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Research Article

Dynamic Changes in Rainfall Necessitate Efficient Rainwater Harvesting in Different Agro-Ecologies of Pakistan for Sustainable Development

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Abstract: Changes in climate together with rapid urbanization are putting immense pressure on the existing agriculture and natural resources of South Asia. The agriculture productivity and livelihoods of a large number of communities have become highly vulnerable to inadequate supplies of water, especially in the rainfed regions. In the present study, spatio-temporal changes in rainfall patterns have been analyzed in different agro-ecologies of Pakistan during 1960-2019 period for sustainable agriculture and natural resource management in the country. Major agro-ecologies identified in the country were western dry mountains over 19.1% area, western dry plateau over 14.4% area, sandy desert over 14% area and northern irrigated plain over 11.3% area of the country. An increase of 30.6% in annual rainfall was observed in the rainfed plateau zone, 14.2% in the piedmont plain and 5.9% in the western dry mountain zone during the 1960-2019 period. In contrast, the rainfall exhibited a 3.2% decrease in the western dry plateau and 6.2% in the coastal zone which is critical for the subsistence agriculture in these arid ecologies. The excess rainwater may be conserved through developing storage/farm ponds and reservoirs for subsequent use during dry periods and recharging groundwater to build resilience against drought/flood conditions. The rainwater harvesting (RWH) has the potential to sustain agricultural productivity and fulfil the growing needs of the population in the arid ecologies of the country. Regular monitoring of the water resources is essential in the context of the rapidly changing environment and growing needs of the population in this arid region in future.

Keywords: Climate Change, Drought, Flood Management, Water Conservation.

1. INTRODUCTION

Global freshwater resources are under continuous pressure due to climate change and population growth [1]. The growing water requirements for agriculture, industrial and urban developments are placing demands and constraints on the natural environment of rainfed regions where rainfall is a primary water source [2, 3]. Pakistan is facing challenge of reduced water availability for her agriculture sector owing to rapid urbanization and changing climate [4]. Groundwater is generally utilized to supplement canal water supplies in the irrigated areas and overcome water-stressed condition in the rainfed areas of the country. As a result of growth in urbanization, extension in industrial and agriculture activities [5-7], groundwater levels are declining putting high stress on the underlying aquifer in the Indus basin [8-11]. According to Qureshi [12], extensive groundwater use in the Indus basin led to an annual decline of about 1.5 m in the watertable, as a result of which aquifer started to drain faster than the natural recharge process [9]. The groundwater levels are declining owing to increase in groundwater discharge from growing number of domestic tube-wells [13, 14] and less rainwater conservation. Rainwater harvesting (RWH) system is generally adopted to mitigate risk of rainfall shortages during drought condition [15, 16]. The system

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comprises of rainwater collection, e.g., through micro to macro catchments, terracing, check dams, rooftops, for direct-use or via some storage facility or recharging of groundwater [17]. Effective RHW can sustain agricultural development, maintain natural water cycle [18] and improve livelihoods of the local communities in the region. There is a need to identify water harvesting and conservation potential to recharge groundwater and enhance agricultural productivity and economic growth in different agro-ecologies. Agro-ecological zones provide relevant information of existing status of environment important for prioritizing research in agriculture and natural resources. It is hypothesized that there exists sufficient rainwater available for storing and utilization for enhancing agricultural and economic productivity in the country. The present study is aimed to analyze spatio-temporal changes in climate during 1960-2019 period in different agro-ecologies of Pakistan for sustainable agriculture and natural resource management in the country.

1.1. Geographical setup

Pakistan has diverse physiography and climate from south to north. The climate varies from subtropical hyper-arid and arid in the southern plains to alpine in the northern mountainous high lands. The annual precipitation is lowest in the southwest and increases gradually towards northeast (Figure 1). About 60-70% of the annual rainfall occurs during the monsoon season (July to September). Annual rainfall reaches more than 1200 mm during summer monsoon and heavy snowfall occurs during the winter season. Winter rainfall storms moving from Quetta valley lose their moisture after reaching central areas. The landform is generally mountainous having topography characterized by Indus River system and numerous intermittent and perennial nullahs/streams. In the east, alluvium deposits occur in the Indus irrigated plains of the Punjab and Sindh provinces and in the west, gravel fans form distinct piedmont zones consisting of finer sediments (sand and silt) and gravels. Major land cover consists of irrigated agriculture over 22% area, forest cover 4% and rock outcrops over 42% mainly in the northern and western mountanous region. Most of the area is used for grazing where livestock provides not only a major source of income but also of food security.

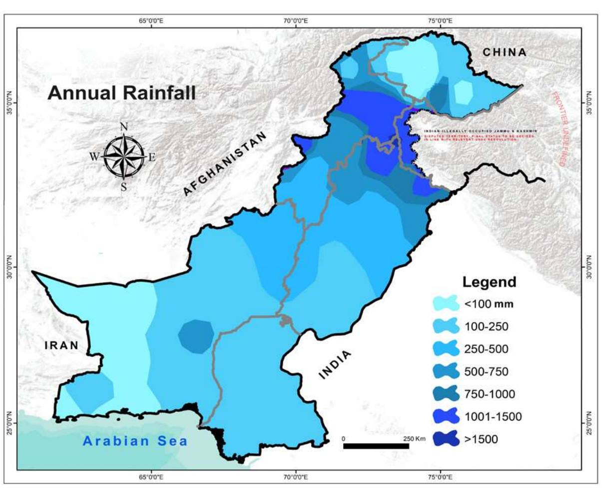

Fig. 1. Annual rainfall distribution in Pakistan.

2. MATERIALS AND METHODS

The climate data of 1960-2019 period was acquired of 59 stations of the country on monthly level from Pakistan meteorological department. The temperature and rainfall data were segregated into 1960-1989 and 1990-2019 climatic normals to perform spatio-temporal analysis of climate in different agro-ecologies of the country. Pakistan Agricultural Research Council [19] updated agro-ecological zones of the country during 2020-2023 based on the existing climate, land use, soils/landforms and irrigation conditions of the country. The ancillary data of topography, soils/landforms, hydrology, irrigation and agriculture were collected from various source departments like Survey of Pakistan, Water and Power Development Authority, and provincial soil survey, irrigation and agriculture departments. The base maps of agro-ecological zones, i.e., physiography, agro-climate, soils/landforms and land use were prepared in ArcGIS software using Universal Transverse Mercator projection system for integration and overlay analysis (Figure 2). The physiography of the country indicated 42% lowlands (< 300 m elevation), 14% plateaus (300 - 700 m), 14% Siwaliks (700 - 1200 m), 13% lower mountains (1200 - 2000 m), 6% Middle mountains (2000 - 3000 m) and 11% high mountains (> 3000 m). The reference evapotranspiration (ETo) along with rainfall data was used to develop agro-climate zones of the country. The ETo was calculated using the Penman-Monteith method (Equation 1) following Allen *et al*. [20].

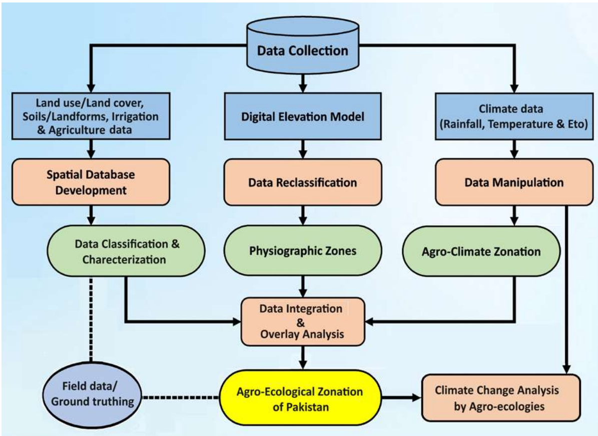

Fig. 2. Flowchart of methodology adopted in the present study.

$$ETo = \frac{0.408\Delta(R_a - G) + \gamma\frac{900}{T+273}u2\,(e_s - e_a)}{\Delta + \gamma(1+0.34u_2)} \quad (1)$$

Where, *ETo* is reference evapotranspiration (mm per day); R_a is net radiation at the crop surface (MJ/m² per day); *G* is soil heat flux density (MH/m² per day); *T* is mean daily air temperature at 2 m height (°C); U_2 is wind speed at 2 m height (m/s); e_s is saturation vapor pressure (kPa); e_a is Actual vapor pressure (kPa); Δ represents Slope of vapor pressure curve(kPa per °C) and γ represents Psychometric constant (kPa per °C). The performance of Penman-Monteith method is quite satisfactory in the diverse climatic conditions of Pakistan as compared with other methods [21].

The ETo data was also used to highlight crop water requirements in different agro-ecologies during 1960-2019 period. The rainfall, temperature and ETo data was interpolated using Inverse distance weighting (IDW) method. The zonal statistics function of ArcGIS was used to determine mean annual values of each parameter for the two normals for each agro-ecological zone of the country. The ranking of climate change as given in Table 1 was used to highlight intensity in different agro-ecologies of the country. The rank 1 denotes minimum change in the climate and rank 10 maximum change in the climate of a zone. One represntative climate station was selected in each agro-ecology based on long-term data availability for consistancy to study trend and change in annual and monthly rainfall during 1960-2019 period. The monthly rainfall data of 1960-1989 and 1990-2019 normals were illustrated graphically for comparison and shift analysis at respective climate station of the ecology. Finally benefits of adoption of RWH interventions were described for different agro-ecologies to improve agriculture productivity in the country.

Table 1. Ranking of climate change used to represent intensity in different agro-ecologies in this study.

S. No.	Intensity	Rank
1	Very low	1
2	Low	2
3	Slightly-low	3
4	Slight	4
5	Below average	5
6	Average	6
7	Moderate	7
8	Moderate-high	8
9	High	9
10	Very high	10

3. RESULTS AND DISCUSSION

3.1. Climate Data Analysis

According to 1990-2019 climatic normal, maximum mean annual rainfall was 1321 at Kakul followed by 869 mm at Jhelum, 378 mm at Faisalabad, 301 mm at D.I. Khan, 245 mm at Quetta and 226 mm at Chhor station. Other stations have < 200 mm rainfall, e.g., 196 mm at Karachi, 164 mm at Hyderabad, 137 mm at Gilgit and least at Panjgur, i.e., 97 mm. The annual rainfall indicated variation from 35 mm at Nokundi in the southwest to over 1827 mm at Murree in the northeast of the country. Over 68.4% area comprising major parts of the Balochistan, Sindh and lower Punjab province receives < 300 mm rains. The rainfall ranges between 300 - 500 mm in 19.1% area of the western and central Punjab, lower and upper Khyber Pakhtunkhwa (KPK) province, and some parts of the Gilgit-Baltistan (GB). About 6.9% area comprising of northern half of the Punjab and KPK provinces receives 500 mm to 1000 mm rains. More than 1000 mm rainfall occurs over 5.6% area comprising northern elevated parts of the Punjab and KPK provinces. The ETo was observed within range of 1500 - 2000 mm in the Punjab, KPK and 70% of the Balochistan province. The Lasbella district in Balochistan showed highest ETo, i.e., within range of 2500 - 2800 mm, while minimum ETo range i.e., 900 - 1000 mm was observed at Astore in GB. The 1000 - 1250 mm ETo range was observed in major parts of the GB and Kashmir areas. Around 70% area of the Sindh province exhibited ETo within range of 2000 mm and 2500 mm.

3.2. Climate Analysis by Agro-Ecology

Agro-ecological zones of Pakistan were developed indicating regions of homogenous climatic, landforms/soils, physiography and land use characteristics in the country [19], as shown in Figure 3. Major zones consist of western dry mountains (WDM) about 19.1%, western dry plateau (WDP) 14.4%, sandy desert (SD) 14% and northern irrigated plain (NIP) 11.3% (Table 2). The WDM zone consists of western parts of the KPK and adjoining Balochistan province where climate is predominantly arid to semi-arid subtropical to temperate and warm Mediterranean. Forest, livestock and horticulture plantation are the major land use here. The WDP zone comprises of major part of the Balochistan province in the southwest where climate is predominantly warm desertic hyper-arid to semi-arid subtropical. Major landuse here is rangeland, livestock, fruits and minor crops. At places, groundwater resource in form of karezes and perennial streams exist to sustain scanty vegetation of drought resistant trees and some agriculture land in patches. The SD zone comprises of Thal and Cholistan deserts in the Punjab, Thar in the Sindh and Kharan desert in the Balochistan province. Climate here is desertic hyper-arid to semi-arid subtropical. Rangeland, livestock and minor crops/fruits are the major landuse in this ecology. Northern dry mountains (NDM) over 9.2% consist of massive snow and glacier resource which contributes meltwater flows to gigantic Indus River system downstream. Mono cropping is practiced here within 2000-3000 m elevation range and double cropping below 2000 m range [22]. Temperate mountains (TM) over 5.9% area, lies within 300 - 6300 m elevation range mainly in the Khyber Pakhtunkhwa and Punjab provinces. Annual rainfall here reaches more than 1200 mm during the summer and heavy snowfall occurs during the winter season. In the northern irrigated and southern irrigated plains, surface water availability sustains year-round cropping intensities [10]. Climate in the former zone is predominantly arid to semi-arid subtropical, whereas in the later zone, climate is predominantly warm desertic hyper-arid to arid subtropical. The rainfed plateau (RP) zone (also called 'Pothwar plateau') stretches over 3% area within 300 - 900 m elevation range mainly in the northwestern part of the Punjab province. Agriculture and livestock are the main landuse here. The piedmont plains (PP) over 7.4% area (Table 2) consist of nearly leveled to undulating piedmont region along Kohistan mountains in the Sindh and Balochistan, Suleiman mountains in the Punjab and KP, besides sub-Himalayan mountains in the Punjab province. During flood season (July-September), the hill-torrent (locally '*Rod Kohi' or 'Sailaba'*) flows in the piedmont plain is diverted to irrigate the agriculture land [23-25]. The coastal zone (CZ) stretches over 9.9% area along Arabian Sea in the south of Sindh and Balochistan provinces (Figure 3). This zone is rich in mangrove forests, fruits, fish and livestock resource. The agro-ecological zones support in selection of suitable crop grown areas and climate smart interventions in the country.

Fig. 3. Reclassified agro-ecological zones of Pakistan.

Climate change analysis was performed at agro-ecological level during the 1960-2019 period (Figure 4). Annual rainfall indicated an increase of about 30.8%, mean temperature 2.6% and ETo 4.2% in the NDM ecology during 1960-1989 and 1990-2019 climatic normals (Table 3). In the TM ecology, annual rainfall indicated an increase of about 3.9%) and ETo 8.3%, while mean temperature exhibited a decrease 5.6% during the two normals. In the RP ecology, annual rainfall indicated an increase from 668 mm to 872 mm (about 30.6%), while mean temperature exhibited a decrease from 21.6°C to 20.7°C (–4.0%) and ETo from 1496 mm to 1493 mm (–0.2%). The WDM ecology indicated an increase in annual rainfall from 271 mm to 287 mm, in mean temperature from 20.5°C to 21.6°C and in ETo from 1661 mm to 1662 mm during the

Table 2. Physical characteristics of major agro-ecological zones of Pakistan.

S. No.	Agro-ecology zone	Area (%)	Mean elevation (m)	Selected station
1	Northern Dry Mountains (NDM)	9.2	4212	Gilgit
2	Temperate Mountains (TM)	5.9	2116	Kakul
3	Rainfed Plateau (RP)	3.0	471	Jhelum
4	Western Dry Mountains (WDM)	19.1	1398	Quetta
5	Northern Irrigated Plain (NIP)	11.3	175	Faisalabad
6	Southern Irrigated Plain (SIP)	5.8	42	Hyderabad
7	Piedmont Plain (PP)	7.4	176	D.I. Khan
8	Western Dry Plateau (WDP)	14.4	902	Panjgur
9	Sandy Desert (SD)	14	179	Chhor
10	Coastal Zone (CZ)	9.9	160	Karachi

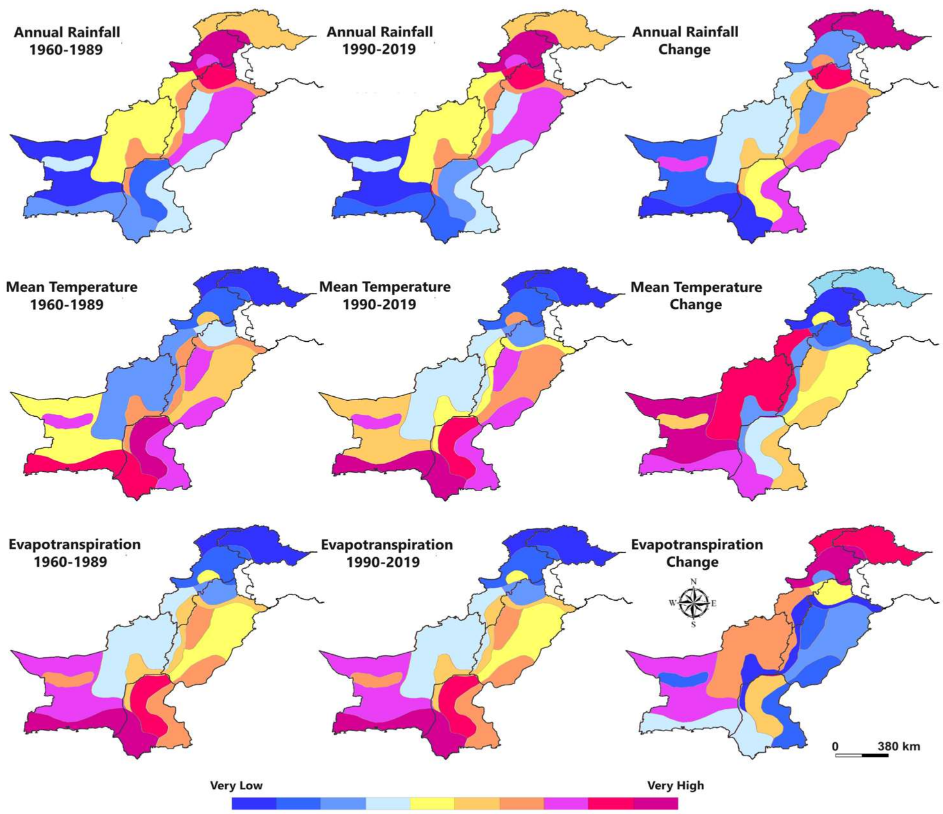

Fig. 4. Changes in climate observed in different agro-ecologies of the country during 1960-2019 period.

two climatic normals. The increase in rainfall in the RP and WDM ecologies would be beneficial for the agriculture, livestock and grazing land. Annual rainfall showed an increase of about 17.2% and mean temperature 0.4%, while ETo exhibited a decrease of 2.3% in the NIP ecology (Table 3).

Whereas, in the SIP ecology, annual rainfall indicated an increase of about 11.2%, while mean temperature exhibited a decrease of about 0.6% during the two normals. In the PP ecology, annual rainfall increased from 330 mm to 377 mm, while mean temperature decreased from 24.6 °C to 24.2 °C and ETo from 1784 mm to 1677 mm during the 1960-2019 period. In contrast, annual rainfall indicated a decrease from 105 mm to 102 mm, while mean temperature exhibited an increase from 22.4 °C to 24.2 °C and ETo from 1939 mm to 1966 mm in the WDP ecology. The SD ecology indicated an increase of about 17.6% in annual rainfall, 1.5% in mean temperature and a decrease of about 2.7% in ETo during the 1960-2019 period. Annual rainfall indicated a decrease from 162 mm to 152 mm (about –6.2%) and ETo from 2160 mm to 2121

Table 3. Climate change analysis by agro-ecology during 1960-2019 period.

Sr. No.	Zones	Rainfall (mm)			Temperature (°C)			Evapotranspiration (mm)		
		1960-1989	1990-2019	Change %	1960-1989	1990-2019	Change %	1960-1989	1990-2019	Change %
1	NDM	274	358	30.8	13.9	14.3	2.6	1077	1122	4.2
2	TM	880	914	3.9	18.3	17.3	–5.6	1182	1279	8.3
3	RP	668	872	30.6	21.6	20.7	–4.0	1496	1493	–0.2
4	WDM	271	287	5.9	20.5	21.6	5.3	1661	1662	0.1
5	NIP	353	414	17.2	24.4	24.5	0.4	1715	1675	–2.3
6	SIP	136	152	11.2	26.7	26.5	–0.6	1975	1974	0.0
7	PP	330	377	14.2	24.6	24.2	–1.7	1784	1677	–6.0
8	WDP	105	102	–3.2	22.4	24.2	8.3	1939	1966	1.4
9	SD	177	208	17.6	25.0	25.4	1.5	1900	1849	–2.7
10	CZ	162	152	–6.2	25.9	26.6	2.7	2160	2121	–1.8

mm (–1.8%), while mean temperature exhibited an increase from 25.9 °C to 26.6 °C (–2.7%) in the CZ ecology (Figure 4). Agriculture is generally vulnerable to changing climate in these areas because of receiving insufficient rains for growing crops and other vegetation [26]. Overall annual rainfall indicated an increase from 277 mm to 310 mm (about 12%) and mean temperature from 22.3 °C to 22.8 °C (2.3%), while ETo exhibited a decrease from 1730 mm to 1721 mm (–0.6%) in the country during the 1960-2019 period. Such changes in climate have resulted in increased floods frequency during the last several decades in the country [27-30].

Annual rainfall trends were observed positive at Gilgit, Jhelum, Faisalabad, D.I. Khan and Chhor, while they were negative at other stations except at Quetta where the trend was found stable (Figure 5). The monsoon rainfall (July-September) exhibited a similar pattern as that of the annual rainfall, however its contribution is much lower in the total rainfall of Gilgit, Quetta and Panjgur due to westerly's effect. The rainfall indicated predominant negative change at Kakul, Quetta, Hyderabad and Panjgur stations, while the change was positive at Gilgit, Faisalabad, D.I. Khan and Chhor stations (Figure 6). The initial positive tendency in rainfall values followed by negative values at Kakul, Jhelum and Quetta stations is likely because of decreasing monsoon intensity in these areas. Mix positive and negative deviations in rainfall were observed at Faisalabad representing NIP ecology and Hyderabad station representing SIP ecology.

3.3. Monthly Rainfall Data Analysis

The monthly rainfall at Gilgit in NDM ecology indicated positive trends for all months (Pearson correlation R values ranging within 0.01 - 0.42) except for April, May, July and October for which they were either negative or stable (Table 4). According to Gadiwala and Burke [31], the prevalence of liquid precipitation exhibits growing temperature warming in this region. The Kakul station in TM ecology exhibited negative trends for all months except for June, September, October and November for which they were positive. On the other hand, Jhelum station in RP ecology indicated prevailing rainfall pattern in most of the months (R values ranging within 0.01 - 0.18) except during May, July, November and December. Similarly, the rainfall indicated prevalence during seven months at Quetta in WDM ecology (R values ranging within 0.03 - 0.24) and seven months at Karachi in CZ ecology (R values ranging within 0.02 - 0.26). In contrast, the rainfall exhibited declining behavior in seven months at Hyderabad in SIP ecology (R values ranging from –0.16 to –0.02) and seven months at Panjgur station in WDP ecology (R values ranging from –0.34 to –0.04). There was mix pattern of monthly rainfall observed at Faisalabad station in NIP ecology and Chhor station in SD ecology. The monthly rainfall at D.I. Khan in PP ecology indicated prevalence during most of the months (R values ranging within 0.08-0.24) except during May and December (Table 4).

The monthly rainfall at Gilgit station indicated variable changes, e.g., positive for months of

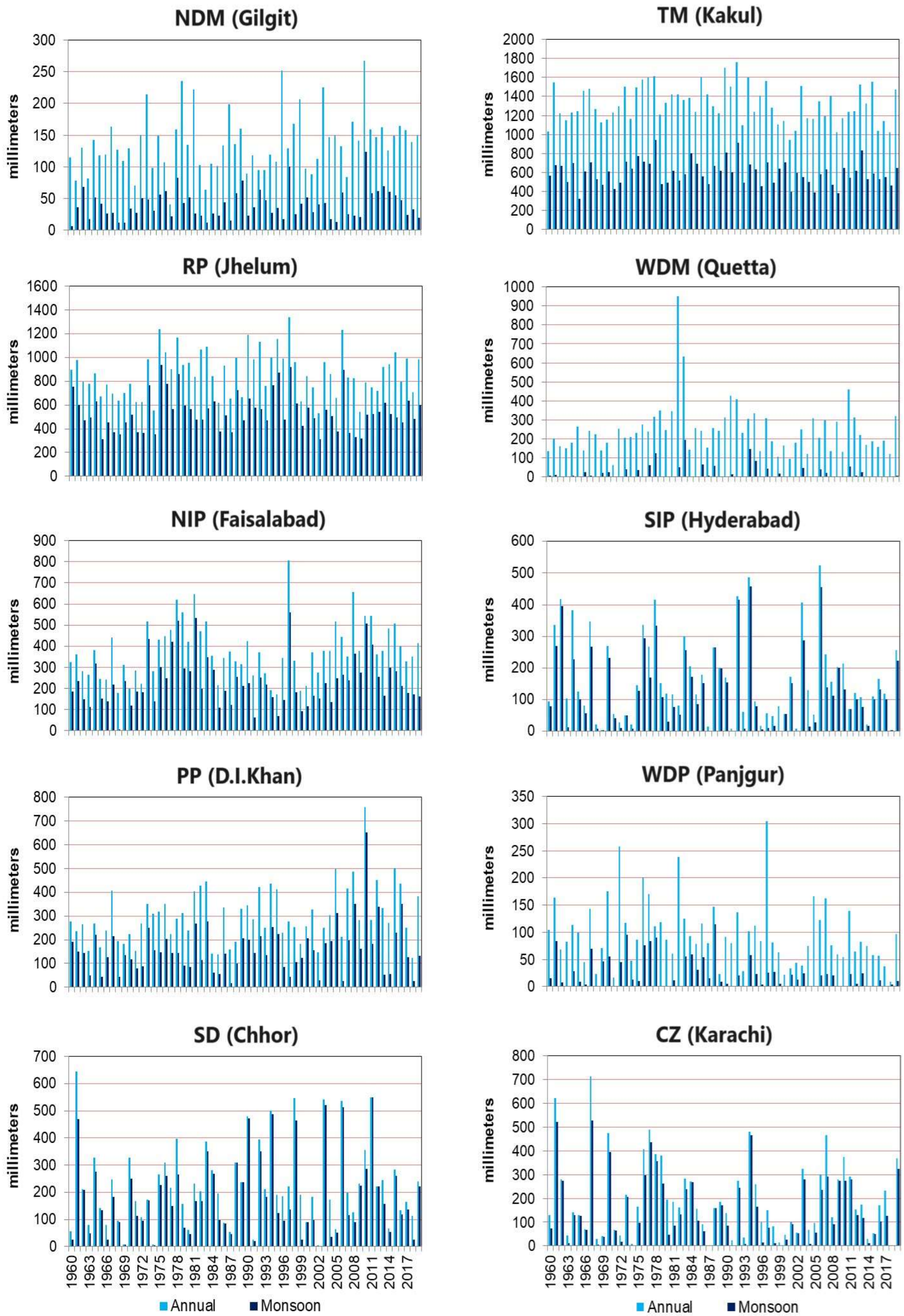

Fig. 5. Annual and monsoonal rainfall variability and trending at different climate stations of the agro-ecological zones.

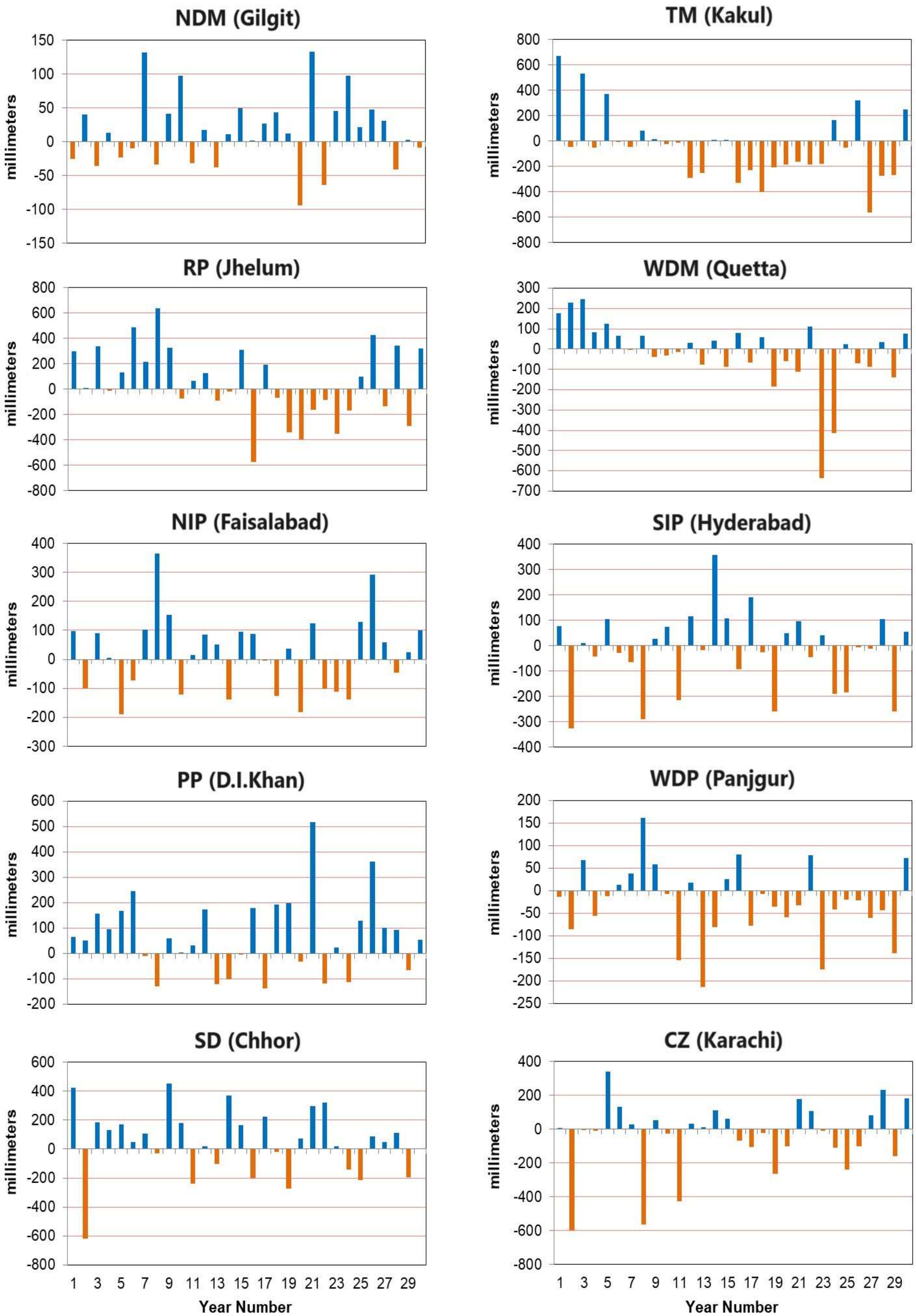

Fig. 6. Change in annual rainfall (positive change in blue and negative change in orange bars) at various climate stations of the agro-ecological zones.

February, June, September and November, and negative for May, July and October during the 1960-2019 period (Table 4). The changes in rainfall were less pronounced at Kakul and Jhelum stations, except a slight decline in peak rainfall at the former station. The peak rainfall also exhibited decline at Faisalabad, Panjgur and Karachi stations. Similarly, the monthly rainfall exhibited negative change for January, March, July and August at Quetta station during 1960-2019 period. The situation appears critical for the arid areas of the country where local communities are dependent on subsistence agriculture. In contrast, the monthly rainfall at D.I. Khan exhibited positive change which may be favorable for rainfed agriculture but risky in terms of flood occurrence. The peak rainfall at Hyderabad and Chhor stations indicated onward shifts, i.e., from July to August during 1960-2019 period (Figure 7).

3.4. Benefits of RWH in Different Ecologies

Rainwater harvesting (RWH) is a mean to reduce water demand in non-consumptive use and the negative impacts of changing rainfall pattern can be significantly reduced through proper rainwater management in the arid and semi-arid regions [32, 33]. Improved rainwater harvesting and conservation can meet future water requirements of the urban and rural areas on sustainable basis [34]. RWH system offers potential for raising high value crops, fruits and vegetables in the RP, PP, WDP and SD zones to sustain agriculture and provide resilience against high risks of climate induced hazards like droughts and floods. RWH should be aimed to collect maximum rainwater through storage, e.g. in tanks, farm ponds and mini-dams for multipurpose use [35]. At the household level, rooftop RWH system can be conveniently stored in tanks for domestic use, growing vegetables and recharging the aquifer. RWH is declared a feasible technology for the hilly areas by the World Bank and under national water policy of Pakistan [36]. The technique is also recommended under the sustainable development goals [37] to meet growing water needs of the rural and urban population. The RWH from the rooftop can be integrated with water conservation system for recharging groundwater as well as for agriculture use [38, 39].

The RWH can be used for recharging groundwater resources in the NIP, RP and WDP ecologies where depletion of groundwater is creating high risk for agriculture development [11, 40]. The culturable wasteland can be developed through utilizing hill-torrent water management techniques like establishing distribution/diversion and conservation structures. In Mithawan piedmont ecology of Punjab, the hill-torrent water generated from rainfall in several catchments had been harnessed in storage reservoirs and channelized for irrigating cultivable land. Three such earthen

Table 4. Pearson R values of rainfall trends at different climate stations during 1960-2019 period.

Period/ Station	Gilgit	Kakul	Jhelum	Quetta	Faisalabad	Hyderabad	D.I. K	Panjgur	Chhor	Karachi
Jan	0.06	–0.04	0.05	–0.07	–0.05	0.08	0.12	–0.18	0.08	0.11
Feb	0.16	–0.01	0.11	0.09	0.14	0.04	0.15	–0.04	0.08	–0.14
Mar	0.01	–0.08	0.01	0.03	0.00	–0.13	0.10	–0.05	–0.15	–0.24
Apr	0.00	–0.04	0.11	–0.06	0.10	–0.02	0.08	–0.05	–0.08	–0.08
May	–0.01	–0.18	-0.02	0.05	0.05	–0.08	-0.15	0.14	0.02	0.09
Jun	0.42	0.14	0.18	0.15	0.34	–0.16	0.30	0.08	–0.03	0.26
Jul	–0.03	–0.01	–0.07	–0.12	–0.02	–0.16	0.10	–0.34	–0.12	–0.26
Aug	0.10	–0.18	0.03	–0.04	–0.06	0.06	0.16	–0.10	0.14	0.04
Sep	0.25	0.01	0.04	0.12	0.33	–0.10	0.24	0.03	0.19	0.02
Oct	–0.04	0.01	0.17	0.04	0.23	0.10	0.19	0.05	0.10	0.09
Nov	0.32	0.06	–0.07	0.24	–0.05	–0.08	0.16	0.15	–0.10	–0.20
Dec	0.08	–0.11	–0.10	–0.08	–0.15	0.05	–0.16	–0.07	0.00	0.03
Annual	0.26	–0.13	0.08	0.00	0.22	–0.11	0.33	–0.22	0.09	–0.12
Summer	0.19	–0.10	0.05	–0.04	0.23	–0.12	0.26	–0.22	0.09	–0.10
Winter	0.18	–0.09	0.07	0.03	0.05	0.03	0.18	–0.12	0.00	–0.15

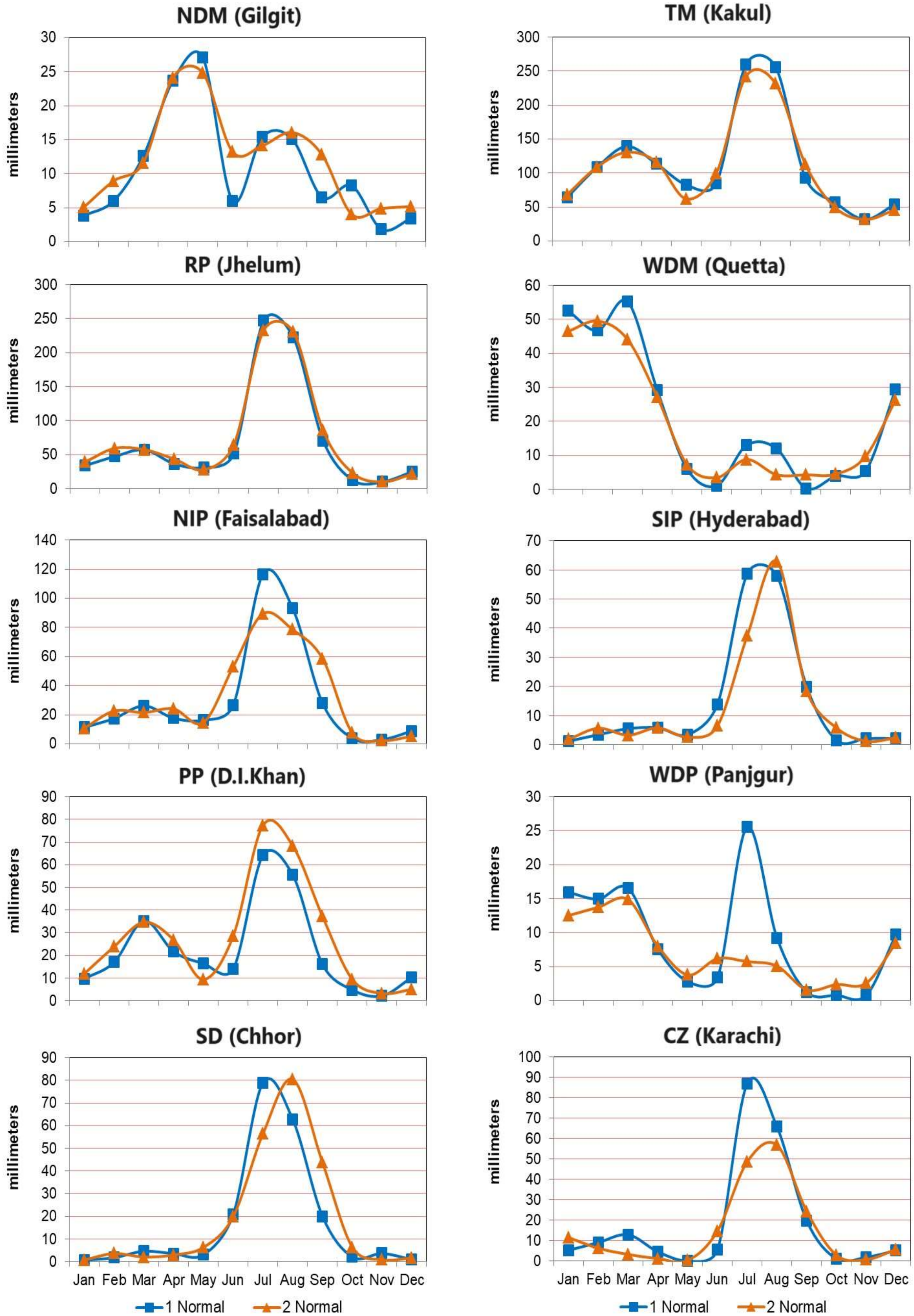

Fig. 7. Comparison between monthly rainfall of 1960-1989 and 1990-2019 climatic normals at selected stations of the ecologies.

reservoirs constructed by Pakistan Agricultural Research Council during 1995-2002 are still supplying water for irrigation use and ensure sustained water supplies during lean period of water availability besides recharging the underlying aquifer. Using the harvested water, the local communities are now growing cotton, wheat and sorghum crops coupled with farmland trees which was not possible before in that harsh mountainous terrain. At places, the stored water is used for growing high value crops through adopting high efficiency irrigation techniques. This integrated water management approach can be adopted to raise fruit orchards and woody trees to meet food, fuel and timber needs of the communities in the arid region.

4. CONCLUSIONS

In the present study, spatio-temporal changes in climate were studied in different agro-ecologies of Pakistan during 1960-2019 period for sustainable agriculture and natural resource management. Major agro-ecological zones identified were western dry mountains over 19.1% area, western dry plateau over 14.4% area, sandy desert over 14% area and northern irrigated plain over 11.3% area of the country. Significant changes in rainfall pattern have been observed in the country during the last several decades likely due to global and regional changes in climate and land use conditions. Annual rainfall indicated 30.6% increase in the rainfed plateau, 14.2% in the piedmont plains, 5.9% in the western dry mountains and about 3.9% in the temperate mountain ecology. In contrast, the rainfall exhibited 3.2% decrease in the western dry plateau and 6.2% in the coastal zone during the 1960-2019 period, which is critical for subsistence agriculture in these arid ecologies. The rainwater may be conserved through developing storage/farm ponds and reservoirs for subsequent use during dry periods and recharging groundwater to build resilience against drought/flood conditions. The rainwater harvesting (RWH) system can be adopted to fulfill growing water requirements of the communities and ensure food security in different ecologies. There is a need to raise awareness and build capacity of the local communities and institutions in efficient water use and advance water harvesting, and conservation techniques for sustainable development in the country. Regular monitoring of the water resource is essential in context of rapidly changing environment and growing needs of the population in the climate vulnerable arid region of the country in future.

5. CONFLICT OF INTEREST

The authors declare no conflict of interest.

6. REFERENCES

1. R. Missaoui, B. Abdelkarim, K. Ncibi, M. Gentilucci, S. Brahmi, Y. Ayadi, and Y. Hamed. Mapping groundwater recharge potential zones in arid region using remote sensing and GIS perspective, Central Tunisia. *Euro-Mediterranean Journal for Environmental Integration* 8: 557-571 (2023).
2. Z. Li, F. Boyle, and A. Reynolds. Rainwater harvesting and greywater treatment systems for domestic application in Ireland. *Desalination* 260: 1–8 (2010).
3. A. Markhi, N. Laftouhi, Y. Grusson, and A. Soulaimani. Assessment of potential soil erosion and sediment yield in the semi-arid N′fs basin (High Atlas, Morocco) using the SWAT model. *Acta Geophysica* 67: 263-272 (2019).
4. World Bank. World development indicators 2017. *The World Bank, Washington DC* (2017). *https://databank.worldbank.org/source/world-development-indicators*.
5. I. Ahmad, S.A.S. Hussain, and M.S. Zahid. Why the Green Revolution Was Short Run Phenomena in the Development Process of Pakistan: A Lesson for Future. *Journal of Rural Development and Administration* XXXV(1-4): 89-104 (2004).
6. A.S. Qureshi, M.A. Gill, and A. Sarwar. Sustainable groundwater management in Pakistan: Challenges and opportunities. *Irrigation and Drainage* 59(2): 107-116 (2010).
7. H. Heidari, M. Arabi, T. Warziniack, and S. Sharvelle. Effects of urban development patterns on municipal water shortage. *Frontiers in Water* 3: 694817 (2021).
8. A. Ashraf, and Z. Ahmad. Regional groundwater flow modeling of Upper Chaj Doab of Indus Basin, Pakistan using Finite element Model (Feflow) and Geoinformatics. *Geophysical Journal International* 173: 17-24 (2008).
9. A.N. Laghari, D. Vanham, and W. Rauch. The Indus basin in the framework of current and future water resource management. *Hydrology and Earth System Sciences* 16: 1063-1083 (2012).

10. A.S. Qureshi. Improving food security and livelihood resilience through groundwater management in Pakistan. *Global Advanced Research Journal of Agricultural Science* 4(10): 687-710 (2015).
11. M. Jabeen, Z. Ahmad, and A. Ashraf. Predicting behaviour of the Indus basin aquifer susceptible to degraded environment in the Punjab province, Pakistan. *Modeling Earth Systems and Environment* 6: 1633-1644 (2020).
12. A.S. Qureshi. Water management in the Indus basin in Pakistan: Challenges and opportunities. *Mountain Research and Development* 31(3): 252-260 (2011).
13. M.T. Sohail, Y. Mahfooz, K. Azam, Y. Yen, L. Genfu, and S. Fahad. Impacts of urbanization and land cover dynamics on underground water in Islamabad, Pakistan. *Desalination and Water Treatment* 159: 402-411 (2019).
14. U.H. Faraz, U.A. Naeem, H.F. Gabriel, N.M. Khan, I. Ahmad, H.U. Rehman, and M.A. Zafar. Impact of urbanization on groundwater levels in Rawalpindi City, Pakistan. *Pure and Applied Geophysics* 178: 491-500 (2021).
15. B. Helmreich, and H. Horn. Opportunities in rainwater harvesting. *Desalination* 248: 118–124 (2009).
16. T. Judeh, and I. Shahrour. Rainwater harvesting to address current and forecasted domestic water scarcity: Application to arid and semi-arid areas. *Water* 13: 3583 (2021).
17. T.M. Boers. Rainwater harvesting in arid and semi-arid zones. International Institute for Land Reclamation and Improvement, *Wageningen University, Netherland,* Publication 55 (1994).
18. K. Kim, and C. Yoo. Hydrological modeling and evaluation of rainwater harvesting facilities: case study on several rainwater harvesting facilities in Korea. *Journal of Hydrologic Engineering* 14: 545-561 (2009).
19. PARC. Agro-ecological zonation of Pakistan: Technical Report. *Pakistan Agricultural Research Council and Ministry of National Food Security and Research, Islamabad* (2024).
20. R.G. Allen, L. Pereira, D. Raes, and M. Smith. Crop Evapotranspiration: Guidelines for computing crop water requirements. FAO Irrigation and Drainage Paper 56. *Food and Agriculture Organization, Rome, Italy* (1998).
21. G. Rasul, and A. Mahmood. Performance Evaluation of Different Methods for Estimation of Evapotranspiration in Pakistan's Climate. *Pakistan Journal of Meteorology* 5(10): 25-36 (2009).
22. A.Q. Suleri, S. Munir, and S.Q. Shah. Impact of Trade Liberalisation on Lives and Livelihood of Mountain Communities in the Northern Areas of Pakistan. Research Report. *Sustainable Development Policy Institute, Islamabad, Pakistan* (2002).
23. M.A. Kamran, and T. Shamshad. Impacts of hill torrents' management on socio-economic conditions of arid land farmers: A case study of Tehsil DG Khan. *Asian Journal of Humanity, Art and Literature* 1(3): 155-162 (2014).
24. S. Farooq, R. Kausar, A. Ashraf, and B. Haider. Exploring surface runoff potential and water harvesting sites in Dera Ismail Khan Rod-kohi area using GIS and Remote sensing. *Proceedings of the Pakistan Academy of Sciences: A. Physical and Computational Sciences* 57(2): 1-10 (2020).
25. T.F. Ahmed, S.U.S. Shah, A.A. Sheikh, H.N. Hashmi, M.A. Khan, and M. Afzal. Flood water management from hill torrents of Pakistan for agriculture livelihood improvement. *Pakistan Journal of Agricultural Research* 34(3): 438-445 (2021).
26. S. Adnan, K. Ullah, S. Gao, A.H. Khosa, and Z. Wang. Shifting of Agro-climatic zones, their drought vulnerability, and precipitation and temperature trends in Pakistan. *International Journal of Climatology* 37: 529-543 (2017).
27. M.T. Arslan. Unusual rainfall shift during monsoon period of 2010 in Pakistan: Flash flooding in Northern Pakistan and riverine flooding in Southern Pakistan. *African Journal of Environmental Science and Technology* 7(9): 822-890 (2013).
28. P. Ganguli, and M.J. Reddy. Evaluation of trends and multivariate frequency analysis of droughts in three meteorological subdivisions of western India. *International Journal of Climatology* 34: 911-928 (2014).
29. MOCC. Framework for implementation of climate change policy. *Ministry of Climate Change, Islamabad, Pakistan* (2014).
30. M.A. Miyan. Droughts in Asian least developed countries: vulnerability and sustainability. *Weather and Climate Extremes* 7: 8-23 (2015).
31. M.S. Gadiwala, and F. Burke. Climate change and precipitation in Pakistan-A meteorological prospect. *International Journal of Economic and Environmental Geology* 4(2): 10-15 (2013).
32. M. Bakir, and Z. Xingnan. GIS and remote sensing applications for rainwater harvesting in the Syrian Desert (Al-Badia). *Twelfth International Water Technology Conference*, *IWTC12 2008 Alexandria, Egypt* (2008).
33. M. Shahid, K.U. Rahman, K.S. Balkhair, and A.

Nabi. Impact assessment of land use and climate changes on the variation of runoff in Margalla Hills watersheds, Pakistan. *Arabian Journal of Geosciences* 13: 1-14 (2020).

34. R. Shabbir, and S.S. Ahmad. Water resource vulnerability assessment in Rawalpindi and Islamabad, Pakistan using Analytic Hierarchy Process (AHP). *Journal of King Saud University-Science* 28: 293-299 (2016).
35. F. van Steenbergen. Groundwater and surface water in the mega-irrigation systems of Pakistan: The Case for conjunctive management. *Water Knowledge Note, World Bank Group* (2019).
36. MOWR. National Water Policy. *Ministry of Water Resources, Government of Pakistan* (2018).
37. C.C. Amos, A. Rahman, J.M. Gathenya, E. Friedler, F. Karim, and A. Renzaho. Roof-harvested rainwater use in household agriculture: Contributions to the sustainable development goals. *Water* 12: 332 (2020).
38. K. Kalhor, and N. Emaminejad. Sustainable development in cities: Studying the relationship between groundwater level and urbanization using remote sensing data. *Groundwater for Sustainable Development* 9: 100243 (2019).
39. D. Zhang, X. Ding, J. Liu, and C. Mei. Review on mechanism and technical measures of urban rainwater harvesting. *IOP Conference Series: Earth and Environmental Science* 983: 012106 (2022).
40. F. van Steenbergen, A.B. Kaisarani, N.U. Khan, and M.S. Gohar. A case of groundwater depletion in Balochistan, Pakistan: Enter into the void. *Journal of Hydrology: Regional Studies* 4: 36-47 (2015).