Nat Hazards (2008) 46:391–413
DOI 10.1007/s11069-007-9191-5

ORIGINAL PAPER

Drought risk assessment in the western part of Bangladesh

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Received: 25 April 2007 / Accepted: 30 October 2007 / Published online: 28 February 2008

Abstract Though drought is a recurrent phenomenon in Bangladesh, very little attention has been so far paid to the mitigation and preparedness of droughts. This article presents a method for spatial assessment of drought risk in Bangladesh. A conceptual framework, which emphasizes the combined role of hazard and vulnerability in defining risk, is used for the study. Standardized precipitation index method in a GIS environment is used to map the spatial extents of drought hazards in different time steps. The key social and physical factors that define drought vulnerability in the context of Bangladesh are identified and corresponding thematic maps in district level are prepared. Composite drought vulnerability map is developed through the integration of those thematic maps. The risk is computed as the product of the hazard and vulnerability. The result shows that droughts pose highest risk to the northern and northwestern districts of Bangladesh.

Keywords Bangladesh · Drought · Hazard · Vulnerability · Risk · GIS

1 Introduction

Bangladesh is one of the most disaster-prone countries in the world. Almost every year, the country experiences disasters of one kind or another, such as tropical cyclones, storm surges, coastal erosion, floods, and droughts, causing heavy loss of life and property and jeopardizing the development activities (Ali 1996). Bangladesh is also one of the most densely populated countries in the world. With over 940 people per square km, it has a per capita income only about US$ 235. Over 40% of the population of the country live in poverty. High spatial and temporal climatic variability, extreme weather events, high population density, high incidence of poverty and social inequity, poor institutional capacity, inadequate financial resources, and poor infrastructure have made Bangladesh highly vulnerable to disaster (Ahmed 2004).

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Drought is a recurrent phenomenon in some parts of Bangladesh. Since its independence in 1971, Bangladesh has suffered from nine droughts of major magnitude (Paul 1998). Despite the recurrent and devastating nature of droughts in Bangladesh, it has attracted far less scientific attention than floods or cyclones (Alexander 1995; Brammer 1987). However, losses from drought are likely to be more severe than from floods in Bangladesh. An analysis of the relative effects of flood and drought on rice production between 1969–1970 and 1983–1984 indicates that drought is more devastating than floods to aggregate production (World Bank Bangladesh 1998). The drought of 1994–1995 led to a decrease in rice and wheat production of 3.5×10^6 t (Rahman and Biswas 1995). This necessitated the import of some 140,000 t of food grain between July 1994 and March 1995. An additional 200,000 t of rice was imported to offset the shortage in national stocks and meet the national demand on an emergency basis (Biswas 1995).

On the global level, impact of natural hazards and disasters are staggering. In Bangladesh, the major natural hazards are also in line with global patterns. In the context of global warming, most of the climatic models project a decrease in precipitation in dry season and an increase during monsoon in south Asia (Christensen et al. 2007). This will cause a cruel combination of more extreme floods and droughts in the region. Due to the land use changes within the country and in neighboring country, Bangladesh has already shown an increased frequency of droughts in recent years (National Drought Mitigation Center 2006). Concern among scientists has grown on changes of precipitation and frequent occurrence of droughts in Bangladesh. Therefore, drought hazards, vulnerability, and risk assessment is essential for implementing mitigation to reduce drought impact in Bangladesh.

A number of studies have been carried out on the impact of droughts on agriculture (Karim et al. 1990; Jabber 1990; Jabber et al. 1982; Saleh et al. 2000; Mazid et al. 2005), food production (Ahmed and Bernard 1989; Ericksen et al. 1993), land degradation (Rasheed 1998; Karim and Iqbal 2001; Government of Bangladesh 2005), economy (Erickson et al. 1993; World Bank Bangladesh 2000), and society (Erickson et al. 1993; Paul 1998) in Bangladesh. The first agricultural drought risk map of Bangladesh was prepared by Karim et al. (1990) by considering the cumulative effect of dry days, higher temperatures during pre-monsoon period and soil moisture availability. WARPO-EGIC (1996) prepared maps of winter and pre-monsoon drought prone areas of Bangladesh using the agroecological zones database and land resources inventory map at 1:1,000,000 scale. Karim and Iqbal (2001) reviewed the concept of WARPO-EGIC (1996) and produced three different drought risk maps for winter, pre-monsoon, and monsoon seasons. They defined drought risk classes as slight, moderate, severe, and very severe related to the yield losses of 15–20%, 20–35%, 35–45%, and 45–70%, respectively, for different crops. No standard drought index method has been used for the assessment of droughts in Bangladesh. Furthermore, no study has been carried out so far to identify the geographic distribution of human vulnerability to drought. The aim of the present study is to characterize the spatial and temporal pattern of drought hazards, identify the vulnerability of various geographic populations to the impact of droughts and mapping drought risk zones of west Bangladesh.

The Standardized Precipitation Index (SPI) method (McKee et al. 1993) has been used for the identification of drought hazard pattern in Bangladesh. Vulnerability of population to droughts has been identified from various socio-economic and physical/structural indicators. The Blaikie et al. (1994) approach in which risk is defined as the product of hazard and vulnerability has been used to identify drought risk pattern. Natural hazards, disasters and risk are essentially geographical in nature (Cutter 1993; Hewitt 1999). Drought risk analysis requires assimilation of physical and socio-economic information from many sites each with a unique geographic location. GIS maintains the spatial location of sampling points or area, and provide tools to relate the sampling data contained through a relational database (Shahid et al. 2000). Therefore, GIS has been used in this study to induce levels of drought risk through the analysis of spatially distributed hydro-meteorological and socio-economic data.

In the next section of the article, methods used for the analysis of drought risk in the western part of Bangladesh have been discussed. Factors that define drought vulnerability in Bangladesh are also identified. This is followed by the results and discussion section, where spatial distribution of drought hazard, vulnerability and risk in western parts of Bangladesh has been discussed.

2 Hydro-climatic condition of Bangladesh

Geographically, Bangladesh extends from 20°34′ N to 26°38′ N latitude and from 88°01′ E to 92°41′ E longitude. Climatically, the country belongs to sub-tropical region where monsoon weather prevails throughout the year. The average temperature of the country ranges from 17 to 20.6°C during winter and 26.9 to 31.1°C during summer. Three distinct seasons can be recognized in Bangladesh from climatic point of view: (i) the dry winter season from November to February, (ii) the pre-monsoon hot summer season from March to May, and (iii) the rainy monsoon season which lasts from June to October (Rashid 1991).

The average annual rainfall of the country varies from 1,329 mm in the northwest to 4,338 mm in the northeast (Shahid et al. 2005). The gradient of rainfall from west to east is approximately 9 mm/km. The western part of Bangladesh experiences an average areal rainfall of approximately 2,044 mm, which is much lower than other parts of the country. The rainfall is also very much seasonal, almost 77% of rainfall occurs during monsoon. In summer, the hottest days experience temperatures of about 45°C or even more in the region. Again in the winter the temperature even falls at 5°C in some places. Hence, the region experiences the two extremities that clearly contrasts with the climatic condition of rest of the country (Banglapedia 2003). The dryness index in the northwestern part of Bangladesh is close to that of a dry region (Shahid et al. 2005). The total annual evapotranspiration is also lower than or equal to annual rainfall in some places. Therefore, the climate of these regions of Bangladesh is sometimes defined as very close to dry. Drought risk assessment is carried out in the western part of Bangladesh. The extent of the study area in Bangladesh is shown in Fig. 1.

There have been changes in the flow of the Ganges River, which is one of the major rivers of Bangladesh, since the Farakka Barrage was made by India in 1975. Recent data suggests that the March flow of Ganges River is as much as 57% lower than in the pre-Farakka days (World Bank Bangladesh 1998). The flow starts decreasing in October and reaches its lowest point in February and March, which persists until June. Low river water flow in dry season caused a significant negative impact on river morphology, salinity, and ecosystems of the western part of Bangladesh. Decreased flow in regional rivers also affects existing traditional and low-lift pump irrigation as well as fisheries. Droughts, almost every year, along with the reduction in the discharge of major rivers, drying of water channels, and falling of groundwater tables due to over-exploitation exacerbates the crisis of water in the area during the dry season.

About 59% of the cultivated area in Bangladesh presently under irrigation and this is expected to increase in future. At the same time, demand for other uses of water is increasing along with population, urbanization, and economic development. A deficit of rainfall or drought causes severe impact on agriculture and economy of the country.

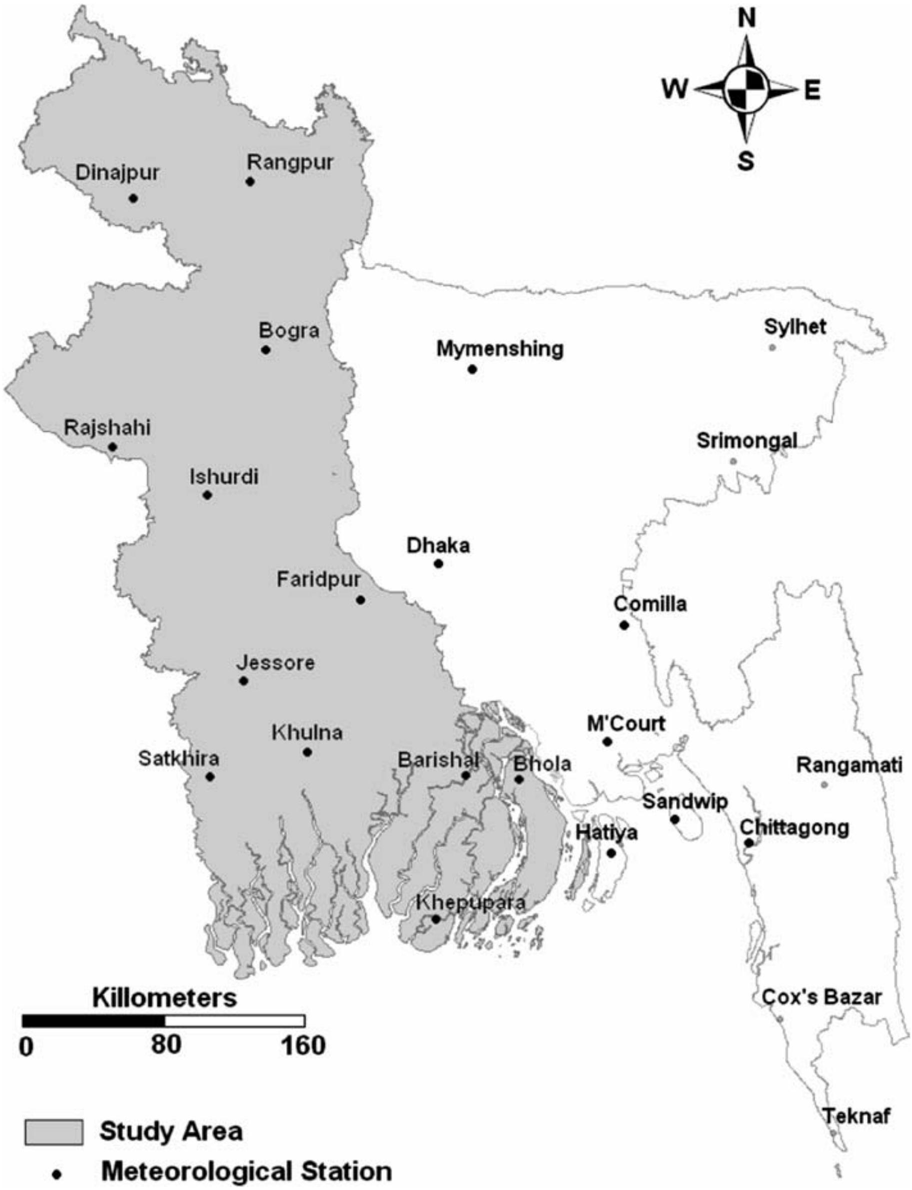

Fig. 1 The extent of the study area and the location of rain-gauge stations in Bangladesh

3 Methodology

Risk is the probability of harmful consequences, or expected losses resulting from interactions between hazards and vulnerable conditions. 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, drought risk depends on a combination of the physical nature of drought and the degree to which a population or activity is vulnerable to the effects of drought.

Therefore, to study the risk of drought, it is essential to study the frequency, severity, and spatial extent of drought as well as the infrastructural and socioeconomic ability of the region to anticipate and cope with the drought. In the present article the following steps are used to identify the drought risk pattern in the western part of Bangladesh.

1. Identify the drought hazard with regard to its spatial extends, frequency and severity.
2. Identify and quantify drought vulnerability, e.g., people, economy and structure exposed to the drought hazard.
3. Compute drought risk pattern from drought hazard and vulnerability.

A brief description of the methods and data used for drought risk assessments of western part of Bangladesh are given below.

4 Drought hazard assessment

In order to investigate the spatial and temporal extents and severity of drought occurrence in the study area, Standardized Precipitation Index (SPI) (Mckee et al. 1993) is used. SPI is a widely used drought index based on the probability of precipitation on multiple time scales. It has been demonstrated by several researches (McKee et al. 1995; Guttman 1998, 1999; Hayes et al. 1999) that the SPI is a good tool in detecting and monitoring the drought events. SPI provides a comparison of the precipitation over a specific period with the precipitation totals from the same period for all the years included in the historical record. In the present article, SPI for 3 and 6 months time steps are computed to study the characteristics of drought in short and medium range time scales. The 3 months SPI is used to describe the dry winter and pre-monsoon droughts, while the 6 months SPI is used to characterize seasonal droughts due to rainfall deficit in monsoon and non-monsoon months.

In order to compute SPI, historic rainfall data of each station are fitted to a gamma probability distribution function:

$$g(x) = \frac{1}{\beta^{\alpha}\Gamma(\alpha)}\chi^{\alpha-1}\mathrm{e}^{-x/\beta} \quad \text{for} \quad x > 0 \tag{1}$$

where $x > 0$ it is the amount of precipitation, $\alpha > 0$ is a shape parameter, $\beta > 0$ is a scale parameter, and $\Gamma(\alpha)$ defines the gamma function.

The maximum likelihood solutions are used to optimally estimate the gamma distribution parameters, α and β for each station and for each (3 and 6 months) time steps:

$$\alpha = \frac{1}{4A}\left(1 + \sqrt{1 + \frac{4A}{3}}\right) \tag{2}$$

$$\beta = \frac{\bar{x}}{\alpha} \tag{3}$$

where

$$A = \ln(\bar{x}) - \frac{\sum \ln(\bar{x})}{n} \tag{4}$$

n, number of precipitation observations.

This allows the rainfall distribution at the station to be effectively represented by a mathematical cumulative probability function as given by:

$$G(x) = \int_0^x g(x)\,\mathrm{d}x = \frac{1}{\beta^\alpha \Gamma(\alpha)} \int_0^x x^{\alpha-1} \mathrm{e}^{-x/\beta}\,\mathrm{d}x \tag{5}$$

since the gamma function is undefined for $x = 0$ and a precipitation distribution may contain zeros, the cumulative probability becomes:

$$H(x) = q + (1 - q)G(x) \tag{6}$$

where q is the probability of a zero. The cumulative probability $H(x)$ is then transformed to the standard normal distribution to yield the SPI (McKee et al. 1993).

As the precipitation rate is fitted to a gamma distribution for different time scales for each month of the year, the resulting function represents the cumulative probability of a rainfall event for a station for a given month of the dataset and at different time scale of interest. This allows establishing classification values for SPI. McKee et al. (1993) classified drought severity according to SPI values as given in Table 1. An SPI of 2 or more means that a very severe drought happens about 2.3% of the time or has a return period of 50 years, SPI between −1.5 and −1.99 means severe drought happens about 4.4% of the time or has a return period of 25 years, and SPI between −1.0 and −1.49 means moderate drought happens about 9.2% of the time or has a return period of 10 years. Detail of the SPI algorithm can be found in Guttman (1998, 1999), McKee et al. (1993; 1995) and Hayes et al. (1999).

The area vulnerable to drought at different time scales is identified on the basis on their percentage of occurrences. The percentage of drought occurrence is computed by taking ratio of drought occurrences in each time step to the total drought occurrences in the same time step and drought category (Sonmez et al. 2005). For the mapping of spatial extents of rainfall and droughts from point data kriging interpolation method is used. Geostatistical analysis tool of ArcMap 9.1 (Environmental System Research Institute 2004) is used for this purpose. Kriging is a stochastic interpolation method (Journel and Huijbregts 1981; Isaaks and Srivastava 1989), which is widely recognized as standard approach for surface interpolation based on scalar measurements at different points. Kriging attempts to express trend in data, so that, ‘‘high points might be connected along a ridge, rather than isolated by bull’s-eye type contours’’ (Sonmez et al. 2005). Study showed that Kriging gives better global predictions than other methods (Oliver and Webster 1990; Zimmerman et al. 1999; van Beers and Kleijnen 2004).

Moderate, severe and very severe drought maps of 3 and 6 months time steps are prepared and then integrated separately to prepare the drought hazard maps at 3 and 6 months time periods. Each drought severity theme is given a particular weight and each

Table 1 Drought categories defined for SPI values

SPI value	Drought category	Probability of occurrence (%)
0 to −0.99	Near normal or mild drought	34.1
−1.00 to −1.49	Moderate drought	9.2
−1.50 to −1.99	Severe drought	4.4
−2.00 and less	Extreme drought	2.3

feature of the theme is given a rating to compute drought severity of the integrated layer. The weights and ratings used for integration are given in Table 2. Drought hazard index (DHI) of integrated layer is calculated as:

$$\mathrm{DHI} = (\mathrm{MD_r} \times \mathrm{MD_w}) + (\mathrm{SD_r} \times \mathrm{SD_w}) + (\mathrm{VSD_r} \times \mathrm{VSD_w}) \quad (7)$$

where, MD_r, ratings assigned to moderate droughts occurrence classes; MD_w, weight given to the theme of moderate drought occurrence theme; SD_r, ratings assigned to severe droughts occurrence classes; SD_w, weight given to the theme of severe drought occurrence theme; VSD_r, ratings assigned to very severe droughts occurrence classes; VSD_w, weight given to the theme of very severe drought occurrence theme

The resulting drought hazard maps are then overlaid on the district map of western Bangladesh to produce the district scale drought hazard maps. Region Wide Overlay or "Cookie Cutter Approach" is used for this purpose. The region wide, or "cookie cutter," approach to overlay analysis allows natural features, such as hazard boundaries or soil polygons, to become the spatial areas which will be analyzed on another map (Institute of Water Research 1996). GIS is used to overlay drought hazards dataset onto the district map and then calculate the area-weighted average DHI for each individual district.

5 Drought vulnerability assessment

The concepts and definitions of vulnerability have been analyzed 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 are 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 human settlements, infrastructure, public policy and administration, organizational abilities, social inequalities, gender relations, economic patterns, etc.

Drought vulnerability is different for different individuals and nations. In developing countries, drought vulnerability constitutes a threat to livelihoods, the ability to maintain productive systems, and economies. In developed economies, drought poses significant

Table 2 Weights and ratings assigned to drought severity themes and features of the themes, respectively

Drought severity	Weight	Percentage of occurrences	Rating
Moderate	1	≤9.0	1
		9.1–10.0	2
		10.1–11.0	3
		≥11.1	4
Severe	2	≤3.5	1
		3.6–4.5	2
		4.6–5.5	3
		≥5.6	4
Very severe	3	≤1.5	1
		1.6–2.0	2
		2.1–2.5	3
		≥2.6	4

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 drought vulnerability index should take into account of ecological, socio-economic and production conditions. However, all the indicators according to the above definition are not readily obtainable and/or quantifiable for Bangladesh. After careful consideration of obtainable/quantifiable socio-economic and physical indicators, four individual socio-economic and three physical/structural indicators are identified as important and pertinent to this study and are subsequently selected to represent the vulnerability of various geographic populations to the impact of droughts. The socio-economic indicators are population density, female to male ratio, percentage of people living below poverty level, and percentage of people depending on agriculture. Three physical/structural indicators are percentage of irrigated land, soil moisture holding capacity and food production per unit area. The assumptions regarding vulnerability to each indicator are explained below:
Socio-economic indicators:

1. Population density: Population density defines number of persons per km^2. From a human or economic perspective, the degree of calamity associated with a disaster will be associated with 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.
2. Female to male 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).
3. Poverty level: In the present study, poverty level represents percentage of people living below the lower poverty line in an area. Vulnerability is a combination of characteristics of a person or group, which derives from the social and economic condition of the individual, family, or community concerned (Blaikie et al. 1994). Therefore, there is a direct and absolute correlation between poverty and vulnerability. As a rule, the poor suffer more from hazards than the rich (Yodmani 2001). In context of Bangladesh, a poor community is not only economically vulnerable but at the same time they have lack of social, cultural and political capacities to cope with disasters.
4. Agricultural occupation: This represents percentage of people depending on agriculture, including farmers and agricultural workers. More than 75% of the people of Bangladesh depend of agriculture. It has been mentioned earlier that agriculture is the most affected sector by drought in Bangladesh. Farmers fail to plant or get less production due to droughts.

Physical/infrastructural factors:

5. Irrigated land: It represents percentage of irrigated land to total land. In Bangladesh about 59% cultivated lands are under irrigation. About 75% water for irrigation comes from groundwater and the rest comes from surface water (Bari and Anwar 2000). Surface and groundwater availability is directly related to meteorological drought.

A deficit of rainfall lowers the groundwater table as well as river water level and makes irrigation costly or sometimes impossible.

6. Soil water holding capacity: It defines the difference in water content between field capacity and permanent wilting point. The soil root zone water-holding capacity is a significant agricultural drought vulnerability factor (Wilheilmi and Wilhite 2002). This property of soil defines its ability to buffer crops during periods of deficient moisture. The geographic pattern of soil water holding capacity is important for studying water stress in plants and critical to water management planning for irrigation (Kern 1995; Klocke and Hergert 1990).
7. Food production: It represents the amount of food produced in metric ton per square kilometer. Droughts in higher food productive area will have higher negative impact on economy compared to lower food productive area. In Bangladesh, 46% of croplands are multiple-cropped and the rest are single cropped. Multiple cropped lands produced more food compared to single-cropped lands.

For each of the above seven indicators four classes were selected, ranging from the lowest to the highest values. The natural break method is used to derive the 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). GIS software ArcView 9.0 is used to identify the natural break points in the data.

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 0–1 according to their values. For all the indicators except soil water holding capacity, classes with higher values are given higher ratings and the classes with lower values are assigned with lower ratings. For soil water holding capacity indicator, classes with higher values are given lower ratings and classes with lower values are given higher ratings as land with low water holding capacity is more vulnerable to drought compared to that of high water holding capacity. The composite drought vulnerability index (DVI) of the integrated layers is calculated by using the following formula:

$$\mathrm{DVI} = \frac{\mathrm{PD_r} + \mathrm{FMR_r} + \mathrm{PL_r} + \mathrm{AO_r} + \mathrm{IL_r} + \mathrm{SWHC_r} + \mathrm{FP_r}}{\text{Number of indicators}} \tag{8}$$

where, $\mathrm{PD_r}$, ratings assigned to population density classes; $\mathrm{FMR_r}$, ratings assigned to female to male ratio classes; $\mathrm{PL_r}$, ratings assigned to poverty level classes; $\mathrm{AO_r}$, ratings assigned to agricultural occupation classes; $\mathrm{IL_r}$, ratings assigned to irrigated land classes; $\mathrm{WRHC_r}$, ratings assigned to soil water holding capacity classes; $\mathrm{FP_r}$, ratings assigned to food production per land unit classes

6 Drought risk assessment

Risk patterns were mapped using the formula (Blaikie et al. 1994; Downing and Bakker 2000; Wilhite 2000),

$$\mathrm{DRI} = \mathrm{DHI} \times \mathrm{DVI} \tag{9}$$

where, DRI is the drought risk index.

DHI in this model represents the probability of occurrence of droughts; DVI represents the broadest concept of drought vulnerability in a region. Due to the product relationship, if there is no chance for the hazard or there is no vulnerability, the drought risk for that location is zero.

7 Data

Monthly rainfall data for the period of 1961–1999 from 12 rain-gauge stations of Bangladesh Meteorological Department (BMD) in the western part of Bangladesh is used for the mapping of spatial extents, severity and frequency of occurrence of droughts in the area. Location of BMD rain-gauge stations in Bangladesh are shown in Fig. 1. The main problem encountered during drought hazard study is the missing rainfall data. The missing of rainfall data is random in most of the stations, however, continuous missing for years is also evident in some stations. Percentage of missing rainfall data in different stations are given in Table 3.

A feed-forward artificial neural network (ANN) based approach similar to that proposed by Teegavarapu and Chandramouli (2005) is used for the estimation of missing rainfall data. The topology of ANN used for the estimation of missing rainfall data is 6:4:1. The topology is selected using a trial and error procedure. The input neurons use values from six neighboring stations around the station of interest and output neuron of the ANN provides the missing value at the station of interest. Historical rainfall data of 19 BMD rain-gauge stations (shown by black bold dot in Fig. 1) of Bangladesh are used for this purpose. The neural network training is done by using supervised back-propagation training algorithm (Haykin 1994).

The performance of ANN method is tested by applying it in estimating historic rainfall data at different rain-gauge stations situated in the western part of Bangladesh. Monthly mean rainfall data from January 1991 to December 1999 is used for this purpose. Root mean squared error (RMSE) given by equations is used to measure the efficiency of the method,

Table 3 Percentage of missing data and root mean squared error (RMSE) during validation of ANN at different stations

Station name	Percentage of missing data	RMSE (for percentage of training data)		
		60%	70%	80%
Barishal	6.2	1.78	1.44	1.06
Bhola	18.8	2.30	1.74	1.52
Bogra	6.2	1.92	1.42	1.09
Dinajpur	24.6	2.25	2.00	1.49
Faridpur	4.9	2.02	1.49	1.12
Ishurdi	17.7	1.71	1.28	0.94
Jessore	5.6	1.86	1.55	1.07
Khepupara	37.2	2.32	2.02	1.44
Khulna	20.9	1.96	1.51	1.03
Rajshahi	16.0	1.84	1.40	1.06
Rangpur	9.4	2.14	1.78	1.40
Satkhira	10.7	2.09	1.71	1.35

$$\mathrm{RMSE} = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(e-a)^2} \tag{10}$$

where n is the total number of observations, e is the estimated value and a is the actual value of the observation.

At first, approximately 60% of the historical data (January 1991–May 1996) are used to train ANN and the rest of the data (June 1996–December 1999) are used for validation. In the next step, the training data is increased to approximately 70% and 80% of the historical data. The iteration limits for ANN during training was kept to 500 for all the cases. The RMS errors during validation of the network at different stations are given in Table 3. The results show that the performance of the ANN-based method increases with the increase of percentage of training data. However, it is clear from the table that it is possible to estimate the missing rainfall data with reasonable error by training the ANN with only 60% of historic data. In the present study, 70% historic rainfall data is used for the training of ANN to estimate the missing rainfall data of all stations except Khepupara. Due to unavailability of data, 60% historic rainfall data is used for the estimation of missing data at Khepupara station.

In order to study the spatial distribution of drought vulnerability, population density, percentage of people depending on agriculture, and female to male ratio maps are prepared from Bangladesh national census data (Bangladesh Bureau of Statistics 2003). Poverty map is prepared from sub-district (Upazilla) level poverty map prepared jointly by Bangladesh Bureau of Statistics and United Nations World Food Programme (Bangladesh Bureau of Statistics and United Nations World Food Programme 2004). Maps of percentage of irrigated land and food production per land unit are prepared from Bangladesh agricultural census data (Bangladesh Bureau of Statistics 2002). Soil moisture holding capacity map is prepared from digital soil map at 1:25,000 scale given in Bangladesh Country Almanac (Bangladesh Country Almanac 2004).

8 Result and discussion

The study produced the maps of drought hazards at 3 and 6 months time steps, map of composite drought vulnerability and maps of drought risk in the western part of Bangladesh. Analysis of drought hazards, vulnerability and risk in Bangladesh are discussed below.

8.1 Drought hazard maps

Drought hazards in the western part of Bangladesh have been investigated based on frequency of the events for each drought category at 3 and 6 months time steps. SPI time series at 3 and 6 months time steps at different stations are given in Figs. 2 and 3, respectively. Percentage of drought occurrence at different stations at 3 and 6 months time steps for varying drought severity categories is calculated from SPI time series. The spatial extent of percentage of drought occurrences of moderate, severe, and very severe categories for 3 and 6 months time steps are shown in Figs. 4 and 5 respectively.

The spatial distribution of moderate droughts (Fig. 4a) indicates that they tend to occur more frequently in southeastern part at 3 months time step. The western and northern parts

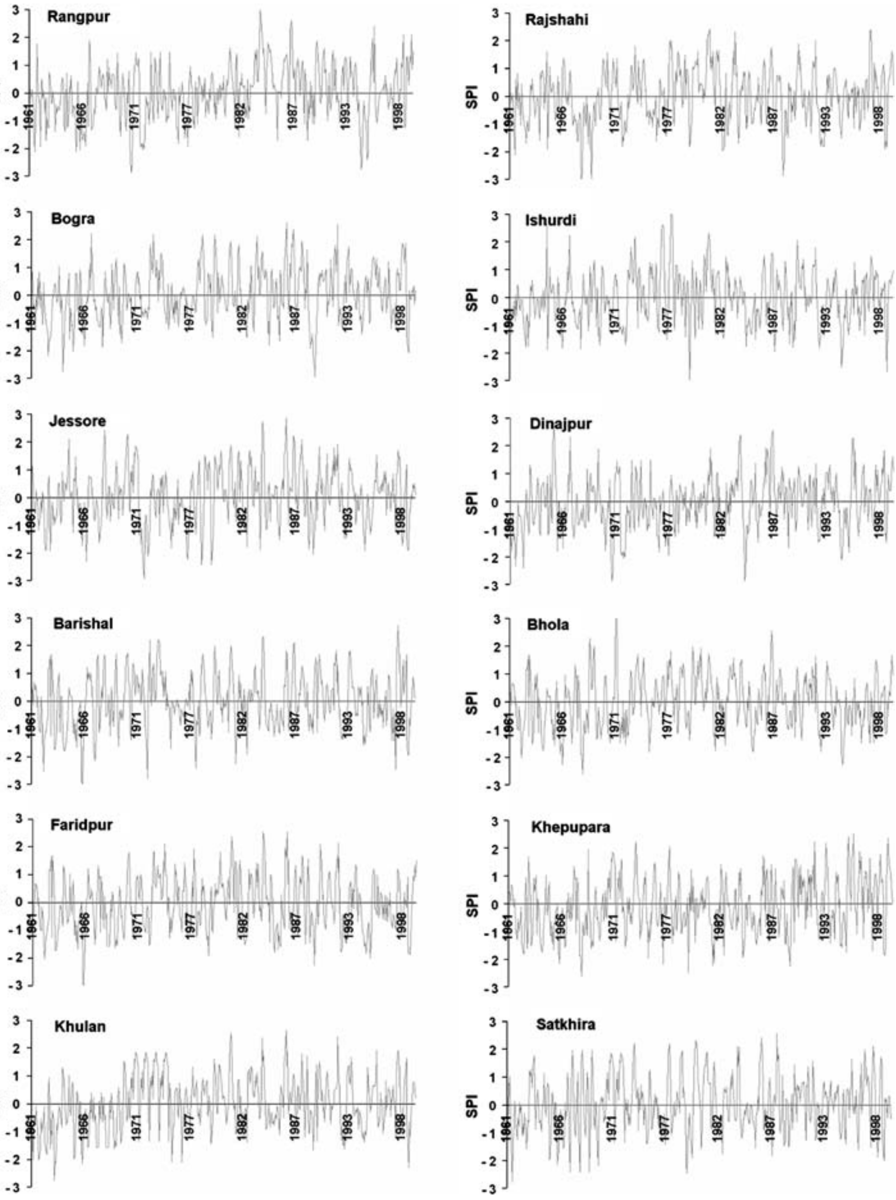

Fig. 2 SPI time series at different station at 3 months time step

experience moderate drought with lower frequencies at this time step. Distribution of severe droughts (Fig. 4b) shows a complete different pattern from moderate drought. The northwestern part of the area is found to be most prone for severe drought at 3 months time step. The central part of the area is found moderately prone and southern coastal part is found less prone for severe drought. Figure 4c shows that very severe droughts at 3 months time step occur in northern part of the area with high frequency and western part with moderate frequency and the central part with less frequency.

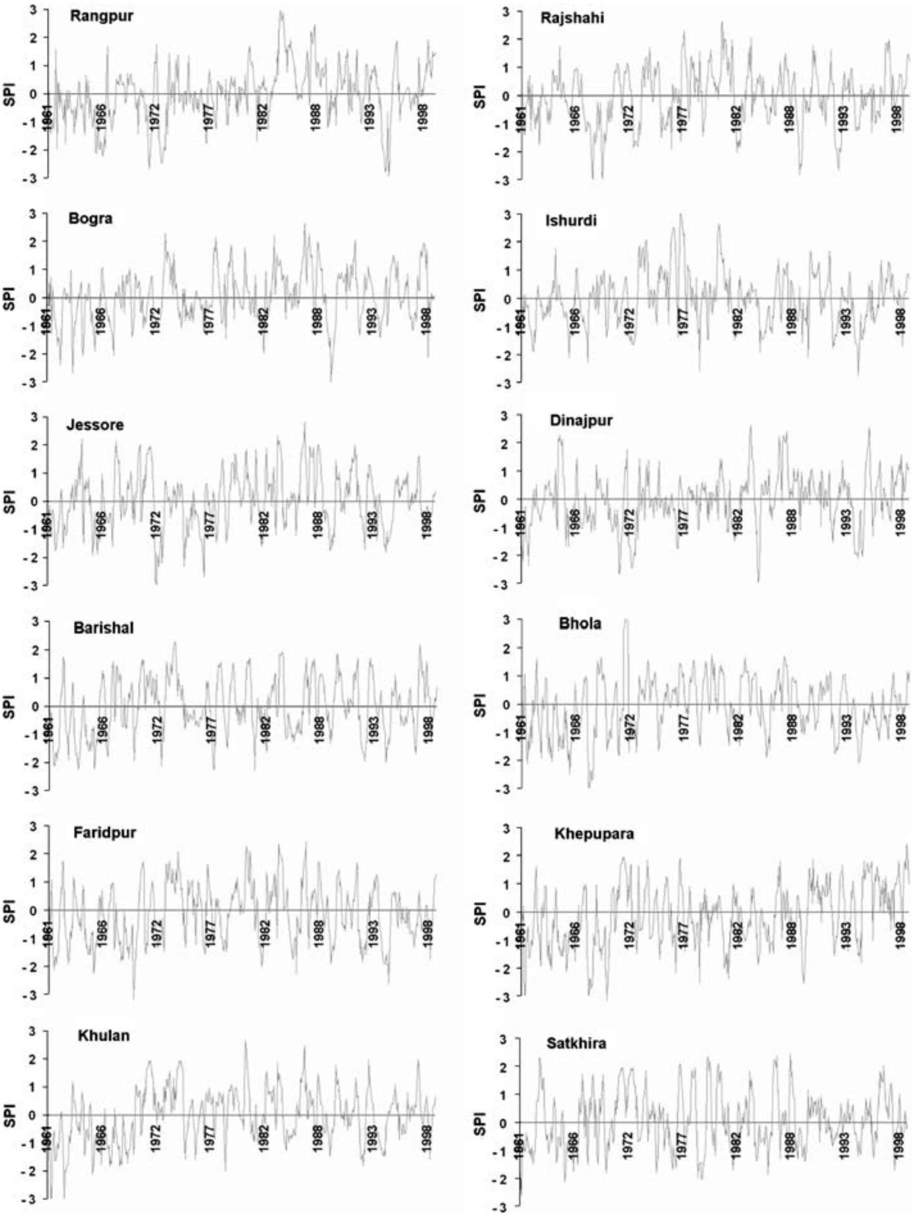

Fig. 3 SPI time series at different station at 6 months time step

As the time step increases to 6 months, moderate drought prone zone is found to shift to southwestern part of the area (Fig. 5a). The northern part is less prone for moderate drought at 6 months time-step compared to southern part. High occurrence of severe droughts is found to expand from northwestern to northern part at 6 months time step (Fig. 5b). Droughts of this category have less frequency in the southern coastal parts. A very severe drought is found to occur in the northern as well as in the northwestern parts

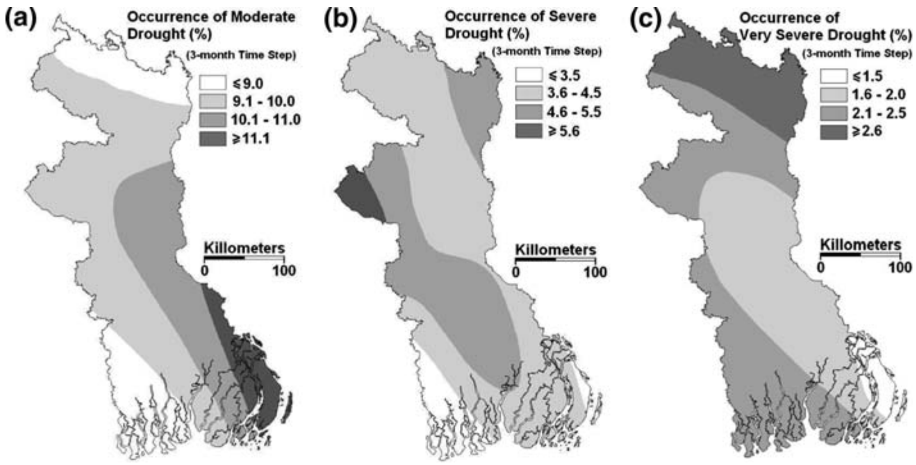

Fig. 4 Spatial extent of (**a**) moderate; (**b**) severe; and (**c**) very severe drought occurrences at 3 months time step

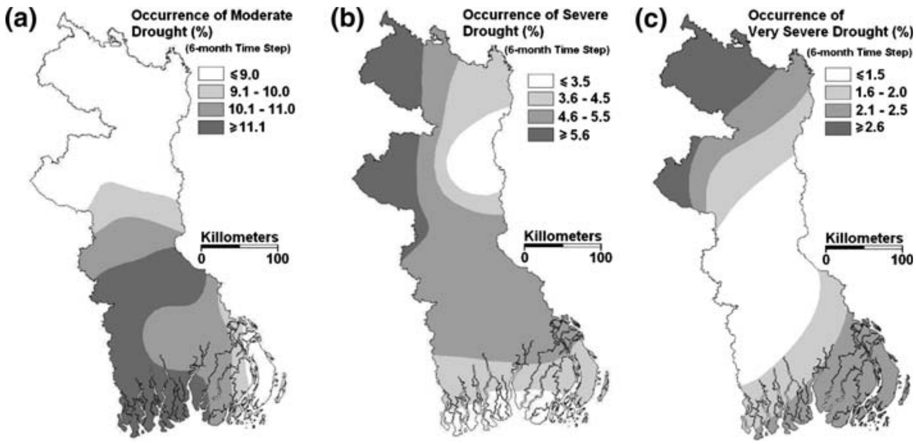

Fig. 5 Spatial extent of (**a**) moderate; (**b**) severe; and (**c**) very severe drought occurrences at 6 months time step

(Fig. 5c). The central part of the area is found less prone for 6 months very severe droughts.

The analysis of drought occurrences at different categories and time-steps indicates that northern and northwestern parts of the country are most prone to severe and very severe droughts. Moderate droughts occur more frequently in the southern part of the country. The central part of the study area is moderately prone for both moderate and severe droughts, but less prone for very severe droughts. There exists no relation between the droughts of short and longer time scales as well as among the severity classes of each time period. It has also been observed that there exists no relation between the rainfall distribution and drought potential zones. The northern region normally receives more than average rainfall of the study area, but the area is highly prone to drought.

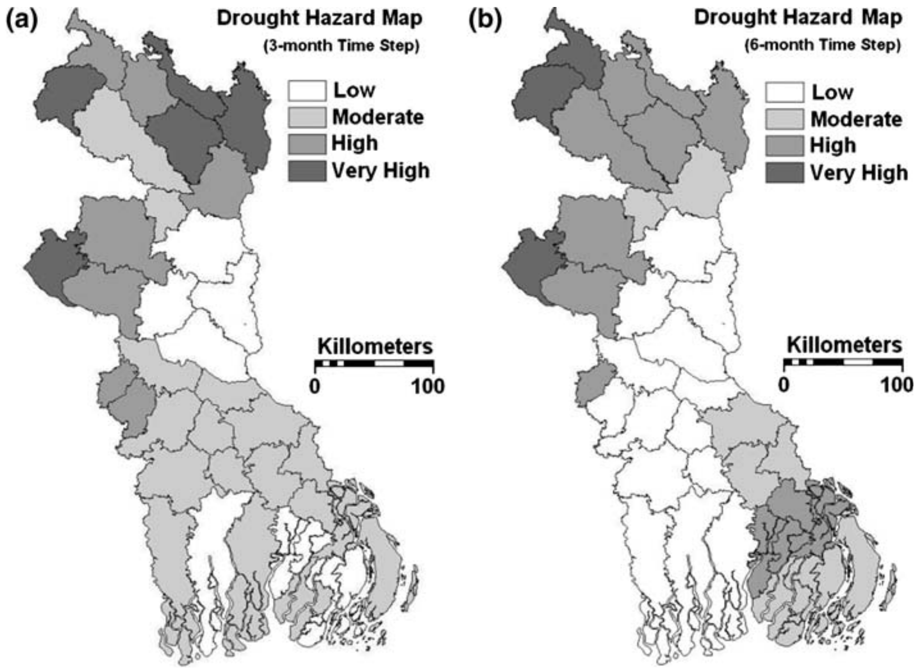

Fig. 6 District level drought hazard maps at (**a**) 3 months, (**b**) 6 months time steps

Moderate, severe, and very severe drought maps of each time periods are integrated by using Eq. 7 and the integrated layer is overlaid on the district map to compute the district average DHI. Finally, the districts are classified according to their DHI values into four classes using natural break method to produce the district scale drought hazard maps at 3 and 6 months time steps as shown in Fig. 6a, b respectively.

From the district level drought hazard maps at 3 and 6 months time steps the study area can be separated into two broad drought hazard zones: high to very high drought hazard zone in the northern, northwestern and central western parts and low to moderate drought hazard zone in the southern and central eastern parts. There is a general notion that Barind Tract, largest Pleistocene physiographic unit of the Bengal basin that covers most parts of the northern and northwestern Bangladesh, is prone to drought (Banglapedia 2003). The drought hazard map obtained in the present study validates the conception. The higher occurrence of droughts in the northwestern part of the country is due to high annual variability of rainfall in the region. For instance, the rainfall recorded in northwestern part of the area in 1981 was about 1,738 mm, but in 1992 it was about 798 mm only (Banglapedia 2003).

8.2 Vulnerability maps

District level maps of socio-economic drought vulnerability indicators viz. population density, female to male ratio, poverty level, and percentage of people depending on agriculture are shown in Fig. 7a–d respectively. The physical/structural maps of drought

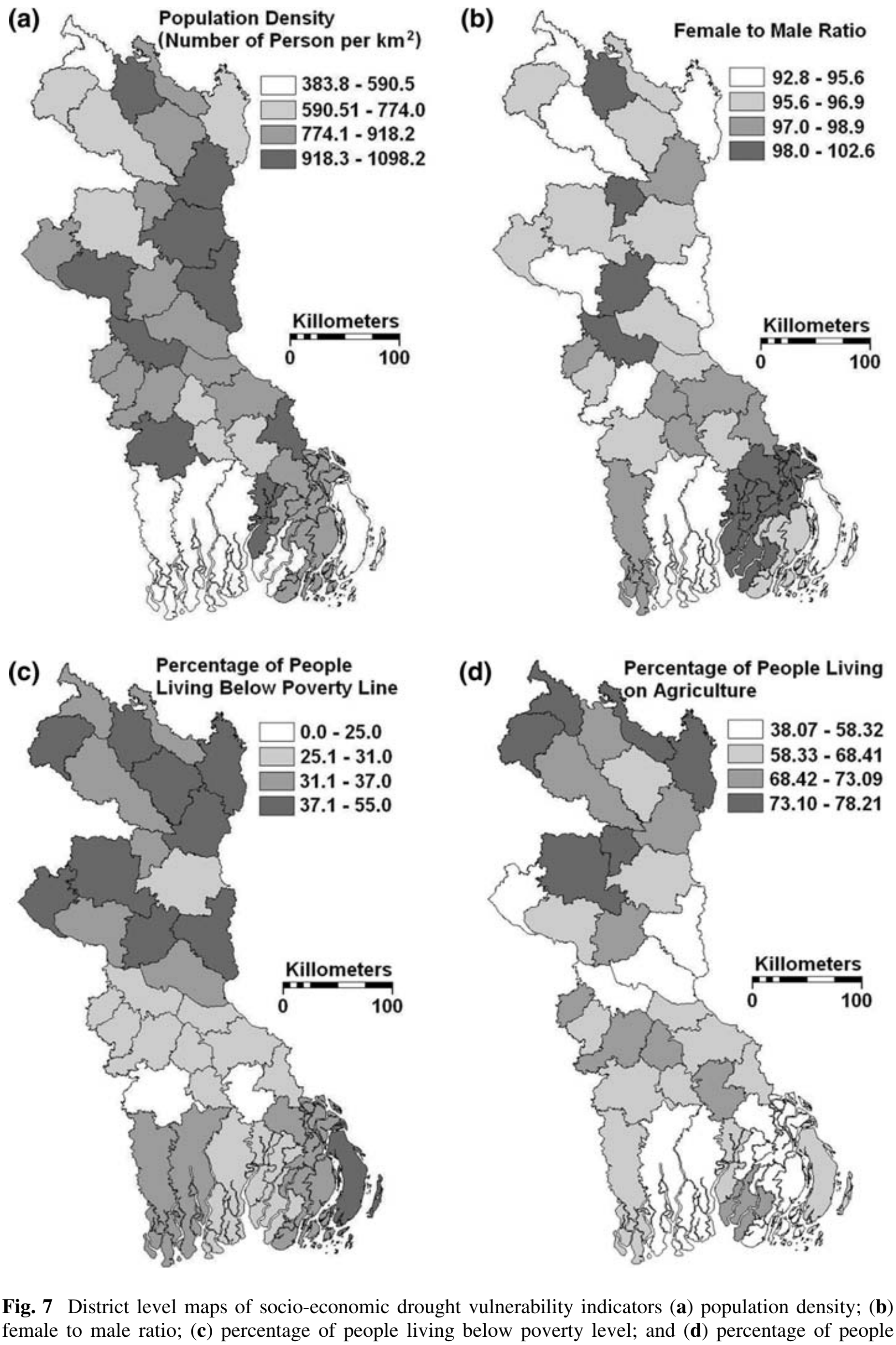

Fig. 7 District level maps of socio-economic drought vulnerability indicators (**a**) population density; (**b**) female to male ratio; (**c**) percentage of people living below poverty level; and (**d**) percentage of people depending on agriculture

vulnerability indicators viz. percentage of irrigated land, soil moisture holding capacity and food production per unit area are shown in Fig. 8a–c respectively.

All the vulnerability indication maps are integrated using Eq. 8 and the district of the integrated layer is classified according to DVI values into four classes using the natural break method to produce the composite drought vulnerability map of west Bangladesh as shown in Fig. 9. From the pattern of vulnerability to drought in the western part of Bangladesh, the study area can be separated into three vulnerable zones: low vulnerability in the southern parts, moderate vulnerability in the central parts and high to very high vulnerability in the northern parts. The highest vulnerabilities are concentrated in the northern and northwestern part of the country where poverty rate is comparatively high, more than 70% of the people depend only on agriculture and a high percentage of land is under irrigation.

8.3 Drought risk maps

Drought hazard and drought vulnerability maps are integrated using GIS to produce the drought risk map of west Bangladesh. The DRI of each district of the integrated layer is calculated using Eq. 9. The districts of the integrated layer are then classified according to DRI values into four classes using natural break method to produces the risk maps of drought hazards at 3 and 6 months time steps as shown in Fig. 10a, b respectively.

Figure 10a shows that 3 months droughts pose highest risk to some northern and northwestern districts of Bangladesh. Few districts in the central part of the study area are exposed to moderate risk. The coastal zone and the central-east part of the area face less risk to droughts of this category. The pattern of 6 months drought risk is more or less similar to 3 months drought. Figure 10b shows that high risk zone of 6 months drought is concentrated in the northern and northwestern side of the country. Few districts in the southern side of the study area are also found moderately risky to drought of this category. Droughts of 6 months time period poses less risk to the coastal and central districts of the study area.

Percentage of area under different drought risk categories in western part of Bangladesh is given in Table 4. The table shows that 21.9% of the area is exposed to very high risk, 12.7% of the area to high risk, and 30.4% of the area to moderate risk at 3 months time period droughts. On the other hand, 18.9% of the area is exposed to very high risk, 13% of the area to high risk, and 19.7% of the area to moderate risk of droughts at 6 months time period.

High poverty rates, dependency on agriculture and irrigation alone with high variability of annual rainfall has made the northern and northwestern parts highly risky to droughts compared to other parts of the country. Poverty alleviation and water conservation are essential reduce the drought impact in the area.

9 Conclusions and recommendations

A study has been carried out to investigate the extent and impact of droughts in the western part of Bangladesh. The higher risk areas are found where both high hazard and high vulnerability coincide. The districts with extremely high risk are concentrated in the northern and northwestern parts of the area which are highly prone to drought hazard and at the same time highly vulnerable to droughts from socio-economic and infrastructural point

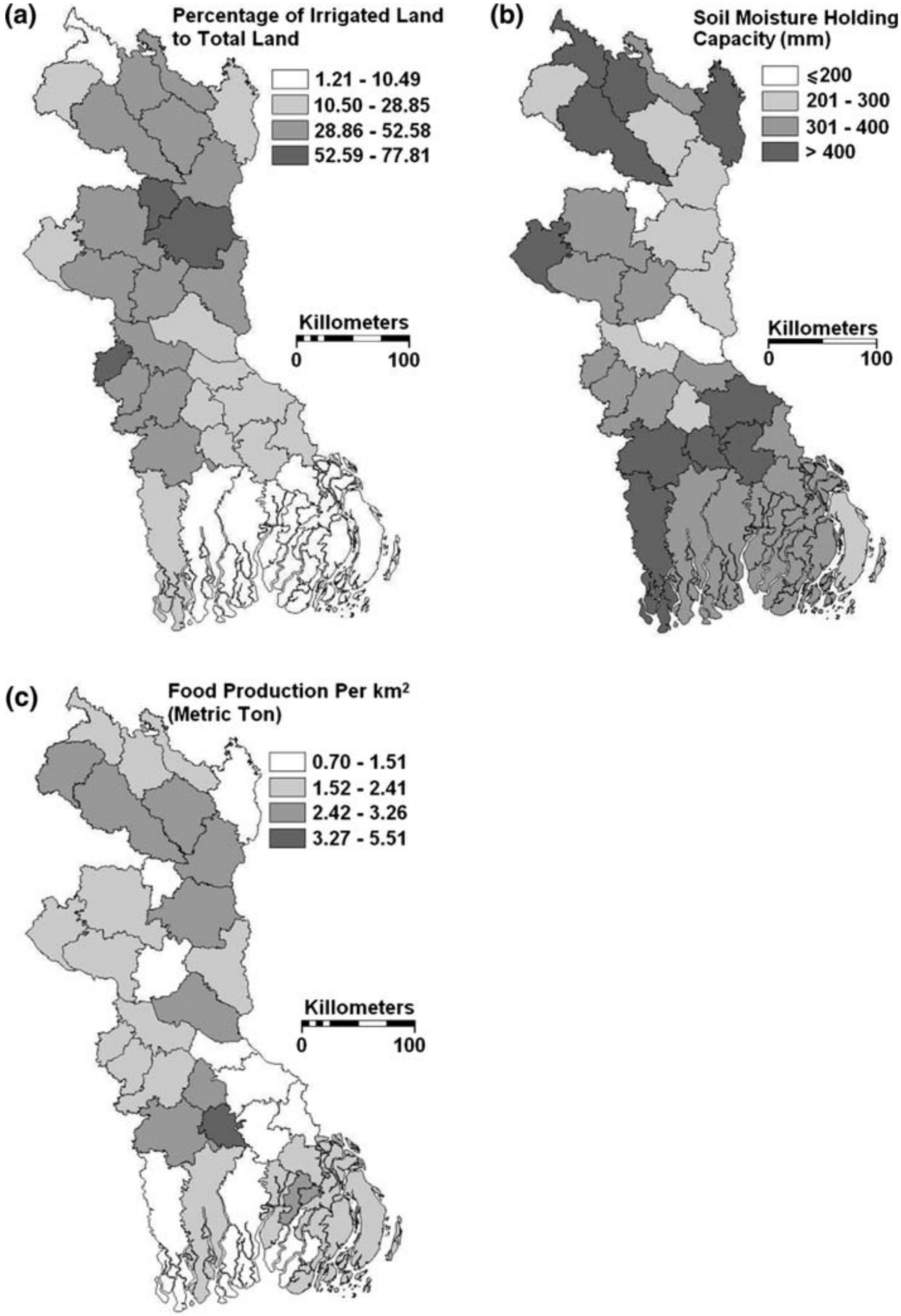

Fig. 8 District level maps of Physical/structural drought vulnerability indicators (**a**) irrigated land; (**b**) soil moisture holding capacity; and (**c**) food production per unit area

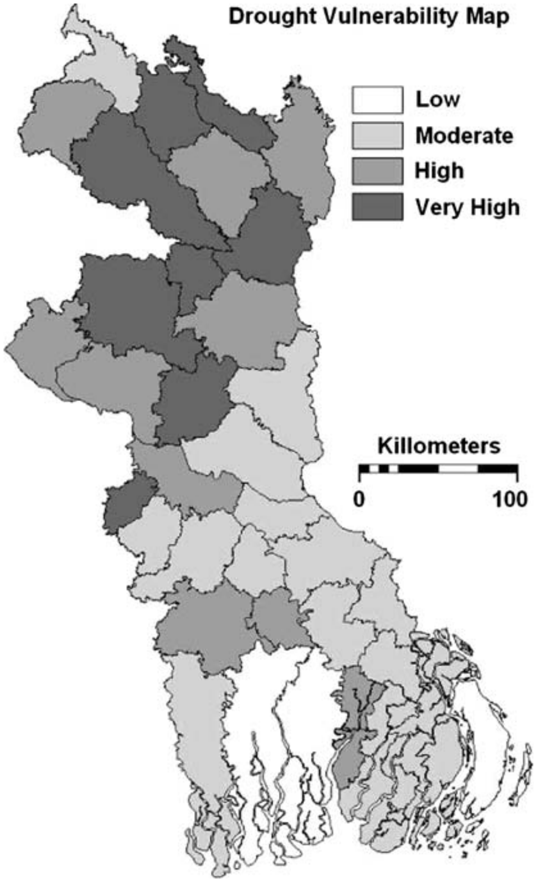

Fig. 9 Composite drought vulnerability map of west Bangladesh

of view. The areas of highest hazard correspond very well, in general, with the areas that are usually thought as drought prone and have records of high levels of agricultural damage due to droughts. Vulnerability study shows that higher poverty rates, dependency on agriculture and irrigation have made the northern and northwestern part of the country more vulnerable to droughts compared to other parts of the country. Better water and crop management, augmentation of water supplies with other sources, increased public awareness and education, intensified watershed and local planning, and water conservation is necessary in the northwestern and northern Bangladesh for drought impact mitigation.

One of the aspects of global climate change scenarios in Bangladesh is the increase frequency and severity of droughts. As it is not possible to change the natural course of events, concerted action at a political and institutional level would most certainly help to build capacity and reduce people's vulnerability to drought impacts. A major outcome of the study is the production of a drought hazard/risk map of the western part of Bangladesh. It is hoped the study will be beneficial to a number of stakeholders in the country, particularly disaster management, but also the agricultural organizations, development/planning authorities, educational authorities and risk insurers to improve their understanding on drought impacts on the western part of Bangladesh. As the assessment of risk is one of the main aspects of drought mitigation and planning, it is hoped that these maps and the study in general will assist in guiding the operational responses of the various

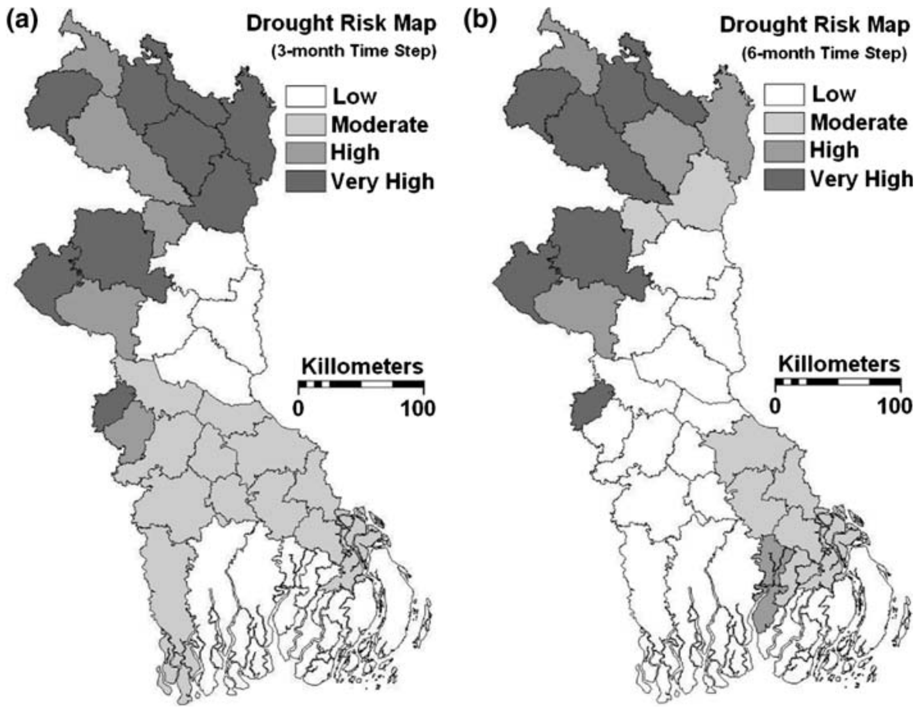

Fig. 10 Risk maps of droughts at (**a**) 3 months, (**b**) 6 months time periods

Table 4 Percentage of area under different drought risk categories in West Bangladesh

Drought period (months)	Percentage of area (%)			
	Very high	High	Moderate	Low
3	21.9	12.7	30.4	35
6	18.9	13	19.7	48.4

authorities, especially in terms of those interventions aimed at disaster risk reduction in Bangladesh.

Acknowledgment This work was supported by a grant from the Alexander von Humboldt foundation to S. Shahid. Authors thank anonymous reviewers for their constructive and helpful feedback on the manuscript.

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