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Research Article

Assessing Drought Variability in Punjab Using Generalized Monsoon Index (GMI) and Monsoon Rainfall Recurrence Intervals

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ABSTRACT

Long-term rainfall data (more than 68 years) of different agroclimatic zones of Punjab were collected from the India Meteorological Department, Pune. All districts were divided into 5 different zones: Sub-Mountain undulating zone, undulating plain zone, central plain zone, western plain zone and western zone. Understanding long-term rainfall dynamics is critical for sustaining agricultural productivity in highly irrigated regions like Punjab, India. This study analyzed 68 years (1951–2018) of monsoon rainfall data (June–September) across 20 districts for five distinct agroclimatic zones. Utilising the Generalised Monsoon Index (GMI) and recurrence analysis, the study identified significant spatial and temporal shifts in precipitation patterns. The findings revealed a significant increase in June rainfall for districts including Hoshiarpur, SAS Nagar, Rupnagar, Muktsar, and the majority of the Central Plain Zone (excluding Ludhiana). In contrast, significant decreases in July rainfall were observed in Gurdaspur, Faridkot, Ferozepur, Bathinda, and Mansa, while in August, declines were observed in Faridkot and Mansa. Stability was noted in districts such as SBS Nagar, Ludhiana, and Sangrur, which showed no significant trends. GMI percentile analysis categorised the 68-year period into 13 severe drought-impact years, 7 moderate drought-impact years, and 7 drought-impact years, with only 14 years reflecting normal crop conditions. Recurrence interval analysis identified 69-year return periods for maximum monsoon rainfall events, with peak intensities varying by district, ranging from 1421 mm (1988) in Amritsar to 607 mm (1970) in Mansa. These findings suggest a transition toward higher intra-seasonal variability, where intensified early-season (June) rain is offset by mid-season deficits. The practical implications of this study are significant for policymakers and agrometeorologists; the results provide a scientific basis for redesigning cropping patterns, optimizing groundwater recharge strategies, and developing district-specific climate adaptation plans to safeguard the "breadbasket of India" against hydrological extremes.

Key words: Agroclimatic zones, Generalized Monsoon Index (GMI), Rainfall trends, Recurrence Interval

Introduction

Punjab has a unique position as India's "breadbasket" and is critically vulnerable to water stress. While the state occupies only 1.5% of the country's geographical area, it contributes nearly 50% of the national food grain pool. This high productivity is sustained by an intensive irrigation system covering 97% of the state's geographical area, with 80% of total water resources dedicated solely to food grain production. The rainfall regime in Punjab is further complicated by stark spatial variations, ranging from 250 mm in the semi-arid southwestern region to over 1000 mm in the sub-mountainous northern region. Rainfall is the essential abiotic factor for the production of various crops,

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especially in the rainfed regions. Therefore, information of the rainfall is needed to maintain the crop productivity and soil moisture of the required area (Adler *et al.,* 2000). Monthly or weekly rainfall analysis is helpful for designing the cropping pattern of a place. It is also beneficial to choose the specific crop species and agronomic practices. (Krishna *et al.,* 2015). In states like Punjab, where most people are engaged in agriculture and industry, water accessibility and shortages are serious problems. Hence, studies on rainfall trends are important for meeting future water demand. Moreover, the Indian economy is largely dependent on highly variable southwest monsoons (Vashisht, 2008). Furthermore, while low-intensity rainfall during the monsoon is the primary driver of groundwater recharge in Northwest India (Asoka *et al*., 2018).

Climate change, which has affected rainfall patterns and temperatures, could have affected our water resources. The change in rainfall pattern is occurring because, as with the increase in temperature, the evaporation rate is also increasing. The combined effect of these changes influences soil moisture levels and agricultural production. In hot summers, water stress will affect crop quality, and water demand will also increase. Rainfall patterns exhibit spatial and temporal variation, ranging from 250 mm in the south-western region to 1000 mm in the northern region of Punjab. Although monsoon rainfall occurs from June to late September, it helps replenish the state's water resources (Govt. of Punjab, 2008). It is observed that there has been a 35% decrease in rainfall over the past 30 years, which affects the three rivers of the state, i.e., Ravi, Beas, and Sutlej. This results in a decrease in Punjab's water resources. The rainfall contributes only 20% of the crop water use, while the other 80% is provided by irrigation and the state's water resources (Water Directorate, 2005).

The fall in the groundwater level was 41.6 cm/year from 1998 to 2008 across different zones of Punjab. The rate of decline was found to be highest in the Central zone (50 cm/year), while in the north east and south west zones, the decline was 33 cm/year and 36 cm/year, respectively (Kaur *et al*., 2017). Rainfall is increasing in some districts in south-west Punjab (Bhatinda and Moga), which presently receive low annual rainfall. The decrease in winter rainfall leads to the exploitation of groundwater to irrigate the Rabi crops (Krishan *et al*., 2015). While previous studies have documented linear trends in precipitation, there is a scarcity of research that links GMI with localized recurrence analysis. Recurrence analysis is essential for understanding the non-linear dynamics and the return periods of extreme events, yet few studies have utilized GMI to explain the teleconnections driving these erratic shifts in Punjab's rainfall. This study aims to fill these gaps by providing a zonal-level analysis of historical and future rainfall dynamics, offering a scientific framework for sustainable hydrological resource management.

Materials and Methods

Description of study area

Punjab state is located in the north-west region of India, and it covers 1.53% of the country's geographical area. It has 50,362 an area of 50,362 km² and a latitude & longitude that extend from 29°33′ to 33°34′ N and 75°53′ to 76°53′ E, respectively. The study was conducted in 20 districts of Punjab, representing five different agroclimatic regions of the state.

Data collection

For this study, long-term data (more than 60 years) of different agroclimatic zones of Punjab have been used. Data on the rainfall has been taken from 1951-2018 and Grided weather data was collected from the India Meteorological Department, Pune. Districts of the state are taken according to the zones like Gurdaspur and Hoshiarpur from Sub- Mountain Undulating Zone; Rupnagar, SBS Nagar and SAS Nagar from Undulating Plain Zone; Ferozepur and Faridkot from Western Plain Zone; Muktsar, Mansa, Barnala, Moga, Bathinda and Sangrur from Western Zone and Amritsar, Fatehgarh sahib, Jalandhar, Kapurthala, Patiala, Taran Tarn and Ludhiana from Central Plain Zone.

Data analysis

The collected rainfall data was analysed in MS Excel. The data was examined for different time series like: weekly, monthly, annually and for monsoon and non-monsoon period.

Trend analysis

Trends in rainfall were determined for the 20 selected districts using various methods. The study also analysed the trends in rainfall during the monsoon period.

Recurrence intervals

It is also known as the return period; it is an average time or estimated average time between events, such as floods or a river discharge flow to occur. To workout rainfall data, analysis was done with the following formula.

$$\text{Recurrence interval} = \frac{Y+1}{R}$$

Where,
Y= total no. of years and
R rank of monthly rainfall, when the data is arranged in descending order.

Yearly analysis of the Generalized Monsoon Index (GMI)

The Generalized Monsoon Index (GMI) is a metric used to assess the performance of monsoon rains in a specific region. It accounts for various meteorological parameters and provides valuable information on monsoon patterns. GMI has been calculated for the 68 years of rainfall data from 1951 to 2018 for the monsoon period, i.e., June to September. GMI is basically the highest as well as the lowest rainfall, and the trend of rainfall during the monsoon period. GMI percentile is defined by the strength of rainfall impacting main crop conditions and it categories the years in different categories like Severe drought impact (GMI_{Pct} 0-20), Drought impact (GMI_{Pct} 21-30), Moderate drought impact (GMI_{Pct} 31-40), Normal Crop conditions (GMI_{Pct} 41-60), Possible above normal crop condition (GMI_{Pct} 61-90), Possible excessive moisture year(GMI_{Pct} 91-100).

Generalized Monsoon Index

Generally, most of the rainfall in Punjab occurs during the southwest monsoon season, from June to September, and variation in monsoon is considered a key factor for socio-economic development, water resources, and agricultural management. It is computed by following formulae:

$$GMI = \Sigma_{i=1}^{n} \frac{NR}{A_{june} + A_{july} + A_{aug} + A_{sept}}$$

Where, i = ith month (June, July, August, September).

NR= Normal or average rainfall of the respective months i.e., June, July, August, September.

A_{june} is actual rainfall of June, A_{july} is actual rainfall of July, A_{aug} is actual rainfall of August, and A_{sept} is actual rainfall of September.

Then, the GMI values are transferred to a percentile rank by arranging them in ascending order. GMI_{Pct} is defined as the strength of rainfall impacting on main crop conditions (Sukamoto *et al.,* 1984) and the $GMI_{Pc\ t}$(GMI percentile) is calculated using the following equation:

$$GMI_{pct} = \frac{r*100}{n+1}$$

Where r is the rank of the number and n is the total number of years. GMI_{Pct} are categorized as follows:

GMI_{pct}	Crop conditions
0-20	Severe drought impact
21-30	Drought impact
31-40	Moderate drought impact
41-60	Normal crop conditions
61-90	Possible above normal crop
91-100	Possible excessive moisture

Results and Discussion

Sub-mountain undulating zone

GMI percentile revealed that in both the districts of the zone, 13 years have been observed as severe drought years, 7 years as drought impact years, 7 years as moderately drought years, and 14 years as normal crop condition years. Whereas, 21 years were under possible above normal crop conditions, and 6 were possible excessive moisture years during 1951-2018 (Table 1). GMI of 4 months showed an increasing trend of rainfall in the June month and decreasing trend of rainfall in the remaining months, i.e., July, August and September, while a significant

Table 1. Generalized Monsoon Index percentile for sub-mountain undulating zone

Districts	Severe Drought Impact	Drought Impact	Moderately Drought Impact	Normal Crop Condition	Possible Above Normal Crop	Possible Excessive Moisture
Gurdaspur	1951, 1983, 1987, 1989, 1990, 1999, 2002-04, 2011, 2012, 2016, 2017	1952, 1962, 1972, 1986, 1991, 2014, 2018	1965, 1980, 1992, 1997, 1998, 2000, 2001	1954, 1966, 1977, 1979, 1981, 1982, 1984, 1985, 1993, 1996, 2006, 2009, 2010, 2015	1953, 1955, 1957, 1959, 1960-64, 1968-70, 1973-76, 1978, 1988, 1994, 2007, 2008, 2011	1956, 1958, 1967, 1971, 1995, 2005
Hoshiarpur	1962, 1965, 1966, 1969, 1973, 1979, 1981-83, 1987, 2004, 2005, 2016	1963, 1974, 1975, 1980, 2003, 2014, 2017	1972, 1989, 1992, 2002, 2006, 2007, 2009	1954-56, 1967-68, 1978, 1984, 1986, 1997, 2000, 2001, 2012, 2015	1952-53, 1957-59, 1961, 1964, 1970-71, 1976-77, 1990-91, 1993, 1996, 1998-99, 2008, 2010, 2013, 2018	1960, 1985, 1988, 1994, 1995, 2011

decrease (at 5% level of significance) in rainfall during the monsoon period has been observed in the month of July only (Fig. 1A).

GMI during the monsoon period showed an increasing trend of rainfall at Hoshiarpur in the months of June, August, and September. A decreasing trend has been observed in July. However, a significant increase was observed in June in the Hoshiarpur district (Fig. 1B).

Undulating plain zone

GMI percentile had been worked out in an undulating plain zone, in which 13 years were observed as severe drought years, among which 7 years at SBS Nagar and SAS Nagar and 6 years at Rupnagar were found as drought impact years, and 7 years were the moderately drought impact years. While all the districts experienced only 6 years as possible excessive moisture years during the monsoon period of 68 years (Table 2). AtSAS Nagar, the increasing trend of GMI has been recorded during June, July, August, and September, whereas a significant increase was observed in the month of June only (Fig. 2A). GMI showed the increasing trendof rainfall in the month of June, and a decrease has been observed during the months of July, August and September. But no significant increase or decrease has been recorded in any of the month during monsoon period at SBS Nagar (Fig. 2B). At Rupnagar significant increase in rainfall during monsoon period has been found in the months of June and August and decreasing trend of GMI in the months of July and September (Fig. 2C).

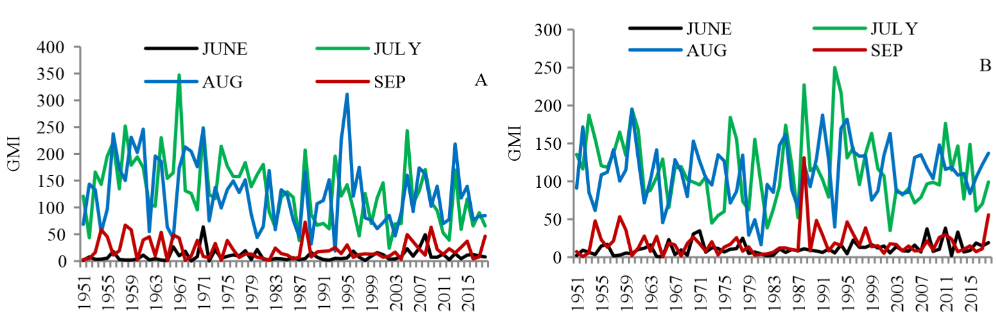


Fig. 1. Generalized Monsoon Index at Gurdaspur (A) and Hoshiarpur (B)

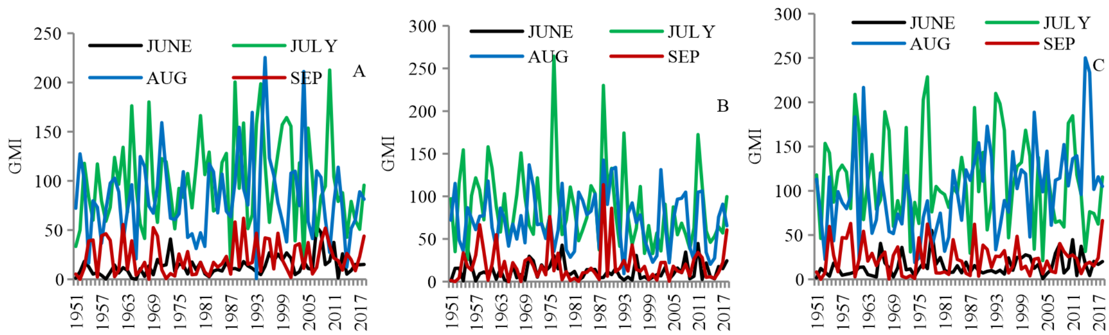


Fig. 2. Generalized Monsoon Index at SAS Nagar (A), SBS Nagar (B) and Rupnagar (C)

Table 2. Generalized Monsoon Index percentile for undulating plain zone

Districts	Severe Drought Impact	Drought Impact	Moderately Drought Impact	Normal Crop Condition	Possible Above Normal Crop	Possible Excessive Moisture
SAS Nagar	1951, 1954, 1963, 1965, 1974, 1978, 1981, 1987, 1991, 2006, 2014-16	1957, 1958, 1967, 1977, 1979, 1984, 2017	1952, 1955, 1956, 1973, 1975, 2002, 2013	1959, 1961, 1966, 1969, 1970, 1976, 1983, 1993, 1997, 2003, 2009, 2012, 2018	1953, 1960, 1962, 1968, 1972, 1980, 1982, 1985, 1986, 1989, 1992, 1996, 1998-01, 2004, 2005, 2008, 2010-11	1964, 1971, 1988, 1990, 1994, 1995
SBS Nagar	1965, 1987, 1992, 1998-01 2004, 2009, 2010, 2013-15	1952, 1963, 1974, 1979, 1980, 1981, 1982	1951, 1955, 1967, 1969, 1983, 1994, 2016	1953, 1959, 1962, 1966, 1973, 1984, 1995, 1996, 2002, 2003, 2005-07, 2017	1954, 1956, 1957, 1958, 1961, 1964, 1968, 1971, 1972, 1975, 1977, 1978, 1985, 1986, 1989, 1991, 1993, 1997, 2008, 2012, 2018	1960, 1970, 1976, 1988, 1990, 2011
Rupnagar	1952, 1965, 1969, 1971, 1973-75, 1981-82, 1987, 2004, 2006	1953, 1955, 1970, 1978, 1979, 1980	1961, 1964, 1984, 1985, 2001, 2007, 2017	1951, 1956-59, 1963, 1968, 1986, 1989, 1992, 2002, 2008, 2006, 2009, 2013	1954, 1966, 1967, 1972, 1976, 1983, 1990, 1991, 1993, 1994, 1995, 1997-00, 2003, 2005, 2010, 2012, 2014, 2018	1960, 1962, 1977, 1988, 2011, 2015

Central plain zone

In central plain zone, all the districts experienced 13 years as severe drought impact years, 7 years a moderately drought impact year and 7 as drought impact years during the monsoon period viz. June, July, August and September (Table 3). Amritsar showed increase in rainfall during all the 4 months of monsoon season whereas, the significant increase

Table 3. GMI percentile at central plain zone

Districts	Severe Drought Impact	Drought Impact	Moderately Drought Impact	Normal Crop Condition	Possible Above Normal Crop	Possible Excessive Moisture
Amritsar	1951, 1952, 1954, 1965, 1972, 1974, 1987, 1991, 2002, 2004, 2007, 2009, 2014	1955, 1962, 1963, 1969, 1983, 1989, 2017	1957, 1986, 1998, 1999, 2010, 2015, 2016	1953, 1956, 1958, 1960, 1964, 1970, 1971, 1979, 1981, 1982, 1992, 2000, 2005, 2018	1959, 1961, 1966, 1967, 1968, 1973, 1977, 1978, 1984, 1985, 1988, 1990, 1993, 1994, 1996, 1997, 2001, 2003, 2006, 2008, 2013	1975, 1976, 1980, 1995, 2011, 2012
Fatehgarh Sahib	1965, 1974, 1979, 1982, 1986, 1987, 1994, 1996, 2004, 2005, 2009, 2014, 2016	1969, 1981, 1990, 1991, 1997, 1999, 2017	1951, 1956, 1963, 1966, 1972, 1984, 2001	1952-55, 1957, 1962, 1968, 1973, 1975, 1980, 1985, 1992, 2006, 2013	1958, 1959, 1961, 1964, 1967, 1971, 1976, 1977, 1978, 1983, 1989, 1995, 1998, 2000, 2002, 2007, 2008, 2012, 2015, 2018	1960, 1988, 1993, 2003, 2010, 2011
Jalandhar	1951, 1969, 1972, 1974, 1977, 1979, 1981, 1983, 1987, 2000, 2004, 2013, 2015	1954, 1955, 1963, 1970, 1982, 1991, 2001	1965, 1976, 1992, 1996, 2006, 2007, 2014	1959, 1961, 1967, 1968, 1971, 1973, 1980, 1984, 1998, 1999, 2002, 2010, 2016, 2017	1952, 1953, 1956, 1957, 1958, 1966, 1975, 1978, 1985, 1986, 1990, 1993, 1994, 1997, 2003, 2005, 2008, 2009, 2012, 2018	1960, 1962, 1964, 1988, 1995, 2011
Kapurthala	1951, 1969, 1972, 1974, 1977, 1979, 1981, 1983, 1987, 2000, 2004, 2013, 2015	1954, 1955, 1963, 1970, 1982, 1991, 2001	1965, 1976, 1992, 1996, 2006, 2007, 2014	1958, 1959, 1961, 1967, 1968, 1971, 1973, 1980, 1984, 1998, 1999, 2002, 2010, 2017	1952, 1953, 1956, 1957, 1962, 1966, 1975, 1978, 1985, 1986, 1989, 1990, 1993, 1994, 1997, 2003, 2005, 2008, 2009, 2016, 2018	1960, 1964, 1988, 1995, 2011, 2012
Ludhiana	1965, 1969, 1974, 1979, 1981, 1982, 1986, 1987, 1992, 1997, 2000, 2004, 2006	1951, 1962, 1996, 1999, 2007, 2015, 2016	1956, 1961, 1968, 1991, 2001, 2002, 2017	1954, 1955, 1959, 1960, 1966, 1970-73, 1976, 1978, 1998, 2013, 2014	1952, 1953, 1957, 1958, 1967, 1975, 1977, 1980, 1983, 1985, 1989, 1990, 1993-95, 2003, 2005, 2008, 2009, 2010, 2018	1963, 1964, 1984, 1988, 2011, 2012
Patiala	1951, 1954, 1963, 1965, 1974, 1978, 1981, 1987, 1991, 2006, 2014, 2016, 2017	1957, 1958, 1967, 1979, 1984, 2015, 2018	1952, 1955, 1956, 1973, 1977, 2002, 2013	1959, 1961, 1966, 1969, 1970, 1975, 1976, 1983, 1997, 1993, 2003, 2007, 2009, 2012	1953, 1960, 1962, 1968, 1972, 1980, 1982, 1985, 1986, 1989, 1992, 1996, 1998, 1999, 2000, 2001, 2004, 2005, 2008, 2010, 2011	1964, 1971, 1988, 1990, 1994, 1995
Tarn Taran	1969, 1972, 1974, 1979, 1987, 1989, 1991, 1998, 1999, 2004, 2009, 2014-15	1952, 1963, 1968, 1981, 1992, 2000, 2017	1951, 1962, 1970, 1994, 1996, 2002, 2007	1954, 1955, 1956, 1965, 1967, 1973, 1982, 1983, 1986, 1995, 1997, 2001, 2010, 2013	1953, 1957, 1958, 1959, 1960, 1964, 1966, 1971, 1976, 1977, 1980, 1984, 1985, 1988, 1990, 1993, 2003, 2005, 2006, 2016, 2018	1961, 1975, 1978, 2008, 2011, 2012

in GMI has been noticed in the month of June only (Fig. 3A).

As evident from Fig. 3B, GMI of June, August and September months showed increasing trend and decreasing trend of rainfall during monsoon season has been found in the month of September. The significant increase in rainfall was observed in the month of June. In Jalandhar, significant increase in rainfall has been experienced during the month of June whereas, increasing trend was observed in the month of September and decreasing trend in rainfall has been noticed during the months of July and August (Fig. 3C).

At Kapurthala except July, other 3 months showed increasing trend of GMI during 1951-2018 While the significant increase in GMI has been recorded in the month of June only (Fig. 4A).

At Ludhiana, it has been noticed that June, July, and September months showed increasing trend of GMI in the last 68 years whereas decreasing trend of GMI has been observed in the month of August and no significant increase or decrease was experienced in any of the monsoon month (Fig. 4B).Patiala districts showed the increasing trend of GMI in June, July and September However, significant increase has been found in the month of June. August month exhibited the decreasing trend of GMI during the monsoon period (Fig. 4C). In Tarn Taran, GMI showed an increasing trend in June and September. A decreasing trend in GMI has been observed in July and August during 1951-2018, and a significant increase has been observed in June (Fig. 4D).

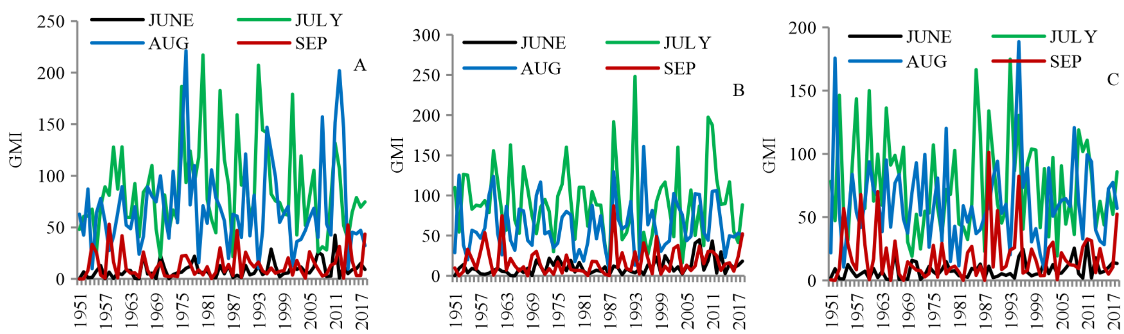


Fig. 3. Generalized Monsoon Index at Amritsar (A), Fatehgarh Sahib (B) and Jalandhar (C)

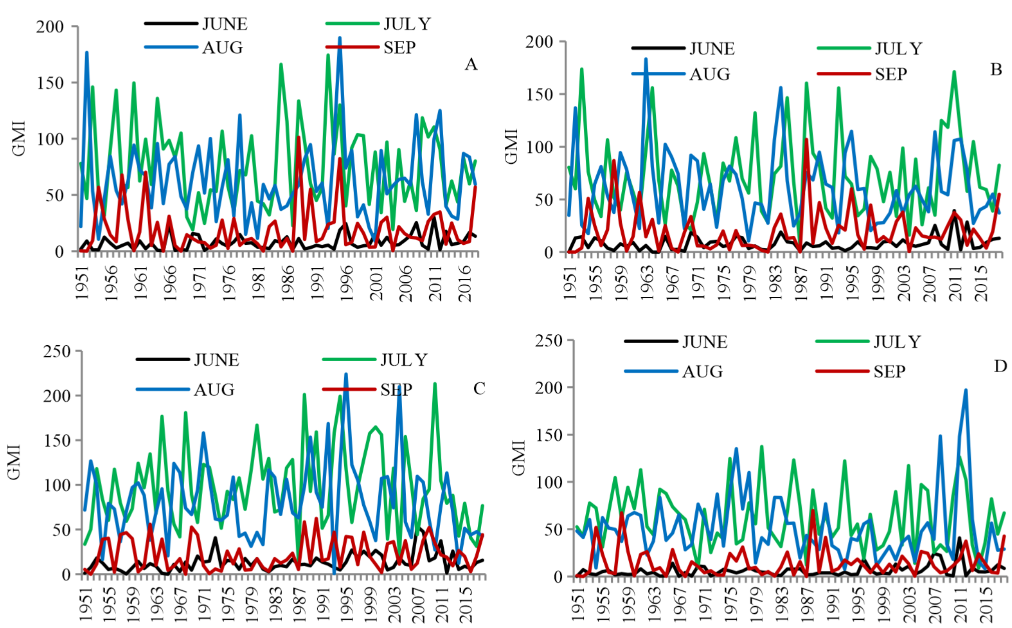


Fig. 4. Generalized Monsoon Index at Kapurthala (A), Ludhiana (B), Patiala (C), and Tarn Taran (D)

Western plain zone

In the western zone, the GMI percentile showed that, at Ferozpur, 1962, 1987, 1991, 1996, 1997-01, 2004, 2014, and 2017 were severe drought impact years. Whereas, at Faridkot, 1967,1979, 1982, 1987, 1989, 1991, 1998-01, 2004 and 2009 were severe drought impact years. In both districts, as in other zones, 7 years were drought-impacted, and 7 years were classified as moderately drought-impacted (Table 4). In Faridkot, an increasing trend in GMI has been observed in June and September, and a decreasing trend in July and August. Both months, i.e., July and August, exhibited a significant decrease in the GMI trend (Fig. 5A). In Ferozpur, an increasing trend in GMI was observed in June, and a decreasing trend in the remaining months of the monsoon season. Whereas, the significant decrease in GMI was noticed in July (Fig.5B).

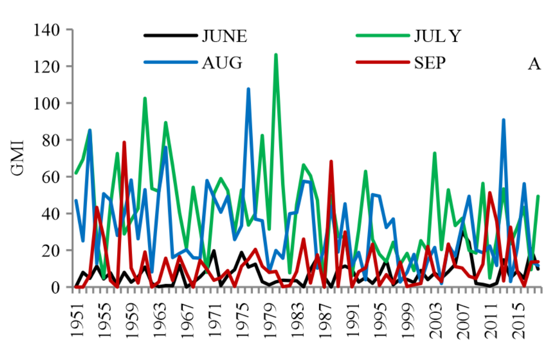
Western Zone

Observations of GMI percentiles for the districts of the western zone revealed that all districts experienced 7 drought-impact years, 7 moderately drought-impacted years, and 13 severely drought-impacted years throughout the monsoon period. The number of years under various GMI percentile categories remains the same; however, the years vary district to district (Table 5).

In Bathinda, an increasing trend in GMI has been observed in June, and a decreasing trend in July, August, and September. While the significant decrease in GMI has been noticed in July over the last 68 years (Fig. 6A). At Barnala increasing trend of GMI has been found in the month of June and September and the decreasing trend in the month of July and August but no significant increase or

Table 4. GMI percentile at western plain zone

Districts	Severe Drought Impact	Drought Impact	Moderately Drought Impact	Normal Crop Condition	Possible Above Normal Crop	Possible Excessive Moisture
Ferozpur	1962, 1987, 1991, 1996, 1997-01, 2004, 2014, 2017	1955, 1967, 1974, 1982, 1989, 1992, 1995	1960, 1977, 1979, 1983, 2011, 2012, 2015	1956, 1959, 1963, 1966, 1968, 1969, 1970, 1975, 1986, 1994, 2002, 2007, 2010, 2018	1951, 1952, 1954, 1957, 1958, 1961, 1965, 1971, 1972, 1973, 1978, 1981, 1984, 1985, 1990, 1993, 2003, 2005, 2006, 2013, 2016	1953, 1964, 1976, 1980, 1988, 1988, 2008
Faridkot	1967, 1979, 1982, 1987, 1989, 1991, 1998-01, 2004, 2009, 2017	1962, 1969, 1974, 1992, 1997, 2002, 2014	1968, 1981, 1995, 1996, 2006, 2012, 2015	1954, 1955, 1957, 1960, 1965, 1966, 1970, 1983, 1986, 1993, 2008, 2010, 2011, 2018	1951, 1952, 1956, 1958, 1959, 1963, 1971, 1972, 1973, 1975, 1977, 1978, 1980, 1984, 1985, 1990, 1994, 2003, 2005, 2007, 2016	1953, 1961, 1964, 1976, 1988, 2013



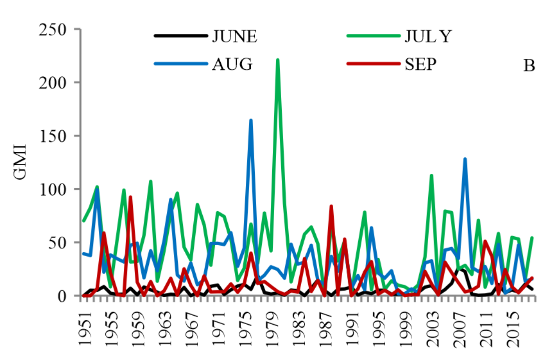


Fig. 5. Generalized Monsoon Index for Faridkot (A) and Ferozepur (B)

Table 5. Generalized monsoon Index percentile at western zone

Districts	Severe Drought Impact	Drought Impact	Moderately Drought Impact	Normal Crop Condition	Possible Above Normal Crop	Possible Excessive Moisture
Barnala	1952, 1961, 1979, 1981, 1982, 1987, 1998, 1999, 2000-02, 2004, 2014	1962, 1968, 1969, 1994, 2007, 2009, 2015	1974, 1996, 1997, 2003, 2006, 2011, 2017	1953-55, 1957, 1965, 1967, 1971, 1977, 1986, 1989, 1991, 1993, 2013, 2016	1951, 1956, 1958, 1960, 1969, 1970, 1972, 1973, 1975, 1976, 1980, 1983, 1977, 1983, 1985, 1992, 2005, 2008, 2010, 2012, 2018	1964, 1978, 1984, 1988, 1990, 1995
Bathinda	1959, 1960, 1961, 1979, 1987, 1989, 1991, 1994, 1999, 2002, 2004, 2011, 2014	1982, 1992, 1996, 1998, 2000, 2001, 2009	1952, 1953, 1955, 1981, 1986, 2006, 2012	1954, 1957, 1969-71, 1974, 1983, 1990, 1997, 2007, 2015-18	1956, 1958, 1963-68, 1972, 1973, 1966, 1967, 1976, 1977, 1980, 1984, 1985, 1993, 1985, 1995, 2003, 2005, 2008, 2010, 2013	1951, 1962, 1975, 1978, 1988, 1995
Mansa	1979, 1981, 1982, 1987, 1989, 1991, 1994, 1996, 1999-02, 2014, 2015	1952, 1980, 1986, 1997, 2004, 2007, 2009	1959, 1965, 1971, 1977, 1992, 2000, 2017	1955, 1967, 1974, 1983, 1984, 1990, 1993, 1998, 2003, 2006, 2011, 2013, 2016, 2018	1951, 1953, 1954, 1957, 1958, 1961-63, 1966, 1969, 1972, 1973, 1976, 1978, 1985, 1995, 1998, 1993, 1988, 1995, 2005, 2008, 2010, 2012	1956, 1960, 1964, 1968, 1970, 1975
Moga	1969, 1979, 1987, 1989, 1991, 1992, 1998-04, 2014, 2015	1952, 1968, 1974, 1986, 1993, 1996, 2011	1955, 1972, 1981, 1982, 1990, 1997, 2013	1951, 1953, 1954, 1956, 1957, 1962, 1965, 1970, 1994, 2002, 2006, 2012, 2017	1958-60, 1961, 1963, 1966, 1967, 1971, 1973, 1976, 1978, 1980, 1983, 1985, 1995, 2003, 2005, 2007, 2010, 2016, 2018	1964, 1975, 1977, 1984, 1988, 2008
Mukatsar	1955, 1959, 1969, 1970, 1979, 1982, 1987, 1991, 2001, 2002, 2004, 2009, 2017	1960, 1974, 1977, 1999, 2000, 2006	1953, 1965, 1968, 1998, 2005, 2008	1951, 1954, 1963, 1981, 1983, 1986, 1989, 1994, 2007, 2010, 2011, 2012, 2016, 2018	1952, 1956-58, 1961, 1962, 1964, 1966, 1967, 1971, 1972, 1973, 1975, 1976, 1980, 1984, 1990, 1993, 1995, 2003	1978, 1985, 1988, 1996, 1997, 2013
Sangrur	1951, 1954, 1974, 1982, 1987, 1991, 1992, 1996, 2000-02, 2014, 2017	1979, 1981, 1999, 2004, 2006, 2013, 2016	1965, 1978, 1986, 1989, 2007, 2009, 2015	1953, 1956, 1961, 1969, 1970, 1972, 1973, 1975, 1980, 1993, 1994, 1997, 1998, 2003	1952, 1955, 1957, 1958, 1959, 1962, 1963, 1966, 1967, 1968, 1971, 1976, 1977, 1983, 1984, 1985, 1990, 2005, 2008, 2010, 2018	1960, 1964, 1988, 1995, 2011, 2012

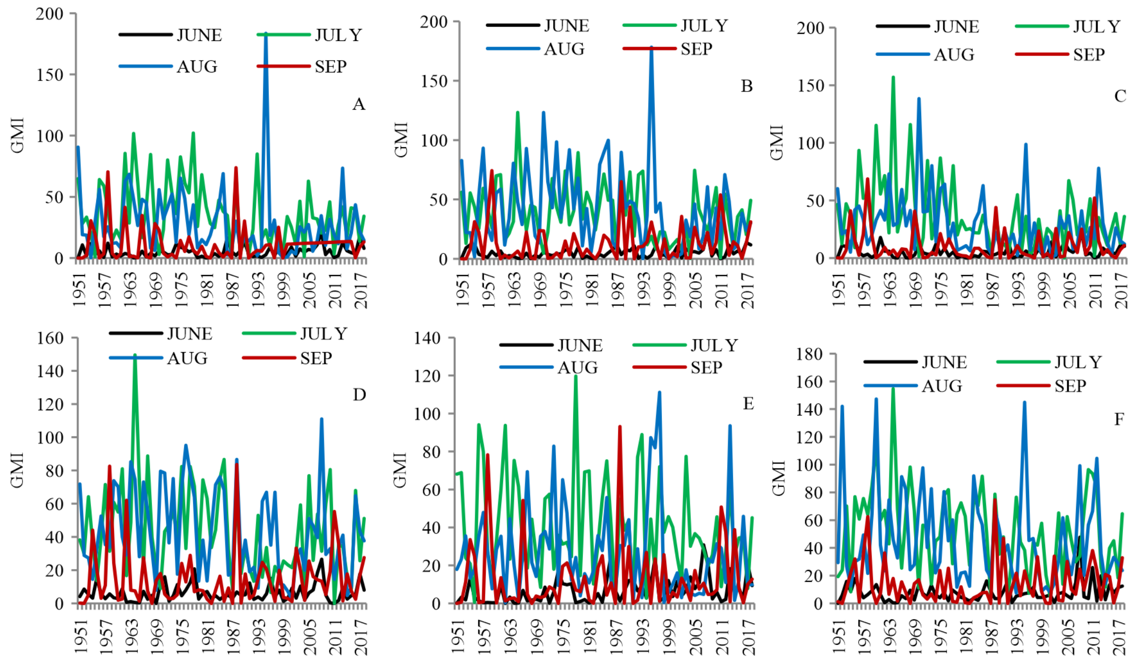


Fig. 6. Generalized Monsoon Index at Bathinda (A), Barnala (B), Mansa (C), Moga (D), Muktsar (E) and Sangrur (F)

decrease in GMI has been noticed in the district during 1951-2018(Fig. 6B). In Mansa, it has been noticed that July, August and September months showed the decreasing trend and June month showed increasing trend of GMI. Whereas a significant decrease has been noticed in the months of July and August (Fig. 6C). At Moga district, GMI analysis indicated the increasing trend of GMI in the months of June and September and decreasing trend in the months of July and August, but no significant increase or decrease in GMI trend has been found in the district (Fig. 6D). At Muktsar increasing trend of GMI has been experienced in the months of June and September. While July and August exhibited a decreasing trend of GMI. The significant increase in GMI has been found in June during the monsoon period in the last 68 years (Fig. 6E). In the Sangrur district, GMI analysis indicated the increasing trend of GMI in the months of June and September and decreasing trend in the months of July and August, but no significant increase or decrease in the GMI trend has been observed in the district (Fig. 6F).

Recurrence Interval of yearly data

A recurrence interval has been observed in the maximum rainfall data from 1951 to 2018 during the monsoon and non-monsoon periods. The return period, or recurrence interval, of 69 years has been observed for the maximum rainfall over the 68 years, meaning the same amount of rainfall is expected to occur after 69 years.

Sub mountain undulating zone

In Gurdaspur and Hoshiarpur, the return period for the maximum rainfall of 1234 mm (1971) and 1220 mm (1998) during the monsoon season is 69 years, respectively. It has been found that maximum rainfall of 742 (1955) and 781 (1955) mm can be expected in a return period of 69 during the non-monsoon period at Gurdaspur and Hoshiarpur, respectively (Table 6). During monsoon season, minimum rainfall of 302 (1987) (Gurdaspur) and 365 mm (1981) (Hoshiarpur) is expected to return in the period of 1.01 years

Undulating plain zone

In the undulating plain zone, at SAS Nagar, SBS Nagar and Rupnagar return period of 69 years have been found for the rainfall of 1228 (1995), 1159 (1988) and 1421 (1988) mm rainfall during Monsoon and 472 (1982), 599 (1955) and 528 (1986) mm during non-monsoon period, respectively (Table 6). After a 1.01-year return period, minimum rainfall of 339 (1987), 159 (2004) and 328 mm (1974) is expected at SAS Nagar, SBS Nagar and Rupnagar, respectively, during the monsoon period.

Central plain zone

In central zone return period of 69 years have been recorded for maximum rainfall of 1204 (2011), 1156 (1988), 1198 (1995), 1195 (1995), 1200 (2011), 1189 (1995) and 1216 (2011) mm during monsoon and 570(1955), 432 (1981), 527 (1955), 517 (1955), 607 (1955), 472 (1982) and 509 (1955) mm during non monsoon period at Amritsar, Fatehgarh Sahib, Jalandhar, Kapurthala, Ludhiana, Patiala and Tarn Taran, respectively (Table 7). Return period of 1.01 years has been observed for the minimum rainfall of 187 (1965), 46 (1987), 224 (1981), 224 (1981), 139 (1987), 309 (2016) and 109 (2004) mm during monsoon season at Amritsar, Fatehgarh Sahib, Jalandhar, Kapurthala, Ludhiana, Patiala and Tarn Taran, respectively.

Western plain zone

In Faridkot and Ferozpur, the return periods for the maximum rainfall of 671 (1958) mm and 964 (1976) mm during the monsoon season are 69 years, respectively. Whereas during the non-monsoon season, maximum rainfall of 462 (1994) and 459 (1994) mm can be expected in a return period of 69 years at Faridkot and Ferozpur, respectively (Table 8). A return period of 1.01 years has been recorded in Faridkot and Ferozepur for the minimum rainfall of 105 mm (1987) and 36 mm (2004), respectively.

Western zone

In western zone return period of 69 years have been recorded for maximum rainfall of 723 (1995), 833 (1988), 607 (1970), 736 (1988), 724 (1988) and 884 (2008) mm rainfall during monsoon and 319 (1975), 447 (1955), 476 (1955), 411 (1955), 383 (1994) and 366 (1955) mm during non monsoon period at Bathinda, Barnala, Mansa, Moga, Muktsar and Sangrur, respectively (Table 9). During monsoon season, a return period of 1.01 years was observed

Table 6. Recurrence Interval for rainfall during monsoon and non-monsoon period at sub mountain undulating zone and undulating plain zone

Return Period (yrs)	Sub mountain undulating zone				Undulating plain zone					
	Gurdaspur		Hoshiarpur		SAS Nagar		SBS Nagar		Rupnagar	
	M (mm)	NM (mm)	M (mm)	NM (mm)	M (mm)	NM (mm)	M (mm)	NM (mm)	M (mm)	NM (mm)
69.00	1234	742	1220	781	1228	472	1159	599	1421	528
34.50	1103	693	1203	464	1214	407	1146	521	1416	520
11.50	990	650	1171	387	1011	321	1006	289	1184	436
4.93	1176	431	1039	293	901	266	799	224	1047	318
2.03	841	258	820	203	769	164	662	155	868	202

M is Monsoon rainfall and NM is Non monsoon rainfall

Table 7. Recurrence Interval for rainfall during monsoon and non-monsoon period at Central zone

Return Period (yrs)	Amritsar		Fatehgarh sahib		Jalandhar		Kapurthala		Ludhiana		Patiala		TarnTaran	
	M	NM	M	NM	M	NM	M	NM	M	NM	M	NM	M	NM
69.00	1203	570	1156	432	1198	527	1195	517	1200	607	1189	472	1216	509
34.50	1120	435	1138	379	1190	427	1100	427	1150	478	1150	407	1079	410
11.50	935	324	904	325	806	336	978	334	842	260	1011	321	697	296
4.93	745	225	783	229	702	218	705	233	710	193	901	266	614	187
2.03	529	148	590	132	547	134	556	130	541	135	767	163	420	113

Table 8. Recurrence Interval for rainfall during monsoon and non-monsoon period western plain zone

Return	Faridkot		Ferozpur	
Period (yrs)	Monsoon rainfall	Non monsoon rainfall	Monsoon rainfall	Non monsoon rainfall
69.00	671	462	964	459
34.50	636	288	761	290
11.50	583	212	672	230
4.93	433	144	470	140
2.03	325	81	332	79

Table 9. Recurrence Interval for rainfall during monsoon and non-monsoon period at western zone

Return	Bathinda		Barnala		Mansa		Moga		Mukatsar		Sangrur	
Period (yrs)	M	NM	M	NM	M	NM	M	NM	M	NM	M	NM
69.00	723	319	833	447	607	476	736	411	724	383	884	366
34.50	680	196	751	275	580	224	720	305	613	213	870	339
11.50	514	132	558	193	472	146	610	197	506	194	696	228
4.93	381	100	492	101	432	94	494	145	411	130	542	154
2.03	269	56	328	71	272	60	370	93	300	72	393	94

for the minimum rainfall of 19 (1999) (Bathinda), 28 (1999) (Barnala), 34 (1987) (Mansa), 104 (2004) (Moga), 78 (1987) (Muktsar) and 83 mm (2001) (Sangrur).

Manikandan *et al.* (2011) reported that the recurrence interval of 72.81 mm rainfall was estimated to occur every 2 years, and for a return period of 100 years and a 1% probability, the one-day maximum rainfall was 173.81 mm, based on 37 years of rainfall data in Tamil Nadu. Bhakar *et al.* (2006) observed that for the 100-year recurrence interval, the highest predictable rainfall in 1, 2, 3, 4, and 5 days is 773.6 mm, 849.34 mm, 874.19 mm, 931.78 mm, and 957.89 mm, respectively. Kumar and Bhardwaj (2015) revealed that in Ludhiana, the maximum rainfall over 38 years (1970-2007) was 105 mm, and the recurrence interval for a 25-year return period was 373 mm. Singh *et al.* (2012) examined 39 years of rainfall data (1973-2011) from the Jhalarapatan region of Rajasthan. They revealed that the maximum rainfall of 252.98 mm was projected to occur in 100 years with 1 % probability, and the minimum rainfall of 44.74 mm was estimated to occur in one day with 99 % probability. There is a clear decline in high-intensity rainfall from the Sub-Mountain Zone (e.g., Rupnagar 1421mm @ 69yr) to the Western Zone (e.g., Mansa 607mm @ 69yr). This confirms that crop water demand in the West is almost entirely dependent on non-monsoon sources. In the Western Plain Zone (Table 8), the Non-Monsoon (NM) rainfall is significantly lower relative to the Monsoon (M) rainfall compared to the Sub-Mountain zones. This suggests that the "*Rabi*" season in the West is subject to much higher water stress. The 11.5-year return period shows that even moderate extremes in the Central Zone (Ludhiana/Patiala) are close to 850-1000 mm, which can lead to localized flooding if drainage is not managed.

The analysis of 68 years of rainfall data across Punjab's agroclimatic zones reveals a significant departure from historical precipitation norms, with profound implications for the state's agricultural resilience. The shift in rainfall timing specifically the significant increase in June rainfall alongside declines in July and August fundamentally alters the crop water demand (CWD) dynamics for the *Kharif* season. The observed increase in June rainfall in districts like Hoshiarpur, SAS Nagar, and the Central Plain zone provides a deceptive sense of water security. While the subsequent significant decrease in July and August rainfall, the critical vegetative and reproductive stages for most *Kharif* crops intensifies the mid-season dry spell phenomenon. Because July is historically the peak rainfall month, a decline here forces farmers to rely heavily on supplemental irrigation resources during periods of high evapotranspiration (ET). This mismatch between natural supply and physiological demand leads to an "irrigation gap," where the energy and groundwater costs for maintaining soil moisture increase exponentially. Furthermore, the GMI percentile results categorizing 27 out of 68 years as experiencing some level of drought impact underscore a persistent state of water deficit that the current cropping intensity cannot sustain. These findings of a 69-year return period for extreme rainfall events alongside a general drying trend in the Western Zone (Faridkot, Mansa, Bathinda) align with broader regional assessments. For instance, Krishan *et al*. (2015) also noted a declining trend in monsoon rainfall across Northwest India, attributing it to the weakening of the Indian Summer Monsoon (ISM) circulation. Our observation of significant July rainfall decreases in Gurdaspur and Ferozepur mirrors the results of Kaur *et al.* (2017), The use of the Generalized Monsoon Index (GMI) reveals a much higher degree of intra-seasonal variability. The practical utility of the GMI as a diagnostic tool is evident. By identifying that only 14 out of 68 years resulted in normal crop conditions, The GMI findings suggest that agricultural authorities must shift from blanket policies to district-specific water management. Moreover, the recurrence analysis provides a baseline for engineering drainage and storage infrastructure; reservoirs must be designed to handle the 69-year return period intensities recorded in the Sub-Mountain zones to prevent flash flooding while simultaneously capturing surplus June runoff for use during the increasingly dry months of July and August.

Conclusion

The analysis of the Generalized Monsoon Index for the sub-mountain undulating zones of Gurdaspur and Hoshiarpur reveals a high degree of inter-annual rainfall variability and its direct consequence on crop conditions. A crossing over six decades, the data revealed that while both districts share a similar geographic classification, their climatic responses often diverge. Gurdaspur exhibits a concerning trend of increasing severe drought frequency in the years to come, whereas, Hoshiarpur shows a more distributed history of climatic extremes. The findings highlight that nearly 40% of the recorded years fall under some form of drought stress, necessitating robust irrigation planning and the adoption of drought-resilient crop varieties. Conversely, the instances of excessive moisture and above normal conditions while less frequent indicate a secondary risk of waterlogging and soil erosion in these undulating terrains. Ultimately, this categorization serves as a vital tool for regional agricultural planning. By understanding these historical patterns, policymakers can develop district-specific contingency plans to mitigate the risks associated with monsoon failure. The increasing volatility observed in recent years underscores the urgency of integrating climate-smart agricultural practices to ensure food security in these environmentally sensitive zones.

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