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Conflicting signals of dry/wet rainfall pattern over the Punjab (Pakistan) during 1961-2015: Complex seasonal changes

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Abstract

In this study, the spatio-temporal characteristics of seasonal and annual rainfall were analyzed during 1961-2015 over nine selected climatic stations of the Punjab province (Pakistan) to identify the dry/wet rainfall events tendencies (moderate/dry) using the Standardized Precipitation Index (SPI) at 10% significance level. The various values of SPI indicate different levels of dry/wet events. An increasing tendency in moderately dry events was observed at two stations in spring, winter and summer while autumn remained unaffected. Significant increase in percentage of extremely dry rainfall events was seen only at two stations. Moderately wet rainfall events during 1990-2015 (F2) increased significantly at seven stations in winter, one in spring, three stations in summer and autumn compared to the period 1961-1990 (F1). The number of significantly extreme wet rainfall events increased at two, two, three, and seven stations in winter, spring, summer, and autumn respectively. Overall winter is vulnerable to moderately wet rainfall events while summer and autumn are subjected to wet extremes at the majority of stations. Drying tendency has little spatial extent and affected only two stations. Seasonal wetting is mostly concentrated in extreme north, mid-south and middle plains of the Punjab province while most wet events occurred during three decades i.e., 1981-1990, 1991-2000 and 2001-2010, the last being the wettest decade. Extremely wet events together with higher daytime temperature have the potential to disturb normal human life and growth of crops especially in summer. The risk of short-term greatest runoff in summer and autumn is very likely due to rainfall extremes.

Keywords: Rainfall pattern; Dry/wet events; Standard Precipitation Index; Seasonal and annual extremes; Climate Change.

1. Introduction

Precipitation is one of the most important meteorological variables in diagnosing climate change as well as exploring the eco-environmental response to climate change on a regional scale (Cannarozzo et al., 2006). Temporal variations in extreme rainfall events are of considerable importance in climate change studies as they greatly affect the socio-economic system in any region. Predicting extreme events of rainfall is a difficult process but it can cause great financial and human losses (Pal and Al-tabbaa, 2009). Extreme wet events of rainfall may lead to severe floods while dry extremes result in frequent droughts and increase in drought affected areas as reported by Solomon et al. (2007. Thus, countries which rely more or less on agriculture are highly vulnerable to the negative impacts of severe rainfall events. The water balance on the earth surface is affected majorly by rainfall instigating significant changes in water resources as explained in the intergovernmental panel on climate change (IPCC, 2001). Droughts in arid and semi-arid area caused by no rainfall may result in land degradation, economic costs and irreversible damage to ecosystem (Winslow et al., 2011). The IPCC (2014) reported that economic losses from weather- and climate-related disasters have increased during the last 60 years and is very likely to have greater impacts on sectors such as water, agriculture and food security, whereas the highest fatality rates and economic losses caused by climate induced disasters are being registered in developing countries. Earlier multiple disaster events in Asia were observed in 2010 mainly because of changes in rainfall pattern which caused drought in Southwest China and severe floods in Pakistan, India, and many other provinces in China (Liang et al., 2011). These extreme rainfall patterns caused great human, financial and agricultural losses in entire South Asian region. Thus, changes in rainfall extremes have a widespread effect on the regional economy, agriculture and ecosystem.

Trends in extreme weather (rainfall and temperature) events can be assessed by analyzing historical data and its statistical properties (Pal and Al-tabbaa, 2009). In their study, Fischer et al. (2011) used daily rainfall data (1961-2007) of 192 weather stations to analyze trend of dry/wet rainfall events in the Zhujiang River Basin, South China. They used two meteorological indices such as Standardized Precipitation Index (SPI) and Palmer Drought Severity Index (PDSI) to recognize extreme rainfall events. Trend in extreme events was assessed using non-parametric Mann-Kendall (MK) test. Results revealed no significant trends in extreme rainfall events though some regional trends were pointed out. Bordi et al. (2004) assessed the variations in dry and wet periods from 1951 to 2000 at 160 stations in the Eastern China. They also used SPI and the principal component analysis (PCA) to analyze the climatic conditions along with co-variability of the stations. Their results revealed more frequent dry conditions in the Northern part of Eastern China. In another study, Spinoni et al. (2015) used three meteorological indices namely SPI, the Standardized Precipitation Evapotranspiration Index (SPEI), and the Reconnaissance Drought Index (RDI) to identify areas vulnerable to extreme rainfall events (droughts or high intensity rainfall) across the Europe. They used daily rainfall and temperature data from 1950 to 2012 and derived potential evapotranspiration (PET) from this data. Their findings revealed that droughts are driven by increase in PET and temperature and decrease in rainfall in different regions. Their study exposed the fact that even significant rainfall increase may lead to drought frequency, severity, and duration if it is concentrated in time and unseasonable.

Majority of the assessment studies in Pakistan have focused on trend detection in normal rainfall and temperature data (e.g. Salma et al., 2012; Rio et al., 2013; Khattak and Ali, 2015) but very little work has been done to investigate variations in rainfall pattern over Pakistan except by Maida and Ghulam (2011). An increase in extreme events of rainfall over most parts of the Pakistan including the Punjab province, Northern areas, Balochistan province, and Azad Kashmir was reported by Maida and Ghulam (2011) though dry and wet events were not identified. Punjab is the agricultural and industrial backbone of Pakistan as it engages nearly 49% of the labor in agricultural and related sectors. It is also worth noticing that Punjab produces 76% of the total annual grain production and is especially dominant in agriculture sector because 56.1% to 61.5% of the total agricultural products are produced in the Punjab (Pakistan Bureau of Statistics, 2011). Wheat and cotton are the major crops grown in the Punjab which ensure food security and considerable livelihood respectively. In Pakistan, it is not possible to make a viable climatological assessment considering many climatological factors. Firstly, this country often facing financial and institutional barriers to establish an advanced climate data evaluation system due to limited resources and unavailability of the modern technological tools. Such studies help in updating climate record of a region. Secondly, no comprehensive study has been carried out to investigate variations in moderate and extreme dry/wet rainfall events over the Punjab using the latest data. Thirdly, researchers consider 35°C as threshold temperature which is an upper limit of survivability for a healthy human under well-ventilated outdoor conditions, whereas a maximum day temperature above 35°C together with high humidity caused by wet events often affects human habitability (Joshi et al., 2011). A large segment of country population lives in the Punjab prone to high humidity (extreme wet events) when temperature is above 35°C in summer. In such situation, it is essential to analyze changes in moderate/extreme rainfall events (dry/wet) in the Punjab (the agricultural and industrial hub of Pakistan) to depict a better picture to policy makers and concerned experts. Extreme dry/wet rainfall events on the Punjab could cause serious threats to the food security of Pakistan. Considering a long-term rainfall data, the main objective of this study was to develop an understanding of the extreme rainfall events (seasonal and annual) on a regional scale and to assess in framing best water management policies to counter balance temporary higher runoff and dry conditions. It could also help in adopting sustainable agricultural practices by managing extreme wet/dry rainfall events and avoiding possible threats to food security.

2. Materials and methods

2.1. Study area

Pakistan comprises of five provinces namely Khyber Pakhtunkhwa, Sindh, Punjab, Gilgit Baltistan, Balochistan and a federally administered tribal area (FATA) as shown in figure 1. The Jhelum, Chenab, Ravi, Bias and Sutlej are the major rivers which flow through the Punjab province of this country. The study area (Punjab) is host to largest share of poulation in Pakistan (Fig. 1). The northern areas of this province receive much more rainfall compared to the southern regions. Jhelum and Sialkot receive the greatest share of rainfall in the range of 768-965 mm/year while Rawalpindi and Lahore receive 430-767 mm/year indicating semi-arid to sub-humid climate (tropical continental) as reported by Khattak and Ali (2015). Thus, both rainfall and humidity decrease while moving from north to south in Punjab resulting dryness in southern districts. Despite the fact that this province has a dry climate, irrigation makes it a rich agricultural land.

2.2. Meteorological data and methodology

Historical monthly rainfall data for nine stations of the Punjab province was provided by the Pakistan Meteorological Department (PMD). Due to unavailability of long term data from Southern Punjab, we considered D.I. Khan climate station data to represent Southern Punjab climatic characteristics. This data was analyzed for rainfall extremes during 1961-2015 except two stations (D.I. Khan and Bahawalpur) where the data available for analysis was from 1980 to 2015. Some basic characteristics of the selected climatic stations are given in figure 2 and Table 1. Seasonal data was derived by taking average of their respective months i.e. winter (December, January and February), spring (March, April and May), summer (June, July and August), and autumn (September, October and November). For seasonal and annual average rainfall, monthly values were added. The first step was to identify moderate/extreme rainfall events (dry or wet) using the SPI, a meteorological drought index developed by Mckee et al. (1993) and to quantify rainfall deficits or excesses in any region.

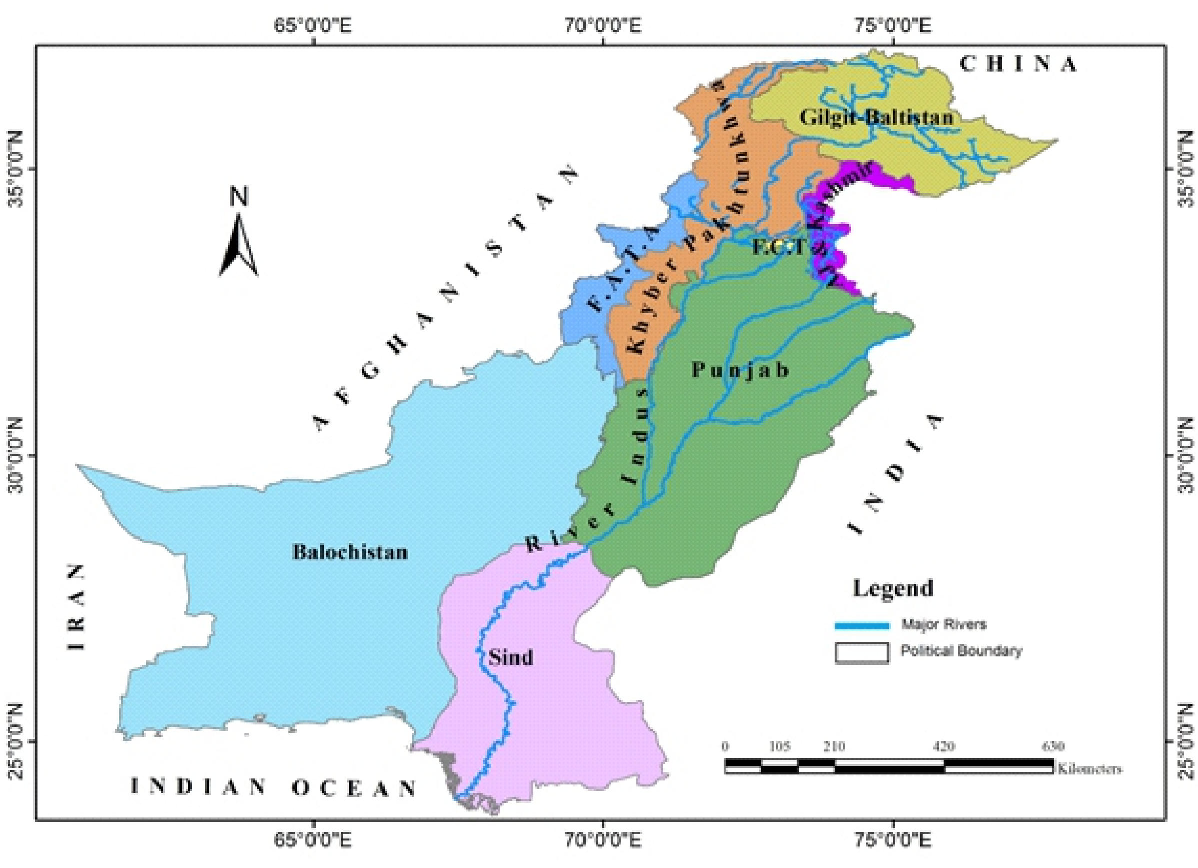

Fig. 1. Map of Pakistan showing study area.

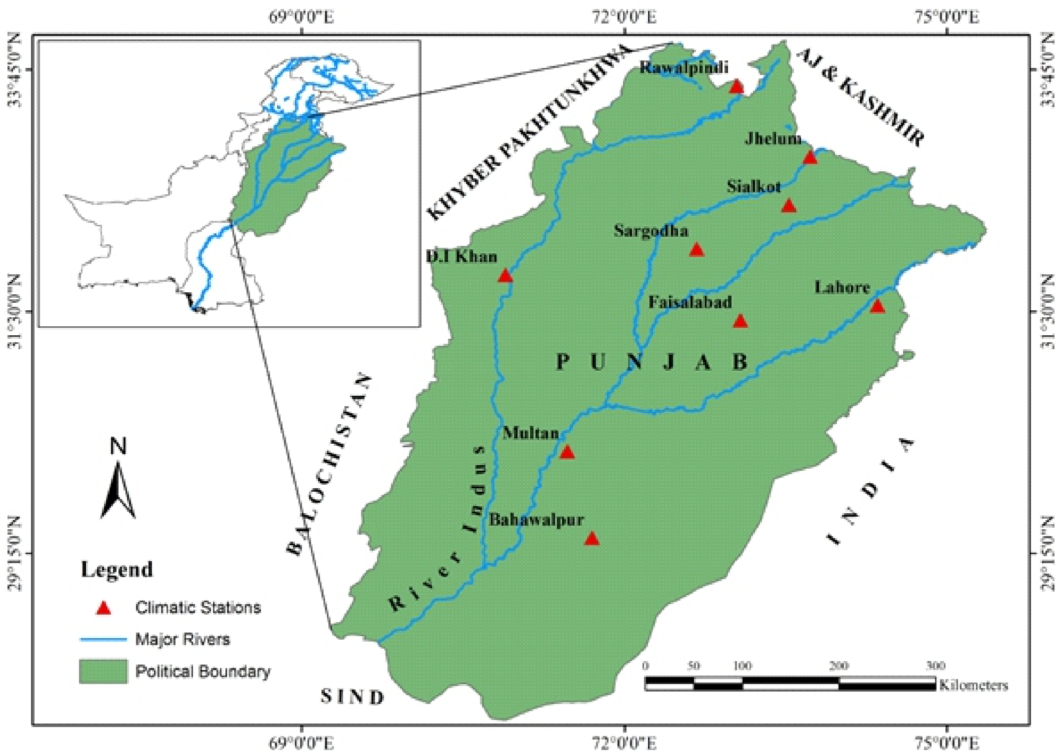

Fig. 2. Geographic locations of nine climatic stations in the study area.

Table 1. Climatic stations with location and Elevation above mean sea level in meters.

S. No.	Station	Latitude (degrees)	Longitude (degrees)	Elevation (m)
1	Faisalabad	31.43	73.13	185.60
2	Lahore	31.55	74.34	214.00
3	Jhelum	32.93	73.73	287.19
4	Multan	30.20	74.43	121.95
5	Sargodha	32.05	72.66	187.00
6	Sialkot	32.51	74.52	255.10
7	Bahawalpur	29.39	71.68	118.00
8	D.I Khan	31.81	70.93	171.20
9	Rawalpindi	33.60	73.10	487.00

2.3. Standardized precipitation index (SPI)

The Standardized precipitation index (SPI) (McKee et al., 1993) is used to quantify the precipitation deficit on multiple time scales and is defined on each of the time scales as the difference between precipitation on the time series (xi) and the mean value (x), divided by the standard deviation (s), i.e.

$$SPI = \frac{x_i - \overline{x}}{s} \quad (1)$$

It is well documented that very seldom the monthly precipitation time series fits a normal distribution, thus precipitation data was transformed to make SPI a standard normal distribution variable. The first step in the SPI calculation is to determine the probability density function (PDF), which describes the long-term observed precipitation. Next, the cumulative probability of the observed precipitation is computed. It was accomplished after applying the Easyfit software 5.0 version and log-normal distribution was found an effective distribution for the data under consideration after comparison among different distributions based on the Kolmogorov-Smirnov and Anderson-Darling tests. After logarithmic transformation of the dataset, the sample mean and variance of the transformed data will be $\hat{\mu}_y$ and $\hat{\sigma}_y$,then the SPI becomes (Zhong et al., 2009);

$$SPI = Z = \frac{\log(x_i) - \hat{\mu}_y}{\hat{\sigma}_y} \quad (2)$$

Intensity of dryness and wetness caused by less or more rainfall was classified based on the SPI values as shown in Table 2 (Bonaccorso et al., 2003). It should be noted that the SPI depends on length of rainfall time series and its mean value and is not an absolute rainfall index. However, it has been frequently used by researchers to depict a general picture of rainfall patterns in various regions of the world. The study area has enough historical rainfall record to determine the SPI values.

Although dryness/wetness is governed by multiple regional factors like mean temperature, PET, soil moisture condition, atmospheric humidity, wind speed, and duration of sunshine, rainfall is the most dominant factor. Due to unavailability of long-term data for other parameters, the analyses were carried out based on only one index (SPI) in this study. Since Punjab province has a very fine network of canals to meet irrigation demands and keeps soil moist. Therefore, being a dominant factor, rainfall was considered to identify dry/wet extremes. Dry and wet rainfall events are often classified by their severity and can be calculated for multiple time scales.

In first step, after recognizing moderate/ extreme rainfall (dry and wet) events based on the SPI, percentage of such events was calculated on seasonal and annual basis in three time periods i.e. 1961-2015 (F1), 1961-1990 (F2) and 1990-2015 (F3) for 10% significance level. These analyses would enable us to know: (1) the percentage of moderate/extreme rainfall events (dry and wet) during F1, F2 and F3 on seasonal and annual basis at nine climatic stations and, (2) the significant increase or decrease in percentage of moderate/extreme rainfall events (dry and wet) in the period F3 when compared with the baseline period (F2). The difference in percentage of moderate/extreme rainfall events during two periods F2 and F3 (% in F3 - % in F2) demonstrates the magnitude of change (tendency) that occurred after 1990s. The reason is that the period from 1960-1990 (F2) had observed very few extreme rainfall events in climatic record thus allowing sustainable agriculture in Punjab. Another reason is that most of the climatic disasters occurred in the form of heavy rainfall in the post 1990 period causing immense agricultural and financial losses in the Punjab province thus demanding investigation of such tendencies in extreme events of rainfall compared to disaster free period (F2).

In second step, the number of dry/wet (both moderate and extreme) months in each year during 1961−2015 were identified. Total number of moderate and extreme dry/wet months in each decade was found to identify decades with greater number of both dry and wet rainfall extremes at various stations. This could help to recognize areas vulnerable to rainfall extremes resulting in temporary drought or occasional higher runoff. Decadal analyses applied which could show tendency of dryness/wetness in rainfall pattern over time at various stations. In last step, months with greatest number of dry/wet rainfall extremes during 1961-2015 were identified. All stations were arranged and analyzed in a way to depict latitudinal variations in rainfall dry/wet events starting with the extreme north to the extreme south of the study area. Thus, both temporal and spatial variations were explored during the study period (1961-2015).

3. Results and discussions

Initial investigation of data revealed few important aspects of variations in rainfall patterns. Firstly, the moderate dry rainfall events (in percentage) were found greater than their associated extreme dry events for the three times periods (F1, F2, and F3) on seasonal and annual basis. Secondly, dominant variations in moderately wet and extremely wet rainfall events were seen in winter and autumn respectively at majority of the stations. Faisalabad and Multan were subjected to greatest number of moderately wet patterns while Rawalpindi and Multan observed greatest number of extreme wet rainfall events on seasonal and annual basis. Moderately dry events were mostly concentrated in spring, summer and winter at fewer stations while extreme dry had no effect on any season. Variations in dry/wet rainfall patterns (both moderate and extreme) were concentrated in extreme north (Rawalpindi) and central plains (Faisalabad and Multan) of Punjab. Majority the wet rainfall events (moderate/extreme) were observed during1980-2010 which occurred mostly in January, March, July, August and November, while dry events were dominant in July and August at majority of the stations. A detailed discussion on the variations both in the dry and wet rainfall patterns is given under various headings in the following sections.

3.1. Seasonal and annual variations in dry/wet rainfall pattern

3.1.1. Moderate rainfall events (dry/wet)

Significant percentage increase in dry/wet events during F3 was identified compared to the baseline period (F2) to see the tendency of dry/wet rainfall patterns. Significant increasing tendency in dry rainfall events (in post 1990 period) was observed at two stations in spring, winter and summer while autumn remained unaffected (Table 3). Thus spring, winter and summer are vulnerable to moderate dry events of rainfall at fewer stations of Punjab. This slight seasonal dryness is mostly concentrated in Faisalabad and Sargodha located in the mid-north of Punjab. On annual basis, significant drying tendency was observed only at two stations (Rawalpindi and Faisalabad). Bahawalpur is the only station which exhibited least tendency of change in all seasons i.e. no significant fluctuation in rainfall pattern during 1961-2015. This might be attributed to very little rain in Bahawalpur resulting in no extreme dry event as the SPI is based on the values of rainfall time series. Thus, the use of SPI to identify rainfall patterns in extremely dry regions does not seem to be a good practice. Wet rainfall events in post 1990 period increased significantly at seven stations in winter, one station in spring, three stations in summer and autumn. On annual basis three stations exhibited significant increasing tendency of wet rainfall events. Among seasons, winter is most vulnerable to changes in moderate wet events of rainfall while spring being least affected (Table 3).

Wetting tendency is very dominant at mid-Northern stations compared to the drying and its temporal and spatial extent was greater as well. Because the wetting tendency was moderate, so it might not lead to produce higher runoff. However, it might increase "mugginess" in summer creating slight difficulty for normal life. Mugginess is the combine measure of temperature and humidity (when temperature is above 35°C) that often affects normal life in extremely wet summers (Joshi et al., 2011). It was interesting to note that both dry and wet rainfall events occurred in same season at many stations suggestive of complex changes in rainfall patterns (e.g. Sargodha and Lahore) where dryness was followed by wetness in most seasons. This alternate drying/wetting in one season causes abrupt fluctuations in groundwater recharge and sometimes energy demands specially in summer. Concentration of rainfall in one month rather than entire season does not ensure effective groundwater recharge as recharge occurs slowly with the passage of time. The effects of non-uniform temporal variations in rainfall (within a season) on various sectors must be investigated.

3.1.2. Extreme rainfall events (dry/wet)

During the post 1990 (F3), the percentage increase (significant) in extreme dry rainfall events relative to baseline period (F2) was observed only at two stations namely Jhelum (winter) and Sargodha (summer).

Table 2. Wet and dry rainfall events classification according to the SPI index (Bonaccorso et al., 2003)

Index Value	Class
$2.00 \geq SPI$	Extreme wet
$1.50 < SPI < 2.00$	Severe wet
$1.00 \leq SPI < 1.50$	Moderate wet
$-1.00 \leq SPI < 1.00$	Normal
$-1.50 \leq SPI < -1.00$	Moderate dry
$-2.00 \leq SPI < -1.50$	Severe dry
$SPI < -2.00$	Extreme dry

Table 3. Percentage of moderate dry/wet events of rainfall on seasonal and annual basis at nine climatic stations of Punjab.

Station	Period	Winter		Spring		Summer		Autumn		Annual	
		Dry	Wet	Dry	Wet	Dry	Wet	Dry	Wet	Dry	Wet
Rawalpindi	F1	9.25	9.25	3.7	3.7	13	14.81	3.7	3.7	9.25	9.25
	F2	10	3.33	3.33	3.33	16.66	6.67	6.66	0	6.67	3.33
	F3	8.33	**16.66**	**4.16**	**4.16**	8.33	**25**	4.16	0	**12.5**	**16.67**
Jhelum	F1	9.25	7.4	3.7	1.85	11.11	12.96	5.55	7.4	14.8	13
	F2	10	3.33	3.33	3.33	6.66	20	10	10	16.7	13.33
	F3	8.3	**10**	**4.16**	0	4.16	16.67	0	4.16	12.5	12.5
Sialkot	F1	13	7.4	1.85	3.7	9.25	5.55	5.55	11.11	9.25	11.11
	F2	13.33	3.33	3.33	3.33	10	0	10	13.33	10	3.33
	F3	12.5	**12.5**	0	**4.16**	8.33	**12.5**	0	8.33	8.33	**16.67**
Sargodha	F1	7.4	7.4	11.11	5.55	5.55	11.11	3.7	3.7	5.55	7.4
	F2	3.33	3.33	3.33	10	10	13.33	3.33	6.66	10	10
	F3	**12.5**	**12.5**	**20.8**	0	8.33	0	**4.16**	0	0	**16.67**
Faisalabad	F1	3.7	5.5	7.4	7.4	7.4	3.7	0	7.4	12.9	7.4
	F2	3.3	3.3	6.6	6.6	3.3	3.3	0	3.3	10	6.6
	F3	**4.1**	**8.3**	**8.3**	**8.3**	**12.5**	**4.1**	0	**12.5**	**16.6**	**8.3**
Lahore	F1	9.2	9.2	5.5	3.7	5.5	5.5	0	9.25	12.9	7.4
	F2	13.33	6.6	3.3	6.6	3.3	3.3	0	6.6	13.3	10
	F3	8.3	**12.5**	**8.3**	0	**8.3**	**8.3**	0	**12.5**	12.5	4.16
D.I Khan	1980-2015	5.8	8.83	3	3	14.7	5.8	21.7	5.8	11.7	0
	1981-1990	0	20	10	0	30	10	10	0	20	0
	1991-2015	**13**	0	0	**13**	8.7	4.3	8.7	8.7	8.7	0
Multan	F1	0	1.8	14.8	11.1	7.4	11.1	0	3.7	11.1	11.11
	F2	0	0	13.3	10	10	10	0	0	10	16.6
	F3	0	**4.1**	**16.6**	**12.5**	4.1	**12.5**	0	**8.3**	4.16	4.16
Bahawalpur	1980-2015	0	2	0	6	0	8	0	4	0	9
	1981-1990	0	0	0	2	0	4	0	0	0	5
	1991-2015	0	**3**	0	**3**	0	2	0	0	0	3

On annual basis, only one station (Sargodha) was affected showing significant increasing tendency of extreme dry events in F3 (Table 4). Thus, none of the stations and seasons (except two stations) was affected by dry extremes. The percentage of extreme dry events was almost negligible when compared to moderate dry events of rainfall at all stations. If this pattern of extreme dry events continued in future, then there is no possibility of rain driven drought in Punjab in coming decades. The percentage wet rainfall extreme events in F3 increased at two, two, three, and seven climatic stations in winter, spring, summer, and in autumn respectively. On annual basis, four stations exhibited significant increasing tendency of extreme wet rainfall events. Thus, among seasons, summer and autumn were most vulnerable to changes in extreme wet rainfall events while winter being least affected at most stations except Bahawalpur. Rawalpindi and D.I Khan suffered changes in wet extremes in most seasons and on annual basis while Sialkot was least affected. Spatial distribution of wetting tendency has been shown in T. 3 to facilitate policy makers to recognize stations vulnerable to wet extremes. Wetting tendency was found mostly concentrated in extreme north, mid-south and middle plains of Punjab. Bahawalpur was the only station which remained unaffected (Fig. 3). Stations with increasing extreme wet events in summer might cause extreme “mugginess” at daytime. Such high mugginess would result in disturbed normal life if same trend continued in near future.

Table 4. Percentage of extreme dry/wet events of rainfall on seasonal and annual basis at nine climatic stations of Punjab.

Station	Period	Winter		Spring		Summer		Autumn		Annual	
		Dry	Wet	Dry	Wet	Dry	Wet	Dry	Wet	Dry	Wet
Rawalpindi	F1	0	3.7	0	5.55	0	3.7	0	7.4	0	5.55
	F2	0	0	0	4.16	0	3.33	0	3.33	0	0
	F3	0	**8.33**	0	**8.33**	0	4.16	0	**12**	0	**12**
Jhelum	F1	1.85	3.7	0	7.4	0	5.55	0	5.55	0	1.85
	F2	0	3.33	0	6.67	0	0	0	6.67	0	0
	F3	**3.33**	3.33	0	8.33	0	**12.5**	0	4.16	0	**4.16**
Sialkot	F1	0	1.85	0	3.7	0	5.55	0	1.85	0	5.55
	F2	0	4.16	0	6.66	0	6.66	0	0	0	6.67
	F3	0	0	0	0	0	4.16	0	**4.1**	0	4.16
Sargodha	F1	0	7.4	0	3.7	3.7	3.7	0	5.55	3.7	1.85
	F2	0	6.67	0	8.33	0	6.66	0	0	0	3.33
	F3	0	8.33	0	0	**8.33**	0	0	**12.5**	**8.33**	0
Faisalabad	F1	0	3.7	0	7.4	1.85	5.5	0	5.5	0	5.5
	F2	0	6.66	0	6.6	3.3	3.3	0	0	0	3.3
	F3	0	0	0	8.3	0	**8.3**	0	**12.5**	0	4.16
Lahore	F1	0	5.5	0	3.7	0	7.4	0	1.8	0	5.5
	F2	0	6.6	0	6.6	0	6.6	0	0	0	3.3
	F3	0	4.1	0	0	0	8.3	0	**4.16**	0	**8.3**
D.I Khan	1980-2015	0	3	0	3	0	5.8	0	3	0	3
	1981-1990	0	10	0	0	0	0	0	0	0	0
	1991-2015	0	0	0	**4.3**	0	**8.7**	0	**4.3**	0	**4.3**
Multan	F1	0	9.2	0	3.7	0	3.7	0	7.4	0	3.7
	F2	0	6.6	0	3.3	0	3.3	0	3.33	0	3.3
	F3	0	**12.5**	0	4.1	0	4.16	0	**12.5**	0	4.16
Bahawalpur	1980-2015	0	7	0	3	0	5.7	0	3	0	3
	1981-1990	0	4	0	0	0	1.5	0	4	0	0
	1991-2015	0	3	0	0	0	1	0	0	0	0

One major issue with the extreme rainfall events is the damage to standing crops due to water ponding in the fields. Crops that are grown in summer and autumn could be highly vulnerable to rainfall extremes at most stations. The risk of short-term flood/runoff in summer is very likely as monsoon often bring disasters in Punjab e.g. the 2010 flood. In this context special varieties of crops must be introduced to resist such extremes in rainfall. New field slopes should be introduced which should not allow ponding in fields. Re-design of existing drainage system is extremely essential to drain off higher short-term runoff caused by rainfall extremes. Settlements close to rivers banks must be removed to avoid human and financial losses. It was interesting to note that total number of moderate rainfall events observed increasing tendency was same as that of extreme rainfall (wet) events when significance was ignored.

3.1.3. Spatial and decadal variations in monthly dry/wet events

For decadal analyses, moderate/extreme months were identified to obtain total number of dry/wet events in all years starting from 1961 to 2015. Meanwhile, identification of daily extremes was avoided because the focus was to recognize dry/wet months having moderate/extreme tendency during 1961-2015 based on the SPI. Moderate and extreme monthly events were added to get total number of dry/wet events in all decades. This led us to know the net count of dry/wet monthly rainfall events irrespective of their intensity i.e. moderate and extreme. Greatest number of dry months was seen in Jhelum (north) while least was observed in Multan (mid-south) during F1.

Faisalabad, Sargodha, Sialkot and Jhelum (middle and north of Punjab) observed greatest number of wet months among all stations while D.I. Khan showed the least number of wet months during 1961 to 2015 (Table 5 and Fig. 3). On monthly basis both dryness/wetness is focused mainly in northern and mid northern stations. Except Bahawalpur all stations observed most of monthly wet events in three decades i.e. during 1981-1990, 1991-2000 and 2001-2010, the last being the wettest decade of all. Thus, the large number of wet months was found during 1980-2010 for the available data record. The two decades (i.e. 1961-1970 and 1971-1980) depicted least number of wet months though equal in number (Table 6). Thus, greatest temporal variation started from 1980s and onwards which might be attributed to global warming, regional changes, local industrial growth and start of urbanization.

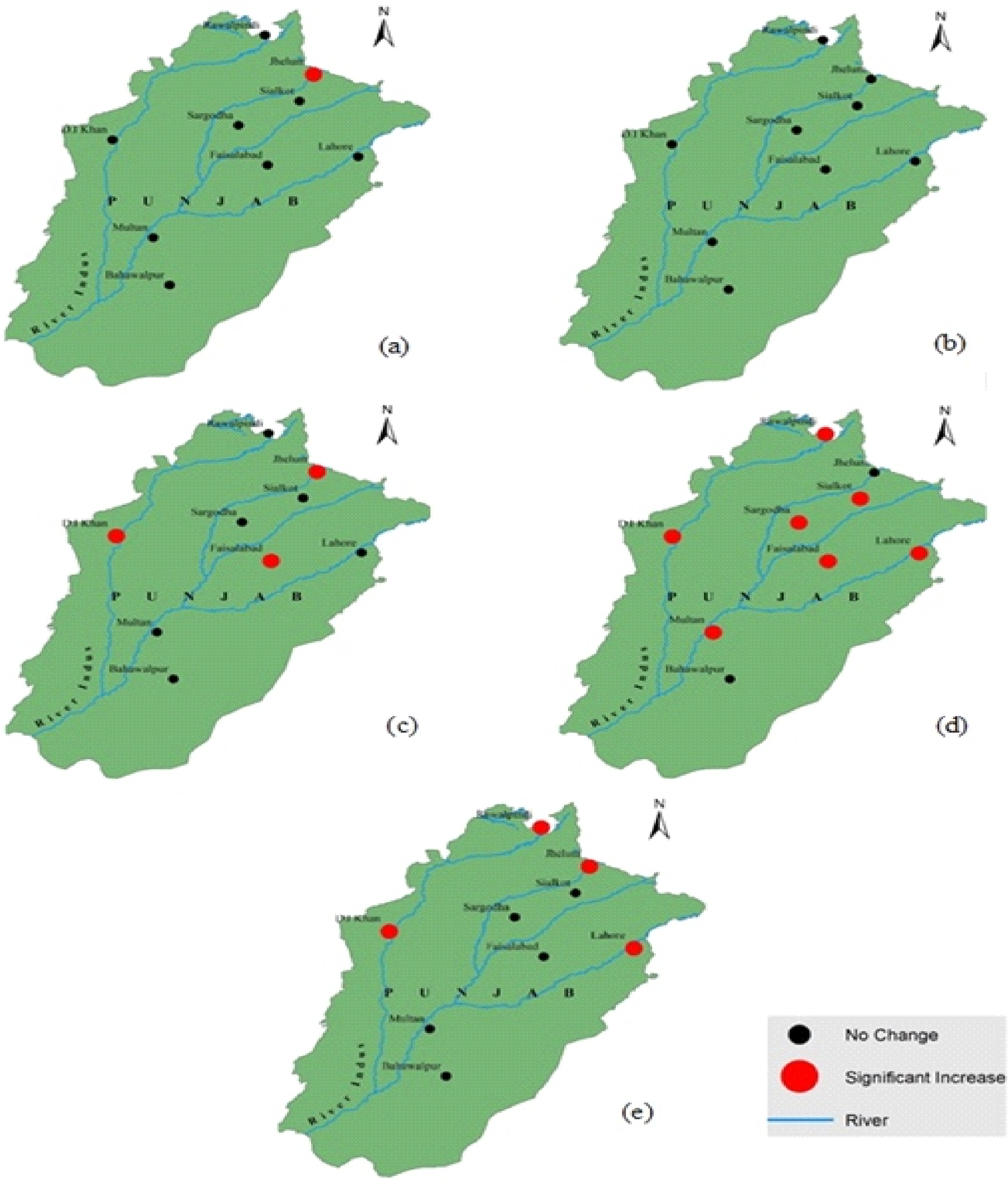

Fig. 3. Showing spatial distribution of changing tendencies in extreme wet events of rainfall in: (a) winter, (b) spring, (c) summer, (d) autumn, and (e) annual over the period 1961–2015. The Black circle indicates "No change" while Red circle shows "significant increase" in % of wet extremes during 1990-2015 relative to 1960-1990.

This study gave considerable insights to the tendencies of dryness/wetness pattern in the province of Punjab, Pakistan. The data at hands was sufficient to achieve the primary purpose of identifying dryness/wetness at selected climatic stations though further investigation is needed for a broader picture of regional tendencies in climate using other indices. The observed increase in wetting patterns (both moderate and extreme) was in perfect agreement with the findings of Khattak et al. (2011) whom reported an increasing rainfall trends at the extreme north and central districts of Punjab. The increase in moderate dry events after 1990 might be connected to ever weakening monsoon system as El-Nino phenomena suppress monsoon rainfall over Pakistan (Ali, 2012). In addition, the La-Nina phenomenon has a negative impact on winter rainfall over Pakistan (Azmat, 2004). It might also be concluded that dryness in Punjab seems to be driven by these two (El-Nino and La-Nina) global climatic drivers. Further research is needed to find possible causes of increasing drying patterns over the Punjab province of Pakistan. In addition, keeping in mind the monthly historical tendency of being dry/wet at various locations, water management experts could be able to formulate mitigation strategies to counter balance instances of possible temporary droughts or abnormal runoff in these areas in respective months.

Rainfall has shown a very low percentage of significant results (Table 7). In general all stations have increasing trends on annual level in which Rawalpindi (3.62 mm/year, very strong) and D.I. Khan (1.96 mm/year, strong) have revealed significant values. Significant positive trends in autumn were seen only at four stations and this is one of the possible cause for rise in rainfall on annual basis at these stations. General positive (Mostly weak and little) trends in winter, spring and summer at all stations were observed with significant values only at Rawalpindi. Thus it can be concluded that Punjab experienced general increasing trends in rainfall on annual basis mainly because of positive trends in autumn (mostly strong). Among all climatic stations Rawalpindi is the only station which has seen highest positive trends in rainfall at all levels despite having greatest warming trend in temperature. Like temperature, increasing rainfall trends can also be observed in extreme north (Rawalpindi) of Punjab. Thus the north and north-eastern districts of Punjab are the victims of significant change in the annual and seasonal rainfall trends.

Table 5. Temporal variations in monthly dry/wet rainfall events in all decades where moderate and extreme were taken together.

Station	Nature of Event	Number of monthly rainfall events (moderate + extreme) in all decades					
		1961-1970	1971-1980	1981-1990	1991-2000	2001-2010	2011-2015
Rawalpindi	Dry	1	2	1	1	5	1
	wet	4	7	13	10	22	13
Jhelum	Dry	12	3	9	5	7	2
	wet	15	12	13	19	14	7
Sialkot	Dry	6	0	3	1	3	1
	wet	13	11	20	20	12	4
Sargodha	Dry	2	2	3	4	10	1
	wet	12	13	17	16	20	4
Faisalabad	Dry	1	2	1	2	1	0
	wet	11	15	16	12	21	9
Lahore	Dry	2	0	2	2	2	2
	wet	6	6	20	14	8	10
D.I Khan	Dry	-	-	2	2	6	3
	wet	-	-	17	11	19	6
Multan	Dry	0	0	0	0	1	0
	wet	6	13	12	16	16	6
Bahawalpur	Dry	-	-	0	0	0	0
	wet	-	-	0	0	0	1

Table 6. Total number of monthly dry/wet rainfall (moderate and extreme) events at nine stations of Punjab in F3 (1961-2015) with their associated months.

Station	Nature of rainfall event	Total No of monthly events (moderate/extreme taken together)	Months frequently subjected to moderate and extreme events of rainfall in F1
Rawalpindi	Dry	11	July, August
	wet	69	April, May
Jhelum	Dry	38	Jan, Aug, Sept
	wet	80	Feb, June, Nov
Sialkot	Dry	14	June, July
	wet	80	Jan, Aug, Oct, Nov
Sargodha	Dry	22	Mar, July, Aug
	wet	82	Jan, Mar, July, Aug, Oct
Faisalabad	Dry	7	August
	wet	84	Jan, June, Aug, Nov
Lahore	Dry	10	July
	wet	64	Jan, Feb, April
D.I Khan	Dry	13	March, July
	wet	53	March. July
Multan	Dry	1	No month affected
	wet	69	March, May, June
Bahawalpur	Dry	0	No month affected
	wet	1	February

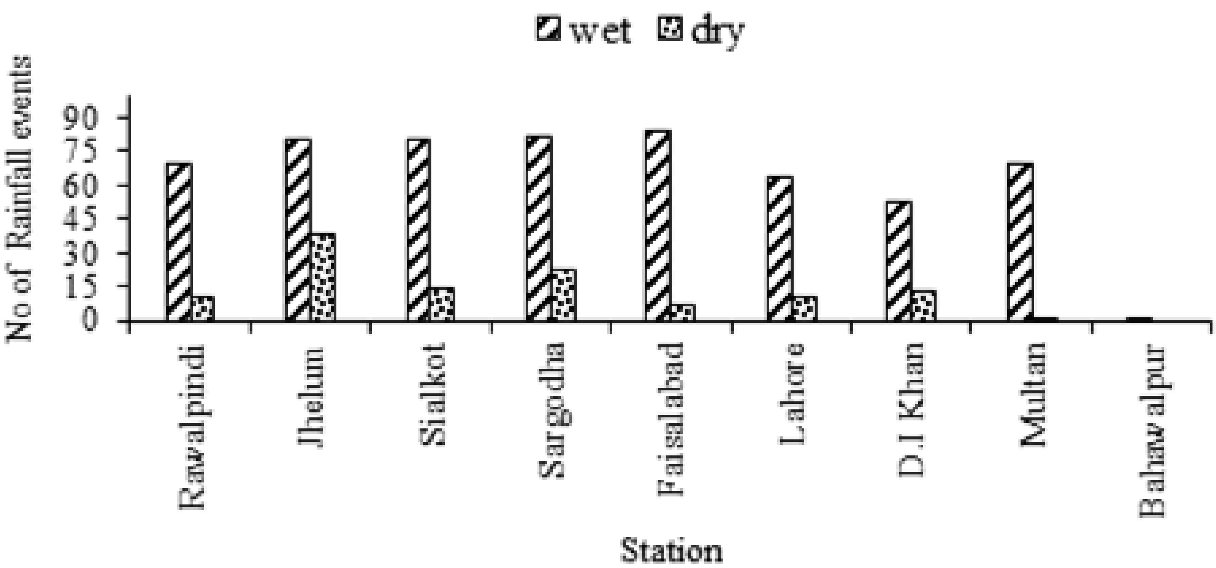

Fig. 4. Number of dry/wet monthly events (both moderate and extreme) during 1961-2015 at nine climatic stations of Punjab arranged in North to South direction (left to right).

Table 7. Results of MK statistic (Zmk) with significance level (p-value) and trend slope for rainfall at climatic stations.

Station	Statistic	Winter	Spring	Summer	Autumn	Annual
Rawalpindi	Z_{mk}	3.23	2.02	2.34	3.22	3.62
	p-value	**0.00**1	**0.043**	**0.020**	**0.001**	**<0.0001**
	Slope	1.701	*1.000*	4.826	2.199	*9.850*
Faisalabad	Z_{mk}	0.28	-0.07	0.71	2.56	1.60
	p-value	0.783	0.946	0.478	**0.010**	0.109
	Slope	0.052	-0.011	0.550	0.949	1.799
Lahore	Z_{mk}	-0.41	-0.38	1.25	0.95	1.60
	p-value	0.682	0.704	0.213	0.340	0.109
	Slope	-0.131	-0.100	1.696	0.494	2.747
helum	Z_{mk}	0.07	-0.72	0.60	0.63	0.23
	p-value	0.941	0.469	0.546	0.526	0.817
	Slope	0.071	-0.458	0.709	0.296	0.402
Multan	Z_{mk}	1.51	0.28	-0.23	2.86	1.60
	p-value	0.130	0.777	0.817	**0.004**	0.110
	Slope	0.227	0.038	-0.124	0.280	1.223
Sargodha	Z_{mk}	0.35	-0.43	0.64	1.38	1.13
	p-value	0.726	0.671	0.521	0.167	0.260
	Slope	0.090	-0.152	0.655	0.475	1.360
Sialkot	Z_{mk}	0.48	0.22	1.37	0.28	1.60
	p-value	0.633	0.829	0.172	0.783	0.109
	Slope	0.284	0.091	2.960	0.276	3.372
Bahwalpur	Z_{mk}	-0.31	2.26	0.12	1.59	1.10
	p-value	0.760	**0.024**	0.903	0.111	0.272
	Slope	-0.663	2.236	0.142	1.888	6.358
D.I Khan	Z_{mk}	0.36	-0.26	1.22	2.87	1.96
	p-value	0.720	0.794	0.224	**0.004**	**0.050**
	Slope	0.103	-0.098	0.852	0.685	1.920

4. Conclusions

Using the monthly rainfall data provided by the PMD, this study identified variations in dry/wet rainfall patterns on seasonal, annual and decadal basis during 1961-2015 for nine climatic stations of the Punjab province (Pakistan). Identification of moderate/extreme dry and wet rainfall events was carried out using the “Standardized Precipitation Index”. Significant increasing wetting tendency over the Punjab province (Pakistan) might be attributed to regional climate changes, El-Nino, and La-Nina which greatly affects rainfall distribution throughout the world. It is emphasized that crop scientists (agronomists), soil conservation experts, and other stack holders must consider these changes while framing policies related to dry/wet rainfall events in the region. The specific conclusions derived from this study are as follows:

- Significant increasing tendency in moderately dry rainfall events (in the post 1990 period) was observed at two stations in spring, winter and summer while autumn remained unaffected (Table 3). Thus spring, winter and summer are vulnerable to moderate dry events of rainfall at fewer stations of the Punjab province. On annual basis, significant drying tendency was observed only at two stations (Rawalpindi and Faisalabad).
- Significant percentage increase of the extremely dry rainfall events during F3 relative to the baseline period (F2) was seen only at two stations namely Jhelum (winter) and Sargodha (summer). On annual basis, only one station (Sargodha) was affected showing significant increasing tendency of extreme dry events. Thus, none of the stations and seasons (except two stations) was affected by dry

extremes. The percentage of extremely dry events was found very small when compared to the percentage of moderately dry rainfall events.

- Moderately wet rainfall events during F3 increased at seven stations in winter, one station in spring, three stations in summer and autumn. On annual basis, three stations exhibited significant increasing tendency of wet rainfall events. Among seasons, winter is most vulnerable to changes in moderate wet events of rainfall while spring being least affected.
- The percentage wet rainfall extreme events in F3 increased at two, two, three, and seven climatic stations in winter, spring, summer, and in autumn, respectively. On annual basis, four stations exhibited significant increasing tendency of extreme wet rainfall events. Thus, among seasons summer and autumn were most vulnerable to changes in extreme wet rainfall events while winter being least affected at most stations.
- Seasonal wetting tendency was mostly concentrated in extreme north, mid-south and middle plains of Punjab. On monthly basis both dryness and wetness were concentrated mainly in the northern and mid northern stations of Punjab. Except Bahawalpur all stations observed most of wet monthly events during three decades (i.e. 1981-90, 1991-2000 and 2001-2010), the last being the wettest decade of all. Thus, greatest temporal variations started from 1980s and continued till date.
- Extremely wet events of rainfall might cause extreme "mugginess" with the potential to disturb normal life in summer. Rainfall extremes can damage standing crops in the form of ponding water in the fields. Crops grown in summer and autumn could be highly vulnerable to rainfall extremes at majority of the stations. The risk of short-term flood/runoff in summer could be expected at stations vulnerable to rainfall extremes.
- Though rainfall amount has increased with time, yet its temporal uniformity has been greatly affected by various climatic factors. Rainfall seems to be concentrated in few months resulting in dry conditions in most part of the year. Such dry conditions often lead to various diseases related to prolonged dryness and dead storage levels in water reservoirs.

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