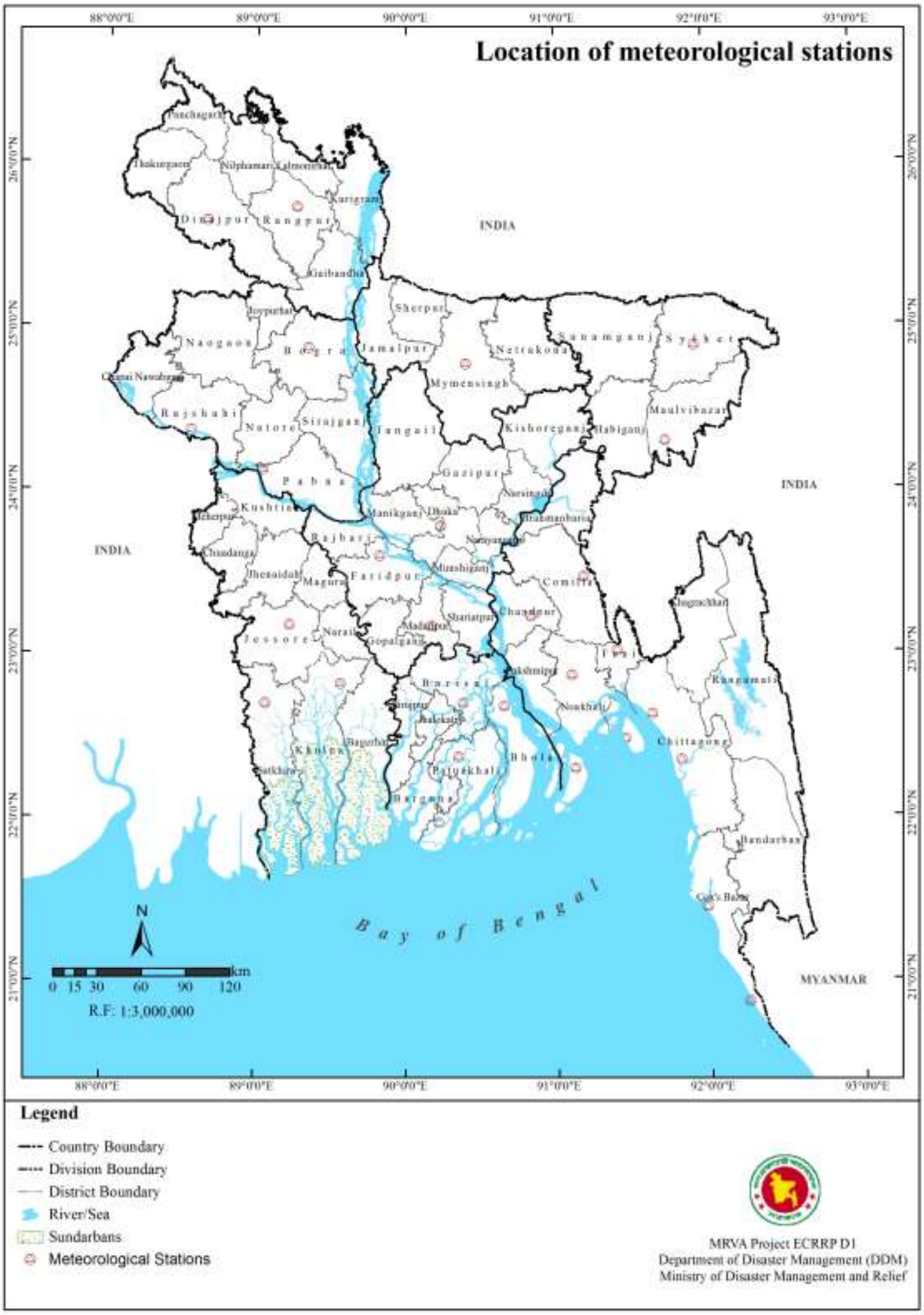


Figure 3.42: Location of meteorological stations in Bangladesh used in the present study
Source: BMD, 2013

Table 3.29: List of rainfall recording stations in Bangladesh

Sl. No.	Station Name	Latitude	Longitude	Period
1	Ambagan (Cht)	22°21´ N	91°49´ E	1999-2013
2	Barisal	22°43´ N	90°22´ E	1949-2013
3	Bhola	22°41´ N	90°39´ E	1966-2013
4	Bogra	24°51´ N	89°22´ E	1948-2013
5	Chadpur	23°14´ N	90°42´ E	1964-2013
6	Chittagong	22°13´ N	91°48´ E	1949-2013
7	Chuadanga	23°39´ N	88°49´ E	1984-2013
8	Comilla	23°26´ N	91°11´ E	1948-2013
9	Cox's Bazar	21°27´ N	91°58´ E	1948-2013
10	Dhaka	23°47´ N	90°23´ E	1953-2013
11	Dinajpur	25°39´ N	88°41´ E	1948-2013
12	Faridpur	23°36´ N	89°51´ E	1948-2013
13	Feni	23°02´ N	91°25´ E	1973-2013
14	Hatia	22°27´ N	91°06´ E	1966-2013
15	Ishurdi	24°09´ N	89°02´ E	1961-2013
16	Jessore	23°12´ N	89°20´ E	1948-2013
17	Khepupara	21°59´ N	90°14´ E	1974-2013
18	Khulna	22°47´ N	89°32´ E	1948-2013
19	Kutubdia	21°49´ N	91°51´ E	1977-2013
20	M. Court	22°52´ N	91°06´ E	1951-2013
21	Madaripur	23°10´ N	90°11´ E	1977-2013
22	Mongla	22°28´ N	89°36´ E	1991-2013
23	Mymensingh	24°44´ N	90°25´ E	1948-2013
24	Patuakhili	22°20´ N	90°20´ E	1973-2013
25	Rajshahi	24°22´ N	88°42´ E	1964-2013
26	Rangamati	22°38´ N	92°09´ E	1957-2013
27	Rangpur	25°44´ N	89°16´ E	1954-2013
28	Sandwip	22°29´ N	91°26´ E	1966-2013
29	Shatkhira	22°43´ N	89°05´ E	1948-2013
30	Sitakunda	21°49´ N	91°51´ E	1977-2013
31	Srimongal	24°18´ N	91°44´ E	1948-2013
32	Syadpur	25°45´ N	88°55´ E	1991-2013
33	Sylhet	24°54´ N	91°53´ E	1956-2013
34	Tangail	24°15´ N	89°56´ E	1987-2013
35	Teknaf	20°52´ N	92°18´ E	1977-2013

Source: Bangladesh Meteorological Department (BMD), 2013

The Student's T test was also used to assess homogeneity by determining whether or not various samples were derived from the same population (Panofsky and Brier, 1968). In a homogeneous series, variations are caused only by the variation in weather and climate (Conrad and Pollak, 1950). Thus, modified series obtained through the subtraction of the reference series from the original series of each station should be more capable of detecting any inhomogeneity resulting from non-climatic factors (Su et al., 2006). After filtering out the possible climatic abruption, the T test was applied on each station. The results reveal a wide range of the 95 percent confidence interval of the difference including zero. Therefore, it is clear that there is no statistically significant variation or break point existing in the rainfall time series.

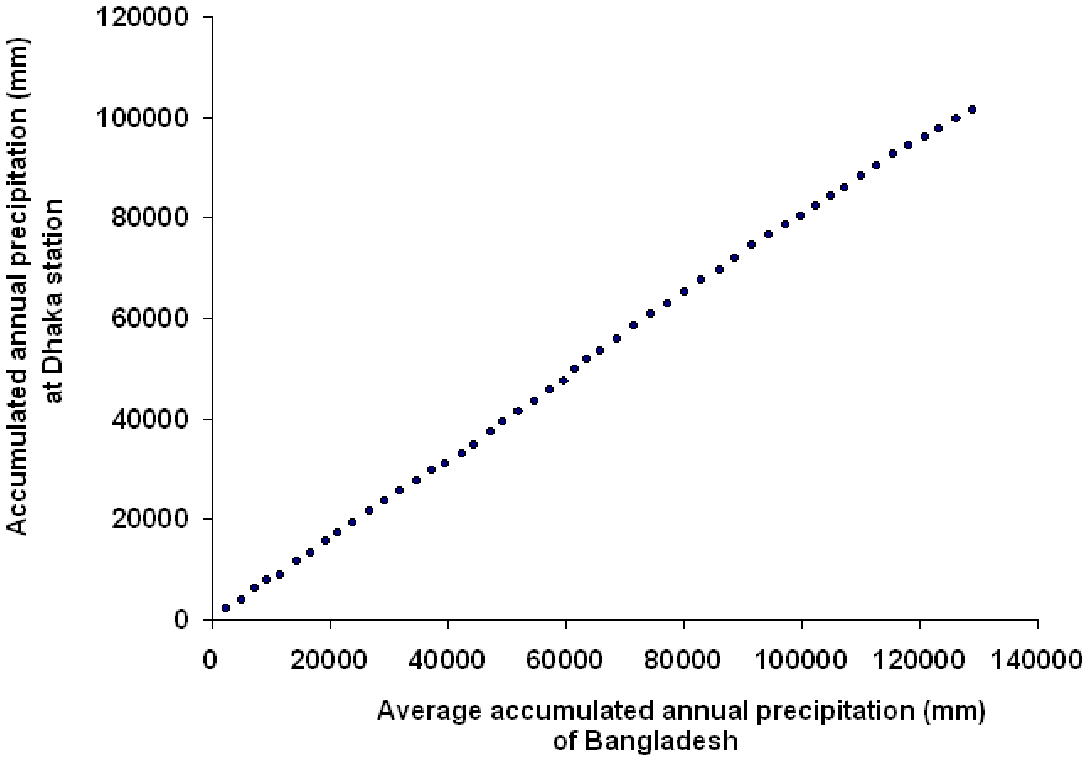


Figure 3.43: The double-mass curve of the rainfall series of Dhaka station

3.5.2 Methodology

As droughts cannot be forecasted, characterisations of droughts through drought indices are generally used for drought monitoring and mitigation or reduction of drought impacts. Common indicators of drought include meteorological variables such as precipitation and evaporation, as well as hydrological variables such as stream flow, ground water levels, reservoir and lake levels, snow pack, soil moisture, etc. Based on these indicators, numerous indices have been developed to characterize droughts (Dracup et al., 1980; Wilhite and Glantz, 1985; Wilhite and Glantz, 1987). However, most of the meteorological drought indices are based mainly on precipitation data, for example the percentage of normal method (Banerji and Chabra, 1964), precipitation deciles method (Gibbs and Maher, 1967), Bhalme-Mooley drought index method (Bhalme and Mooley, 1980), standardized precipitation index method (McKee et al., 1993), effective drought index (Byun and Wilhite, 1999), etc. Among these methods, the standardized precipitation index (SPI) quantifies the precipitation deficit for multiple time steps, and therefore facilitates the temporal analysis of droughts. It has been found that SPI is better able to show how drought in one region compares to drought in another region (Guttman, 1998). It has also been reported that SPI provides a better spatial standardization than the other indices (Lloyd-Hughes and Saunders, 2002). Therefore, SPI is used in this report to study the spatial and temporal characteristics of meteorological drought of Bangladesh.

Standardized Precipitation Index

Standardized precipitation index (Mckee et al., 1993) is a widely used drought index based on the probability of precipitation for multiple time scales, for instance one, three, six, nine, or twelve months. SPI can be calculated by simply taking the difference of the precipitation (x_i) from the mean ($\bar{x}_i$) for a particular time step, and then dividing it by the standard deviation (σ),

$$SPI = \frac{(x - \bar{x})}{\sigma} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots.. \quad (3)$$

Computation of SPI becomes complicated when the SPI is normalized to reflect the variable behavior of precipitation for time steps shorter than 12 months. To overcome this problem, historic rainfall data are usually fitted to a gamma distribution. This is done through a process of maximum likelihood estimation of the gamma distribution parameters, α and β. This allows the rainfall distribution at the station to be effectively represented by a mathematical cumulative probability function (McKee et al., 1993). Based on the historic rainfall data, the probability of the rainfall being less than or equal to a certain amount is then identified. If a particular rainfall event gives a low probability on the cumulative probability function, it indicates a likely drought event. Details of SPI computation are given below.

To compute SPI, historic rainfall data of each station are fitted to a gamma probability distribution function:

$$g(x) = \frac{1}{\beta^{\alpha}\Gamma(\alpha)} \chi^{\alpha-1} e^{-x/\beta} \qquad for \quad x > 0 \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (4)$$

Where $x > 0$ it is the amount of precipitation, $\alpha > 0$ is a shape parameter, $\beta > 0$ is a scale parameter, and $\Gamma(\alpha)$ defines the gamma function.

The maximum likelihood solutions are used to optimally estimate the gamma distribution parameters, α and β for each station and for each time steps:

$$\alpha = \frac{1}{4A}\left(1 + \sqrt{1 + \frac{4A}{3}}\right) \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (5)$$

$$\beta = \frac{\bar{x}}{\alpha} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots.. \quad (6)$$

Where, $A = \ln(\bar{x}) - \frac{\sum \ln(x)}{n}$ …………………………….. (7)

n = number of precipitation observations.

This allows the rainfall distribution at the station to be effectively represented by a mathematical cumulative probability function as given by:

$$G(x) = \int_0^x g(x)dx = \frac{1}{\beta^\alpha \Gamma(\alpha)} \int_0^x x^{\alpha-1} e^{-x/\beta} dx \qquad \ldots\ldots\ldots\ldots\ldots\ldots \qquad (8)$$

Since the gamma function is undefined for $x = 0$ and a precipitation distribution may contain zeros, the cumulative probability becomes:

$$H(x) = q + (1-q)G(x) \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \qquad (9)$$

Where q is the probability of a zero. The cumulative probability $H(x)$ is then transformed to the standard normal distribution to yield the SPI (McKee et al., 1993).

As the precipitation rate is fitted to a gamma distribution for different time scales for each month of the year, the resulting function represents the cumulative probability of a rainfall event for a station for a given month of the dataset and at different time scales of interest. This allows establishing classification values for SPI. A functional and quantitative definition of drought can be established for each time scale. A drought event for a time scale is defined in this project as a period in which the SPI reaches a value of -1.0 and is continuously negative. McKee et al. (1993) defined the drought intensity according to SPI values as given in Table 3.30. An SPI of -2 or less means that an extreme drought, SPI between -1.5 and -1.99 means severe drought, and SPI between -1.0 and -1.49 means moderate drought.

The SPI provides a comparison of the precipitation over a specific period with the precipitation totals from the same period for all the years included in the historical record. For example, a six-month SPI at the end of October compares the May-October precipitation total in that particular year with the May to October precipitation totals of all the years. Consequently, it facilitates the temporal analysis of drought phenomena. Detail theory of SPI can be found in McKee et al. (1993).

Table 3.30: Drought categories defined for SPI values

SPI Value	*Drought Category*
0 to -0.99	Near normal or mild drought
-1.00 to -1.49	Moderate drought
-1.50 to -1.99	Severe drought
-2.00 and less	Extreme drought

Source: McKee et al. (1993)

In this study, drought intensity classes proposed by McKee et al. (1993) are only used.

Calculation of Drought Severity with Different Return Periods

A return period is an estimate of the likelihood of an event, such as a flood or drought. It is a statistical measurement typically based on historic data denoting the average recurrence interval over an extended period of time. When the concept of the return period is applied to drought-related variables, the return period will be the average time between events with a certain magnitude or less.

Risk related to droughts (or any other extreme event) is the probability that one or more droughts with a duration (or magnitude) greater than or equal to a specified length (or magnitude) occur during the project life. Risk is the probability of failure of achieving the intended performance level of the design objective (Yen, 1989). From a management point of view, risk of failure is commonly defined as the probability that one or more droughts (or any other extreme events) greater than the design drought occur during the life of the structure (Yen, 1970). A return period is an estimate of the likelihood of an event or the expected time interval between two consecutive events or inter-arrival time or recurrence interval. Therefore, calculating the return period of droughts or any other extreme events help policy makers understand risk more clearly. Extreme events are widely expressed by return periods in hydrology and water resources engineering. It has been used for risk analysis for a long time, for instance to decide whether a project should be allowed to go forward in a zone of a certain risk, or to design structures to withstand an event with a certain return period.

Droughts cannot be predicted. Therefore, their magnitude and frequency are treated using probability concepts to represent droughts at that location. Return period is the expected time interval between two consecutive events or inter-arrival time or recurrence interval. A drought event may be a single event (such as a rainfall deficit more than a certain threshold in a given year) or a run (such as a drought lasting for a few years). In addition, the underlying hydrologic series may be dependent or independent of time. For single events and independent series, the return period is simply $T=1/p$, where, p is the occurrence probability of the single event. On the other hand, for run events, the return period based on first arrival time is the expected number of years to the end of the first run that is greater or equal to a specified run length (drought duration). Likewise, a return period based on inter-arrival time is the expected number of years between the ends of two consecutive runs of specified (run) length (Fernandez and Salas 1999).

In the present study, drought events are computed for three-, four- and six-month time periods. SPI for three-, four- and six-month time periods are computed at the end of different climatic and cropping seasons to understand the frequency of occurrence of droughts in each season. Therefore, drought for a particular season in a year is a single event and it is also independent to other years. Therefore, the return period is calculated as $T=1/p$, where, p is the occurrence probability of drought event in a year.

It should be remembered that a drought with a return period of ten years does not mean this drought will occur once every ten years. As noted, drought has a 10 percent probability of being exceeded in any year, and there is no preclusion of the ten-year drought being exceeded in several consecutive years.

Mapping Using GIS

Drought is a dynamic phenomenon that changes over time and space. Therefore, complete analysis of drought requires study both of its spatial and temporal extents. Hydrological investigation over a large area requires assimilation of information from many sites each with a unique geographic location (Shahid et al., 2000). GIS maintains the spatial location of sampling points, and provides tools to relate the sampling data contained through a relational database. Therefore, it can be used effectively for the analysis of spatially distributed hydro-meteorological data and modeling. In the present report, GIS is used for spatial modeling of droughts of Bangladesh during various seasons.

For the mapping of spatial extents of rainfall and droughts from point data, Kriging interpolation method is used. The geostatistical analysis tool of ArcMap 9.1 (ESRI, 2004) is used for this purpose. Kriging is a stochastic interpolation method (Journel and Huijbregts, 1981; Isaaks and Srivastava, 1989), which is widely recognized as standard approach for surface interpolation based on scalar measurements at different points. Studies show that Kriging gives better global predictions than other methods (Van Beers and Kleijnen, 2004). However, Kriging is an optimal surface interpolation method based on spatially dependent variance, which is generally expressed as semi-variogram. Surface interpolation using Kriging depends on the selected semi-variogram model and the semi-variogram must be fitted with a mathematical function or model. Depending on the shape of semi-variograms, spherical and Gaussian models are used in the present study for their fitting.

3.5.3 Analysis of Hazard Assessment

The study produced the maps of drought hazards at three-, four-, and six-month time steps. Analysis of drought hazard maps is given below.

Drought in Bangladesh

Drought hazards in Bangladesh have been investigated based on severity of drought with different return periods during different climatic and cropping seasons. For this purpose, SPIs are calculated for three-, four- and six-month time steps. SPI time series at six-month time steps at different stations of Bangladesh are given in Figure 3.44, which shows the occurrences of drought in different years in different stations in Bangladesh. Most parts of Bangladesh experienced drought in the years 1963, 1966, 1968, 1973, 1977, 1979, 1982, 1989, 1992 and 1994–1995, 1999, 2006. Besides that the figures show that droughts at local scale in very common. For example, SPI time series at Rangpur station shows that moderate drought is an every year phenomenon is the region.

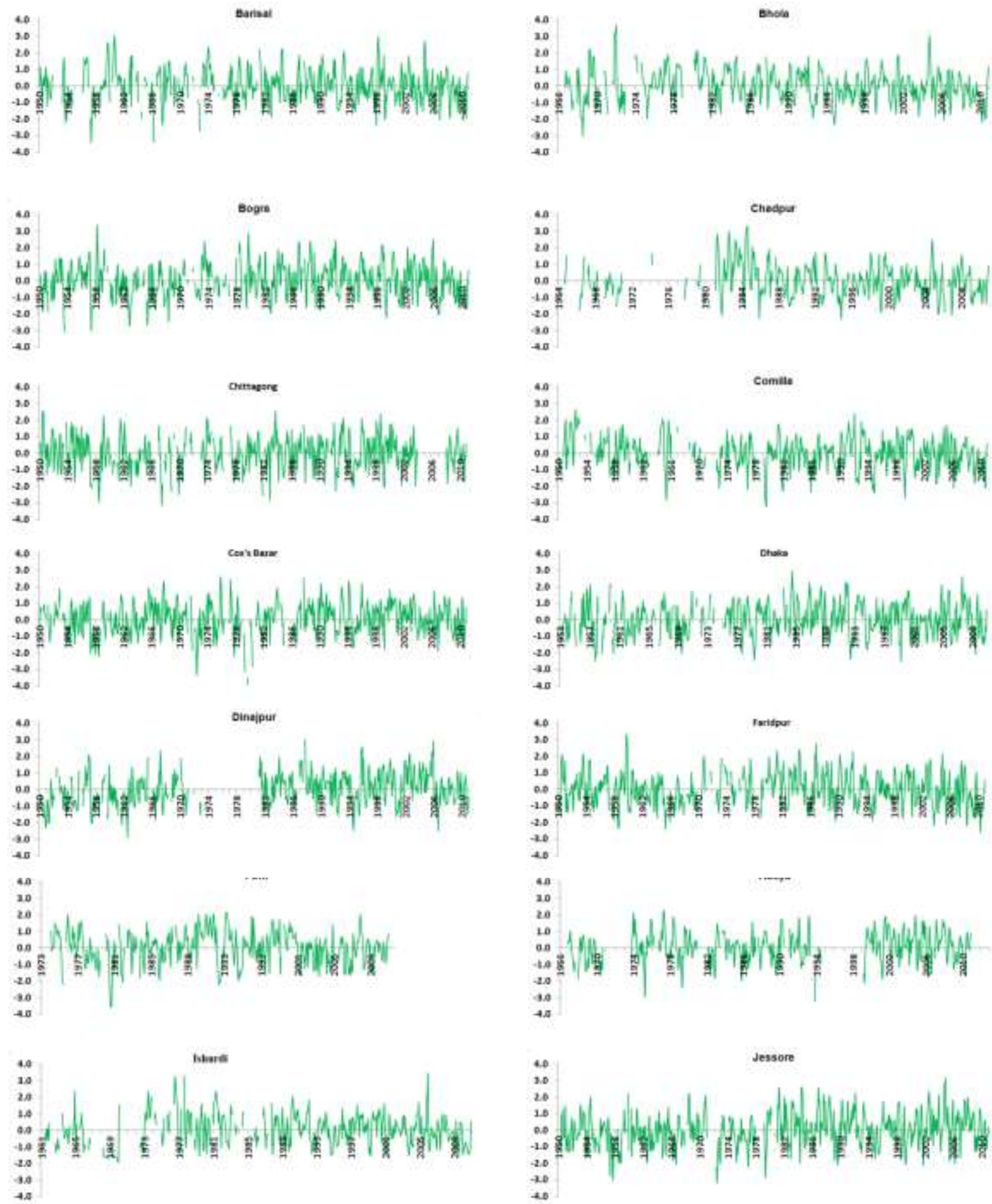


Figure 3.44: SPI time series at six-month time steps at different rainfall stations (contd..)

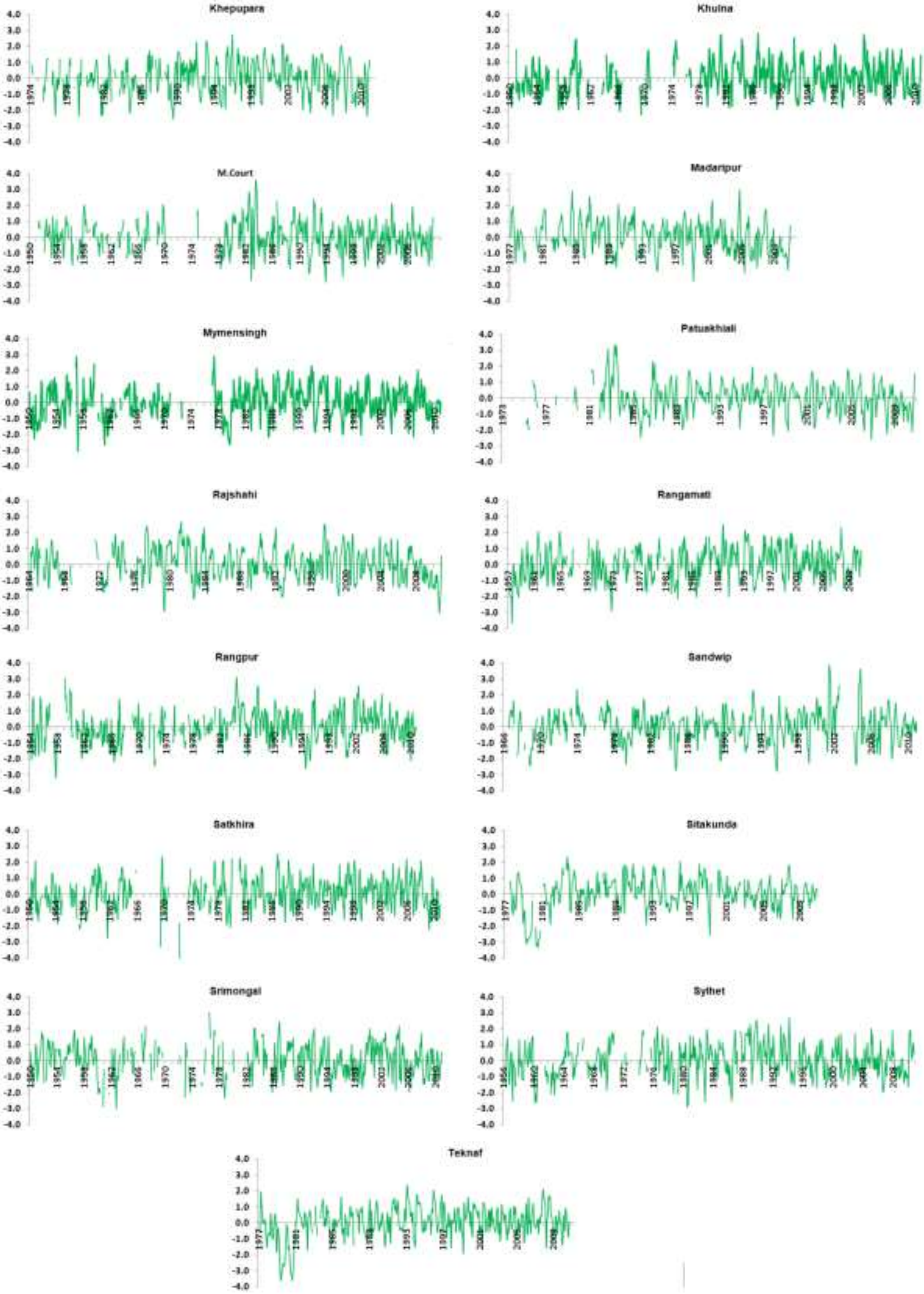


Figure 3.44: SPI time series at six-month time steps at different rainfall stations

Severity of Drought with Different Return Periods

The severity of drought with different return periods are calculated by plotting the SPI data against the cumulative frequency function or the exceedence frequency on the probability scale. The SPI values representing droughts are bounded on the left by zero and it has a pronounced positive skew. Therefore, log-normal distribution is used for the calculation of return period. The SPI series is first plotted against the cumulative frequency function or the exceedence frequency on the probability scale. The horizontal scale is then transformed to log scale so that the cumulative distribution function for data that follow a normal distribution will plot as a straight line. In the present analysis, data for all drought categories are found to fit a straight line when horizontal scale is transformed to log scale. It means that the data is suitable for analysis by using log-normal plotting.

Drought hazards in Bangladesh have been investigated based on the frequency of the events for each drought category during different climatic and cropping seasons. SPI value computed at the last month of a season with a time scale that spans over that season defines the rainfall deficit of the whole season and therefore is used for the calculation of return period of drought of that season. For example, for the calculation of return period of Kharif droughts, six-month SPI in the month of October is used as it represents the rainfall deficit from May to October in a year. Sample time series of six-month SPI in the month of October at Rajshahi station was shown in Figure 3.45 and Dhaka station in Figure 3.46. Missing SPI can be noticed in the figures in some years. This is due to the missing of rainfall value in any month between May to October in that year. The calculation of the six-month SPI in October requires rainfall values for all months between May to October. Therefore, a missing rainfall value in any month between May to October in any year causes missing values of the six-month SPI in October. However, as the return period of drought is calculated by using probabilistic approach, it can be considered that missing SPI values for few years will not change the probability of occurrence of particular type of drought. In the present study, a four-month SPI computed for the month of September as used for the analysis of monsoon drought, s six-month SPI computed for the month of October as used for understanding Kharif drought characteristics, a six-month SPI computed for the month of April was used to characterize Rabi droughts, a three-month SPI computed for the month of May was used for understanding pre-monsoon or pre-Kharif drought characteristics, and a three-month SPI computed for the month of February was used for the analysis of winter droughts.

To compute the severity of drought with different return periods, the negative SPI values are separated from the SPI time series and then ordered according to their magnitude. Then the probability of occurrence of each drought event is calculated. Finally, the return of each SPI event is found by inversing the probability of occurrence. The SPI values are then plotted again their corresponding return period in a log-normal scale to calculate the return periods of droughts with different severity. The plots of return periods of six-month SPI in the month of October at Rajshahi and Dhaka stations are shown in Figure 3.45 and 3.46.

The SPI-Return period plots are used to calculate the severity of drought with different return periods such as the SPI values for 10-, 50- and 100-year return period droughts. For example, Figure 3.47(a) shows that 10-, 50- and 100-year return periods Kharif SPI at

Rajshahi stations are -1.02, -1.87 and -2.3, respectively. At Dhaka stations, 10-, 50- and 100-year return periods, Kharif SPI are -1.05, -1.48 -2.4, respectively (Figure 3.47(b)). A less negative SPI means less severity of drought with a particular return period.

Spatial Pattern of Drought Severity

The SPI values of droughts during different climatic and cropping seasons with 10-, 50- and 100-year return periods at all stations are calculated and given in Table 3.31. The values are also used to prepare the corresponding maps by using Geostatistical analysis tool of ArcMap. The spatial characteristics of droughts in Bangladesh in different climatic and cropping seasons are discussed below.

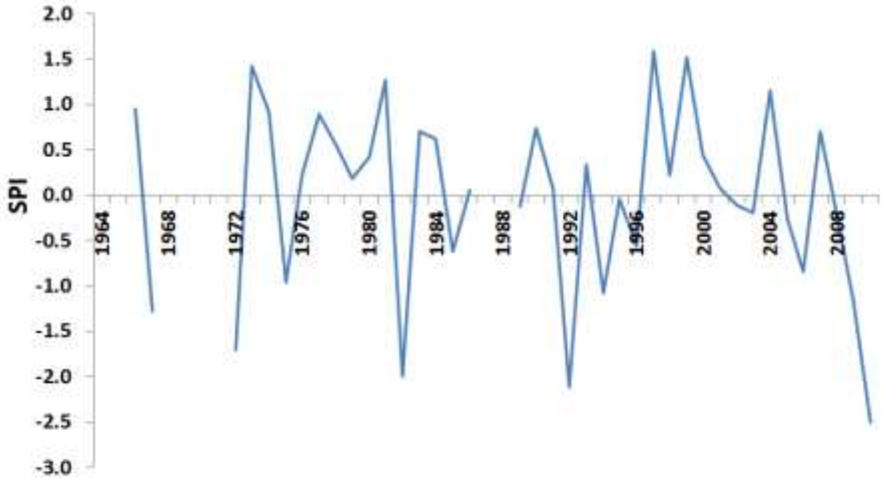


Figure 3.45: Time series of six-month SPI in October at Rajshahi

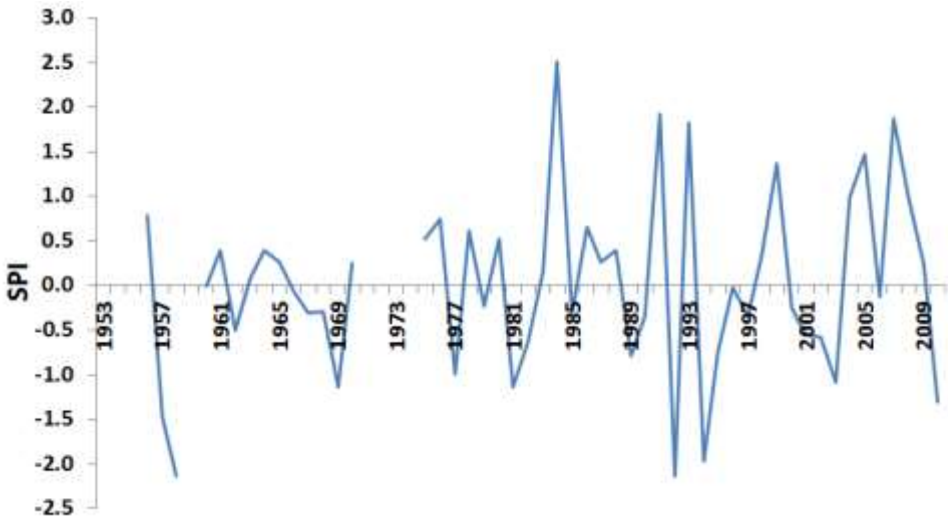
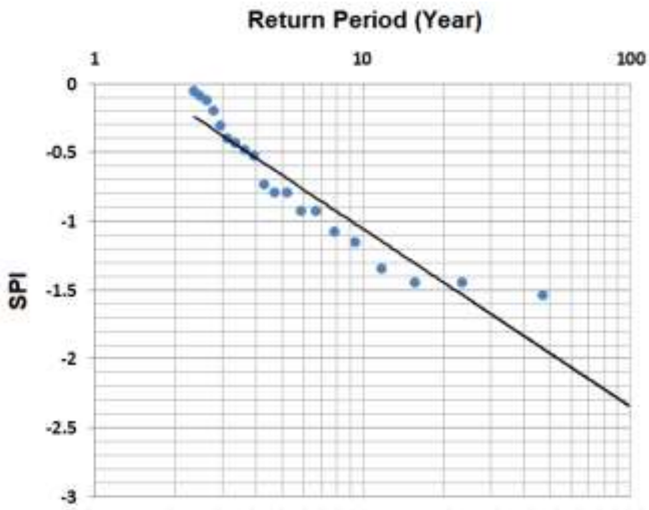


Figure 3.46: Time series of six-month SPI in October

(a) Rajshahi



(b) Dhaka

Figure 3.47: Return period plot of six-month SPI in the month of October at (a) Rajshahi and (b) Dhaka stations

Table 3.31: Return periods of 10, 50 and 100 year SPI values for all climatic and cropping stations at all stations in Bangladesh

Season	Kharif			Pre-Kharif/Pre-Monsoon			Winter			Monsoon			Rabi		
Return Period	**10**	**50**	**100**	**10**	**50**	**100**	**10**	**50**	**100**	**10**	**50**	**100**	**10**	**50**	**100**
Station	**SPI (Standardized Precipitation Index)**														
Barisal	-1.22	-2.00	-2.40	-1.00	-1.80	-2.20	-0.85	-1.50	-1.80	-1.05	-1.82	-2.19	-0.92	-2.07	-2.60
Bhola	-1.02	-1.60	-2.00	-1.30	-2.35	-2.80	-0.95	-1.60	-1.90	-1.19	-2.15	-2.60	-0.95	-1.82	-2.20
Bogra	-1.30	-2.35	-2.80	-1.40	-3.00	-3.70	-0.81	-1.51	-1.80	-1.2	-2.19	-2.60	-1.35	-2.49	-2.97
Chadpur	-1.10	-1.92	-2.30	-1.15	-2.10	-2.51	-0.67	-1.28	-1.60	-1.09	-2.05	-2.49	-0.90	-1.87	-2.27
Chittagong	-1.27	-2.40	-2.90	-1.20	-2.30	-2.75	-0.84	-1.55	-1.90	-1.05	-1.90	-2.22	-1.20	-2.30	-2.77
Comilla	-1.19	-2.20	2.61	-1.10	-1.91	-2.30	-0.06	-1.15	-1.23	-1.20	-2.15	-2.55	-1.35	-2.67	-3.20
Cox's Bazar	-1.16	-2.17	-2.60	-1.10	-2.02	-2.45	-0.75	-1.28	-1.50	-0.95	-1.80	-2.12	-1.15	-2.12	-2.56
Dhaka	-1.30	-2.50	-3.00	-1.30	-2.40	-2.90	-1.04	-1.94	-2.35	-1.10	-2.00	-2.40	-1.42	-2.90	-3.50
Dinajpur	-1.49	-2.30	-2.70	-1.20	-2.40	-2.90	-0.49	-0.75	-0.89	-1.45	-2.45	-3.20	-1.30	-2.42	-2.90
Faridpur	-1.29	-2.25	-2.70	-1.30	-2.60	-3.20	-0.90	-1.62	-1.92	-1.10	-2.00	-2.40	-1.20	-2.50	-3.03
Feni	-0.90	-1.92	-2.40	-0.95	-1.80	-2.30	-1.21	-2.2	-2.65	-1.29	-2.25	-2.65	-1.00	-1.80	-2.32
Hatia	-0.48	-1.15	-1.20	-1.00	-1.74	-2.21	-0.9	-1.33	-1.52	-1.10	-1.90	-2.20	-0.80	-2.10	-2.70
Ishurdi	-1.18	-2.20	-2.70	-1.12	-2.15	-2.6	-1.00	-1.85	-2.20	-1.40	-2.60	-3.12	-1.20	-2.18	-2.60
Jessore	-1.30	-2.49	-2.80	-1.35	-2.85	-3.5	-0.81	-1.41	-1.70	-1.29	-2.30	-2.72	-1.30	-2.30	-2.75
Khepupara	-1.09	-1.95	-2.30	-0.95	-1.70	-2.2	-1.30	-2.2	-2.65	-1.12	-2.22	-2.70	-1.05	-2.00	-2.40
Khulna	-1.08	-2.13	-2.60	-1.30	-2.30	-2.8	-0.61	-1.1	-1.25	-1.39	-2.70	-3.25	-0.89	-2.00	-2.45
M. Court	-0.95	-1.70	-2.00	-1.30	-2.42	-2.91	-0.89	-1.59	-1.89	-1.30	-2.60	-3.15	-1.10	-2.10	-2.55
Madaripur	-1.21	-2.30	-2.70	-1.20	-1.92	-2.32	-1.10	-1.9	-2.29	-1.40	-2.90	-3.50	-1.39	-2.40	-2.84
Mymensingh	-1.40	-2.70	-3.30	-1.10	-2.10	-2.55	-0.75	-1.42	-1.74	-0.19	-0.58	-0.76	-1.40	-2.70	-3.40
Patuakhili	-0.80	-1.70	-2.10	-0.91	-2.72	-2.1	-1.20	-2.25	-2.70	-1.10	-1.95	-2.40	-0.80	-1.52	-1.86
Rajshahi	-1.47	-3.00	-3.70	-1.25	-2.40	-2.9	-1.00	-1.85	-2.20	-0.41	-0.90	-1.16	-1.32	-2.45	-2.91
Rangamati	-1.18	-2.37	-2.90	-1.10	-1.85	-2.3	-0.8	-1.23	-1.50	-1.19	-1.90	-2.22	-1.37	-2.60	-3.10
Rangpur	-1.31	-2.62	-3.20	-1.25	-2.30	-2.8	-0.95	-1.80	-2.19	-1.20	-2.21	-2.70	-1.40	-2.85	-3.50
Sandwip	-0.95	-1.60	-1.90	-1.4	-2.70	-3.3	-1.12	-2.10	-2.30	-1.17	-2.1	-2.51	-1.00	-1.98	-2.40
Shatkhira	-1.09	-2.12	-2.60	-1.00	-2.00	-2.4	-0.7	-1.30	-1.60	-1.20	-2.15	-2.55	-1.14	-2.25	-2.75
Sitakunda	-0.60	-1.15	-1.50	-1.10	-2.20	-2.8	-0.67	-1.29	-1.61	-0.70	-1.95	-2.40	-0.90	-1.75	-2.12
Srimongal	-1.19	-2.25	-2.70	-1.2	-2.10	-2.51	-1.00	-1.72	-2.05	-1.12	-2.10	-2.45	-1.30	-2.50	-3.05
Sylhet	-1.15	-2.00	-2.30	-1.00	-2.01	-2.49	-1.20	-2.30	-2.75	-0.90	-2.20	-2.60	-0.95	-1.90	-2.31
Teknaf	-0.40	-0.92	-1.30	-1.20	-2.20	-2.7	-0.65	-0.90	-1.10	-0.60	-1.20	-1.45	-0.90	-2.02	-2.51

Using the SPI index at 29 stations as shown in Table 3.31, drought hazard maps are developed for Pre-Kharif/Pre-Monsoon, Kharif, Monsoon, Winter and Rabi seasons for 10-, 50- and 100-year return periods. Since the effects of drought will be maximum during crops growing seasons of pre-Kharif/pre-monsoon and Kharif only, analysis of drought hazard maps was carried out only for 10-year return period, since this will help to plan any disaster risk reduction measures.

Pre-Monsoon/Pre-Khraif Hazard Analysis (10-year Return Period)

The pre-monsoon/pre-Kharif drought hazard map with a 10-year return period is shown in Figure 3.48. The country is covered by two drought categories, near normal and moderate. The distribution of moderate drought hazard area in each district is given in Table 3.32.

Table 3.32: Area (km^2) and percentage of moderate hazard category in pre-monsoon/ pre-Kharif season

Divisions	Districts	Area (km^2) and percentage of moderate drought hazard category in Pre- monsoon / pre-Kharif season	
		Area(km^2)	**Percentage**
Rajshahi	Bogra	1938.39	66.87
	Chapai Nawabganj	1702.55	100.00
	Joypurhat	1012.41	100.00
	Naogaon	3409.12	99.23
	Natore	106.88	5.62
	Rajshahi	1150.67	47.44
Rangpur	Dinajpur	3444.30	100.00
	Gaibandha	582.73	27.56
	Lalmonirhat	149.63	12.00
	Nilphamari	1393.92	90.13
	Panchagarh	1404.62	100.00
	Rangpur	1212.36	50.50
	Thakurgaon	1781.74	100.00

Kharif Drought

Spatial distribution of drought hazard during Kharif with a 10-year return period shows that moderate drought can occur once in every ten years in the whole country, except in the coastal region and north-eastern part of the country, where it is near normal conditions (Figure 3.51). The distribution of moderate drought hazard area for a 10-year return period in each district is given in Table 3.33.

Table 3.33: Area (km^2) and percentage of moderate drought hazard category in the Kharif season

Divisions	Districts	Area (km^2) and percentage of moderate drought hazard category in the Kharif season	
		Area	**Percentage**
Barisal	Barisal	2485.2	89.3
	Bhola	524.4	15.4
	Jhalokati	526.5	74.5
	Pirojpur	785.7	61.5
	Bandarban	305.4	6.8
	Brahmanbaria	1881.2	100.0

Divisions	Districts	Area (km^2) and percentage of moderate drought hazard category in the Kharif season	
		Area	Percentage
Chittagong	Chandpur	1645.3	100.0
	Chittagong	2325.3	44.0
	Comilla	3146.3	100.0
	Feni	990.4	100.0
	Khagrachhari	2749.2	100.0
	Lakshmipur	1230.9	85.5
	Noakhali	2088.3	56.7
	Rangamati	5923.8	96.9
Dhaka	Dhaka	1463.6	100.0
	Faridpur	2052.9	100.0
	Gazipur	1806.4	100.0
	Gopalganj	1468.7	100.0
	Kishoreganj	2688.6	100.0
	Madaripur	1125.7	100.0
	Manikganj	1383.7	100.0
	Munshiganj	1004.3	100.0
	Narayanganj	684.4	100.0
	Narsingdi	1150.1	100.0
	Rajbari	1092.3	100.0
	Shariatpur	1174.1	100.0
	Tangail	3414.4	100.0
Khulna	Bagerhat	1932.7	48.8
	Chuadanga	1174.1	100.0
	Jessore	2606.9	100.0
	Jhenaidah	1964.8	100.0
	Khulna	2908.4	66.2
	Kushtia	1608.8	100.0
	Magura	1039.1	100.0
	Meherpur	751.6	100.0
	Narail	968.0	100.0
	Satkhira	2548.2	66.8
Mymensingh	Jamalpur	2115.2	100.0
	Mymensingh	4394.6	100.0
	Netrakona	2794.3	100.0
	Sherpur	1364.7	100.0
Rajshahi	Bogra	2898.7	100.0
	Chapai Nawabganj	1702.6	100.0
	Joypurhat	1012.4	100.0
	Naogaon	3435.7	100.0
	Natore	1900.2	100.0
	Pabna	2376.1	100.0
	Rajshahi	2425.4	100.0
	Sirajganj	2402.1	100.0

Divisions	Districts	Area (km^2) and percentage of moderate drought hazard category in the Kharif season	
		Area	Percentage
Rangpur	Dinajpur	3444.3	100.0
	Gaibandha	2114.8	100.0
	Kurigram	2245.0	100.0
	Lalmonirhat	1247.4	100.0
	Nilphamari	1546.6	100.0
	Panchagarh	1404.6	100.0
	Rangpur	2400.6	100.0
	Thakurgaon	1781.7	100.0
Sylhet	Habiganj	2636.6	100.0
	Maulvibazar	2799.4	100.0
	Sunamganj	3747.2	100.0
	Sylhet	3452.1	100.0

3.5.4 Map Contents

3.5.4.1 Pre-monsoon/Pre-Kharif Drought

Pre-monsoon/pre-Kharif drought is calculated by using the three-month SPI in the month of May (from March to May). The spatial distribution of 10-, 50- and 100-year return period SPI values during pre-monsoon season are shown in figure 3.48, 3.49, and 3.50. The spatial distribution of 10-year return period drought (Figure 3.48) reveals that pre-monsoon drought with moderate intensity occur only in the northwest part of the country. In other parts of the country, it can be categorized as near normal. It means that 10-year return period pre-monsoon drought occurs only in the northwest part of the country.

Figure 3.49 shows that extreme drought can occur in the whole country, except severe drought in the northeastern part of the country for 50-year return period of pre-monsoon/pre-Kharif drought. Spatial patterns of pre-monsoon/pre-Kharif SPI values for the 100-year return period is more or less similar to that of 50-year return period. Figure 3.50 shows that during pre-monsoon/pre-Kharif season, extreme drought can occur through the entire country every 100 years. Overall, the results show that pre-monsoon/pre-Kharif droughts are more severe in the northwest region of Bangladesh in the 10-year return period.

3.5.4.2 Kharif Drought

A major portion of rainfall in Bangladesh occurs in Kharif season (May to October). In some parts of Bangladesh, such as in the north and northwest, more than 85 percent of rainfall occurs during Kharif season. Therefore, rainfall during Kharif season plays a major role in agriculture and food security of the country. It is also the major source of groundwater replenishment. A deficit of rainfall during Kharif season severely impacts on Kharif crops. If the groundwater is not properly replenished, the groundwater-based irrigation during Rabi and pre-Kharif season can be affected. Therefore, drought during Kharif season is most hazardous for Bangladesh compared to any other climatic or cropping seasons. Drought during Kharif season is estimated by using the six-month SPI in the month October. Spatial distributions of 10-, 50- and 100-year return periods of Kharif drought in Bangladesh are shown in Figure 3.51, Figure 3.52 and Figure 3.53 respectively.

Spatial distribution of Kharif with a 10-year return period shows that moderate drought can occur once in every ten years in the whole, except in coastal region and northeast part of the country (Figure 3.51).

Extreme drought at 50-year return periods is possible during Kharif season in entire Bangladesh except coastal area, as shown in Figure 3.52. Kharif drought with a 100-year return period is widespread in Bangladesh (Figure 3.53). Spatial distribution of SPI values for Kharif drought with a 100-year return period indicates extreme drought all over the country.

The Kharif season drought hazard maps developed are validated by comparing them with Rainfall, SPI and NDVI, and is given in Annexure V.

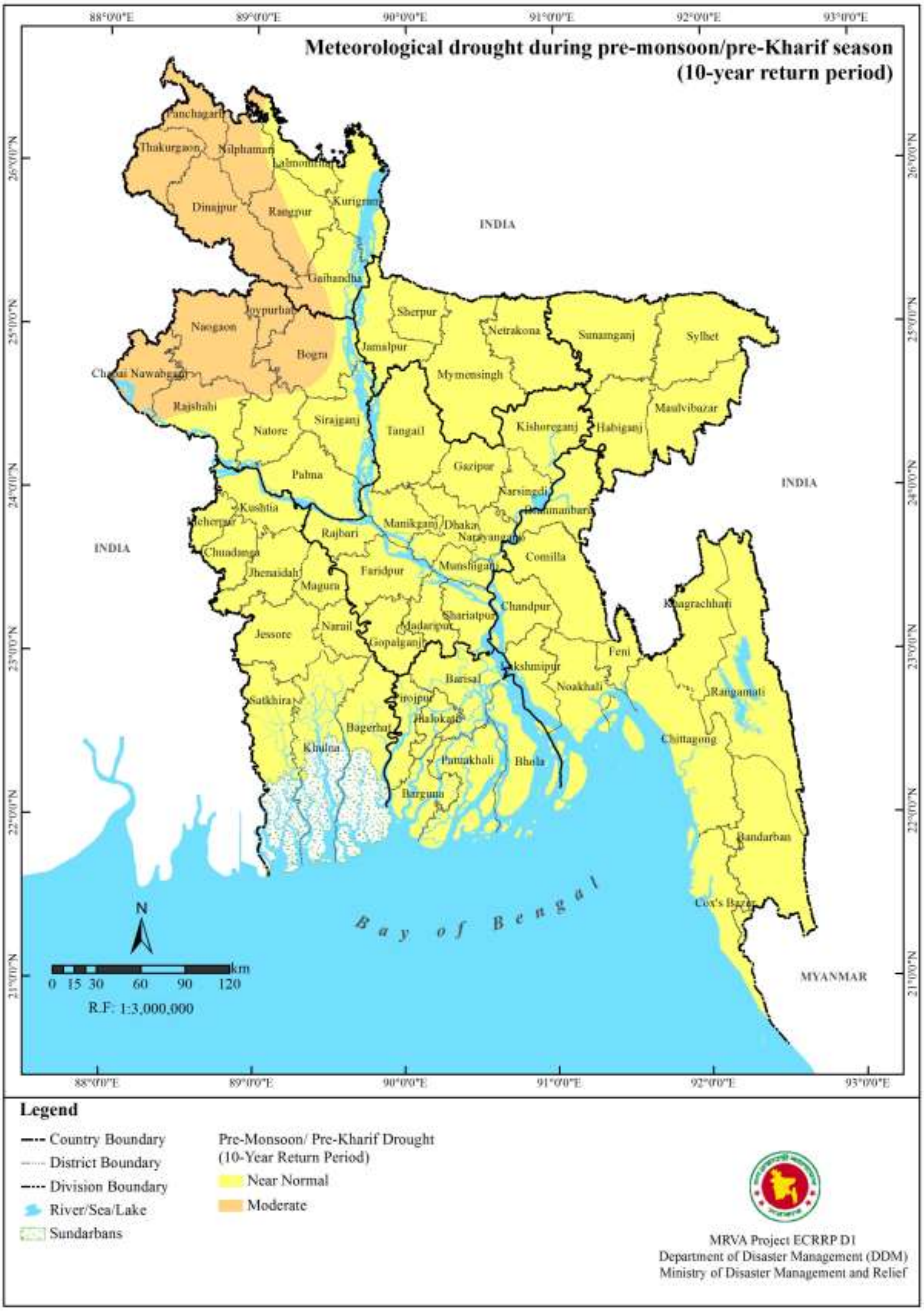


Figure 3.48: Meteorological drought during pre-monsoon/pre-Kharif season (March to May)

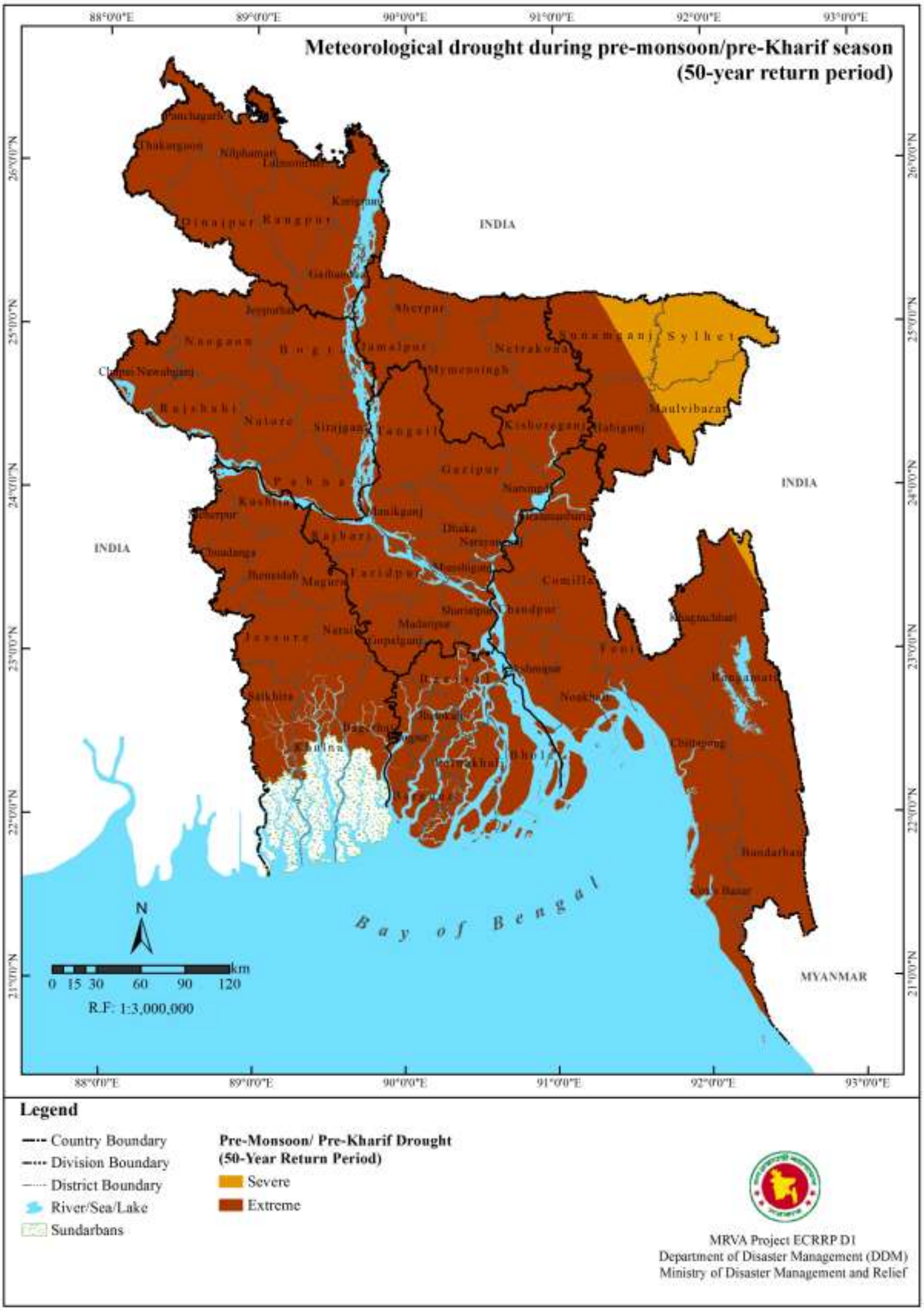


Figure 3.49: Meteorological drought during pre-monsoon/pre-Kharif season (March to May)

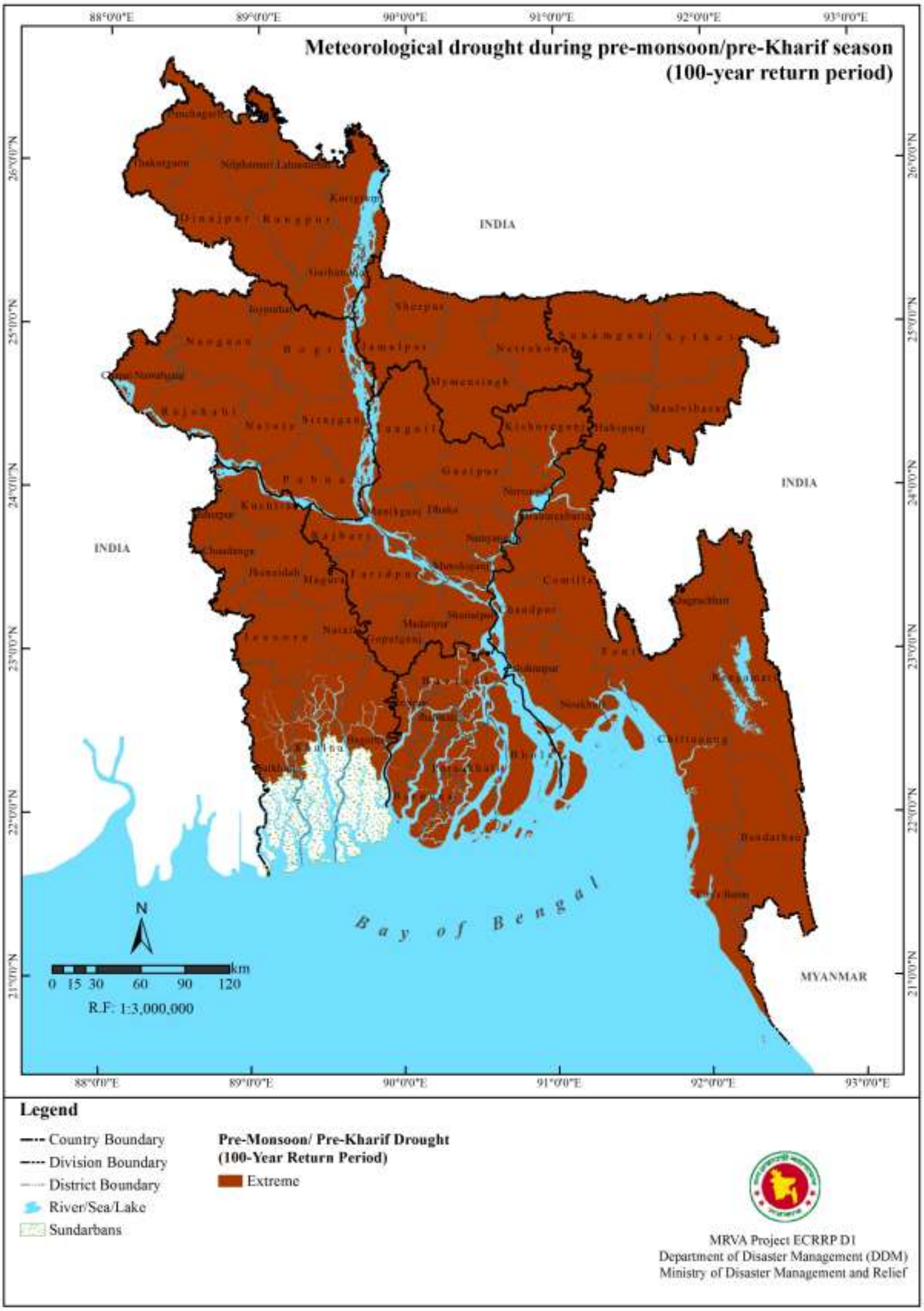


Figure 3.50: Meteorological drought during pre-monsoon/pre-Kharif season (March to May)

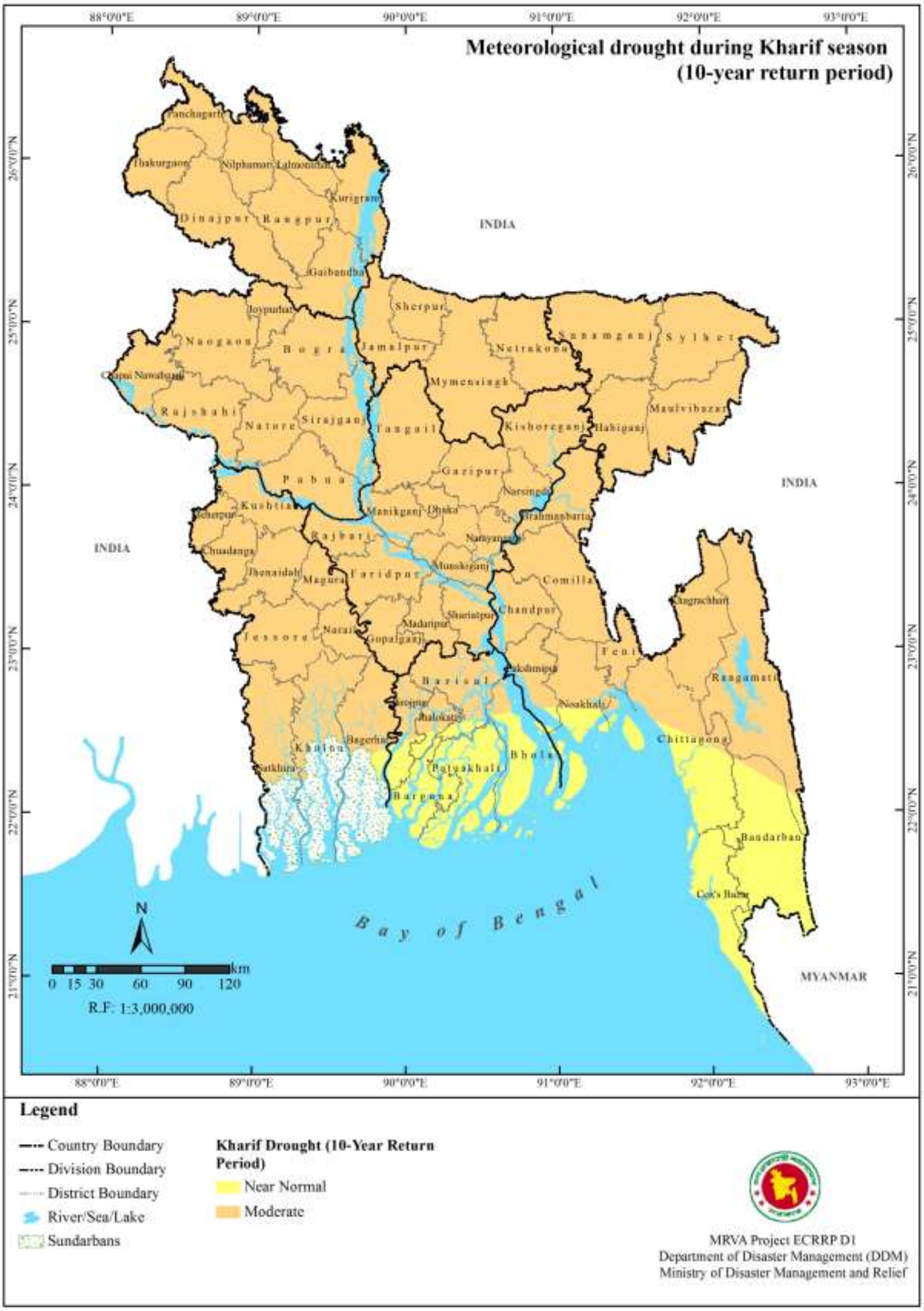


Figure 3.51: Meteorological drought during Kharif season (May to October)

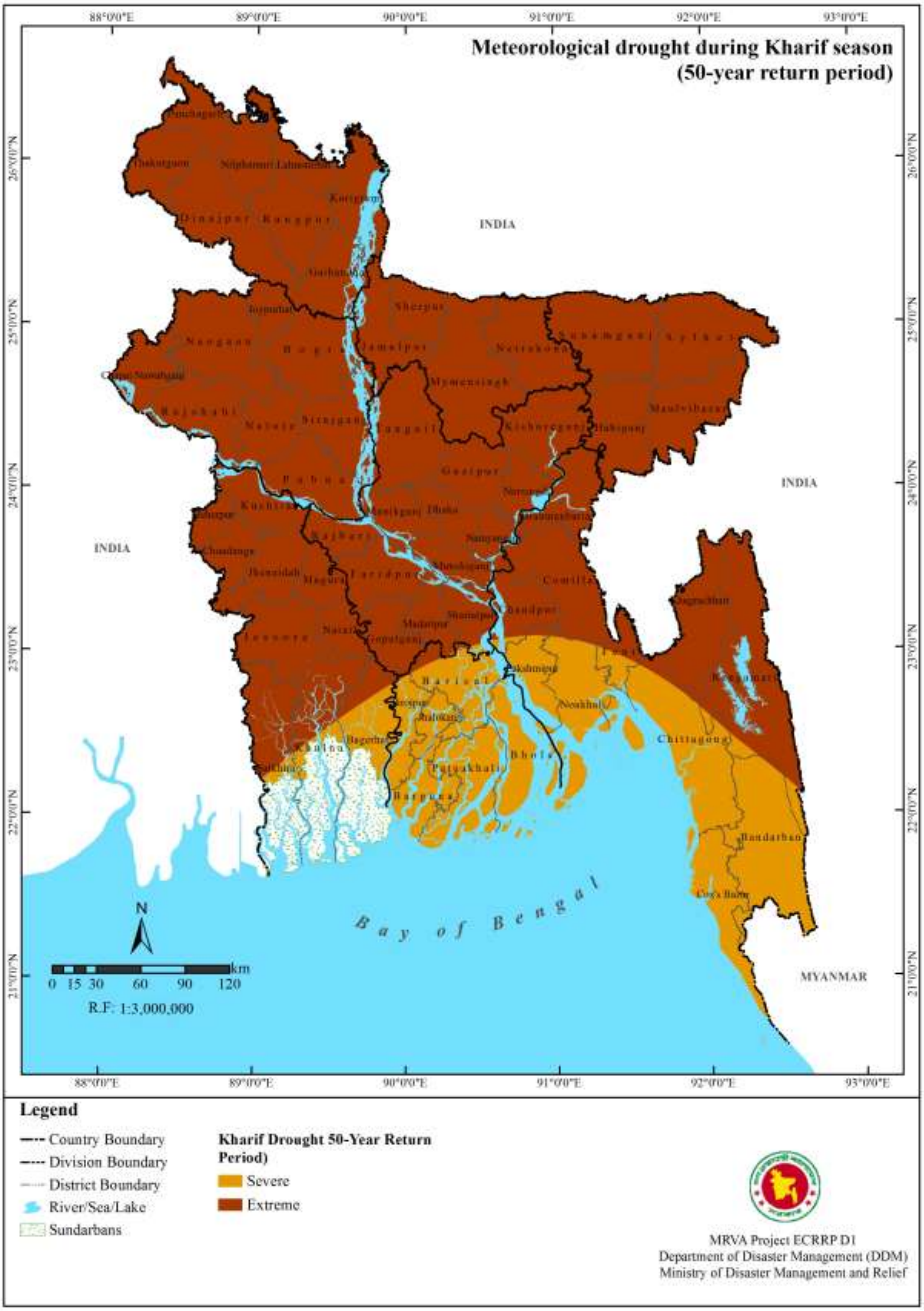


Figure 3.52: Meteorological drought during Kharif season (May to October)

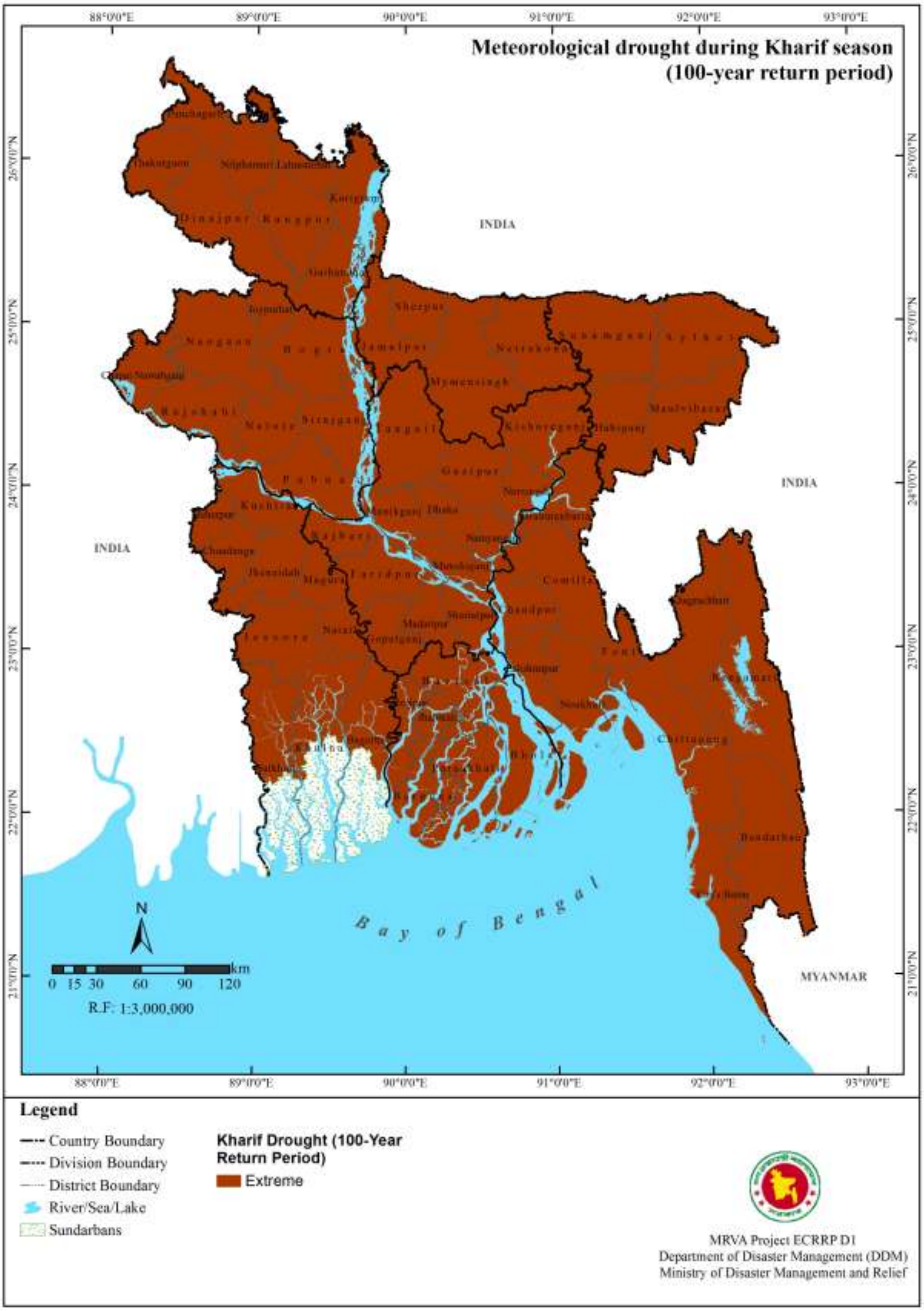


Figure 3.53: Meteorological drought during Kharif season (May to October)

3.5.4.3 Monsoon Drought

About 75 percent of rainfall in Bangladesh occurs during monsoon (June to September). Therefore, rainfall deficit or drought during monsoon has severe implications on the agro-based economy of Bangladesh. In the present study, SPI values for different return periods of monsoon drought are derived from four-month SPI at the month September. Spatial distributions of 10-, 50- and 100-year return period SPIs during monsoon are shown in Figure 3.54, Figure 3.55 and Figure 3.56 respectively.

As can be seen in Figure 3.54, the spatial distribution of monsoon drought categories with 10-year return period reveal that moderate category is possible in the entire country except some parts of hill track region where near normal conditions prevail. Figure 3.55 shows that 50-year return period monsoon drought can be extreme in most parts of the country and severe in the southeast part. The 100-year return period monsoon (Figure 3.56) shows that the extreme drought can occur in the entire country except the southern part of hill track region, where severe drought can occur.

3.5.4.4 Winter Drought

Only 3 percent of rainfall of occurs during winter season in Bangladesh. Crops during winter mainly depend on irrigation. Consequently, drought during winter months has relatively less impact on the agriculture in Bangladesh. However, very little rainfall or drought during winter often causes impacts on the ecosystem and aggravates environmental pollution in the country. In the present study, a three-month (December to February) SPI in the month of February is used to assess winter drought. Spatial distributions of 10-, 50- and 100-year return periods of winter drought in Bangladesh are shown in Figure 3.57, Figure 3.58 and Figure 3.59 respectively.

As shown in Figure 3.57, winter drought with a 10-year return period is near normal in the entire country, except in Sylhet district where it falls in the moderate category. The 50-year return period shows moderate drought in the northwest and southern parts of the country, and severe drought in the remaining parts of the country (see Figure 3.58), while the 100-year return period shows severe drought throughout the entire country and extreme drought in the northeast as shown in Figure 3.59.

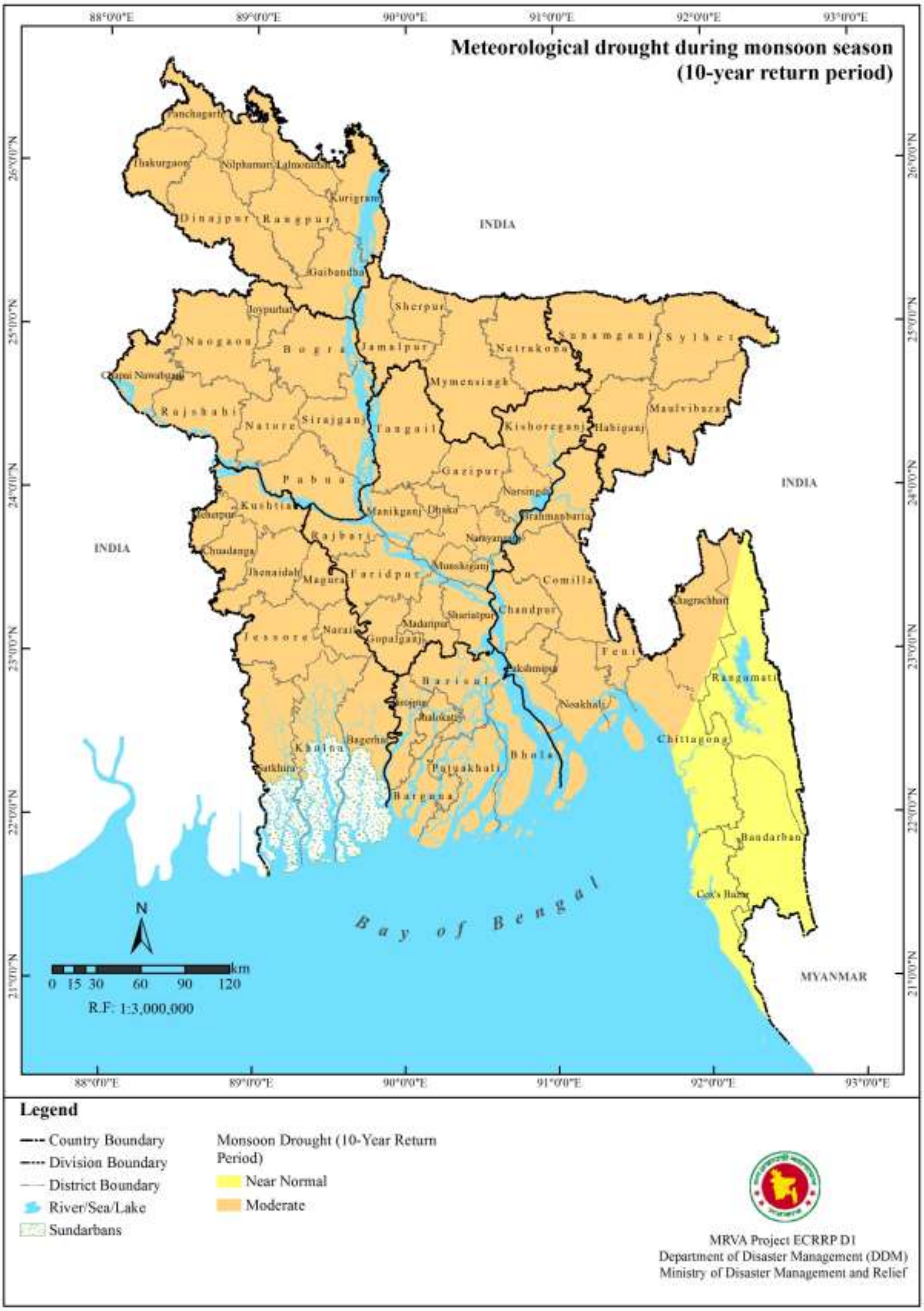


Figure 3.54: Meteorological drought during monsoon season (June to September)

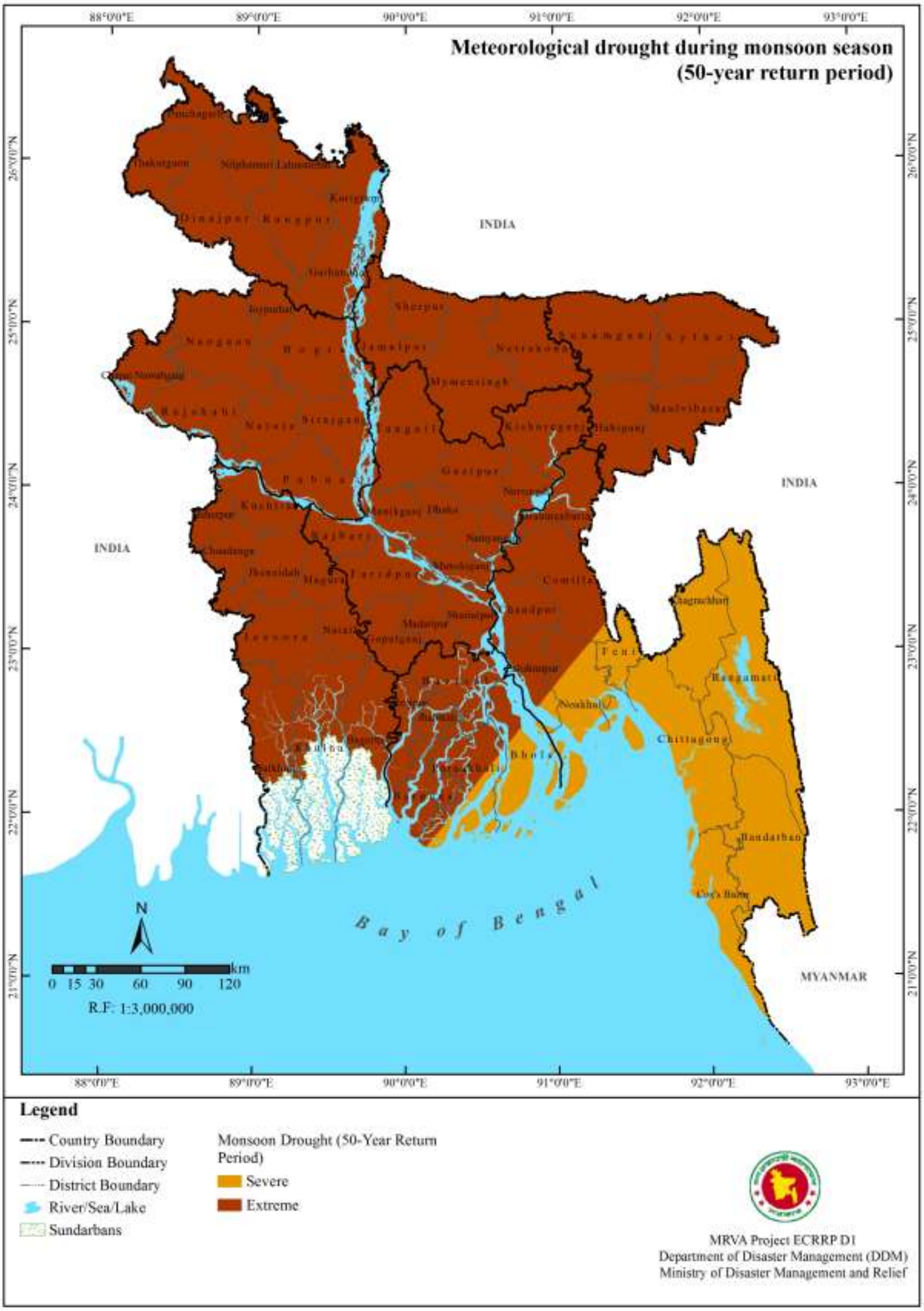


Figure 3.55: Meteorological drought during monsoon season (June to September)

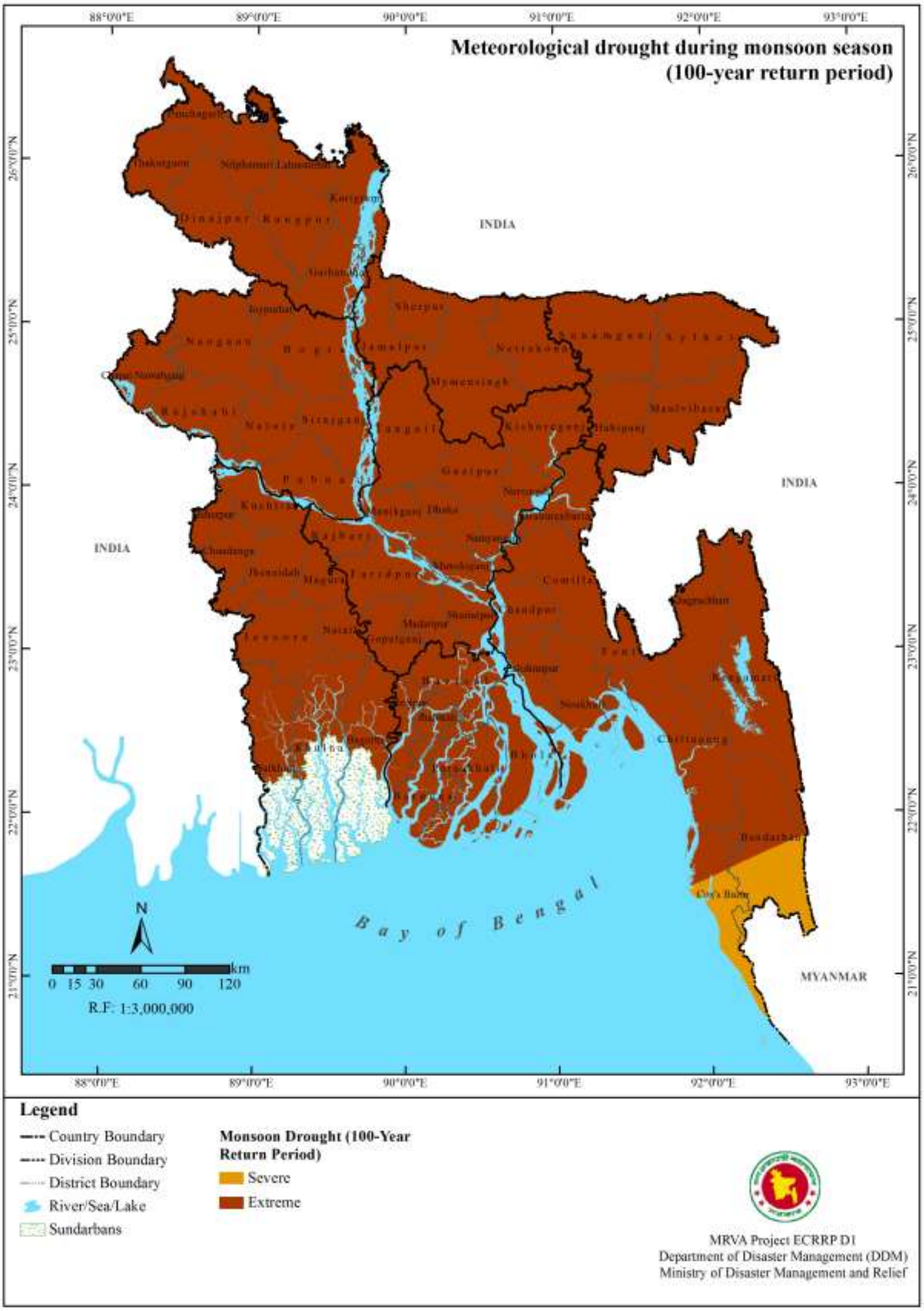


Figure 3.56: Meteorological drought during monsoon season (June to September)

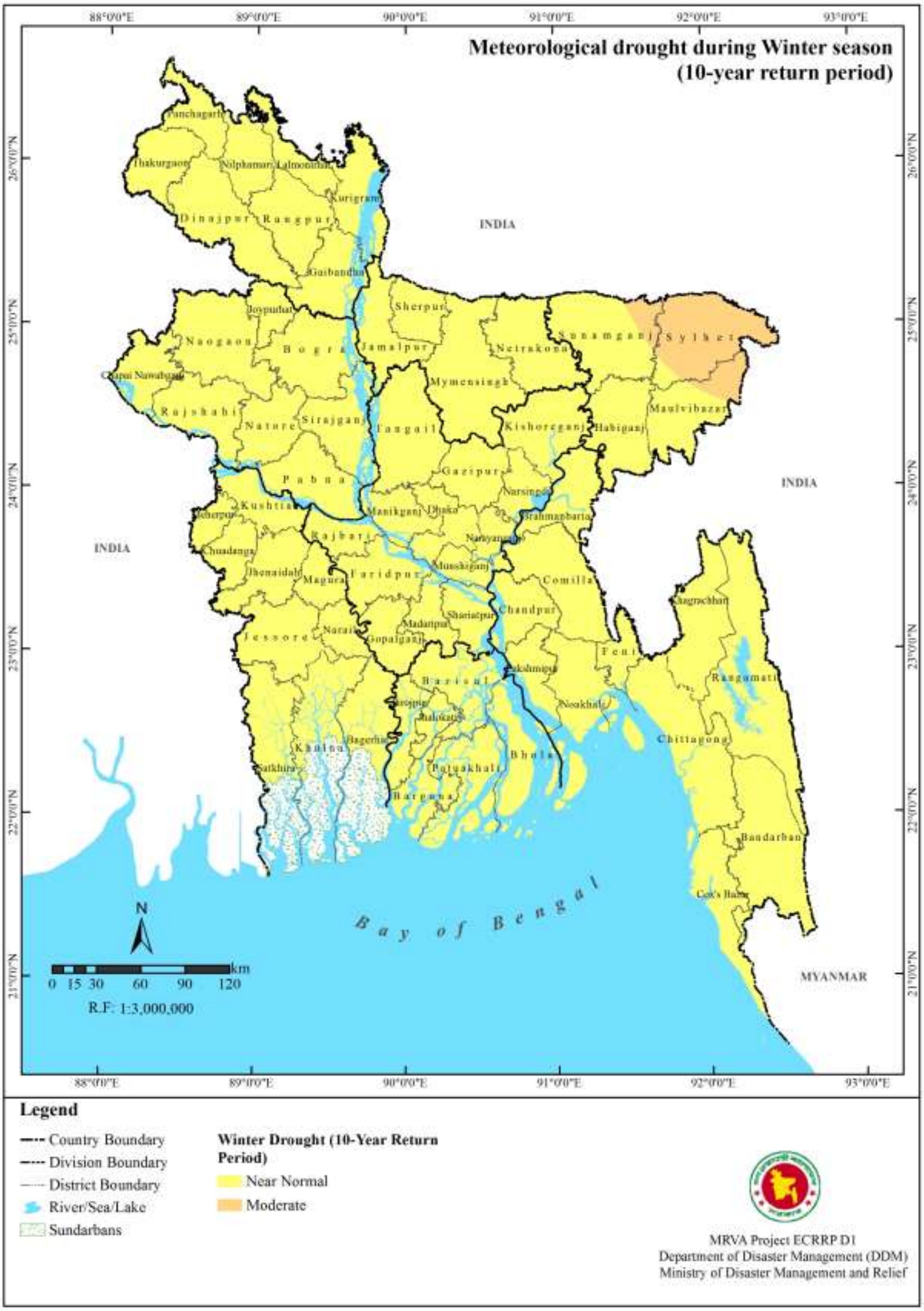


Figure 3.57: Meteorological drought during winter season (December to February)

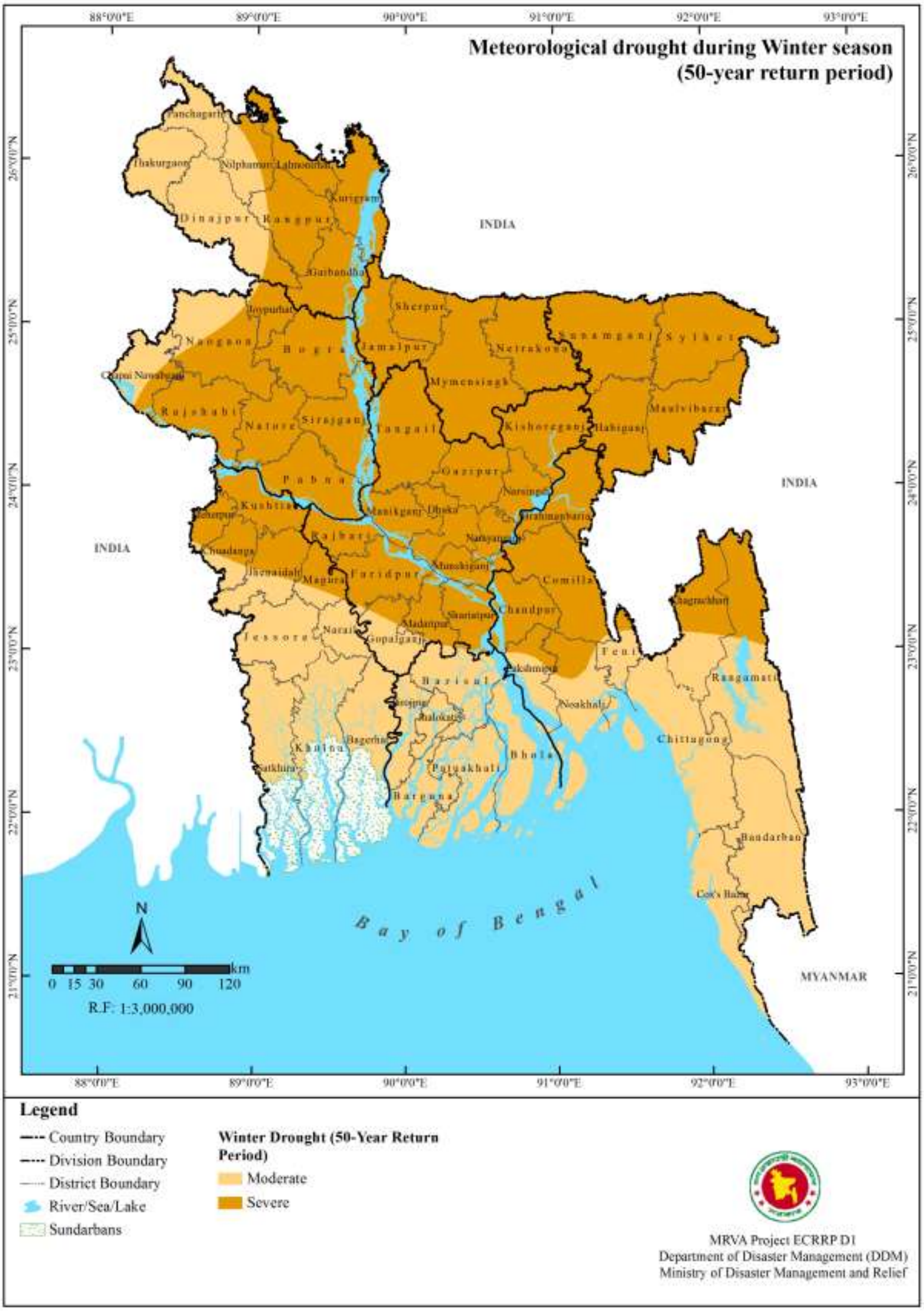


Figure 3.58: Meteorological drought during winter season (December to February)

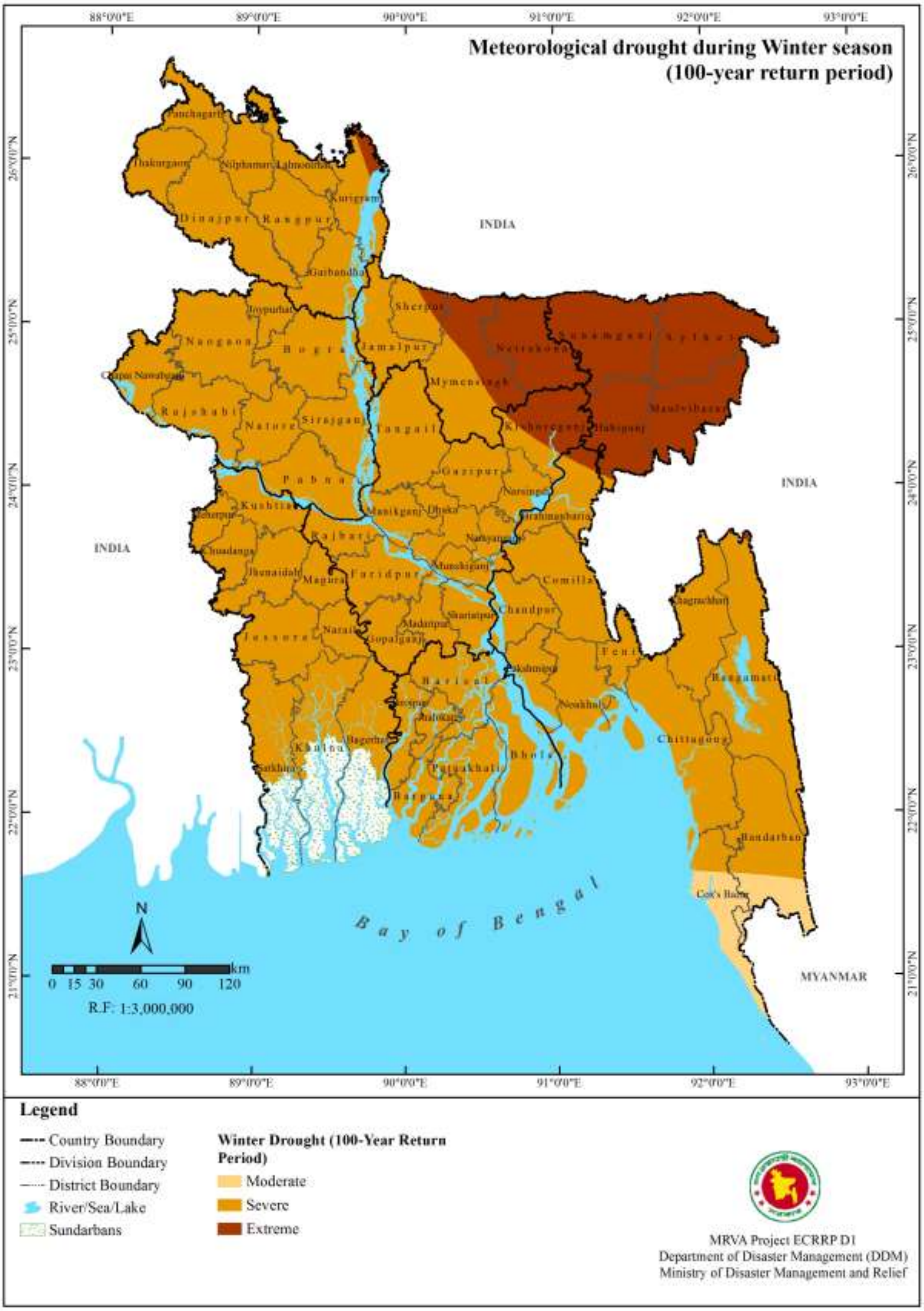


Figure 3.59: Meteorological drought during winter season (December to February)

3.5.4.5 Rabi Drought

Rainfall during Rabi season is low compared to the Kharif season. Crops during Rabi season mainly depend on irrigation. Consequently, drought during Rabi season is relatively less important compared to the Kharif season. Drought during Rabi season (November to April) is estimated by using a six-month SPI in the month April. Spatial distributions of 10-, 50- and 100-year return periods of Rabi drought in Bangladesh are shown in Figure 3.60, Figure 3.61 and Figure 3.62 respectively.

It can be seen from Figure 3.60 that a 10-year return period during Rabi season is moderate in most of the country and near normal in southern coastal area. The 50-year return period drought during Rabi season is extreme and the southwest part falls under the severe category as shown in Figure 3.61. The Rabi season drought of a 100-year return period falls under the extreme category throughout the entire country (Figure 3.62).

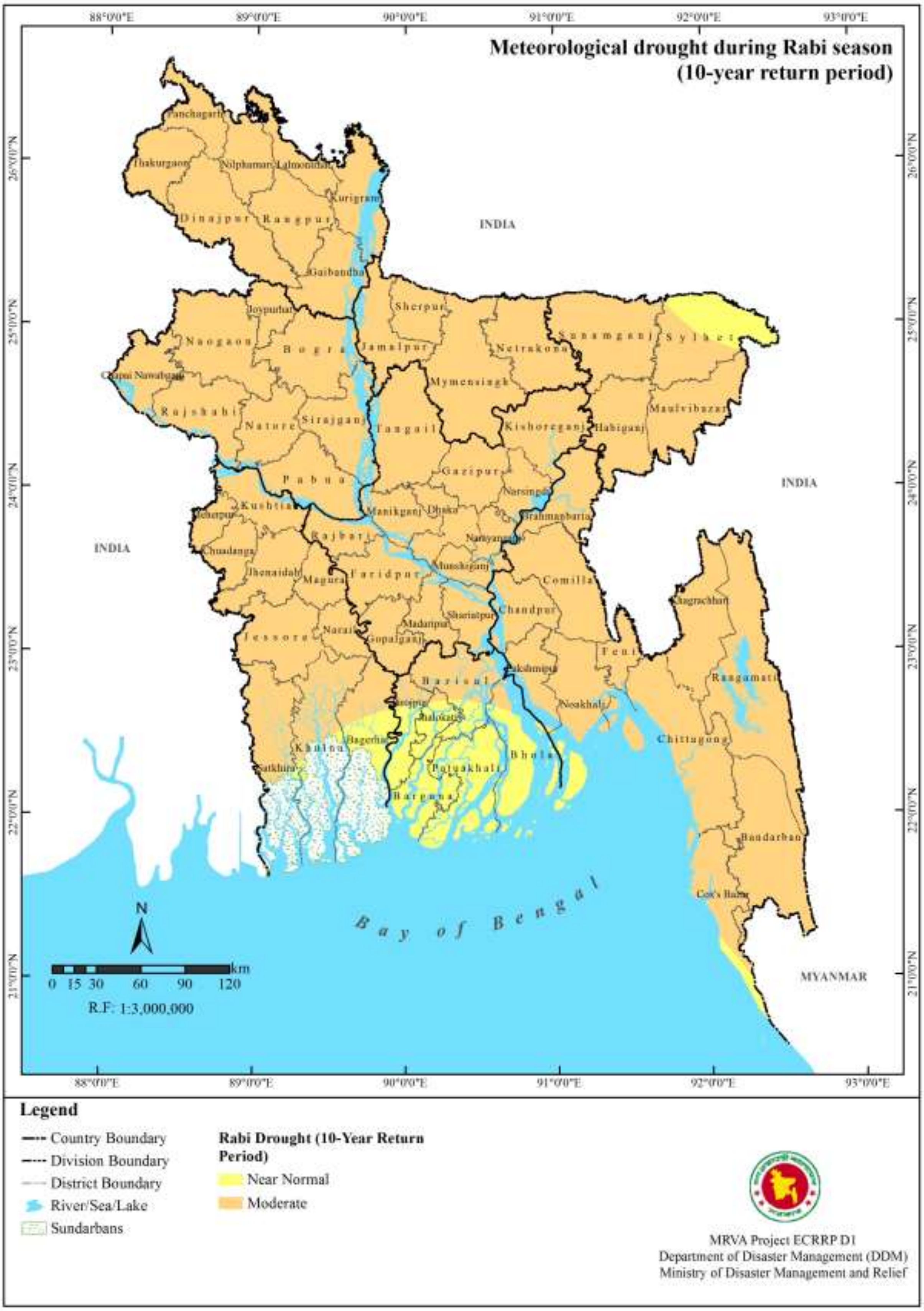


Figure 3.60: Meteorological drought during Rabi season (November to April)

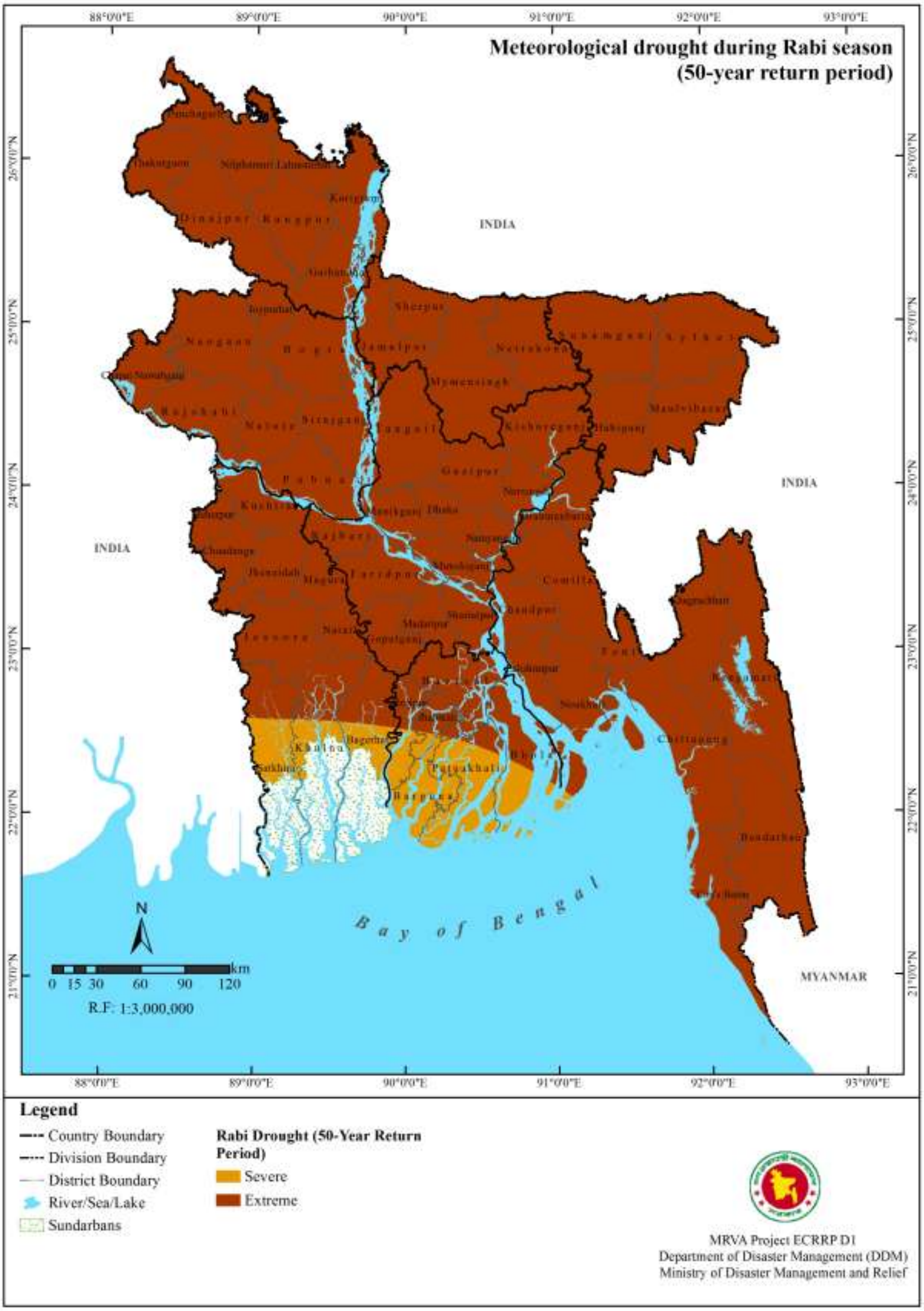


Figure 3.61: Meteorological drought during Rabi season (November to April)

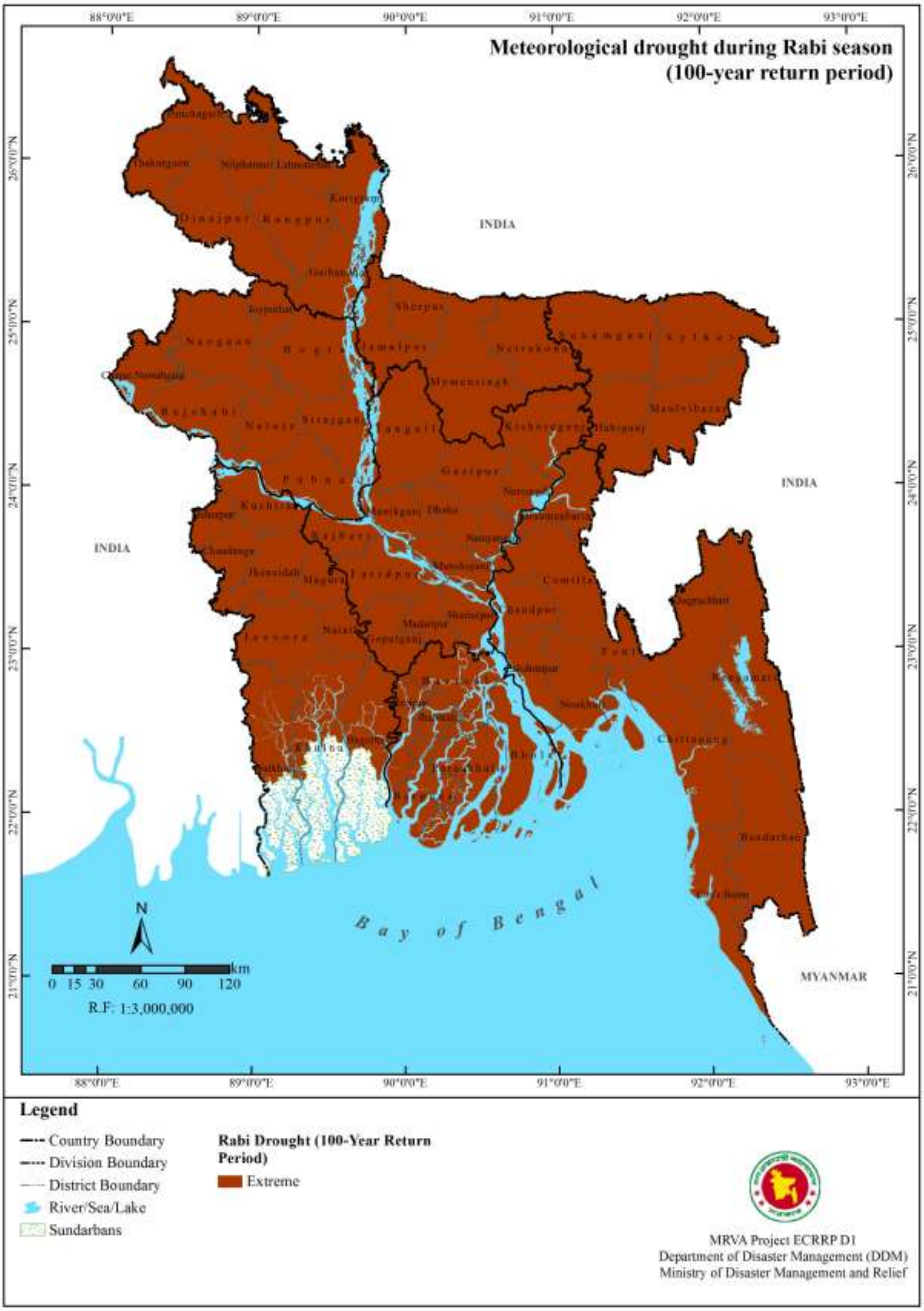


Figure 3.62: Meteorological drought during Rabi season (November to April)

3.5.5 Application of Maps

The output products of this study provide an essential step toward addressing the issue to drought vulnerability in the country and can be used in guide for drought management strategies for mitigation purposes. Identifying regional vulnerabilities can lead to adjustment in practices in water resource sectors and can help decision makers to take the drought into account from hazard perspective and include the concept of drought vulnerability into natural resource planning. This can further help the decision makers to select suitable strategy for food security, cropping pattern and resource mobilization.

3.5.6 Special Remarks

Besides its advantages, practical applications of the SPI possess some disadvantages (Guttman, 1999). One of the limitations includes:

SPI analysis has its strength in identifying temporal variation in precipitation at different locations with respect to their climatological values, but there is not much value in spatial comparison of SPI to identify drought prone area.

3.5.7 Recommendations

Since localized irrigation schemes exist in some of the drought prone areas, more detailed data of such schemes may be incorporated in detailed localized studies for drought hazard assessment.

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References

World Risk Report, (2013). Developed by UN_EHS and University of Bonn for Alliance Development Works. Accessed on 10 April, 2014.

http://www.worldriskreport.org/fileadmin/PDF/2013/WorldRiskReport_2013_online.pdf

Ministry of Finance, (2010). Strategic Program for Climate Resilience: Bangladesh, 2010. Economic Relations Division, Website: www.climateinvestmentfunds.org/cif/node/2416. Accessed on 12 April, 2015.

Strategic Program for Climate Resilience, (2010). Climate Investment funds, Meeting of the PPCR Sub-Committee, Washington, D.C.

UNISDR, (2008). "Indicators of Progress: Guidance on Measuring the Reduction of Disaster Risks and the Implementation of the Hyogo Framework for Action" January 2008; Table 4.4, page 13.

UNISDR, (2012). UNISDR Annual Report 2012.

World Bank, (2014). Bangladesh country Profile. http://www.worldbank.org/en/country/bangladesh. Accessed on 10 April, 2014.

Flood Hazard

Adaptation Learning Mechanism, (2015). http://www.adaptationlearning.net/bangladesh/profile. Accessed on 10 April, 2014.

BBS, (2012). Bangladesh Population Census, 2011, Bangladesh Statistical Yearbook 2012. Bangladesh Bureau of Statistics, Ministry of Planning, Government of Bangladesh.

BWDB, (2012). Hydro-meteorological data observations, Water Bangladesh Water Development Board, Ministry of Water Resources, Bangladesh.

Cruger Consult, (1992). Flood Hydrology Study under FAP-25: Flood Modelling and Management, Main Report, June 1992.

DHI, (2004). Study on Natural reverse flow in the Tonle Sap river, Danish Hydraulic Institute (DHI) Water & Environment/Mekong River Commission Secretariat, Vientiane

Goswami, (1985). Brahmaputra River, Assam India: Phisiography, Basin Denudation and Channel Aggradation. American Geophysical Union, Paper No. 5W0234.

IWM, (2012). Regional Hydrological Models of Bangladesh, 2012.

MPO, (1986). Technical Report No. 11: Floods and Storms under National Water Plan in Master Plan Organisation. Assisted by UNDP and BRD consultants: Harza, M. MacDonald, Meta Systems, Engineering and Planning Consultants, March 1986.

WARPO, (2005). National Adaptation Program of Action (NAPA): Water, Coastal Areas, Natural Disaster & Health Sector, Water Resources Planning Organization (WARPO), Dhaka.

Storm Surge Hazard

CDMP, (2009). Tsunami and storm surge risk maps of Bangladesh. Institute of Water Modelling.

Emanuel, K., R. Sundararajan, and J. Williams, (2008). Hurricanes and global warming: Results from downscaling IPCC AR4 simulations. Bull. Am. Meteorol. Soc., 89, 347–367.

Harper, B. A. and Holland, (1999). An updated parametric model of the tropical cyclone, pp.893-896

Harper, B. A. Harper, B.A., Hardy, T.A., Mason, L.B., Bode, L., Young, I.R. and Neilson, P, (2001). Queensland Climate change and community vulnerability to tropical cyclones, Ocean Hazard Assessment – Stage 1, Report, Department of Natural Resources and Mines, Queensland, Brisbane, Australia, 368p.

Holland, G. J., (1980). An Analytic Model of the Wind and Pressure Profiles in Hurricanes. Monthly Weather Bulleting, (American Meteorological Society), V108, 1212-1248.

IPCC, (2014). Fifth Assessment Report (AR5) of the United Nations Intergovernmental Panel on Climate Change (IPCC).

IWM, (2013). Hydraulic and Morphological Modelling Study to Aid Technical Feasibility Studies & detailed Design for Coastal Embankment Improvement Project (CEIP). Done by Institute of Water Modelling. Client: Bangladesh Water Development Board.

IWM-DHI, (2001). Hydraulic Modelling Study, Second Coastal Embankment Rehabilitation Project (CERP). Done by Institute of Water Modelling. Client: Bangladesh Water Development Board.

IWM and BCAS, (2013). Local Level Hazard maps for Flood, Storm Surge and Salinity. A Study Report by IWM and BCAS for Comprehensive Disaster Management Programme (CDMP) II, Ministry of Disaster Management and Relief, Bangladesh.

Murakami, H., M. Sugi, and A. Kitoh, (2013). Future changes in tropical cyclone activity in the North Indian Ocean projected by high-resolution MRI-AGCMs. Climate Division, 40, 1949–1968

Amal C. Phadke, Christopher D. Martino, Kwok Fai Cheung, Samuel H. Houston, (2003). Modelling of tropical cyclone winds and waves for emergency management, Ocean Engineering, V.30 (4), pp.553-578.

Schloemer, R. W., (1954). Analysis and Synthesis of Hurricane Wind Patterns over Lake Okechobee, Fl. Hydromet Rep., 31, 49pp.

SAARC, (2007). South Asia Disaster Report. www.saarc-smdc.nic.in/sdr_p.asp. Accessed on 10 April, 2014.

Vecchi, G. A., and B. J. Soden, (2007). Effect of remote sea surface temperature change on tropical cyclone potential intensity. Nature, 450, 1066–1069

WAPRO, (2005). Impact Assessment of Climate Change on Coastal Zone of Bangladesh. Water Resources Planning Organisation, Ministry of Water Resources, Dhaka.

Young, I. R. And Sobey, R. J., (1981). The numerical prediction of tropical cyclone wind-waves, James Cook University of North Queensland, Townville, Department of Civil and Systems Engineering Research Bulleting No. CS20

Yu, J., Y. Wang, and K. Hamilton, (2010). Response of tropical cyclone potential intensity to a global warming scenario in the IPCC AR4 CGCMs. J. Climatology, 23, 1354–1373

Landslide Hazard

ADPC, (2012a). Report on the Landslide Hazard Zonation mapping at Cox's Bazaar and Teknaf in Bangladesh – A Comprehensive Disaster Management Programme CDMP-II publication by Data Experts (Pvt.) Limited and ADPC.

ADPC, (2012b). "Multi Hazard Risk Assessment in the Rakhine State of Myanmar, Part I": Landslide hazard assessment part (47 – 57). DPC report.

Aleotti, P and Chowdhury R, (1999). Landslide hazard assessment: summary review and new perspectives. Bulletin of Engineering Geology and the Environment. 58 (1), pp 21-44.

Amanullah Bin Mahmood and Mamunul H. Khan, (2008). Landslide Vulnerability of Bangladesh Hills and Sustainable Management Options: A Case Study of 2007 Landslide in Chittagong City. International Seminar on "Management and Mitigation of Water Induced Disaster" to be held on 21-22 April 2008 in Kathmandu, Nepal.

BMD, (2013). Rainfall data of Bangladesh. Bangladesh Meteorological Department, Dhaka.

CDMP, (2011). Rainfall Triggered Landslide Hazard Zonation in Cox's Bazar and Teknaf Municipalities. Unpublished report of ADPC and data-EX for Comprehensive Disaster Management Programme-II.

Champati Ray, P. K., Lakhera, R. C., (2004). Landslide Hazards in India, Proc. Asian Workshop on Regional Capacity Enhancement for Landslide Mitigation (RECLAIM), organized by Asian Disaster Preparedness Centre (ADPC), Bangkok and Norwegian Geo-technical Institute, Oslo.

Chau, K.T., Y.L. Sze, M.K. Fung, W.Y. Wong, E.L. Fong, L.C.P. Chan, (2004). Landslide hazard analysis for Hong Kong using landslide inventory and GIS. Computers and Geosciences 30, 429–443.

Das I. C., (2011). Spatial statistical modelling for assessing landslide hazard and vulnerability, PhD thesis at ITC, The Netherlands (p 77).

Islam, N. (1994). Urban land management in Bangladesh: The status and issues. The Urban Management Programme-Asia Occasional Paper 12. Urban Management Programme Regional Office for Asia and Pacific.

Khatsu Petevilie, (2005). "Urban multi-hazard risk analysis using GIS and Remote Sensing: A case study of landslide, earthquake and fire hazard in a part of Kohima Town, India". Unblished M.Sc. thesis of ITC – IIRS joint education programme.

Lee S., Choi J., Min K., (2002). Landslide susceptibility analysis and verification using the Bayesian probability model. Env. Geol. 43, 120-131.

Hamidur Rahman Md. and Younus Ahmed Khan, (1995). Landslides and Stability of Coastal Cliffs of Cox's Bazar Area, Bangladesh Natural Hazards 12: 101-118, 1995.

Nadim Farrokh, Oddvar Kjekstad, Pascal Peduzzi, Christian Herold, Christian Jaedicke, (2006). Global landslide and avalanche hotspots. Landslides, 3: 159 – 173.

NBRO, (1995). Landslide Hazard Zonation project, Sri Lanka. Landslide Studies and Services Division of National Building Research Organization, Colombo.

Norman, P.S., (1992). "Evaluation of the Barapukuria coal deposit NW Bangladesh". Geological Society, London, Special Publications (Geological Society of London) 63: 107. doi:10.1144/GSL.SP.1992.063.01.10. Retrieved April 27, 2010.

Organization of American States, (2002). Primer on Natural Hazard Management in Integrated Regional Development Planning. Chapter 10: Landslide Hazard Assessment. Publication of Organization of American States. http://www.oas.org/dsd/publications/unit/oea66e/begin.htm#Contents. Accessed on 25 July, 2014.

Technical Report, (2008). Identification of Landslide causes and recommendations for risk reduction. Chittagong Divisional Office, Chittagong, Bangladesh.

USGS and GSB, (2001). Digital Geologic and Geophysical Data of Bangladesh. U.S. Geological Survey Open File Report 97-470H.

WARPO, (2012). Land Use map of Bangladesh, Water Resources Planning Organisation.

ASTER DEM, (2013). http://www.jspacesystems.or.jp/ersdac/GDEM/E/4.html

Drought Hazard

Aguilar E., J. Soley, L. Aguilar, J. J. Sinay,T. C. Peterson, I. Gonza´lez Garci´a, J. L. Va´zquez, B. Olmedo, L. A and R. Mayorga lvarez, E. Sa´nchez, M. Baca, P. Rami´rez Obando, R. M. Araujo, M. Bautista, R. Frutos, A. Rosa Santos, C. Castan˜o´n, G. I. Herna´ndez Oviedo, M. Gutie´rrez, C. E. Ojeda Espinoza, C. Centella, R. Nu´n˜ ez, J. A. Retana, V. E. Valle, L. Herrera, F. Obed, M. Solera, M. Brunet, E. Ruano, J. E. Salgado, J. Espinosa, M. Haylock, D. Marti´nez, H. Benavides, (2005). Changes in precipitation and temperature extremes in Central America and northern South America, 1961–2003. Journal of Geophysical Research, 110, D23107, doi:10.1029/2005JD006119.

Ahmed R., Bernard A., (1989). Rice price fluctuation and an approach to price stabilization in Bangladesh. International Food Policy Research Institute, Washington.

Ahmed Rafique and Il-Kon Kim, (2003). Patterns of daily rainfall in Bangladesh during the Summer Monsoon Season: Case Studies at Three Stations, Physical Geography 24 (4):295-318 ·

Alexander D, (1995). Changing perspectives on natural hazards in Bangladesh. Nat Hazards Obs. 10 (1):1–2.

Banerji, S.; Chabra, B. M., (1964). Drought characteristics and estimating probabilities of their occurrences. In Surface waters symposium. Publication No. 63, 189–192, Belgium. Belgium: WMO/IASH

Bhalme H.N., Mooley D.A., (1980). Large scale droughts/floods and monsoon circulation. Monthly Weather Review, 108: 1197–1211.

Biswas P.R., (1995). Food: stock, import and price. Dhaka Cour 11(34): 9.

BMD, (2013). Meteorological data of Bangladesh, Bangladesh Meteorological Department, Ministry of Defence, Government of Bangladesh.

Brammer, H., (1987). Drought in Bangladesh: Lessons for planners and administrators. Disasters, 11 (1). 21–29.

Byun Hi-Ryong and Donald A. Wilhite, (1999). Objective Quantification of Drought Severity and Duration American Meteorological Society, 2747 – 2756.

Cordery, I. and M. McCall, (2000). A Model for Forecasting Drought from Teleconnections. Water Resources Research 36:763-768.

Conrad, V.; L.W. Pollak. (1950). Methods in Climatology. Harvard University Press.

Dash, B.K., M. Rafiuddin, F. Khanam, and M.N. Islam, (2012). Characteristics of Meteorological Drought in Bangladesh. Natural Hazards 64 (2):1461-1474.

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

Erickson N.J., Ahmad Q.K., Chowdhury A.R., (1993). Socio-economic implications of climate change for Bangladesh. Bangladesh Unnayan Parishad, Dhaka.

ESRI, (2004). Arc Map 9.1. Environmental Systems Research Institute, Redlands, California.

FAO, (1999). World Soils Book Series - Scientific Figure on Research Gate. https://www.researchgate.net/278652497_fig1_Figure-3-13-Crop-calendar-of-Bangladesh. Accessed 7 Apr, 2014.

Gibbs W.J., Maher JV., (1967). Rainfall deciles as drought indicators. Australian Bureau of Meteorology Bulletin 48, Commonwealth of Australia: Melbourne.

Government of Bangladesh, (2005). National Action Programme (NAP) for combating desertification, Ministry of Environment and Forests, Government of the People's Republic of Bangladesh, Bangladesh Secretariat, Dhaka. http://www.doe-bd.org/nap_2006.pdf. Accessed on 21 Oct 2014.

Guttman N.B., (1998). Comparing the Palmer drought index and the standardized precipitation index. J Am Water Resources Association. 34 (1): 113–121.

Habiba Umma, Rajib Shaw & Yukiko Takeuchi, (2011). Drought risk reduction through a Socio-economic, Institutional and Physical approach in the northwestern region of Bangladesh, Environmental Hazards, 10:2, 121-138, DOI: 10.1080/17477891.2011.582311

Habiba U. and Shaw R., (2013). Enhancing Farmers Resilience to Cope with Climate Induced Drought in Northwestern Bangladesh. Journal of Disaster Research, 8 (1), 203-204.

Samsuddin Shahid and Manul Hazarika, (2010). Ground water Drought in Northwestern districts of Bangladesh, Water Resources Management, 24: 1989-2006.

http://www.irri.cgiar.org/publications/wrrc/wrrcPDF/session6-06.pdf. Accessed on 29 Oct 2014.

IPCC, (2007). Regional climate projections. In: Solomon, S.D., Qin, M., Manning, Z., Chen, M., Marquis, K.B., Averyt, M.T., Miller, H.L. (Eds.) Climate change 2007: the physical science basis. Fourth assessment report of the intergovernmental panel on climate change (IPCC), Cambridge University Press, Cambridge, UK.

Isaaks, H.E. and Srivastava, R.M., (1989). An Introduction to Applied Geostatisitics. Oxford University Press.

Jabbar M.A., (1990). Causes and effects of drought/aridity in Bangladesh using remote sensing technology. In: Proceedings of ESCAP workshop on remote sensing technology in application to desertification/vegetation type mapping, Tehran.

Jabbar M.A, Chaudhury M.U., Huda M.H.Q., (1982). Causes and effects of increasing aridity in Northwest Bangladesh. In: Proceedings of first thematic conference on remote sensing of arid and semi-arid lands, Cairo, Egypt.

Journel, A.G. and C. J. Huijbregts, (1981). Mining Geostatistics. Academic Press, New York.

Karim Z, Ibrahim A, Iqbal A, Ahmed M, (1990). Drought in Bangladesh agriculture and irrigation schedule for major crops, Bangladesh Agricultural Research Center (BARC) Publication No. 34, Dhaka.

Karim Z, Iqbal M.A, (2001). Impact of land degradation in Bangladesh: changing scenario in agricultural land use, Bangladesh Agricultural Research Center (BARC), Dhaka.

Kohler, M., (1949). On the Use of Double Mass Analysis for Testing the Consistency of Meteorological Records and for Making Required Adjustments. Bulletin of the American Meteorological Society 30:188-189.

Lloyd-Hughes B, Saunders M.A., (2002). A drought climatology for Europe. International Journal of Climatology 22: 1571–1592.

LPDAAC, (2014). MODIS Products - Vegetation Indices 16-day. https://lpdaac.usgs.gov/products/modis_products_table/mod13q1. Accessed 7 Apr., 2014.

Mazid M.A., Mortimer M.A., Riches C.R., Orr A, Karmaker B, Ali A, Jabbar MA, Wade LJ (2005). Rice establishment in drought-prone areas of Bangladesh. In: Toriyama K., Heong K.L., Hardy B. (eds) Rice is life: scientific perspectives for the 21st century. International Rice Research Institute, Manila (Philippines).

McKee T.B., Doesken N.J., Kleist J., (1993). The relationship of drought frequency and duration to time scales. Eighth Conference on Applied Climatology, American Meteorological Society: Jan. 17–23, Anaheim CA; 179–186.

National Drought Mitigation Center, (2006). What is drought? Understanding and defining drought, http://www.drought.unl.edu/whatis/concept.htm. Accessed on 29 Oct 2013.

Paul B.K., (1998). Coping mechanisms practiced by drought victims (1994/5) in North Bengal, Bangladesh. Applied Geography. 18 (4): 355–373.

Panofsky, H. A. and Brier, G. W. (1968). Some Applications of Statistics to Meteorology, The Pennsylvania State University, University Park, PA, USA, 224.

Thomas C. Peterson, David R. Easterling, Thomas R. Karl, Pavel Groisman, Neville Nicholls, Neil Plummer, Simon Torok, Ingeborg Auer, Reinhard Boehm, Donald Gullett, Lucie Vincent, Raino Heino, Heikki Tuomenvirta, Olivier Mestre, Tama Szentimrey, James Salinger, Eirik J. Førland, Inger Hanssen-Bauer, Hans Alexandersson, Philip Jones and David Parker, (1998). Homogeneity Adjustments of In-situ Atmospheric Climate Data: A Review. International Journal of Climatology, 18: 1493 – 1517.

Rahman A and Biswas P.R., (1995). Devours resources. Dhaka Courier. 11 (42): 7–8.

Rahman, M.W. and Parvin, L., (2009). Impact of Irrigation on Food Security in Bangladesh for the Past Three Decades. Journal of Environmental Protection, 1, 40-49.

Rasheed K.B.S., (1998). Status of land resource use and desertification, drought and land degradation in Bangladesh: obstacles and effective policy options and measures for sustainable use of land resources. In: Proceedings of the national awareness seminar on combating land degradation/desertification in Bangladesh.

Rashid H.E., (1991). Geography of Bangladesh. University Press Ltd, Dhaka.

Saleh A.F.M., Mazid M.A., Bhuiyan S.I., (2000). Agro hydrologic and drought-risk analyses of rainfed cultivation in northwest Bangladesh. In: Tuong TP, Kam SP, Wade LJ, Pandey S, Bouman BAM, Hardy B. (eds.) Characterizing and understanding rainfed environments. International Rice Research Institute, Manila (Philippines).

Shahid, S., Nath, S.K., Roy, J. (2000) 'Ground water potential modelling in a softrock area using GIS', International Journal of Remote Sensing, 21 (9), 1919–1924.

Shahid, S., Chen, X. and Hazarika, M. K., (2005). Assessment aridity of Bangladesh using geographic information system, Dhaka, Bangladesh.

Shahid, S., 2008. Spatial and Temporal Characteristics of Droughts in the Western Part of Bangladesh. Hydrological Processes, 22 (13), 2235-2247.

Shahid, S., (2010). Recent trends in the climate of Bangladesh. Climate Research, 42 (3), 185-193.

Shahid, S. and Behrawan, H., (2008). Drought risk assessment in the western part of Bangladesh, J. of Natural Disaster, 46 (3): 391-413.

Shahid, S and Hazarika, M. K., (2010). Groundwater drought in the northwestern districts of Bangladesh, Water Resources Management, 24:1989–2006, DOI 10.1007/s11269-009-9534-y.

Su, B.D., Jiang, T. and Jin, W.B., (2006). 'Recent trends in observed temperature and precipitation extremes in the Yangtze River basin, China', Theoretical Applied Climatology, 83, 139–151.

Thenkabail, P. S., Gamage, M. S. D. N., Smakhtin, V. U., (2004). The use of remote sensing data for drought assessment and monitoring in Southwest Asia. Research Report 85. Colombo, Sri Lanka: International Water Management Institute.

Van Beers, W.C. and J.P. Kleijnen, (2004). Kriging Interpolation in Simulation: A Survey. In: Proceedings of the 2004 Winter Simulation Conference, R.G. Ingalls, M.D. Rossetti, J.S. Smith, and B.A. Peters (Editors). Washington, D.C.

Vogt J. V. and F. Somma (Eds.) (2000). Drought and Drought Mitigation in Europe, Kluwer Academic Publishers.

WARPO-EGIC, (1996). An atlas of selected maps and spatial data in Bangladesh. Jointly published by Water Resources Planning Organization and Environmental and Geographic Information Center, Dhaka, Bangladesh.

Wilhite D.A., Glantz M.H., (1985). Understanding the drought phenomenon: the role of definitions. Water International 10 (3): 111–120.

Wilhite, D.A., Glantz, M.H., (1987). In Understanding the drought phenomenon: the role of definitions. Wilhite, D.A., Easterling, W.E., Wood, D.A. (Eds.). Planning for Drought. Vestview Press, Boulder CO, USA.

Wood D.A. (eds)., (1987). Planning for Drought. Vest view Press: Boulder, CO; 11–27.

World Bank, (2000). Bangladesh agriculture in the 21st century. World Bank Bangladesh Publication, Dhaka.

Yen, B. C., (1970). Risks in hydrologic design of engineering projects. J. Hydr. Div. ASCE, 96 (4), 959–966.

Yen, B. C., (1989). Engineering approaches to risk and reliability analysis. 'Risk analysis and management of natural and man-made hazards', Y. Y. Haimes and E. Z. Stakhiv, eds., ASCE, 22–49.

You, Q., Kang, S., Aguilar, E. and Yan, Y., (2008). 'Changes in daily climate extremes in the eastern and central Tibetan plateau during 1961–2005', J Geophysical Research. doi:10.1029/2007JD009389.

Earthquake Hazard

Alam, E., Dominey-Howes, D., Chagué-Goff, C., and Goff, J., (2012). Tsunamis of the northeast Indian Ocean with a particular focus on the Bay of Bengal region-A synthesis and review. Earth-Science Reviews, 114, 175–193.

BNBC, (1993), Bangladesh National Building Code-1993, Housing and Building Research Institute, Dhaka, Bangladesh.

Choudhury, Jamilur Reza, (2005), Options for Urban Disaster Risk Management: The Bangladesh Experience, Paper presented at the National Workshop on "Options for Urban Disaster Risk Management in Bangladesh" organized by the Comprehensive Disaster Management Programme, MoFDM.

DDM, (2011). Previous website of DDM. http://old.ddm.gov.bd/earthquake.php

CDMP-II, Ministry of Disaster Management and Relief (2014). Seismic Risk Assessment in Bangladesh for Bogra, Dinajpur, Mymensingh, Rajshahi and Tangail City Corporation/Paurashava Areas, Bangladesh. Government of Peoples Republic of Bangladesh.

Technological Hazard

Paul, H. L., Antunes, A. P. M., Covington, A. D., Evans, P. Phillips, P. S., (2013). Bangladeshi leather industry: An overview of recent sustainable developments. Journal- Society of Leather Technologists and Chemists 97:25-32.

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Annexure – I: Division/District/Upazila codes as used in Census, 2011 by BBS

Table A1.1 : Division/District/Upazila codes as used in Census, 2011 by BBS

Division	District	Upazila	Name of Upazila
10	**BARISAL DIVISION**		
10	**4**	**BARGUNA**	
10	4	9	AMTALI
10	4	19	BAMNA
10	4	28	BARGUNA SADAR
10	4	47	BETAGI
10	4	85	PATHARGHATA
10	**6**	**BARISAL**	
10	6	2	AGAILJHARA
10	6	3	BABUGANJ
10	6	7	BAKERGANJ
10	6	10	BANARIPARA
10	6	32	GAURNADI
10	6	36	HIZLA
10	6	51	BARISAL SADAR
10	6	62	MEHENDIGANJ
10	6	69	MULADI
10	6	94	WAZIRPUR
10	**9**	**BHOLA**	
10	9	18	BHOLA SADAR
10	9	21	BURHANUDDIN
10	9	25	CHAR FASSON
10	9	29	DAULAT KHAN
10	9	54	LALMOHAN
10	9	65	MANPURA
10	9	91	TAZUMUDDIN
10	**42**	**JHALOKATI**	
10	42	40	JHALOKATI SADAR
10	42	43	KANTHALIA
10	42	73	NALCHITY
10	42	84	RAJAPUR
10	**78**	**PATUAKHALI**	
10	78	38	BAUPHAL
10	78	52	DASHMINA
10	78	55	DUMKI
10	78	57	GALACHIPA
10	78	66	KALA PARA

Division	District	Upazila	Name of Upazila
10	78	76	MIRZAGANJ
10	78	95	PATUAKHALI SADAR
10	**79**	**PIROJPUR**	
10	79	14	BHANDARIA
10	79	47	KAWKHALI
10	79	58	MATHBARIA
10	79	76	NAZIRPUR
10	79	80	PIROJPUR SADAR
10	79	87	NESARABAD (SWARUPKATI)
10	79	90	ZIANAGAR
20	**CHITTAGONG DIVISION**		
20	**3**	**BANDARBAN**	
20	3	4	ALIKADAM
20	3	14	BANDARBAN SADAR
20	3	51	LAMA
20	3	73	NAIKHONGCH HARI
20	3	89	ROWANGCHHARI
20	3	91	RUMA
20	3	95	THANCHI
20	**12**	**BRAHMANBARIA**	
20	12	2	AKHAURA
20	12	4	BANCHHARAMPUR
20	12	7	BIJOYNAGAR
20	12	13	BRAHMANBAR IA SADAR
20	12	33	ASHUGANJ
20	12	63	KASBA
20	12	85	NABINAGAR
20	12	90	NASIRNAGAR
20	12	94	SARAIL
20	**13**	**CHANDPUR**	
20	13	22	CHANDPUR SADAR
20	13	45	FARIDGANJ
20	13	47	HAIM CHAR
20	13	49	HAJIGANJ
20	13	58	KACHUA

Division	District	Upazila	Name of Upazila
20	13	76	MATLAB
20	13	79	UTTAR MATLAB
20	13	95	SHAHRASTI
20	**15**	**CHITTAGONG**	
20	15	4	ANOWARA
20	15	6	BAYEJID BOSTAMI THANA
20	15	8	BANSHKHALI
20	15	10	BAKALIA THANA
20	15	12	BOALKHALI
20	15	18	CHANDANAISH
20	15	19	CHANDGAON THANA
20	15	20	CHITTAGONG PORT THANA
20	15	28	DOUBLE MOORING THANA
20	15	33	FATIKCHHARI
20	15	35	HALISHAHAR THANA
20	15	37	HATHAZARI
20	15	39	KARNAFULI THANA
20	15	41	KOTWALI THANA
20	15	43	KHULSHI THANA
20	15	47	LOHAGARA
20	15	53	MIRSHARAI
20	15	55	PAHARTALI THANA
20	15	57	PANCHLAISH THANA
20	15	61	PATIYA
20	15	65	PATENGA THANA
20	15	70	RANGUNIA
20	15	74	RAOZAN
20	15	78	SANDWIP
20	15	82	SATKANIA
20	15	86	SITAKUNDA
20	**19**	**COMILLA**	
20	19	9	BARURA
20	19	15	BRAHMAN PARA
20	19	18	BURICHANG

Division	District	Upazila	Name of Upazila
20	19	27	CHANDINA
20	19	31	CHAUDDAGRAM
20	19	33	COMILLA SADAR DAKHIN
20	19	36	DAUDKANDI
20	19	40	DEBIDWAR
20	19	54	HOMNA
20	19	67	COMILLA ADARSHA SADAR
20	19	72	LAKSAM
20	19	74	MANOHARGANJ
20	19	75	MEGHNA
20	19	81	MURADNAGAR
20	19	87	NANGALKOT
20	19	94	TITAS
20	**22**	**COX'S BAZAR**	
20	22	16	CHAKARIA
20	22	24	COX'S BAZAR SADAR
20	22	45	KUTUBDIA
20	22	49	MAHESHKHALI
20	22	56	PEKUA
20	22	66	RAMU
20	22	90	TEKNAF
20	22	94	UKHIA
20	**30**	**FENI**	
20	30	14	CHHAGALNAIYA
20	30	25	DAGANBHUIY AN
20	30	29	FENI SADAR
20	30	41	FULGAZI
20	30	51	PARSHURAM
20	30	94	SONAGAZI
20	**46**	**KHAGRACHHARI**	
20	46	43	DIGHINALA
20	46	49	KHAGRACHHARI SADAR
20	46	61	LAKSHMICHHARI
20	46	65	MAHALCHHARI
20	46	67	MANIKCHHARI
20	46	70	MATIRANGA
20	46	77	PANCHHARI
20	46	80	RAMGARH

Division	District	Upazila	Name of Upazila
20	**51**	**LAKSHMIPUR**	
20	51	33	KAMALNAGAR
20	51	43	LAKSHMIPUR SADAR
20	51	58	ROYPUR
20	51	65	RAMGANJ
20	51	73	RAMGATI
20	**75**	**NOAKHALI**	
20	75	7	BEGUMGANJ
20	75	10	CHATKHIL
20	75	21	COMPANIGANJ
20	75	36	HATIYA
20	75	47	KABIRHAT
20	75	80	SENBAGH
20	75	83	SONAIMURI
20	75	85	SUBARNA CHAR
20	75	87	NOAKHALI SADAR (SUDHARAM)
20	**84**	**RANGAMATI**	
20	84	7	BAGHAI CHHARI
20	84	21	BARKAL
20	84	25	KAWKHALI (BETBUNIA)
20	84	29	BELAI CHHARI
20	84	36	KAPTAI
20	84	47	JURAI CHHARI
20	84	58	LANGADU
20	84	75	MANIARCHAR
20	84	78	RAJASTHALI
20	84	87	RANGAMATI SADAR
30	**DHAKA DIVISION**		
30	**26**	**DHAKA**	
30	26	2	ADABAR THANA
30	26	3	ASHULIA THANA
30	26	4	BADDA THANA
30	26	5	BANGSHAL THANA
30	26	06	BIMANBANDA R THANA
30	26	8	CANTONMENT THANA
30	26	9	CHAK BAZAR

Division	District	Upazila	Name of Upazila
			THANA
30	26	10	DAKSHINKHAN THANA
30	26	11	DARUS SALAM THANA
30	26	12	DEMRA THANA
30	26	14	DHAMRAI
30	26	16	DHANMONDI THANA
30	26	18	DOHAR
30	26	24	GENDARIA THANA
30	26	26	GULSHAN THANA
30	26	28	HAZARIBAGH THANA
30	26	29	JATRABARI THANA
30	26	30	KAFRUL THANA
30	26	32	KADAM TALI THANA
30	26	33	KALABAGAN THANA
30	26	34	KAMRANGIR CHAR THANA
30	26	36	KHILGAON THANA
30	26	37	KHILKHET THANA
30	26	38	KERANIGANJ
30	26	40	KOTWALI THANA
30	26	42	LALBAGH THANA
30	26	48	MIRPUR THANA
30	26	50	MOHAMMADPUR THANA
30	26	54	MOTIJHEEL THANA
30	26	62	NAWABGANJ
30	26	63	NEW MARKET THANA
30	26	64	PALLABI THANA
30	26	65	PALTAN THANA
30	26	66	RAMNA THANA
30	26	67	RAMPURA THANA
30	26	68	SABUJBAGH THANA
30	26	72	SAVAR

Division	District	Upazila	Name of Upazila
30	26	74	SHAH ALI THANA
30	26	75	SHAHBAG THANA
30	26	76	SHYAMPUR THANA
30	26	80	SHER-E-BANGLA NAGAR THANA
30	26	88	SUTRAPUR THANA
30	26	90	TEJGAON THANA
30	26	92	TEJGAON IND.AREA THANA
30	26	93	TURAG THANA
30	26	95	UTTARA THANA
30	26	96	UTTAR KHAN THANA
30	**29**	**FARIDPUR**	
30	29	3	ALFADANGA
30	29	10	BHANGA
30	29	18	BOALMARI
30	29	21	CHAR BHADRASAN
30	29	47	FARIDPUR SADAR
30	29	56	MADHUKHALI
30	29	62	NAGARKANDA
30	29	84	SADARPUR
30	29	90	SALTHA
30	**33**	**GAZIPUR**	
30	33	30	GAZIPUR SADAR
30	33	32	KALIAKAIR
30	33	34	KALIGANJ
30	33	36	KAPASIA
30	33	86	SREEPUR
30	**35**	**GOPALGANJ**	
30	35	32	GOPALGANJ SADAR
30	35	43	KASHIANI
30	35	51	KOTALIPARA
30	35	58	MUKSUDPUR
30	35	91	TUNGIPARA
30	**48**	**KISHOREGANJ**	
30	48	2	AUSTAGRAM
30	48	6	BAJITPUR

Division	District	Upazila	Name of Upazila
30	48	11	BHAIRAB
30	48	27	HOSSAINPUR
30	48	33	ITNA
30	48	42	KARIMGANJ
30	48	45	KATIADI
30	48	49	KISHOREGANJ SADAR
30	48	54	KULIAR CHAR
30	48	59	MITHAMAIN
30	48	76	NIKLI
30	48	79	PAKUNDIA
30	48	92	TARAIL
30	**54**	**MADARIPUR**	
30	54	40	KALKINI
30	54	54	MADARIPUR SADAR
30	54	80	RAJOIR
30	54	87	SHIB CHAR
30	**56**	**MANIKGANJ**	
30	56	10	DAULATPUR
30	56	22	GHIOR
30	56	28	HARIRAMPUR
30	56	46	MANIKGANJ SADAR
30	56	70	SATURIA
30	56	78	SHIBALAYA
30	56	82	SINGAIR
30	**59**	**MUNSHIGANJ**	
30	59	24	GAZARIA
30	59	44	LOHAJANG
30	59	56	MUNSHIGANJ SADAR
30	59	74	SERAJDIKHAN
30	59	84	SREENAGAR
30	59	94	TONGIBARI
30	**67**	**NARAYANGANJ**	
30	67	2	ARAIHAZAR
30	67	4	SONARGAON
30	67	6	BANDAR
30	67	58	NARAYANGANJ SADAR
30	67	68	RUPGANJ
30	**68**	**NARSINGDI**	
30	68	7	BELABO
30	68	52	MANOHARDI

Division	District	Upazila	Name of Upazila
30	68	60	NARSINGDI SADAR
30	68	63	PALASH
30	68	64	ROYPURA
30	68	76	SHIBPUR
30	**82**	**RAJBARI**	
30	82	7	BALIAKANDI
30	82	29	GOALANDAGH AT
30	82	47	KALUKHALI
30	82	73	PANGSHA
30	82	76	RAJBARI SADAR
30	**86**	**SHARIATPUR**	
30	86	14	BHEDARGANJ
30	86	25	DAMUDYA
30	86	36	GOSAIRHAT
30	86	65	NARIA
30	86	69	PALONG (SADAR)
30	86	94	ZANJIRA
30	**93**	**TANGAIL**	
30	93	9	BASAIL
30	93	19	BHUAPUR
30	93	23	DELDUAR
30	93	25	DHANBARI
30	93	28	GHATAIL
30	93	38	GOPALPUR
30	93	47	KALIHATI
30	93	57	MADHUPUR
30	93	66	MIRZAPUR
30	93	76	NAGARPUR
30	93	85	SAKHIPUR
30	93	95	TANGAIL SADAR
40	**KHULNA DIVISION**		
40	**1**		**BAGERHAT**
40	1	8	BAGERHAT SADAR
40	1	14	CHITALMARI
40	1	34	FAKIRHAT
40	1	38	KACHUA
40	1	56	MOLLAHAT
40	1	58	MONGLA
40	1	60	MORRELGANJ

Division	District	Upazila	Name of Upazila
40	1	73	RAMPAL
40	1	77	SARANKHOLA
40	**18**	**CHUADANGA**	
40	18	7	ALAMDANGA
40	18	23	CHUADANGA SADAR
40	18	31	DAMURHUDA
40	18	55	JIBAN NAGAR
40	**41**	**JESSORE**	
40	41	4	ABHAYNAGAR
40	41	9	BAGHER PARA
40	41	11	CHAUGACHHA
40	41	23	JHIKARGACHHA
40	41	38	KESHABPUR
40	41	47	KOTWALI
40	41	61	MANIRAMPUR
40	41	90	SHARSHA
40	**44**	**JHENAIDAHA**	
40	44	14	HARINAKUNDA
40	44	19	JHENAIDAHA SADAR
40	44	33	KALIGANJ
40	44	42	KOTCHANDPUR
40	44	71	MAHESHPUR
40	44	80	SHAILKUPA
40	**47**	**KHULNA**	
40	47	12	BATIAGHATA
40	47	17	DACOPE
40	47	21	DAULATPUR THANA
40	47	30	DUMURIA
40	47	40	DIGHALIA
40	47	45	KHALISHPUR THANA
40	47	48	KHAN JAHAN ALI THANA
40	47	51	KHULNA SADAR THANA
40	47	53	KOYRA
40	47	64	PAIKGACHHA
40	47	69	PHULTALA
40	47	75	RUPSA
40	47	85	SONADANGA THANA

Division	District	Upazila	Name of Upazila
40	47	94	TEROKHADA
40	**50**	**KUSHTIA**	
40	50	15	BHERAMARA
40	50	39	DAULATPUR
40	50	63	KHOKSA
40	50	71	KUMARKHALI
40	50	79	KUSHTIA SADAR
40	50	94	MIRPUR
40	**55**	**MAGURA**	
40	55	57	MAGURA SADAR
40	55	66	MOHAMMADPUR
40	55	85	SHALIKHA
40	55	95	SREEPUR
40	**57**	**MEHERPUR**	
40	57	47	GANGNI
40	57	60	MUJIB NAGAR
40	57	87	MEHERPUR SADAR
40	**65**	**NARAIL**	
40	65	28	KALIA
40	65	52	LOHAGARA
40	65	76	NARAIL SADAR
40	**87**	**SATKHIRA**	
40	87	4	ASSASUNI
40	87	25	DEBHATA
40	87	43	KALAROA
40	87	47	KALIGANJ
40	87	82	SATKHIRA SADAR
40	87	86	SHYAMNAGAR
40	87	90	TALA
45	**MYMENSINGH**		
45	**39**	**JAMALPUR**	
45	39	7	BAKSHIGANJ
45	39	15	DEWANGANJ
45	39	29	ISLAMPUR
45	39	36	JAMALPUR SADAR
45	39	58	MADARGANJ
45	39	61	MELANDAHA
45	39	85	SARISHABARI
45	**61**	**MYMENSINGH**	
45	61	13	BHALUKA
45	61	16	DHOBAURA
45	61	20	FULBARIA
45	61	22	GAFFARGAON
45	61	23	GAURIPUR
45	61	24	HALUAGHAT
45	61	31	ISHWARGANJ
45	61	52	MYMENSINGH SADAR
45	61	65	MUKTAGACHHA
45	61	72	NANDAIL
45	61	81	PHULPUR
45	61	94	TRISHAL
45	**72**	**NETROKONA**	
45	72	4	ATPARA
45	72	9	BARHATTA
45	72	18	DURGAPUR
45	72	38	KHALIAJURI
45	72	40	KALMAKANDA
45	72	47	KENDUA THANA
45	72	56	MADAN
45	72	63	MOHANGANJ
45	72	74	NETROKONA SADAR
45	72	83	PURBADHALA
45	**89**	**SHERPUR**	
45	89	37	JHENAIGATI
45	89	67	NAKLA
45	89	70	NALITABARI
45	89	88	SHERPUR SADAR
45	89	90	SREEBARDI
50	**RAJSHAHI DIVISION**		
50	**10**	**BOGRA**	
50	10	6	ADAMDIGHI
50	10	20	BOGRA SADAR
50	10	27	DHUNAT
50	10	33	DHUPCHANCHIA
50	10	40	GABTALI
50	10	54	KAHALOO
50	10	67	NANDIGRAM
50	10	81	SARIAKANDI
50	10	85	SHAJAHANPUR
50	10	88	SHERPUR

Division	District	Upazila	Name of Upazila
50	10	94	SHIBGANJ
50	10	95	SONATOLA
50	**38**	**JOYPURHAT**	
50	38	13	AKKELPUR
50	38	47	JOYPURHAT SADAR
50	38	58	KALAI
50	38	61	KHETLAL
50	38	74	PANCHBIBI
50	**64**	**NAOGAON**	
50	64	3	ATRAI
50	64	6	BADALGACHHI
50	64	28	DHAMOIRHAT
50	64	47	MANDA
50	64	50	MAHADEBPUR
50	64	60	NAOGAON SADAR
50	64	69	NIAMATPUR
50	64	75	PATNITALA
50	64	79	PORSHA
50	64	85	RANINAGAR
50	64	86	SAPAHAR
50	**69**	**NATORE**	
50	69	9	BAGATI PARA
50	69	15	BARAIGRAM
50	69	41	GURUDASPUR
50	69	44	LALPUR
50	69	63	NATORE SADAR
50	69	91	SINGRA
50	**70**	**CHAPAI NABABGANJ**	
50	70	18	BHOLAHAT
50	70	37	GOMASTAPUR
50	70	56	NACHOLE
50	70	66	NABABGANJ SADAR
50	70	88	SHIBGANJ
50	**76**	**PABNA**	
50	76	5	ATGHARIA
50	76	16	BERA
50	76	19	BHANGURA
50	76	22	CHATMOHAR
50	76	33	FARIDPUR
50	76	39	ISHWARDI

Division	District	Upazila	Name of Upazila
50	76	55	PABNA SADAR
50	76	72	SANTHIA
50	76	83	SUJANAGAR
50	**81**	**RAJSHAHI**	
50	81	10	BAGHA
50	81	12	BAGHMARA
50	81	22	BOALIA THANA
50	81	25	CHARGHAT
50	81	31	DURGAPUR
50	81	34	GODAGARI
50	81	40	MATIHAR THANA
50	81	53	MOHANPUR
50	81	72	PABA
50	81	82	PUTHIA
50	81	85	RAJPARA THANA
50	81	90	SHAH MAKHDUM THANA
50	81	94	TANORE
50	**88**	**SIRAJGANJ**	
50	88	11	BELKUCHI
50	88	27	CHAUHALI
50	88	44	KAMARKHANDA
50	88	50	KAZIPUR
50	88	61	ROYGANJ
50	88	67	SHAHJADPUR
50	88	78	SIRAJGANJ SADAR
50	88	89	TARASH
50	88	94	ULLAH PARA
55	**RANGPUR DIVISION**		
55	**27**	**DINAJPUR**	
55	27	10	BIRAMPUR
55	27	12	BIRGANJ
55	27	17	BIRAL
55	27	21	BOCHAGANJ
55	27	30	CHIRIRBANDAR
55	27	38	FULBARI
55	27	43	GHORAGHAT
55	27	47	HAKIMPUR
55	27	56	KAHAROLE
55	27	60	KHANSAMA

Division	District	Upazila	Name of Upazila
55	27	64	DINAJPUR SADAR
55	27	69	NAWABGANJ
55	27	77	PARBATIPUR
55	**32**	**GAIBANDHA**	
55	32	21	FULCHHARI
55	32	24	GAIBANDHA SADAR
55	32	30	GOBINDAGANJ
55	32	67	PALASHBARI
55	32	82	SADULLAPUR
55	32	88	SAGHATTA
55	32	91	SUNDARGANJ
55	**49**	**KURIGRAM**	
55	49	6	BHURUNGAMARI
55	49	8	CHAR RAJIBPUR
55	49	9	CHILMARI
55	49	18	PHULBARI
55	49	52	KURIGRAM SADAR
55	49	61	NAGESHWARI
55	49	77	RAJARHAT
55	49	79	RAUMARI
55	49	94	ULIPUR
55	**52**	**LALMONIRHAT**	
55	52	2	ADITMARI
55	52	33	HATIBANDHA
55	52	39	KALIGANJ
55	52	55	LALMONIRHAT SADAR
55	52	70	PATGRAM
55	**73**	**NILPHAMARI**	
55	73	12	DIMLA
55	73	15	DOMAR
55	73	36	JALDHAKA
55	73	45	KISHOREGANJ
55	73	64	NILPHAMARI SADAR
55	73	85	SAIDPUR
55	**77**	**PANCHAGARH**	
55	77	4	ATWARI
55	77	25	BODA
55	77	34	DEBIGANJ
55	77	73	PANCHAGARH SADAR
55	77	90	TENTULIA
55	**85**	**RANGPUR**	
55	85	3	BADARGANJ
55	85	27	GANGACHARA
55	85	42	KAUNIA
55	85	49	RANGPUR SADAR
55	85	58	MITHA PUKUR
55	85	73	PIRGACHHA
55	85	76	PIRGANJ
55	85	92	TARAGANJ
55	**94**	**THAKURGAON**	
55	94	8	BALIADANGI
55	94	51	HARIPUR
55	94	82	PIRGANJ
55	94	86	RANISANKAIL
55	94	94	THAKURGAON SADAR
60	**SYLHET DIVISION**		
60	**36**	**HABIGANJ**	
60	36	2	AJMIRIGANJ
60	36	5	BAHUBAL
60	36	11	BANIACHONG
60	36	26	CHUNARUGHAT
60	36	44	HABIGANJ SADAR
60	36	68	LAKHAI
60	36	71	MADHABPUR
60	36	77	NABIGANJ
60	**58**	**MAULVI BAZAR**	
60	58	14	BARLEKHA
60	58	35	JURI
60	58	56	KAMALGANJ
60	58	65	KULAURA
60	58	74	MAULVI BAZAR SADAR
60	58	80	RAJNAGAR
60	58	83	SREEMANGAL
60	**90**	**SUNAMGANJ**	
60	90	18	BISHWAMBARPUR
60	90	23	CHHATAK
60	90	27	DAKHIN SUNAMGANJ
60	90	29	DERAI

Division	District	Upazila	Name of Upazila
60	90	32	DHARAMPASHA
60	90	33	DOWARABAZAR
60	90	47	JAGANNATHPUR
60	90	50	JAMALGANJ
60	90	86	SULLA
60	90	89	SUNAMGANJ SADAR
60	90	92	TAHIRPUR
60	**91**	**SYLHET**	
60	91	8	BALAGANJ
60	91	17	BEANI BAZAR
60	91	20	BISHWANATH

Division	District	Upazila	Name of Upazila
60	91	27	COMPANIGANJ
60	91	31	DAKHIN SURMA
60	91	35	FENCHUGANJ
60	91	38	GOLABGANJ
60	91	41	GOWAINGHAT
60	91	53	JAINTIAPUR
60	91	59	KANAIGHAT
60	91	62	SYLHET SADAR
60	91	94	ZAKIGANJ

Annexure – II: Flood inundation area (km^2) and percentage in flood inundation depth category and Flood hazard level

Table A2.1: Flood inundation area (km^2) and percentage in flood inundation depth category and Flood hazard level

Division	District	Area of inundation (km^2) and percentage in each depth of Flood												Flood Affected Area (km^2)	Total Area (km^2)	%	Flood Hazard level
		< 0.3 m		0.3 - 0.9 m		0.9 - 1.8 m		1.8 - 3.6 m		> 3.6 m		Not Affected					
		Area	%	Area	%	Area	%	Area	%	Area	%	Area	%				
Barisal	Barguna	0.06	0.0	2.21	0.1	67.55	3.7	33.96	1.9	0.00	0.0	1727.53	94.3	103.8	1831.31	5.7	VL
	Barisal	173.77	6.2	741.18	26.6	1042.94	37.5	295.78	10.6	3.02	0.1	527.83	19.0	2256.7	2784.52	81.0	VH
	Bhola	7.53	0.2	70.59	2.1	56.54	1.7	9.86	0.3	2.71	0.1	3256.26	95.7	147.2	3403.48	4.3	VL
	Jhalokati	2.58	0.4	20.72	2.9	360.44	51.0	119.13	16.9	1.03	0.1	202.86	28.7	503.9	706.76	71.3	H
	Patuakhali	12.85	0.4	103.33	3.2	360.73	11.2	15.47	0.5	1.26	0.0	2727.67	84.7	493.6	3221.31	15.3	VL
	Pirojpur	0.99	0.1	29.47	2.3	418.87	32.8	115.54	9.0	0.00	0.0	712.93	55.8	564.9	1277.8	44.2	M
Chittagong	Bandarban	0.00	0.0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	4479.01	100.00	0.0	4479.01	0.0	VL
	Brahmanbaria	53.48	2.8	48.99	2.60	269.61	14.33	1076.21	57.21	422.23	22.44	10.68	0.57	1870.5	1881.2	99.4	VH
	Chandpur	447.19	27.2	90.58	5.51	520.31	31.62	352.06	21.40	5.57	0.34	229.62	13.96	1415.7	1645.32	86.0	VH
	Chittagong	4.14	0.1	1.33	0.03	3.63	0.07	1.41	0.03	0.00	0.00	5272.40	99.80	10.5	5282.92	0.2	VL
	Comilla	266.38	8.5	415.30	13.20	891.11	28.32	1390.31	44.19	176.11	5.60	7.10	0.23	3139.2	3146.3	99.8	VH
	Cox's Bazar	0.00	0.0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	2491.85	100.00	0.0	2491.85	0.0	VL
	Feni	136.65	13.8	72.26	7.30	258.63	26.11	290.61	29.34	1.35	0.14	230.86	23.31	759.5	990.36	76.7	H
	Khagrachhari	0.00	0.0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	2749.16	100.00	0.0	2749.16	0.0	VL
	Lakshmipur	435.16	30.2	242.50	16.84	187.64	13.03	19.74	1.37	3.25	0.23	552.11	38.33	888.3	1440.39	61.7	H
	Noakhali	121.10	3.3	403.43	10.95	653.79	17.74	162.57	4.41	0.09	0.00	2344.87	63.62	1341.0	3685.87	36.4	L
	Rangamati	0.00	0.0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	6116.11	100.00	0.0	6116.11	0.0	VL
Dhaka	Dhaka	215.58	14.7	73.80	5.04	256.56	17.53	570.24	38.96	304.08	20.78	43.34	2.96	1420.3	1463.6	97.0	VH
	Faridpur	1285.83	62.6	8.25	0.40	123.05	5.99	410.05	19.97	44.88	2.19	180.81	8.81	1872.1	2052.86	91.2	VH
	Gazipur	937.06	51.9	135.89	7.52	184.32	10.20	310.02	17.16	223.65	12.38	15.40	0.85	1791.0	1806.36	99.1	VH

Division	District	Area of inundation (km^2) and percentage in each depth of Flood												Flood Affected Area (km^2)	Total Area (km^2)	%	Flood Hazard level
		< 0.3 m		0.3 - 0.9 m		0.9 - 1.8 m		1.8 - 3.6 m		> 3.6 m		Not Affected					
		Area	%	Area	%	Area	%	Area	%	Area	%	Area	%				
	Gopalganj	71.79	4.9	115.57	7.87	379.60	25.85	859.32	58.51	5.38	0.37	37.08	2.52	1431.7	1468.74	97.5	VH
	Jamalpur	194.97	9.2	217.80	10.30	645.46	30.52	852.58	40.31	37.29	1.76	167.07	7.90	1948.1	2115.16	92.1	VH
	Kishoreganj	80.61	3.0	143.12	5.32	366.43	13.63	939.97	34.96	1110.06	41.29	48.39	1.80	2640.2	2688.59	98.2	VH
	Madaripur	31.97	2.8	149.24	13.26	469.84	41.74	397.51	35.31	19.36	1.72	57.77	5.13	1067.9	1125.69	94.9	VH
	Manikganj	17.42	1.3	50.77	3.67	268.98	19.44	762.74	55.12	129.07	9.33	154.68	11.18	1229.0	1383.66	88.8	VH
	Munshiganj	3.92	0.4	17.35	1.73	104.62	10.42	657.95	65.51	165.75	16.50	54.70	5.45	949.6	1004.29	94.6	VH
	Mymensingh	1680.94	38.3	545.70	12.42	945.81	21.52	1023.27	23.28	143.53	3.27	55.32	1.26	4339.2	4394.57	98.7	VH
	Narayanganj	24.49	3.6	12.91	1.89	55.31	8.08	527.95	77.14	62.31	9.10	1.40	0.21	683.0	684.37	99.8	VH
	Narsingdi	115.23	10.0	92.00	8.00	256.47	22.30	555.43	48.29	121.34	10.55	9.67	0.84	1140.5	1150.14	99.2	VH
	Netrakona	418.05	15.0	263.09	9.42	568.27	20.34	978.04	35.00	500.13	17.90	66.70	2.39	2727.6	2794.28	97.6	VH
	Rajbari	849.97	77.8	1.73	0.16	16.65	1.52	71.04	6.50	23.79	2.18	129.10	11.82	963.2	1092.28	88.2	VH
	Shariatpur	5.80	0.5	90.84	7.74	476.77	40.61	419.72	35.75	19.92	1.70	161.00	13.71	1013.1	1174.05	86.3	VH
	Sherpur	342.28	25.1	183.51	13.45	284.04	20.81	347.12	25.44	176.35	12.92	31.37	2.30	1333.3	1364.67	97.7	VH
	Tangail	1213.16	35.5	344.16	10.08	564.76	16.54	961.51	28.16	140.33	4.11	190.43	5.58	3223.9	3414.35	94.4	VH
Khulna	Bagerhat	18.72	0.5	44.75	1.13	211.49	5.34	33.95	0.86	0.00	0.00	3650.19	92.20	308.9	3959.11	7.8	VL
	Chuadanga	1150.47	98.0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	23.63	2.01	1150.5	1174.1	98.0	VH
	Jessore	2336.66	89.6	2.44	0.09	4.98	0.19	7.76	0.30	4.48	0.17	250.63	9.61	2356.3	2606.94	90.4	VH
	Jhenaidah	1924.76	98.0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	40.01	2.04	1924.8	1964.77	98.0	VH
	Khulna	41.52	0.9	31.58	0.72	183.70	4.18	272.25	6.20	0.00	0.00	3865.40	87.96	529.1	4394.45	12.0	VL
	Kushtia	1266.09	78.7	3.46	0.21	27.50	1.71	89.68	5.57	16.93	1.05	205.15	12.75	1403.6	1608.8	87.2	VH
	Magura	1031.70	99.3	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	7.40	0.71	1031.7	1039.1	99.3	VH
	Meherpur	736.34	98.0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	15.28	2.03	736.3	751.62	98.0	VH
	Narail	941.63	97.3	3.61	0.37	2.55	0.26	2.98	0.31	0.00	0.00	17.22	1.78	950.8	967.99	98.2	VH
	Satkhira	88.20	2.3	53.37	1.40	68.70	1.80	92.65	2.43	24.23	0.63	3490.14	91.43	327.1	3817.29	8.6	VL

Division	District	Area of inundation (km²) and percentage in each depth of Flood												Flood Affected Area (km²)	Total Area (km²)	%	Flood Hazard level
		< 0.3 m		0.3 - 0.9 m		0.9 - 1.8 m		1.8 - 3.6 m		> 3.6 m		Not Affected					
		Area	%	Area	%	Area	%	Area	%	Area	%	Area	%				
Rajshahi	Bogra	777.96	26.8	314.00	10.83	781.08	26.95	805.56	27.79	27.93	0.96	192.14	6.63	2706.5	2898.68	93.4	VH
	Joypurhat	658.95	65.1	6.87	0.68	32.42	3.20	143.36	14.16	64.91	6.41	105.90	10.46	906.5	1012.41	89.5	VH
	Naogaon	1563.77	45.5	514.42	14.97	665.42	19.37	594.02	17.29	51.22	1.49	46.79	1.36	3388.9	3435.65	98.6	VH
	Natore	1748.00	92.0	1.84	0.10	1.90	0.10	26.40	1.39	8.92	0.47	113.15	5.95	1787.0	1900.19	94.0	VH
	Chapai Nawabganj	1352.37	79.4	6.32	0.37	48.55	2.85	138.20	8.12	89.50	5.26	67.61	3.97	1634.9	1702.55	96.0	VH
	Pabna	1699.95	71.5	3.28	0.14	45.01	1.89	315.71	13.29	72.09	3.03	240.09	10.10	2136.0	2376.13	89.9	VH
	Rajshahi	2119.09	87.4	32.72	1.35	34.90	1.44	28.79	1.19	10.69	0.44	199.17	8.21	2226.2	2425.37	91.8	VH
	Sirajganj	66.07	2.8	90.29	3.76	453.47	18.88	1156.13	48.13	131.64	5.48	504.46	21.00	1897.6	2402.05	79.0	H
Rangpur	Dinajpur	2256.27	65.5	329.12	9.56	263.77	7.66	336.63	9.77	237.10	6.88	21.40	0.62	3422.9	3444.3	99.4	VH
	Gaibandha	1437.84	68.0	28.61	1.35	89.09	4.21	188.12	8.90	45.44	2.15	325.68	15.40	1789.1	2114.77	84.6	VH
	Kurigram	918.07	40.9	24.63	1.10	154.75	6.89	463.67	20.65	142.50	6.35	541.43	24.12	1703.6	2245.04	75.9	H
	Lalmonirhat	754.97	60.5	16.71	1.34	29.99	2.40	115.49	9.26	169.48	13.59	160.73	12.89	1086.6	1247.37	87.1	VH
	Nilphamari	1430.77	92.5	20.99	1.36	19.05	1.23	28.72	1.86	12.03	0.78	35.02	2.26	1511.6	1546.59	97.7	VH
	Panchagarh	1387.20	98.8	0.09	0.01	0.00	0.00	0.00	0.00	0.00	0.00	17.33	1.23	1387.3	1404.62	98.8	VH
	Rangpur	2079.37	86.6	3.23	0.13	9.13	0.38	87.83	3.66	130.87	5.45	90.13	3.75	2310.4	2400.56	96.2	VH
	Thakurgaon	1757.04	98.6	5.35	0.30	2.63	0.15	0.00	0.00	0.00	0.00	16.72	0.94	1765.0	1781.74	99.1	VH
Sylhet	Habiganj	479.63	18.2	38.33	1.5	113.57	4.3	1013.77	38.5	956.92	36.3	34.37	1.3	2602.2	2636.59	98.7	VH
	Maulvibazar	1044.62	37.3	75.48	2.7	111.76	4.0	521.63	18.6	985.55	35.2	60.34	2.2	2739.0	2799.38	97.8	VH
	Sunamganj	78.06	2.1	52.14	1.4	193.23	5.2	1260.73	33.6	1860.34	49.6	302.69	8.1	3444.5	3747.18	91.9	VH
	Sylhet	251.06	7.3	66.23	1.9	257.99	7.5	1354.36	39.2	1468.09	42.5	54.35	1.6	3397.7	3452.07	98.4	VH
Total Area (km²) / Average inundation (%)		42548.10	35.30	6457.51	4.23	14865.35	11.38	23605.45	18.34	10354.7	6.58	49737.64	24.17	97831.1	147568.74	75.83	

Annexure – III: Surge Induced Inundation Map under Climate Change Condition for Cyclone SIDR (2007)

Simulation of storm surge model for climate change condition was carried under this study on cyclone SIDR (2007). Increase of wind speed and increase of sea level were considered during the simulation of climate change condition.

A 3.1 Selection of Sea Level Rise

There are four different scenarios named as RCP (Representative Concentration Pathways) scenarios are described in the 5th IPCC report. The characteristics of those scenarios are described in the table A3.1.

Table A3.1: Main characteristics of RCP scenarios

Scenario / Component	RCPT2 .6	RCPT4.5	RCPT6	RCPT8.5
Greenhouse gas emission	Very Low	Medium low mitigation / Very Low baseline	Medium baseline high mitigation	High baseline
Agricultural Area	Medium for crop land and pasture	Very Low for both crop land and pasture	Medium for crop land but very low for pasture	Medium for both crop land and pasture
Air Pollution	Medium-Low	Medium	Medium	Medium-High

Source: IPCC, 2014.

In the 5th IPCC report the projection of SLRs are also stated according to these four scenarios. The projected SLRs are furnished in the

Figure A3.1 for 2081 to 2100. It is evident from the figure that maximum SLR has been predicted as 63cm for RCP 8.5 which was selected under this study as sea level rise.

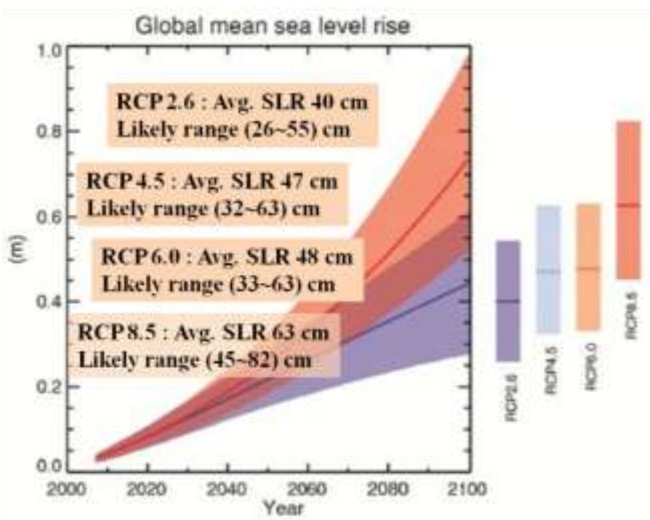

Figure A3.1: Predicted SLRs for different RCP scenarios for 2081-2100

Source: IPCC, 2014.

A.3.2 Increase of wind speed

Projection on cyclone intensity in the 5th IPCC report is furbished in the Table A3.2. The table describes the projection for global and North Indian Ocean. As the Bay of Bengal is in North Indian Ocean, the projection for North Indian Ocean was selected for this study. It is evident from the Table A3.2 that the increase in intensity varies from 0.2% to 7% in North Indian Ocean in the year 2100 and for this study 7% increase in wind speed was selected.

Table A3.2: Projection on cyclone intensity (AR5)

Tropical Cyclone Intensity Projections (%)					
Metric/ Reference	**Technique/ Model**	**Resolution/ Metric Type**	**Climate Change Scenario**	**Global**	**North Indian Ocean**
Vecchi et. al.	Emanuel PI, reversible w/ diss. Heating	Max Wind speed (%)	CMIP3 18-model A1B (100-year trend)	2.6%	4.4%
Yu et. al.	Emanuel PI modified by vertical wind shear	Max Wind speed (%)	CMIP3 18 model ensemble 1% per yr CO_2 70-year trend		3.3%
Murakami et. al.	IMAIMRI global AGCM time slice	V3.1 20 km	Downscale CMIP3 multi-model ens. A1B change (2075-2099 minus control)	11%	5%
		V3.2 20 km: Avg. max winds over lifetime of all TCs		4%	**7%**
Emanuel et. al.	Stat./Dyn. Model	Max Wind speed (%)	CMIP3 7-model Al B (2181-2200 minus 1981-2000)	1.7%	0.2%

Simulation of Storm Surge (SIDR) Model for Climate Change

A simulation of storm surge model (for SIDR 2007) was carried out incorporating sea level rise (63cm) and increase of wind speed (7% for North Indian Sea) for 2100 to assess the pattern of surge induced inundation depths. The inundation maps for base condition and climate change condition for Sidr (2007) are furnished in Figure A3.2 and Figure A3.3 respectively.

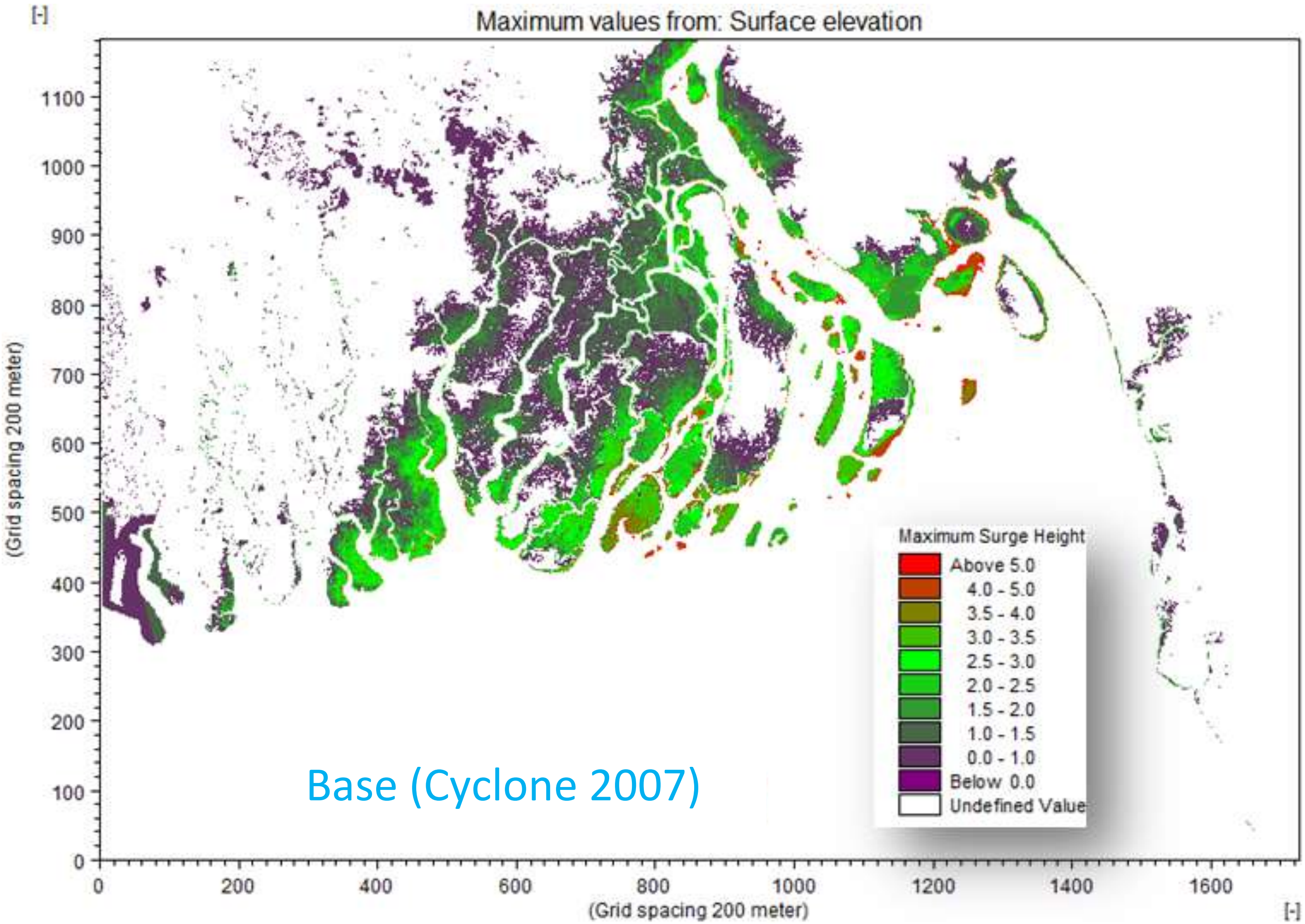

Figure A3.2: Inundation depth map for cyclone SIDR (2007)

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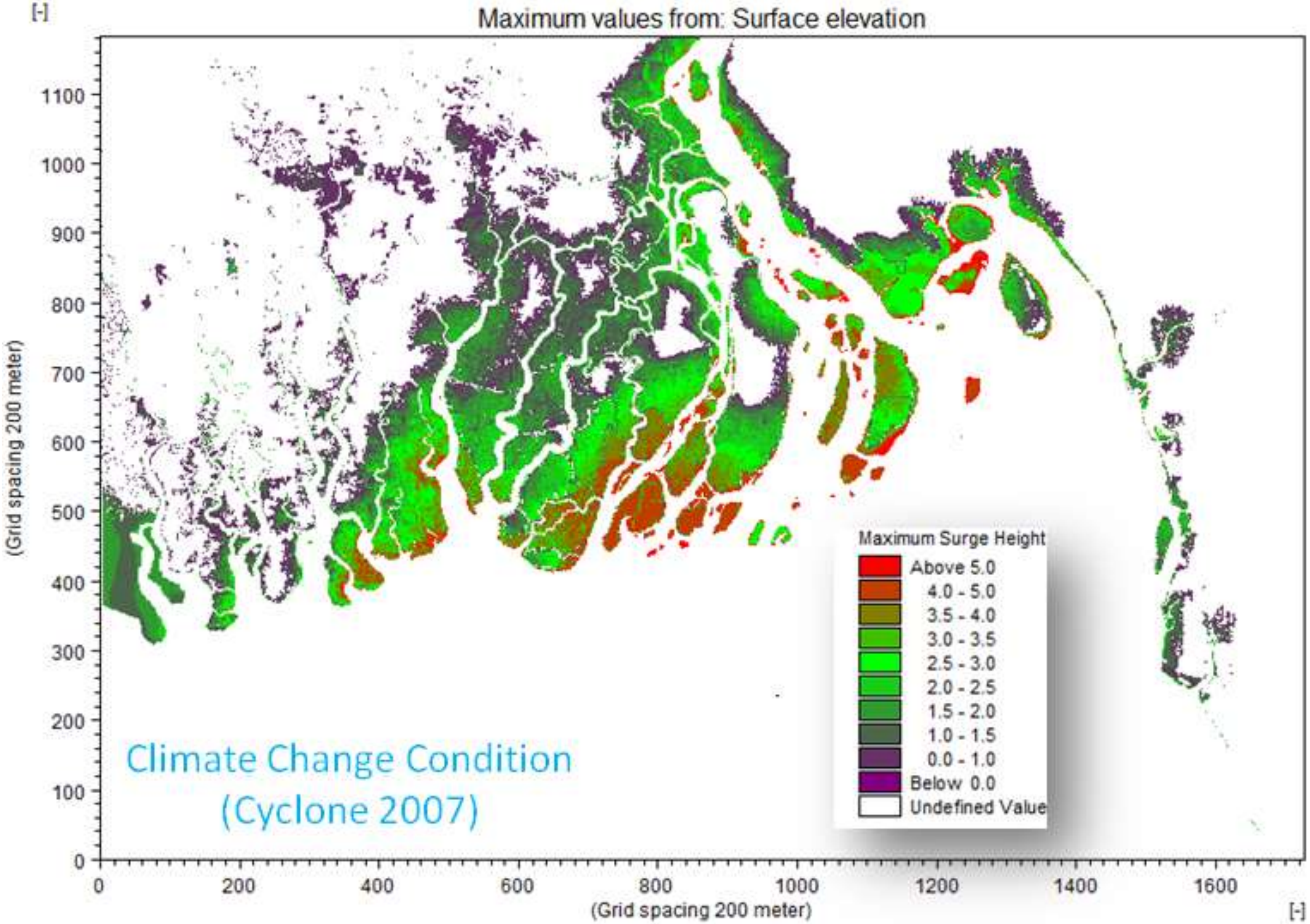


Figure A3.3: Inundation depth map for cyclone SIDR (2007) considering SLR (63cm) and increase in wind speed (7%)

Annexure – IV: Rainfall induced landslide susceptibility maps at district level

Rainfall induced landslide susceptibility maps of all landslide prone districts i.e. Chittagong, Cox's bazar, Rangamati, Bandarban, Khagrachari, Sylhet are shown in Figures A4.1 to A4.6.

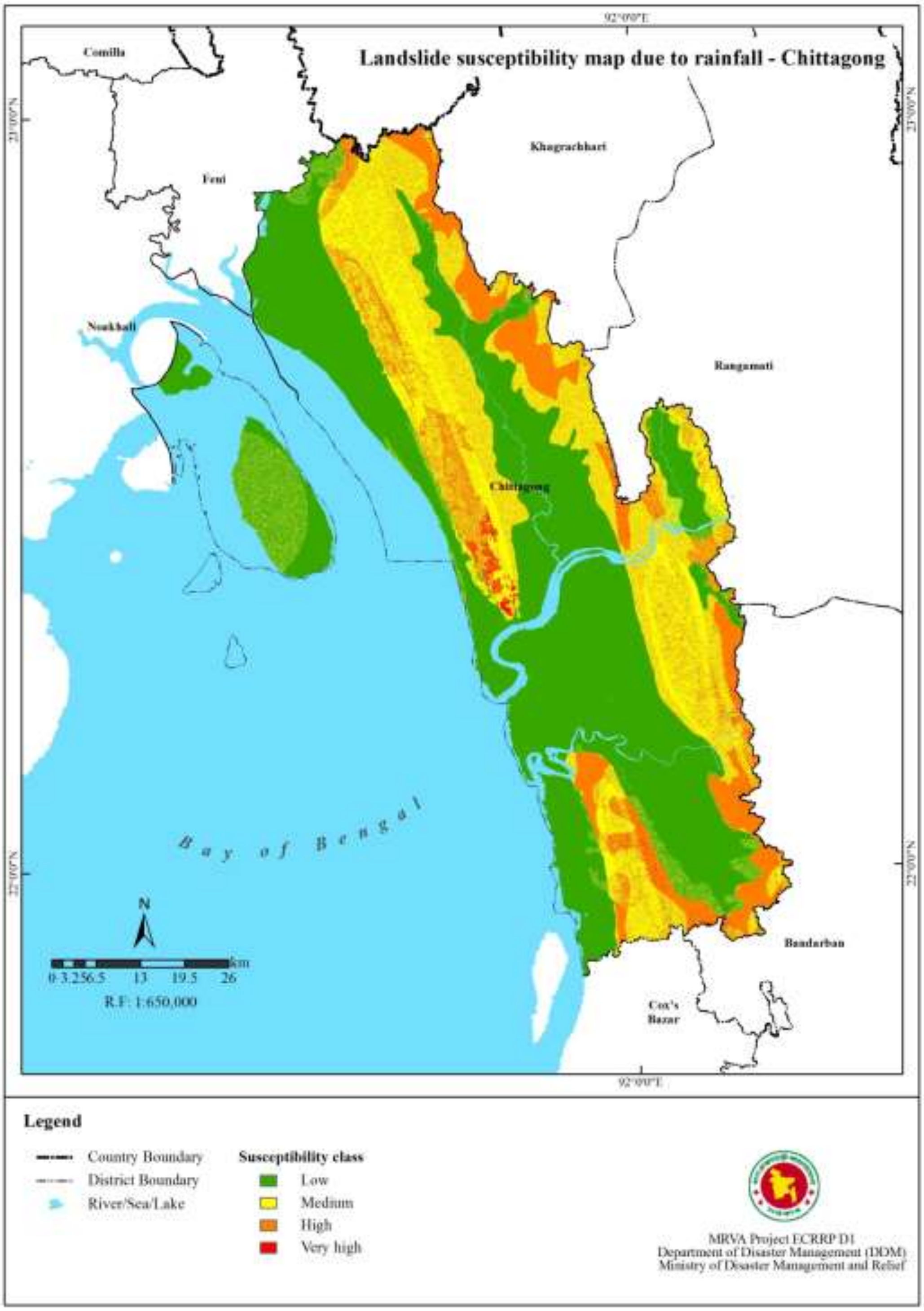


Figure A4.1: Landslide susceptibility map due to rainfall - Chittagong

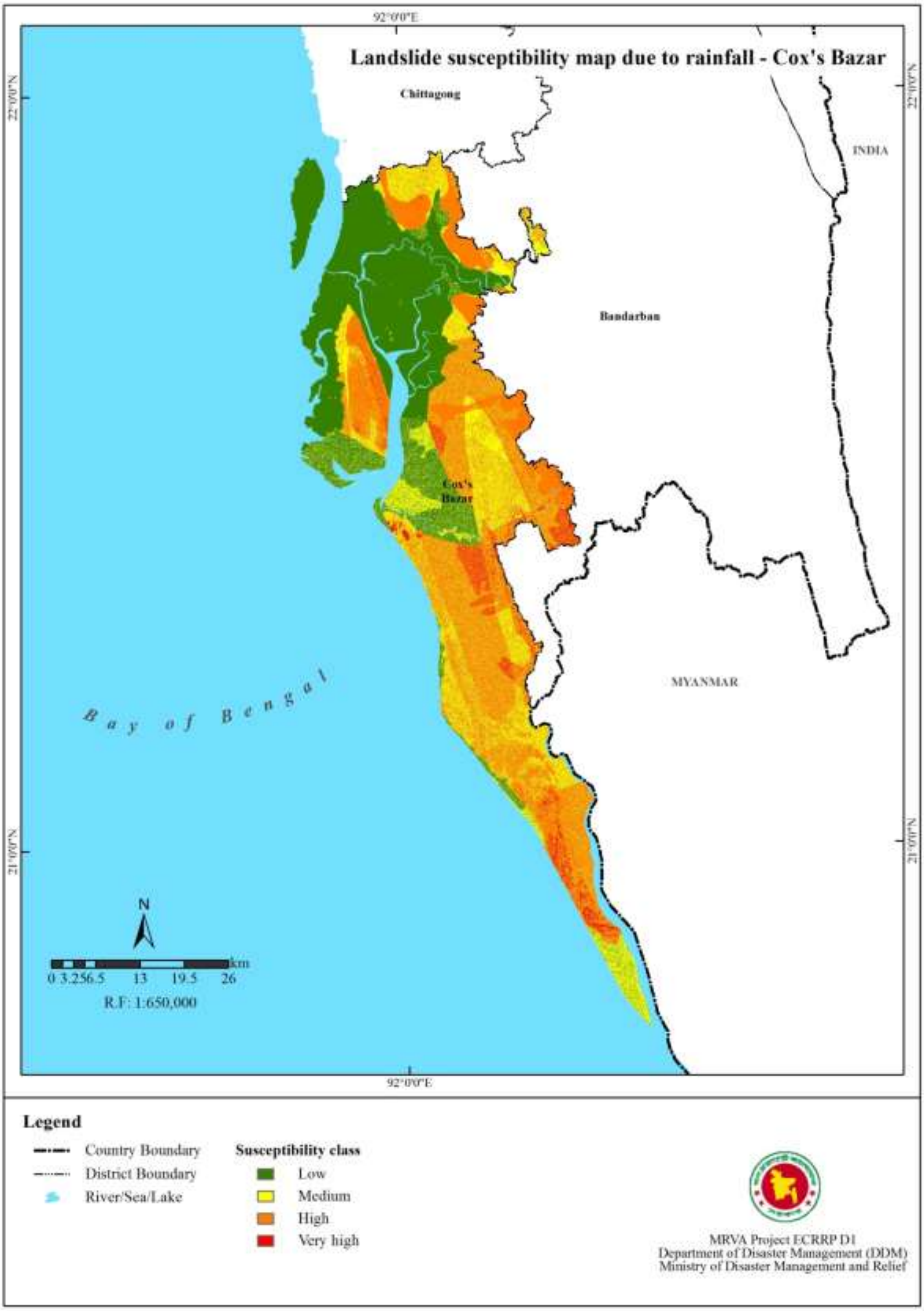


Figure A4.2: Landslide susceptibility map due to rainfall - Cox's Bazar

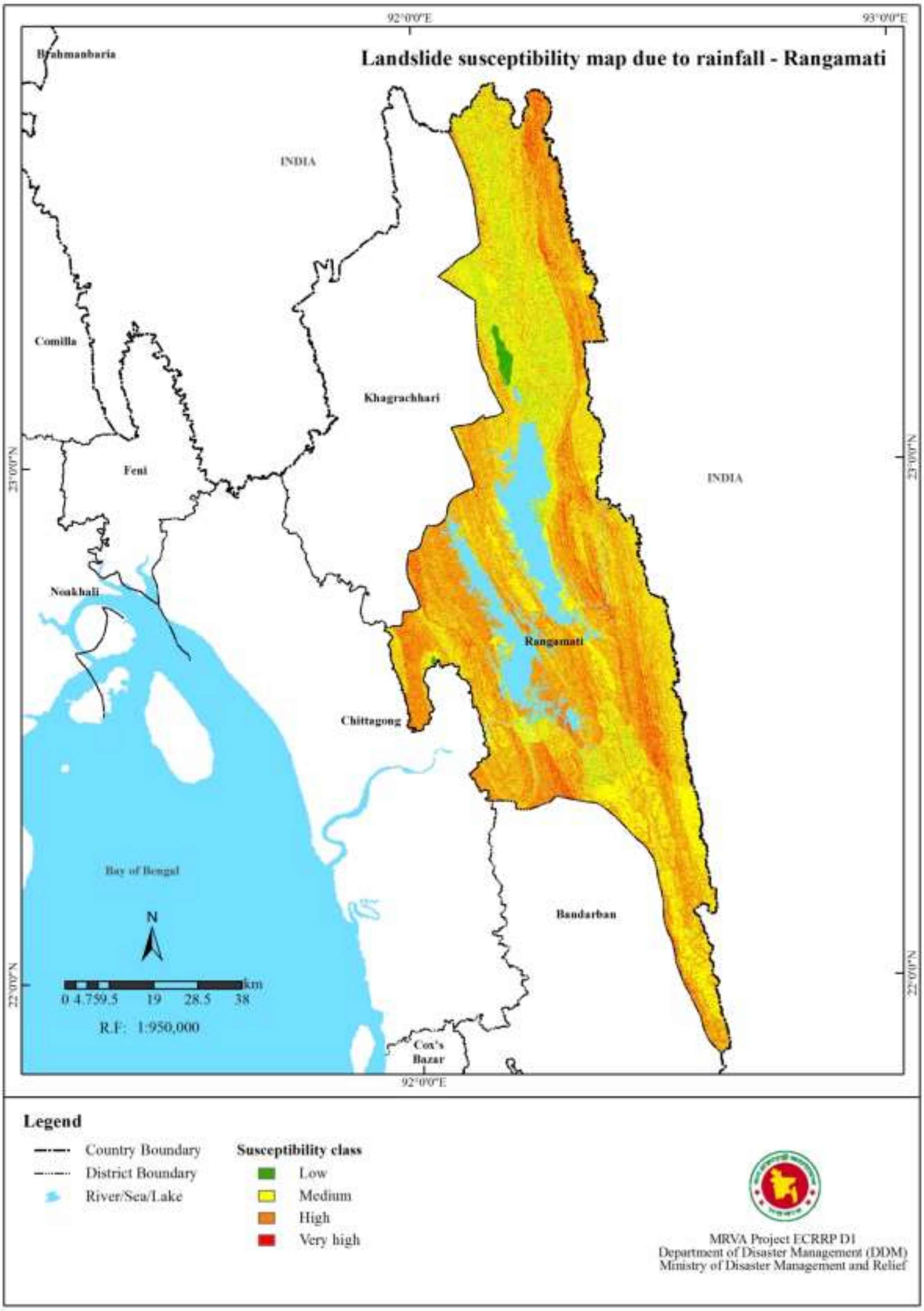


Figure A4.3: Landslide susceptibility map due to rainfall - Rangamati

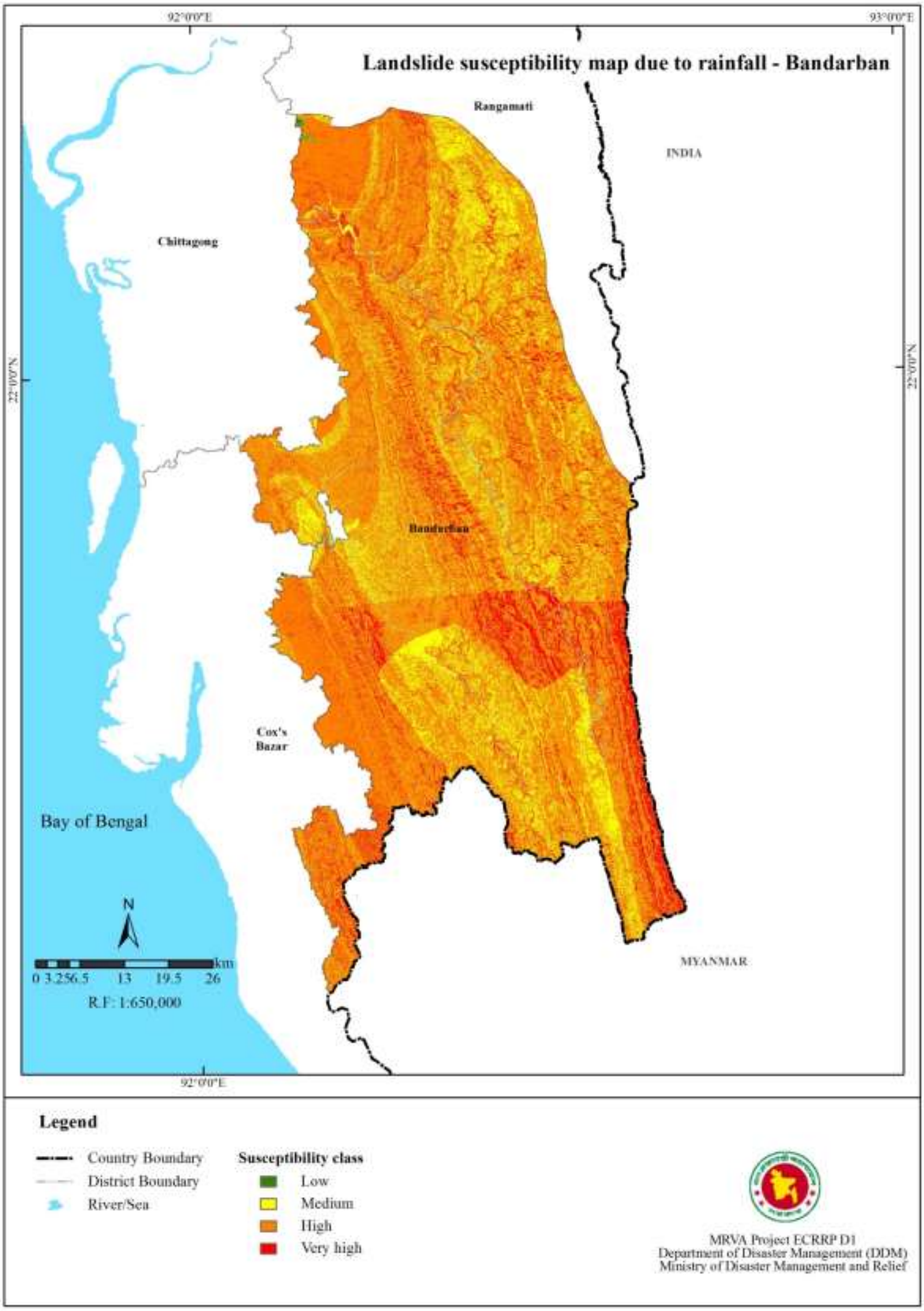


Figure A4.4: Landslide susceptibility map due to rainfall - Bandarban

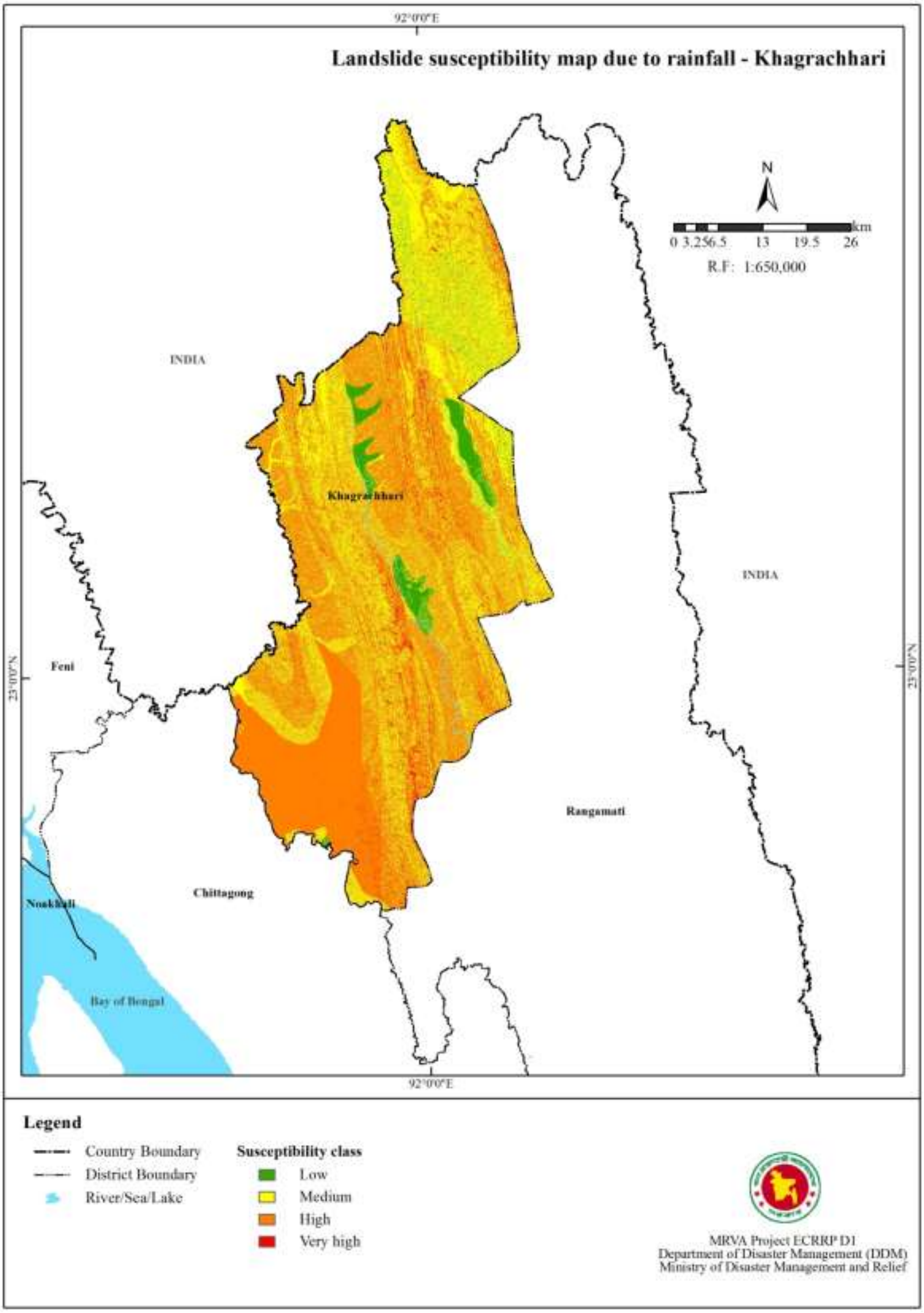


Figure A4.5: Landslide susceptibility map due to rainfall - Khagrachhari

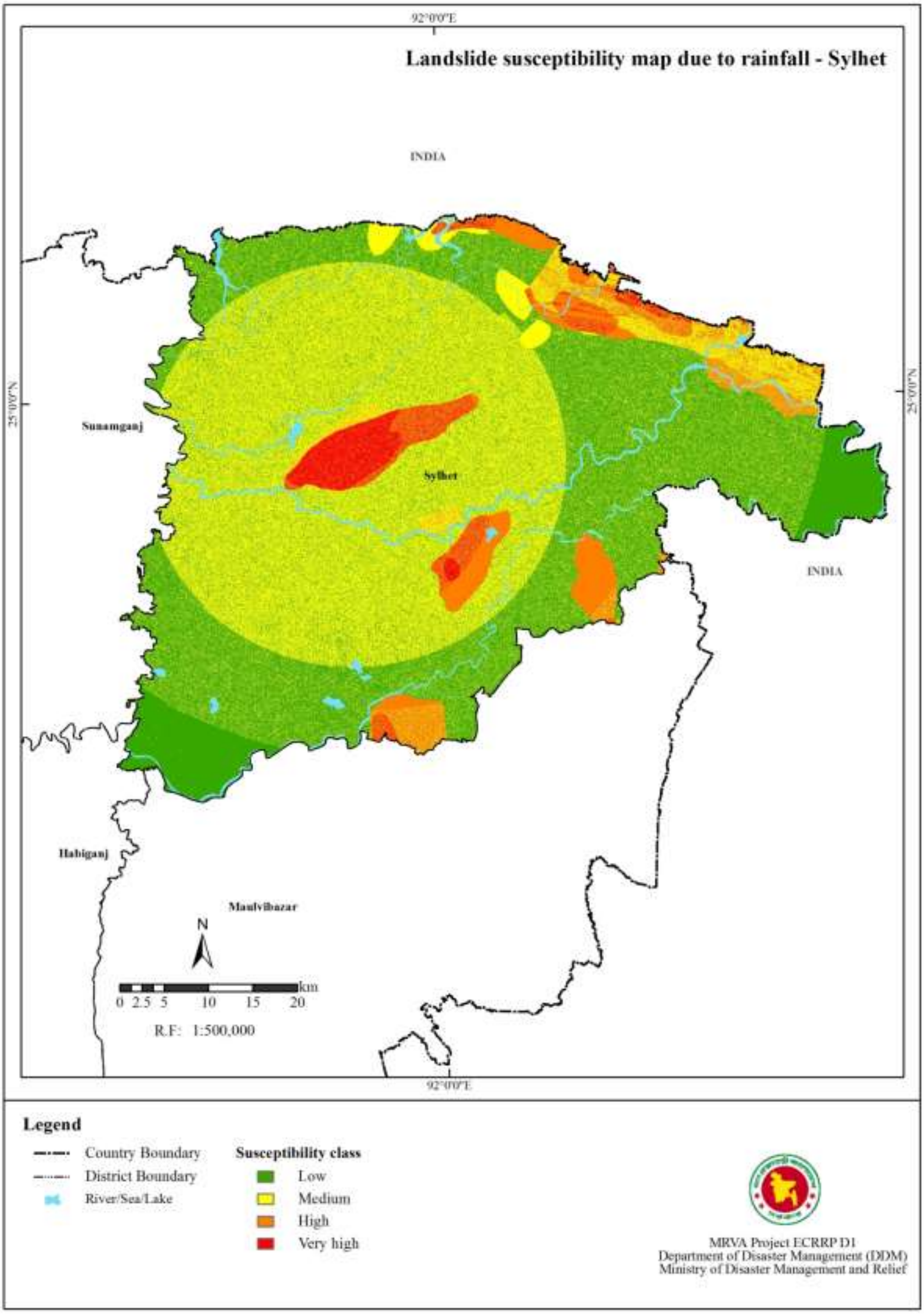


Figure A4.6: Landslide susceptibility map due to rainfall - Sylhet

Earthquake induced landslide susceptibility maps at district level

Earthquake induced landslide susceptibility maps of all landslide prone districts i.e. Chittagong, Cox's bazar, Rangamati, Bandarban, Khagrachari, Sylhet are shown in Figures A 4.7 to A 4.12.

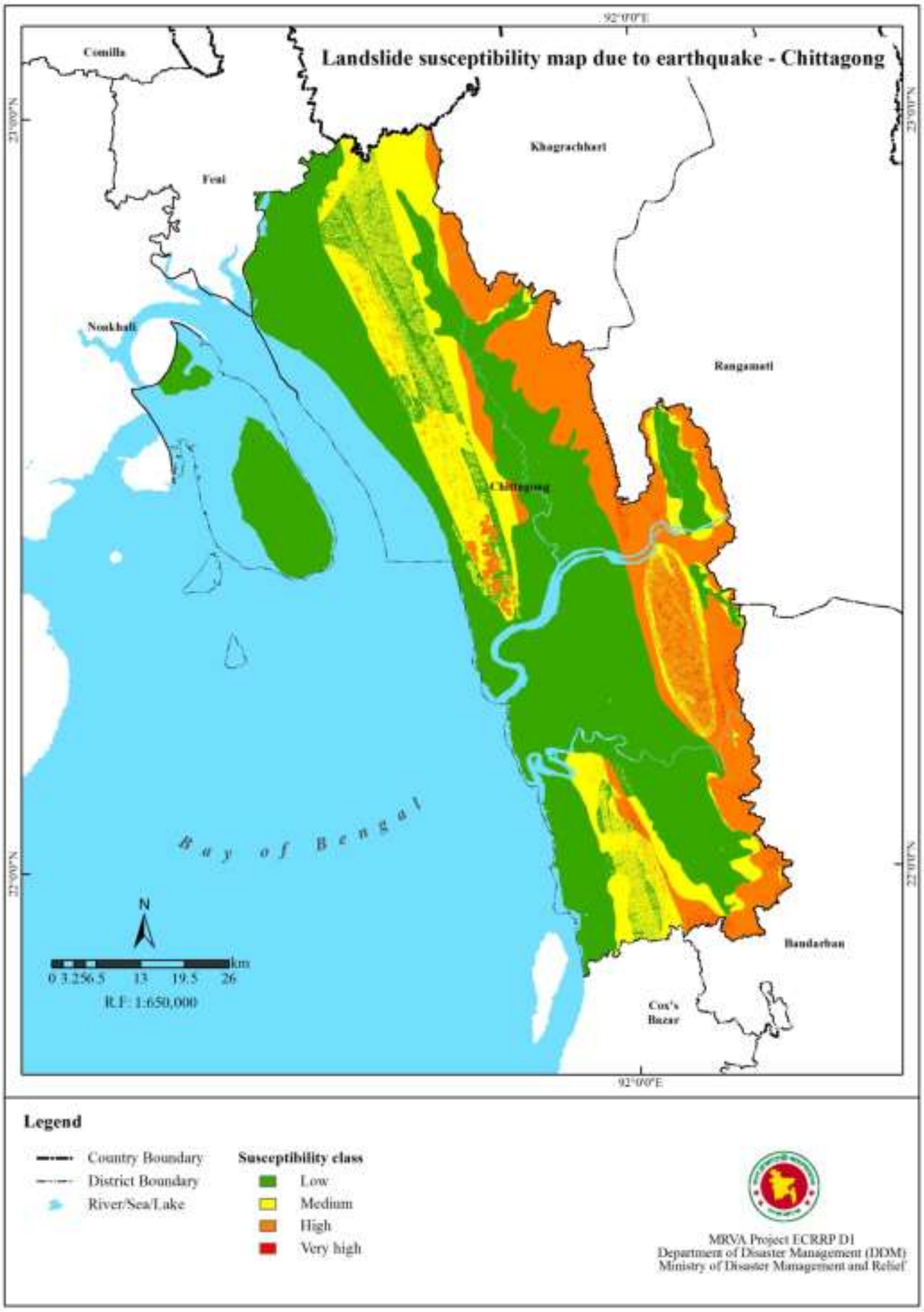


Figure A4.7: Landslide susceptibility map due to earthquake - Chittagong

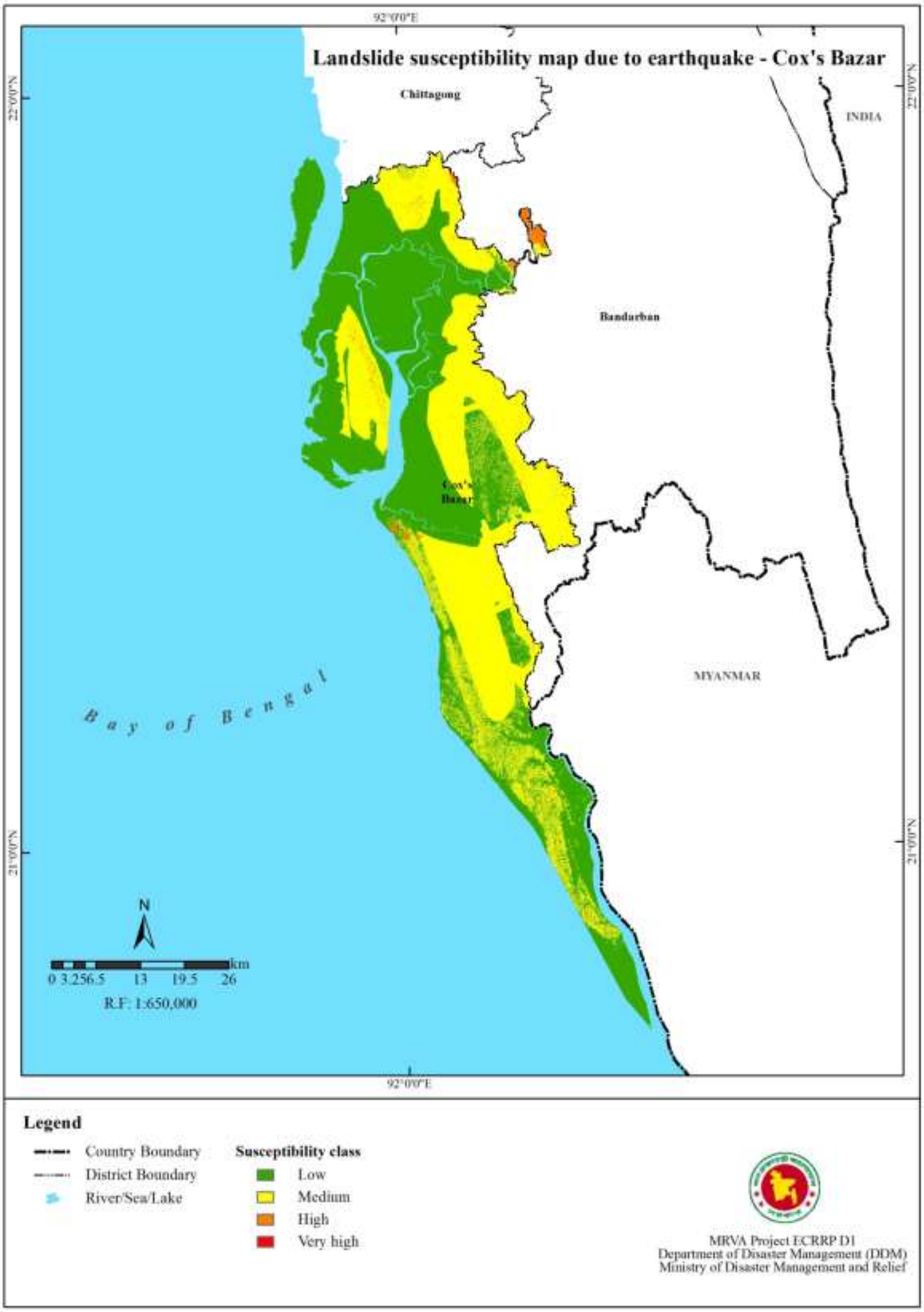


Figure A4.8: Landslide susceptibility map due to earthquake - Cox's Bazar

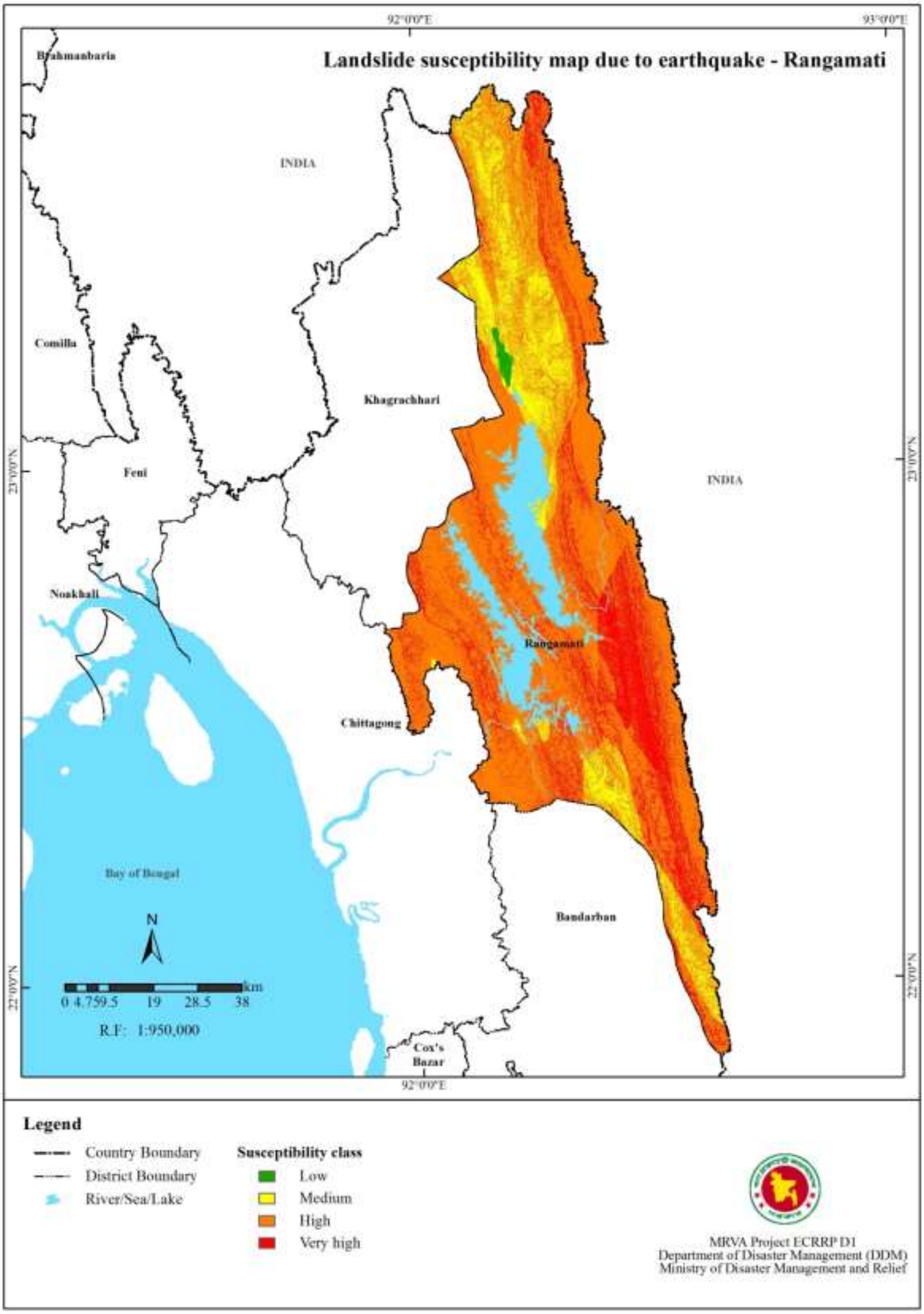


Figure A4.9: Landslide susceptibility map due to earthquake - Rangamati

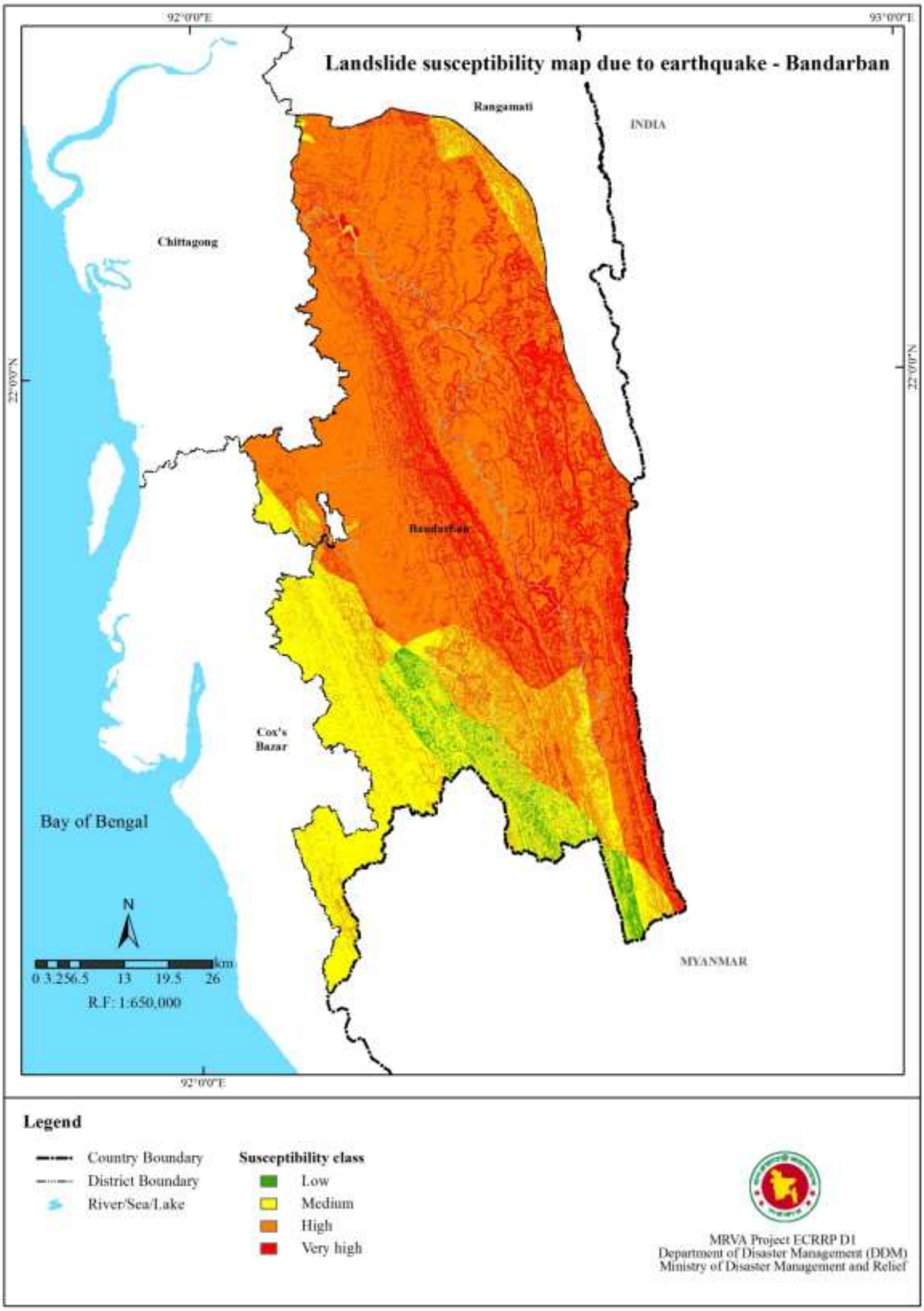


Figure A4.10: Landslide susceptibility map due to earthquake - Bandarban

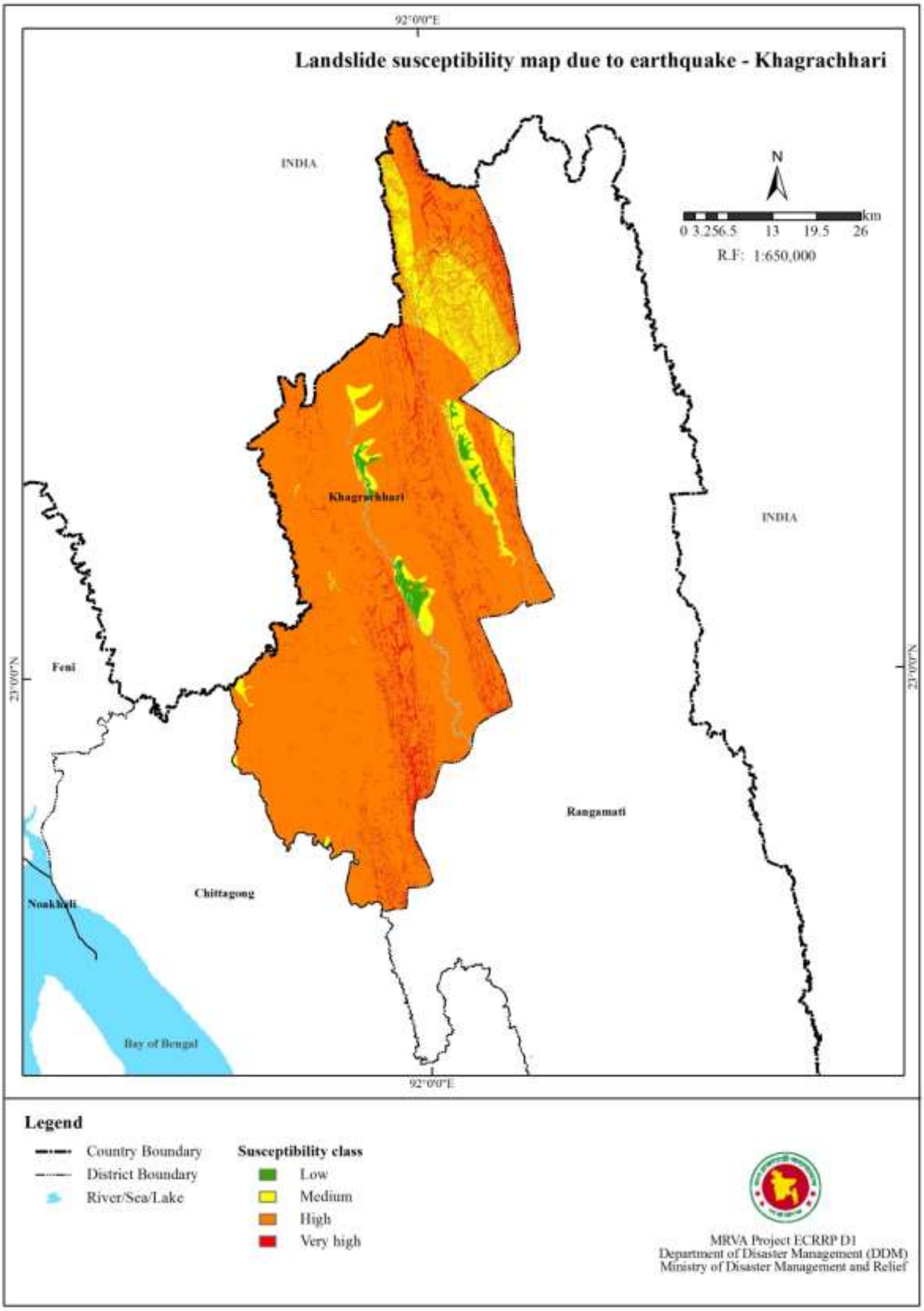


Figure A4.11: Landslide susceptibility map due to earthquake - Khagrachhari

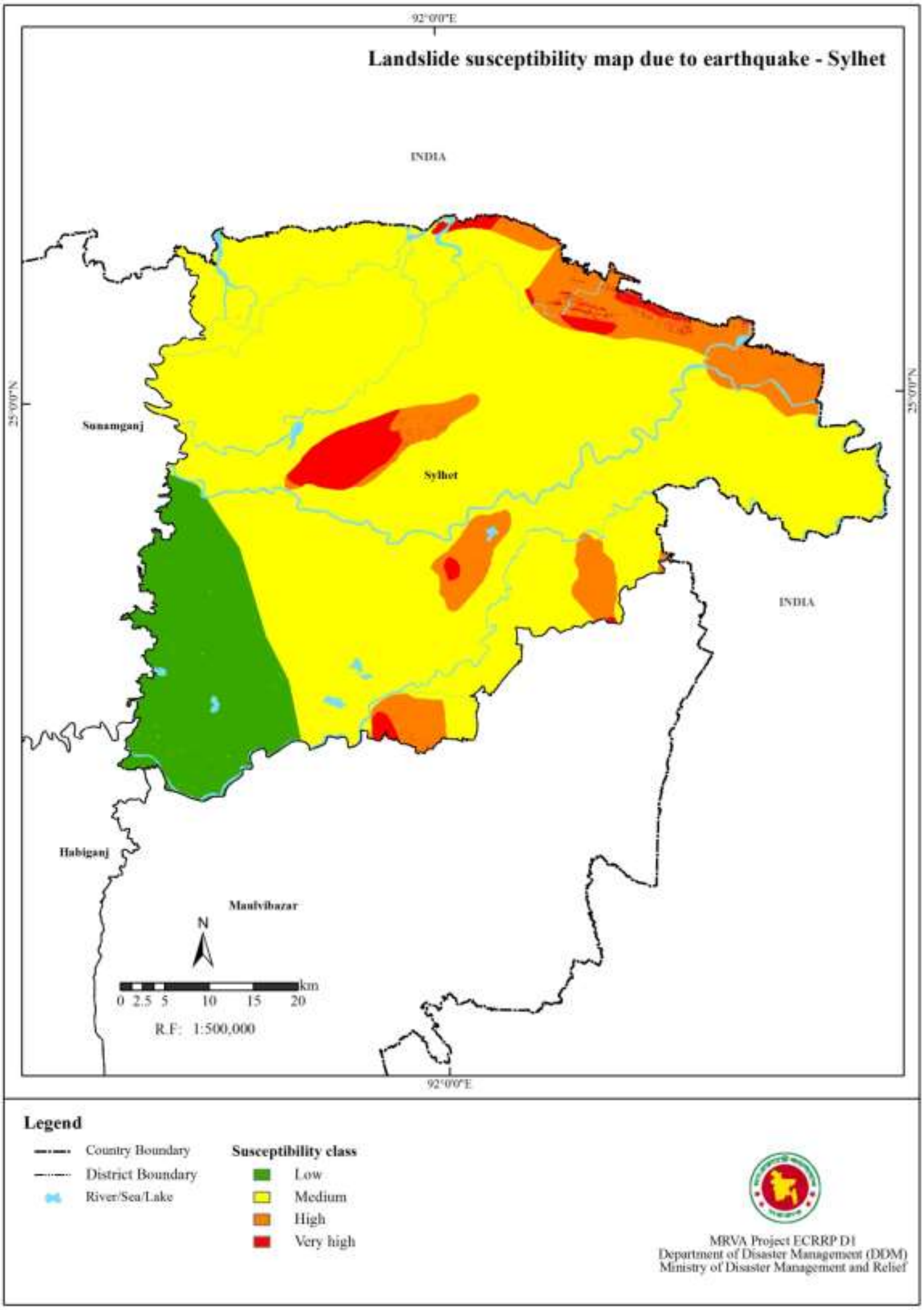
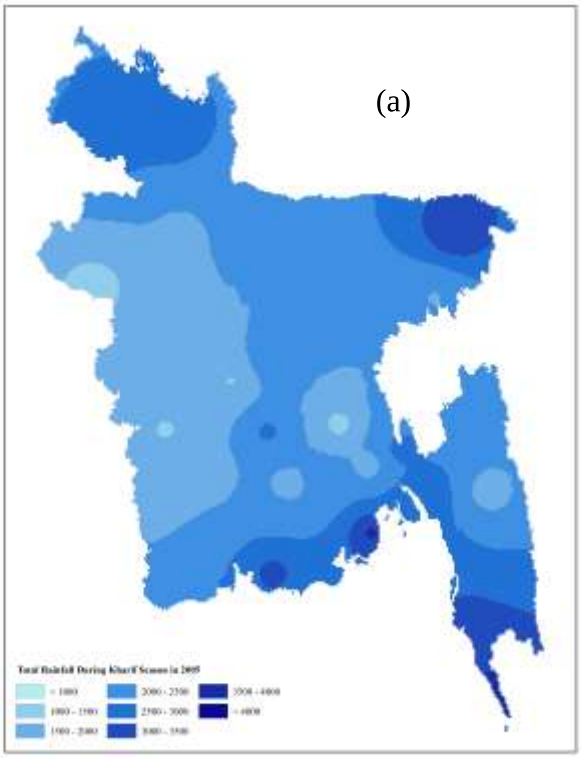
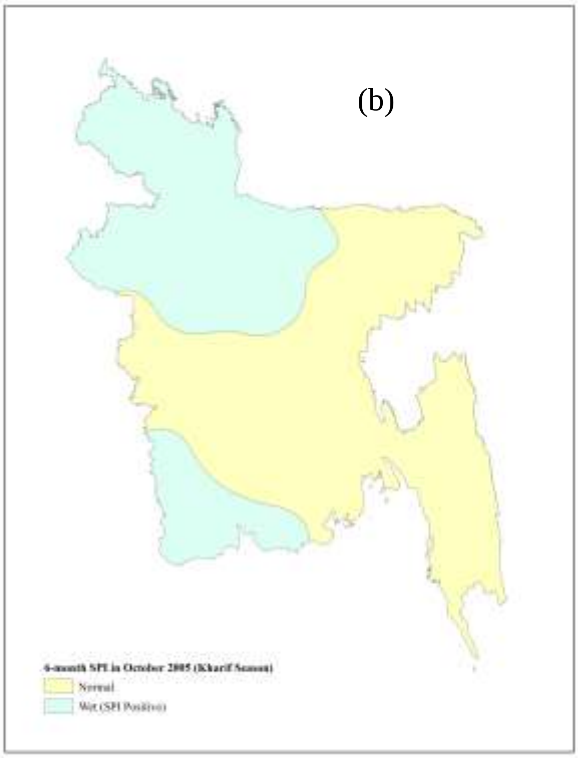


Figure A4.12: Landslide susceptibility map due to earthquake - Sylhet

Annexure V: Comparison between Rainfall Map, SPI Map and NDVI During Kharif Season

Rainfall maps and drought maps derived from SPI are compared with remote sensing based index Normalized Difference Vegetation Index (NDVI) during 2006, which is a drought year and 2005/2007 non-drought years. Analysis is done for the crop-growing period of Kharif season. A six-month time scale of SPI in October is produced together with the total rainfall during Kharif season from 2005 to 2007. Figure A5.1(a), A5.1(c) and A5.1(e) shows the total rainfall from May to October in 2005, 2006 and 2007, respectively. Meanwhile, Figure A5.1(b), A5.1(d) and A5.1(f) show the six-month SPI for the same period in 2005, 2006 and 2007, respectively. The SPI map in Figure A5.1(b) shows a favorable condition in major parts of Bangladesh, where northwest and southwest part of the country show wet conditions. Figure A5.1(c) shows very less total rainfall in 2006 compared to 2005 (Figure A5.1(a)) and 2007 (Figure A5.1(e)), with minimum total rainfall of 950 mm in the northwest part of the country. Spatial distribution of SPI in Figure A5.1(d) shows that low moderate to low extreme drought occur in the northwest part of the country in 2006. Similar to the 2005 condition, the whole part of the country is less prone to drought in 2007 as can be seen in Figure A5.1(f).





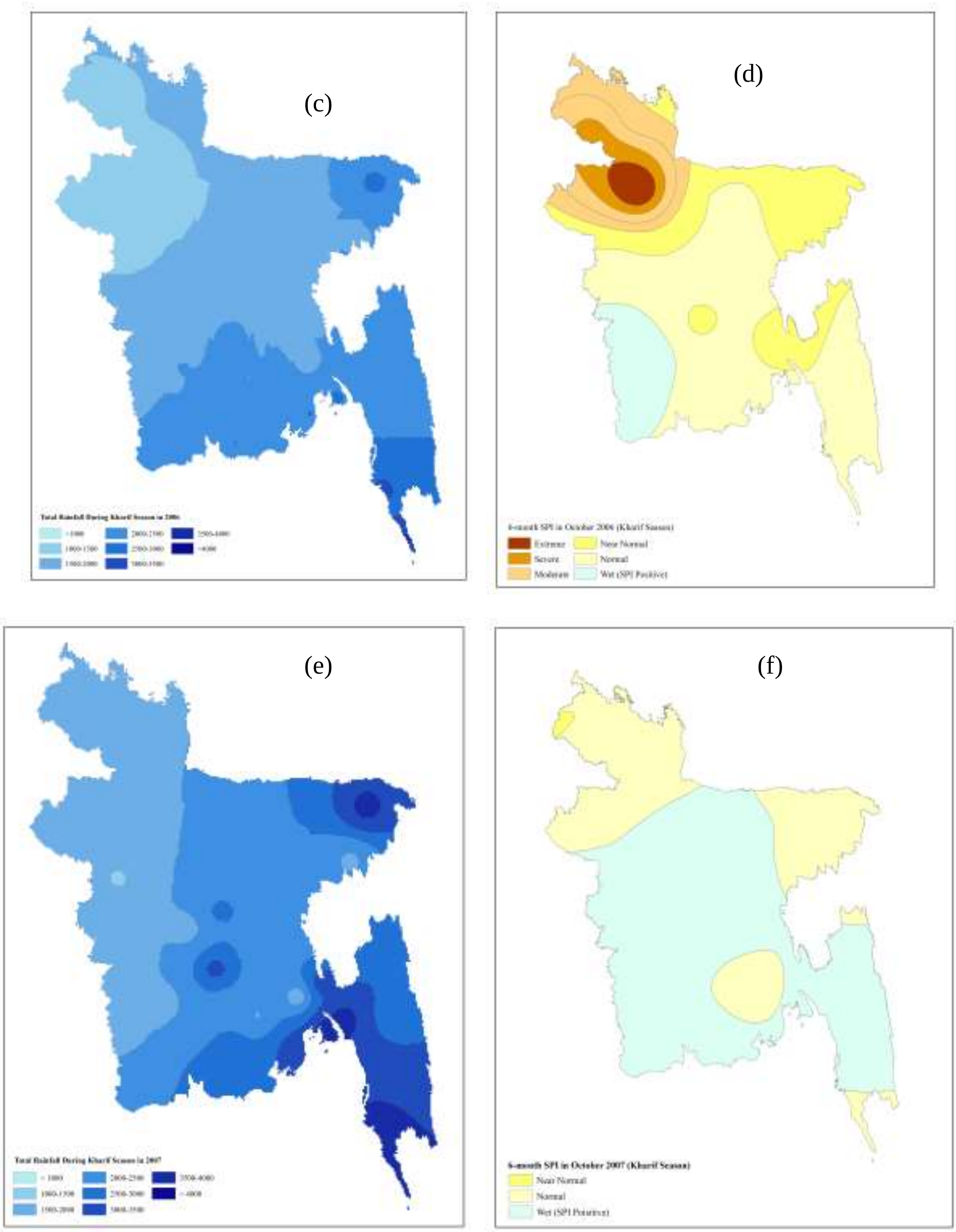


Figure A5.1: Maps of total rainfall during Kharif season in (a) 2005, (c) 2006, (e) 2007; Maps of the six-month SPI during Kharif season in (b) 2005, (d) 2006, (f) 2007

A time series of 16-day composite NDVI (MOD13Q1) products MODIS satellite were downloaded from extracted from Land Processes Distributed Active Archive Center (LP DAAC, 2014) to show the status of vegetation during Kharif season in 2005 to 2007 (Figure A5.2). The dates in which vegetation status is compared are given in Table A5.1.

Table A5.1: Dates in which vegetation status during Kharif season was compared

Date of the year (DOY) or Julian day	Date	Date of the year (DOY) or Julian day	Date
113	23-Apr	209	28-Jul
129	9-May	225	13-Aug
145	25-May	241	29-Aug
161	10-Jun	257	14-Sep
177	26-Jun	273	30-Sep
193	12-Jul	289	16-Oct

As mentioned previously, drought condition is identified by SPI in northwest part of Bangladesh in 2006. However, there is no distinct pattern of drought that can be observed from the 16-day NDVI products in different years. Since NDVI is not a drought index, monthly NDVI (MOD13A3) was used to calculate NDVI deviation, by taking the difference between the NDVI for a particular month and a long-term mean monthly NDVI (2001-2012) for that month. Figure A5.3 shows NDVI deviation from May to October from 2005 to 2007. Similarly, the NDVI deviation maps are not showing an abnormal situation or drought in 2006 compared to 2005 and 2007. It seems that NDVI is not directly affected by rainfall. It is known from previous studies that NDVI has a lagged response to drought. Vegetation response to rainfall deficits has lagged due to availability of residual moisture stored in the soil. NDVI lags up to three months behind antecedent precipitation, and it depends on the irrigation practices in the region (Thenkabail et al., 2004). Lag time in irrigation areas is longer than in rainfed areas. Based on the Local Government Engineering Department (LGED) data in 2003, irrigation coverage in Bangladesh is not equally distributed and it is mostly located in the north and northwest part of the country (Rahman & Parvin, 2009). The percentage of irrigated area is highest (75-100 percent) in 11 districts, including Dinajpur, Rangpur, Bogra, Thakurgaon, Nilphamari, Joypurhat, Rajshahi, Meherpur, Magura, Jessore, and Kishoreganj. Therefore, a direct comparison between rainfall, SPI and NDVI is not feasible without considering the coverage of irrigated area.

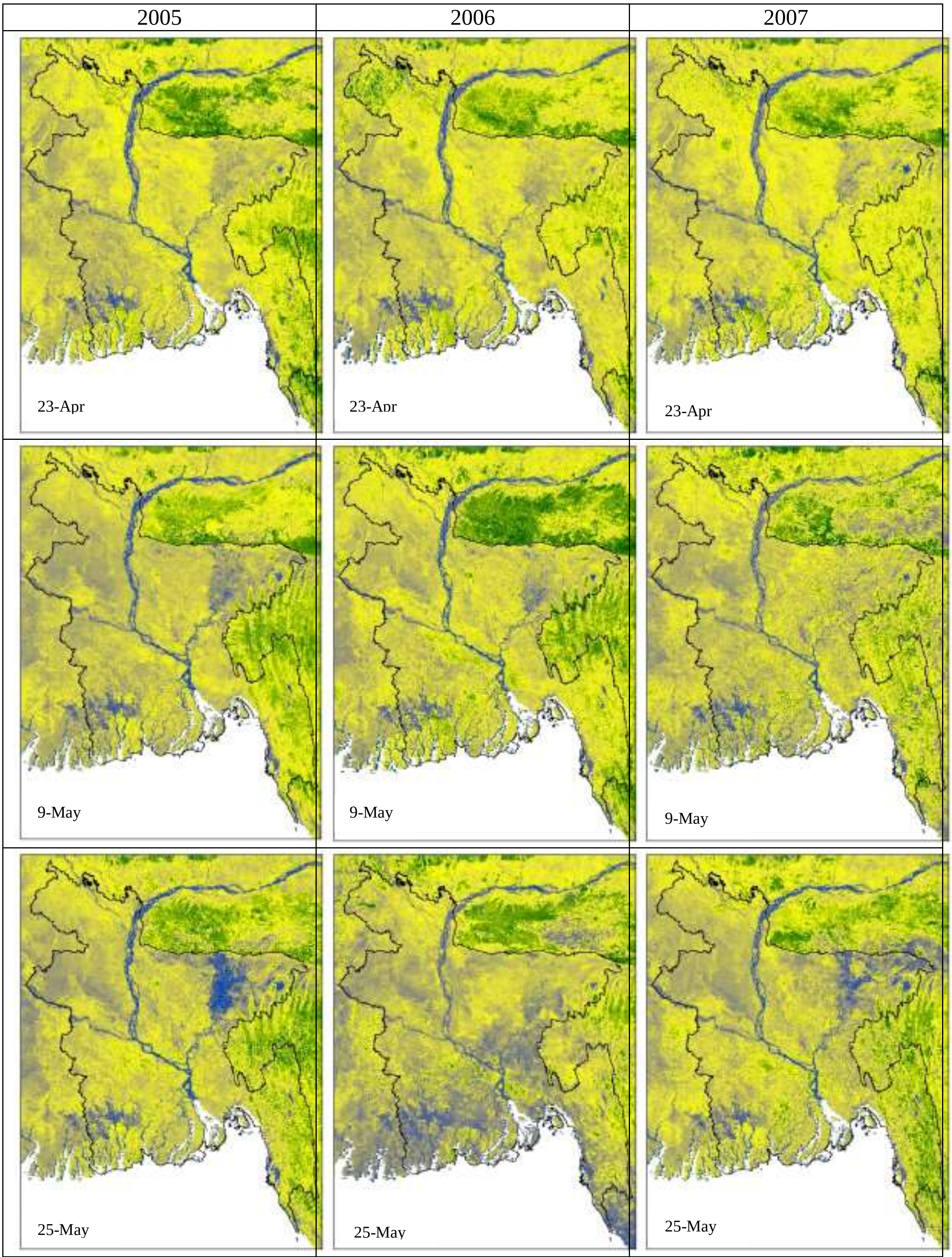


Figure A5.2: Time series of NDVI in Bangladesh during Kharif season (May-October) from 2005 to 2007

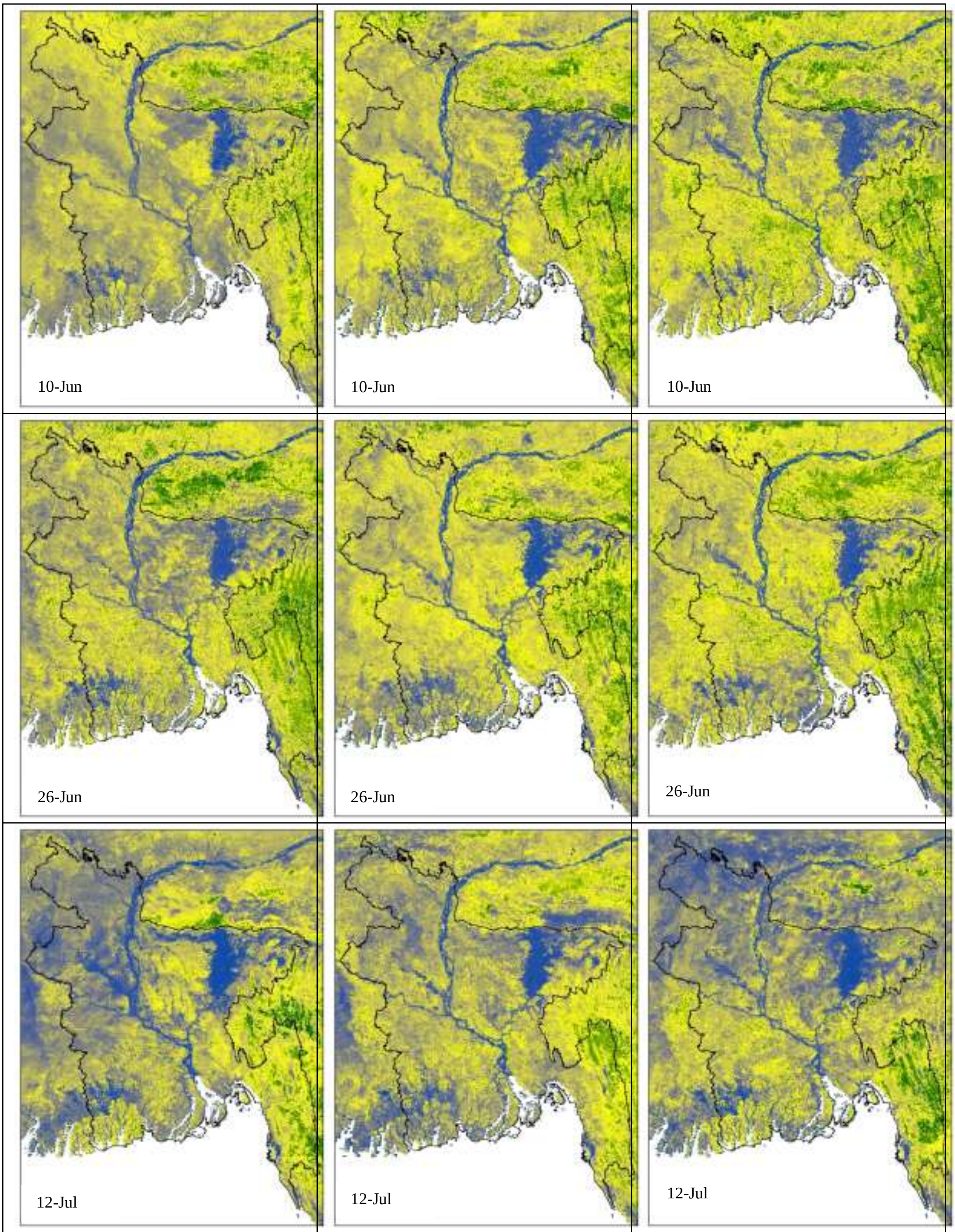


Figure A5.2: Time series of NDVI in Bangladesh during Kharif season (May-October) from 2005 to 2007 (contd.)

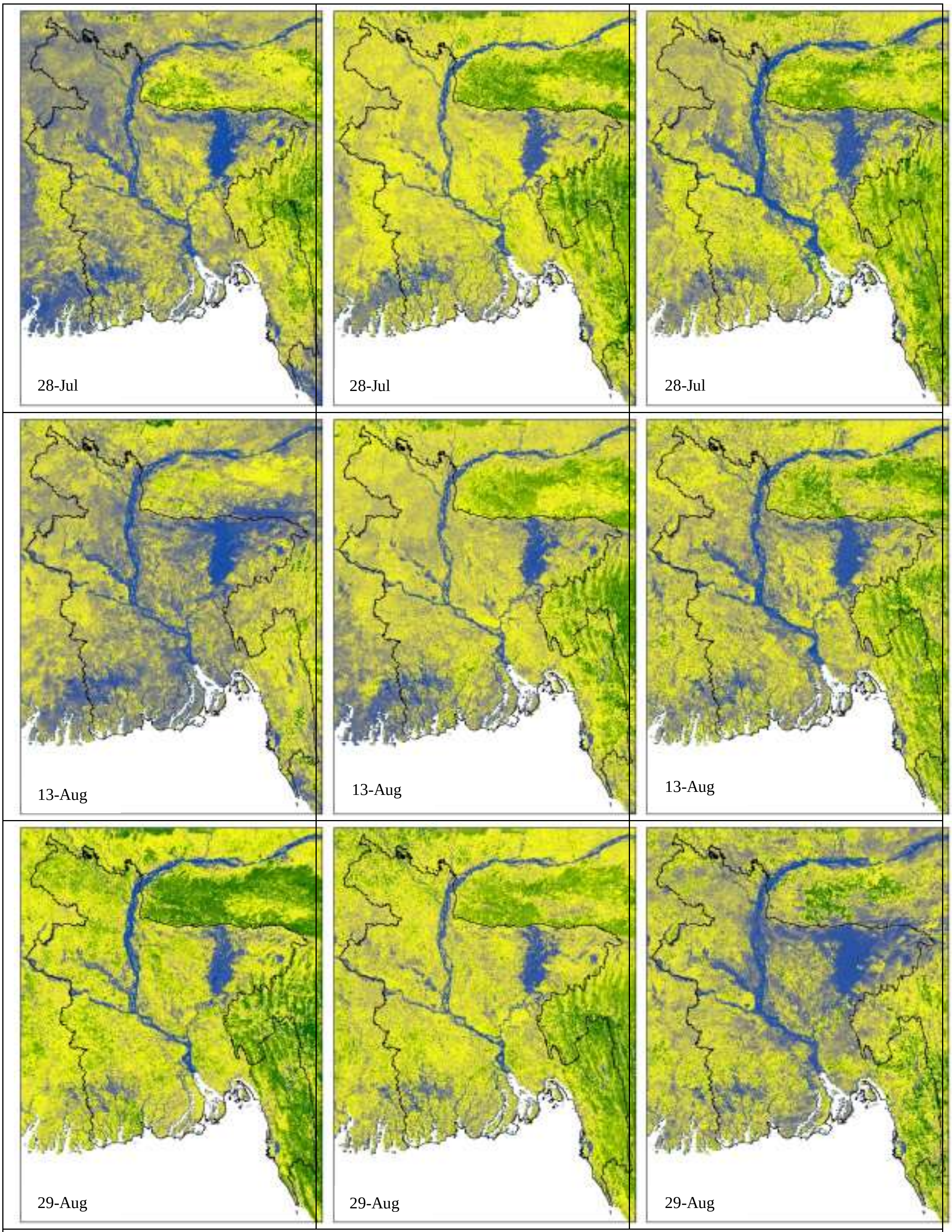


Figure A5.2: Time series of NDVI in Bangladesh during Kharif season (May-October) from 2005 to 2007 (contd.)

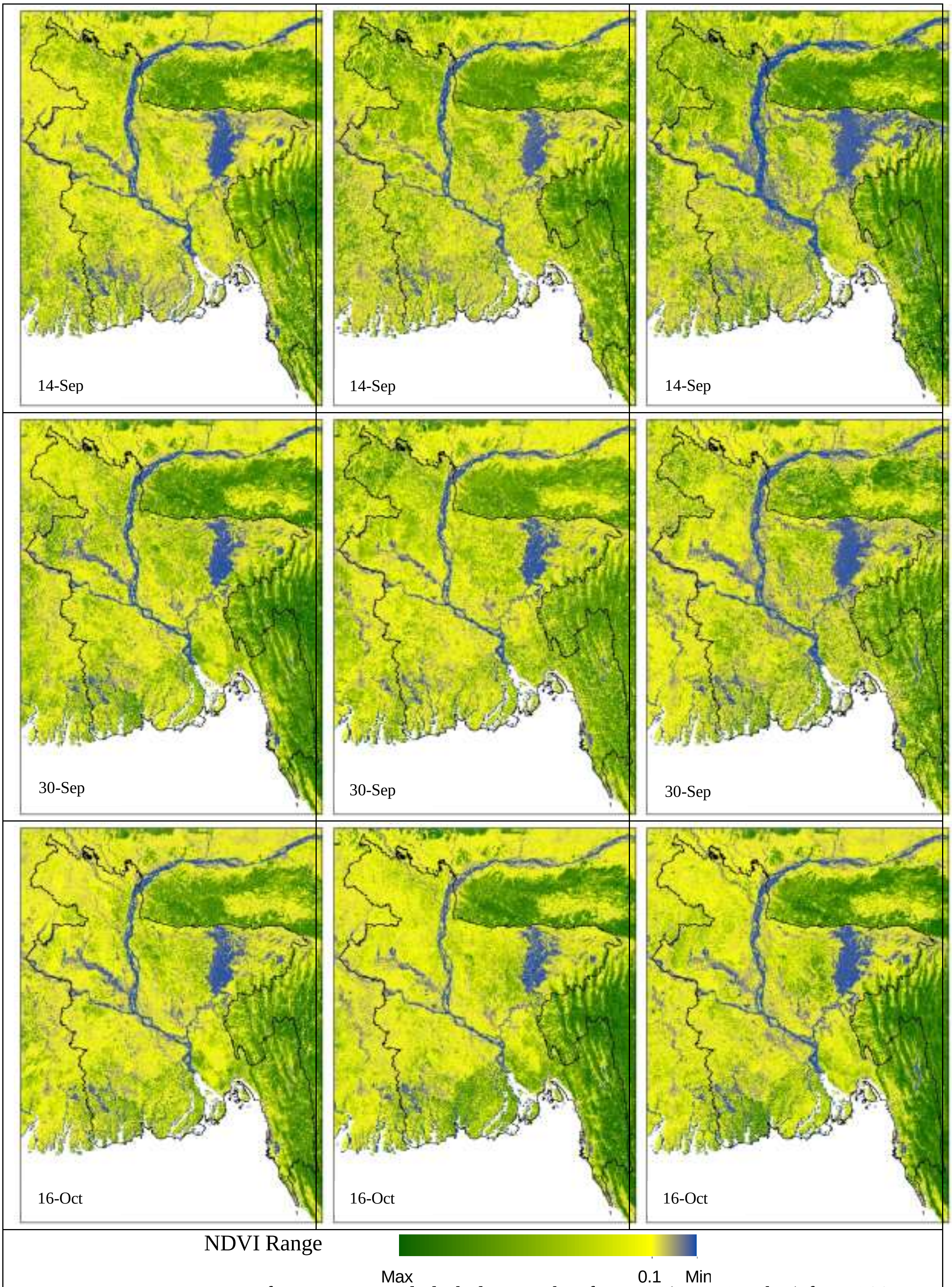


Figure A5.2: Time series of NDVI in Bangladesh during Kharif season (May-October) from 2005-2007

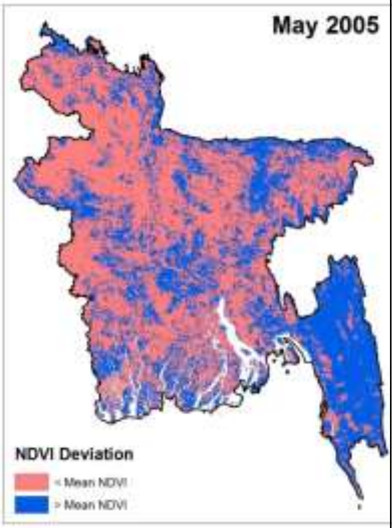
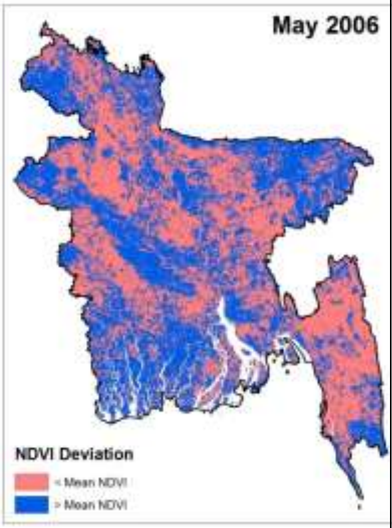
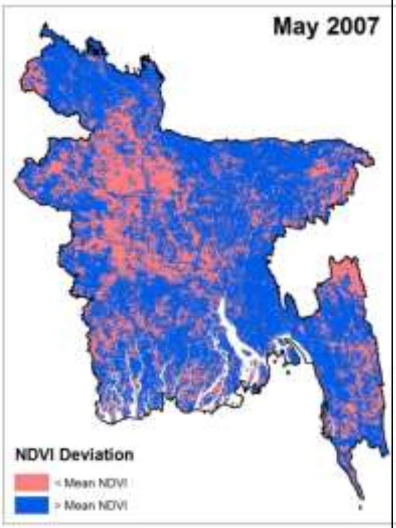
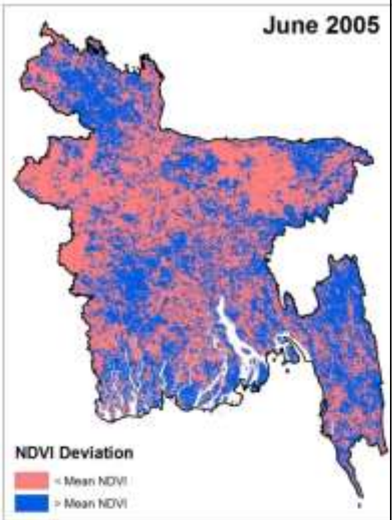
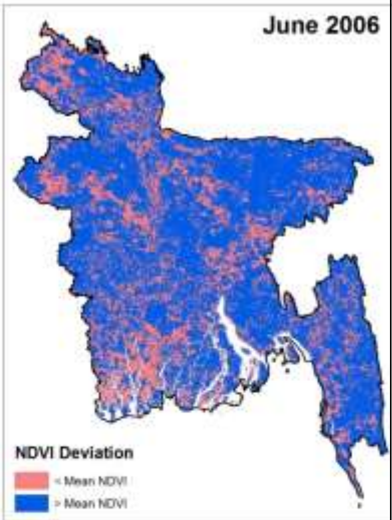
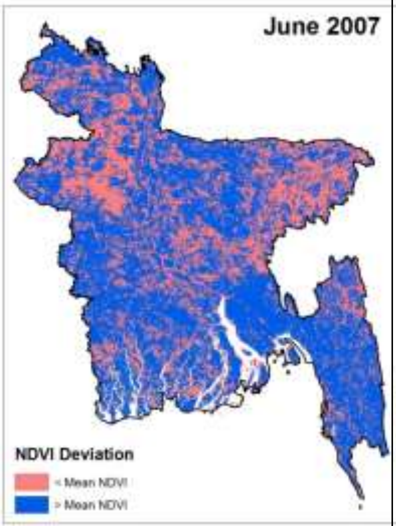
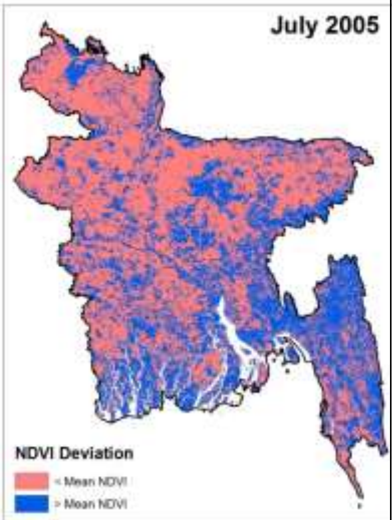
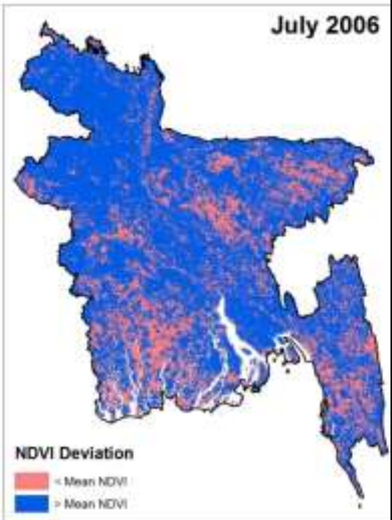
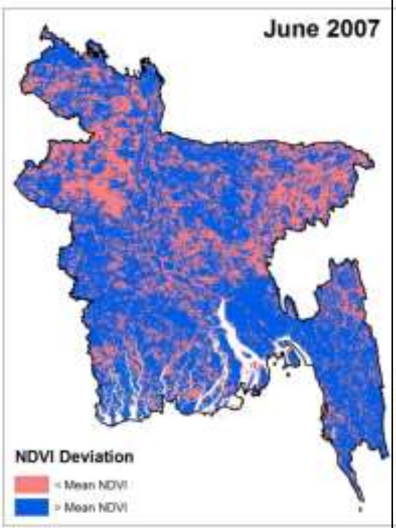
2005	2006	2007
		
		
		

Figure A5.3:Time series of NDVI Deviation in Bangladesh during Kharif season (May- October) from 2005 to 2007

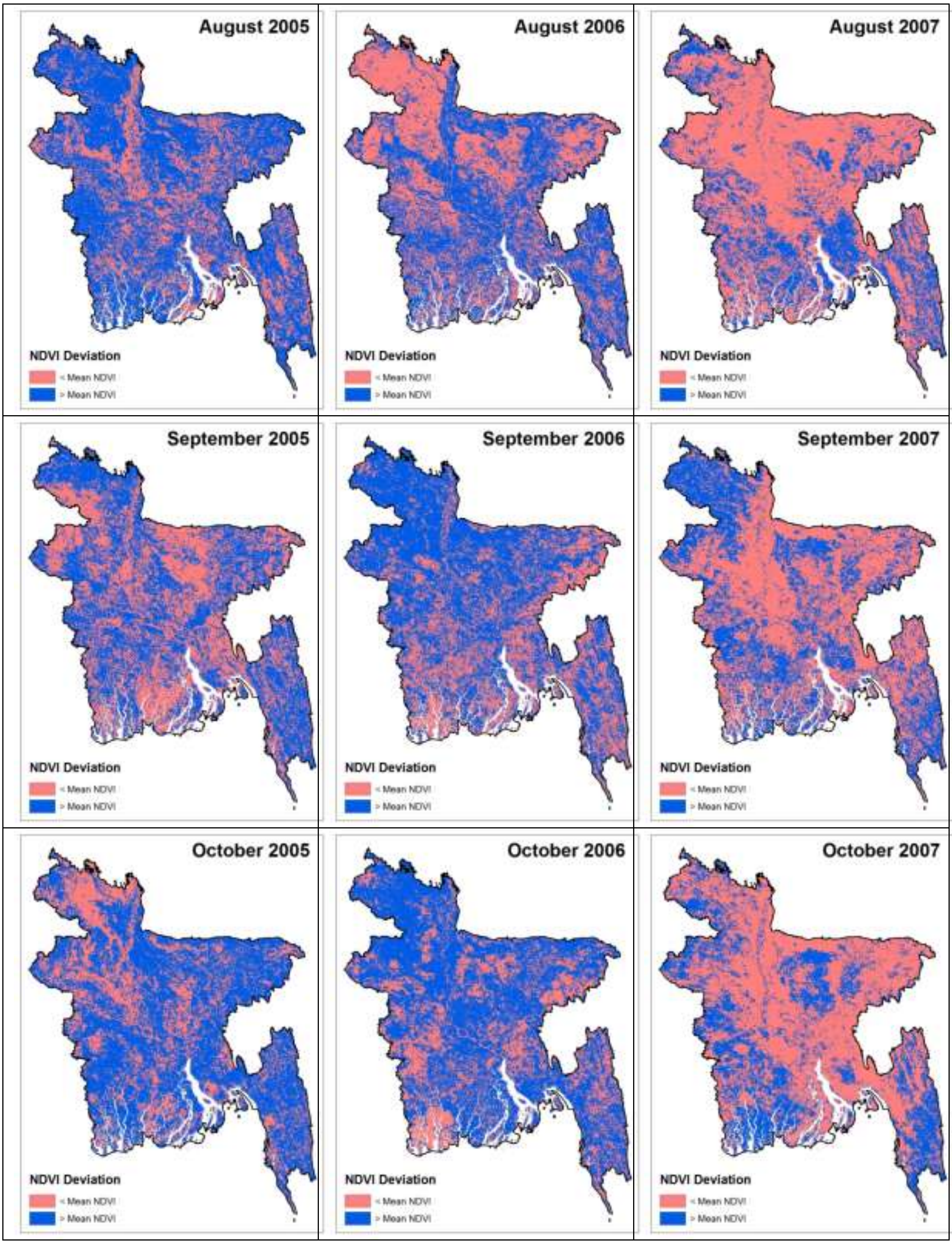


Figure A5.3: Time series of NDVI Deviation in Bangladesh during Kharif season (May-October) from 2005 to 2007.

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