doi:10.1111/j.1467-9493.2006.00254.x

GIS-based flood hazard mapping at different administrative scales: A case study in Gangetic West Bengal, India

Joy Sanyal and X.X. Lu

Department of Geography, National University of Singapore, Singapore

Correspondence: X.X. Lu (email: geoluxx@nus.edu.sg)

This paper addresses the need for an efficient and cost-effective methodology for preparing flood hazard maps in data poor countries, particularly those under a monsoon regime where floods pose a recurrent danger. Taking Gangetic West Bengal, India, as an example and using available historical data from government agencies, the study compiled a regional map indicating hazard prone subregional areas for further detailed investigation, thereby isolating actual high risk localities. Using a GIS (Geographical Information System), a composite hazard index was devised incorporating variables of flood frequency, population density, transportation networks, access to potable water, and availability of high ground and maximum risk zones were mapped accordingly. A digital elevation model derived from high resolution imagery available in the public domain was used to calculate elevated areas suitable for temporary shelter during a flood. Selecting administrative units of analysis at the lowest possible scales – rural development blocks (regional) and revenue villages (subregional) – also ensures that hazard mapping is prepared in line with the existing rural planning and administrative authorities responsible for remedial intervention.

Keywords: GIS, flood, hazard mapping, ASTER DEM, composite index

Introduction

Flood, a natural and perennial phenomenon in many low-lying deltaic areas, can be viewed as beneficial, especially for enhancing soil fertility on flood plains, but also as a hazard – as endangering human life, property and the environment, whether induced by natural events and/or human interference (Godschalk, 1991). Mapping flood hazard is not a new endeavour in the global North – the Federal Emergency Management Agency (http://www.fema.gov/nfip) in the USA, for example, has created a range of products and services from up-to-date flood insurance maps to post-disaster hazard mitigation technical support. Conventional hazard maps are data intensive, particularly using high resolution terrain data, and continuously upgraded to keep pace with dynamic land use changes within flood-prone areas. The costs of preparing high resolution Digital Elevation Models (DEM) in flood hazard mapping, which is the approach emphasized in a number of scientific investigations (e.g. Leenaers & Okx, 1989; Townsend & Walsh, 1998; Norman *et al.*, 2001; Sanyal & Lu, 2004), are too prohibitive for many countries of the South where technology and available geospatial data are scarce. Islam and Sado (2000a,b) attempted to formulate an appropriate methodology for flood hazard mapping in data poor Bangladesh. Considering three major flood events over a past decade, they derived a measure of 'flood affected-frequency' by assigning a higher hazard rank to a particular pixel in the Advanced Very High Resolution Radiometer (AVHRR) imagery that was subject to inundation through most of those events. A composite hazard rank was devised and flood hazard maps prepared accordingly for different physiographic, geologic and administrative divisions of Bangladesh. A subsequent study (Islam & Sado, 2002) integrated population density into the flood hazard maps in order to create land development priority maps. While such synthetic maps are useful for overall management of flood plains and national level macro planning, the primary source of data used, the US National Oceanic and Atmospheric Administration's AVHRR images of 1 km^2 spatial resolution, are not detailed enough to facilitate micro level planning in affected localities.

Several factors need to be considered in accurate flood hazard mapping under conditions of data and other material scarcities that typify the situation in most countries of the global South. For instance, flood hazard can be quantified by examining the occurrence of flood over a span of years, the size of the population vulnerable to floods and the available infrastructure and supplies to enable practical and timely intervention during a contingency. Generally, quantitative data on each of these factors come under and from a number of different authorities; thus, the format and spatial resolution of data representation varies between sources. In a GIS (Geographical Information System) environment, the primary concern is to append a database to a spatial unit for performing geographic analysis. Thus, the choice of the scale at which to map becomes key to the optimum use of available data. The creation of a very high spatial resolution GIS database is costly and time-consuming. This paper demonstrates that a moderate resolution regional study would suffice to identify hazard prone and vulnerable zones. Further and detailed investigation efforts can then be focussed on these areas and hazard maps prepared based on accurate and village level data.

In this study, the Gangetic West Bengal region of India was chosen as the study area and mapped at two different scales; regional and subregional. In both cases, administrative units were selected as the most appropriate unit of investigation for the simple reason that these are the very units demarcating policy and planning authorities and resource allocation crucial to any practical intervention. The unit at the regional scale, the development block, is the smallest rural administrative unit in India in relation to water and irrigation management. The subregional unit of analysis, the revenue village, is the lowest rural statutory unit that comes under the block administration. Taken together, revenue villages and development blocks make up the total rural frame of each district in India. Another obvious advantage in using administrative units of analysis is that census data on past floods, population and infrastructure are tabulated according to these boundaries. Additionally, because the terrain of Gangetic West Bengal has very little variation, administrative scales are most suitable for hazard mapping in this region.

Study area

Three major river basins of the southern West Bengal state, namely the Bhagirathi-Hoogly, Jalangi and Churni, comprise the study area designated as Gangetic West Bengal; all three rivers are distributaries of the main branch of the Ganga River (Figure 1). Gangetic West Bengal is overwhelmingly rural and agricultural; hence, the Kolkata Urban Agglomeration (the administrative unit comprised of the state capital and its peri-urban suburbs), which also compose part of the deltaic region,[1] were deliberately excluded to maintain homogeneity in the economic and demographic characteristics of the study area.

Bagchi's (1945) subregional classification of the Bengal Delta classifies the study area as a moribund delta. The rivers are in their decaying stages and land building processes have ceased, although due to the comparatively higher elevation and high levees, the study area is less flood prone than areas further to the south. The elongated depression area between the Bhagirathi and Jalangi rivers, together with the almost entirely

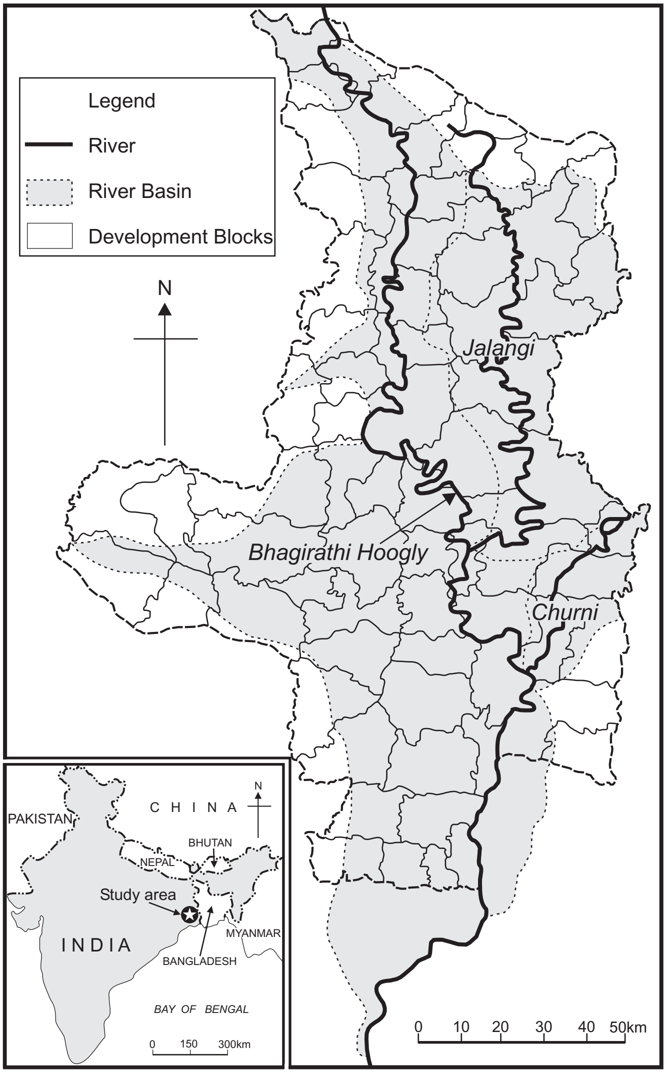

Figure 1. *Gangetic West Bengal study area.*

low-lying Churni Basin area, comprise a zone that is particularly prone to flooding. Goswami (1983) identified a belt of depression that extends diagonally from southwest to northeast of the southern districts of West Bengal, bounded by a 10 m contour line in the Nadia and Hoogly districts, which encompass part of the study area. The interfluves of the numerous distributaries are ill drained (Spate *et al*., 1967) and frequently cause waterlogging during the southwest monsoon season in June–September, leading ultimately to stagnation and the development of palaeo-channels known as *bills*. The abundance of ox bow lakes and misfit river channels are also characteristic of this part of Gangetic West Bengal; stagnant water bodies and marshy land dot the landscape, some of which are spill channels of the Damodar River that had lost their headwater to silting or to a shift in its course (Spate *et al*., 1967). The overall geomorphology of the study area depicts a degenerating fluvial system.

The West Bengal Delta is traditionally identified in India as a flood prone area: as at 2000, flooding was recorded for 52 out of the 57 years since Independence in 1947 (www.wbiwd.com). Located at the tail end of the extensive Ganga Basin, West Bengal has a very limited capacity to control extreme hydrological events ensuing from the upper catchment of River Ganga and its tributaries. Of these, the years 1956, 1959, 1978, 1995, 1999 and 2000 are recorded as abnormally high precipitation years with severe floods (Basu, 2001). In terms of extent and devastation caused, the September–October 2000 flood was among the worst (Rudra, 2001), with official estimates of 23 756 km^2 inundated, affecting 171 development blocks and 22.1 million people and with damages and losses estimated at about USD 1132 million.

Although the Irrigation and Waterways Department (IWD) of West Bengal has broadly identified flood prone areas of the state, there have been no attempts to integrate the hydrological facts with socioeconomic or infrastructural data. In India, as in many other countries of the South, crucial anti-flood undertakings are handicapped by financial constraints. In order to optimize the use of precious funds, therefore, it is critical that planners are equipped with sufficiently accurate and detailed flood hazard maps to enable them to zoom in on high risk zones more likely to require urgent attention.

Flood hazard mapping at the regional scale

Flood frequency mapping

The most important factor determining flood hazard is flood frequency. Available data for the decade 1991–2000 was obtained from the IWD's annual flood reports and used to produce a map depicting the frequency of flood occurrences in the state (Figure 2). From the archived information, most community development blocks in the northern part of Gangetic West Bengal had recorded six flood events during the decade, whereas a number of blocks in the southwest part had recorded none.

A limitation of block administration records is that the entire block is reported as 'inundated' even if, most of the time, only a part is affected. As a gauge for accuracy, relevant archived reports for a part of Nadia district were compared with a 1 : 250 000 flood map created in 1998 by the District Irrigation Division. This showed that where a total area of 1553 km^2 had been recorded as flood affected, only 671 km^2 (43.2 per cent) had actually been inundated. The percentage varied across the comprising blocks in the district for particular flood events – ranging from 15.5 per cent in Kaligunj to 99.2 per cent in Karimpur-1 (named in Figure 3 further below). Therefore, the regional flood frequency map does not depict the actual flood prone localities within each block, but usefully serves to identify those that should be prioritized for carrying out subsequent high cost and time-consuming subregional village-level studies. In this context, using available archived data to roughly estimate flood proneness is a simple and cheap alternative to expensive high resolution terrain data or remote sensing.

Variables used for hazard mapping

A flood hazard map integrating hydrological data with socioeconomic variables could be used to account for intangible damage (Boyle *et al.*, 1998). The variables considered here include population density (pop-den), road density and access to safe drinking water (Table 1). Population density of each block is chosen as an indicator of the economic assets under potential flood threat and provides a guide to the commensurate relief measures required. For the rapid evacuation of affected communities during a

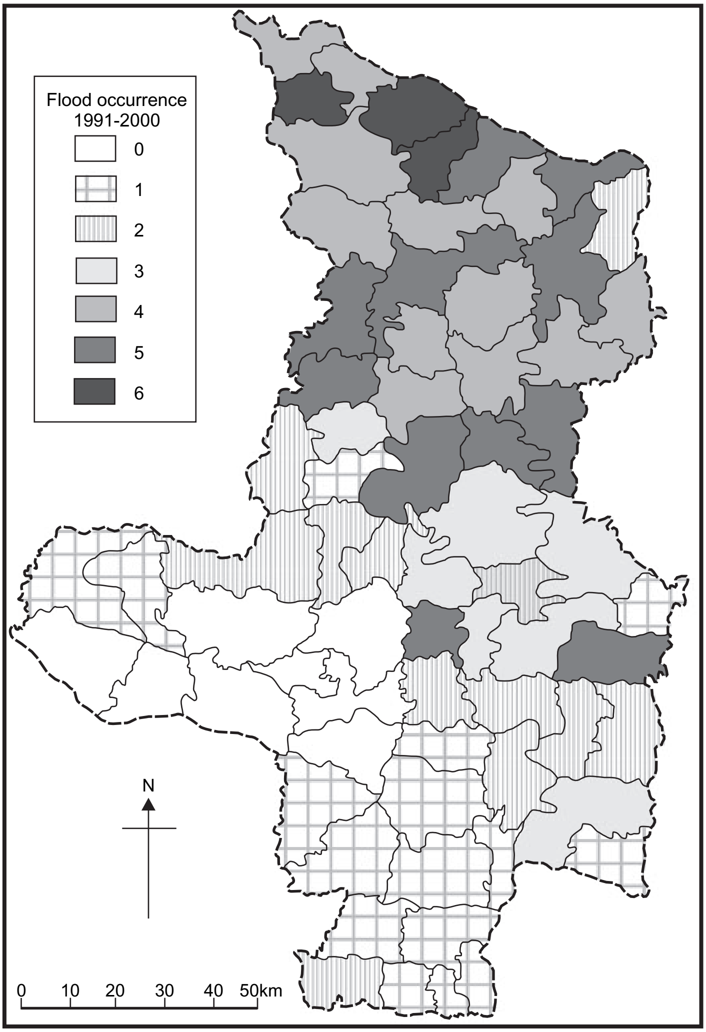

Figure 2. *Flood occurrence in Gangetic West Bengal study area, 1991–2000 (data compiled from annual flood reports archived by IWD, West Bengal).*

hazardous flood, a good network of all-weather roads is essential – a factor that has received considerable attention in recent times and been recognized as a core nonstructural requirement of flood management (Rashid *et al*., 2000; Rashid & Haider, 2002). Therefore, the calculation omitted nonsurfaced roads that cannot be relied on during the monsoon season.

Any comprehensive flood management strategy includes protecting vulnerable populations from intangible damage. In Gangetic West Bengal the outbreak of waterborne, in particular diarrhoeal, diseases is a major concern after floodwaters recede (Sur *et al*., 2000; Kunni *et al*., 2002). Access to safe drinking water is thus another key element in post-flood hazard management. To quantify this aspect of hazard another variable, termed 'epidemic', was devised to measure the percentage of villages having no access to safe drinking water to the total number of villages in each of the development blocks.

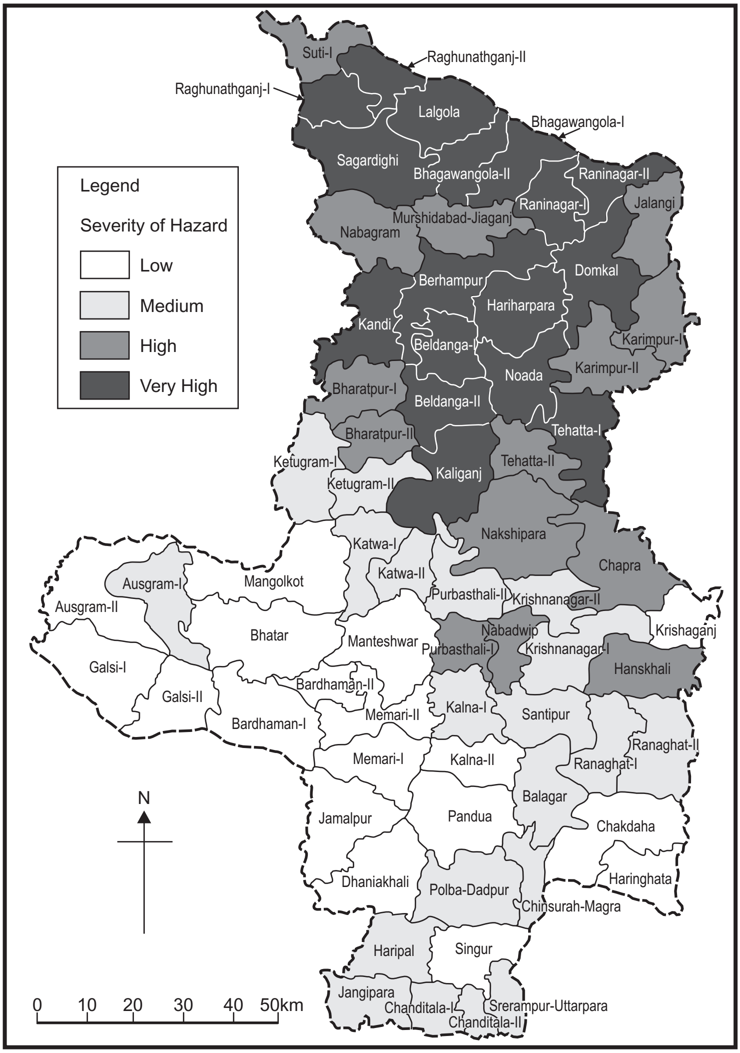

Figure 3. *The regional-scale map of flood hazard by development blocks in the Gangetic West Bengal study area (based on inundation maps prepared by IWD, West Bengal).*

Weighting scheme for the composite hazard index

The weighting scheme for the hazard index was implemented in three steps. First, in order to depict the heterogeneity of different environmental and socioeconomic factors contributing to flood hazard, all four variables were standardized and named (Table 1). Second, a knowledge-based weighting scheme was applied to each of the four variables: indicators that represent a high level of dispersion across development blocks were given more weight; a variable depicting a uniform situation across the study area is not likely to distinguish between hazardous and non-hazard zones. The variable 'flood-prone' was attached to high importance because where the risk of inundation is very low the other variables cannot indicate or contribute to flood hazard. A scheme of progressive weighting was adopted (Table 2) based on the premise that flood hazard for a particular block increases in a nonlinear manner with the number of flood occurrences over the 10-year period. In other words, the hazard curve becomes progressively steeper at the higher

Table 1. Data used in deriving flood hazard variables and maps at regional and subregional scales.

Study scale	Suitable scale of representation	Hazard indicators	Hazard factor	Variable name	Source
Regional (development block level)	1 : 500 000	Number of flood occurrences 1991–2000	Risk of flooding	Flood-prone	IWD annual flood reports.
		Population density (persons km^{-2})	Economic assets under flood threat	Pop-den	Census of India, 2001
		Road density (km km^{-2})	Ease of evacuation and sending relief	Evacuation	District Statistical Handbook (1998)
		Access to safe drinking water (% of villages having no safe source)	Outbreak of a waterborne disease in the post-flood situation	Epidemic	District Statistical Handbook (1998)
Subregional (revenue village level)	1 : 63 360	Number of flood occurrences 1991–2000	Risk of flooding	Flood-prone	IWD maps showing inundated area for each year
		Pop-den (persons/hectare)	Economic assets under flood threat	Pop-den	Census of India, 2001
		Availability of higher ground (highest elevation in each revenue village)	Availability of potential flood shelter	Shelter	ASTER DEMs supplied by USGS

Table 2. Differential weighting (k) of 'flood-proneness'.

Flood occurrence frequency (flood-prone)	Value of K
1–2	0.25
3	1.5
4	2.5
5	4.0
6	5.5

values of 'flood-prone'. The variable 'pop-den' was not assigned a high weight as blocks situated nearer the Kolkata metropolitan fringe that have a higher population density than the rest would be classified as a high hazard zone only by virtue of this fact.

The final composite index of flood hazard was calculated as follows:

$$\text{Flood hazard index} = \text{st\_flood-prone} \times k + [\text{st\_pop-den} \times 1.4 + \text{st\_even} \times (-1.2) + \text{st\_epdm} \times 1]$$

where k is a weighting factor for the st_flood-prone (Table 2).

The guiding principle for selecting these weights was to ensure the dominance of the 'flood-prone' in the composite index; different combinations of the weighting factors were applied to the data and the results studied before arriving at these. It should be pointed out that the resultant composite index can be modified moderately depending on local conditions.

After the final flood hazard index was devised, it was depicted in a choropleth map (Figure 3). Hazard values were divided into four classes on the basis of quartile measurements. The high flood hazard zones of the Bhagirathi and Jalangi basins are represented by the clustered blocks in the northern part of Gangetic West Bengal (in the extreme south two blocks, Chanditala I and Chanditala-II fall under the high hazard category by virtue of their proximity to Kolkata and higher population density).

Flood hazard mapping at the subregional scale

The regional flood hazard classification of Gangetic West Bengal into different flood hazard zones is, however, a small-scale hazard map not capable of revealing adequate detail for practical measures in hazard management. This calls for a large-scale and very detailed hazard mapping of maximum risk zones, which in the overall situation presented by Figure 3 identifies the majority of the blocks in the northeast. This justified the adoption of a cost and time intensive approach of mapping flood at the subregional, or revenue village, scale. Blocks in Jalangi Basin exhibiting very high occurrences of flood in 1991–2000 were chosen for subregional analysis.

Flood frequency mapping

The revenue village, the smallest rural unit of human settlement, was chosen as the most meaningful unit of analysis for subregional mapping. Available historical maps showing the annual flood affected areas for 1991–2000 prepared at various scales (1 : 250 000 to 1 : 2 000 000) by the West Bengal IWD were used to map flood frequency at this level (Table 1). The inundated areas in each year were converted into individual GIS layers; flood occurrence for each revenue village was calculated by intersecting each map with the village boundary layer (Figure 4). The southwest part of the Jalangi Basin is very flood prone, with as many as five or six flood events in the 10-year period. Villages located along the eastern bank also experience a higher frequency of inundation.

Although Figure 4 depicts the actual disposition of the flood prone zone more accurately than mapping from the archived data at the regional level, this is compromised due to inconsistencies in mapping scales for different years. However, while heterogeneity in the scale would affect the accuracy, a recurring flood occurrence over the 10 years would reveal a trend of inundation for particular villages. This time series approach provides a conclusion that is less likely to be influenced by errors in reporting flood for a specific year.

Variables used for hazard mapping

Apart from the flood prone and population density variables, other physical and socioeconomic variables can be used in formulating a composite hazard index at the subregional level. During inundation, affected populations have to be evacuated temporarily; relatively higher ground that is unlikely to be submerged by floodwaters can serve as safe grounds for shelter. Thus, three variables; flood frequency, population density and shelter, were considered for subregional level hazard mapping (Table 1).

The availability of suitable higher ground in each revenue village (Figure 5a) was calculated from the completed DEM derived from ASTER (Advanced Spaceborne Thermal Emission and Reflection Radiometer) images – a free product obtained from the United States Geological Survey (http://edcdaac.usgs.gov/aster/ast14dem.html). ASTER

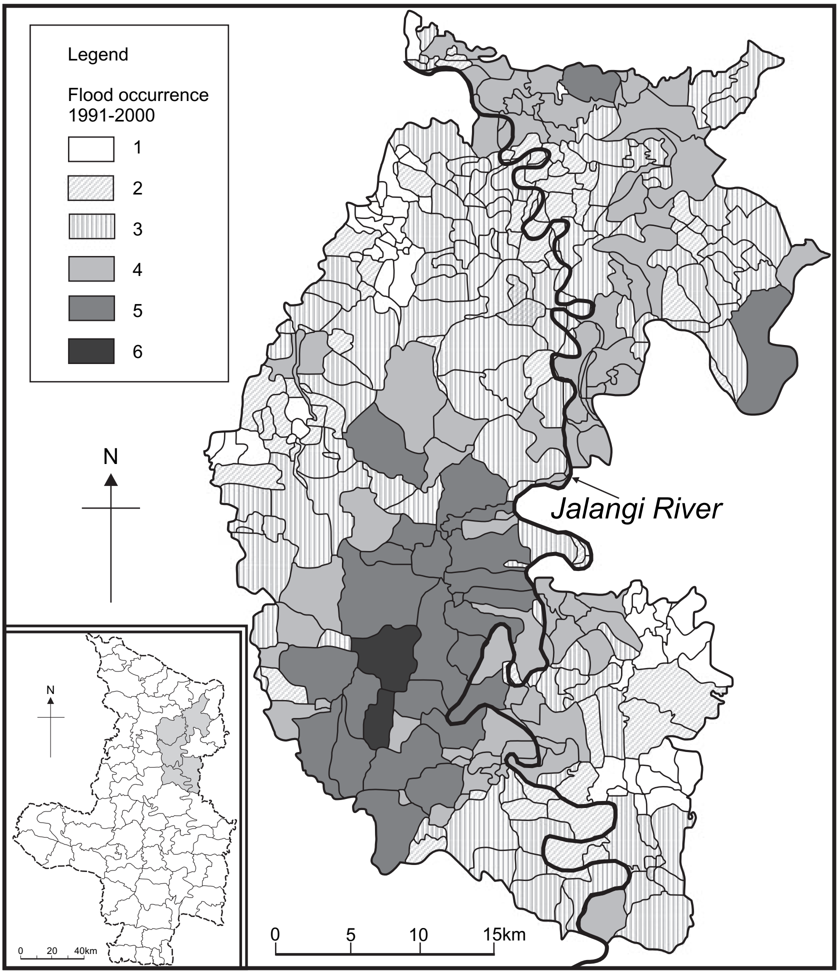

Figure 4. *Recorded flood occurrences in 1991–2000 by revenue villages in the subregional study area.*

imagery has a horizontal spatial resolution of 30 m with a relative vertical accuracy of more than 10 m, which matches the accuracy standard of 1 : 50 000 to 1 : 250 000 maps. Villages where the maximum elevation is still below a critical threshold, which means the population has no access to suitable refuge during contingency, are classified as under high potential risk for flood and other associated hazards.

Calculating a composite hazard index

Villages were ranked for each of the three hazard indicators. The non-numerical nature of the indicators, especially shelter, does not allow statistical calculation. Hazard ranks are commonly integrated into a multiplicative model to create a composite hazard index (Islam & Sado, 2000a,b). A knowledge-based ranking procedure was adopted to effectively use all hazard indicators in a composite framework (Table 3).

Assigning a hazard rank to shelter requires a detailed and in-depth knowledge of the local topography, most critically, to identify the active flood plain and the break of slope that separates it from adjacent higher ground. The main objective of the analysis was to

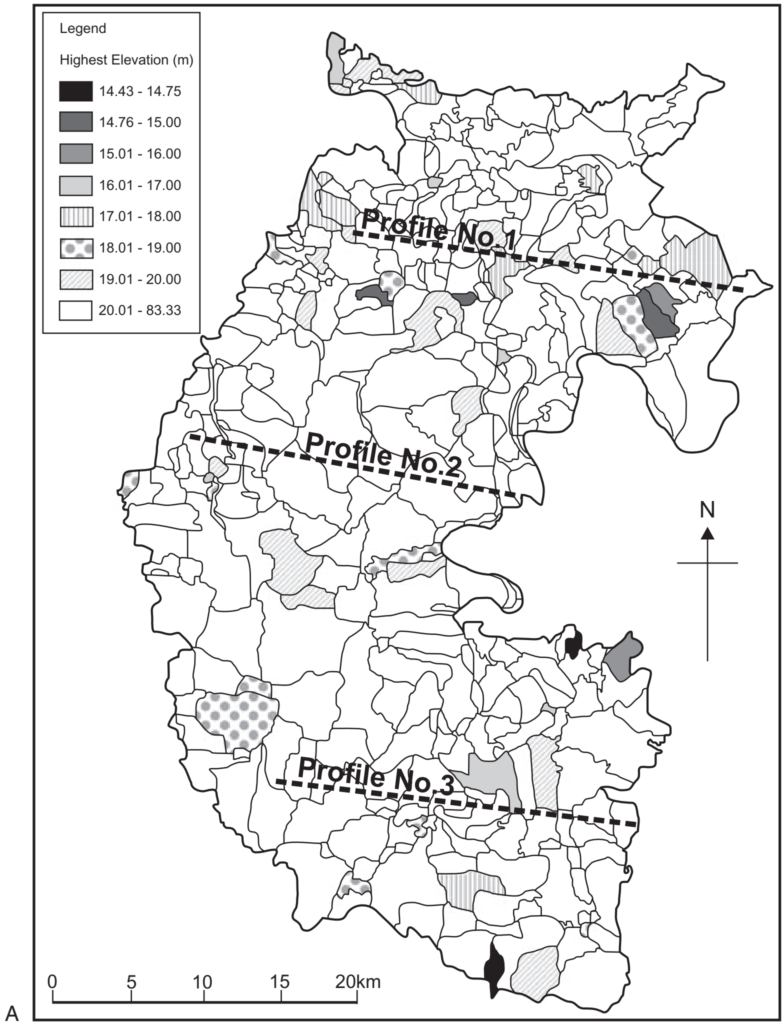

Figure 5a. *Potential flood shelters in the subregional study area.*

Table 3. Knowledge-based flood hazard ranking of different indicators at the subregional (revenue village) scale.

Flood occurrences 1999–2000 (fld-fqr)	Hazard rank (r_fld-fqr)	Population density (person/hectare)	Hazard rank (r_pop)	Highest elevation (m) of each village (shelter)	Hazard rank (r_shelter)
0	0	0	0.25	>20	1
1	1	0.01–5.40	1	19–20	1.5
2	1.2	5.41–7.84	1.5	18–19	2.5
3	2	7.85–11.62	2.5	17–18	3
4	4.5	11.63–80.29	4	16–17	3.5
5	6	>80.29	6	15–16	4
6	6			<15	6

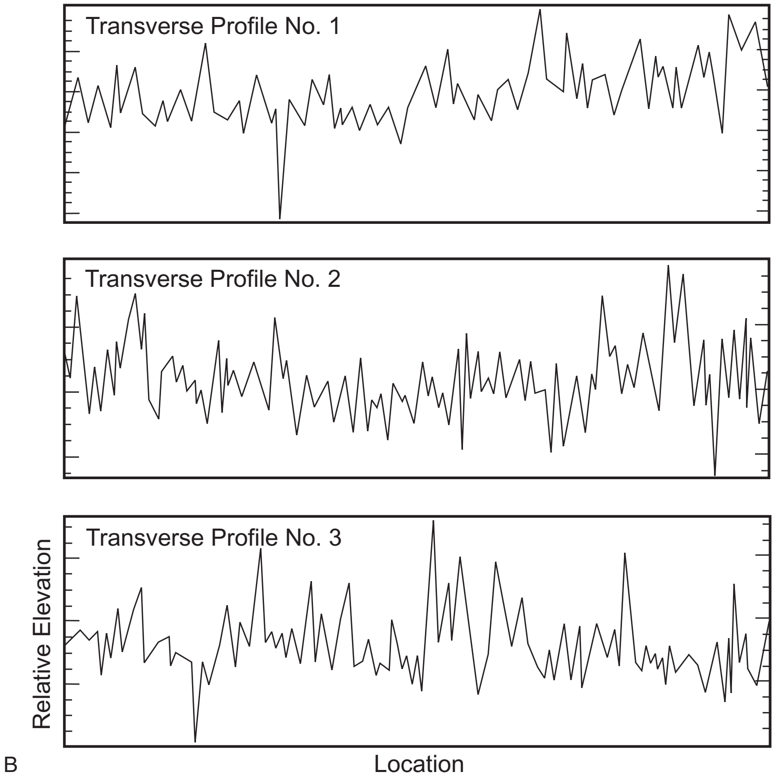

Figure 5b. *Potential flood shelters in the subregional study area.*

obtain a general identification of the critical elevation threshold above which floodwaters are not likely to rise and which can be a potential flood shelter. Three transverse profiles across Jalangi River were drawn from the ASTER DEM to determine the break of slope or critical elevation value (Figure 5b). These show that elevations above 20 m could be considered potential flood shelters; flood threat increases in a nonlinear manner at elevations below 20 m (Sanyal & Lu, 2005). Therefore, revenue villages having their highest elevation below 16 m were assigned a high hazard rank as they would be under threat in a moderate flood event.

The final composite index of flood hazard for the subregional scale was devised as:

$$\text{Flood hazard index} = (\text{flood-prone} \times \text{pop-den} \times \text{shelter})$$

The hazard index was classified into four categories by a natural break scheme to present a rational picture of the hazard scenario (Figure 6), identifying break points by the inherent clustering pattern of the data and setting class boundaries where there are relatively big jumps in the data values (Minami, 2000).

The flood hazard map at the micro or subregional village scale level shows that the northwest part of the study area is comparatively less flood prone. A probable reason could be the higher western bank of River Jalangi and the existence of natural levees preventing frequent spilling over the right bank. In the west part of the area, where some villages have been subject to river flooding five or six times in the period 1991–2000, not all of these are classified under the very high hazard category. The presence of

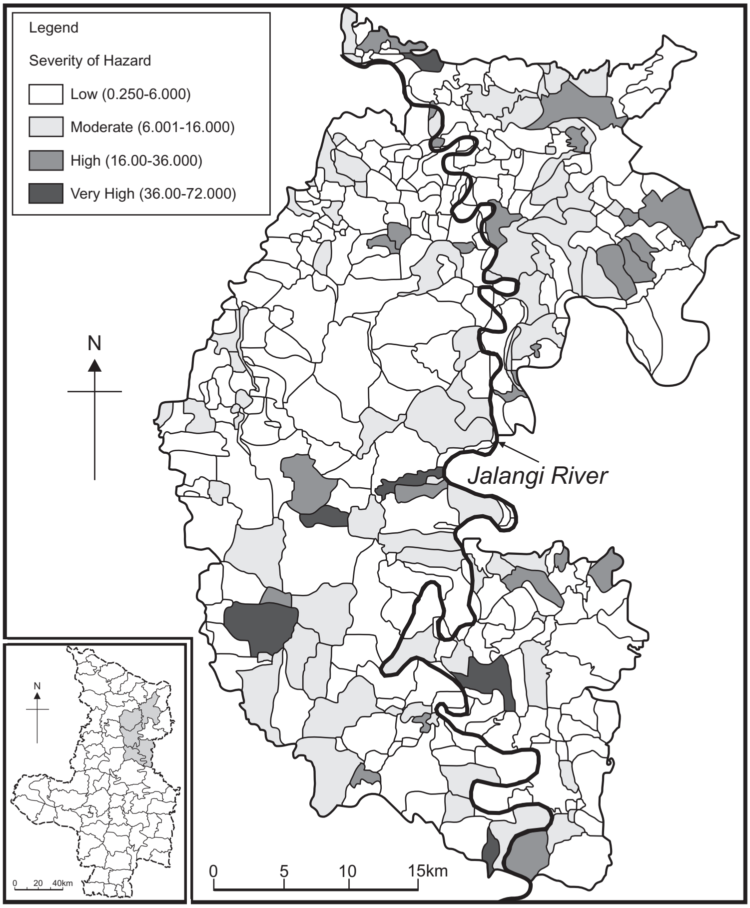

Figure 6. *Subregional flood hazard map based on the composite index.*

higher ground for shelter during flood has relegated some of these villages into moderate or low hazard categories. A low population density in some of the villages also had a partial effect on the overall hazard zone classification; some that did not experience a large number of flood occurrences during the study decade have been categorized as high or very high hazard zones because there is no potential flood shelter, suggesting that even a flood of moderate magnitude could severely endanger the situation of the local people.

Conclusion

The conventional approaches of mapping flood hazard using high resolution DEM or satellite images acquired during a flood as the key information for flood vulnerability of an area are too costly, if not unaffordable or impossible to access, for many countries of the South. This study demonstrated an efficient way of creating flood hazard maps by making full use of available datasets of moderate resolution, including information on flood extent from archived records and maps prepared by local government agencies and free ASTER DEM products that may have immense potential in application for flood mapping in data poor countries. More emphasis is put on the general trend of flooding by using time series data, rather than depending on a particular incident. The integration of hydrological data with socioeconomic information can effectively identify actual localities deserving greatest attention. These hazard maps would facilitate flood plain zoning and other remedial land use planning measures. The analysis presented here is not aimed at formulating a flood management strategy for Gangetic West Bengal, but to show how a synthetic flood hazard map can be produced by using available information from local governmental agencies. While acknowledging that the accuracy of key information and past records of flooding depends on the scale of the maps, the methodology proposed offers promise for planning authorities in flood prone regions in countries where real constraints in access to spatial data prevail.

This analysis adopts similar methods to Islam and Sado (2000a; 2000b) in terms of producing a synthetic flood hazard map, but differs in the working scales and datasets used by addressing regional (macro) and subregional (micro) administrative scales in a GIS environment. Regional flood hazard mapping was used to identify highly vulnerable zones that required following up through cost and time intensive detailed village level analyses. Mapping at different scales creates an opportunity to use a wide range of relevant data collected by administrative units at different levels. It is evident that GIS has an important role to play in natural hazard management (Coppock, 1998). The main advantage of using GIS for flood management is that it not only generates a visualization of flooding but also allows for practical estimation of the probable hazard due to flood (Clark, 1998).

Acknowledgements

This research was funded by the National University of Singapore research grant (Grant No.R-109-000-049-112). We are also grateful to the Irrigation and Waterways department of the West Bengal government for granting access to the annual flood reports in its archives.

Endnote

1 The districts constituting the Bengal Delta region are eastern Budhman, Murshidabad, Hoogly, Howrah, western North 24 Pargana, most of Nadia and Kolkata. The current study area is composed of the districts of Murshidabad, Nadia, Hoogly and the northern part of North 24 Pargana.

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