Geospatial Modelling for Flood Management in a Rural Development Block of Orissa, India

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Abstract

The research examines the use of GIS and spatial statistics for management of flood vulnerability and risk in a rural environment. Housing, critical facility, economic, environmental and health, societal, relief and rescue vulnerability and risk are taken into account in this study. Location and priority quotients of vulnerability and risk and their spatial representation using spatial analysis are found to be providing significant support in decision making process. The spatial context of vulnerability, risk and related maps and database created are found to be highly necessary in generating valuable and timely information for effective disaster management practice. Specific research directions in the line of advanced spatial and attribution analysis are also suggested in this research.

Keywords: *GIS; flood; vulnerability; risk; management priority; location quotient, priority quotient*

Introduction

Geospatial modelling and prioritization of policies are necessary for effective disaster management practice. It is evident from the increasing attention received by GIS and spatial statistics in hazard research. A key role of GIS has been in devising ways to manage and analyze the data produced in disaster management situations. Vulnerability and risk assessment coming under prevention phase are the most important steps in the six phased disaster management process.

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Flood disaster has maximum frequency and has caused maximum amount of damage in India, as compared to other natural disasters (NIDM, 2009). According to Dhar *et al.* (2003), monsoon rainfall magnitude is not the only cause of flooding in the coastal Orissa. Lower channel depth and slope value, human intervention in the form of deforestation and commercial exploitation of silts deposited on natural levees also enhance the risk of flooding. Disaster risk reduction and more robust development planning are crucial in adapting to the increasing risks associated with climate change. This is particularly important in the face of mounting vulnerability to flood hazards, as reflected, for instance, in rising numbers of people affected and escalating levels of economic damage (Aalst, 2009). The essence of this paper is to propose a geospatial model for assisting the decision making process of flood managers.

Geospatial technology is necessary for immediate as well as long term response to natural hazards. GIS application in disaster risk management ranges from database creation, inventory, overlay, risk analysis, cost benefit analysis, scenario analysis, decision matrix, sensitivity analysis, geoprocessing, spatial statistics and many other complex spatial decision making tools and algorithms (Menon & Sahay, 2006). Management of disaster data include data integration, ingestion, information retrieval, filtering and data mining for decision support.

According to Islam and Sado (2004), flood hazard assessment can be done using flood frequency, depth, land cover, physiographic and geologic divisions also. Weighted score on the basis of flood frequency and depth can be given to each division for calculating hazard ranks. 'Analytical Hierarchical Process' is another important method used for hazard zonation. Decision factors such as geomorphic features, elevation, vegetation and land cover can be used and their relative importance weights are calculated using this method.

Vulnerability is defined as the degree of loss to a given element of risk or set of such elements, resulting from the occurrence of natural phenomenon of a given magnitude (UN, 1991). Risk is the chance of loss as defined as a measure of the probability and severity of adverse effect to health, property, environment and other things of value. It is a function of both natural hazard and vulnerability. Spatial pattern of vulnerability and risk provide important information about risk elements and prioritization of mitigation process (Ross, 1987). 'Risk and vulnerability assessment tools' prepared by NOAA, USA (1999), describes the process in six steps as hazard analysis, critical facilities analysis, economic analysis, environmental analysis, societal analysis and mitigation opportunities analysis. 'Hazard, risk and vulnerability assessment tool kit', prepared by Ministry of Public Safety and Solicitor General, Provincial Emergency Program, State of

British Columbia , Canada (2004) uses simple ranking method on the basis of risk profiles drawn from likelihood of disaster occurrence and consequent impact.

Oswald and Sinclair (2005) proposed seven broad categories of values in flood plain management. They are community identity and community attributes, community economic development, technical and non-structural approaches, civic engagement, flood legacy, personal rights & liberties and shared values. According to Hall *et al.* (2003), flood risk to environment, society and economy are cumulative effects of change. Hence, long term scenarios are required for sustainable flood management policies. Environmental vulnerability embraces various political, social, economic and biophysical dimensions that shape and conjure risk to hazards. Lack of resource in community decreases the resilience to hazards. Policy and institutional reforms and improved knowledge management are required to sustainably address the risks.

Materials and Methods

Study area and data

The area under study is Mahakalapada block belonging to the coastal district of Kendrapada in Orissa state (Fig. 1). The area comes under Mahanadi delta region. The block consists of 26 gram panchayats or GPs (Administrative unit consisting of some villages). The river Mahanadi passes through the area which comes under its flood velocity zone. Agriculture is the principal land use and aquaculture is practised in coastal GPs (Fig. 2). Total population of the area accounts to 1,91,745 (Census of India, 2001). A symbiotic relationship exists between flood, cyclone and economic backwardness of the area (Satapathy, 2007).

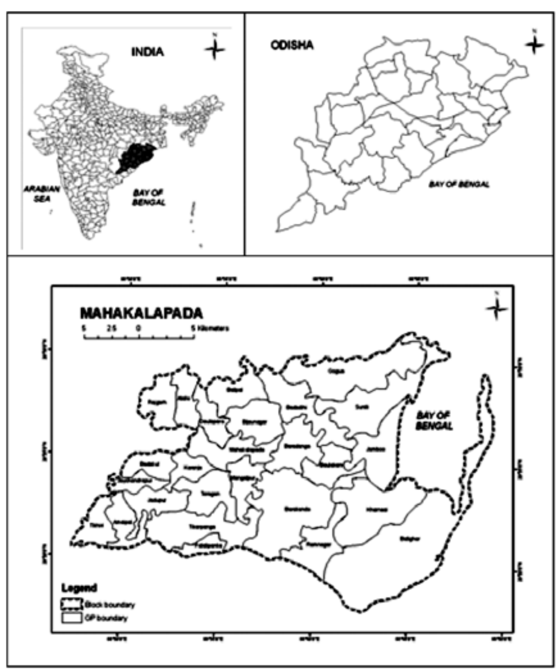

Fig 1. Location of the study area

IRS ID LISS III imagery of 2003 and relevant Survey of India toposheets are used for land use analysis and reference. Data regarding flood frequency is collected from District Emergency office. Census of India, 2001 data is used for acquiring socio-economic information. District Revenue office data is used to estimate the economic impacts of hazard and primary survey was carried out to collect data not available in secondary form.

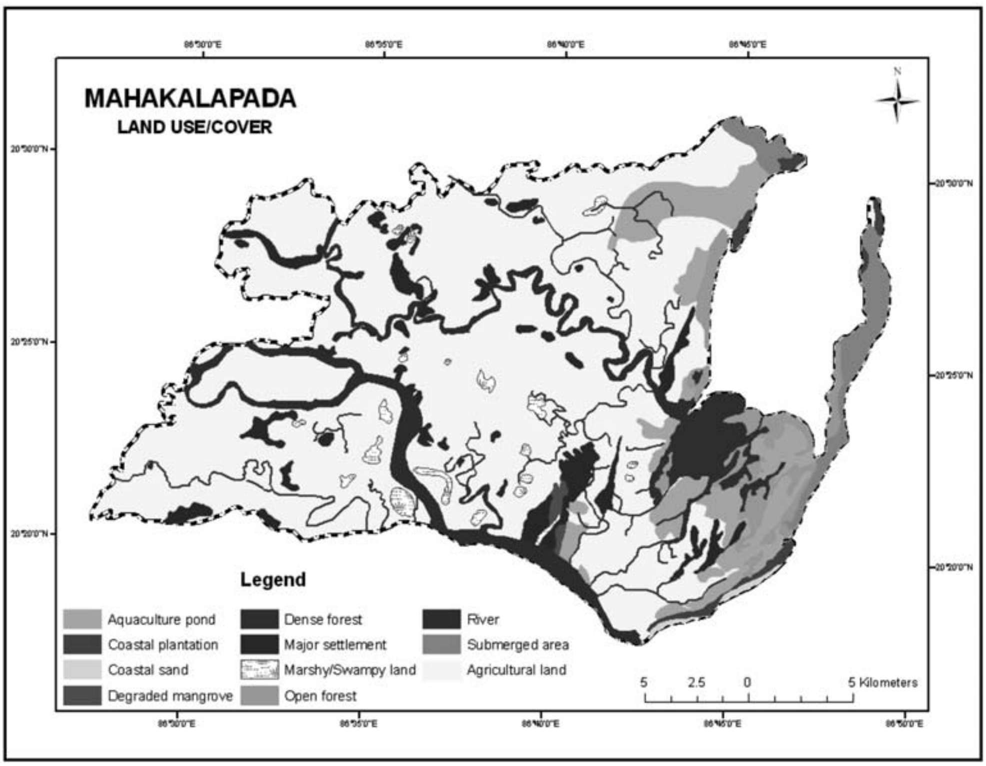

Fig 2. Land use / cover map of Mahakalapada

Methods

Hazard zonation of the area is done using a simple method which can be performed with easily available data. Two basic types of hazard factors are used for hazard zonation. Flood frequency and depth are considered as hydraulic factors and quality of flood water drainage is taken as geomorphic factor for hazard zonation. Quality of flood water drainage is evaluated on the basis of percentage of area of each GP under high soil moisture in post flood scenario, which is acquired from the IRS 1D LISS III imagery (2003) of the study area. Ranking matrix in three dimensional multiplication modes (Table 1) has been used to calculate the composite flood hazard index, using hazard ranks of individual hazard factors. A scheme of progressive weightage (Sanyal & Lu, 2003) has been adopted for the variable 'hazard rank (HR)' so that the hazard curve becomes progressively steeper at the higher values of 'hazard factors'. The exponential function (e^x) is used to model hazard phenomena because a constant change in the independent variables (hazard factors) give the same proportional change (increase or decrease) in the dependent variable (hazard rank). Ranks of hazard, vulnerability and risk are simplified to a 5 point scale from low to high.

Table 1. Concept of ranking matrix

X (columns), Y (rows)

HR	**0.12**	**0.34**	**0.94**	**2.57**	**7.08**
0.12	0.01	0.04	0.11	0.30	0.84
0.34	0.04	0.11	0.31	0.87	2.40
0.94	0.11	0.31	0.88	2.41	6.65
2.57	0.30	0.87	2.41	6.60	18.19
7.08	0.84	2.40	6.65	18.19	50.12

XY

HR	0.84	2.40	6.65	18.19	50.12
0.12	0.10	0.28	0.79	2.18	6.01
0.34	0.28	0.81	2.26	6.18	17.04
0.94	0.78	2.25	6.25	17.09	47.11
2.57	2.15	6.16	17.09	46.74	128.8
7.08	5.94	16.99	47.08	128.78	354.84

Gram panchayat wise vulnerability and risk assessment for elements, such as houses, critical facility, economy, environment, society, relief and rescue are carried out separately. Vulnerability is determined in the face of high flood hazard. In case of housing study the predominant material of roof and wall, damage history are taken as components of structural vulnerability and position with respect to base flood level is taken as component of operational vulnerability. Health Centre, school building, road, community building, telecommunication facility are taken under critical facility category and their structural and operational vulnerability are calculated using the codes prescribed by Vulnerability Atlas of India (1997).

Crop damage history, agricultural efficiency, live stock vulnerability on the basis of availability of shelter and medical care are considered to assess economic vulnerability. Availability of sanitation facility, drainage connectivity for waste water outlet and livestock vulnerability is taken as factors for determining environmental and health vulnerability.

Population density, population under critical age group, population below poverty line, crime incidence and intensity, mental preparedness are considered as elements of societal vulnerability. Vulnerability of road, level of road network development, disaster cognizance level, efficiency history of relief distribution system are taken into account for calculating relief and rescue vulnerability. Level of road network development is determined by calculating cyclomatic number (μ= no. of edges - no. of vertices + no. of graphs) for each GP and behavioural matrix is used to determine cognizance level. Literacy percentage, used as the determining factor for ability use incoming information and quality of incoming information are taken as components of the matrix.

Itemized and relative rating scales are used for ranking individual factors. These are principally knowledge based ranks. Combined vulnerability score is calculated from these values and then multiplied with composite hazard indices to determine risk scores. Categorization of risk scores is carried out by using ranking matrix in two dimensional multiplication modes. On the basis of vulnerability and risk scores, maps showing these categories are prepared and high priority elements are shown for different GPs. GIS and remote sensing techniques such as classification, topology building, fuzzy analysis, query and categorization are applied in Arc GIS and ERDAS environment to develop thematic maps. Structured questionnaire and group discussion methods are used for primary data collection from the samples selected by stratified random sampling method. Self rating method is used for collection of behavioural data. 5 point Likert scale is used to rank them. Likert scale measures the level of agreements of respondents to questionnaire statements (Kerlinger, 1986).

Solution matrices are prepared for vulnerability and risk scores by standardising the rank of individual vulnerable category on the basis of qualitative index (Table 2). The qualitative indices are transformed into quantitative ranks of 1 to 5. These values are used in the solution matrices, to calculate location quotient for GPs and priority quotient for vulnerable categories. Severity of a risk component with respect to average value of risks prevailing in the area is represented by priority quotient. Vulnerability and risk representation of a GP with respect to average representation levels of the block is represented by location quotient. On the basis of these quotients priority ranks are assigned. Priority ranks of individual vulnerability and risk category are also assigned using combined scores of these categories for all the GPs, which reveals block level scenario of vulnerability and risk. This will help in block level disaster management program. The formulae used for calculating location and priority quotients are as follows:

$$\text{P} = \frac{\Sigma \text{ v or r ranks for all individual categories in the GP}}{(\Sigma \text{ v or r ranks of all the GPs} \div \text{Total number of GPs})}$$

$$\text{r r category} = \frac{\Sigma \text{ ranks of all the GPs for that category}}{\Sigma \text{ ranks of all the categories of v or r} \div \Sigma \text{ v or r categories}}$$

ation Quotient; PQ: Priority Quotient; v: vulnerability; r: risk)

On the basis of the above quotients, priority ranks are assigned. Using these ranks management priority maps is prepared. The term 'management priority' is used in the sense that in mitigation programs the ranks will determine priority elements. Also during an unexpected disaster in a low hazard risk area, vulnerability score will help to determine priority functions of disaster management. Product moment correlation coefficient between combined vulnerability and risk scores is calculated to test the effectiveness of the ranking system used. Relationship between vulnerable and risk elements have been estimated by using Spearman's rank difference method. The overall methodology framework is given in Fig. 3.

Table 2. Framework for solution matrix for vulnerability / risk analysis

Vulnerable element	Vulnerability / risk ranks of individual gram panchayats on 5 point scale						Total (GP1 to GP26)	Priority quotient	Priority rank
	GP1	GP2	GP3	GP4	GP5	GP6……			
Housing facility	4	5	1	3	2	1	82	1.01	2
Critical facility	3	4	1	2	1	1	62	0.76	3
Economy	4	5	1	3	2	1	82	1.01	2
Environment & health	5	5	2	3	2	2	94	1.16	1
Society	4	5	1	3	2	1	82	1.01	2
Relief & rescue	4	5	1	3	2	1	82	1.01	2
Total	24	29	7	17	11	7			
Location quotient	1.28	1.55	0.37	0.90	0.58	0.37			
Priority rank	2	1	7	4	6	7			

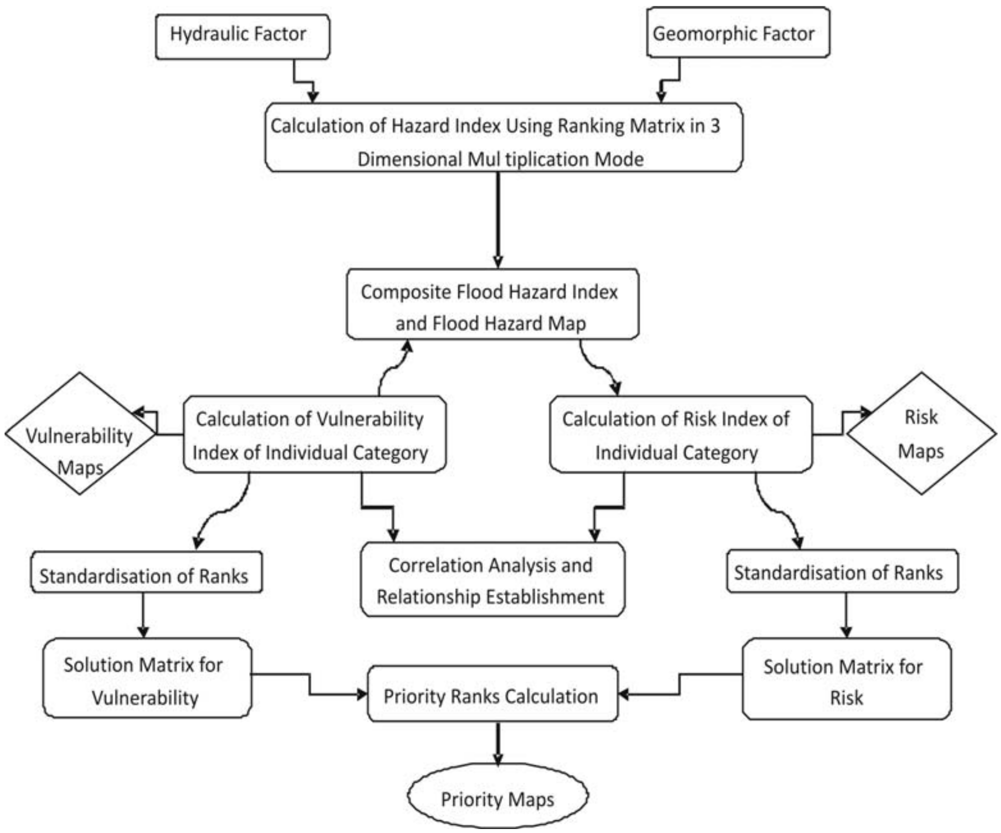

Fig 3. Methodology framework

Results and Discussion

The composite flood hazard indices showed high and medium risk in most of the GPs. The GPs of north east portion are comparatively low risk areas due to relatively higher altitude (Fig. 4). Most of the GPs come under moderately high to high housing risk. The critical facility vulnerability is found to be moderately low. This is because of hazard resilient construction works carried out in post super cyclone that hit the state in 1999.

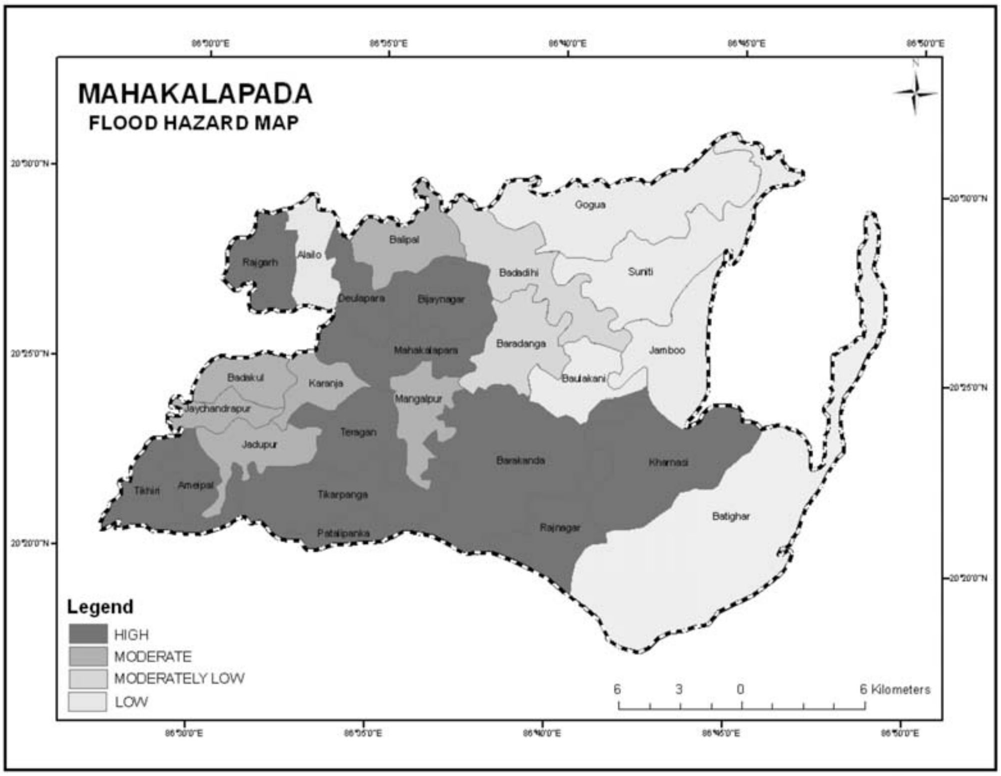

Fig 4. Flood hazard map of Mahakalapada

Economic vulnerability and risk are found to be high for most of the GPs. Threats to livelihood is a serious concern in the area. The environmental and health vulnerability assessment showed high risk prevailing in most of the GPs. Low economic development, lack of awareness about sanitation, lack of safe shelter for livestock are the factors responsible. Societal vulnerability and risk are found to be moderately high to moderately low for many areas. The priority concern is found to be lack of mental preparedness. Relief and rescue vulnerability and risk are found to be heterogeneously distributed. Operational vulnerability of roads is the priority concern for this category.

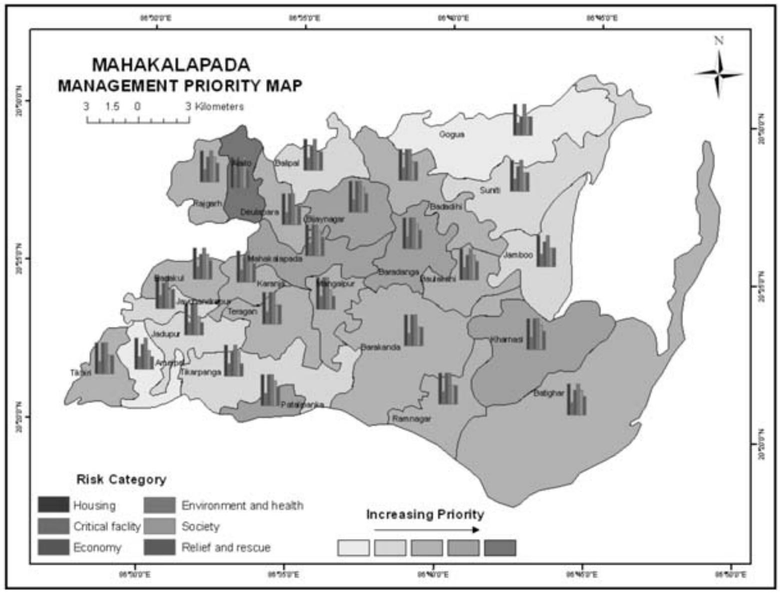

Fig 5. Management priority map based on vulnerability score and priority rank

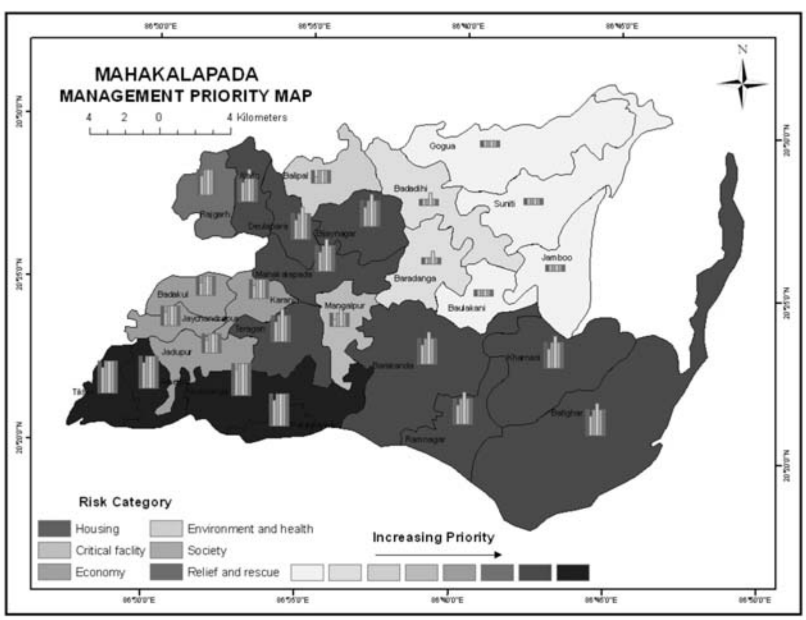

Fig 6. Management priority map based on risk score and priority rank

On the basis of location quotients Alailo, Baradanga, Bijaynagar, Kharnasi, Mahakalapada and Patalipanka GPs are found to be over represented in terms of fair value of vulnerability (Fig. 5). Ameipal, Batighar, Baulakani, Bijaynagar, Deulapada, Tikhiri, Ramnagar, Rajgarh are found to be over represented in terms of risk (Fig. 6). Hence these areas should be given first priority in mitigation programs. It is found that at block level, environment and health are at highest risk and critical facilities are at lowest risk. Similarly environment, health and housing facility have highest vulnerability (Fig. 7).

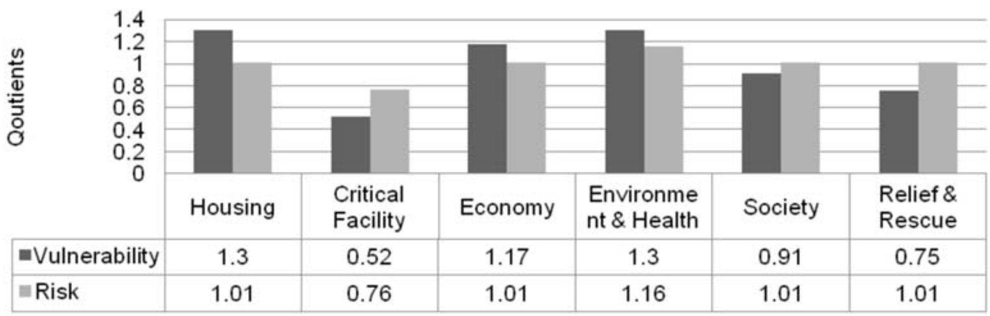

Fig 7. Priority Quotient at block level for combined vulnerability and risk

Product moment correlation coefficient (r) between combined vulnerability and risk scores is + 0.34, which confirms the absence of perfect positive correlation between variables. Hence it is inferred that there is absence of unfair amount of interplay between variables. This shows that the ranking system used in the study is efficient. The rank correlation coefficient (p) between risk elements is found to be ranging from 0.8 to 1. This shows serious symbiotic relations between these elements which demands integrated and holistic disaster resilient development policies for the block.

Conclusion

The application of a GIS and spatial modelling for natural hazard risk management is an emerging science. Providing a spatial context for risk is critically important for risk reduction. The maps and database created on vulnerability and risk can provide valuable and timely information for effective disaster management practice. Integration of priority ranks in geospatial data gives readily representable and cognizable information to disaster managers which would otherwise require tedious mathematical processes. These data can further be manipulated through spatial and attribution query in GIS environment to help the spatial decision making process for ready response to disaster. A further future development of the proposed approach can include detailed study of individual categories of risk and their minute interrelationships using advanced spatial and attribution query methods in GIS environment. The approach may also be used for developing the decision support system for flood management.

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