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International Environmental Conflict Management in Transboundary River Basins

Ameneh Mianabadi, et al. *[full author details at the end of the article]*

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Abstract
Despite signing a bilateral water treaty in 1973, water utilization in the Hirmand River Basin (HRB) has been a source of dispute between Iran and Afghanistan for many decades. While Iran accuses Afghanistan of depriving it of the Hirmand water due to dam construction in the upper basin, Afghanistan assures that it enforces the treaty. An evident reduction of the Hirmand River flow to Iran in recent years is fully attributed by Afghanistan to a reduction in precipitation in the basin. Although Iran disagrees and remains unconvinced by this line of reasoning. A fundamental lack of trust in collected and shared hydrological data has hindered dialog between the two neighbors. To address this issue, this study investigates the use of remote sensing information, as an independent source of data, for fact-finding in a highly disputed transboundary river basin. For this purpose, historical data (34 years) from two satellite precipitation products, PERSIANN-CDR and CHIRPS, were used to understand if precipitation characteristics and, subsequently, rainfall-runoff regimes have changed in the HRB. Results reveal that the frequency and amount of heavy precipitation have been increasing over the mountainous areas. The total amount of precipitation has been increasing significantly. The intensity of heavy precipitation, however, has been decreasing over the basin. In the upper basin, the duration of the wet period has increased, although the share of wet months in annual precipitation has been decreasing. In the lower basin, trends in seasonal and annual precipitation and most of the indices are insignificant, indicating water availability issues cannot be attributed to the changes in precipitation in the downstream area itself. These results can be used as an integral part of mutual fact-finding and trust-building exercise that supports water diplomacy to promote environmental cooperation between Iran and Afghanistan.

Keywords Transboundary environmental dispute · Environmental conflict management · Hirmand River basin · PERSIANN-CDR · CHIRPS

1 Introduction

There are about 310 transboundary river basins, 600 international aquifers, and more than 1600 shared lakes and reservoirs in the world (UNECE/UNESCO 2015; UNEP 2015; UNEP-

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DHI and UNEP 2016). These shared water resources can be a source of both cooperation and conflict (Mianabadi et al. 2014). In addition, there are 234 transboundary wetlands shared among 91 countries, listed in the Ramsar Convention (Griffin and Ali 2014) of which only 16 have formal transboundary agreements and shared management plans (Griffin and Ali 2014). The utilization of shared environmental and water resources has been a challenging socio-political issue for riparian countries (Colvin et al. 2015; Abel et al. 2019). To deal with this issue, it is essential to use diplomatic tools and effective cooperative mechanisms to reorient neighbors in conflict and build trust and peace among riparian states.

International and transboundary environmental system are complex and coupled human-ecological systems. These systems often are more complex than internal environmental ones. Because, in addition to typical complexities of internal systems, there are political and national security aspects in transboundary basins that increase the complexity in these shared water and environmental systems (Mianabadi 2016). Some transboundary systems may suffer from mistrust among riparian states due to cultural differences and historical events (e.g. the Nile basin) and others from underlying political issues (e.g. the Euphrates and Tigris river basins) in hydropolitical relationships (Mianabadi et al. 2015). Environmental and water disputes in transboundary systems are rather wicked complex problems that are not merely rooted in technical issues as they come with socio-cultural and political dimensions. To take the first steps in international environmental and water conflict management, it is necessary to enhance environmental diplomacy and promote cooperation by building mutual trust.

The Hirmand[1] River Basin (HRB) (Fig. 1) is a transboundary river basin shared among Afghanistan (89%), Iran (9%), and Pakistan (2%) (UNEP 2006). The river is the main source of water for Lake Hamoun that is an international transboundary wetland located in the Sistan area at the border of Iran and Afghanistan. In 1975, the wetland was designated as a protected site under the Ramsar Convention. The socio-economic and environmental importance of the HRB for both Iran and Afghanistan makes it a source of water dispute for more than 200 years. In 1973 a treaty was signed between the two riparian countries. Based on this treaty, an average amount of 26 m^3/s (820 MCM) from the Hirmand River should flow to Iran in a normal water year. Despite the treaty, Lake Hamoun has recently dried up and was added to the Montreux Record of wetlands in danger in 1990 (The Ramsar Convention on Wetlands 2011).

Lake Hamoun desiccation has had severe consequences in the Sistan area such as massive sand storms in the region. The strong winds, commonly known as the "120-day wind", blow during the summer and move the fine sands from the lake bed to a hundred or more villages and cover the houses and agricultural lands (Rashki et al. 2012). The majority of people in the Sistan are employed in agriculture, fisheries and animal husbandry sectors. Suffering from the severe water shortage, loss of income, dust storms, and other hardships, the rural community is pushed to leave the area and emigrate to other places (Statistical Center of Iran 2016).

There is no consensus between Afghanistan and Iran over the reasons behind drying Lake Hamoun. Iran argues that anthropogenic activities in the upstream HRB have resulted in reduced water flow to Iran far below what is designated in the 1973 treaty. Afghanistan, however, assures that it intends to enforce the treaty (The Guardian 2017) and attributes the flow reduction to a significant decline in precipitation in recent years (DeutscheWelle 2018). This issue has considerably raised dispute between both countries at different governmental levels. The road to water cooperation in the HRB will be paved by the mutual fact-finding and trust-building. Monitoring and evaluation can be an important tool for improving the

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[1] It is called "Helmand" in Afghanistan

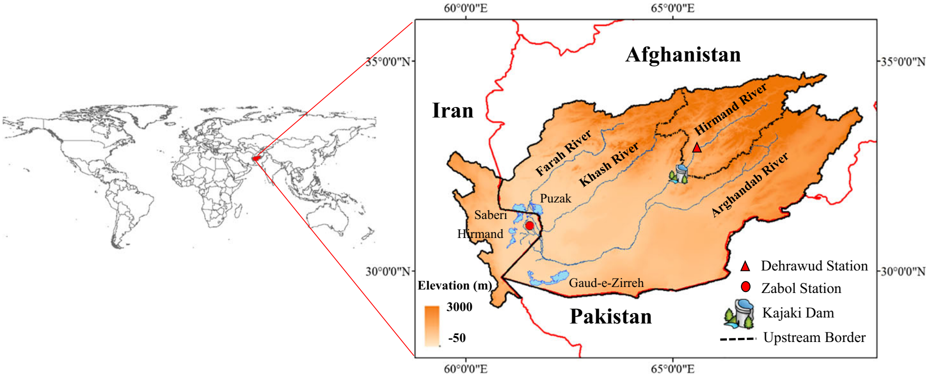

Fig. 1 Location of the HRB shared between Afghanistan and Iran

management of interventions aimed at sustainable development in the international transboundary waters environment (Uitto 2004). Therefore, it is essential to manage this increasing dispute by evaluating and investigating the changes in precipitation in the HRB, by reliable and independent knowledgeable methods which could be validated by riparian countries.

To detect the trends in precipitation in the HRB, we applied the non-parametric Mann–Kendall test (Mann 1945; Kendall 1975), which is widely used for trend analysis especially in hydrological and climatological studies (Nalley et al. 2013; Pingale et al. 2014; Degefu et al. 2019). According to the World Meteorological Organization (WMO), trend analysis of climatic variables requires long term (at least 30 years) historical data (Burroughs 2003). In Afghanistan, due to political instability, meteorological stations with long-term data availability are scarce. Moreover, a fundamental lack of trust in collected and shared hydrological data limits access to the reliable data in the HRB. To cope with this limitation, this study investigates the use of remote sensing information, as an independent and alternative source of data, for fact-finding in this disputed transboundary river basin. Previous studies showed that the satellite data can help for the fact-finding in transboundary river basins (e.g., Hossain et al. 2017; Khairul et al. 2018; Eldardiry and Hossain 2019). To have reliable results, we applied two satellite products, PERSIANN-CDR and CHIRPS, which provide long-term precipitation estimates. PERSIANN-CDR (Ashouri et al. 2015) is widely applied in meteorological and hydrological studies in recent years (e.g., Guo et al. 2016; Liu et al. 2017; Sun et al. 2019; Sobral et al. 2020). CHIRPS dataset (Funk et al. 2015) has also been validated in some regions with reasonable performance (e.g., Ayehu et al. 2018; Dinku et al. 2018; Gao et al. 2018; Rivera et al. 2018). Thus, we applied these two datasets for the purpose of this study.

This paper is organized as follows: In Section 2 and 3, the study area and data used for the analysis are described, respectively. In Section 4, the applied methods are presented. Next, Section 5 describes the results of analysis and discussion of the results. Finally, Section 6 is dedicated to the conclusions and suggestions for future research.

2 Study Area

The international HRB has a total area of 367,000 km^2 (Fig. 1). The Hirmand River, with a total length of 1050 km, is the longest international river in Afghanistan. It originates from the

Hindu Kush mountains and flows into the Hamoun-e-Puzak wetland which is mainly located in Afghanistan. During the high flow of the river, the Hamoun-e-Puzak merges with the Hamoun-e-Saberi (59% in Iran, 41% in Afghanistan) and the Hamoun-e-Hirmand which is entirely in Iran. In such situations, the three lakes form the great Lake Hamoun, with nearly 4500 km^2 of surface area. Then the surplus water overflow into the Gaud-e-Zirreh (in the south) which is normally dry. In this situation, the length of the river would increase by 200 km (Najafi and Vatanfada 2011).

The international Hirmand River water flow varies considerably within and between years. Approximately 84% of the river water flows during February–June. Precipitation mostly occurs as snow in winter in the mountainous areas of the basin, with a mean annual between about 50 mm in the southwest and about 300 mm in the northeast (Goes et al. 2016; Thomas et al. 2016). In the Sistan area in Iran, the mean annual precipitation is approximately 55 mm (Thomas et al. 2016; Mianabadi et al. 2019) with years less than 10 mm (1987, 2001, and 2010) and maximum annual rainfall of 129 mm (in 2005).

The potential evaporation in Zabol station in Iran (Fig. 1) is 2059 mm. The high amount of evaporation comes from the strong winds combined with the low amount of relative humidity and high summer temperatures in the regions. The phenomenon of "120 days wind" with a prevailing speed of approximately 10 ms^{-1} occurs in the region in summer (Van Beek et al. 2008). The relative humidity in the south of the basin is about 25%. The mean temperature is 22 °C in Zabol station, while in the delta, the temperature exceeds 50 °C in summer (Van Beek et al. 2008). Such a hot and dry climate in Sistan increases the crop water requirement and irrigation demand, which is provided by the water extracted from the river and the lake. In addition to irrigation, the river and the lake water is used for the fishery, animal husbandry, and domestic consumptions. Therefore, the Hirmand River, as the main water supply of the Lake Hamoun, is a vital resource for the Great Sistan Plain, a shared plain between Afghanistan and Iran. In addition to economic and environmental values, like the Ganges River, a holy river for Hindus; the Lake Hamoun is also a sacred lake for Zoroastrians. Because they believe that Zarathustra's seeds are preserved in this lake. Accordingly, the Lake Hamoun plays a significant role in social, economic, cultural, political, and environmental life of the Great Sistan Plain.

The water dispute on the HRB water has been ongoing for more than 200 years. The debates between Iran and Afghanistan became more challenging after defining the Afghan-Iranian border in 1872 (Dominguez et al. 1951). These debates finally led to the water treaty between the two countries in 1973. Despite having five transboundary river basins (Amu Darya, Kabul River, Hirmand River, Hari Rud River, and Murghab River) and six riparian countries (Iran, Pakistan, China, Tajikistan, Uzbekistan, Turkmenistan), Afghanistan has only one formal water treaty with its neighbors for shared utilization of transboundary rivers, i.e. the 1973 treaty with Iran. In contrast, Iran has various water agreements with its neighbors including the former Soviet Union countries (Turkmenistan, Azerbaijan, and Armenia), Turkey, Afghanistan, and Iraq on most of its transboundary basins. Based on the 1973 treaty, an average amount of 26 m^3/s water from the Hirmand River should be delivered by Afghanistan to Iran in a normal water year. A normal water year was defined as a year during which the total flow of water measured at Dehrawoud hydrometric station (see Fig. 1), at the upstream of the Hirmand River, is 5661.715 MCM (The Afghan-Iranian Helmand river water treaty 1973). Article IV of the treaty stipulates that, in years when the water flow is less than that of normal years due to climatic factors, the amount of 26 m^3/s should be adjusted. Afghanistan also agreed that it should not take any actions to deprive Iran, totally or partially, of its water right to the Hirmand water.

Water challenges between two riparians remained despite ratifying the treaty. For example, during Taliban rule (1996–2001) the water flow from the Hirmand was halted and Lake Hamoun dried up. It was likely due to combined effects of drought and increasing irrigation of newly extended opium-poppy fields in the south of Afghanistan as well as the construction of upstream infrastructures (Weier 2002). After 2002, water flow resumed, but it remained a source of dispute between two countries (Kutty 2014). Iran accuses Afghanistan of depriving Iran of the Hirmand, by construction dams and infrastructures in the upstream of the river to divert water for irrigation. Iran argues that the remarkable increase in irrigated areas in Afghanistan in the past decades (Hajihoseini 2014; FAO 2015; Mansfield 2017) has caused a significant reduction in water flow into Iran, such that the Lake Hamoun dried up again in 2017. Most of the irrigated area in Afghanistan is under poppy production with a water requirement of five times more than wheat water requirement (Najafi and Vatanfada 2011). The area of the cultivated land under opium poppy in Afghanistan has been increasing from 71,000 ha in 1994 to 328,000 ha in 2017 (UNODC 2017). The Helmand province located in the HRB particularly is a locus for opium-poppy cultivation in Afghanistan with about 144,000 ha in 2017 (UNODC 2017).

On the other hand, Afghanistan assures that it intends to enforce the treaty (The Guardian 2017), but, despite significant opposition from Iran, more dams continue to be built in Afghanistan (Thomson 2018). The director of International Treaties and Conventions at the Afghan Ministry of Foreign Affairs rejected the Iranian claim about not respecting the water rights of Iran and claimed that during the last 40 years, Iran has received several times more water than what was specified in the water treaty. Afghanistan also claimed that due to a significant reduction in precipitation during recent years, water cannot be completely delivered into Iran based on the 1973 treaty. This dispute between Afghanistan and Iran, such that the president of Iran, Hassan Rouhani, said that his government could not remain silent about the environmental damages arising from dam construction by Afghanistan on the rivers flowing into Iran. The Afghan government responded that building dams on the Helmand River was a top priority for the government and it was intent on continuing with its plans.

Since distrust foster strained relations between Iran and Afghanistan over shared waters, this tension can be addressed by trust-building and accountability measures. Accordingly, investigating the change in precipitation in the HRB can be fruitful as a part of joint fact-finding and mutual trust-building to tackle these issues between two riparian countries.

3 Data

No doubt, data and information access, and exchanges are widely considered to be fundamental components of long cooperative history over shared transboundary river basins (Gerlak et al. 2010). In water diplomacy literature, data and information exchange is supported as the first step to achieving cooperation and joint management of transboundary waters (Duda and La Roceh 1997; Gerlak 2004). Accordingly, water resources data and information exchange is considered as a key principle of some landmark international transboundary water conventions such as the 1966 Helsinki Rules and the 1997 UN Convention on the Law of Non-Navigational Uses of International Watercourses (Gerlak et al. 2010). Nevertheless, data and information exchange is one of the main challenging issues of many treaties and international river basin organizations (Mostert 2003; Bitew and Gebremichael 2011).

This issue has been one of the fundamental causes of water dispute between two riparian countries over the HRB utilization. Due to poor infrastructure and limited meteorological monitoring systems arising from war and extended period of political instability in Afghanistan, the long term data for trend analysis of precipitation is scarce (Savage et al. 2009). Furthermore, many of reliable historical data sets were lost under Taliban rule (1994–2001). Last but not the least, like many Middle Eastern riparian countries, two countries are reluctant to share reliable data.

To address these limitations and issues, the satellite precipitation products can be applied as an alternative tool for precipitation measurement in transboundary river basins. The satellite products, such as PERSIANN (Hsu et al. 1997), CMORPH (Joyce et al. 2004), and TMPA (Huffman et al. 2006), have been developed by combining passive microwave and infrared observations from satellite sensors. While the mentioned products provide a nearly global scale coverage, their duration is insufficient for climate studies. Furthermore, the temporal and/or spatial resolution of some products is too coarse for a reliable analysis of climate extremes (Ashouri et al. 2015). Recently, a new global satellite-based precipitation product was released by NOAA National Climatic Data Center (NCDC), termed “Precipitation Estimation from Remotely Sensed Information using Artificial Neural Networks-Climate Data Record” (PERSIANN-CDR; Ashouri et al. 2015). It is developed based on PERSIANN algorithm (Hsu et al. 1997) using the archive of Gridded Satellite (GridSat-B1) Infrared (IR) Data (Knapp 2008) for precipitation estimation and monthly Global Precipitation Climatology Project (GPCP) rain gauge (WCRP 1986; Adler et al. 2003) for bias correction (Nguyen et al. 2017). PERSIANN-CDR provides daily precipitation at a 0.25° spatial resolution with a near-global coverage (60°S-60°N) from 1 January 1983 to the present. Thus, it provides a dataset with sufficient duration for trend analysis of climatic variables.

In addition to PERSIANN-CDR, another new satellite-based rainfall product that was released by U.S. Geological Survey (USGS) and Santa Barbara Climate Hazards Group, University of California (Funk et al. 2015), named Climate Hazards Group InfraRed Precipitation with Station data (CHIRPS) is applied in this study. This product was developed based on global Cold Cloud Duration (CCD) rainfall estimates which were calibrated by the TMPA 3B42 v7 (Huffman et al. 2006). It also incorporates station data for bias correction. CHIRPS provides daily precipitation at 0.05° and 0.25° spatial resolution with a quasi-global coverage (50°S-50°N) from 1 January 1981 to the present. To remain consistent with PERSIANN-CDR, this study used CHIRPS data with a spatial resolution of 0.25°.

Several researchers have applied PERSIANN-CDR to trend analysis in extreme precipitation indices (e.g., Katiraie-boroujerdy et al. 2016; Arvor et al. 2017; Nguyen et al. 2017). CHIRPS product is also used for this isuue (e.g., Gebrechorkos et al. 2019; Cavalcante et al. 2020). These studies show that PERSIANN-CDR and CHIRPS are fruitful and reasonably accurate for climate studies and trend analysis purposes. In this study, accordingly, the daily PERSIANN-CDR and CHIRPS estimates are applied for trend analysis of precipitation amount and extreme precipitation indices over the international HRB.

4 Methods

Changes in the global climate in recent decades have been leading to changes in the amount, frequency, and intensity of extreme rainfall which, in turn, have induced catastrophic floods and droughts in many countries in the world. These phenomena can result in socio-economic consequences and influencing the policy determination in several sectors, including agriculture, industries, and drinking water supply (Yazid and Humphries 2015). Furthermore, precipitation governs the partitioning of available water in a basin into runoff and evaporation. Hence, any changes in time in precipitation partitions are transformed into changes in both runoff and evaporation (Attogouinon et al. 2017). Such changes would affect water availability in the basin. Therefore, it is important to investigate how extremes change at spatial and temporal scales. The extremes are often studied by considering the extreme precipitation indices established by WMO (Klein Tank et al. 2009). The indices are including monthly maximum 1-day precipitation (Rx1day), monthly maximum consecutive 5-day precipitation (Rx5day), Simple precipitation intensity index (SDII), annual count of days when $P \geq 10$ mm (R10mm), annual count of days when $P \geq 20$ mm (R20mm), maximum length of dry spell (CDD), maximum length of wet spell (CWD), the annual sum of precipitation in days where daily precipitation exceeds the 95th percentile of daily precipitation (R95pTOT), the annual sum of precipitation in days where daily precipitation exceeds the 99th percentile of daily precipitation (R99pTOT) and annual total precipitation in wet ($\mathrm{P} \geq 1$ mm) days (PRCPTOT). Among these indices, Rx1day, Rx5day, R95pTOT, R99pTOT, and PRCPTOT measures the precipitation depth (mm), SDII indicates precipitation intensity (mm/day), R10mm and R20mm represent the frequency of precipitation (days), and CDD and CWD measures the duration of precipitation (days). Accordingly, in addition to the trend in annual and seasonal precipitation amount, the trend in extreme precipitation indices was also analyzed in this study.

While climate change is going to be considered as a driver forcing for the water shortage in the Sistan area, it is important to know how precipitation has been changing in the HRB at basin and sub-basin scales. Therefore, in addition to providing the spatial distribution of trends in precipitation amount and indices, trend analysis was also conducted for the HRB as a whole. Since it is important to know about the probable reason for water shortage in the Sistan area in Iran, the part of the HRB located in Iran (hereafter HRB-Iran) was also considered for this purpose. Moreover, since the Dehrawoud station is the representative of a water year to be normal, wet, or dry, the part of the HRB located upstream of the Kajaki dam (hereafter HRB-UoK) was included in our investigation. For this purpose, the amount of each variable for the pixels located in the basin was averaged and assigned to the basin.

Trend analysis of the hydroclimatic variables with non-normal distribution is commonly conducted by the non-parametric Mann–Kendall test. The Mann-Kendall (MK) test is defined as follows:

$$z_{MK} = \begin{cases} \frac{S-1}{\sqrt{\mathrm{V(S)}}} ifS > 0 \\ 0 ifS = 0 \\ \frac{S+1}{\sqrt{\mathrm{V(S)}}} ifS < 0 \end{cases} \tag{1}$$

in which

$$S = \sum_{k=1}^{n-1} \sum_{j=k+1}^{n} \mathrm{sign}(x_j - x_k) \tag{2}$$

$$V(S) = \frac{\left[n(n-1)(2n+5) - \sum_{i=1}^{m} t_i(t_i - 1)(2t_i + 5)\right]}{18} \tag{3}$$

In these equations, $V(S)$ is the variance of S, n is the number of data points, t_i is the number of ties for the i-th value, m is the number of tied groups, and x_j and x_k are the sequential data values. The positive (negative) value of z_{MK} indicates an increasing (decreasing) trend.

5 Results and Discussion

5.1 Spatial Distribution of Trends

Trends in seasonal and annual precipitation over the HRB are shown in Fig. 2. Based on PERSIANN-CDR, the trend in annual precipitation in the mountainous areas in the northeast is significantly increasing at 90%, 95%, and 99% confidence levels. The positive trend is observed in other areas of the basin, although it is not statistically significant. The decreasing trend observed in the northwest of the basin is also insignificant. Analysis using CHIRPS shows an increasing trend in annual precipitation over all parts of the basin, except in a small area at the border of the two riparian countries. The increasing trend in the north, east, and northeast of the basin is significant and so is the decreasing trend at the border area.

At seasonal scale, PERSIANN-CDR shows significant increasing trends in precipitation of the mountainous areas in all seasons. However, CHIRPS reveals significant increasing trends in precipitation in winter and spring in this area and decreasing trend in summer and autumn. The decreasing trend in summer in the mountainous areas is significant, but, due to the low amount of precipitation in summer compared to annual precipitation (4.5%), its trend has no significant contribution in annual precipitation trend. In the other areas of the basin, decreasing or increasing trend is not significant, except for spring precipitation estimated by CHIRPS. CHIRPS results show an increasing trend in precipitation in spring over all parts of the basin. Generally, significant increasing trends in precipitation estimated by CHIRPS are more evident than that of PERSIANN-CDR.

The increasing trend in the mountainous areas might be due to the changes in the form of precipitation from snow to rain. Hajihosseini et al. (2016) found a consistent increase in flows from November to February and a consistent decrease in flows in June and July. They concluded that these changes are due to less snowpack, increase of snowmelt-runoff in winter and decrease of snowmelt-runoff in summer. The seasonal snowmelt has a large and crucial role in water resources (Adler et al. 2019). While the form of precipitation may change from snow to rain, the results of Masoumzadeh (2018) reveal that snow cover in the mountainous areas which is the source of water of Hirmand did not significantly decrease during 2007–2017. Therefore, the decreasing trend in water flow in the Dehrawoud station could not be significant and consequently, the water flows into Iran should be delivered based on the treaty.

The spatial distribution of trends in extreme precipitation indices is shown in Figure S1 in the Supplementary file. According to this figure, Rx1day has been decreasing over the HRB, more significantly in PERSIANN-CDR. Rx5day shows a decreasing trend in PERSIAN-CDR, but an increasing trend in CHIRPS. For the mountainous areas in the northeast, Rx1day and Rx5day have been insignificantly increasing, more spatially extended for Rx5day. Furthermore, SDII, R95pTOT, and R99pTOT have been decreasing over the HRB. Results of PERSIANN-CDR and CHIRPS for R10mm and R20mm are a little different. While PERSIANN-CDR shows a significant decreasing trend in R10mm for almost all parts of the basin, CHIRPS shows a significant increasing trend in R10mm in

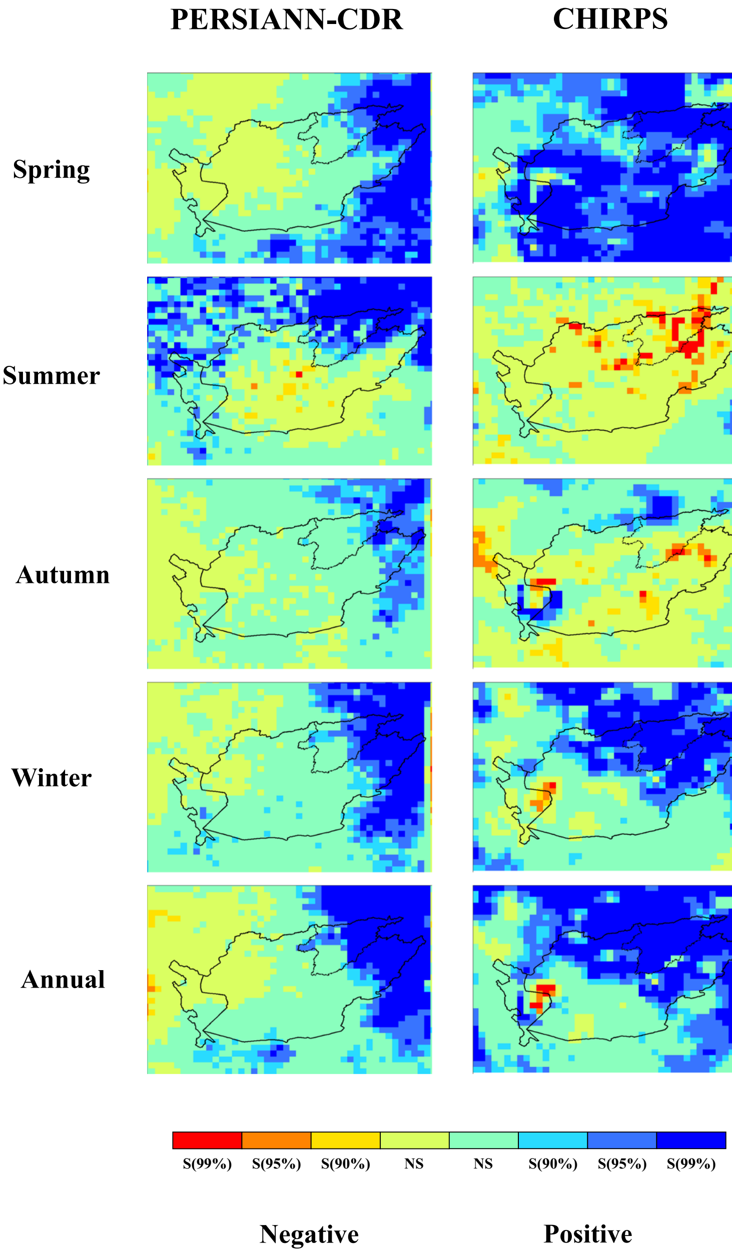

Fig. 2 Spatial distribution of trends in annual and seasonal precipitation

the north, east, and northeast of the basin covering mostly in the mountainous areas. Moreover, decreasing trend in R20mm in PERSIANN-CDR is mostly significant. For CHIRPS, the trend in R20mm is insignificantly decreasing in some areas and insignificantly increasing in some small areas. Generally, positive trends in Rx5day and R10mm over the mountainous areas in CHIRPS indicate that the frequency and amount of the heavy precipitation have been increasing. Increasing the frequency and amount of the heavy precipitation over the mountainous areas increases the river flows at the upstream of the Kajaki dam (Dehrawoud station). However, these trends are not increasing in PERSIANN-CDR. It is worthy to mention that the frequency and amount of heavy precipitation in the other parts of the basin have been decreasing.

The significant decreasing trend in SDII indicates that the intensity of precipitation has been decreasing over the HRB. The trend in CDD is different for PERSIANN-CDR and CHIRPS. While PERSIANN-CDR shows a decreasing trend in the mountainous areas and an increasing trend in the desert areas, CHIRPS reveals an increasing trend in the mountainous areas and a decreasing trend in the desert areas. In contrast, both products show almost a similar trend in CWD. CWD has been significantly increasing in most parts of the basin. It indicates that the maximum length of the wet spell is becoming longer over the HRB. It also supports the decreasing trend of SDII as indicated by Powell and Keim (2014). R95pTOT and R99pTOT show decreasing trends for both PERSIANN-CDR and CHIRPS. PRCPTOT is significantly increasing in the mountainous areas and insignificantly decreasing in the other parts of the basin, pointing towards wetter conditions in the mountainous areas and drier conditions in the other parts.

5.2 Trend Analysis at the Basin Scale

Figure 3 shows the temporal trends in seasonal and annual precipitation in the HRB, HRB-UoK, and HRB-Iran from 1983 to 2016. According to this figure, in 2001, the basin received the least amount of precipitation during 34 years. It is more clear for PERSIANN-CDR than CHIRPS.

Generally, the amount of precipitation estimated by PERSIANN-CDR is more than that of CHIRPS, especially in summer. Furthermore, PERSIANN-CDR shows a more variable annual precipitation than CHIRPS. Figure 4 demonstrates that the trends in spring, winter, and annual precipitation are positive. For CHIRPS, positive trends in spring and annual precipitation are significant. While PERSIANN-CDR shows positive trends in summer and autumn precipitation, CHIRPS indicates the trends are negative. However, both positive and negative trends are insignificant. The trend in the HRB-UoK is positive at seasonal and annual scales except for summer precipitation estimated by CHIRPS. Increasing trends are significant for spring, winter, and annual precipitation. The significant trend in precipitation in the HRB-UoK arises from the significant positive trend in precipitation in the mountainous areas. In HRB-Iran, trends in precipitation for PERSIAN-CDR and CHIRPS are the opposite. Except for spring precipitation estimated by CHIRPS, trend (either positive or negative) are not significant in HRB-Iran. It indicates that changes in precipitation characteristics are not responsible for the water crisis in the Sistan area. Accordingly, there is no significant reduction in precipitation in the HRB during 1983–2016. This issue is also confirmed by Figure S2. The figure shows the change in the water of the Lake Hamoun during 1983–2016 from the Landsat images. It can be seen that the change in the water of the lake is not following the annual precipitation amount during the presented period. The amount of annual precipitation during the 2013–2016 period is more than that of during 1993–1999, however, the lake is almost dried up.

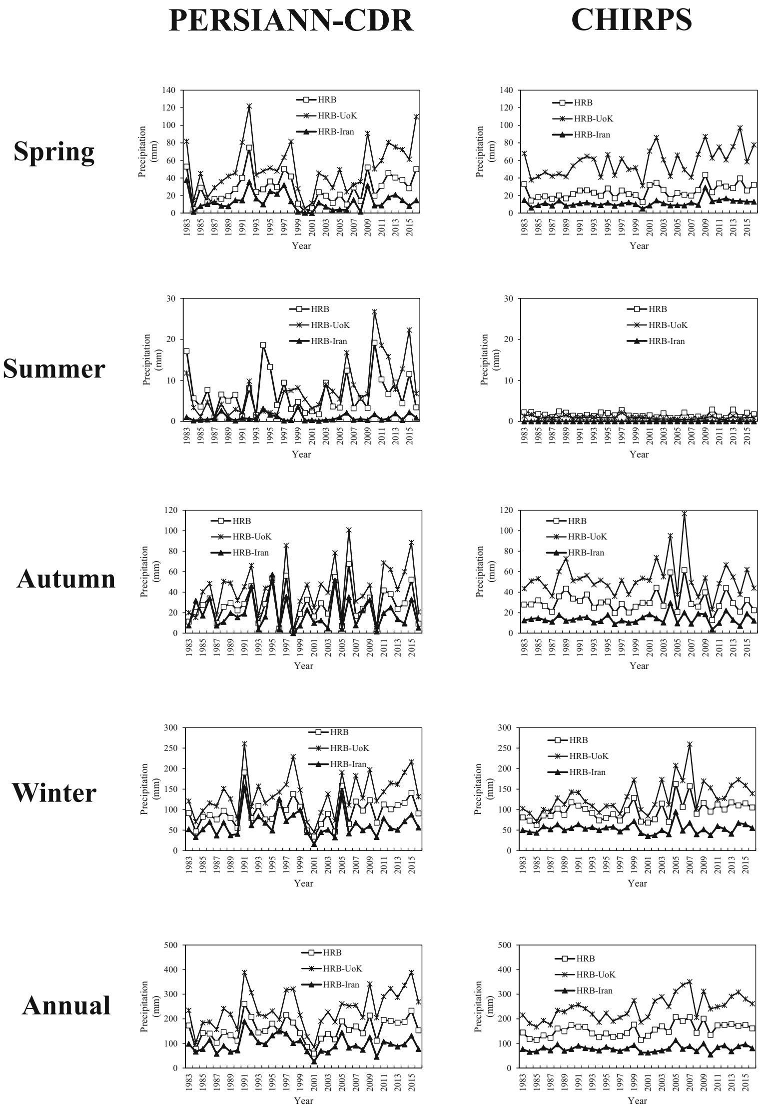

Fig. 3 Temporal trends in seasonal and annual precipitation over the HRB, HRB-Iran, and HRB-UoK

Temporal trends in extreme precipitation indices over the HRB, HRB-UoK and HRB-Iran are demonstrated in Figure S3. According to the results of PERSIANN-CDR, the year 2001 was the driest year during these 34 years and from 2001 upward, the amount, intensity, and frequency of precipitation were increasing, especially over HRB-UoK. Such results are not shown clearly by CHIRPS. The temporal trend of R95pTOT and R99pTOT shows that from 2000 to 2016, precipitation amount on extremely wet days has been negligible, while precipitation amount on very wet days has been increasing. Figure S4 illustrates the Z value of the Mann-Kendall test. The

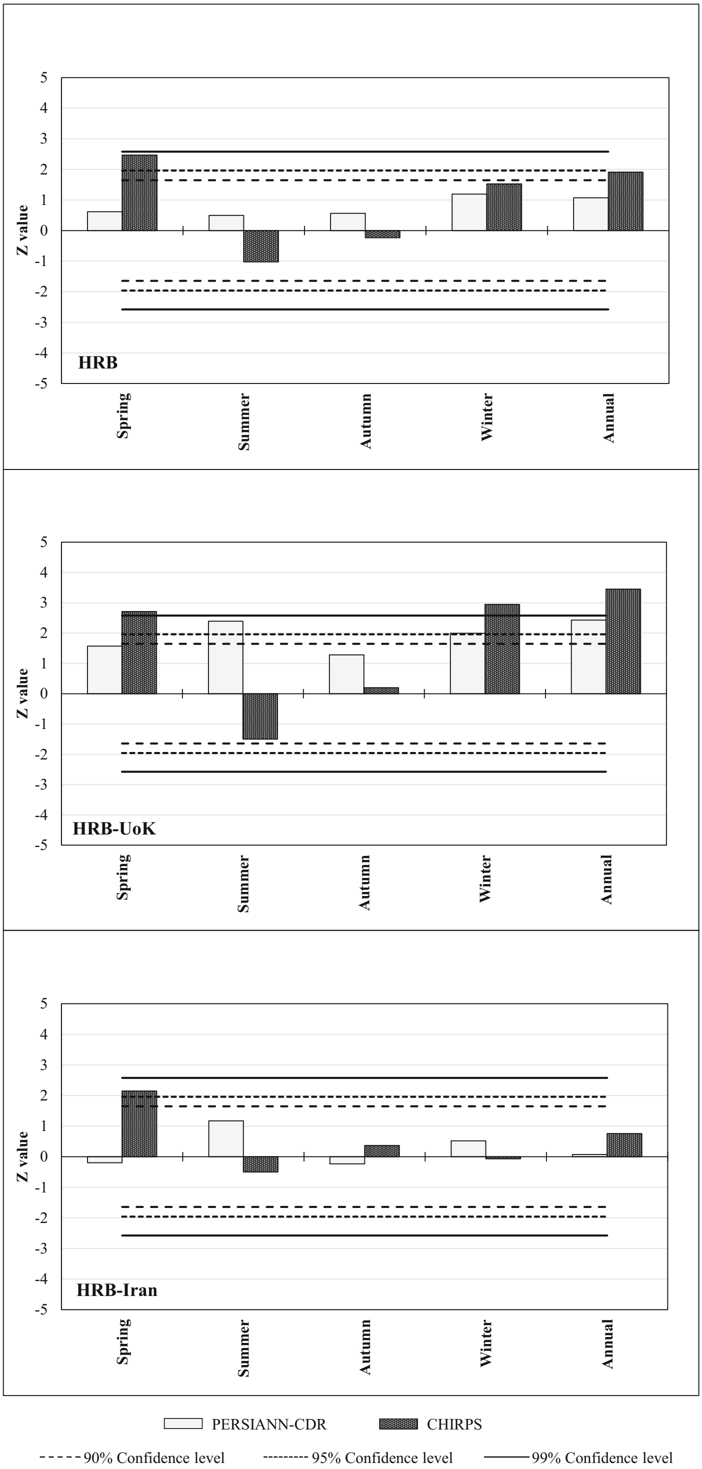

Fig. 4 Value of Z for seasonal and annual precipitation series at the basin and sub-basin scales

results of PERSIANN-CDR show that, except for CWD and PRCPTOT, trends in the other indices have been decreasing over the HRB and HRB-UoK. CHIRPS shows positive trends for Rx5day and R10mm for the HRB and HRB-UoK as well as CWD and PRCPTOT. In HRB-UoK, the results of CHIRPS show an increasing trend for CDD as well. According to the negative trends in R95pTOT and R99pTOT, the amount of precipitation in very wet and extremely wet days has been decreasing. Both models demonstrate a significant decreasing trend in SDII and significant increasing trends in CWD and PRCPTOT for HRB-UoK, indicating the increasing duration of wet spells and total precipitation and decreasing intensity of precipitation at the upstream of Kajaki dam. The decreasing trend in the intensity of precipitation can lead to a decreasing trend in the runoff. In HRB-Iran, except for CWD, the other indices are decreasing. In general, results indicate that the HRB-UoK is significantly getting wetter and HRB-Iran is insignificantly getting drier. The results of Mianabadi et al. (2019) also showed that the southeast of Iran where HRB-Iran is located has been getting drier during 1966–2015. The decreasing trends in some characteristics of precipitation can be justified due to the significant reduction in precipitation in 2001. Although precipitation amount and extreme indices show increasing trends from 2001 to 2016, these increasing trends could not compensate for the remarkable low amount of precipitation in 2001.

5.3 A Focus on the HRB-UoK

Since water flow at Dehrawoud station is dependent on precipitation in the HRB-UoK, the change in precipitation in this sub-basin was further investigated, by considering 10-year moving average precipitation, trends in monthly precipitation, and contribution of precipitation of wet and dry months in annual precipitation.

Figure 5 demonstrates that, in the HRB-UoK, the 10-year moving average has been increasing at seasonal scales, except for spring in PERSIANN-CDR and summer in CHIRPS. In spring, the 10-year moving average has been fluctuating but generally decreasing. Results also reveal that the 10-year moving average at the annual scale is increasing as well. It indicates that precipitation has been increasing during 1983–2016 in the HRB-UoK.

Figure 6 shows trends in monthly precipitation over the HRB-UoK. Results of PERSIAN-CDR demonstrate that trends in monthly precipitation are increasing in all months except in March and December. These increasing trends are significant for February, June, July, August, September, October, and November. According to CHIRPS, precipitation in July, August, and December are decreasing which is significant in July and December. Increasing precipitation in February, April, and November is significant.

The mean monthly amount of precipitation during 1983–2016 from PERSIANN-CDR and CHIRPS products are presented in Table S1. As seen in the Table, January, February, March, April, and December are considered as wet months and June, July, August, September, and October as dry months. According to the results of PERSIANN-CDR, significant positive trends in June, July, August, September, and October represent that the contribution of dry months' precipitation in annual precipitation has been increasing, significantly (See also Fig. 7). It means that the pattern of precipitation is changing in the HRB-UoK, such that the precipitation and growing season are going to be in-phase. In contrast, the contribution of wet months' precipitation in annual precipitation has a significant negative trend (See also Fig. 7) which leads to undesirable consequences for renewable water in the basin. This decreasing trend is significant for PERSIANN-CDR and insignificant for CHIRPS. Moreover, precipitation in dry months is significantly

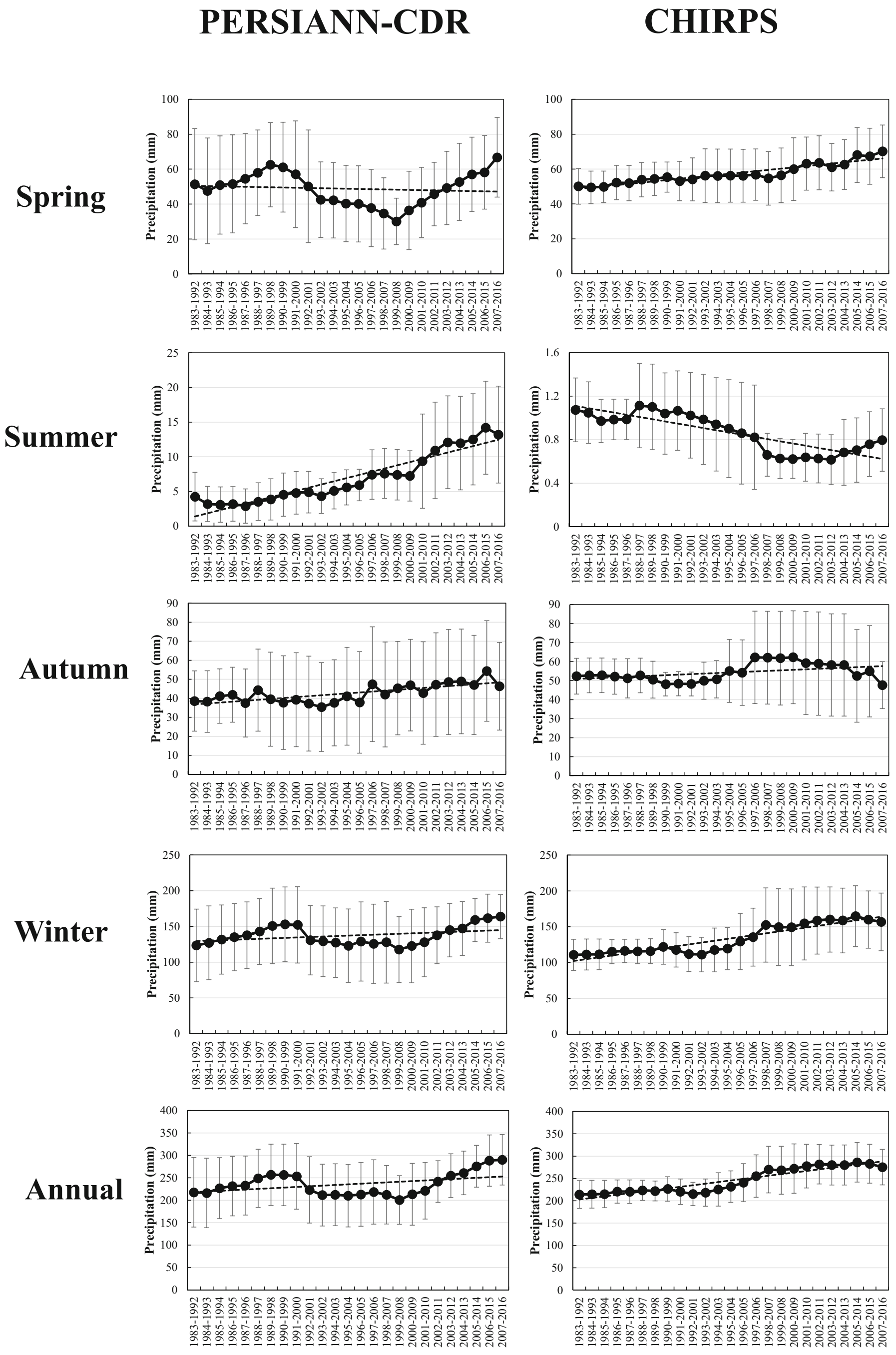

Fig. 5 10-year moving average of precipitation in the HRB-UoK at seasonal and annual scales

decreasing which is not considerably contributed in annual precipitation, due to a low amount of precipitation in these months.

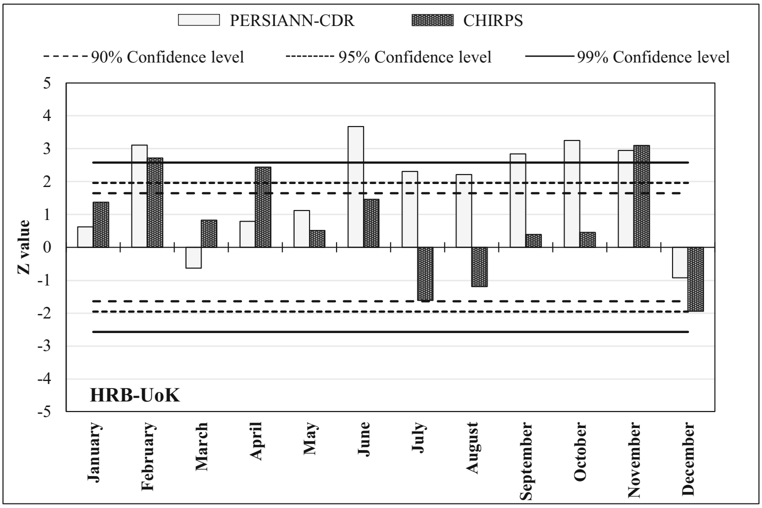

Fig. 6 Value of Z for monthly precipitation series in the HRB-UoK

6 Conclusions

Due to the low flow of the Hirmand River water into Iran, Lake Hamoun has been dried up in recent years, leading to various social, economic, environmental, and political consequences. On one hand, Iran accuses Afghanistan of depriving its water right. On the other hand, Afghanistan disputed claims that the reduction in precipitation amount during recent years has led to less water flow into Iran. This study investigated trends in precipitation characteristics during 1983–2016 to understand if precipitation characteristics have changed in the HRB. Due to poor infrastructure in Afghanistan and lack of trust in collected and shared hydrological data between Afghanistan and Iran, access reliable data is a considerable limitation. Thus, in this study, the satellite products of PERSIANN-CDR and CHIRPS, as an independent source of data, were applied.

According to the results of this study, there is no significant reduction in precipitation in the HRB during 1983–2016 to limit delivering water of the Hirmand River to Iran according to the water treaty. However, it should be mentioned that the water balance of the catchment cannot be detected by only considering precipitation. Estimating the runoff in the basin needs to consider more components such as infiltration, snowmelt, the water stored in the reservoirs and so on which are not included in this study. Therefore, the study needs to be expanded to look at other processes. For example, evidence for major increases in irrigated area, trends in actual evaporation, and surface water extent changes in both countries within the basin can be considered. Future work can focus on these processes using remote sensing data for further investigation of water balance in the HRB.

From the policy-making point of view, in addition to appropriate management of water resources in the Sistan area, it is definitely necessary for both riparian countries to cope with the water problems in this region, through cooperative hydropolitical approaches and collaborative integrated management. The shared Lake Hamoun is so important for environmental and economic life in both Afghanistan and Iran. Therefore, supplying the environmental water right of the lake, which has not been considered in the 1973 water treaty, should be considered

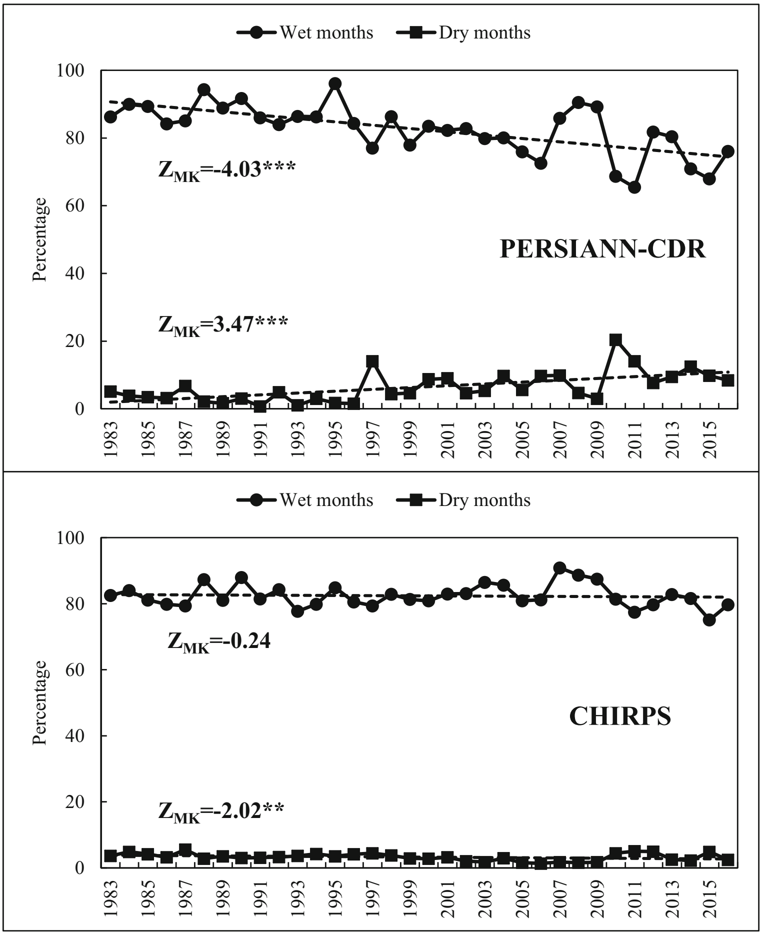

Fig. 7 Trend in the contribution of wet and dry months' precipitation in annual precipitation

as a vital demand for two riparian countries in water negotiations. Undoubtedly, since transboundary basins do not recognize the political boundaries, the lack of cooperation of riparian countries on the shared water resources will be detrimental to both countries. Cooperation between riparians can restore the environmental and economic life in the region, especially for the residents of both countries in the Great Sistan. Furthermore, with the growing regional effects of climate change, the lack of appropriate data sharing mechanisms, as an important part of cooperative transboundary governance, can exacerbate the human and environmental issues in the region. Accordingly, to achieve good governance in the basin, it is essential to design and implement data sharing as well as supplying environmental water rights mechanisms. For this purpose, using remote sensing products can be seen as the first step towards trust-building to enhance water diplomacy efforts in the region. The results of this study can be used as an example to guide similar analysis in other transboundary wetlands, lakes, and basins where disagreement over data records hinders mutual collaboration to jointly combat water-related issues that are behind socio-political and environmental challenges.

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Compliance with Ethical Standards

Conflict of Interest None.

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Affiliations

Ameneh Mianabadi[1] • **Kamran Davary**[1] • **Hojjat Mianabadi**[2] • **Poolad Karimi**[3]

✉ Ameneh Mianabadi
amianabadi@mail.um.ac.ir; ammianabadi@gmail.com

Kamran Davary
k.davary@um.ac.ir

Hojjat Mianabadi
Hmianabadi@modares.ac.ir

Poolad Karimi
P.karimi@un-ihe.org

[1] Water Science and Engineering Department, Faculty of Agriculture, Ferdowsi University of Mashhad, Mashhad 9177948944, Iran

[2] Water Engineering and Management Department, Tarbiat Modares University, Tehran 1497713111, Iran

[3] Water Science and Engineering Department, IHE Delft Institute for Water Education, Delft 2601 DA, The Netherlands