American Scientific Research Journal for Engineering, Technology, and Sciences (ASRJETS)
ISSN (Print) 2313-4410, ISSN (Online) 2313-4402

http://asrjetsjournal.org/

Prediction of Storm Surge and Risk Assessment of Rakhine Costal Region

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Abstract

Rakhine coastal region, western coast of Myanmar, is prone to cyclone and storm surge flooding. The probability of cyclone in Rakhine coast is more than those of any other places of Myanmar coast. That's why, it is very essential to develop storm surge risk maps for Rakhine state. The study area for numerical simulation covers the latitude 14° to 22° N and longitude 89.8° to 98.1° E. Five historical storm surge heights along the coast are determined both by empirical equation and simulated using Delft 3D numerical model coupling with Delft Dashboard and, compared with observed peak surge. Hazard maps of storm surge are developed by modelling three cyclone scenarios for respective recurrence interval. In this study, population data, housing data and livelihood data of Rakhine State during the period of 2010 are adopted for vulnerability analysis. Vulnerable maps for human and social sector, physical infrastructure sector and production sector are developed by using Analytical Hierarchy Process. Finally, risk maps for population, production, infrastructure and livelihood sector of Rakhine State by village tracts are developed by using ArcGIS 10.3.

Keywords: Rakhine coastal region; Storm surge; Delft 3D model; Hazard map; Vulnerable map; Risk map.

1. Introduction

Myanmar, borders with the Bay of Bengal and Andaman Sea, with its 2400 km long coastline is potentially threatened by the waves, cyclones and associated weather. As a tropical agricultural country, the majority of the people live in the fertile plain land along the coastal region which is often flood hazards occur.

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Low-lying deltassuch as Ayeyarwaddy Delta and Rakhine coastal areas of Myanmar are prone to flooding, which cause large economic damages and risks to lives of thousands of people. The most devastating hazard event, cyclone Nargis, hit the country in 2008 and did a significant damage to the lives and properties in the Ayeyarwady delta region. More than 80,000 people died, thousands of families were homeless and many basic infrastructures were damaged due to this disaster. Cyclone Giri (October 2010) and cyclone Mala (April 2006) are prime examples of recent cyclones that heavily affected Rakhine State.

The severity of the storm surge depends primarily on meteorological forces, such as air pressure difference, wind speed and direction. The meteorological conditions are affected by the path and the velocity of the depression systems moving across the sea. When winds push water towards the coast, they tend to accrue into what is commonly referred to as storm surge. If a particular high surge occurs together with high tides, both effects amplify and can result in increased sea water level and serious flood in coastal areas. Accurate predictions of storm surge are of importance in many coastal areas. This study reveals the prediction of storm surge using both empirical equation and numerical simulation of Delft 3D due to combined effect of meteorological forcing and tidal forcing.

In order to minimize the risk from such flooding, both structural and non-structural measures should be implemented in this area. Rather than completely relying on large structural measures, which may not be sustainable due to time consumption and economic condition of the developing countries, hence, it is essential to improve the present flood management system of Myanmar with non-structural measures. Flood inundation maps, vulnerable maps and risk maps of Rakhine State may be useful tools which may aid in mitigating and managing the flood hazard as such non-structural measure. Therefore, storm surge inundation maps of different cyclone scenarios for the coastal region of Rakhine have been developed by using Remote sensing ArcGIS software techniques. The vulnerability assessment followed a semi-analytical, semi-empirical approach utilizing the Analytical Hierarchy Process (AHP).The degree of vulnerability was estimated for the Social and Human sector, Physical Infrastructure sector, and Production sector with respect to storm surge hazard. The risk associated storm surge hazards and vulnerability is evaluated and presented in a map format.

2. Location of the Study Area

Rakhine State, a western coastal region of Myanmar, lies between latitude 17º 21' N and 21º 24' N and longitude 92º 10' E and 94º 54' E, bordering Bangladesh on the northwest, Chin state on the north, Magway Region, Bago Region and Ayeyarwady Region on the east. Rakhine coastal zone is bounded by the Bay of Bengal in the west and total land area is 367,780 km^2. The mountain ranges within the stretches from Bangladesh to Chin State slope downward north to south having elevations of about 900 meter. The northern valley area is narrower than southern valley; better known as the Sittwey valley considerably wide. The Rakhine coastal Region stretches 740 km from Naff River to Mawdin point. The upper part of the coastline is shallow and deltaic. The southern part is more or less rocky. Continental shelf down to 200 m depth is narrow compared to other areas. Maungdaw, Sittwe, Kyauphyu district is situated in northern part and Thandwe district is situated in southern part of Rakhine State. The location of the study area is shown in Figure 1.

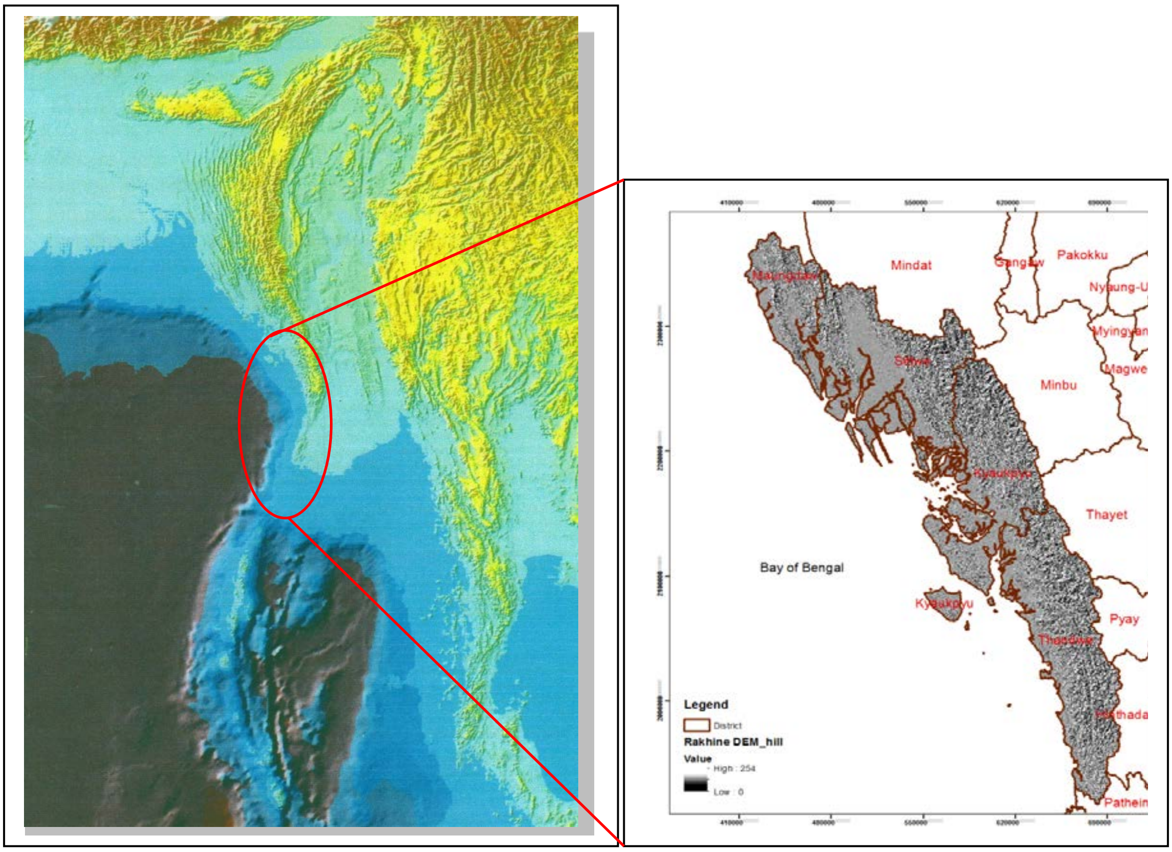


Figure 1: Location Map of the Study Area

3. Data and Methodology

In this study, study area covers western coast of Myanmar under UYM zone 47 N. To find the maximum storm surge height for different return periods, maximum cyclonic wind speed data of cyclones in the Bay of Bengal that approached the coast of Rakhine State during the period of from 1967 to 2010 data were obtained from the Indian Meteorological Department. Gumbel parameters are estimated by adopting Method of Moment (MOM), Maximum likelihood Method (MLM), Method of Least Square (MLS), Order Statistic Approach (OSA) and Probability Weighted Moment (PWM). Goodness of Fit test (Anderson-Darling (AD) and Kolmogorov-Smirnov (KS)), Diagnostic test (Root Mean Square Error), and Model performance indicator (Correlation Coefficient) are used to choose suitable method for Gumbel parameters. Gumbel distribution (1985-Type I extreme value distribution) is utilized for determining cyclone intensity scenarios for respective recurrent interval. Storm surge heights for different return periods due to wind stress is determined by using empirical surge height prediction method modified by Tareque & Chowdhury. Bathymetry of study area is developed by Delft 3D Quick-IN applying different data sources such as GEBCO-08, modified ETOPO-5 and Navigation chart from Navioncs website. Delft Dashboard and Delft-3D numerical model are used for cyclone, tide and storm surge modelling. ASTM 30 meter resolution DEM of Rakhine State, Freeman & Lee Mehaute equation for constant surge height intrusion distances and ArcGIS software (10.3) considering surge decay coefficients of study area are used to develop storm surge hazard maps. Population data, housing data, livelihood data during the period of 2010 collected from General Administration Department of Rakhine State and Myanmar Information Management

Unit and, paddy yield data from World Food Program are used for vulnerability analysis. Multi criteria decision making method (Analytical Hierarchy Process) is used to evaluate vulnerability coefficient for flood risk maps. The flow chart of the study is shown in Figure 2.

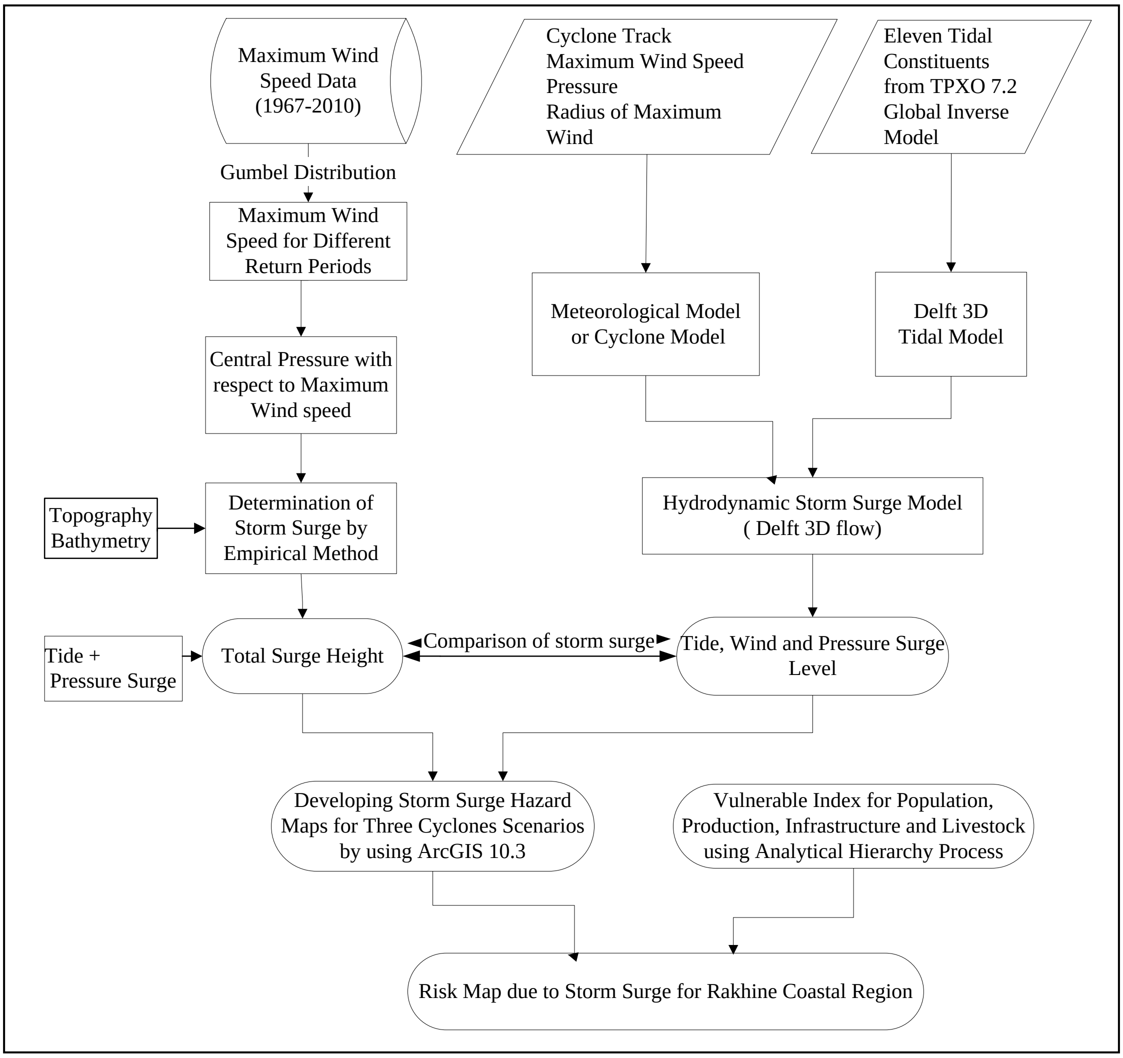


Figure 2: Flow Chart for Implementation Program of the Study

4. Empirical Prediction of Storm Surge

In this paper, Maximum wind speed and minimum sea level pressure relationship chart and Bretschneider's wind stress formulation which is modified by Tareque @ Chowdhury is adopted to forecast the surge levels for Rakhine coastal region. Two main components of the surge are (a) air pressure variation effect and (b) onshore wind stress effect [6].

(a) Inverted Barometer Effect

The inverted barometer effect is the tendency for the water surface to be sucked upwards in region of low atmospheric pressure. During the storm, the water surface rise is centered at the eye of the storm and depends directly on the central pressure relative to normal sea level pressure. The surge height due to air pressure variation effect is;

$$S_p=(1013-P_c)*0.033$$

(1)

Where, S_p is storm surge in feet of sea water and P_c is pressure of storm centre in millibars [5].

(b) Wind Stress Effect

Generally, the large component of storm surge is due to the wind stress on the water surface. The surge height due to wind stress effect is computed by equation (2), [6]

$$S=\frac{13\times10^{-6}LV^2}{\left(5\times10^6+LV^2\right)^{0.2}} \quad (2)$$

Where, S is the areal average surge height in m, L is the length of the continental shelf in kilometer up to 200 meter depth of contour; V is the cyclonic wind speed in km h^{-1}. Length of continental shelf in kilometer up to 200 meter depth of contour is measured by constructing bathymetry contour map of Bay of Bengal and coastal line by using ArcGis software. The coastal length of study area is divided 15 segments by 35 kilometer interval. The results measured length between two points (difference in latitude and longitude) by ArcGis software is compared with calculated distance given by Haversine formula. The value of L is obtained as aerial average length of Rakhine coastal Region. 139 km for Maungdaw district, 83 km for Sittwe District, 45 km for Kyaukphyu District, 36 km for Thandwe District and 76 km for the Rakhine Coastal Region. An average value of maximum tidal range (2.4 m) corresponding to spring tide was obtained from several tidal stations along the seaboard of Rakhine State. Accordingly, the computed maximum surge levels near the shoreline were super-imposed with a further rise in water level of 1.2 m to take into account the worst-case tidal effect. Total surge height with respect to sea level can be found from the combination of surge height due to wind stress, surge height due to pressure deficit and mean tide height [7].

5. Numerical Storm Surge Delft 3D Modelling

Delft 3D flow solves the unsteady shallow water wave equation in two (depth average) or three dimensions. The system of equation includes the horizontal equation of motion, the continuity equation and the transport equation for conservative constituents. These equations are formulated in orthogonal curvilinear co-ordinate or in spherical coordinate on the globe in Delft-3D. The flow can be forced tide due to at the open boundary, wind stress at the free surface and, pressure gradients (both free surface gradients and density gradients) [8].

5.1. Hydrodynamic Equation

Delft 3D-Flow solves the Navier Stokes equations for incompressible fluid under the shallow water equation and the Boussinesq assumption. This set of partial differential equations in combination with an appropriate set of initial and boundary conditions is solved on a finite difference grid. The three dimensional hydrodynamic equations used in delft 3D are defined as;

$$\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y} + \frac{\omega}{D+\xi}\frac{\partial u}{\partial \sigma} - fv = \frac{P_x}{P_0} + F_x \frac{1}{(D+\xi)^2}\frac{\partial}{\partial \sigma}\left(v_v \frac{\partial u}{\partial \sigma}\right) + M_x \quad (3)$$

$$\frac{\partial v}{\partial t} + u\frac{\partial v}{\partial x} + v\frac{\partial v}{\partial y} + \frac{\omega}{D+\xi}\frac{\partial v}{\partial \sigma} - fu = \frac{P_x}{P_0} + F_y \frac{1}{(D+\xi)^2}\frac{\partial}{\partial \sigma}\left(v_v \frac{\partial v}{\partial \sigma}\right) + M_y \quad (4)$$

$$\frac{\partial \xi}{\partial t} + \frac{\partial[(D+\xi)u]}{\partial x} + \frac{\partial[(D+\xi)v]}{\partial y} + \frac{\partial \omega}{\partial \sigma} = h.(q_{in} - q_{out}) \quad (5)$$

where:

u, v = velocity in x, y –direction [m/s]

x, y = horizontal spatial co-ordinates [m]

t =time co-ordinate [s]

f = Coriolis coefficient [1/s]

σ = scaled vertical co-ordinate [-]

ω = velocity in the σ-direction in the σ co-ordinate system [m/s]

ρ_0 = reference density of water [kg/m^3]

P_x, P_y = gradient hydrostatic pressure in x, y direction [$kg/m^2/s^2$]

F_x , F_y = turbulent momentum flux in x, y direction [m/s^2]

D = depth to horizontal reference plane [m]

ξ = water level above reference [m]

v_v = vertical eddy viscosity [m^2/s]

M_x, M_y = source or sink of momentum in x, y direction respectively [m/s^2]

$q_{in,}q_{out}$ = local source, sink per unit volume [1/s]

5.2. Data and Methodology

5.2.1. Delft Dashboard

Delft Dashboard is a standalone Matlab based graphical user interface aimed at supporting modelers in setting up new and existing models. This model is developed by the Deltares which makes it possible to quickly set up hydrodynamic models anywhere in the world, by coupling the automatic grid generation tools in Delft Dashboard to online datasets that contain global bathymetric data, tide data and output from meteorological models.

5.2.2. Bathymetry data set and Grid generation

The efficiency of a model to simulate tide and storm surge accurately depend on the extent to which the shallow depths are represented precisely. The role and important of the real and accurate bathymetry dataset of numerical model to reproduce the observation tidal elevations and currents have been highlighted in many researches [14]. Bathymetry of study area is developed by Delft 3D Quick-IN applying different data sources such as GEBCO-08, modified ETOPO-5 and Navigation chart from Navioncs website**.** According to the sensitivity analysis on combined effect of tide and storm surge with three different grid sizes of the model on three cyclones, simulated results from alternative 1 (3 km grid size) at three landfall points are underestimated relating with observed peak surge and simulated results from alternative 3 (0.5 km grid size) are overestimated. In Alternative 2 (1 km grid size), the simulated result is nearly the same with observed surge in Nargis and Giri cyclone. The results are shown in Table 1. Therefore, the orthogonal curvilinear grid with a resolution grid size 1 km is selected to use for storm surge simulation and are generated around the interested area (Myanmar coast) of latitude 14° to 22° N and longitude 89.8° to 98.1° E from Delft Dashboard. The orthogonality of the grid is 0.2, the smoothness and aspect ratio of the gird are 1 and 1.06 respectively.

Table 1: Comparison of simulated and observed peak surges for three alternative grid resolutions of three historical cyclones

Alternative	Grid Size (km)	Simulated Peak Surge (m)		
		Mala Cyclone	Nargis Cyclone	Giri Cyclone
1	3	2.5	5.0	5.5
2	1	3.0	7	5.0
3	0.5	3.5	7.5	5.5
Observed Peak Surge		4.57	7.02	5

5.2.3. Tropical Cyclone Model (Wind Enhance Scheme)

For modelling tropical cyclone over the Rakhine coastal region of Myanmar, tropical cyclone tool box of Delft Dashboard is used in order to obtain parametric model with high resolution grid. It includes an easy-to-use user interface for this WES (Wind Enhancement Scheme) model (the tropical cyclone toolbox). With the inclusion of the cyclone toolbox in Delft Dashboard, the generation of cyclone wind fields for these models became much easier and faster. With this feature, it is possible to incorporate the track information and directly convert this information into 2D wind fields on a moving circular 'spider' web grid using the Wind profile, Vmax-Pc relation and Rmax relation [8].

5.2.4. Tidal Model

To consider combined effect of tide on storm surge along the Rakhine coastal region, two dimensional modelling system developed by Deltares is used. The numerical solution of the equations is obtained by discretizing the equations in space using an explicit finite difference scheme over a uniform staggered Arakawa-C grid and in time using Alternating Differential Implicit (ADI) technique. Due to unavailability of measurement near the open ocean boundary, tidal amplitudes and phases of the main semidiurnal and diurnal tidal Constituents (*M2*, *S2*, *N2*, *K*1, *O1*,P1, *M*2, *S*2 and *K*2) extracted from the global ocean tidal model TPXO 7.2 on 1/4 ×1/4 degree resolution global grid were prescribed at boundary cells and linearly interpolated. A free slip condition was applied on the closed boundaries with a zero value of normal velocity. Time step of 20 seconds is set in all simulations to ensure the stability and accuracy of the model. Initial conditions of water levels were set as zero in all simulations and running a full lunar month. Values of water density and gravitational acceleration were set as 1023 kg·m^{-3} and 9.81 ms^{-2}, respectively.

5.3. Delft 3D Storm Surge Modelling for Rakhine Coast

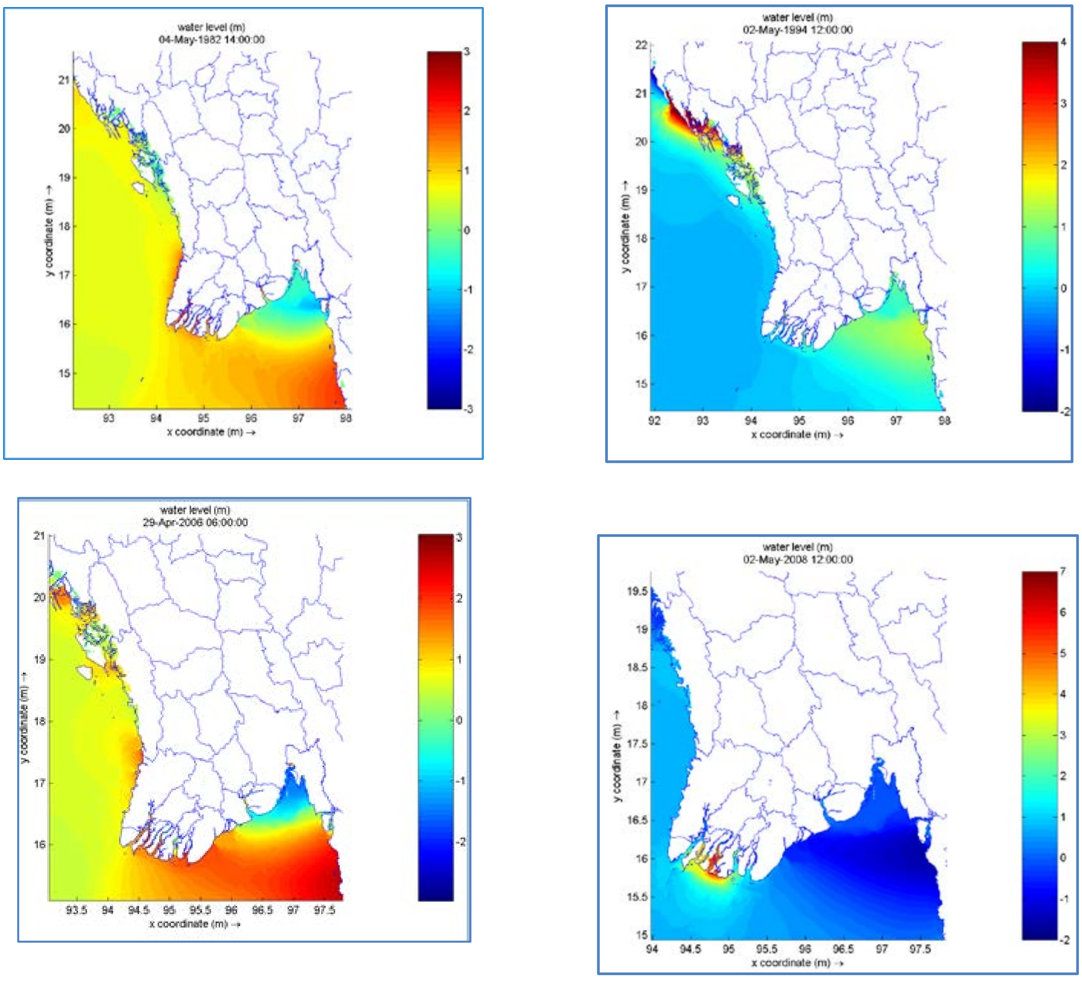


Figure 3: Simulated peak surge of (a)1982 Gwa cyclone (b) 1994 Maungdaw cyclone (c) 2006 Mala cyclone (d) 2008 Nargis cyclone

6. Evaluation of Storm Surge Model Performance

Storm surges for five historical cyclones are simulated and determined by using numerical model and empirical equations (1) and (2) and, summarized in Table 2. Observed peak surges for five cyclones are obtained from Department of Meteorology and Hydorlogy, Myanmar. According to these values, simulated surge for

Table 2: Comparison of Observed, Empirical and Simulated Peak Surge

	Name	Date	Observed Surge (m)	Simulated Surge (m)	Empirical Surge (m)	Landfall Point
1	Gwa Cyclone	4.5.1982	3.7	3.08	3.3	Near Gwa
2	Maungdaw Cyclone	2.5.1994	3.66	3.7	5.2	Near Maungdaw
3	Mala Cyclone	29.4.2006	4.57	3.0	4.53	Near Gwa
4	Nargis Cyclone	2.5.2008	7.02	7.0	7.55	Ayarwaddy
5	Giri Cyclone	29.10.2010	5.0	5	3.8	Kyaukphyu

Developing Storm Surge Hazard Maps for Rakhine State

Rakhine is the most vulnerable region to storm surge due to cyclone generated mostly in the Bay of Bengal as it is the highest probability of cyclone landfall place compared to the other coastal region of Myanmar (Delta region and Tanitheryi coast). Maximum cyclonic wind speeds in the Bay of Bengal that approached to Rakhine Coast during the period of from 1967 to 2010 were statistically analysed by five Gumbel parameter estimation methods (Method of Moment, Maximum likelihood Method, Method of Least Square, Order Statistic Approach and Probability Weighted Moment). Goodness of Fit test (Anderson-Darling (AD) and Kolmogorov-Smirnov (KS)), Diagnostic test (Root Mean Square Error), and Model performance indicator (Correlation Coefficient) are used to choose suitable method for Gumbel parameters and is shown in Table 3.

According to mentioned statistical parameters, AD and KS of five methods of Gumbel distribution are less than the theoretical values ($AD_{0.05}$=0.757; $KS_{0.05,11}$=0.410; $KS_{0.05,13}$=0.377) at five percent significance level and at this level, all five methods are found to be suitable for determination of estimators of Gumbel distribution for the region under study. The correlation coefficient (CC) between recorded and estimated wind speeds by all five methods of Gumbel distribution is almost equal as 0.9581 and, Method of Moment is chosen as the best suitable method since this method gives the least value of RMSE. To find the design wind speeds for different return periods, location and scale parameter of 101 km/h and 48.7421 km/h given by Method of Moment are used in Gumbel's (1958) distribution in probabilistic approach. Design wind speeds for various recurrent intervals are deduced accordingly, wind speed 200 km/h for 5year return period (scenario-1), 250 km/h for 10 year return period (scenario-2) and 280 km/h for 20 year return period (scenario-3). Time and space varying wind field of each cyclone scenario is carried out using Delft-Dashboard cyclone tool box. Storm surge simulation for each scenario is carried out for a large set of synthetic track, as there is considerable uncertainty on the potential cyclone tracks of land fall point. Storm surges of different cyclone scenarios for northern part of Rakhine Coast are simulated by Delft 3D numerical model and, as for southern part, storm surge determined by empirical equation. The maximum surge heights corresponding to three cyclone scenarios data are exported as x coordinate, y coordinate and water depth over all grid points of entire model domain by using Delft 3D Quick plot tool which is the Matlab based GUI enable data processing and visualization in multiple format.

Table 3: Computed values of AD, KS, RMSE and CC given by Respective Estimation Methods of Gumbel Parameters

	MOM	MML	MLS	OSA	PWM
AD	0.4156	0.4181	0.3370	0.3436	0.3497
KS	0.1310	0.1285	0.1207	0.1297	0.1151
RMSE	17.6282	17.7007	18.4985	18.3889	18.4832
CC	0.958140	0.958125	0.958128	0.958127	0.958128

To develop Storm surge hazard maps, Arcgis 10.3 and 30 meter resolution Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) Global Digital Elevation Model of study area are used. Width of constant surge is determined by using surge intrusion distance (equation 6). Slope of different districts is calculated within the range of 10 m elevation of ASTER value in each cell by using ArcGIS software. Land use map of Rakhine State is shown in Figure 4. Friction factor was assumed as 0.03. For the modeling, the total inundation length from the coast line due to flood depth of 4 m is assumed to be affected up to 4 km for scenario 1. For scenario 2 and 3, total inundation limit from the coastline is assumed as 10 km and elevation at end of surge for all scenarios is assumed as 1m. By using maximum surge height from both empirical equation and numerical model, hazard map of storm surge for Rakhine State is developed by ArcGIS software. Storm surge hazard map of three cyclone scenarios can be seen in Figure 5. Surge intrusion distance developed by Freeman & Lee Mehaute [6];

$$X= \frac{4(4+1.5h)^2}{3(4+h)(S_b+ f/8)} \tag{6}$$

Where, h is surge height, S_b is the land slope, f is the friction factor and X is the storm surge intrusion distance from coast line to inland. Surge decay coefficient of the hazard model is calculated by the equation (7).

$$SDC= \frac{\text{Surge height - Average elevation at end of the surge}}{\text{Total inundation width - Width of constant surge}} \tag{7}$$

To develop the storm surge risk map of Rakhine State, cyclone scenario-2 (cyclone intensity 250 km/h) that is the same as Giri cyclone intensity, is chosen to consider the storm surge impact. The affected villages and area due to storm surge flood for cyclone scenario (2) is shown in Figures 6 and 7. It is found that villages by simulation are more affected than those during Giri Cyclone (2010) in some townships such as Kyaukphyu.

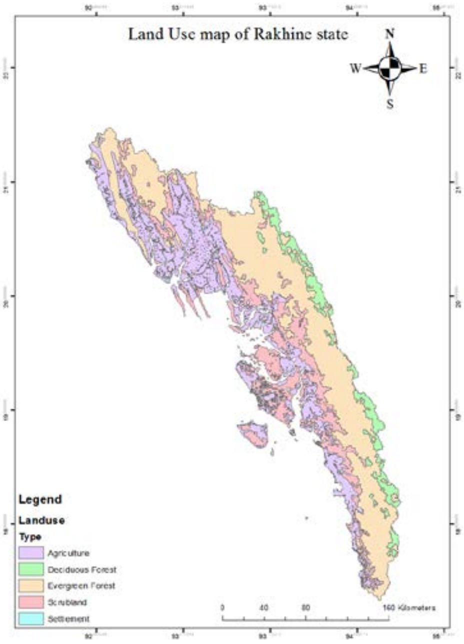


Figure 4: Land Use Map of Rakhine State

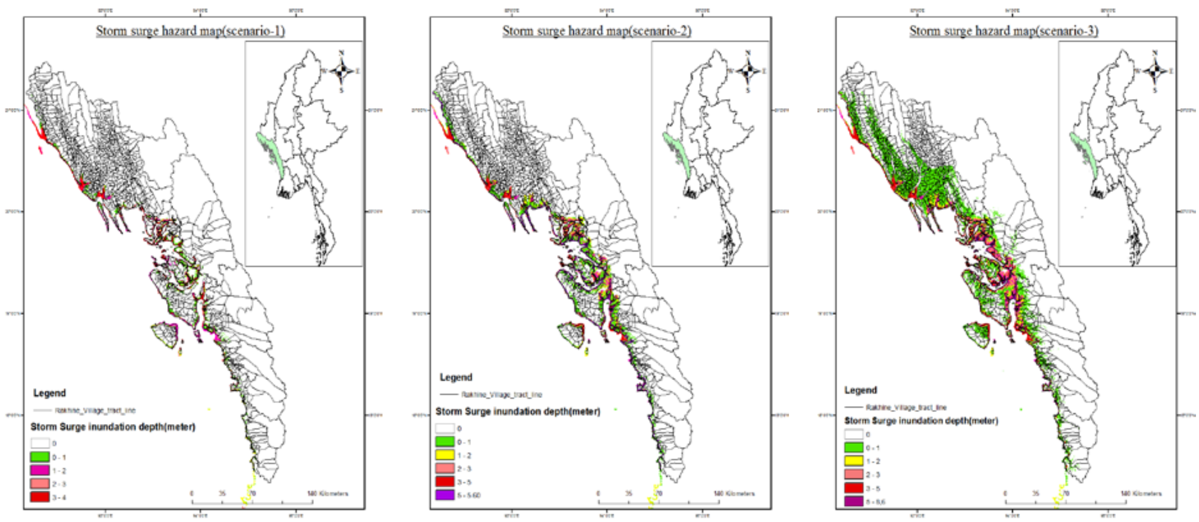


Figure 5: Storm Surge Hazard Maps of Three Cyclone Scenarios

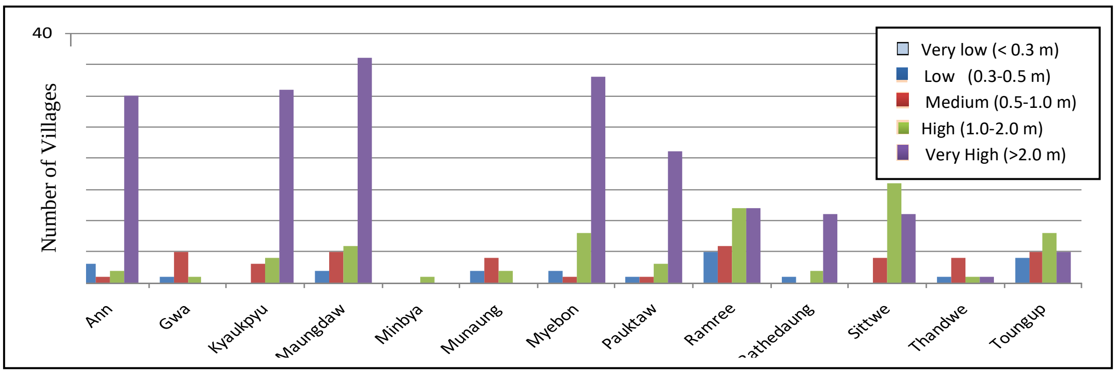


Figure 6: Number of Villages Affected by Simulated Storm Surge Flooding

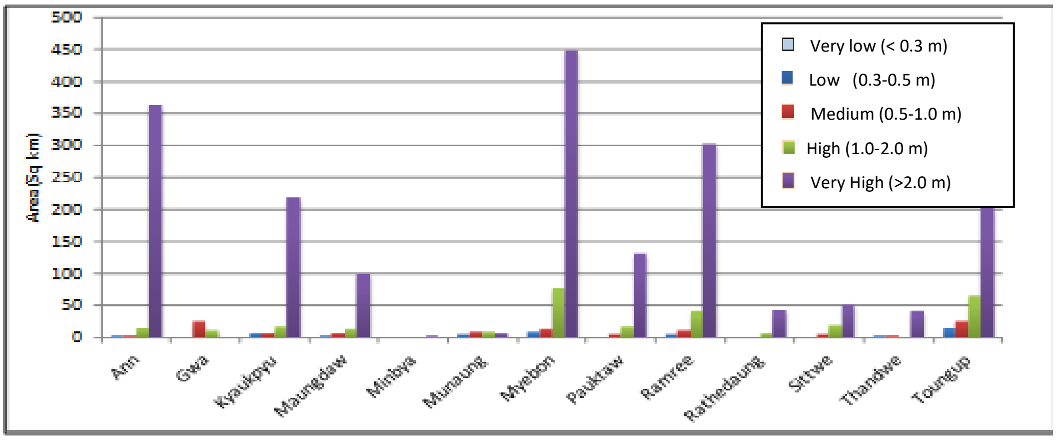


Figure 7: Area Affected by Storm Surge Flooding in Different Depth Surge Flooding in Different Depth

6. Vulnerability Assessment

For this study, vulnerability assessment has been conducted for three particular sectors considering the priority of the state. These are presented in Table 4. Based on the surveying data from twenty villages, relative intensity importance of vulnerability is analyzed by using AHP. The human and social sector covers age, gender, and occupation. The infrastructure sector covers building types and the production sector covers the production of paddy/rice in Rakhine state. To estimate the vulnerability for these three sectors, this study adopted Analytical Hierarchy process (AHP). To make decision as rational, it is needed to quantify these subjective opinions into subjective values for developing vulnerable map. Flow Chart for developing flood vulnerability mapping is illustrated in Figure 8.

Table 4: Sectors & Related Indicators Considered for Vulnerability Assessment Tools

No.	Sector	Indicators	Data Source
1	Human and Social Sector	(a) Population: age group & gender structure. (b) Livelihood: different occupations like agriculture, livestock, fisheries, business and service.	Government Administration Department
2	Infrastructure Sector	Building Types: concrete, masonry, brick nogging, wood and hut	GAD & Field Survey
3	Production Sector	Annual paddy/rice production in Rakhine State	World Food Program

6.1. Vulnerability Assessment on Population

For this study, population vulnerability has been analyzed based on the age and gender. In Rakhine State, the number of women is more than that of men. About 27% of the population is women aged 18 years plus, 24%

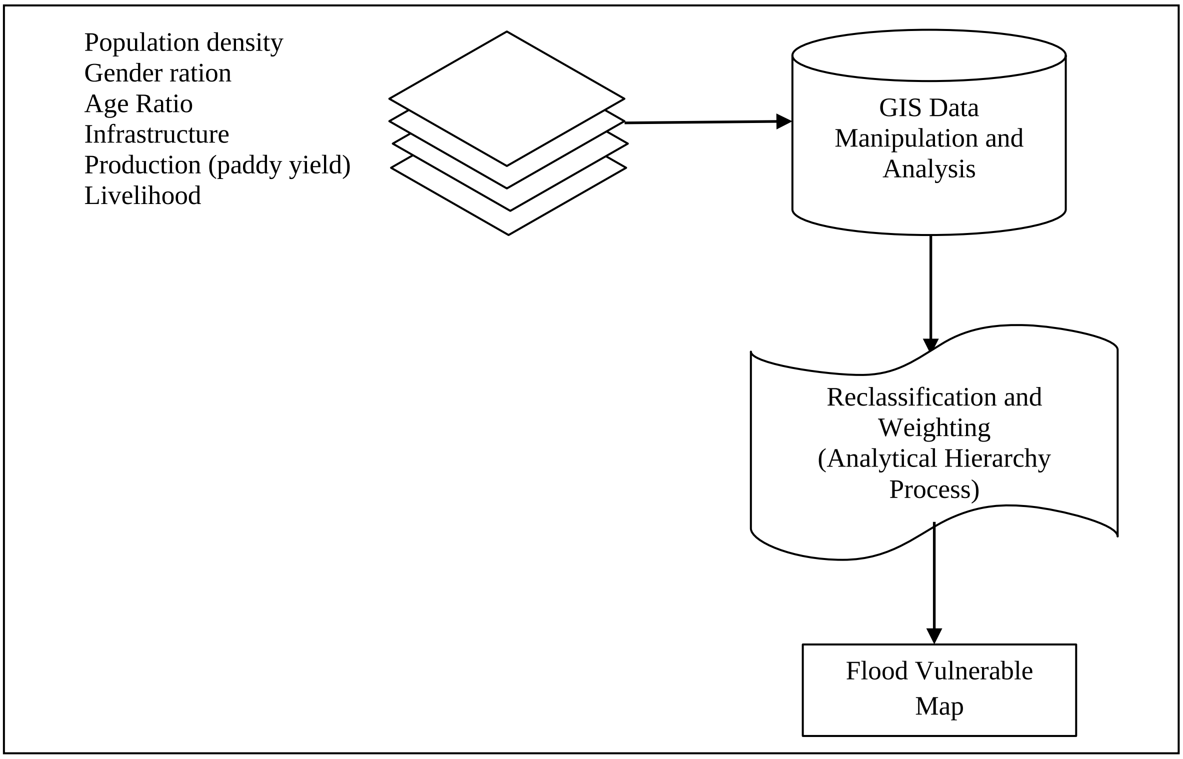


Figure 8: Flow Chart for Developing Flood Vulnerability Mapping

under 18 years and 25 % & 24% of the population are male of 18 years plus and below 18 years category respectively. Relative importance of population calculated by pairwise comparison of AHP is shown in Table 5 and population sensitivity indices are evaluated according to the conceptual equation (8) by using the relative importance (or weights) of different population groups.

Table 5: Relative Importance (SRP) by population group

Population Group	Relative Importance (SRP)
Male > 18	0.05
Female > 18	0.18
Male < 18	0.22
Female < 18	0.54

$$PI=\left(\sum_{i=1}^{Np} FP_i \times SRP_i\right)\times ToP \quad (8)$$

where, PI = Population Sensitivity Index, FP_i = Fraction of Each Population Group (obtained from GAD, General Administration Department), SRP_i = Relative Importance for Each Population Group, ToP =Total Number of Population within the Village Tract (obtained from GAD) and Np = Number of Population Group: 4 in this study. The population sensitivity index (PSI) was calculated for every administrative unit. Finally the calculated population sensitivity indices were divided into five quantile groups.

6.2. Vulnerability Assessment on Production

Rakhine is an agriculture based state in Myanmar. The main crops of the state include paddy, beans, fruits etc. Among the agricultural product; paddy/rice contributes about 80% of its total GDP. For this study, paddy has been considered for analyzing the vulnerability of production sector. Since this is the main production, the impact of any hazard on this production sector would bring an effect in the state and national economy as well.

6.3. Vulnerability Assessment on Infrastructure

Housing is the main infrastructure to be considered for vulnerability assessment since this is very important to understand the risk to take initiatives for reducing human casualty to any hazard. During this study, vulnerability has been considered for all the building types available in the townships of Rakhine state. Rakhine state is dominated by wooden and hut structure of housing across the townships. This is because of the remoteness of the state from the main part of the country and the economic status of the people. About 56% of the houses are hut (made of local available materials) followed by 38% wood, 3% brick nogging, 2% masonry, 0.5% concrete and 0.9% different types of structures. Infrastructure sensitivity indices for storm surge hazard are computed based on the breakdown of structural typologies in each village tract, according to the following conceptual equation (9) and using the relative importance factors (or weights) of different structure typology groups shown in Table 6.

Table 6: Relative Importance (SRS) by Structure Typology Group

Structure Typology	Relative Importance (SRS)
Concrete	0.03
Masonry	0.05
Brick-Nogging	0.07
Wood	0.12
Hut	0.58
Others	0.15

$$SSI=\left(\sum_{i=1}^{Ns} FS_i \times SRS_i\right)\times ToS \tag{9}$$

where, SSI = Infrastructure Sensitivity Index, FS_i = Fraction of each structure topology group, SRS_i = Relative importance for each structure topology group, ToS = Total number of structure within the village tract, and Ns = Number of structure topology group. The infrastructure sensitivity index (SSI) was calculated for every administrative unit. The calculated infrastructure sensitivity indices were divided into five quantile groups.

6.4. Vulnerability Assessment on Livelihood

More than 50 percent of the people in Rakhine State earn their living from agriculture. Thirteen percent of the community engaged in fisheries and ten percent in livestock management. The remaining 25 percent earn their living from service, business and other unofficial activities. The relative importance (SRL) for each livelihood group is computed using a pair-wise comparison under the Analytical Hierarchy Process. The computed SRL's are presented in Table 7. Livelihood sensitivity indices for all hazards were calculated according to the conceptual equation (10) using the relative importance factors (or weights) of different livelihood groups.

Table 7: Relative Importance (SRL) by Livelihood

Livelihood Group	Relative Importance (SRL)
Agriculture	0.27
Fisheries	0.52
Livestock	0.14
Others (Service+Business)	0.07

$$LSI=\left(\sum_{i=1}^{No} FL_i \times SRL_i\right)\times ToP_{18} \quad (10)$$

where, LSI = Livelihood Sensitivity Index, FLi = Fraction of Each Livelihood Group, SRLi = Relative Importance for Each Livelihood Group, ToP_{18} = Total Number of Population (Above 18) within the Village Tract, No = Number of Livelihood Group.

7. Mapping of Hazard and Vulnerability Categories to Numeric Indices

The qualitative levels of the hazard and vulnerability defined are converted into equivalent numeric values for computing the risk indices, as following Table 8. Five quantile groups of hazard categories are classified based on storm surge heights as very low for less than 0.3 m, low for 0.3 to 0.5 m, and medium, high and very high as shown in Figure 6 and Figure 7. Five quantile groups of hazard index for each sector are categorized by their respective amount of sensitivity indices. Hazard maps and vulnerable assessments due to storm surge for Rakhine coastal region is shown in Figure 9 and Figure 10.

Table 8: Numeric Indices for Hazard and Vulnerability

Hazard or Vulnerability Category	Hazard Index	Vulnerability Index
None	0	N/A
Very Low	1	1
Low	2	2
Medium	3	3
High	4	4
Very High	5	5

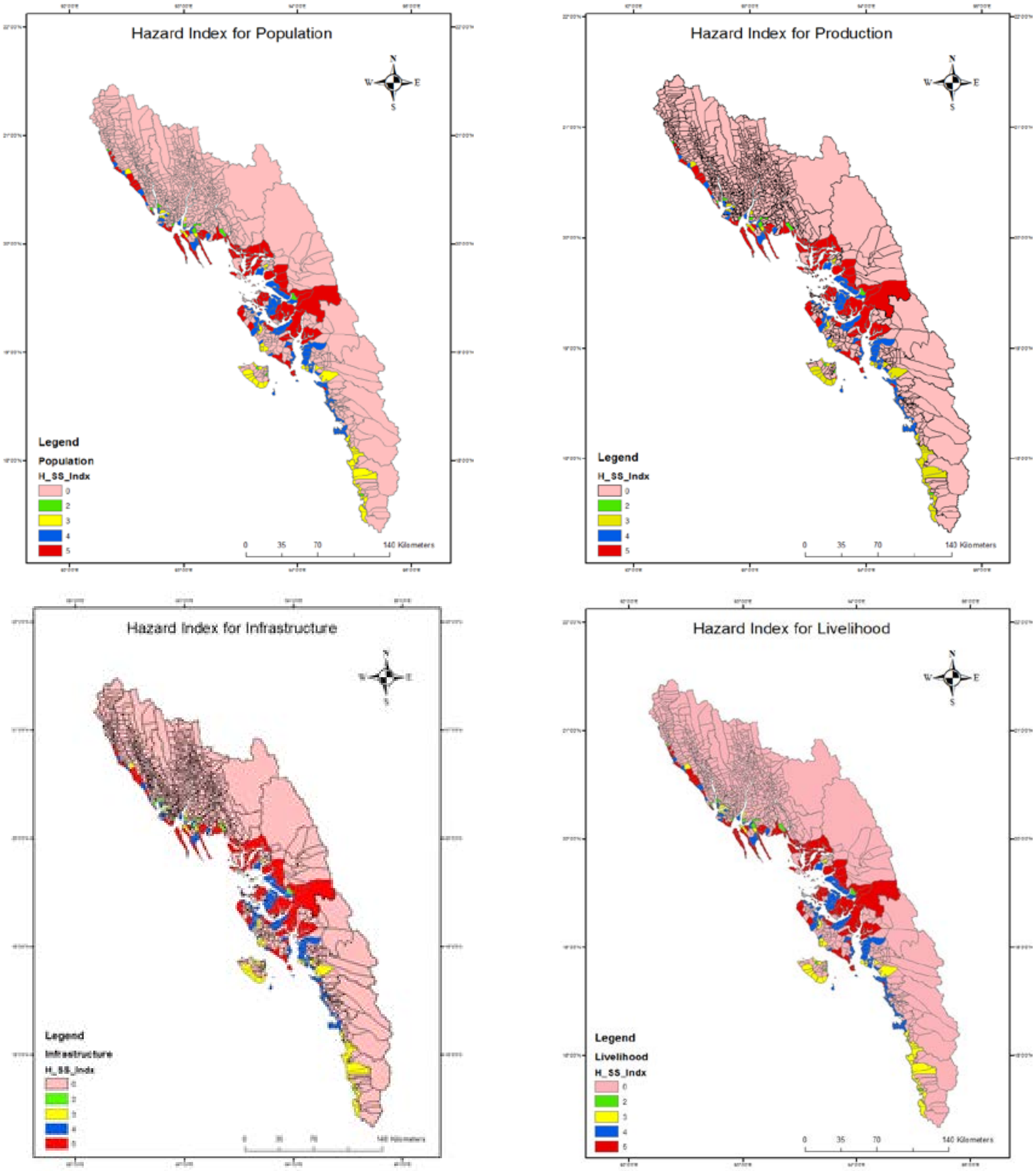


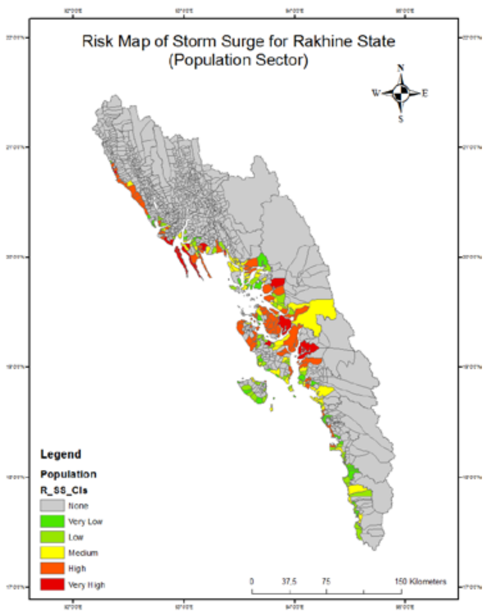
Figure 9: Hazard Maps of Various Categories

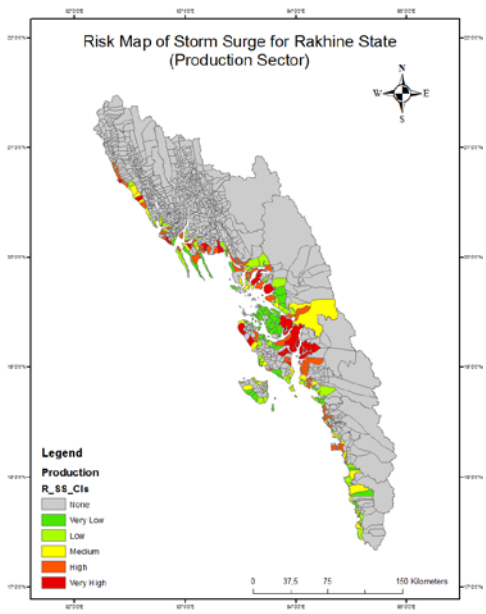
8. Risk Assessment of Storm Surge for Rakhine Coastal Region

The risk is portrayed in terms of an 'Risk Index' estimated for each village tract in Rakhine State. A fundamental equation for determining the risk index for hazard type *i* and vulnerability of sector *j* is as follows.

$$\text{Risk Index}_{ij} = (\text{Hazard Index})_i \times (\text{Vulnerable Index})_j \quad (11)$$

Risk assessment of storm surge for various categories in Rakhine State is shown in Figure 11. Table 9 summarizes number of village tracts under various risk levels.





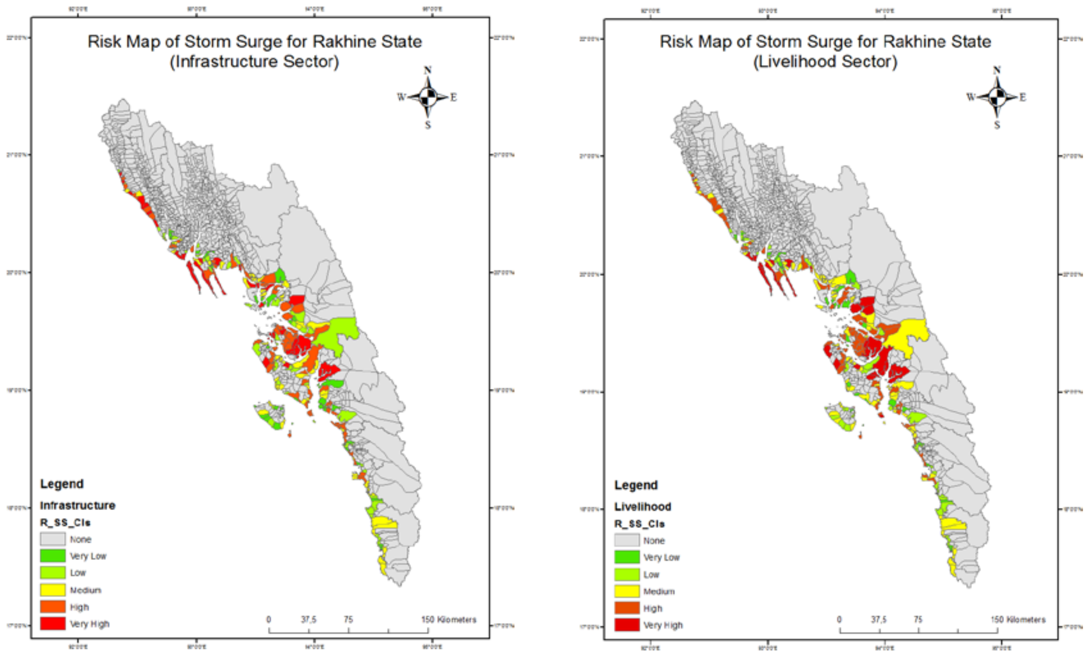


Figure 10: Risk Assessment of Population, Production, Infrastructure and Livelihood Sector

Table 9: Number of Village Tracts under Various Risk Levels

Risk Level	Livelihood	Population	Infrastructure	Production
None	835	835	835	835
Very Low	28	36	33	55
Low	40	57	46	64
Medium	68	49	54	37
High	63	65	58	51
Very High	24	16	32	16

9. Discussion and Conclusion

The storm surge model developed in the present work is capable of reproducing total water level due to the passage of a cyclone across Rakhine coast. From the vulnerable study, it is observed that Maungdaw Township is the most vulnerable in respect of population prone to storm surge. About 56 village tracts is ‘highly’ vulnerable followed by 35 village tracts of ‘very high’ vulnerability to storm surge hazard. Similarly population of Minbya, Myebon and Kyauktaw are highly vulnerable in 25 village tracts and about 15 village tracts where it is very highly vulnerable. The main reason of high vulnerability of these townships is due to the composition of age and gender structure of the population. It is noted that vulnerability for the production sector is more prominent as for Mrauk-U, Pauktaw, Minbya, Kyauktaw and Rathedaung Township. Most of the village tracts in these townships are high to very high vulnerable in context of production sector to the storm surge.

Vulnerability on production is less in Gwa, Ann, Sittwe, Thandwe, Toungup and Kyaukpyu Township. Eastern part of the state is less vulnerable to production sector since these areas are reserved forest and have no scope of paddy production. It is evident from the study that the vulnerability of livelihood due to storm surge is 22% high, 24% medium, 18% low and 20% very low. It is observed that the buildings in Buthidaung, Kyauktaw, Maungdaw, Minbya, Myebon and Pauktaw Township are predominated to different hazards. The extreme water levels being estimated in the present study can be a major input to design marine structures for the protection of coast and onshore facilities. It is expected that the study will provide most useful information for decision makers to prioritize risk mitigation investments and measures to strengthen the emergency preparedness and response mechanisms with respect to storm surge flooding.

10. Recommendation

Finer hybrid grid resolution near the coast should be used in storm surge modeling because the simulation results largely depend on grid resolution. Accurate prediction of wind wave, together with non-linear interaction with tide and storm surge, is also essential and need to be included in the further studies. In order to simulate surges inside the rivers and estuaries, river systems need to be included, which is not considered in this study. In this study, sensitivity analysis of the storm surge hazard is only considered for vulnerability. Not only sensitivity but also resilience function in vulnerability should be considered for further study.

Acknowledgements

The author would like to express her deepest gratitude to Department of Myanmar Information Management unit, General Administration Department of Rakhine State and Jonathan from World Food Program, who support the required data for this study. The author is also very grateful to Professor Marcel Stieve and Associate Professor Martine Rutten from TU Delft who gave valuable advices and supervised me as mobility exchange student during the period of research program in TU Delft, Netherland with the financial support of EMMA 2014 program.

References

[1] Hans E, Rosendal & Samuel L.Shwe, , “Relation of Maximum Sustained Wind Speed to Minimum Sea Level Pressure in Central North Pacific Tropical Cyclones, "NOAA Technical Memorandum NWSTM-24.

[2] Bretschneider C L. "Engineering aspects of hurricane surge" Estuary and Coastline Hydrodynamics (Ed AT Ippen), 1966.

[3] Reid R 0 "Approximate response of water level on a sloping shelf to a wind fetch which moves towards shore" Beach Erosion Board, Tech Memo No 83, 1956.

[4] Richard Silvester, "Computation of Storm Surge" Chapter 121, 1:1995-2010, Asian Institute of Technology, Bangkok, Thailand.

[5] “Guide to Storm Surge Forecasting”, WMO-No.1076, 2011 edition.

[6] M. Mozzammel Hoque, Abdullah & M.Shah Alam Khan, “Storm Surge Flooding in Chittagone city and associated risks”, presented at Anaheim, California, June 1996. IAHS Publ. no. 239, 1997.

[7] "Multi Hazard Risk Assessment in Rakhine State of Myanmar", UNDP, 2010.

[8] Delft 3D flow user manual, Version: 3.15.34158, 28 May 2014

[9] Wallingford, H.R.: Flood Risk to People, Flood Hazard Research Centre, Middlesex University, London, 2006.

[10] Emanuel, K., and Jagger, T. 2010. "On estimating hurricane return periods". Journal of Applied Meteorology and Climatology. 49: 837-844.

[11] GEBCO, 2010. General bathymetric charts of the oceans. International Hydrographic Organization and the Intergovernmental Oceanographic Commission (IOC) of UNESCO, 2010. Available at: http://www.gebco.net

[12] Gumbel, E. J. Statistics of Extremes. Columbia University Press, 1958.

[13] Rupp, J.A., and Lander, M.A., 1996. "A technique for estimating recurrence intervals of tropical cyclone-related high winds in the tropics": Results from Guam. Journal of Applied Meteorology, 35: 627-637.

[14] PC Sinha, S.K Dube, A.K Mitra and T.S Murty. "A tidal flow model for the Gulf of Kachchh, India". Marine Geodesy, 23:117-132, 2000.

[15] J. K. Panigrahi • J. K. Tripathy • A. S. N. Murty . "Extremity analysis of storm surge for fixing safe design" Springer Science, Nat Hazards, 20 June 2010.