A GRID-BASED APPROACH FOR SPATIAL VULNERABILITY ASSESSMENT TO FLOODS: A CASE STUDY ON THE COASTAL AREA OF BANGLADESH

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ABSTRACT:

Vulnerability assessment is a significant component of effective disaster management. Following the Hyogo Framework for Action 2005-2015, countries need to identify appropriate vulnerability indicators and to assess the impact of disasters. Vulnerability assessment is a prerequisite for disaster risk reduction and capacity building of communities. It can play an important role especially for developing countries to achieve the Millennium Development Goals (MDGs). At present, no standard method of vulnerability assessment exists. Different scientific communities follow different approaches. In this paper, the authors present a grid-based approach for spatial vulnerability assessment to floods with special reference to Bangladesh. Some advantages of a raster (or 'grid')-based approach are demonstrated particularly to overcome the problems of data availability and to increase the transferability and applicability of a spatial vulnerability assessment. At first, a GIS-based approach is developed to transform census-based population data to 100x100 m population grids. Different vulnerability domains and indicators are selected in consultation with disaster experts, stakeholders, and the community people. As vulnerability is multidimensional, a comprehensive approach is followed, which reflects various physical, social, economic and environmental factors. Relative weights are assigned to the selected vulnerability domains and indicators on the basis of expert opinions using the Analytic Hierarchy Process (AHP) and pairwise comparisons. Then spatial vulnerabilities are assessed using the GIS weighted overlay techniques. Finally, the authors present some key findings and discuss the transferability of the approach to other areas.

1. INTRODUCTION

1.1 Motivation

Vulnerability assessment is increasingly being considered as a key step towards effective disaster risk reduction (Birkmann, 2006). In many vulnerable countries, disaster management is usually concentrated on disaster relief, response, and rehabilitation activities. Several studies suggest that a paradigm shift is needed from disaster relief and response to disaster risk and vulnerability reduction (Birkmann, 2006; Yodmani, 2001). Realizing the importance of disaster risk and vulnerability reduction, the United Nations in 1989 declared the 1990s as the 'International Decade for Natural Disaster Reduction (IDNDR)'. Over the past years, the international community has placed more emphasis on a collective requirement worldwide to increase the understanding of vulnerability and develop methodologies and tools for its assessment.

The final declaration of the World Conference on Disaster Reduction (WCDR) in 2005 in Kobe, Japan came up with the Hyogo Framework for Action (HFA) for the period 2005-2015. It underlined the necessity to develop vulnerability indicators in order to enable decision-makers to assess the impact of disasters (UN, 2005). The Hyogo framework emphasises that there is a close relationship between vulnerability assessment and sustainable development. Sustainable development is characterized by the three main pillars: social, economic, and environmental (UN, 1993). The Hyogo framework underlines that impact of disasters on (1) social, (2) economic, and (3) environmental conditions should be examined through necessary indicators. As per the strategies adopted by the Hyogo framework, respective countries need to develop vulnerability indicators as a key activity.

In addition to the Hyogo framework, respective countries need to achieve the Millennium Development Goals (MDGs) within the target deadline of 2015. Disaster risk reduction (DRR) is a key strategy especially for vulnerable countries to achieve the MDGs. The countries need to ensure the reduction of risk and vulnerabilities in order to achieve the millennium development goals within the deadline. The achievement of the MDGs within the target deadline will be unsustainable and difficult if DRR is not properly ensured. For example, frequent natural disasters such as floods, cyclones, earthquakes, etc may deteriorate the poverty situation and affect the overall development of vulnerable countries. As a result, the achievement of the MDGs of these countries may be obstructed or delayed (Vashist and Das, 2009).

Vulnerability assessment is a prerequisite for disaster risk and vulnerability reduction. It plays an important role to identify the extent and level of vulnerabilities and coping capacities to disasters within the communities. This paper presents a grid-based methodology for spatial vulnerability assessment to floods with special reference to Bangladesh. The methodology incorporates different physical, social, economic, and environmental indicators for spatial vulnerability assessment to floods. A case study is conducted at the Dacope sub-district in the coastal and southern part of Bangladesh. As no grid-data exist for the study area, the study presents a GIS-based approach for transforming census-based population and socio-economic data to grid-based data at relatively finer resolution (100x100 m).

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1.2 Statement of the problem

Almost all the countries in the world are prone to one or more forms of disaster. Frequent occurrence of natural disasters causes huge loss of lives, properties, and physical infrastructure. It also causes socio-economic disruptions and environmental degradation in the affected communities. Disaster statistics indicate that the frequency and intensity of extreme natural events have increased in recent years (UNDP, 2004). The Least Developed Countries (LDCs) and coastal areas are particularly vulnerable to the impacts of natural and climate-induced disasters. The Asian Tsunami as well as the tremendous impacts of hurricane Katrina in New Orleans point out the special vulnerability of coastal zones, their inhabitants, economics, and ecological systems (Kaiser, 2007). Coastal areas are at great risk due to climate change, an accelerating sea level rise, salinity intrusion, erosion, an increase of extreme natural events, etc.

The occurrence of disasters is almost unavoidable. However, timely and appropriate measures can help reduce the adverse effects and negative consequences caused by disasters. The consequences of a disaster event such as flood or cyclone depend on vulnerability of affected socio-economic and ecological systems (Cutter, 1996). Therefore, vulnerabilities of different socio-economic and environmental systems need to be properly assessed. In addition, vulnerability and risk maps based on proper vulnerability assessment may help decision makers to adopt appropriate policies and actions (De Bruijn and Klijn, 2009).

Though the assessment of vulnerabilities is essential, it is complicated due to the social, economic, political, and institutional patterns of societies (Villagrán, 2008). At present, no standard model/methodology exists to carry out spatial vulnerability assessment (Thywissen, 2006; Alwang et al., 2001; Brooks, 2003). Different scientific communities follow different approaches for spatial vulnerability assessment. Additionally, vulnerability and risk assessments are not properly done and available in many disaster prone countries. For example, Bangladesh being one of the most flood prone countries in the world lacks proper vulnerability and risk assessment. In maximum cases, the analysis of disaster damages mainly focuses on the economic evaluation of tangible effects, and important social and ecological aspects of vulnerabilities are neglected.

Therefore, it is a challenge to develop a wider perspective for vulnerability assessment including physical, social, economic, ecological, and other important factors. Several studies suggest that there is necessity to develop a comprehensive methodology for spatial vulnerability assessment. The potential methodology should incorporate relevant vulnerability indicators and appropriate approaches for spatial vulnerability assessment. In addition, vulnerability assessment should be conducted at the appropriate level/scale.

1.3 Grid-based spatial vulnerability assessment

The selection of appropriate approach and methodologies is important for spatial vulnerability assessment to disasters. Most existing methodologies used for vulnerability assessment are based on administrative units/boundaries. The administrative units are used as the operational unit for vulnerability and risk assessment. But in this approach, detailed spatial variation of hazards and damages are overlooked. This approach also suffers from a classical problem of geography - the modifiable area unit problem (MAUP) (Su et al., 2005). On the other hand, grid (raster)-based approaches have many advantages over the administrative boundaries for spatial vulnerability assessment. Additionally, a grid-based method is useful for monitoring of vulnerability over the periods and incorporating new indicators or components.

To implement grid-based methodologies, availability of grid data at proper resolution is essential. Grid-based population and other socio-economic data at proper resolution play an important role in spatial planning, disaster and crisis management, risk and vulnerability assessment, etc (Aubrecht et al., 2010). Schneiderbauer (2007) mentioned in his study that the lack of recent population data at finer spatial resolution hampers the crisis management activities. Grid-based data play an important role for their integration into spatial analysis and modelling. Additionally, grid data at finer resolution are vital for spatial vulnerability assessment at the local or community level.

Kienberger et al. (2009) used grid data for spatial modelling of socio-economic vulnerability in the Salzach River, Austria. Census population data are usually available on aggregated grid cells (1 km) in Austria. But presently no grid-based data at higher resolution exist especially in the developing countries. In these countries, population census data are usually used for different applications. Population censuses are usually carried out every ten years in the developing countries. Census results are made available to the public in aggregated forms as statistical yearbooks. Population data based on censuses are available per administrative boundaries or political units. These population data based on vector layers are difficult to integrate into spatial modelling (Schneiderbauer, 2007, p. 70).

Over the past years, a number of initiatives have been undertaken by the scientific communities to develop the techniques to transform population vector data based on census counts to raster data especially at the global level. The first global population density estimation in raster format was developed under the requests from the international agriculture research institutes (Deichmann, 1996). The Centre for International Earth Science Information Network (CIESIN) at Columbia University has developed the “Gridded Population of the World” (GPW), a large-scale data product that demonstrates the spatial distribution of population across the globe at a resolution of 2.5 arc-minute (5 km). In addition, the centre also developed the Global Rural-Urban Mapping Project (GRUMP) population dataset at a resolution of 30 arc-seconds.

In another initiative, the LandScan dataset developed by the Oak Ridge National Laboratory (ORNL), USA provide population density grids at the global level at approximately 1 km resolution through an interpolation method. In this approach, the allocation of population is based on weighting computed from slope categories, distance from major roads, and land cover. From the currently available population data in grid formats, it can be noted that the resolution of the data is relatively coarser. Therefore, these population datasets are not really useful for different applications especially at the local/community level, and more precise population density datasets at finer scales are essential. In addition, grid dataset for some socio-economic indicators such as income, health, water, sanitation, poverty, etc are not available from the existing initiatives.

2. STUDY AREA AND DATA

2.1 Study area

Dacope, an upazila (sub-district) of Khulna district of Bangladesh, is selected to test the developed methodology for spatial vulnerability assessment to floods. The major aspects, which motivated the selection of the study area, are the availability of data, socio-economic characteristics of the area, the level of vulnerability, effects of past disasters, the necessity for flood risk and vulnerability assessment, etc. Figure 1 shows the location of the study area in context of Bangladesh and the coastal area. The study area is located in the south-western and coastal areas of the country. It lies between 22°24' and 22°40' N and between 89°24' and 89°35' E. The study area is divided into a total of 10 unions (administrative units of the local government system in Bangladesh) and 26 mauzas (lowest administrative sub-units).

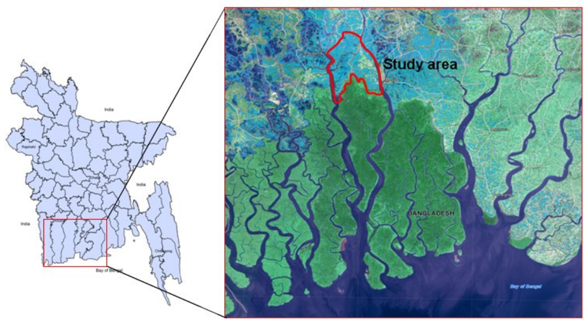

Figure 1. Location of the study area

The upazila occupies a total area of 991.57 sq km including 495 sq km of the Sundarbans reserve forest (BBS, 2001). According to the national population census 2001, the total population of the upazila is 157,489. During the field survey in 2010, the 2001 population census was the latest source of population data for this area. Under the study, the population is projected with the annual growth rate of 1.4 percent to estimate the number of population in 2010. The projected population of the upazila in 2010 is 180,980. The population density is 183 per sq km considering the total area of the upazila including the forest area. But excluding the forest area, the population density of the study area is 616 per sq km. According to the Bangladesh population census 2001, the overall literacy rate of Dacope upazila is 49.34%.

Figure 2 shows various physical features of the study area. The road infrastructure of the area is not in good condition. Recent natural disasters show that the embankments are highly vulnerable to the impacts of floods, cyclones and other natural disasters. According to the Bangladesh population census 2001, predominant housing structure of the upazila is kutcha (89.81%), which is characterized by housing materials such as mud, thatch, bamboo, etc. These kutcha structures are very susceptible to natural hazards such as floods, cyclones, storm surges, etc. Besides, a large number of people have no electricity connections. The upazila lacks adequate health facilities. There is only one hospital located at the upazila headquarters. In addition, the study area has no adequate safe drinking water and sanitation facilities. People face huge problems regarding safe drinking water and sanitation especially during and after extreme natural disasters.

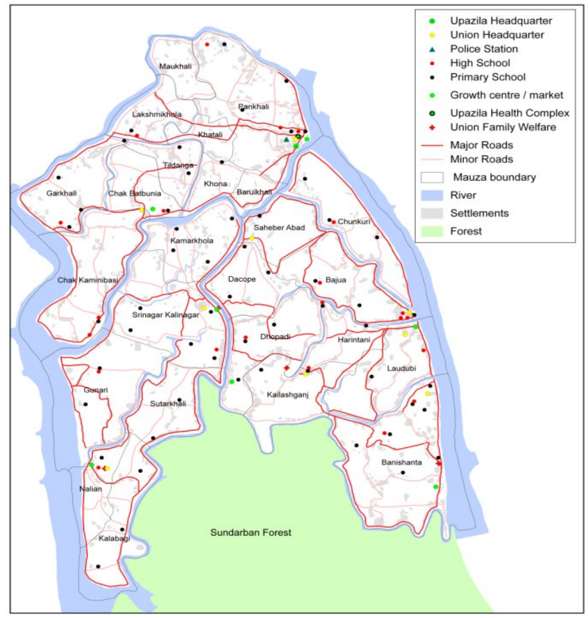

Figure 2. Physical features of the study area

2.2 Data collection

Different datasets such as ancillary data, population census data, GIS data, and a number of satellite images are collected for spatial vulnerability assessment to floods. Population census and other socio-economic data are collected from the Bangladesh Bureau of Statistics (BBS). Population census is usually conducted every ten years in Bangladesh. The national population census 2001 was the latest source of population and other socio-economic data for the study area during the field survey in 2010. The GIS datasets are collected from the GIS unit of the Bangladesh Local Government Engineering Department (LGED). These datasets include different administrative boundaries, rivers, roads, embankments, settlements, educational institutions, health centres, shelters, markets, etc.

2.3 Preparation of grid-based data at finer resolution

Grid-based population and other socio-economic data are essential for the implementation of the grid-based approach for spatial vulnerability assessment. Still, the required grid-based dataset at finer resolution are not available for the study area. Therefore, a GIS-based methodology is developed to transform census population data of different mauzas to population grids (100x100 m). For this purpose, two assumptions are made, namely that people only live within outlines of the settlements, and they are evenly distributed within these areas. The whole methodology is divided into a number of subsequent steps. For this purpose, population census data, settlement data and other geospatial datasets are used. For transformation of census population data into grid population data, geographic information system (GIS) techniques are used.

Under the approach, mauza-wise settlements are identified overlaying the mauza boundaries and the settlement data using the identity method in an ArcGIS software environment. The numbers of population living in individual settlements of different mauzas are calculated. Hence, a vector grid polygon layer with 100 m grid sizes is created using the Hawths Tool in ArcGIS environment. Then the vector grids and settlements having population counts are overlaid using the intersection method. Subsequently, population numbers for the intersected settlements are calculated and these population numbers are then converted into raster grids with 100 m resolution using the 'polygon to raster conversion' method in ArcGIS. Figure 3 shows the prepared population grids (100x100 m) of the study area.

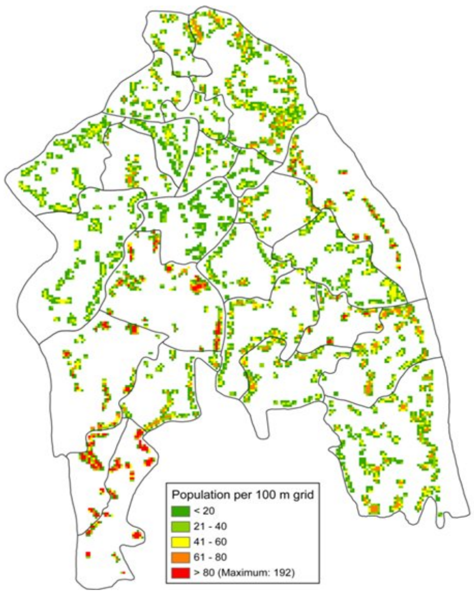

Figure 3. Prepared population grids (100 m)

3. SPATIAL VULNERABILITY ASSESSMENT

3.1 Selection of vulnerability domains and indicators

Various studies indicate that appropriate vulnerability domains and indicators can play an important role for spatial vulnerability assessment (Kienberger et al., 2009). It is difficult to directly measure vulnerability due to its multidimensional characteristics. For its spatial measurement, different physical, social, economic, and environmental dimensions should be taken into account. For the present study, vulnerability domains and indicators are selected which shall reflect major study area characteristics. This is based on consultations with the disaster experts and the community people and on literature review. The selected indicators particularly address the type of hazard, different dimensions of vulnerability, relative importance of the indicators, and other factors.

Table 1 shows the vulnerability domains and respective indicators selected in the present study for the spatial vulnerability assessment to floods. In total, 12 vulnerability domains are selected and divided into two major categories: nine domains fall into the group 'sensitivity domains' and three belong to 'coping capacity domains'. For each of the 12 domains, a number of indicators are selected to assess and analyse different aspects of the respective vulnerability domain. In total, 44 indicators are selected under the different domains for the spatial vulnerability assessment to floods.

Sensitivity domains	**Indicators**
Population and age	Population density, Population aged <10 years, Population aged 10-60 years, Population aged >60 years, Population having any sort of disability, Dependency ratio
Livelihood and poverty	Number of unemployed people, People living below the poverty line, People engaged in agriculture, People engaged in small business, People engaged in household works
Health	Distance to nearest hospital, Distance to nearest primary health care facilities, Number of village doctors available
Water and sanitation	Households using pond water, Households using tube well water, Households using tap or filter water, Households having sanitary latrine, Households having no toilet facilities
Housing and shelter	Households having thatched houses using bamboo and mud, Households having houses using corrugated iron sheets, Households having houses using brick or concrete materials, Distance to nearest shelters
Roads and other infrastructure	Distance to major roads, Distance to minor roads, Distance to nearest growth centre or market, Proportion of people having electricity connection
Land use/cover	Agricultural lands, Settlements, River or water bodies,
Environment	Area under shrimp cultivation, Area having salinity intrusion
Gender	Female literacy rate, Sex ratio, Female workers engaged in non-agricultural works
Coping capacity domains	
Assets	Households having radios, Households having televisions, Households having fixed or mobile phones, Households having bicycles, Households having agricultural lands
Education and human resource capacity	Adult literacy rate, School attendance rate
Economic alternatives	Proportion of non-agricultural workers, Distance to nearest city or town

Table 1. Selected vulnerability domains and indicators

3.2 Assigning relative weights

The Analytic Hierarchy Process (AHP) is used under the present approach for making priorities and assigning weights to the selected vulnerability domains and indicators. The AHP is a multi-criteria decision making method that uses hierarchical structures to represent a problem and then develop priorities for alternatives based on the judgements of the experts or users (Saaty, 1980). It provides a comprehensive and rational framework for structuring a decision problem. It is a method to derive ratio scales from paired comparisons. The method deals with the consistency of the judgements given by the experts or users.

Under the AHP, pairwise comparisons are used to determine the relative importance of each alternative in terms of each criterion. A pairwise comparison matrix is used to compare and rank the selected vulnerability domains and indicators through the judgements by the experts. A pairwise comparison matrix consists of elements expressed on a numerical scale. The experts are asked to prioritize the vulnerability domains and indicators on the basis of a pairwise comparison weighting scale. The weighting scale consists of nine qualitative terms that are associated with nine quantitative values. The scale enables the decision-maker to incorporate experience and knowledge intuitively and indicate how many times an element dominates another with respect to the criterion.

Figure 4 shows the resulting ranking of the 12 selected vulnerability domains from the weighting using the AHP method with its pairwise comparisons. The total weight of all vulnerability domains equals 1. The domain 'livelihood' has received the highest score of 0.226. Other vulnerability domains receiving higher scores are 'housing' (0.169), 'roads and other infrastructure' (0.144), and 'environment' (0.103). Similarly, the weights of the respective indicators under each domain are also determined, and the consistency level of the expert judgements is maintained.

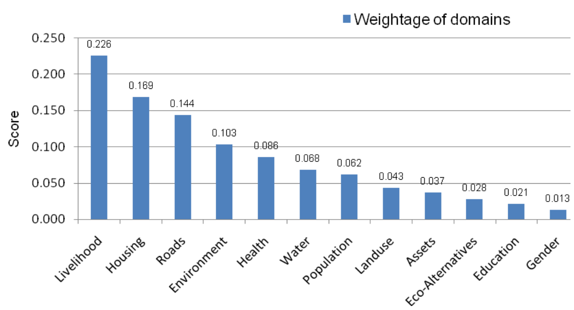

Figure 4. Ranking of the selected vulnerability domains

4. RESULTS AND DISCUSSION

Finally, an overall vulnerability assessment is performed using the selected sensitivity and coping capacity domains. For this purpose, the selected sensitivity and coping capacity domains are overlaid using the assigned relative weights within the ArcGIS software environment. Figure 5 shows the overall vulnerability assessment results. The level of vulnerability shown in the figure ranges from least to high. The overall vulnerability assessment results in a significant share of vulnerable areas. In particular, the classes 'most vulnerable', 'medium vulnerable' and 'least vulnerable' account for approximately 1.5%, 25% and 10% of the area, respectively.

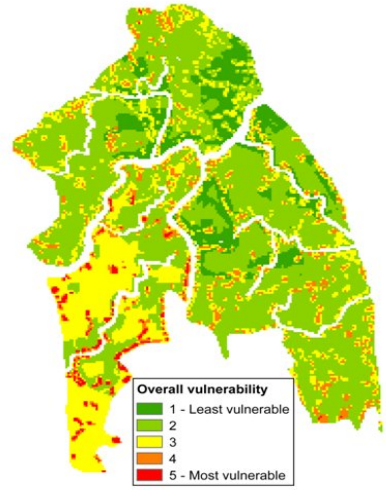

Figure 5. Overall vulnerability assessment results

In general, the south-western part of the study area is more vulnerable than other parts. The major reasons for the high level of vulnerability in this area are poor road infrastructure and embankments, extensive shrimp cultivations, high salinity, proximity to the coast, frequent occurrence of cyclones and tidal floods, high poverty levels, lack of health and safe drinking water facilities, etc. Conversely, the north-eastern parts are assessed less vulnerable due to their proximity to the upazila headquarters and hospital, availability of better road infrastructure, etc.

The vulnerability assessment results based on this approach are promising. It turned out that the AHP method is well suited to effectively differentiate vulnerability to disasters spatially. As this grid-based approach is relatively new, especially for developing countries, there are a number of challenges for its implementation. One of the challenges is the lack of grid-based population and socio-economic data. Recently a number of initiatives are undertaken to develop global grid population dataset such as the LandScan population grid. But the resolution of these population grid dataset is considerably coarser. High resolution grid data are crucial for spatial vulnerability assessment at the local or community level.

5. CONCLUSIONS

The paper presents a grid-based methodology for spatial vulnerability assessment to floods with special reference to Bangladesh. For the implementation of the methodology, a simple GIS-based approach is developed for preparation of the grid population data at finer resolution (100 m). The developed vulnerability assessment methodology is comprehensive, and it incorporates necessary physical, social, economic, and environmental indicators. The developed methodology can play an important role for spatial vulnerability assessment for Bangladesh as well as other vulnerable nations. This methodology can be adapted to other areas and contexts considering different relevant factors such as local area characteristics, selection of necessary vulnerability domains and indicators, availability of data, study objectives, etc. It is also recommended that appropriate vulnerability domains and indicators should be selected for future vulnerability assessments.

A number of potential areas are identified here for future research in the area of grid-based vulnerability assessment. Firstly, more researches need to develop grid-based population and socio-economic data at finer resolution especially in the context of developing countries. Secondly, grid-based methodologies for vulnerability assessment are still new. More research needs to be conducted in order to establish this integrated methodology for spatial vulnerability assessment. More emphasis should be given to spatial vulnerability assessment to disasters at the local or community level.

Thirdly, the development of a grid-based multi-hazard approach for spatial vulnerability assessment seems to be a logical next step. Future research will incorporate hazards such as cyclones, earthquakes, droughts, etc. Fourthly, proper validations of the vulnerability assessment results and the methodology developed are needed. Rigid validation through field checks beyond the fieldwork in this study is indispensable if this approach shall substitute existing vulnerability assessment methodologies.

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