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# Evaluating Drought Vulnerability by the Markov Chain Model in Barind Tract of Bangladesh

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ABSTRACT

In recent years the environment of the northwestern part of Bangladesh has undergone serious deterioration due to climate change. The climate plays a significant role in agriculture. Rainfall is the most important climate parameter affecting crop production of the Barind tract of Bangladesh. Water deficits and excess water are the greatest constraints for rain-fed rice yields in this area. The daily rainfall data for 30 years (1981-2011) of two rainfall stations, Rajshahi and Ishwardi, in the Barind region is considered in this study. At first, the daily data were converted into 10 days of data to analyze by the Markov Chain Model. Drought lasts for a short time only but has complicated features of the climate system. The Markov Chain Model was used to evaluate the Drought Index using a higher probability matrix. The higher transition probability matrix for Ishwardi stations indicates occasional drought for a 7mm threshold value. But Rajshahi station indicates occasional drought for 5 mm and mild drought for 7.5 mm. In the pre-kharif season, both stations indicate occasional drought for both 5 mm & 7 mm, respectively. Again, in the kharif season, both stations indicate occasional drought for both 5 mm & 7 mm, respectively. However, in the Rabi season, both stations indicate chronic drought for both 5 mm & 7 mm, respectively. This study would be constructive to agricultural planners and irrigation engineers in identifying areas where agricultural development should be focused as a long-term drought improvement strategy in the Barind region.

## Introduction

Bangladesh has a tropical monsoon climate with two main seasons: hot and wet (April-October) and dry and cool (November-March) (Nizamuddin 2010; Islam et al. 2021a). Annual rainfall varies from 1200 mm in the west to over 6000 mm in the northeast (Hasan et al. 2014). Northeasterly winds bring cool air from November to February, resulting in mostly dry weather (Hansen et al. 2008). Bangladesh is one of the most disaster-prone countries in the world (Barua et al. 2016; Rahman et al. 2017; Islam et al. 2021b). It is highly vulnerable to natural disasters among developing countries worldwide due to its unpredictable climate, low, flat topography, unique hydrogeological features, and complex geomorphology (Tahasin et al. 2024). High population density, widespread poverty, and social inequity increase the severity of disasters (Ahmed 2004; Mujeri and Mujeri 2020). Almost every year, the country experiences disasters such as tropical cyclones, storm surges, coastal erosion, floods, and droughts, leading to heavy loss of life and property while jeopardizing development activities (Ali 1996; Dastagir 2015; Ripon and Al-Mamun 2020). Drought is a natural phenomenon that typically starts with a substantial reduction in precipitation, resulting in decreased soil moisture and reduced stream flow discharge (Rahmati et al. 2020) which frequently affects the northwestern area. Drought

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severity increasingly poses a threat to agricultural productivity in the Barind tract (Rahman and Rahman 2018). While natural climate variability contributes to drought events, human activities like deforestation, excessive water use, and climate change increase their frequency and intensity (Das et al. 2023). Bangladesh has suffered from nine major droughts since 1971 (Paul 1998; Shahid 2008; Shahid and Behrawan 2008; Rahaman et al. 2016). Bangladesh is expected to experience more frequent and severe droughts in the near future (Rahman et al. 2023). Despite the recurrent and devastating nature of droughts have received far less scientific attention compared to floods or cyclones (Alexander 1995; Brammer 1987; Shahid and Behrawan 2008; Khan et al. 2020). The drought of 1994-1995 caused significant reductions in rice and wheat production (Rahman and Biswas 1995; Habiba et al. 2010; Hossain and da Silva 2013). Globally, the impact of natural hazards and disasters is staggering (Tang et al. 2019), and in Bangladesh, the major natural hazards align with global patterns (Shahid and Behrawan 2008). With global warming, climatic models project a decrease in dry-season precipitation and an increase during monsoons in South Asia (Christensen et al. 2007; Loo et al. 2015). There is growing concern among scientists about changes in precipitation patterns and the frequent occurrence of droughts in Bangladesh (Mohsenipour et al. 2018). The first agricultural drought risk map for Bangladesh was prepared by Karim et al. (1990), considering factors like dry days, higher temperatures during the pre-monsoon period, and soil moisture availability (Shahid and Behrawan 2008). WARPO-EGIC (1996) developed maps of winter and pre-monsoon drought-prone areas using the agroecological zones database and land resources inventory map at a 1:1,000,000 scale. Karim and Iqbal (2001) and Habiba and Shaw (2014) reviewed WARPO-EGIC's work and produced separate drought risk maps for the winter, pre-monsoon, and monsoon seasons.

However, no standardized drought index method has been applied for drought assessment in Bangladesh, and no studies have identified the geographic distribution of human vulnerability to drought. This study seeks to address the gaps in current research by utilizing standardized drought indices for a comprehensive drought risk assessment in Bangladesh. The objectives of this study are 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.

## Materials and methods

### *Data and Study Area*

Data was collected from the two stations from the Barind region which are Rajshahi and Ishwardi (Fig. 1). The measurement unit of rainfall is a millimeter (mm) with a standard rain gauge. Rainfall collected from Bangladesh Meteorological Department, Dhaka, Bangladesh over the range January 1981 to December 2011 (30 years).

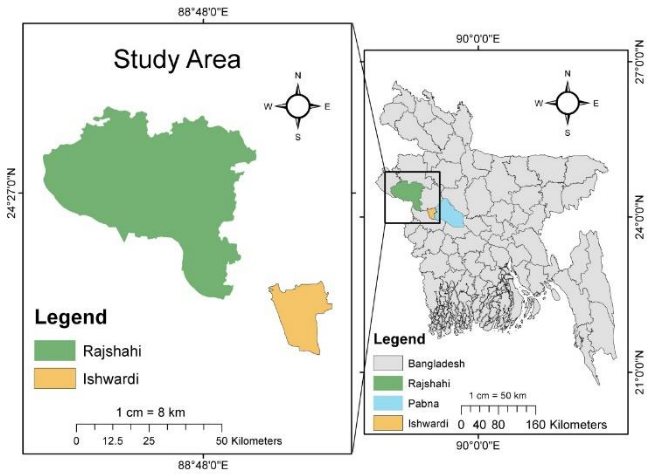


**Fig. 1.** Location of study area

### *Climate and Seasons of the Selected Area*

The climate conditions of Rajshahi and Ishwardi are fairly uniform. In Bangladesh, there are three agro-climate seasons: Pre-kharif (summer- March to May); Kharif (monsoon- June to October), and Rabi (winter-November to February).

### *Model buildings*

**Markov chain model:** A Two-state Markov chain Method was used to calculate the two conditional probabilities (1) α, the probability of a wet week following a dry week, and (2) β, the probability of a dry week following a wet week. Two states of Markov chain for the combination of conditional probabilities shown in Table 1.

Let us, sequences of conditional probabilities which are denoted by,

$$P_0 = \Pr\{W/D\}$$
$$P_1 = \Pr\{W/W\} \quad \ldots\ldots\ldots\ldots\ldots (1)$$

**Table 1.** Markov chain for the combination of conditional probabilities

| | | Future state | |
|---|---|---|---|
| | | **Dry** | **Wet** |
| **Present state** | **Dry** | 1-α | α |
| | **Wet** | β | 1-β |

**Method of Markov chain model:** The sequences in daily rainfall occurrences can be described by a simple Mavkov chain model. Additional evidence to indicate the feasibility of using Katj (1974), Anderson and Goodman (1957), and Mavkov chain model has been presented by Rahman (1999 a, b).

Let, $X_0$, $X_1$, $X_2$,………….., $X_n$ be random variables distributed identically and talking only two values, namely 0 and 1, with probability one, i.e., Firstly assume that,

$P(X_{n+1}=x_{n+1}:X_n=x_n, X_{n-1}=x_{n-1},\dots,X_0=x_0)=P(X_{n+1}=x_{n+1} I X_n=x_n)$

Where, $X_0, X_1, \dots, x_{n+1} \varepsilon \{0,1\}$.

In other words, it is assumed that the probability of wetness of any week depends only one whether the previous week was wet or dry given the event on the previous week. The probability of wetness is assumed independent of further preceding weeks, So $\{X_n, n=0,1,2,\dots\}$ is a Markov chain (Medhi 1981). Probability matrix was considered as-

$$P_{ij}=\begin{bmatrix} P_{00} & P_{01} \\ P_{10} & P_{11} \end{bmatrix} \dots\dots\dots\dots\dots\dots \quad (2)$$

Where, $p_{ij}=P(X_1=j \mid X_0=i)$ i,j=0,1.Note $P_{00}+P_{01}=1$ and $P_{10}+P_{11}=1$

Let, $P=P(X_0=1)$, Here P is the absolute probability of a week being wet during the most monsoon period.

Clearly, $P(X_0=0)=1-p$

For a stationary distribution,

$$[1-P \quad P]\begin{bmatrix} P_{00} & P_{01} \\ P_{10} & P_{11} \end{bmatrix}=[1-P \quad P]$$

This gives,

$$p=\frac{P_{01}}{1-(P_{11}-P_{01})}$$

It is further assumed that $P_{ij}$'s remained constant over the years. The maximum likelihood estimates of $P_{01}$ and $P_{11}$ are appropriate relative functions.

Let Y be the random variable such that Y=number of wet weeks among a n weeks period i.e.,

$$Y=X_0+X_1+\dots\dots\dots\dots\dots+X_{n-1}$$

For large n, Y follows normal distribution with

$$\text{Mean} = n*p$$

$$\text{Variance} = n*p*(1-p)*\frac{1+P_{11}-P_{01}}{1-P_{11}+P_{01}}$$

Where, p is the stationary probability of a week being wet.

This is an asymptotic result that indicates neither the exact distribution for small n nor the rapid approach to normality (Feller 1964).

## Results

***The transition probability matrix (converted in 10 days) with a 5mm threshold value***

For Rajshahi,

$$P=\begin{bmatrix} P_{00} & P_{01} \\ P_{10} & P_{11} \end{bmatrix} = \begin{bmatrix} 0.95791282 & 0.04208718 \\ 0.02945154 & 0.97054846 \end{bmatrix}$$

Where, DI= $P_{11}$* $P_{01}$= 0.04084765 (Chronic Drought)

The higher transition probability matrix for Rajshahi station (converted in 10 days with threshold value 5mm) was found to be stable after 60 steps.

$$P^{60} =\begin{bmatrix} P_{00} & P_{01} \\ P_{10} & P_{11} \end{bmatrix} = \begin{bmatrix} 0.418 & 0.582 \\ 0.405 & 0.595 \end{bmatrix}$$

Here, DI= $P_{11}$* $P_{01}$= 0.346290 (Occasional drought)

For Ishwardi,

$$P=\begin{bmatrix} P_{00} & P_{01} \\ P_{10} & P_{11} \end{bmatrix} = \begin{bmatrix} 0.98626198 & 0.01373802 \\ 0.09207709 & 0.90792291 \end{bmatrix}$$

Where, DI= $P_{11}$* $P_{01}$= 0.01247306 (Chronic Drought)

The higher transition probability matrix for Ishwardi station (converted in 10 days) with a threshold value of 5mm became stable after 47 steps and the values are-

$$P^{47} =\begin{bmatrix} P_{00} & P_{01} \\ P_{10} & P_{11} \end{bmatrix} = \begin{bmatrix} 0.874 & 0.126 \\ 0.866 & 0.134 \end{bmatrix}$$

Here, DI= $P_{11}$* $P_{01}$= 0.016884 (Chronic Drought)

In Fig. 2, the red line indicated a Drought Index (DI) of 0.04084765, which signified chronic drought (Banik et al. 2002; Alam et al. 2014; Meghla and Rahman

2020). After 60 steps, the transition probability matrix became stable. Finally, the DI reached 0.346290 (Fig. 2), indicating Occasional drought (Banik et al. 2002). The blue line showed a DI) of 0.01247306, which indicated chronic drought (Banik et al. 2002). After 47 steps, the transition probability matrix became stable. Finally, the Drought Index reached 0.016884 (Fig. 2), indicating chronic drought (Banik et al. 2002*;* Alam et al. 2014; Meghla and Rahman 2020).

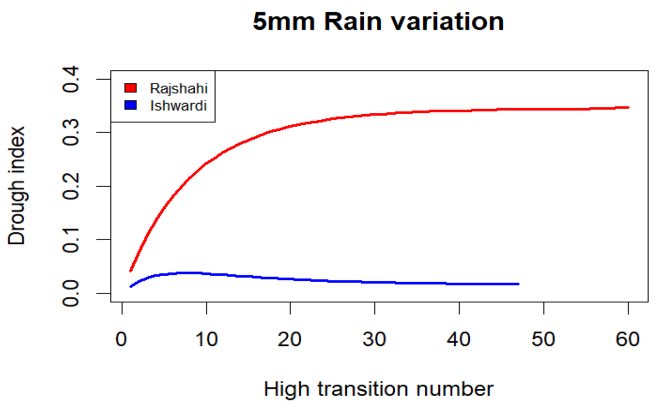


**Fig. 2.** Ten days' time period of drought sensitivity using Markov chain with 5mm threshold value

***The transition probability matrix (converted in 10 days) with 7.5mm threshold value***

For Rajshahi,

$$P=\begin{bmatrix} P_{00} & P_{01} \\ P_{10} & P_{11} \end{bmatrix} = \begin{bmatrix} 0.9603568 & 0.03964321 \\ 0.0319132 & 0.96808680 \end{bmatrix}$$

Where, DI= $P_{11}$* $P_{01}$= 0.03837807 (Chronic Drought)

The higher transition probability matrix for Rajshahi station (converted in 10 days with a threshold value of 7.5mm) became stable after 59 steps and the values are-

$$P^{59}=\begin{bmatrix} P_{00} & P_{01} \\ P_{10} & P_{11} \end{bmatrix} = \begin{bmatrix} 0.452 & 0.548 \\ 0.439 & 0.561 \end{bmatrix}$$

Here, DI= $P_{11}$* $P_{01}$= 0.307428 (Mild Drought)

For Ishwardi,

$$P=\begin{bmatrix} P_{00} & P_{01} \\ P_{10} & P_{11} \end{bmatrix} = \begin{bmatrix} 0.96120416 & 0.03879584 \\ 0.02789992 & 0.97210008 \end{bmatrix}$$

Where, DI= $P_{11}$* $P_{01}$= 0.0377134 (Chronic Drought)

The higher transition probability matrix for Ishwardi station (converted in 10 days) with a threshold value of 7.5mm became stable after 63 steps and the values are-

$$P^{63}=\begin{bmatrix} P_{00} & P_{01} \\ P_{10} & P_{11} \end{bmatrix} = \begin{bmatrix} 0.425 & 0.575 \\ 0.411 & 0.589 \end{bmatrix}$$

Here, DI= $P_{11}$* $P_{01}$= 0.338675 (Occasionally Drought)

In Fig. 3, the red line showed that the DI = 0.03837807, which indicated chronic drought (Banik et al. 2002). After 59 steps, the transition probability matrix became stable. Finally, the DI reached 0.307428 (Fig. 3), indicating mild drought (Banik et al. 2002). The blue line showed that the DI = 0.0377134, which indicated chronic drought (Banik et al. 2002; Alam et al. 2014; Meghla and Rahman 2020). The next higher transition probability matrix indicated the DI = 0.037908, which also represented chronic drought. Similarly, after 63 steps, the transition probability matrix became stable. Finally, the DI reached 0.338675 (Fig. 3), indicating occasional drought (Banik et al. 2002; Alam et al. 2014).

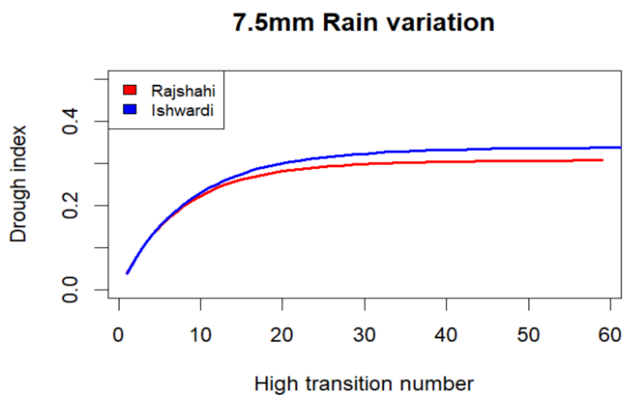


**Fig. 3.** Ten days' time period of drought sensitivity using Markov chain with 7.5mm threshold value

***The transition probability matrix (pre-kharif season in 10 days) with a 5mm threshold value***

For Rajshahi,

$$\begin{bmatrix} 0.85281385 & 0.1471861 \\ 0.01615547 & 0.9838445 \end{bmatrix}$$

DI= $P_{11}$* $P_{01}$= 0.1448042 (Severe Drought)

The following is the higher transition probability matrix for Rajshahi station (pre-kharif season in 10 days) with a threshold value of 5mm.

$$\begin{bmatrix} P_{00} & P_{01} \\ P_{10} & P_{11} \end{bmatrix}$$

Here, in the 1st cell, the values of the corresponding higher transition probability matrix are, $P_{00}$=0.853, $P_{01}$=0.147, $P_{10}$=0.016, $P_{11}$=0.984.

For Ishwardi,

$$\begin{bmatrix} 0.91860465 & 0.08139535 \\ 0.03531786 & 0.96468214 \end{bmatrix}$$

DI= $P_{11}$* $P_{01}$= 0.07852064 (Chronic Drought)

The following is the higher transition probability matrix for Ishwardi station (pre-kharif season in 10 days) with a 5mm threshold value.

$$\begin{bmatrix} P_{00} & P_{01} \\ P_{10} & P_{11} \end{bmatrix}$$

Here, in the 1st cell, the values of the corresponding higher transition probability matrix are, $P_{00}$=0.919, $P_{01}$=0.081, $P_{10}$=0.035, $P_{11}$=0.965.

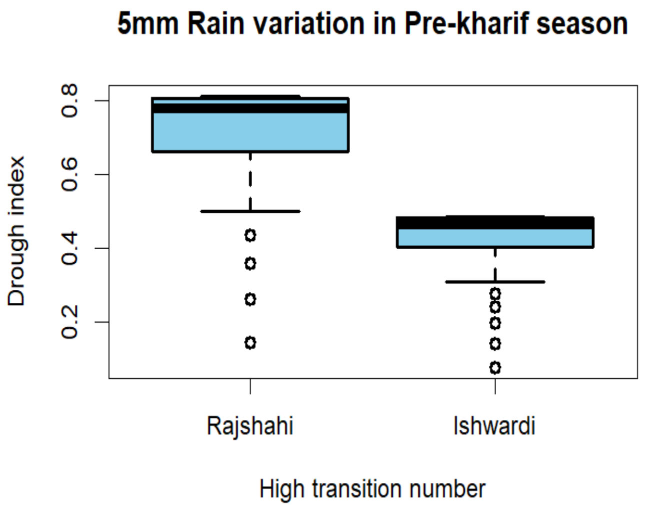


**Fig. 4.** Ten days' time period of drought sensitivity using Markov chain in a pre-kharif season with a 5mm threshold value

The plot for Rajshahi showed a higher median drought index and a wider interquartile range compared to Ishwardi. In contrast, Ishwardi displayed a lower median, narrower interquartile range, and fewer outliers. This comparison highlighted regional differences in the drought index response to rainfall variations during the pre-kharif season. Rajshahi's DI was 0.1448042, indicating severe drought (Banik et al. 2022 Megha and Rahman, 2020). The next higher transition probability matrix indicated a DI of 0.144648, also representing severe drought. After 34 steps, the transition probability matrix stabilized, and the DI reached 0.812696 (Fig. 4), indicating occasional drought (Banik et al. 2002). For Ishwardi, the DI was 0.07852064, indicating chronic drought (Banik et al. 2002; Alam et al. 2014; Meghla and Rahman 2020). The next higher transition probability matrix indicated a DI of 0.078165, also representing chronic drought. After 42 steps, the transition probability matrix stabilized, and the Drought Index reached 0.486494 (Fig. 4), indicating occasional drought (Banik et al. 2002).

***The transition probability matrix (pre-kharif season in 10 days) with 7.5mm threshold value***

For Rajshahi,

$$\begin{bmatrix} 0.85267035 & 0.1473297 \\ 0.01933174 & 0.9806683 \end{bmatrix}$$

DI= $P_{11}$* $P_{01}$= 0.1444816 (Severe Drought)

The following are the higher transition probability matrix for Rajshahi station (pre-kharif season in 10 days) with threshold value 7.5mm.

$$\begin{bmatrix} P_{00} & P_{01} \\ P_{10} & P_{11} \end{bmatrix}$$

Here, in the 1st cell the values of the corresponding higher transition probability matrix are, $P_{00}$=0.853, $P_{01}$=0.147, $P_{10}$=0.019, $P_{11}$=0.981.

For Ishwardi,

$$\begin{bmatrix} 0.92028986 & 0.07971014 \\ 0.04104478 & 0.95895522 \end{bmatrix}$$

DI= $P_{11}$* $P_{01}$= 0.07643845 (Chronic Drought)

The following are the higher transition probability matrix for Ishwardi station (pre-kharif season in 10 days) with threshold value 7.5mm.

$$\begin{bmatrix} P_{00} & P_{01} \\ P_{10} & P_{11} \end{bmatrix}$$

Here, in the 1st cell the values of the corresponding higher transition probability matrix are, $P_{00}$=0.920, $P_{01}$=0.080, $P_{10}$=0.041, $P_{11}$=0.959.

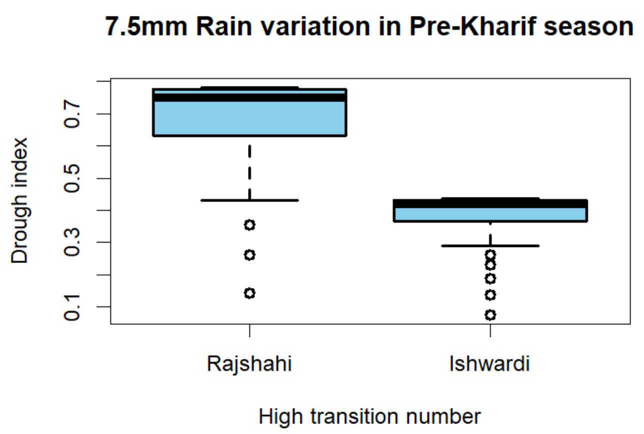


**Fig. 5.** Ten days' time period of drought sensitivity using Markov chain in pre-kharif season with 7.5mm threshold value

The plot for Rajshahi showed a higher median drought index and a wider interquartile range compared to Ishwardi. In contrast, Ishwardi displayed a lower median, narrower interquartile range, and more outliers. This comparison highlighted regional differences in the drought index response to rainfall variations during the pre-kharif season. Rajshahi's DI was 0.1444816, indicating severe drought (Banik et al. 2002; Alam et al. 2014; Meghla and Rahman 2020). The next higher transition probability matrix indicated a DI of 0.144207, also representing severe drought. After 32 steps, the transition probability matrix stabilized, and the DI reached 0.782334 (Fig. 5), indicating occasional drought (Banik et al. 2002). For Ishwardi, the DI was 0.07643845, indicating chronic drought (Banik et al 2002; Alam et al. 2014; Meghla and Rahman 2020). The next higher transition probability matrix indicated a DI of 0.076720, also representing chronic drought. After 40 steps, the transition probability matrix stabilized, and the Drought Index reached 0.435584 (Fig. 5), indicating occasional drought (Banik et al. 2002; Meghla and Rahman 2020).

***The transition probability matrix (kharif season in 10 days) with 5mm threshold value***

For Rajshahi,

$$\begin{bmatrix} 0.92003763 & 0.07996237 \\ 0.04721754 & 0.95278246 \end{bmatrix}$$

DI= $P_{11}$* $P_{01}$= 0.0761867 (Chronic Drought)

The following is the higher transition probability matrix for Rajshahi station (kharif season in 10 days) with a threshold value of 5mm,

$$\begin{bmatrix} P_{00} & P_{01} \\ P_{10} & P_{11} \end{bmatrix}$$

Here, in the 1st cell, the values of the corresponding higher transition probability matrix are, $P_{00}$=0.920, $P_{01}$=0.080, $P_{10}$=0.047, $P_{11}$=0.953

For Ishwardi,

$$\begin{bmatrix} 0.85974026 & 0.1402597 \\ 0.01205876 & 0.9879412 \end{bmatrix}$$

DI= $P_{11}$* $P_{01}$= 0.1385683 (Severe Drought)

The following is the higher transition probability matrix for Ishwardi station (kharif season in 10 days) with a threshold value of 5mm.

$$\begin{bmatrix} P_{00} & P_{01} \\ P_{10} & P_{11} \end{bmatrix}$$

Here, in the 1st cell, the values of the corresponding higher transition probability matrix are, $P_{00}$=0.860, $P_{01}$=0.140, $P_{10}$=0.012, $P_{11}$=0.988.

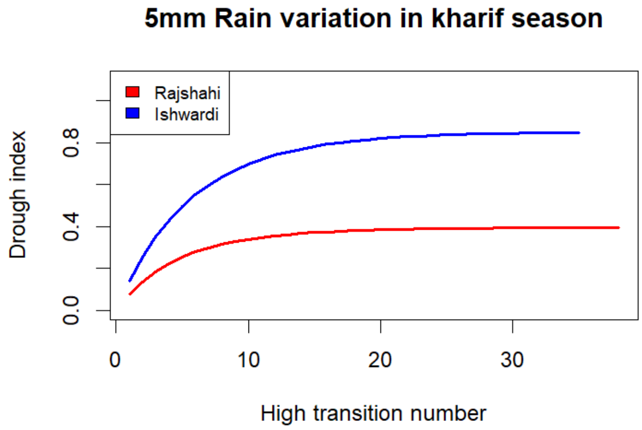


**Fig. 6.** Ten days' time period of drought sensitivity using Markov chain in kharif season with 5mm threshold value

In Fig. 6, the red line shows a DI of 0.0761867, indicating chronic drought (Banik et al. 2002; Alam et al. 2014; Meghla and Rahman 2020). The next higher transition probability matrix indicates a DI of 0.076240, which also represents chronic drought. After 38 steps, the transition probability matrix stabilized, and the DI reached 0.395000, indicating occasional drought (Banik et al. 2002). The blue line showed a DI of 0.1385683, indicating severe drought. The next higher transition probability matrix indicated a DI of 0.138320, which also represented chronic drought. After 35 steps, the transition probability matrix stabilized, and the DI reached 0.848232 (Fig. 6), indicating occasional drought (Banik et al. 2002; Meghla and Rahman 2020).

***The transition probability matrix (kharif season in 10 days) with 7.5mm threshold value***

For Rajshahi,

$$\begin{bmatrix} 0.93139629 & 0.06860371 \\ 0.05240175 & 0.94759825 \end{bmatrix}$$

DI= $P_{11}$* $P_{01}$= 0.0650088 (Chronic Drought)

The following are the higher transition probability matrix for Rajshahi station (kharif season in 10 days) with threshold value 7.5mm.

$$\begin{bmatrix} P_{00} & P_{01} \\ P_{10} & P_{11} \end{bmatrix}$$

Here, in the 1st cell the values of the corresponding higher transition probability matrix are, $P_{00}$=0.931, $P_{01}$=0.069, $P_{10}$=0.052, $P_{11}$=0.948.

For Ishwardi,

$$\begin{bmatrix} 0.86193294 & 0.1380671 \\ 0.01599459 & 0.9840054 \end{bmatrix}$$

DI= $P_{11}$* $P_{01}$= 0.1358588 (severe Drought)

The following are the higher transition probability matrix Ishwardi station (kharif season in 10 days) with threshold value 7.5mm.

$$\begin{bmatrix} P_{00} & P_{01} \\ P_{10} & P_{11} \end{bmatrix}$$

Here, in the 1st cell the values of the corresponding higher transition probability matrix are, $P_{00}$=0.862, $P_{01}$=0.138, $P_{10}$=0.016, $P_{11}$=0.984.

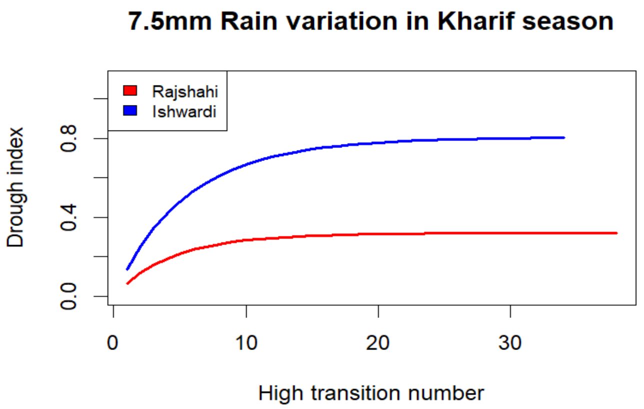


**Fig. 7.** Ten days' time period of drought sensitivity using Markov chain in kharif season with 7.5mm threshold value

The red line showed a DI of 0.0650088, indicating chronic drought (Banik et al. 2002; Alam et al. 2014; Meghla and Rahman 2020). The next higher transition probability matrix indicated a DI of 0.065412, also indicating chronic drought. After 38 steps, the transition probability matrix stabilized, and the DI reached 0.321473 (Fig. 7), indicating occasional drought (Banik et al. 2002; Alam et al. 2014; Meghla and Rahman 2020). The blue line showed a DI of 0.1358588, indicating severe drought. The next higher transition probability matrix indicated a DI of 0.135792, also representing chronic drought. After 34 steps, the transition probability matrix stabilized, and the DI reached 0.802807 (Fig. 7), indicating occasional drought (Banik et al. 2002; Alam et al. 2014).

***The transition probability matrix (rabi season in 10 days) with 5mm threshold value***

For Rajshahi,

$$\begin{bmatrix} 0.98371011 & 0.01628989 \\ 0.08319185 & 0.91680815 \end{bmatrix}$$

DI= $P_{11}$* $P_{01}$= 0.0149347 (Chronic Drought)

The following is the higher transition probability matrix for Rajshahi station (rabi season in 10 days) with a threshold value of 5mm.

$$\begin{bmatrix} P_{00} & P_{01} \\ P_{10} & P_{11} \end{bmatrix}$$

Here, in the 1st cell, the values of the corresponding higher transition probability matrix are, $P_{00}$=0.984, $P_{01}$=0.016, $P_{10}$=0.083, $P_{11}$=0.917.

For Ishwardi,

$$\begin{bmatrix} 0.98443193 & 0.01556807 \\ 0.08131488 & 0.91868512 \end{bmatrix}$$

DI= $P_{11}$* $P_{01}$= 0.0143047 (Chronic Drought)

The following are the higher transition probability matrix Ishwardi station (rabi season in 10 days) with a threshold value of 5mm.

$$\begin{bmatrix} P_{00} & P_{01} \\ P_{10} & P_{11} \end{bmatrix}$$

Here, in the 1st cell, the values of the corresponding higher transition probability matrix are, $P_{00}$=0.984, $P_{01}$=0.016, $P_{10}$=0.081, $P_{11}$=0.919

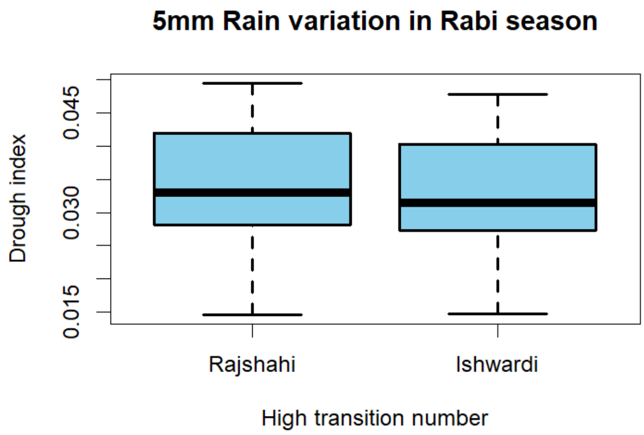


**Fig. 8.** Ten days' time period of drought sensitivity using Markov chain rabi season with 5mm threshold value

Rajshahi and Ishwardi both showed almost similar median drought index and interquartile range, with no outliers in either region. There was no significant difference in drought severity between the two regions. The DI for Rajshahi was 0.0149347, indicating chronic drought (Banik et al. 2002; Alam et al. 2014; Meghla and Rahman 2020). The next higher transition probability matrix indicated a DI of 0.014672, also signifying chronic drought. After 49 steps, the transition probability matrix stabilized, and the final was 0.026712 (Fig. 8), indicating chronic drought

(Banik et al. 2002). For Ishwardi, the DI was 0.0143047, indicating chronic drought. The next higher transition probability matrix indicated a Drought Index of 0.014704, also representing chronic drought. After 51 steps, the transition probability matrix stabilized, and the final DI was 0.025740 (Fig. 8), indicating chronic drought.

***The transition probability matrix (rabi season in 10 days) with a 7.5mm threshold value***

For Rajshahi,

$$\begin{bmatrix} 0.98728948 & 0.01271052 \\ 0.08888889 & 0.91111111 \end{bmatrix}$$

DI= $P_{11}$* $P_{01}$= 0.01158069 (Chronic Drought)

The following are the higher transition probability matrix Rajshahi station (rabi season in 10 days) with a threshold value of 7.5mm.

$$\begin{bmatrix} P_{00} & P_{01} \\ P_{10} & P_{11} \end{bmatrix}$$

Here, in the 1st cell, the values of the corresponding higher transition probability matrix are, $P_{00}$=0.987, $P_{01}$=0.013, $P_{10}$=0.089, $P_{11}$=0.911.

For Ishwardi,

$$\begin{bmatrix} 0.98624440 & 0.0137556 \\ 0.09129512 & 0.9087049 \end{bmatrix}$$

DI= $P_{11}$* $P_{01}$= 0.01249978 (Chronic Drought)

The following are the higher transition probability matrix Ishwardi station (rabi season in 10 days) with a threshold value of 7.5mm.

$$\begin{bmatrix} P_{00} & P_{01} \\ P_{10} & P_{11} \end{bmatrix}$$

Here, in the 1st cell, the values of the corresponding higher transition probability matrix are, $P_{00}$=0.986, $P_{01}$=0.014, $P_{10}$=0.091, $P_{11}$=0.909.

Rajshahi and Ishwardi both exhibited nearly identical median drought indices and interquartile ranges, with no outliers present in either region. No significant difference in drought severity was observed between the two regions. The DI for Rajshahi was 0.01158069, indicating chronic drought (Banik et al. 2002; Alam et al. 2014; Meghla and Rahman 2020). The next higher transition probability matrix showed a DI of 0.011843, also indicating chronic drought. After 48 steps, the transition probability matrix stabilized, and the final DI was 0.015730 (Fig. 9), indicating chronic drought. In Ishwardi, the DI was 0.01249978, indicating chronic drought (Banik et al. 2002). The next higher transition probability matrix showed a DI of 0.012726, also indicating chronic drought. After 48 steps, the transition probability matrix stabilized, and the final DI was 0.017145 (Fig. 9), indicating chronic drought.

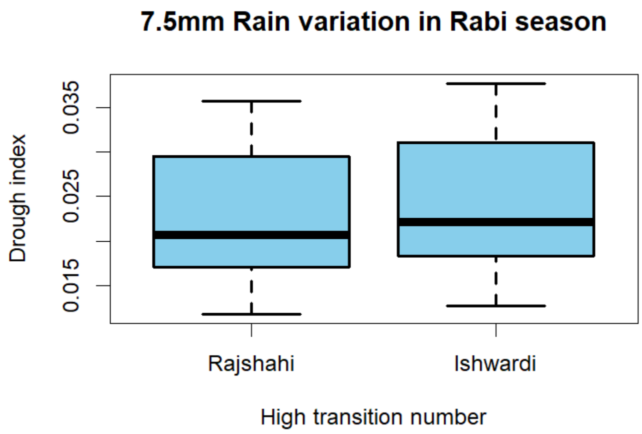


**Fig. 9.** Ten days' time period of drought sensitivity using Markov chain in rabi season with 7.5mm threshold value

## Discussion

***Rajshahi station of 5mm and 7.5mm Threshold value***

At Rajshahi station, the analysis of the DI highlighted seasonal and rainfall-level variations in drought severity. With an annual rainfall of 5mm, the first transition matrix demonstrated chronic drought with a DI value of 0.04084765, while the stable higher transition matrix represented occasional drought with a DI value of 0.346290. At 7.5mm rainfall, the first transition matrix indicated chronic drought with a DI of 0.03837807, while the stable higher matrix suggested mild drought with a DI of 0.307428. In the pre-kharif season, with 5mm rainfall, the first transition matrix showed severe drought with a DI of 0.1448042, whereas the stable higher transition matrix indicated occasional drought with a DI of 0.812696. Likewise, the initial transition matrix shown severe drought with a DI of 0.1444816 in the stable higher matrix at 7.5mm rainfall, then moved to occasional drought (DI = 0.782334). Furthermore, a chronic drought with a DI of 0.0761767 was the first matrix for this situation. The first transition matrix revealed chronic drought (DI = 0.0650088) in the kharif season with 5mm rainfall; the stable upper matrix moved to occasional drought with a DI of 0.395000. At 7.5mm rainfall, the first transition matrix still indicated chronic drought with a DI of 0.0149347, while the stable higher matrix showed occasional drought with a DI of 0.321473. Both matrices reflected chronic drought at different rainfall levels in the rabi season. For 5mm rainfall, the first transition matrix reported a DI of 0.026712, and the stable higher matrix showed a similar result with a DI of 0.015730. At 7.5mm rainfall, the DI was 0.01158069 for the first matrix and 0.015730 for the stable higher matrix.

***Ishwardi station of 5mm and 7.5mm Threshold value***

Based on both first transition and stable higher transition matrices, drought conditions were assessed at Ishwardi station using DI values for threshold rainfall levels of 5 mm and 7.5 mm. The first transition matrix showed a DI of 0.01247306, indicating chronic drought given an annual rainfall of 5 mm. By comparison, the stable higher transition matrix exhibited a DI of 0.016884, likewise suggesting persistent drought. For an annual rainfall of 7.5 mm, the first transition matrix showed a DI of 0.0377134, reflecting chronic drought, whereas the stable higher matrix indicated occasional drought with a DI of 0.338675. In the pre-kharif season, the first transition matrix for 5 mm rainfall recorded a DI of 0.07852064, indicating chronic drought, while the stable higher transition matrix showed a DI of 0.486494, suggesting occasional drought. For 7.5 mm rainfall, the first transition matrix recorded a DI of 0.07643845, reflecting severe drought, while the stable higher matrix recorded a DI of 0.435584, also indicating occasional drought. During the kharif season, at 5 mm rainfall, the first transition matrix revealed a DI of 0.1385683, indicating severe drought, while the stable higher transition matrix showed a DI of 0.848232, suggesting occasional drought. At 7.5 mm rainfall, the first transition matrix indicated severe drought with a DI of 0.1358588, while the stable higher matrix recorded a DI of 0.802807, also indicating occasional drought. In the Rabi season, at 5 mm rainfall, the first transition matrix recorded a DI of 0.0143047, indicating chronic drought, while the stable higher transition matrix also maintained chronic drought with a DI of 0.025740. At 7.5 mm rainfall, the first transition matrix showed a DI of 0.01249978, indicating chronic drought, whereas the stable higher matrix recorded a DI of 0.017145, continuing to reflect the chronic drought condition. This analysis shows how drought severity changes with different seasons and rainfall variations, highlighting the importance of managing water resources in a flexible way. The varying drought indices in the first and stable higher transition matrices for each season emphasize how drought conditions can change. Understanding these changes is key to creating strategies for better water management to ensure that resources are used wisely and communities remain resilient to climate change.

## Conclusion

A comprehensive study was conducted focusing on the Rajshahi and Ishwardi rainfall stations in the Barind tract using the Markov Chain model. Results demonstrate a complex situation of the frequency and severity of droughts through the season which can significantly impact the agricultural system. At Rajshahi station, the DI indicates annual chronic drought, with irregular droughts in the pre-kharif and kharif seasons, and increased vulnerability during the rabi season. Ishwardi shows similar trends, with extreme drought in the rabi season and occasional droughts in the pre-kharif and kharif seasons. The findings highlight the importance of threshold-specific rainfall and seasonal variability in determining agricultural drought in a specific area. Chronic water scarcity in the rabi season suggests the need for drought mitigation strategies, such as water-efficient irrigation or drought-resistant crops. Efficient water management and crop selection are crucial during pre-kharif and kharif seasons. This study provides valuable insights for policymakers to prioritize drought intervention, enhancing agricultural sustainability and resilience in the Barind region.

**Competing Interest:** The authors declare that they have no known competing financial interests.

**Authors' contribution:** MSR conceived the concept and wrote the recommendation for the article. MAI wrote the draft. NM and MB collected data and edited the manuscript. MMH arranged the tables and figures and finalized the full manuscript.

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