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Parametric Assessment of Pre-Monsoon Agricultural Water Scarcity in Bangladesh

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Abstract: This study assesses the geographical distribution of agricultural water scarcity in Bangladesh in order to streamline the adaptation measures. The agricultural water scarcity was assumed to be a system with five subsystems, namely, groundwater depth, surface water availability, rainfall availability, groundwater salinity for irrigation, and surface water salinity for irrigation. The catastrophe-theory-based multi-criteria decision making approach was used for the estimation of agricultural water scarcity index from five subsystem indices. The obtained results showed that agriculture in about 6.3% of the area of the country is experiencing very high-risk water scarcity, 19.1% with high water scarcity, 37.2% with moderate water risk, and the rest is low or no risk of water scarcity for agriculture. Results showed that the western part of Bangladesh was more vulnerable to agricultural water scarcity. The analysis of the results showed that higher agriculture water scarcity in the northwest region resulted from water unavailability, and in the southwest region it was closely related to poor water quality. The severe areas of water scarcity are very similar to those that are usually regarded as water-scarce. The approach presented in this study can be used for rapid but fair assessment of water scarcity with readily available data, which can be further improved by incorporating other factors related to water scarcity.

Keywords: water scarcity; catastrophe theory; standardized precipitation index; salinity; streamflow; groundwater; pre-monsoon; Bangladesh

1. Introduction

Growing water demand due to population growth, economic development, and declining water supply have caused water scarcity in many countries across the world [1]. It has been reported that approximately 36% or 2.4 billion of the global population are already living under water stress [2]. The global water demand will continue to grow with population growth and economic development [3]. The world's population will be 9.6 billion in 2050 [4], and 70% more food will be required to feed this growing population [5]. A rapid growth in agricultural activities for supplemental food production will cause 55% increase in global water demand by 2050 [6]. The greatest increases will be observed in the developing countries that are already experiencing water stress conditions [3]. This will make water resources scarcer in the developing regions, especially those are located in Asia [7].

South Asia, inhabited by around 30% of the world population, is declared as a water-scarce region [7]. It has been reported that water security is becoming an important issue in South Asia due to rapid socio-economic development [8]. The Economic and Social Commission for Asia and the Pacific (ESCAP) [9] identified India, Pakistan, Maldives, Nepal, and Bangladesh as water hotspots in the region. Bangladesh, with a population of 156 million over a small land area, is highly dependent on irrigated agriculture [10]. Recently, Vörösmarty et al. [11], based on a multi-factorial water security index, showed very high (0.8–1) water scarcity threat over Bangladesh on a threat scale of 0 (no apparent threat) to 1 (extremely threatened).

Several droughts indices have been developed to assess water stress in terms of quantitative availability of water resources. Those indices are widely used for estimation of meteorological droughts or deficit of rainfall, such as the Standardized Precipitation Index [12], Standardized Precipitation Evapotranspiration Index [13], etc.; hydrological droughts or inadequacy in surface and subsurface water resources, such as the Surface Water Supply Index [14], Streamflow Drought Index [15], etc.; and agricultural droughts or lack of sufficient soil moisture required for crop growth, such as the crop moisture index [16] and the Soil Wetness Deficit Index [17], etc. Besides those, aggregate drought indices based on all physical forms of drought (meteorological, hydrological, and agricultural), such as the Aggregate dryness Index [18], Nonlinear Aggregate Drought Index [19], etc., have been developed and used for the assessment of droughts and water scarcity. However, water scarcity does not only depend on physical availability of water resources, but also the quality of water. This is particularly true for the region where water quality is not sufficient for irrigation. Few studies have been conducted to assess water scarcity during different cropping seasons using drought indices [20,21]. All those studies were unable to depict the spatial distribution of agriculture water scarcity of Bangladesh due to ignorance of water quality and groundwater depth.

Water scarcity in Bangladesh is a recent phenomenon resulting from the geography, climate change, and socio-domestic status of the region [10]. Moreover, high demand and insufficient availability of water for irrigation, intervention in Trans Boundary Rivers, unreliable rainfall, and salinity intrusion in coastal rivers, particularly during the pre-monsoon (March to May), cause seasonal water scarcity [22]. Additionally, the country is also considered as one of the most vulnerable countries in the world to climate change [23]. The country often experiences extreme floods [24], cyclones [25], storm surges [26], and droughts. Thus, a comprehensive assessment of present situation for agricultural water scarcity during the pre-monsoon season is important in order to propose necessary adaptation measures for sustainability of water resources.

Agricultural water scarcity assessment is a multi-attribute comprehensive assessment system that encompasses different dimensions such as water availability, water quality, water accessibility, etc., which need to be clearly addressed using appropriate indices. In the past, several water scarcity assessment indices were developed and applied, including the Falkenmarker indicator [27], water resources vulnerability index [28], water poverty index [29], watershed sustainability index [30], etc. Although these indices have been successfully implemented in some regions, they are not fully applicable to other regions [31]. Additionally, these indices need the judgment of decision makers to assign weights for obtaining the relative importance of one indicator over the other [32]. The weight assigned by decision makers reflects the personal preference for a specific region or purpose, which eventually precludes their global application.

Therefore, this study used the catastrophe theory to assign weights to different indicators. The proposed method avoids the direct involvement of decision makers and draws the weights by its inner mechanism [32]. This study aims to assess agricultural water scarcity in Bangladesh using the catastrophe theory by considering availability and quality of water resources during the pre-monsoon crop growing season. The possible changes in agricultural water scarcity due to climate change were also assessed through literature reviews. Finally, the ongoing adaptation measures were evaluated for streamlining.

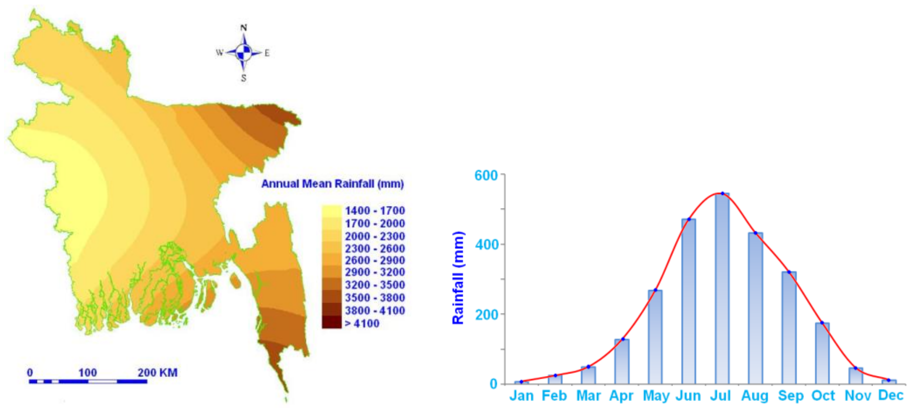
2. Study Area

Bangladesh covers an area of 144,000 km^2, located on deltas of three mighty rivers of Asia, namely, Ganges, Brahmaputra, and Meghna. Geographically, it is situated between latitude 20°34′ N and 26°38′ N, and longitude 88°01′ E and 92°41′ E. The topography of the country is very flat with some highlands in the southeast and the northeast. Elevation of about 80% of the land of the country lies between 0 and 100 m.

2.1. Climate

Bangladesh has a monsoon-dominated tropical humid climate with periodic rain variation, moderately warm temperatures, and high humidity. The climate of Bangladesh can be classified into four seasons: (i) hot pre-monsoon summer (March to May); (ii) hot, humid, and rainy monsoon (June to September); (iii) post-monsoon (October–November); and (iv) dry winter (December to February) [33]. The annual average rainfall varies from about 1500 mm in the northwest to more than 4200 mm in the northeast. Seasonal variation of rainfall is also very high. The spatial and seasonal rainfall variations are shown in Figure 1. About 75% of the total rainfall occurs during the monsoon. Only 10% of the total rainfall occurs during the pre-monsoon, and it is also very unreliable. The climate of pre-monsoon season is governed by the occurrence of thunderstorms. Warm moisture air in the low level and cold air in the high level provide favorable conditions for convections, causing thunderstorms. Thunderstorms bring rainfall ranges from 150 mm in the west-central part to more than 800 mm in the northeast [34].

The hottest month of the country is April, and the coolest is January. In April, the maximum temperature rise is 41 °C, and in January, for most of the country the average temperature at nighttime goes down to 10 °C. The seasonal variation in average temperature is shown in Figure 2. Low rainfall and high temperature make water resources in Bangladesh often scarce during pre-monsoon.



(**a**) (**b**)

Figure 1. (**a**) Spatial and (**b**) monthly distribution of rainfall in Bangladesh.

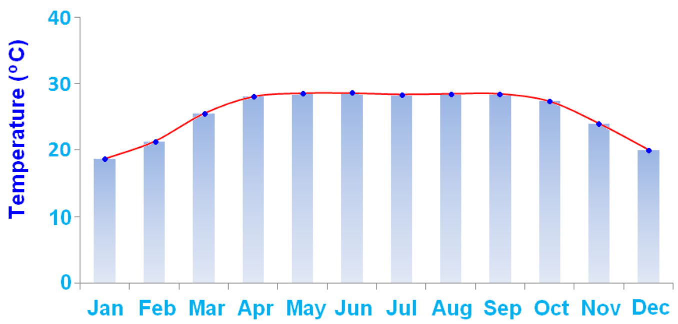


Figure 2. Monthly distribution of average temperature in Bangladesh.

2.2. Agriculture

Agriculture is one of the prime producing parts of the economy of Bangladesh, which contributes 21% to the national Gross Domestic Product (GDP) and provides 66% labor supply for employment. About 57.4% of the total land area is utilized for cultivation [34]. Rice productivity is the most significant source for economy of the country. There are three prime seasons of cultivation in Bangladesh, namely, pre-monsoon (pre-Kharif), monsoon (Kharif), and winter (Rabi). Boro is the main rice variety predominantly grown in the pre-monsoon season. Boro rice is cultivated in 80% of the total cultivable land and contributes 55% of the total rice production in Bangladesh [35]. Boro rice is cultivated under an irrigation scheme, and due to unavailability of surface water during pre-monsoon, mainly groundwater is used for irrigating Boro rice field.

2.3. Water Stress

The irrigation water-wells in Bangladesh has grown by more than ten-fold in last two decades (Figure 3). The huge withdrawal of groundwater for irrigation has caused overdraft and gradual declination of groundwater level. Groundwater level in some parts of the country goes below the operating range of shallow tube-wells during the irrigation period.

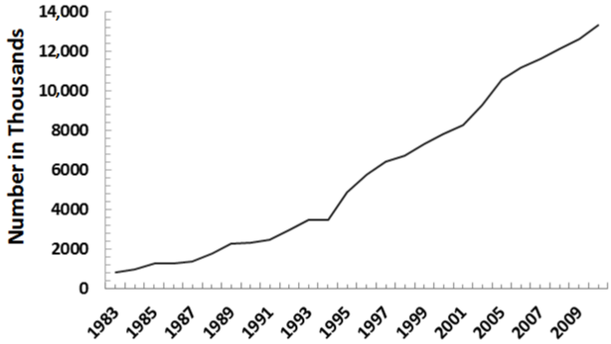


Figure 3. Increasing number of groundwater wells in Bangladesh over the time period 1983–2010 [36].

Salinity in streamflow and groundwater is another major factor of water scarcity in Bangladesh. Reduction of freshwater flow from rivers and improper management of groundwater has caused sea water intrusion of coastal aquifers [37]. Seasonal salinity of groundwater in the year 2004 in the coastal region is shown in Figure 4. Groundwater salinity in some parts in the coastal regions has reached beyond the tolerance level of crops, especially during pre-monsoon, and made the resources completely unsuitable for irrigation. It is anticipated that the situation will certainly be worsening in near future due to sea level rise induced by climate change.

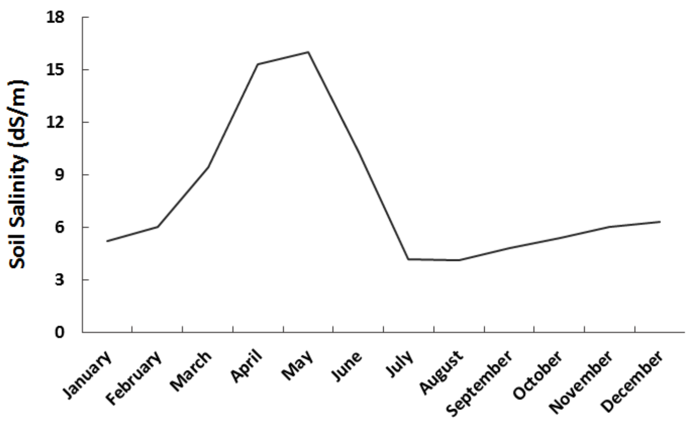


Figure 4. Seasonal variability of groundwater salinity (2004) in southwest Bangladesh [38].

3. Methodology

3.1. Framework of This Study

Water scarcity in agriculture is directly related to both water availability and water quality. Water sources in Bangladesh include surface water, including rainfall and river water, and groundwater.

Therefore, the agricultural water scarcity in Bangladesh during the pre-monsoon season was evaluated from groundwater availability (average depth of groundwater), available rainfall, river water availability, groundwater salinity for irrigation, and surface water salinity for irrigation. Following steps were used to quantify the agricultural water scarcity:

1. Standardized precipitation index (SPI; [12]) during the pre-monsoon season was estimated from the long-term monthly rainfall record to assess the spatial distribution of the return periods of meteorological droughts. Rainfall was considered less available in the area with lower return period of meteorological drought and vice versa.
2. Spatial distribution of groundwater depth was estimated by interpolating the average groundwater depth during the pre-monsoon season to measure the availability of groundwater resources.
3. The ratio of low lift pump (LLP) used for surface water irrigation to groundwater abstraction wells was used as a proxy indicator to measure the contribution of surface water in irrigation during the pre-monsoon season.
4. Spatial distribution of groundwater salinity for irrigation was calculated by interpolating the groundwater salinity data.
5. The surface water salinity map prepared by Soil Resource Development Institute (SRDI) and was used to assess the spatial distribution of surface water salinity for irrigation.
6. All the maps described in steps 1 to 5 were assigned weights using the catastrophe theory.
7. Finally, all the maps were integrated into the map of agriculture water scarcity.

3.2. Data and Sources

Rainfall data from 30 rain-gauge stations for the period 1961–2010 was obtained from Bangladesh Meteorological Department (BMD). Bi-monthly groundwater depth data of 503 groundwater monitoring wells for the time period 1996–2009 was obtained from Bangladesh Water Development Board. Therefore, this time period of rainfall and groundwater data were selected for the analysis. Groundwater salinity data were collected from the Public Health Engineering Department of Bangladesh (PHEDB). Surface water salinity map was collected from SRDI. The agricultural statistics data were collected from Bangladesh Bureau of Statistics. Locations of rain gauges and groundwater monitoring stations are shown in Figure 5.

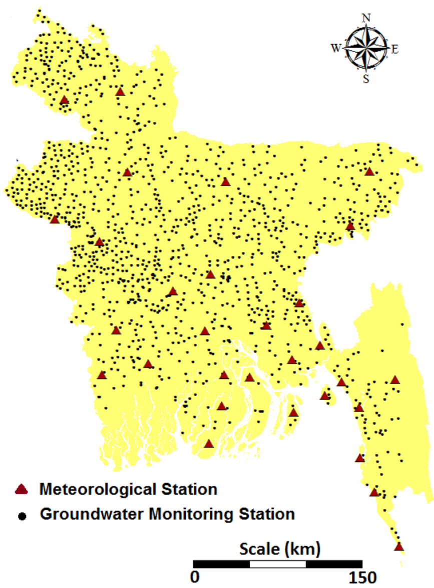


Figure 5. Location of rain gauges and groundwater monitoring stations in Bangladesh.

3.3. Standardized Precipitation Index (SPI)

SPI can be used for year-to-year comparison of rainfall over a specific period, and therefore it facilitates the temporal analysis of rainfall deficit. To compute SPI, rainfall data for a time scale are fitted to a probability distribution function. The resulting function represents the cumulative probability of a rainfall event for a given time scale. In the present study, three-month SPI in the month of May was calculated to identify the rainfall deficit over the pre-monsoon season (March to May). In general, SPI was classified to identify the rainfall deficit or dry events: extreme dry (SPI < -2.0), severe dry (SPI < -1.5), moderate dry (SPI < -1.0), and normal (SPI > -1.0).

3.4. Catastrophe Theory

The catastrophe progression method based on catastrophe theory [39] was used for the estimation of agricultural water scarcity from different subsystem indicators. In the catastrophe progression method, the state of a system is described by the state variable (agricultural water scarcity) and control parameters (subsystem indicators). The influence of control variables on the state variable is estimated using catastrophe fuzzy membership function instead of user's preferences. The procedure used for the estimation of agricultural water stress using the catastrophe progression method is outlined below:

1. The agricultural water stress depends on number of factors, depending on geographical context of a region. Therefore, agricultural water stress system is divided into number of subsystems each consist of an evaluation indicator system.
2. The catastrophe model for the indicator system is determined based on the levels of which the evaluation indicators are decomposed. For example, the butterfly catastrophe model is used when an evaluation indicator is decomposed into four levels.
3. A standardized method is used to convert the indicator values to dimensionless numbers in the range of 0 to 1 in order to remove the influence of range and units of different indicators.
4. The catastrophe model is used to estimate the value of fuzzy membership function for standardized evaluation indicator values.
5. The process is repeated to fuzzy membership function values of all indicators.
6. The average of standardized indicator values is estimated as the weight of each control variable on state variable considering complementarity principle, which means the control variables can compensate each other.

There are seven catastrophe models, namely, fold, cusp, dovetail, butterfly, swallowtail, hyperbolic umbilical, and parabola umbilical catastrophe models, as shown in Table 1, where x is state variable, and *a*, *b*, *c*, and *d* are control parameters.

Table 1. Seven types of catastrophe models [39].

Catastrophe Model	Control Parameters	State Variables	Potential Function
Fold	1	1	$V_a(x) = 1/3x^3 + ax$
Cusp	2	1	$V_{ab}(x) = 1/4x^4 + 1/2ax^2 + bx$
Dovetail	3	1	$V_{abc}(x) = 1/5x^5 + 1/3ax^3 + 1/2bx^2 + cx$
Butterfly	4	1	$V_{abcd}(x) = 1/6x^6 + 1/4ax^4 + 1/3bx^3 + 1/2cx^2 + dx$
Oval umbilici point	3	2	$V_{abc}(x, y) = x^3 - xy^2 + a(x^2 + y^2) + bx + cy$
Elliptic umbilici point	3	2	$V_{abc}(x, y) = x^3 - xy^2 + a(x^2 + y^2) + bx + cy$
Parabolic umbilici point	4	2	$V_{abc}(x, y) = x^2y + y^4 + ax^2 + by^2 + cx + dy$

For the assessment of water scarcity, it is considered that water scarcity is consisted of a number of subsystems. Each subsystem is consisted of a number of indicators. The catastrophe model type for a subsystem was determined according to the number of indicators of the subsystem. The appropriate catastrophe model was used to normalize the data of each indicator of a subsystem to get the fuzzy membership function of the subsystem. Details of the estimation of fuzzy membership functions for different subsystems of water scarcity are discussed below.

3.4.1. Selection of Indicators

The selection of indicators mainly depends on the objective of study and availability of the data [32]. Practically, the availability of data is a major constraint in the selection of indicators. Thus, in the present study indicators were selected based on the availability of data. The details of the indicators in subsystems and their scarcity levels are shown in Table 2.

Table 2 shows that pre-monsoon drought, groundwater depth, groundwater salinity, surface water availability, and surface water salinity are the subsystems of agricultural water scarcity. Groundwater depth characterizes the groundwater storage and provides indirect knowledge of groundwater recharge and discharge [40]. Therefore, it is used as an indicator of groundwater availability and accessibility in this study. Each subsystem is further classified as extreme, severe, moderate, and mild. The catastrophe models can handle a maximum of four control variables. Therefore, the subsystems are classified into four classes to show the variability in data. These types of classifications can also be seen from the studies of [41,42]. However, the data of indicators are classified into four classes according to collected data using the natural break method. Natural break is a common method widely used to classify the data. The method attempts to find the most suitable class range by testing them against the distribution of the data [43]. In other words, natural break classification minimizes the differences between values within the classes and maximizes differences between values within in different classes.

Table 2. Levels of any subsystems.

Sub-System	Indicator	Data
Pre−Monsoon Drought	Extreme	−2.5 to −2.25
	Severe	−2.25 to −2
	Moderate	−2 to −1.75
	Mild	−1.75 to −1.5
Groundwater Salinity (dS/m)	Mild	<6
	Moderate	6 to 8
	Severe	8 to 10
	Extreme	>10
Groundwater Depth (m)	Mild	<8
	Moderate	8 to 10
	Severe	10 to 15
	Extreme	>15
Surface Water Salinity (dS/m)	Mild	<6
	Moderate	6 to 8
	Severe	8 to 10
	Extreme	>10
Surface Water Availability (%)	Extreme	0 to 0.13
	Severe	0.14 to 0.42
	Moderate	0.43 to 0.72
	Mild	0.73 to 1

3.4.2. Standardization of Data

Because the measuring units of different indices are usually different, standardization which transforms into the dimensionless form is necessary. The equation used for standardization of "the larger the better" indices is

$$x'_i = \frac{x_i - x_{min}}{x_{max} - x_{min}}. \tag{1}$$

The equation used for standardization of 'the smaller the better' indices is

$$x_i' = 1 - \frac{x_i - x_{min}}{x_{max} - x_{min}} \quad (2)$$

where, i is the attribute, x_i is the original value of i, and x_{max} and x_{min} are maximum and minimum values, respectively.

In the present study, groundwater and surface water salinity and groundwater depth were considered as "the smaller the better or less water scarcity", as higher values of these indicators indicate higher water scarcity. On the other hand, the pre-monsoon drought and surface water availability were considered as "the higher the better or less water scarcity", as higher values of those indicators indicate less water scarcity.

3.4.3. Normalization for Catastrophe Theory

Catastrophe models are used for normalization of subsystem indicator values and the estimation of weight of each subsystem. In this study, the butterfly catastrophe model was used, and the number of control parameters was four in all the cases. The butterfly model is defined as,

$$x_a = a^{1/2}, x_b = b^{1/3},\ x_c = c^{1/4} \text{ and } x_d\ = d^{1/5} \quad (3)$$

where, x is the state variable, and a, b, c, and d are the control parameters.

The complementary or non-complementary principle can be used for the estimation of subsystem weight from normalized values of indicator [32]. The complementary method is used in this study as the subsystems complement each other in defining water stress.

3.4.4. Computation of Agricultural Water Scarcity

In order to assess the agricultural water scarcity, initially the thematic maps of groundwater depth, groundwater salinity, surface water contribution, surface water salinity, and pre-monsoon drought index were generated by using ArcGIS. The thematic maps were then assigned weights and the features of each theme were assigned ratings using catastrophe theory. The overlay tool in ArcGIS was used to identify the agricultural water scarcity index (AWSI) for Bangladesh using the following equation:

$$AWSI = GWD_w GWD_r + SWA_w SWA_r + RD_w RD_r + GWQ_w GWQ_r + SWQ_w SWQ_r \quad (4)$$

where, GWD, SWA, RD, GWQ, and SWQ represent groundwater depth, surface water availability, pre-monsoon drought, groundwater salinity, and surface water salinity, respectively; subscript w represents weight of each subsystem, and r represents the rank or importance of different classes of the indicator in a subsystem.

4. Results

4.1. Representation of Five Subsystems

To identify agricultural water scarcity, the maps of groundwater depth, pre-monsoon drought, surface water availability, groundwater salinity, and surface water salinity were prepared in ArcGIS. The groundwater depth map shown in Figure 6 is prepared using the groundwater depth values. It can be seen that groundwater depth is classified into four classes: >15 m, 10–15 m, 8–10 m, and <8 m. Classification was done based on the suction lift capacity of shallow water-wells. The figure shows that groundwater during the pre-monsoon goes below 15 m in some pockets located in northwest and central parts of Bangladesh. A groundwater level drop below 10 m is common in the whole northwest. On the other hand, groundwater in the north, northeast, and the coastal region was found to be near the surface during the pre-monsoon season. Therefore, it can be remarked that groundwater is hard to access for irrigation in the northwest during the pre-monsoon season.

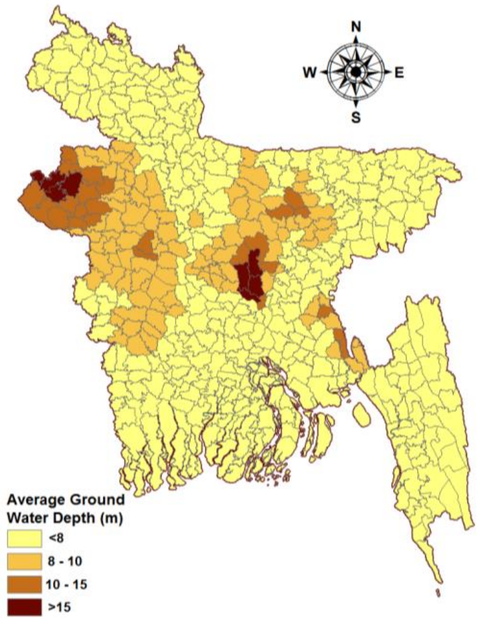


Figure 6. Spatial distribution of average groundwater depth in Bangladesh during the pre-monsoon season.

Figure 7 shows the pre-monsoon drought patterns. It can be seen that doughty severity are classified into four classes to demarcate different drought-prone zones. The figure shows that droughts are more frequent in the north-central and the northwest, and less frequent in the northeast. Therefore, it can be remarked that water scarcity due to pre-monsoon droughts is more in the northwest.

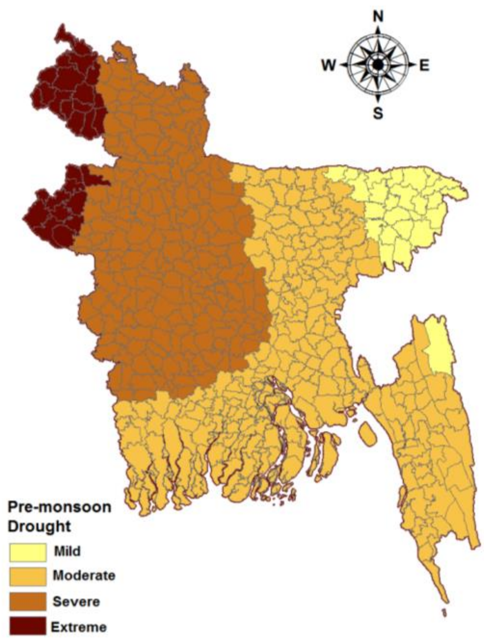


Figure 7. Spatial distribution of pre-monsoon drought index in Bangladesh.

Groundwater salinity zones were classified according to salinity tolerance level of crop. The map of groundwater salinity was prepared by interpolating groundwater salinity data using the ordinary kriging method and shown in Figure 8. Ordinary kriging was used for interpolation of point data in this study as it showed least root mean square error in interpolation. The map shows that groundwater in the coastal zones, especially the southwest coastal region, is heavily contaminated by saline water and made the groundwater completely unsuitable for irrigation.

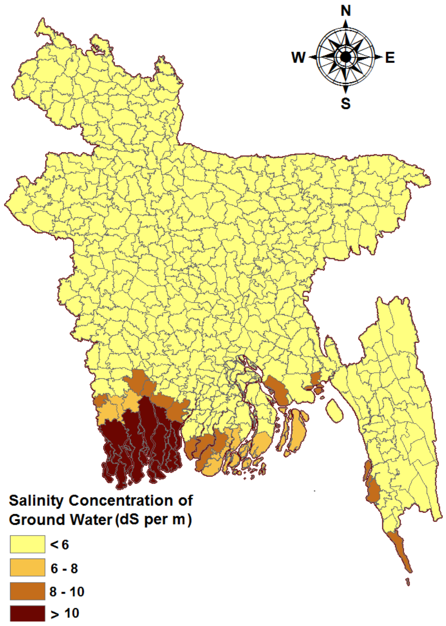


Figure 8. Spatial distribution of groundwater salinity in Bangladesh.

The percentage of surface water contribution to total irrigation supply during the pre-monsoon season was estimated from the ratio of LLP. Therefore, it was considered that contribution of surface water to total irrigation in an area depends on the availability of surface water. Surface water contribution to irrigation during the pre-monsoon is shown in Figure 9. The map shows that surface water availability in two third area of Bangladesh is very poor.

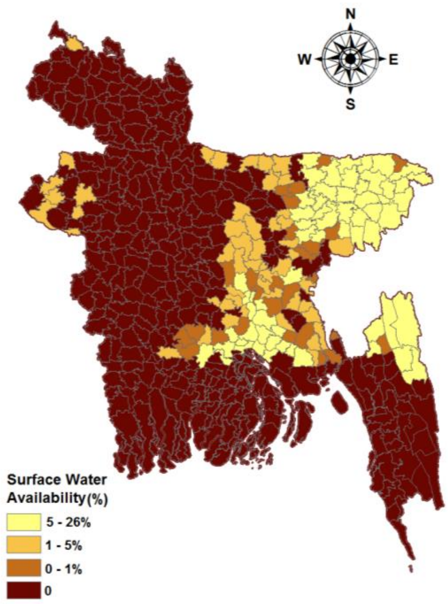


Figure 9. Spatial distribution of surface water availability during pre-monsoon season in Bangladesh.

The surface water salinity map prepared by SRDI of Bangladesh was used in this study. Surface water salinity during the pre-monsoon is shown in Figure 10. The map shows that surface water in the coastal zones, especially in the southwest coastal region, is heavily contaminated by saline water. Moreover, salinity was found to exceed the tolerance limit [44], which decreases the yield potential of crops in a major part of coastal Bangladesh, and therefore becomes completely unsuitable for irrigation.

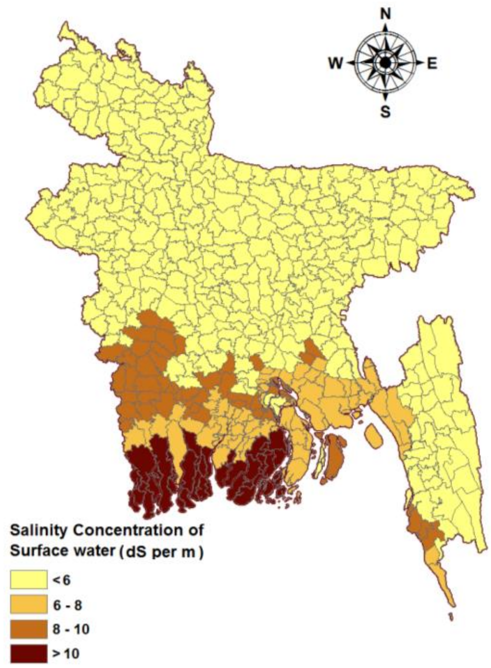


Figure 10. Spatial distribution of surface water salinity in Bangladesh.

4.2. Application of the Catastrophe Theory

The catastrophe theory was applied to derive the weights for delineating the agricultural water scarcity map. The catastrophe theory defines agriculture water scarcity as a system while pre-monsoon drought, groundwater depth, groundwater salinity, surface water availability, and surface water salinity are defined as five subsystems. The subsystem is further defined by indicators which contain the collected data. The data of indicators were standardized using Equations (1) and (2). After standardization of data, the butterfly model of the catastrophe theory was used to derive the weights. The butterfly model was selected as each subsystem has four indicators. The standardized raw data were normalized using the normalization formula of the butterfly model of Equation (3). For example, the values of the indicators of pre-monsoon drought subsystem were calculated using butterfly model as, Extreme = $a^{1/2} = 1^{1/2} = 1$; Severe = $a^{1/3} = 0.67^{1/3} = 0.875$; Moderate = $a^{1/4} = 0.33^{1/4} = 0.758$; and Mild = $a^{1/5} = 0^{1/5} = 0$. The normalized values are the rank or influence of different classes of indicator. For example, 1 is the rank of extreme drought, 0.875 is the rank of severe drought, and so on. The average of the normalized values of the indicators, $(1 + 0.875 + 0.758 + 0)/4 = 0.658$ is the weight of the pre-monsoon drought subsystem. Similarly, the weights of all subsystems were derived and given in Table 3.

In the catastrophe theory, the weight of a subsystem depends on the variance among the mean value of subsystem indicators. It estimates similar weight of two subsystems when the variabilities of both subsystem indicators are similar. The major advantage of the catastrophe-theory-based weighting approach is that it estimates the real influence of each subsystem according to its indicator values.

Table 3. Standardized and weighted values of any component of water scarcity.

System	Sub-System	Indicator	Data	Standardize	Weight
Agricultural Water Scarcity	Pre-Monsoon Drought	Extreme	−2.375	1	0.658
		Severe	−2.125	0.67	
		Moderate	−1.875	0.33	
		Mild	−1.625	0	
	Groundwater Depth (m)	Extreme	15	1	0.702
		Severe	12.5	0.8	
		Moderate	9	0.6	
		Mild	0	0	
	Groundwater Salinity (dS/m)	Extreme	0	0	0.715
		Severe	7	0.7	
		Moderate	9	0.9	
		Mild	10	1	
	Surface Water Availability (%)	Extreme	0.065	1	0.669
		Severe	0.28	0.73	
		Moderate	0.58	0.36	
		Mild	0.87	0	
	Surface Water Salinity (dS/m)	Extreme	0	0	0.715
		Severe	7	0.7	
		Moderate	9	0.9	
		Mild	10	1	

Finally, Equation (4) was used to calculate the agricultural water scarcity using the overlay tool of ArcGIS. It was observed that AWSIs in the integrated layer varied between 0.067 and 0.543. They were then classified into four classes using the natural break method to prepare the map of agricultural water scarcity, which is shown in Figure 11.

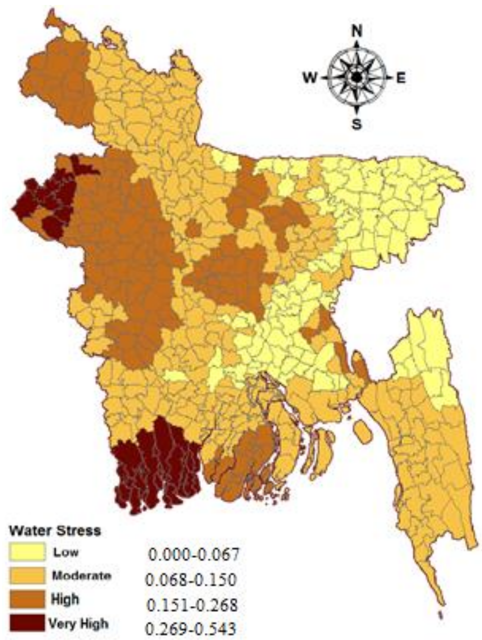


Figure 11. Geographical distribution of agricultural water scarcity during the pre-monsoon season in Bangladesh.

Overall, high water scarcity is found in some northern, northwestern, most central districts, and the coastal zone of Bangladesh. Most districts in the western and southern parts of the country have moderate water scarcity. On the other hand, water scarcity is found less in the northeast and the eastern parts of Bangladesh.

The areas of highest water scarcity correspond very well, in general, with the areas that are usually thought as water-scarce and have records of high levels of agricultural damage due to water scarcity. Reports of various governmental and non-governmental organizations working on natural resources of Bangladesh also mentioned decrease in crop production due to water scarcity in northwest and southwest Bangladesh [45]. Summarization of recent media reports on water scarcity in different parts of Bangladesh also revealed that the problem is acute in the northwest districts and southwestern coastal region.

A radar chart was used to show the effect of different factors on water scarcity in the northwest, southwest, and central areas of Bangladesh where water scarcity was more than moderate (Figure 12).

Figure 12 reveals that unavailability of surface water resources, droughts, and limited accessibility of groundwater resources during the dry season have made the northwest region of the Bangladesh highly vulnerable to water scarcity. On the other hand, extreme salinity in surface and groundwater has made the southwest region of the country highly vulnerable to water scarcity. The possible changes in water scarcity due to climate change and adaptation measures that can be adopted to reduce the impacts of water scarcity in Bangladesh are discussed in adaptation of water scarcity section.

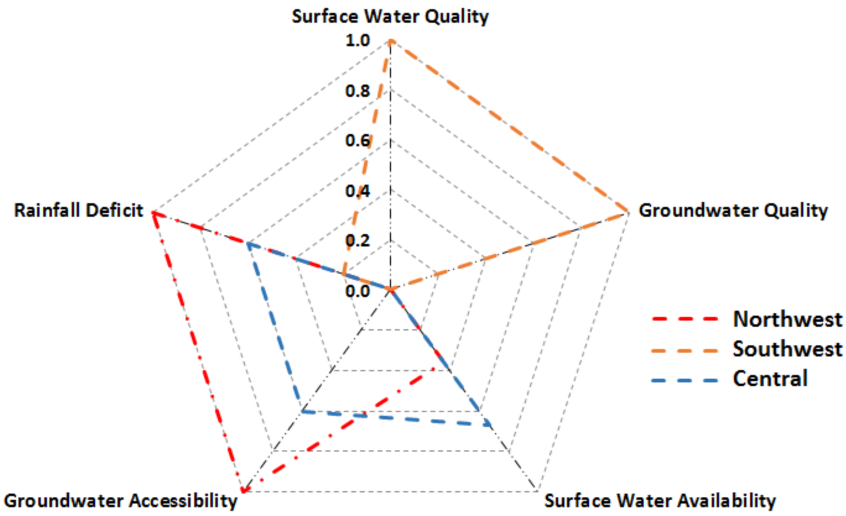


Figure 12. Effect of different factors on water scarcity in the northwest, southwest, and central regions of Bangladesh.

5. Discussion

5.1. Water Scarcity in Southwest Bangladesh

The sea water ingress through the creeks contaminates the aquifers in the coastal region of Bangladesh. Inundation through tidal flooding and upward or lateral movement of saline groundwater during the dry season cause soil salinity in the region [46]. Increasing salinity in surface and groundwater is a major concern in the southwest coastal region of Bangladesh. The new lands in the region are affected by salinity every day, and then the availability of freshwater resources for drinking water, irrigation, agriculture, and other uses are gradually limited. Ali [47] reported that rice production has been reduced in some parts of southwest Bangladesh by 69% over the time period 1983–2003. Sarwar [48] reported that 23% of reduction happened because of increased salinity in the soil and water. It can be anticipated that situation will become aggravated in the near future due to sea level rise and the increasing severity and frequency of storm surges and tidal flooding due to climate change. It has been reported that the rate of land-falling tropical storms has increased by 1.18 times per year since 1950 [49]. The average sea level in the coast region of Bangladesh is projected to increase in the range from 0.3–1.0 m by 2100 [50], which is supposed to intensify surge heights. According to World Bank [51], the increased salinity alone from a 0.3-m sea level rise will cause a net reduction of 0.5 million metric tons of rice production in Bangladesh. On the other hand, Payo et al. [52] found small changes in soil salinity in the coastal region of Bangladesh for different climate change scenarios, including relative sea-level rise in 2050. However, their results indicated that more inter-season variability in rainfall and river flow due to climate change may increase of salinization of agriculture soils in coastal Bangladesh. Therefore, it can be remarked that salinity in the coastal region of Bangladesh will continue to increase and will severely affect the agro-based economy and people's livelihood if proper adaptation measures are not taken.

5.2. Water Scarcity in Northwest Bangladesh

The geology of northwest Bangladesh does not support for large-scale exploitation of groundwater. Shwets et al. [53] suggested that the fast discharge of groundwater towards the rivers of the Gangetic-influenced area results in scarcity of both surface- and groundwater by declining of water table and ceasing the groundwater withdrawal operations for the domestic and agricultural utilization in bigger scale. Consequently, excessive groundwater exploration after the introduction of a groundwater-based irrigation project has caused the lowering of groundwater level in the region [40]. According to Bangladesh Agricultural Development Corporation (BADC; [54]), the groundwater-based irrigation system in the area has reached a critical phase with croplands in many places going out of the reach of shallow-level aquifer due to fast depleting groundwater. Declination of groundwater level below the operating range of irrigation wells during peak irrigation period is a common problem in the region in the recent years [54]. The situation is worsening gradually with the expansion of irrigated agricultural lands. Climate change may affect groundwater resources and aggravate the situation in future. Döll [55] reported that the densely populated south Asian region is highly sensitive to the decreases in groundwater recharge due to climate change because of the high dependency on groundwater. Saleh et al. [56] found that average groundwater level during the pre-monsoon irrigation period decreased by 0.15–2.01 m due to an increase in temperature of 1.0–5.0 °C. Modeling groundwater level under general circulation model revealed that groundwater levels in Northwest Bangladesh would drop by only 0.18 to 0.45 m, under a 1.5 °C temperature rise scenario [57]. This indicates that climate change will aggravate the existing condition of water scarcity in the region.

5.3. Adaptation of Water Scarcity

Various measures were taken by government and non-government organizations working in the southwest coastal region to build resilience to water scarcity due to environmental changes. The farmers in coastal region of Bangladesh are trying to adapt with growing salinity through digging canals to flush freshwater through fields in order to reduce salinity, and cultivation of salinity tolerance crops. However, flushing freshwater through fields is not often possible due to the unavailability of freshwater, and therefore a large portion of cultivable lands remain fallow throughout the year. On the other hand, agricultural agencies of government have claimed to develop salinity tolerance crops, though they are still not available to farmers. A study also showed that the coastal region of Bangladesh is too salty for salt-tolerant rice [58]. Therefore, cultivation of tolerance crops is rarely practiced in the region.

In order to adapt with growing water scarcity, farmers should be encouraged to reschedule the cropping period to take the maximum advantage of rainfall during the pre-monsoon season [59]. Government support should be provided toward excavation and re-excavation ponds or canals to store monsoon rain for irrigation during the dry period. In addition, the stored freshwater can be used for flushing the salts from the soil. High salinity tolerance crops should be approached easily available to farmers. The farmers should also be trained properly to grow salinity tolerance crops. Besides that, improving agricultural practices and developing integrated farming should be encouraged for resilient livelihoods in saline-prone regions [60]. Groundwater from deep aquifers can be exploited for irrigation. It has been reported that deep aquifers in many coastal regions are still not contaminated with salinity [61]. However, it should be noted improper exploitation of groundwater can pollute even the deep aquifer. Therefore, coordinated exploitation of groundwater with reliable scientific information is required. Furthermore, structural measures like building dykes and embankments can also be made in the coastal region to resist saline water intrusion as a long-term mitigation measure.

About 80% of the land of Bangladesh is extremely flood-prone, and therefore it is not possible to manage water scarcity through regulatory measures such as building dams and reservoirs. Groundwater is the sole source of water during the dry period in drought-prone regions. Therefore, the national water policy encouraged groundwater development for irrigation in the 1980s. However, overexploitation of groundwater to meet the ever-increasing irrigation demand has caused the decline of groundwater level and water scarcity in drought-prone northwest Bangladesh. A number of measures have been taken to adapt with water scarcity in the region, which include rainwater harvesting, changes irrigation practices, expanding food storage facilities, promoting backyard farming to supplement food supplies, promoting microcredit and educating people about its use, and forming and training community groups to implement and maintain these various measures [62]. However, those were not enough to maintain the sustainable groundwater yield due to extensive use of groundwater, extension of agricultural land, and changes in climate. It has been reported that groundwater level in the study area has declined steadily over the recent decades [60]. Furthermore, national water resources management plans are necessary to build resilience to increasing water scarcity in the context of climate change.

Development of surface water resources for irrigation is essential in order to reduce the growing pressure on groundwater in the region. In addition, rainwater harvesting for supplemental irrigation and recharging groundwater is very important for the region. The concept of integrated water resources management (IWRM) can be adopted to enhance adaptive capacity to climate change.

6. Conclusions

This study has been carried out to understand the present situation of water scarcity, considering that it will help in water resources planning, development, and management in the context of growing water scarcity. The obtained results showed that agriculture in about 6.3% of the area of the country is experiencing very high-risk water scarcity, 19.1% with high water scarcity, 37.2% with moderate water risk, and the rest is low or no risk of water scarcity for agriculture. The result showed that agricultural water scarcity is more in the western part of Bangladesh compared to the east. Frequent occurrence of drought has appeared in the northwestern part of Bangladesh, making it susceptible to water scarcity. On the other hand, high salinity in groundwater has turned up in the southwestern part of Bangladesh and is affecting agricultural productivity. Existing evidence indicate that water scarcity will increase in the near future due to population growth and climate change. This study emphasizes adaptation to growing water scarcity through rainwater harvesting, changing irrigation practices, crop scheduling, and management of groundwater resources. It is expected that the study will be beneficial to number of stakeholders, including national and local agencies and policy makers to understand the present situation of water scarcity as well as to plan adaptation to growing water scarcity at the climate change situation. However, some areas are important to be considered: (1) concepts and mechanisms of agricultural water scarcity still need further study; (2) the catastrophe model for agricultural water scarcity still needs further improvement. We only set up a system with five subsystems, but because agricultural water scarcity is influenced by many subsystem indicators, it still needs more subsystems. Besides this, future study is required concerning the adaptation strategies, which should be paid more attention by both local government and international researchers.

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