

Waterlogging and flood hazards vulnerability and risk assessment in Indo Gangetic plain

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Abstract The recurrent flooding during monsoon and subsequent waterlogging in the northern Bihar plains and the magnitude of losses due to these hazards indicate the continuing vulnerability of the region to flood and waterlogging. Management of floods and waterlogging hazards in highly flood-prone regions of India, including Bihar state has been largely response oriented with little or no attention to mitigation and preparedness. This paper presents a method for spatial, Geographic Information Systems-based assessment of flood and waterlogging vulnerability and risk in northern Bihar plains. Multi-temporal satellite data was used to evaluate the area statistics and dynamics of waterlogging over the period from 1975 to 2008. The flood proneness is evaluated at district level with reference to flood inundation during a period from 1998 to 2008. Census data were used to examine the socio-economic characteristics of the region through computation of population density, cultivators, agricultural labourers, sex ratio, children in age group 0–6 years and literates. The geohazard map derived by combining area prone to waterlogging and flood inundation was multiplied with socio-economic vulnerability map to derive the flood-waterlogging risk map of the region. The result shows that flood and water-logging pose highest risk to the central districts in the northern Bihar plains with 50.95% of the total area under high and very high risk.

Keywords Northern Bihar plains · Flood · Waterlogging · Hazard · Vulnerability · Risk · Remote sensing · GIS

1 Introduction

Indo-Gangetic plain (IGP) is considered as one of the largest plains in the world formed by the river systems. Indus, Ganga, Yamuna, Ghaghara, Gandak and Kosi emerging from the Himalayas and debauching the IGP are among the rivers, which carry and transport the highest sediment loads in the world (Tejwani 1987). Paralleling the Southern Himalayan

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Province, about 1,700 km long and 200–300 km wide (geographical area ~6,00,000 sq km). The IGP are still active alluvium plains with general slope of the ground from west to east and elevation of about 200 m above m.s.l. in the western parts to near the sea level in the eastern parts. Average annual rainfall varies between 300 and 1,600 mm, roughly linearly increases eastward at the rate of 0.6 mm/km (Singh and Sontakke 2002).

The area of the Indo-Gangetic plains is nearly 13% of the total geographical area of the country, and it produces about 50% of the total food grains to feed 40% of the population of the country (Srivastava et al. 1994). Food grain production in India crossed 200 Mt mark in year 1999–2000, in comparison with 50.82 Mt in 1950–1951. In spite of technological advancement in agriculture, large year-to-year variations in production continue, which is related to fluctuations in monsoon at a gross level. Wheat, the second most important food grain crop, contributes about 37% to the total food grain production in India. Lying within the Indo-Gangetic plain the states of Punjab, Haryana, Uttar Pradesh, Madhya Pradesh and Bihar contribute about 93% of wheat production in India (Nain et al. 2002).

In India, an estimated 2.46 Mha of land is reported to have suffered from waterlogging (Anonymous 1991), and the area containing salt-affected soils has been estimated to be 7.0 Mha (Abrol and Bhumbra 1971). Waterlogging, closely associated with salinization and/alkalinization, continues to be a threat to sustained irrigated agriculture, affecting an estimated 6 million ha of fertile land in India (National Commission on Agriculture 1976). About 4.5 million hectares of land have already become barren (Singh 1992) and more lands are being encroached upon by these problems every year, depending on the climate, topographic, geohydrologic and groundwater conditions.

India is estimated to have about 58.2 million hectares of wetlands (Prasad et al. 2002), many of which are distributed around the Indo-Gangetic plains. Generally regarded as “a water-surplus area” (Ghosh et al. 2004), the entire region is characterized by palaeo levees, swamps or flood basins locally called “Chauras” relict palaeo channels aggraded to different extents, meander belts, ox-bow lakes and cut-off loops (Ahmad 1971). The four crop seasons in descending order of area cultivated are Kharif (June–October), Rabi (November–February), Aghani and Garma (March–May). The major crops are rice, maize and wheat. The presence of waterlogged area affects the cultivation pattern as more people are involved in paddy, wetland paddy and sugarcane cultivation during the Kharif season in the villages near the wetland (Ambastha et al. 2007).

Canal irrigation was introduced at the end of the nineteenth century to minimize the problem of aridity and to stabilize crop yields in various parts of the IGP. This resulted in the expansion of the cultivated area. However, introduction of irrigation during the dry climate without the provision of drainage led to soil salinization and alkalinization within a few years due to rise in the groundwater table (Abrol 1982).

Groundwater remains the lifeline of socioeconomic development in the Ganga Alluvial plain (part of the IGP drained by Gangetic river system) since the dawn of civilization in the Indian sub-continent. The quaternary sequence, forming top layer of the thick unconsolidated sediments of the Ganga Alluvial plain, holds nearly 30% of the total annual replenish able groundwater resource of India (Govt. of India 2006). Increasing groundwater extraction from Ganga Alluvial plain has resulted in surfacing of aquifer-stress symptoms like lowering of water levels and groundwater quality deterioration (World Bank 1998). The vast variation, both in space and time, in the availability of water in different regions of Bihar state has created a food–drought–flood syndrome with some areas suffering from flood damages and other areas facing acute water shortage (Saha et al. 2009).

Waterlogging and flood constitutes the main hazards in the northern Bihar plains resulting due to surplus water availability in the region. The severity of these hazards turns into a disaster due to existence of high population density with low socio-economic status. Therefore, examination of vulnerability of society to these hazards in view of changing climatic conditions needs evaluation of past and present spatial occurrence of these hazards vis-à-vis socio-economic conditions of present population existing in these regions.

North Bihar is undoubtedly the most backward region, as reflected through its lowest urbanization level (6.7%), the lowest literacy rate (42.1%) and the highest decadal growth rate of population (29.3%) (census 2001). The vast area of northern Bihar plains is one of the victims of regional disparities in development, where both the growth process as well as the pace of rural poverty reduction has been much slower than elsewhere in India (IFAD 2003). The economy of Bihar state is largely service oriented. As of 2008, agriculture accounts for 35%, industry 9% and service 55% of the economy of the state (<http://industries.bih.nic.in/Slides01/Presentation.pdf>). The estimates of rural poverty in India relating to 1993–1994 indicate that a little more than half the rural population (58.7%) of northern Bihar plains live below poverty line whereas for India as a whole the corresponding ratio stands at one-third (36.7%). The demographic pressure on its land resources is 983 persons per sq km which is one of the highest in whole of the country and even in the world. This is more than two and a half times the national average of 324 persons per sq km. The soil of entire northern Bihar plains is alluvial in nature whose high natural fertility had attracted population over centuries, resulting in its high population density.

In northern Bihar plains 61.6% of its total area is available for cultivation. Rural population/hectare of net cultivated area is 14.1 compared to 5.2 in India, whereas average size of holding (ha) in north Bihar is 0.65 compared to 1.57 in India. The proportion of the population below the poverty line at the district level in the Indo-Gangetic plain (IGP) shows highest incidence of poverty in northern Bihar plains (39.3%) (Erenstein et al. 2010). The implications of repeated occurrence of floods in many districts of northern Bihar plains is not restricted to only loss of crops, livestock and property, its impact on the poverty levels in the area is also very decisive as the poorer households in the rural areas are far more affected by the floods than the relatively richer ones. For poorer households, the floods not only imply loss of their current income but also destruction of their houses made up of mud and bricks.

The present study pertains to vulnerability and risk assessment of flood and waterlogging hazard of northern Bihar plains. Multitemporal satellite data of the years 1975, 2001 and 2008 were used to evaluate the area statistics and dynamics of waterlogging. District-level flood proneness is evaluated with reference to flood inundation. Census data were used to get district-wise socio-economic characteristics in terms of population density, sex ratio and population of cultivators, agricultural labourers, children in age group of 0–6 years and literates. The geohazard map derived by combining waterlogging and flood hazard maps was combined with vulnerability map derived from socio-economic indicators to get risk map of the region. Paper also discusses the future projection of rainfall under changing climatic conditions and flood disaster in the region.

2 Study area

The area under investigation comprises of 21 districts in the northern Bihar plains. It is located between 83°50′–88°20′E longitude and 25°35′–25°10′N latitude, covering a total

area of 55,860 sq km. Lying within the eastern parts of Indo-Gangetic plains, the area exhibit diversity in its regional climate due to its physiographic settings. The area is bounded by Himalayas in the north and by plateau region on the south. The area is drained by a number of large perennial tributary streams of Ganga, namely Gandak, Kosi, Baghmata, Kamla–Balan and their tributaries.

The normal annual rainfall in the Gangetic plains varies from 60 cm to more than 160 cm. The temperature in the Gangetic plains varies from 2 to 15°C in winter to 25–45°C during summer (Singh 1994). The mean sea level elevation from north to south ranges from 35 to 90 m. The slope in the upstream area is towards the south, which changes to SE in the downstream region. The river systems of northern Bihar plains are among the most dynamic river systems in the world (Gole and Chitale 1966; Wells and Dorr 1987; Jain and Sinha 2003, 2004). Channel morphology and fluvial processes are dependent variables which essentially reflect water discharge and sediment supply.

Major portion of the state comprises of highly productive land over the alluvial plains developed by a large number of tributary streams of river Ganga. The recurrent and annual flooding in the major tributaries results in high seasonal waterlogging conditions. Due to flooding and subsequent waterlogging, a large area of productive lands turn into wasteland restricting crop growth in the Kharif as well as Rabi season. The region lies within the ITCZ (inter-tropical convergence zone), which receives very high rainfall during SW Indian monsoon. The high rainfall in the plain region and high cumulative runoff brought by rivers draining the upper catchment regions in the Himalayan terrain has made the low-lying areas in the north Bihar plain highly prone to flooding and water-logging hazards (Fig. 1).

3 Methodology and data used

In the present study, satellite images of IRS-AWIFS (2008), LANDSAT-ETM⁺ (2001) and LANDSAT-MSS (1975) were used. Unsupervised classification technique was used on each satellite images to classify it into two classes viz; surface waterlogging areas and non-surface waterlogging areas. District-wise area under surface waterlogging in each of the 21 districts was calculated using 2008, 2001 and 1975 images. Per cent area under surface waterlogging in each district was computed with reference to total area under surface waterlogging. Further, water-logging hazard rating (1–4) was assigned in which districts with higher percentage of area under surface waterlogging were assigned higher ratings and vice versa. In this way, we prepared a waterlogging hazard map for a given period, say 1975. Similarly, water-logging hazard map for the periods 2001 and 2008 was prepared. Finally, composite water-logging hazard map was prepared by addition of all the ratings assigned to each district in all the temporal water-logging hazard maps in GIS environment. A composite flood inundation map was prepared for the period 1998–2008 based on MODIS data-derived flood maps obtained from Dartmouth flood observatory. Per cent flood area in each of the 21 districts was calculated with reference to district area. Flood hazard ratings (1–4) were assigned to each district on the basis of its per cent area under flood inundation to obtain flood hazard map. Composite waterlogging hazard map and flood hazard map were spatially joined in GIS to prepare Geohazard map. Ancillary data (census of India, 2001) was used for computation of district-wise percentage of population density, cultivators, agricultural labourers, literates, sex ratio and children in age group 0–6 years. Ratings (1–4) were assigned according to their assumed vulnerability to said disasters. For each of the above six socio-economic indicators, four classes of vulnerability

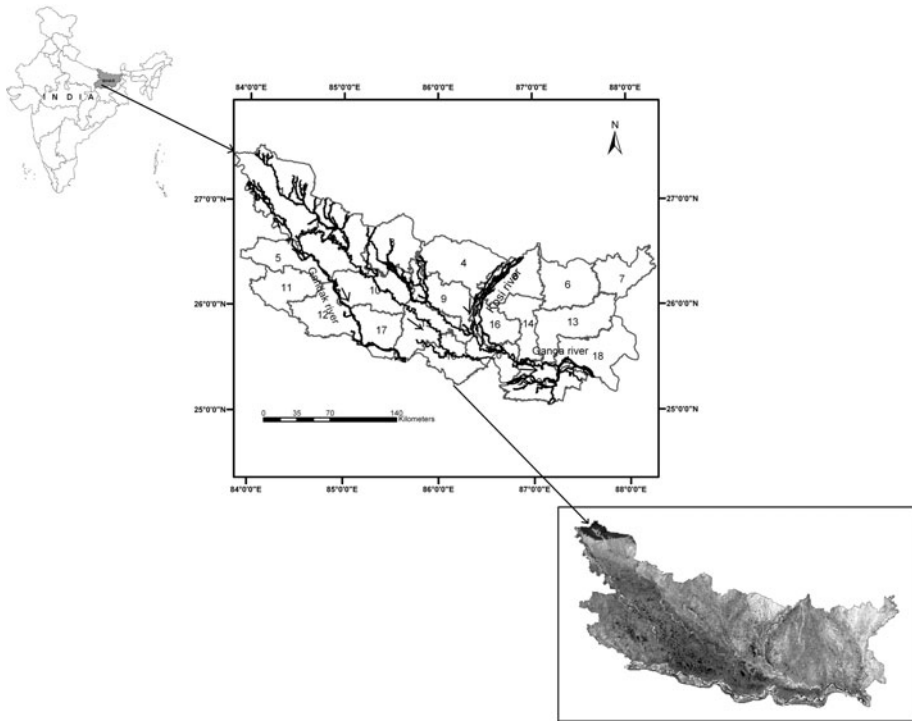


Fig. 1 Location map of the study area showing district boundaries along with stream network. The AWIFS satellite image (Band 4) of the area acquired in January, 2008 exhibit waterlogging areas in shade of black colour in the south and central portion of the area. Forest cover is present in extreme NW corner, whereas agriculture and fallow lands appear in grey and white colour tones

viz; low, medium, high and very high were assigned corresponding to the lowest to the highest values of their percentage in each category. A composite vulnerability map is generated by integrating the district-level thematic maps of all indicators. For this purpose, each class of an indicator is assigned a rating within a scale of 1–4 according to vulnerability class. For all the indicators, classes with higher vulnerability are given higher ratings and the vulnerability with lower values is assigned with lower ratings. District-wise vulnerability map was prepared by adding all of the aforementioned themes in GIS environment.

Geohazard map and vulnerability map were multiplied in GIS domain to prepare flood–water-logging risk map. In the present article, the following main steps are used to quantify the risk pattern in the northern Bihar plains.

Where, GHI in this model represents the district-level geohazard vulnerability index; HVI represents the district socio-economic vulnerability index.

1. Computation of district-wise area under water-logging and flood hazards.
2. District-wise computation hazard vulnerability with reference to population density, children in age group 0–6 years, sex ratio (female/male), population of workers (agricultural labourers and cultivators) and literates.
3. Computation of flood and waterlogging risk from geohazard and hazard vulnerability map. The detail of the methodology adopted in the study is presented in the methodology flow chart (Fig. 2).

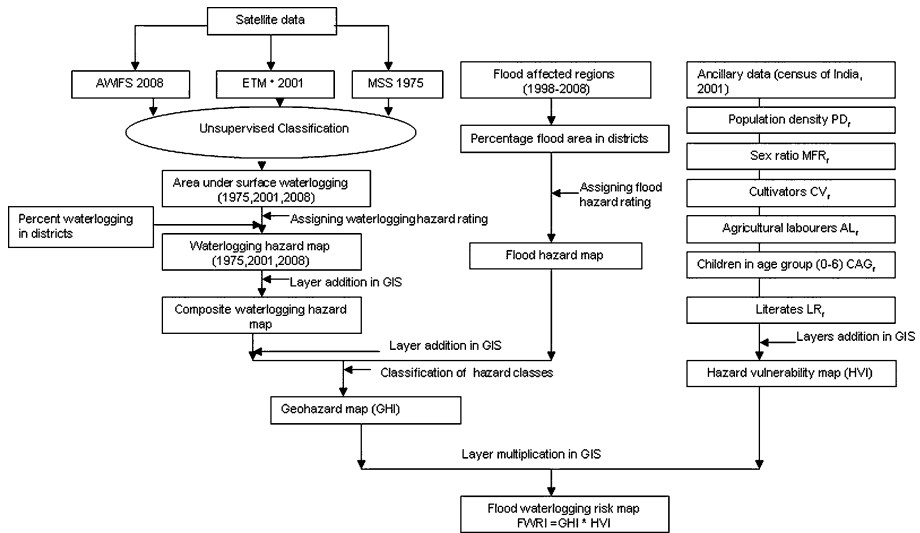


Fig. 2 Flow chart of the methodology for flood-waterlogging risk mapping

4 Results

4.1 Waterlogging

Waterlogging is a dynamic phenomenon which is governed by the hydrological regime of the terrain. The soil moisture regime is mainly affected by variations in annual precipitation, evapotranspiration, seepage from canals and the leaching of surplus water into the sub-soil. When the groundwater table approaches the land surface (<2 m deep), it starts to affect the normal air circulation in the root zone of most plants, which ultimately affects their normal growth and yield (Sujatha et al. 2000). An area is said to be waterlogged when the water table rises to an extent that the soil pores in the root zone of a crop become saturated, resulting in restriction of the normal circulation of air, decline in the level of oxygen and increase in the level of CO₂ (Anonymous 1976). The use of space-borne multispectral data has been shown to have potential for deriving information on the nature, extent, spatial distribution and magnitude of waterlogging. In the present study, unsupervised classification technique which uses ISODATA algorithm (Kindscher et al. 1998) was adopted to segment the image into the desired land cover classes. In an unsupervised classification, pixels with similar spectral characteristics in the different bands of a satellite sensor are identified and grouped into spectral classes using a statistical clustering procedure. Based on spectral similarity, visual interpretation of the classes and a prior knowledge of the study area; entire image was classified into two classes viz non-waterlogging area and surface waterlogging area. Surface waterlogged areas and water bodies exhibit similar reflectance characteristics which can be discriminated from other associated land covers like salt affected soils, forest, fallow land and crop lands by virtue of the very low spectral response in all the bands, especially in the near infrared (0.77–0.86 μm) (Dwivedi and Sreenivas 1998). In the standard false colour composite (band 432 in RGB) of the satellite image, waterlogged areas appear as shades of blue–light blue, greenish blue, bluish green, etc., depending upon surface wetness, water depth and the presence of

sediments. In the present study, author used satellite images of the year 1975 (LANDSAT MSS), 2001 (ETM⁺), 2008 (AWIFS) to demarcate surface waterlogging condition in these years. As the command area receives rainfall during early June to late October, in standard FCC generated from space-borne multispectral data acquired during November/December the seasonally waterlogged areas show very clearly in different shades of blue and cyan (Dwivedi et al. 1999, Fig. 3).

The area statistics computed for waterlogged lands in different period images clearly indicate a substantial increase in seasonal surface water-logging condition during the period for 1975–2008. The area statistics of mapped seasonal waterlogged lands (including water bodies) was evaluated and compared to understand waterlogging dynamics over the years. It was calculated that an area of 1,294, 5,020 and 1,948 sq km of area was affected by surface waterlogging in the year 1975, 2001 and 2008, respectively. The trend clearly shows an increase in the waterlogging in the month of November/December. The explanation for large area under waterlogging during the months of November/December in 2001 is due to flood inundation over a large area in the preceding monsoon period of July–August 2001 in the area. District-wise water-logging status was calculated to examine the waterlogging hazard and vulnerability at district level.

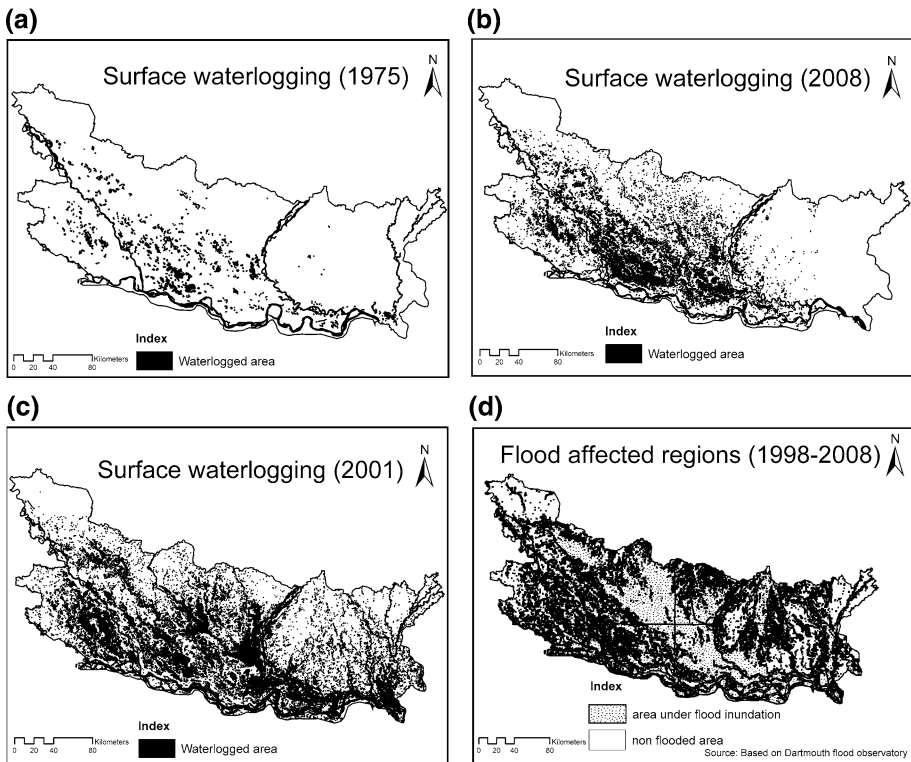


Fig. 3 a Showing the surface waterlogging condition in the month of December/January of 1975 b showing the surface waterlogging condition in the month of January of 2008 c showing the surface waterlogging condition in the month of November/December of 2001. The black portion in the central and southern parts of the map indicates waterlogged and flooded regions in parts of the northern Bihar plains d flood inundation map prepared for northern Bihar for the period 1998–2008 (based on MODIS data derived flood maps obtained from Dartmouth flood observatory)

4.2 Floods

The Indo-Gangetic plains are drained by some of the largest river systems in the world. These plains are also severely affected by frequently occurring disastrous floods and are presently regarded as the worst flood affected region in the world (Agarwal and Narain 1996). The plains of north Bihar are some of the most susceptible areas in India, prone to flooding and recorded the highest number of floods during the last 30 years (Kale 1997). The total area affected by floods has also increased during these years.

Drained by two major rivers, the Kosi and Gandak, and several smaller river systems such as Burhi Gandak, Baghmata and Kamla–Balan, the plains of north Bihar have experienced extensive and frequent loss of life and property over the last several decades (Sinha and Jain 1998). The available data suggest that during 1954–1990, more than 2,700 billions of rupees were spent on the flood control measures in India, but the annual flood damage increased nearly 40 times and annual flood affected area increased 1.5 times in this period (Agarwal and Narain 1996). Therefore, flood hazard mapping vulnerability assessment constitutes a vital component for appropriate land use planning in flood-prone areas of this region.

In the present study, a composite flood inundation map was prepared for the period 1998–2008 based on MODIS data derived flood maps obtained from Dartmouth flood observatory (<http://www.dartmouth.edu/~floods/>). The GIS data base on spatial flood inundation was created to examine the flood hazards in each district of the study area during the observation period. The total area under flood inundation during the period 1998–2008 was 34,802 sq km which is 62% of the total study area. The aforementioned statistics clearly depict that majority of area in the northern Bihar plains is liable to flood inundation.

4.3 Flood and water-logging hazard assessment

District-wise area of surface waterlogging in each of the 21 districts in the study area was calculated using 2008, 2001 and 1975 images, respectively. Percentage of area under surface waterlogging in each district was computed with reference to the total area under surface waterlogging. Surface waterlogging hazard rating was assigned to each district, and districts with higher percentage area under surface waterlogging were assigned higher ratings and vice versa. Water-logging hazard map was prepared by integration of water-logging maps of 2008, 2001 and 1975 by addition of all the ratings assigned to each district in each map in GIS environment. Further, a composite flood inundation map was prepared for the period 1998–2008 based on MODIS data derived flood maps obtained from Dartmouth flood observatory. Percentage flood area in each of the 21 districts was calculated and flood hazard ratings were assigned to each district as per the rating given in the (Table 1) to obtain flood hazard map. Waterlogging hazard map and flood hazard map were added in GIS to prepare geo hazard map. Geohazard vulnerability index (GHI) is calculated as:

$$GHI = CWH_r + FAR_r \quad (1)$$

where CWH_r is the ratings assigned to composite waterlogging hazard map; FAR_r is the ratings assigned to composite flood inundation map.

In the above equation, composite waterlogging hazard is calculated as:

$$CWH_r = (SW_{r1975} + SW_{r2001} + SW_{r2008})$$

Table 1 showing surface water-logging and flood hazard rating assigned to each district based on the percentage of area under waterlogging and flood inundation

Flood & waterlogging observation period	Percentage area covered	Hazard ratings
Surface waterlogging (1975, 2001, 2008)		
	Below 3	1
	3–6	2
	6–9	3
	Above 9	4
Flood affected regions (1998–2008)		
	Below 40	1
	40–60	2
	60–80	3
	Above 80	4

where SW_{r1975} is the ratings assigned based on surface waterlogging during 1975; SW_{r2001} is the ratings assigned based on surface waterlogging during 2001; SW_{r2008} is the ratings assigned based on surface waterlogging during 2008 (Fig. 4).

4.4 Socio-economic vulnerability assessment

The concepts and definitions of vulnerability have been analysed by many authors (Kates 1985; Blaikie et al. 1994; Downing and Bakker 2000). The most common concept of vulnerability is that it describes the degree to which a socio-economic system or physical assets is either susceptible or resilient to the impact of natural hazards (Wilhelmi and Wilhite 2002). It is determined by a combination of several factors including condition of

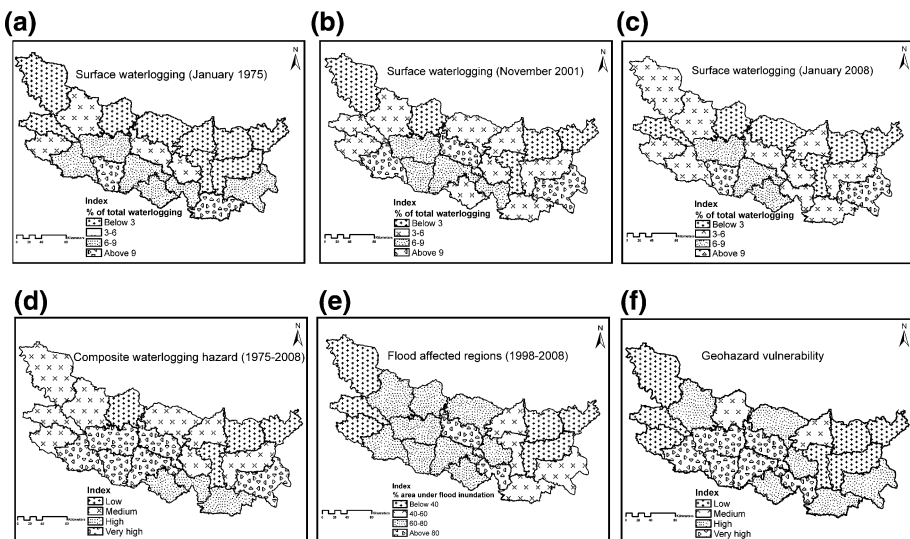


Fig. 4 District-level percentage of surface waterlogging to total waterlogging in **a** 1975 **b** 2001 **c** 2008 **d** composite waterlogging hazard map **e** flood affected districts during 1998–2008 **f** geohazard vulnerability map

human settlements, infrastructure, public policy and administration, organizational abilities, social inequalities, gender relations, economic patterns, etc. flood and waterlogging vulnerability is different for different individuals and nations. In developing countries, flood and waterlogging vulnerability constitutes a threat to livelihoods, the ability to maintain productive systems, and economies. In developed economies, flood and waterlogging poses significant economic risks and costs for individuals, public enterprises, commercial organizations and governments (Downing and Bakker 2000). Therefore, selection of vulnerability indicators is directly relevant to the local study context and the particular hazard (United Nation Development Program 2004). A holistic flood and waterlogging vulnerability index should take into account ecological, socio-economic and production conditions. However, all the indicators according to the aforementioned definition are not readily obtainable and/or quantifiable for the study area. Farming is the largest private sector enterprise in India where nearly 58.9% of the workers depend upon agriculture for their income and livelihoods (Swaminathan 2001). Therefore, alleviating rural poverty and improvements in the socio-economic condition of society can be accomplished by increasing the productivity of agricultural fields and reducing the impacts of flood and waterlogging hazards to lessen the land degradation.

The Indo-Gangetic plain also known as food belt of India ranks as one of the most extensive fluvial plains of the world. The people of the northern Bihar plain are primarily dependent on agriculture and are of low-income group. The Fig. 5 clearly indicates that district Purina has the maximum percentage (69%) of main workers as agricultural labourers and cultivators, whereas district Bhagalpur has the lowest percentage (42%). Percentage of main workers household industry and as other workers is highest in district Begusarai (27%) and lowest in Madhepura (9%). Marginal workers as agricultural labourers and cultivators are highest in district Supaul (26%) and lowest in Kishanganj (11%). Marginal workers in household industry and as other workers are highest in Bhagalpur (6%) and lowest in Purnia (1%). Cumulative percentage of the main and marginal workers as agricultural labourers and cultivators indicate that a large proportion ranging from (67%) Begusarai to (90%) Madhepura of workers population is directly dependent on agriculture. Therefore, in the events of flooding, the society gets affected worse, as a large number of agricultural fields are inundated under flood water during highly productive Kharif season (SW monsoon period). Under such adverse conditions, people are left with no option other than migration to other places as there agricultural fields are submerged in water due to flooding. When the flood water receded, portion of a large agricultural field comes under waterlogging because of poor external drainage and drainage congestion. Therefore, flood-waterlogging hazards which occur synchronously severely affect the socio-economic conditions of the people of northern Bihar plains then any other natural hazard. Therefore to evaluate the risk due to these hazards, understanding of socio-economic condition of population is of prime importance. Following factors are considered important societal element for flood waterlogging risk evaluation in this region.

1. Cultivators and agricultural labourer: On an average, 79% of the workers population of northern Bihar plains depend of agriculture which would be most affected by flood and waterlogging. Loss of crops due to flood inundation or reduced yield under waterlogging conditions affect cultivator's annual income as their major stock mainly comes from Kharif crops. The lack of crop insurance and loan for agriculture increases their societal vulnerability to flood and waterlogging hazards. It is evaluated that the average cultivator including main and marginal workers among various districts in northern Bihar is 28% (Fig. 6a). The cultivators fail to plant or get less production due to flood and waterlogging, whereas agricultural labourers lose their wages as their entire wages depends on their

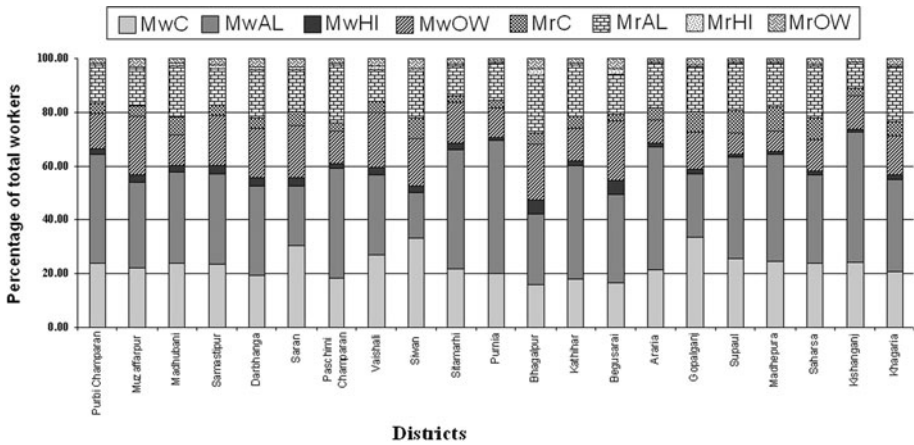


Fig. 5 Bar diagram showing the percentage distribution among the total workers in each district of northern Bihar plains. It clearly shows that majority of worker belong to main worker and marginal worker as agricultural labourers and cultivators, whereas minor percentage is represented by worker in other categories (abbreviation used in the figure: MWC stands for main workers as cultivators, MwAL for main workers as agricultural labourers, MwHI for main workers in household industry, MwOW for main workers as other workers, MrC for marginal workers as cultivators, MrAL for marginal workers as agricultural labourers, MrHI for marginal worker in household industry, MrOW for marginal workers as other workers)

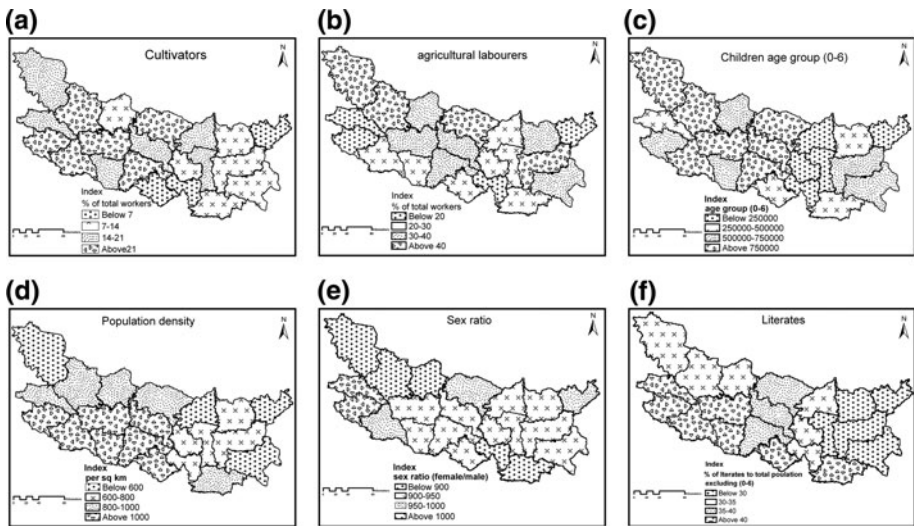


Fig. 6 District-level maps of socio-economic indicators of flood-waterlogging vulnerability **a** percentage of cultivators **b** percentage of agricultural labourers **c** children in age group 0–6 years **d** population density **e** sex ratio (female/male) **f** literates

number of working days towards crop production, failure of crops and subsequent disruption of transport network due to flooding made them jobless and homeless. As majority of agricultural labourer comes from other district areas and made their families prone to ill effects of flood induced disasters. It is evaluated that the average agricultural labourer

including main and marginal workers among various districts in northern Bihar is 51% (Fig. 6b).

2. Children in age group of 0–6 years: The children in this age group are directly affected by these hazards due to their negligible coping capabilities during hazard and their survival during postdisaster events. Average children in age group of 0–6 years among various districts in northern Bihar are 5,30,337 (Fig. 6c).

4. Population density: Population density defines number of persons per sq km. From a human or economic perspective, the degree of calamity associated with a disaster will depend on the population density of the affected area. Disasters with similar severity will affect more people if they occur in a highly populated area compared to less populated area. Average population density among various districts in northern Bihar is 983 persons per sq km (Fig. 6d).

5. Sex Ratio: It represents number of women to number of men in an area. Vulnerability and coping capacity are closely linked. Women and men are differently affected by disasters. Women generally have lower access to all forms of capital and are therefore more vulnerable to disasters than men. It has been shown in widely diverse populations that women are most at risk when disaster unfolds, whether it is a drought (Vaughan 1987) or a cyclone (Ikeda 1995). As flood occur during monsoon in the northern Bihar which coincide with the Kharif crop season, a number of men working as agricultural labourer left their native place for need of wages to other agricultural areas in neighbouring district and states. The woman who left the house, therefore become vulnerable to flood events. Also during floods, the disruption of telecommunication and transport network made their escape to safer places more difficult. Average sex ratio among various districts in northern Bihar is 925 (Fig. 6e).

6. Literates: It represents the number of literates in an area. As literacy help in understanding the nature of hazard, its severity and their response to the morning just before and soon after the event struck a place issued by disaster management authorities, areas with high percentage of literates can be treated as region with higher coping ability regions. Average population percentage of literates among various districts in northern Bihar is 33% (Fig. 6f).

For each of the above six socio-economic indicators, four classes of vulnerability viz; low, medium, high and very high were defined, corresponding to the lowest to the highest values of their percentage in each category. Equal interval classification is used to derive these four classes. A composite vulnerability map is generated by integrating the district-level thematic maps of said socio-economic indicators. For this purpose, each vulnerability class of an indicator is assigned a numerical rating within a scale of 1–4 according to their vulnerability. For all the indicators, classes with higher vulnerability are given higher ratings and vice versa. The composite flood-waterlogging vulnerability index of the integrated layers is calculated by using the following formula:

$$HVI = PD_r + MFR_r + AL_r + CV_r + CAG_r + LR_r / \text{number of indicators} \quad (2)$$

where PD_r is the ratings assigned to population density; MFR_r ; is the ratings assigned to female-to-male ratio; AL_r ; is the ratings assigned to percentage population of agricultural labourers; CV_r ; ratings assigned to percentage population of cultivators; CAG_r ; ratings assigned to population of children in age group 0–6 years; LR_r ; ratings assigned to percentage population of literates.

The composite vulnerability map was classified into 4 classes indicating prone to socio-economic vulnerability as low, medium, high and very high (Fig. 7). The natural break

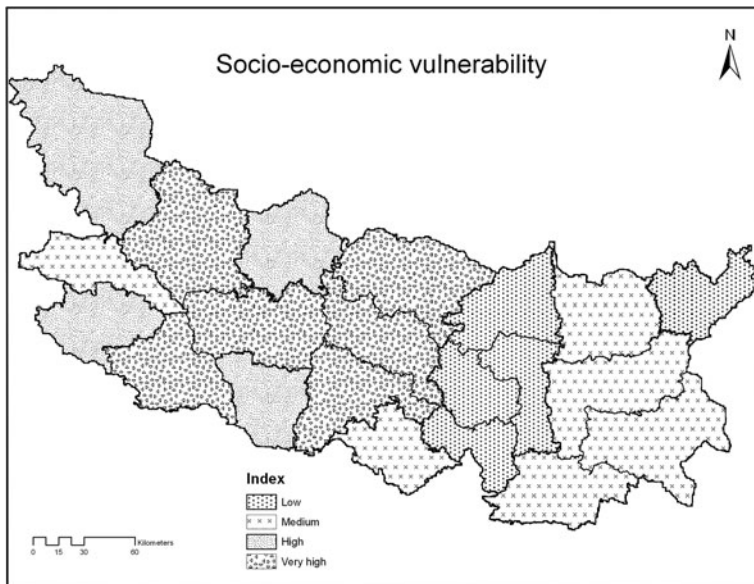


Fig. 7 Composite district socio-economic vulnerability map of study area

method was used to derive these classes. This method creates range according to an algorithm that uses the average of each range to distribute the data more evenly across the ranges. This method ensures that the ranges are well represented by their averages, and that the data values within each range are fairly close together (Smith 1986). Arc GIS is used to identify the natural break points in the data.

It is clear from Fig. 7 that high and very high vulnerability areas exist in the north west and central parts of state, whereas medium and low vulnerability area lies in the north east and eastern part of the area.

4.5 Flood and waterlogging risk assessment

Risk is the probability of harmful consequences, or expected losses resulting from interactions between hazards and vulnerable conditions (Blaikie et al. 1994; Downing and Bakker 2000; Wilhite 2000). Therefore, a conceptual approach to risk assessment can be broken down into a combination of the hazard and vulnerability. Similar to other natural hazard risks, flood and waterlogging risk depends on a combination of the physical nature of flood and waterlogging severity and its interaction with a population or vulnerability. To study the risk of flood and waterlogging hazards, it is essential to study the severity, and spatial extent of these hazards as well as the socioeconomic ability of the region to anticipate and cope with the hazards.

In the present study, the geohazard map derived by integration of waterlogging and flood affected regions was used along with the socio-economic vulnerability map to deduce the flood-waterlogging risk pattern at district level using the product relation between hazard and vulnerability given by (Blaikie et al. 1994; Downing and Bakker 2000; Wilhite 2000).

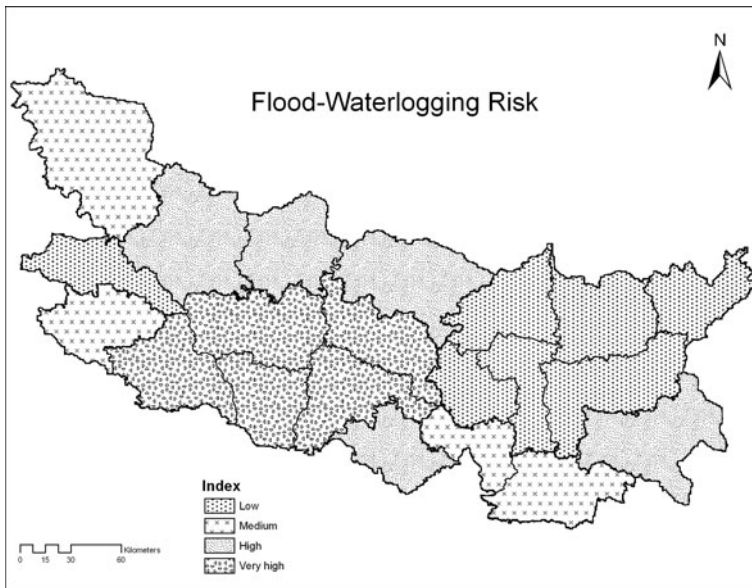


Fig. 8 Flood-waterlogging risk map of the study area

Table 2 Area statistics of flood-waterlogging risk class in the study area

Flood-waterlogging risk class	Area (sq km)	% of study area
Low	15,889	28.44
Medium	11,515	20.61
High	15,432	27.63
Very high	13,024	23.32

$$FWRI = (GHI) \times (HVI)$$

where GHI in this model represents the district-level geohazard vulnerability index; HVI represents the district socio-economic vulnerability map index. Due to the product relationship, if there is no chance for the hazard or there is no socio-economic vulnerability, the flood waterlogging risk for that location is zero.

The risk map prepared based on said model (Fig. 8) indicates very high (23.32%) and high (27.63%) flood-waterlogging risk in the central parts of the state. The western, north-western parts come under medium (20.61%)-risk zone, whereas eastern parts mainly come under low-(28.44%) risk zone (Table 2).

5 Conclusion

The present study was taken up to examine the flood and waterlogging risk in the northern Bihar plains. It indicates very high and high risk in the central parts of the study area, whereas the western, north-western regions come under medium risk, and eastern parts

mainly come under low-risk zone. About 50.95% of the total study area comes under high- and very high-risk zone, whereas 20.61, 28.44% falls under medium- and low-risk zone. The higher risk areas correspond to both high hazard and high vulnerability which are highly prone to flood and waterlogging hazards and at the same time highly vulnerable to these hazards from socio-economic point of view. There was an increase by fifty per cent in the waterlogging areas during the period from 1975 to 2008. The total area under flood inundation during the period 1998–2008 was comprised of 62% of the study area indicating high vulnerability of the region towards flood and subsequent waterlogging. The main causes of floods in the Gangetic plains are inadequate capacity within river banks to contain high flows, river bank erosion and silting of river beds (Rakesh et al. 2005). The excess water with high sediment flux released in during monsoon periods therefore causes extensive floods in Gangetic plains.

In India, the analysis of seasonal and annual air temperatures, using the data for 1881–1997 has shown a warming trend of 0.57°C per 100 years (Pant and Kumar 1997). Substantial increases in greenhouse gases are likely in the future as a consequence of which global mean surface temperature is expected to increase by between 1.4 and 3°C for low emission scenarios and between 2.5 and 5.8°C for high-emission scenarios by 2100 with reference to 1990 (Houghton et al. 2001). The changing climatic conditions with more intense rainfall predicted in future (Singh and Sontakke 2002) can trigger more sediment flux in the upper catchment which can change the pattern of floods and subsequent waterlogging in this region.

In view of the existing status of combined risk posed by flood and waterlogging together and increasing demands of water for agriculture, a holistic, well-planned long-term strategy is needed for sustainable water resources management in this part of Gangetic plains. Any planning for regulating the flood water discharge should be done after proper evaluation of micro relief as well as subsurface hydrological regimes in the northern Gangetic plains of Bihar. Implementation of mitigation measures to contain flood and waterlogging hazards would require participation of all stakeholders, particularly the local population and government. Since the physiographic and geohydrologic setting of northern Bihar plains has wide similarity to other parts of the Gangetic plains, the methodology presented in the present study can be applied to other regions.

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