Contributions of Climate Change and Human Activities on Runoff Variations in the Central Part of Tajikistan in Central Asia

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Abstract

Comprehensive studies of the contributions of climate variation and anthropogenic activities to runoff alterations are essential for sustainable management of water resources in Central Asian countries. In the Kofarnihon River Basin (KRB) in Central Asia, both changing climate conditions and anthropogenic activities are known to have caused variations to the hydrological cycle. Therefore, quantifying the net influence of human contribution to the runoff changes is a challenge. In this study, by applying the original and modified Mann–Kendall trend test, Pettitt test, double cumulative curve and elasticity methods the historical trends and breakpoint changes of the hydro-climatic variables including temperature, precipitation, potential evapotranspiration, and runoff over the 1950–2016 along were determined, in addition the contributions of climate variation and anthropogenic activities to runoff changes in the KRB were evaluated. The trend analysis exhibited a significant increasing trend in annual temperature and potential evapotranspiration and the annual precipitation trend showed insignificant decreasing trend during the 1950–2016 time period. The breakpoint change was detected in runoff occurs in 1991. Further, the time series (1950–2016) are separated into the prior impacted period (1950–1991) and post impacted period (1992–2016) with trend test. The results showed that anthropogenic activities played a dominant role in changes in the runoff with a contribution of 79.94% in the upstream and 97.78% in the downstream of the KRB. Climate change contributed to 20.06% in the upstream and 7.53% in the downstream of the catchment during the post impacted period. In the land-use type changes, the dominant role played construction land which showed that the area from 248.63 km^2 in 1990 increased to 685.45 km^2 (175.69%) in 2015. The findings suggest that it is essential to adopt effective steps for sustainable development of ecological, hydrological and social order in the KRB in Central Asia.

Keywords: runoff variation, climate change, human activities, MK test, climate elasticity, Kofarnihon River Basin.

1. INTRODUCTION

In recent years, due to regular variations in water resources and the phenomenon of natural disasters, studies estimating the hydrological response to climate variability and anthropogenic activities have been given more attention. In many basins worldwide the variations in the climate and human disturbances cause serious changes in the ecological and hydrological patterns (Jiang et al., 2015; Piao et al., 2010; Zhao et al., 2014). Such variations also lead to changes in hydrological processes in the mountainous areas, causing more serious problems with water availability in the downstream areas in the arid and semi-arid areas, leading to irreversible changes to riparian ecological systems, such as degradation in aquatic ecosystems, reduction in lake areas, and fragmentation of natural habitats (Milly et al., 2005; Xue et al., 2017; Zhang et al., 2011). The physical and ecological processes are the most essential in the outermost level of the land, runoff is closely associated to each aspect of anthropogenic activity which is affecting land use, agricultural irrigation, vegetation growth, construction of hydraulic structures and the quality and volume available for provincial water use (Ranasinghe et al., 2019; Wada et al., 2017). Thus, it is especially crucial to evaluate the response of hydrological regimes to climate variability and anthropogenic activities in order to improve our idea of hydrological regime and develop scientifically based strategies for sustainable supervision in the case of water resources (Hijioka et al., 2014; Punkari et al., 2014).

The formation of runoffs have been influenced by several factors, including air temperature, atmospheric rainfalls, landscape, plant cover, and soil structure (Tarboton, 2003). The influence of different influences on runoff has been investigated by earlier works, among which climate variability and anthropogenic activities have abundant implications. Wang et al. (2019) studied the influence of climate variation and land practice variations on runoff in Haihe River Basin, and in this catchment the forest has the strong impact on runoff under climate variability. Alizadeh et al. and Dong et al. pointed out that various reaches of the basin were influenced contrarily by the climatic and human influences (Alizadeh et al., 2019; Dong et al., 2012a). Oki and Kanae (2006) presented that the global warming induce the changes of the regional continuous circulation of water which will obliquely induce variations in runoff. Anthropogenic activities may also lead to serious adverse impacts on air, water and land pollution, which, in turn, can disturb living conditions. The extensive utilization of water resources has led to large alterations in surface water and direct or indirect alterations in the measurable and qualitative features of runoff could be caused by the human disturbances of the natural surroundings and forming the river basin's surfaces (Pachauri et al., 2014a; Prestele et al., 2017).

In the last decade many endeavor have been made to quantify the influences of climate variability and anthropogenic activities on runoff processes (Ahn and Merwade, 2014; Kong et al., 2016; Tang et al., 2014). Ahn and Merwade (2014) studied the effects of climatic variations and anthropogenic disturbances on runoff conditions in combination with trend analysis and hydrological modeling using historical measured data in Indiana, New York, Arizona, and Georgia in the USA. Ahn and Merwade (2014) point out that in all four states relative to climate impacts the anthropogenic impacts are greater on runoff at most gauging stations. Previously many studies have been conducted in Southeastern and Central Asian river basins to determine the effect of climate variability and anthropogenic disturbances using different hydrological models and hydrological sensitivity methods (Bissenbayeva et al., 2019; Bu et al., 2018; Chang et al., 2015; Dong et al., 2012a; Gulakhmadov et al., 2020a; Guo et al., 2016; Lee and Kim, 2017; Li et al., 2014; Li et al., 2016a; Li et al., 2016b; Ma et al., 2008; Rakhimova et al., 2020; Wang et al., 2015; Xue et al., 2017; Yan et al., 2020; Zhao et al., 2015; Zhao et al., 2014; Zhou et al., 2018).

In Central Asia, Xue et al. (2017) quantitatively analyzed the factor which caused by climatic and anthropogenic disturbances to the variation of the runoff in the Tarim River Basin by applying the DCC method and Budyko methods and explored that the sensitivity analysis showed the runoff more most susceptible to variability in landscape parameters. Bissenbayeva et al. (2019) based on potential evapotranspiration and precipitation applied the hydrological sensitivity method to assess the influences of climate change and anthropogenic disturbances on average annual runoff during the 1960–2015 time period in the Arys River Basin and Keles River Basin in Central Asia. The result of the hydrological sensitivity method showed that over both basins the annual runoff decreased due to anthropogenic factors, the reduction percentages ranged from 59% to 99% (Bissenbayeva et al., 2019). The climate elasticity, double cumulative curve methods, Pettitt test, and Mann–Kendall trend test were used by Rakhimova et al. (2020) in the Buqtyrma River Basin in Central Asia to examine the trends and breakpoint changes of the hydro-climatic data, the influence of climate variation and anthropogenic factor to runoff variations during the 1950–2015 period (Rakhimova et al., 2020). Rakhimova et al. (2020) reported that the in the lower reaches changes in runoff was stronger (84.66%) which was induced by human disturbances than in the upper reaches and middle reaches.

In our previous study the authors showed the hydrologic response to climate change Gulakhmadov et al. (2020a) by applying the SWAT model in the mountainous Vakhsh River Basin (VRB) in Central Asia to simulate the effect of climate variation on runoff changes. It was found that global warming accelerated the process of snow/glacier melting which has induced an increasing runoff in the VRB in Central Asia in recent decades (Gulakhmadov et al., 2020a). In literature different methods have been shown to highlight individual influences of climate variation on runoff changes from effects of anthropogenic activities. One of the simple approaches is the Mann-Kendall test, which is a widely use approach to amalgamate trend test examination with empirical statistical methods (Tang et al., 2014). Empirical statistical methods on the basis of the historical hydro-climatic data series typically create the ratio of runoff and climatic factors (Gao et al., 2011; Zhao et al., 2014). Also, for the more systematic procedure of identifying the runoff variation from the hydro-climatic data series, the empirical statistical approach could be aggregated with the Budyko analysis and Double Cumulative Curve method (Ahn and Merwade, 2014; Bao et al., 2012; Donohue et al., 2011; Zhao et al., 2014). Hydrological models are consistent such as a physically-based semi-distributed SWAT model (Mango et al., 2010), MIKE SHE (Bourgault et al., 2014), Variable Infiltration Capacity (Xu et al., 2013), generalized additive model (Schilling et al., 2010) and Hydrologic Engineering Center's-Hydrologic Modeling System (HEC-HMS) (Dvory et al., 2018; Teng et al., 2018) to quantify effect of climate change on runoff and have been used these models in different basin globally. Hence, these hydrological models generally require different datasets which therefore restrict their application in some river basins with limited records (Chiew et al., 2006). The climatic elasticity method is a useful and alternative method for quantifying variations in runoff, which was suggested by (Arora, 2002; Fu et al., 2007; Wang et al., 2016; Zhang et al., 2001).

It can be revealed that quantitative study of the response of hydrological regimes to climate variability and anthropogenic intervention has not yet been carried out in the Kofarnihon River Basin in Central Asia. The objectives of this study are: 1) to determine statistically the presence or absence of variable trends and the critical breakpoint change in annual hydro-climatic variables including potential evapotranspiration, temperature, precipitation, and runoff at Dahana Station and Tartki Station in the KRB from 1950 to 2016 using the Mann-Kendall test, Modified Mann-Kendall test and Pettitt test; 2) to investigate sensitivity and contributions rate of both the specific influences of climate variation and anthropogenic interferences to runoff changing processes and estimate the contribution of impacts between upper reaches in mountains and lower reaches in plain regions in the KRB with the climate elasticity method and the double cumulative curve method. This study will comprehensively enhance our understanding of the runoff process and develop scientifically based plans for sustainable management of water resources in the upstream and downstream region of the Kofarnihon River Basin.

2. DATA AND METHODS

2.1 Study Area

Kofarnihon River (KR) is the third largest inflow of the Amu Darya River (ADR) and it flows through Tajikistan and partially forms the border between Tajikistan and Uzbekistan in Central Asia and lies between longitude 68°-70°E and latitude 37°-39°N. The KR is flowing into ADR 36 km below in the confluence of the Panj and Vakhsh rivers. Before reaching the ADR the total distance of the KR is 387 km and the overall area of the basin is 11590 km^2, of which 8070 km^2 is mountainous area (Dukhovniy and Makhramov). Elevation in the Kofarnihon River Basin ranges from 304 to 4830 m above sea level (Figure 1).

[Insert Figure 1]

The Kofarnihon River has a snow-glacial type of feeding. Its module of the annual runoff is 30–50 l/(km^2). Seasonal snow plays the main role in the formation of high water; therefore its duration is determined mainly by the water reserves in the snow. The peak of the flooding period with the highest annual water discharge takes place in May–June. In July, the boundary of seasonal snow melting approaches the glacial zone. In August, the water discharge is still quite high, and in September-October the low-water period begins, lasting until the end of March (Catalog of glaciers of the USSR.).

2.2 Data Source

The climate and hydrological data include information on mean annual temperature, annual precipitation, and annual runoff over the Kofarnihon River Basin. The climate data was obtained for seven stations from the Agency of Hydrometeorology of the Committee for Environmental Protection under the Government of the Republic of Tajikistan (Table 1). From the Ministry of Energy and Water Resources of the Republic of Tajikistan were supplied the hydrological data (Table 1). The accuracy of the climate data was compared with two other sources such as (http://www.pogodaiklimat.ru) and (http://snobear.colorado.edu/Markw/Geodata/geodata.html) which provide hydro–climatic data for Central Asian countries. In the downstream area of the Kofarnihon River Basin at the Tartki discharge station, around 6-year gaps in the annual runoff data were found, which were corrected with the linear regression method. The accuracy of the runoff data in the upstream region was associated with the data of OSHC "Barqi Tojik" (http://www.barqitojik.tj/) where the company OSHC "Barqi Tojik" has its observational point for measuring the river runoff of the Varzob River. Further due to lack of climate data such as wind speed, solar radiation, and humidity the Hargreaves method for estimation of the potential evapotranspiration (PET) was adopted. In addition, PET was calculated with the time series of the Climate Research Unit (CRU, TS v.4.02) over the period of 1950–2016 (Zhang et al., 2016). The CRU dataset is comparatively authentic for use in Central Asia (Guo et al., 2018).

[Insert Table 1]

In Central Asian, Tajikistan known as a predominantly mountainous landscape. Mountains occupied nearly 93% of the Tajikistan's territory. For the water availability in Central Asia region Tajikistan's glaciers play an important role. Along with Kyrgyzstan the high concentration of glaciers of Tajikistan provide nearly 70% of the rivers in the Aral Sea Basin (Dukhovniy and Makhramov). The economy is mainly supported by light industry, non-ferrous metallurgy, and agriculture in Tajikistan. The hydropower potential is big and according to Ministry of Energy and Water Resources of the Republic of Tajikistan from the possible energy capacity around 5% is used. Nearly 25% of the total GDP comes from the agricultural sector and it is responsible for 70% of the employment in Tajikistan. The main crops are cotton, vegetables, cereals, melons, and fruits. The melting of glaciers in Kyrgyzstan and Tajikistan will have contrary influences on water presence in the downstream country such as Uzbekistan, where from the total water intake about 90% is utilized in agriculture (Gupta et al., 2009).

According to the FAO AQUASTAT database (http://www.fao.org/nr/water/aquastat/data/) in Tajikistan annually 10.96 km^3 water is withdrawing for agriculture, however, in the territory of Tajikistan near 64 km^3 water is forming and the remaining water is falling in Amu Darya River and Syr Darya River – two main tributaries of Aral Sea. Tajikistan's population is 9.2 million, with almost three-quarters of the country living in rural areas. In the last decade (2000–2010), the average annual water intake from surface sources was 9 km³, from underground - about 2 km³ (Dukhovniy V.A. , 2019). Tajikistan annually consumes about 15–20% of the volume of water formed within its boundaries. The efficiency of irrigation systems is 55–65%. Irrigated agriculture consumes about 85% of the total amount of water taken, and household and drinking water supply consuming - 4%, industry - 4%, fisheries - 1%, and other industries - 6% (Dukhovniy V.A. , 2019).

Reforms in the agricultural sector, a change in the structure and areas of agricultural crops, the growth of unused irrigated land, and irrigation systems failure has led to a decrease in water consumption by 10–15% compared to the Soviet period. Due to the failure to implement measures on irrigation systems, as a result, more than 60 thousand hectares of irrigated land are not used annually. In Tajikistan, 4.8 million hectares are used for agriculture or 33% of the total area of the country including 3.8 million hectares of natural pastures, about 850 thousand hectares of arable land, and 138 thousand hectares of perennial plantations. The lands of settlements occupy about 156 thousand hectares and will continue to increase due to the expansion of the boundaries of settlements and the growth of the population. In terms of the provision of forest resources, Tajikistan ranks last among the countries of Central Asia. The irrigated land change over two last decades is shown in Table 2.

[Insert Table 2]

The main sowing of agricultural crops in Tajikistan is shown in Figure 2. According to the results of sowing winter and spring crops in all categories of economic entities of the 2019 harvest, the sown area of crops amounted to 846,990 hectares. Of the total sown area, 45.3% are grain crops, 25.5% - industrial crops - cotton, 6.1% - potatoes, 7.9% - vegetables (including seeds), 2.6% - melons and 12.6% - forage crops.

[Insert Figure 2]

The total population of Tajikistan under the Soviet Union in 1950 was 1.5 million. Over the past 70 years, the Tajikistan's population has grown by more than 6 times. The annual rate of natural growth is 2.3%. Only one-fourth of Tajikistan's residents live in cities, making the country the least urbanized country in the region. The highest population density (90–110 person/km^2) is characteristic of the northern, central, and southern regions and regions with developed agriculture and industry, while the lowest density is in the Pamir region (3 person/ km^2). The average population density is 55 person/km^2. The population growth rate is shown in Figure 3.

[Insert Figure 3]

2.3 Methodology

2.3.1 Mann–Kendall Trend Test

The Mann–Kendall (MK) test is a non-parametric test for identifying the significance of trends in hydro-climatic data (Hamed, 2008). Based on the linear regression the trend rate m_1 was identified using Equation (1).

$$y = m_1 x_t + c_o, \tag{1}$$

where x shows the runoff, precipitation, temperature, and PET during the 1950–2016 time period. The significance of $m_1$was verified by the *t*-test. The positive and negative values of m_1, indicates an growing and a declining trend of PET, temperature, precipitation, and runoff in specific time series (Mavromatis and Stathis, 2011). Yue and Wang (2002) pointed out that the puissance of the trend depends on the sample size, magnitude of trend, the number of changes over a time series, and the adjusted significance level. Since x_j and x_k in time series $X = [x_1, x_2, ..., x_n]$ are independent, by Equation (2) the MK test statistics (S) and signs are determined.

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

$$sgn(X_j - X_k) = \begin{cases} if\,(X_j - X_k) > 0, +1 \\ if\,(X_j - X_k) = 0, 0 \\ if\,(X_j - X_k) < 0, -1 \end{cases}, \tag{3}$$

where *n* is the number of the variable set, x_j and x_k are the sequential variables at times j and k, and *sgn* is the *sign* function that takes on magnitudes of –1, 0, and +1. The subsequent value of S shows growing or declining trends in hydro-climatic variable sets.

$$Var(S)=\frac{n(n-1)(2n+5)-\sum_{k=1}^{p} t_k(t_k-1)(2t_k+5)}{18}, \tag{4}$$

The tied group's number is shown by the p-value, and the t_k is number of measured variability in the kth group. Identified by Equation (5) the (STS) standardized test statistic (Z_S).

$$Z_S=\begin{Bmatrix} \frac{S-1}{\sqrt{Var(S)}}, S>0 \\ 0, S=0 \\ \frac{S+1}{\sqrt{Var(S)}}, S<0 \end{Bmatrix}, \tag{5}$$

where Z_S demonstrates the significance of the trend. The STS is employed to test the null hypothesis, H_0 if $Z_s>Z_{\alpha/2}$, and α indicates the confidence level. In the current research, if a trend in the runoff, precipitation, temperature, and PET time series is statistically significant at significance level α=0.01 (or 99% confidence spans), α=0.05 (or 95% confidence spans) and α=0.1 (or 90% confidence spans). At the 1%, 5%, and 10% significance degree, the null hypothesis of no trend is rejected if Z_s>1.45, Z_s>1.96 and Z_s>2.56, respectively. In Appendix A the comprehensive description of the modified Mann–Kendall test can be found.

2.3.2 Change Point Detection

To determine a single breakpoint change the Pettitt test (Pettitt, 1979) is used. Generally, is adjacent breakpoint change exist in a series, the maximum value K_T will be identified as the breakpoint change:

$$K_T=max\left|U_{t,T}\right| \tag{6}$$

$$U_{t,T}=\sum_{i=1}^{t}\sum_{j=t+1}^{T} sgn(X_i+X_j) \tag{7}$$

If $\left|U_{t,T}\right|$ growths with time t, this indicates that the order does not have a breakpoint change over the year in long-term datasets; conversely, if $\left|U_{t,T}\right|$ indicates a decrease trend compared to time t, this indicates that a breakpoint change happened in the series. The breakpoint change of the series is situated at K_T, showed that the statistic is significant. The significance probability of K_T is approximated for $p \leq 0.05$ with

$$p = 2\exp\left(\frac{-6K_T^2}{T^3 + T^2}\right) \tag{8}$$

2.3.3 Double Cumulative Curve Method

The double cumulative curve (DCC) is the graph of the accumulated data of one variable contrary to the accumulated data of another associated variable for a simultaneous period (Searcy and Hardison). In this study, a DCC method along with the linear regression lines was applied to determine the change of runoff in the prior impacted period and in the post impacted period. This method recently became a useful tool for determining changes in the hydrological regime as a result of the anthropogenic activities (Gao et al., 2017). The relative changes in runoff over the post impacted period can be estimated using equations adapted to the DCC in the prior impacted period, which can be showed as:

$$S_c = \alpha * \sum P + b \tag{9}$$

where S_c is the computed cumulative runoff, $\sum P$ is the measured station of the cumulative precipitation, and α and b are parameters examined by using the linear regression lines in the DCC in the prior impacted period.

2.3.4. Method of Climate Elasticity

In the current analysis, the climate elasticity method has been used to identify the influence of climate variability and human intervention on runoff. Equation (10) presented the overall variation in runoff as a mixture of climate variability and human intervention (Zhou et al., 2018):

$$\Delta R = \Delta R_{clim} + \Delta R_{hum}, \tag{10}$$

where ΔR is the mean annual runoff of measured recorded variability, ΔR_{clim} is the variation in mean annual runoff in consequence of climate change, and ΔR_{hum} is the variation in average annual runoff due to human intervention. Once ΔR_{clim} is determined, ΔR_{hum} can be found by employing Equation (10).

The comparative contribution of climate variability and human activities to runoff can be stated as Equations (11) and (12):

$$Rate_{clim} = \frac{\Delta R_{clim}}{\Delta R} \times 100\% \tag{11}$$

$$Rate_{hum} = \frac{\Delta R_{hum}}{\Delta R} \times 100\% \tag{12}$$

where $Rate_{clim}$ and $Rate_{hum}$ indicate the percentages of the influence induced by climate variability and the human intervention on the runoff variation.

The sensitvity of runoff to climate variability can be determined applying climate elasticity method. Perturbations of potentialevapotranspiration (PET) and precipitation can induce an alteration in water balance at the reference anlysis. Therefore, the total variation in the average annual runoff can be determined with Equation (13):

$$\Delta R_{clim} = \varepsilon_P \frac{R}{P} \Delta P + \varepsilon_{PET} \frac{R}{PET} \Delta PET, \tag{13}$$

where ΔPET is the potential evapotranspiration and ΔP is precipitation, respectively; for the sensitivity examination, two parameters, ε_{PET} and ε_P (ε_{PET} and ε_P are the elastic coeffcients of potentialevapotranspiration and precipitation), were described:

$$\varepsilon_P = 1 + \frac{\phi F'(\phi)}{1 - F(\phi)} \tag{14}$$

$$\varepsilon_{PET} = \frac{-\phi F'(\phi)}{1 - F(\phi)} \tag{15}$$

$$\varepsilon_P + \varepsilon_{PET} = 1 \tag{16}$$

where ϕ indicates the dryness coefficient, provided by $\phi = PET/P$ (the potential evapotranspiration is PET and P is precipitation*)*. Equations (17) and (18) are described the $F(\phi)$ *and* $F'(\phi)$ (Zhang et al., 2001):

$$F(\phi) = \frac{1 + \omega\phi}{1 + \omega\phi + \frac{1}{\phi}} \tag{17}$$

$$F'(\phi) = \frac{1 + 2\frac{\omega}{\phi} - 1 + \frac{1}{\phi^2}}{\left(1 + \omega\phi + \frac{1}{\phi}\right)^2} \tag{18}$$

where ω shows the plant-available water capacity coeffcient connected to vegetation category (Zhang et al., 2004), which vary from 0.01 to 2.0. Using Equation (19) this coefficient can be examined. The Equation (19) was developed by Zhang et al. (2004) to simulate the total evaporation at the watershed scale:

$$\frac{E}{P} = \frac{1 + \frac{\omega \times PET}{P}}{1 + \frac{\omega \times PET}{P} + \frac{P}{PET}} \tag{19}$$

where the values indicate evapotranspiration E, potentialevapotranspiration *(PET),* and precipitation *(P)* during a period. The theory of a water-based balance provides a basis for analyzing hydrological behavior in a basin and shows interconnections of *E, P,* and *R*:

$$E = P - R - \Delta S. \tag{20}$$

where *R* and *P* indicate runoff and precipitation, *ΔS* shows the soil moisture content, *ΔS* can be assumed to be zero for a longperiod of time series (i.e., ten years or more).

3. RESULTS

3.1 Trend and Breakpoint Analysis of the Temperature, Precipitation and Potential Evapotranspiration Series

In accordance with the long-term measured recorded station hydro–climatic data in the upstream and downstream of the ungauged Kofarnihon River Basin, the trends and magnitudinal changes in temperature, precipitation, potential evapotranspiration were computed by utilizing the non-parametric Mann–Kendall and modified Mann–Kendall tests. In addition the present work employed Pettitt's test to determine the variations during the 1950–2016 time period. In this study, the accessibility of measured station data in the KRB and its application in regional study were important to obtain comprehensive results of the hydro–climatic variation and influence of climate alteration on water regimes in recent decades. The changes in temperature, potential evapotranspiration and precipitation during the 1950–2016 time period in downstream and upstream regions of KRB are shown in Figure 4.

[Insert Figure 4]

Our results observed a rising trend in annual temperature in the downstream at a rate of 0.023 °C/year and the upstream at a rate of 0.0108 °C/year. The decreasing trend of annual precipitation was observed at a rate from –0.0124 mm/year to –0.2134 mm/year in both downstream and upstream regions of KRB. However, the increasing trend in annual potential evapotranspiration was found at a rate of 0.4142 mm/year in the downstream and at a rate of 0.3899 mm/year in the upstream regions of the catchment.

The results of the annual temperature, annual precipitation and annual potential evapotranspiration, the breakpoint change identification, and the original and modified Mann-Kendall trend tests during the 1950–2016 time period are shown in Table 3. Based on the modified MK test the annual temperature indicated a significant rising trend in the upstream and downstream regions of the Kofarnihon River Basin. The annual precipitation exhibited a decreasing trend; hence, either original or modified MK tests showed that the declining trend is not statistically significant in both upstream and downstream regions of the catchment. The modified MK test presented a significant rising trend in the annual potential evapotranspiration in the upstream and downstream parts of the KRB over the reference time period (1950–2016). The region of the current study faces climate variability, as observed the temperature increases in the KRB which causes increasing evapotranspiration and the humidity in the catchment is increasing with higher temperatures. In our previous study, the authors demonstrated the seasonal trend analysis of temperature, precipitation and streamflow of KRB with comparison to the fifth assessment report (AR5) of the Intergovernmental Panel on Climate Change (IPCC) (Gulakhmadov et al., 2020b).

[Insert Table 3]

The breakpoint change examination of hydro-climatic factors was investigated by the Pettitt test. In the downstream regions the abrupt change points for the annual mean temperature occurred around in 1976 and in the upstream regions in 1996. In this study, the change points occurrence for the temperature in the downstream and upstream in line with the study of Rakhimova et al. (2020) and Bissenbayeva et al. (2019) in Central Asia. The change point detected in 1969 for the precipitation and in 1998 for potential evapotranspiration during the 1950–2016 time period in both upstream and downstream parts of the KRB. The Pettitt’s test results presented that in this mountainous region, especially in the low-altitude areas of the catchment the earlier changes detected. This variability could be associated to the earlier impacts of climate variation on the low-altitude regions of the mountainous Kofarnihon River Basin in Central Asia.

3.2 Identification of Breakpoint Change and Trend Examination of Runoff

In accordance with the long-term data of runoff in the downstream and upstream of the Kofarnihon River Basin the trend examination was applied (Figure 5). In the upstream regions of the Kofarnihon River Basin, the average annual runoff varied from 640.52 to 1571.21 mm during the 1950–2016 time period and the mean annual was revealed to be 1010.35 mm. In the downstream areas of the KRB, the range of mean annual runoff was observed to be 324.62 to 815.86 mm with an annual mean of 583.16 mm.

The result of the modified MK test demonstrated a significant increasing trend in the upper reaches and lower reaches regions of the catchment, as shown in Table 4. In the upstream and downstream parts of the KRB the statistics values of Z based on the modified MK test were 3.561 and 5.307, respectively. The annual runoff indicated a rising trend all over the study region by 1.3361 and 2.4674 mm/year in the upstream and downstream regions of KRB. During the last 66 years, the runoff has been rising in the Kofarnihon River in Central Asia.

[Insert Figure 5]

Climate change is an essential factor in runoff variability. Uneven allocation of temperature, evaporation, and precipitation alteration can impact the temporal and spatial characteristics of water resources. In addition, continuous variations in the climate and land use might impact natural runoff. In this study, based on historical runoff trends was found the identification of the beginning period of land use alterability. To better understand the tendencies and breakpoint change in the annual runoff series the Pettitt's test method was implemented to the annual mean runoff in the upstream and downstream of the KRB. The analysis based on the Pettitt test method found that for the annual mean runoff an abrupt change in the upper reaches and lower reaches regions of the Kofarnihon River Basin occurred in 1991 as shown in Table 2. This result is confirmed by the study of Bissenbayeva et al. (2019) who found the change point in 1991 for the Arys River Basin in Central Asia.

[Insert Table 4]

In addition, the precipitation–runoff double cumulative curve (DCC) method for annual average runoff and precipitation was also employed to detect the breakpoint change in the annual runoff series in the upstream and downstream of the KRB. The previous studies confirmed that the DCC method has multiple abrupt points and assumes that the abrupt change might have resulted from climate variability and as well from human activities (Dong et al., 2012a; Wang et al., 2013). The result of the cumulative annual runoff and cumulative annual precipitation are shown in Figure 6. According to the DCC method, the abrupt change is also occurred in 1991, which shows that the runoff and precipitation have quite a homogeneous trend before 1991. This uniform is present the relationship between cumulative annual runoff and precipitation with two nearly straight lines in various slopes, which describe that the character of the runoff has changed after 1991 (Figure 6). Therefore, the regression line until 1991 is supposed to show the characteristics of the Kofarnihon River runoff under natural conditions. The period before 1991 can be considered as a prior impacted period without human disturbances and the period of 1992–2016 can be considered as a post impacted period.

[Insert Figure 6]

Further, for the period of the study runoff was split into the baseline measure period (1950–1991) during which the impact of climate change and anthropogenic activities on runoff was negligible influenced, and the change period (1992–2016) during which increasing climate variation and human intervention caused an evident disturbance of the runoff for both upstream and downstream areas. Consequently, the post impacted period was divided into five subperiods: 1992–1996, 1997–2001, 2002–2006, 2007–2011 and 2012–2016 respectively. A potential case for the change might be that runoff was influenced by melting snow and frozen soil in the upstream region, which was vulnerable to climate variability, whereas the downstream region was more affected by anthropogenic factor. In the long-term, these variations in annual runoff, and potential evapotranspiration precipitation can have serious consequences on the ecological balance of wetlands and sustainable agricultural development.

3.3 Effects of Climate Variability and Anthropogenic Intervention on Runoff

Identifying the elasticity of runoff to climate change remains a complex issue in hydrology due to the joint assessment between hydrological soil conductivity, soil water-holding capacity, climate, and land-use change (Wu et al., 2018; Zhou et al., 2018). To represent the interaction inter water and heat limitation to runoff, it is possible to present the series data of potential evaporation, precipitation, and aridity index, which can be utilized to assess the effect of climate variation on runoff. In the upstream areas of the KRB are located many small and medium-size of the glaciers (Catalog of glaciers of the USSR.) and the Kofarnihon River is snowmelt fed and glacier-fed type of river. It is essential to note that in this river basin except for precipitation, runoff is also impacted by evapotranspiration, soil thawing, and freezing processes and ice–snow melting. The movements of the runoff are–mostly the outcome of hydrological watershed processes and depends on features, such as the impact of climate variability and human intervention (Dong et al., 2012b).

In this study, based on the long-term hydro-climatic data the climate elasticity method was applied to identify the influence of climate variability and human disturbances on runoff in the upstream and downstream regions of the Kofarnihgon River Basin. In order to figure out the further influence of anthropogenic intervention in the post impacted period, five pairs of observed runoff under an approximately equal quantity of potential evapotranspiration and precipitation are shown in Table 3. In the upstream and downstream of the Kofarnihon River Basin the prior impacted period was ranged from 1950 to 1991 and the period which was impacted by human activities has been ranged from 1992 to 2016. Therefore, the runoff variations in each six year period from the post impacted period 1992–2016 are compared with prior impacted period 1950–1991.

In the upper parts and lower parts of the Kofarnihon River Basin, the total alteration in runoff is 99.64 mm and 46.69 mm, in precipitation 5.19 mm and –0.32 mm, and in potential evapotranspiration 10.77 mm and 8.05 mm for the period 1992–2016 compared to the period of 1950–1991.

[Insert Table 5]

The variation in runoff induced by anthropogenic intervention is 79.65 mm (79.94%) in the upstream and 136.22 mm (92.47%) in the downstream of the KRB during the 1992–2016 time period (Table 5). The variation caused by climate variability is 19.99 mm (20.06%) in the upstream and –11.09 mm (7.53%) in the downstream regions between 1992 and 2016, respectively. The analysis of each six year period which was separated for the post impacted period, it was revealed that the most significance influence of climate variability 245.98 mm (97.78%) occurred between 2002 and 2006 in the upstream and 82.87 mm (49.66%) between 1992 and 1996 in the downstream areas. The most significance effect of human disturbances was observed during the period of 1992–1996 in the upstream 111.76 mm (58.93%), while in the downstream region of the KRB the most significance impact of human activities was revealed 120.42 mm (84.11%) during the period of 1997–2001. Our study revealed that the impact of anthropogenic intervention was a dominant factor in the runoff changes in the KRB. This paper has quantified that in the mountainous upstream part of the KRB there is reasonably less exposure to human activities. Also, the effect of climate variability takes place in this study and the analysis demonstrated that during 66 years the trend of air temperature is continuously increased in the KRB. This phenomenon might cause rapid snowmelt in the KRB, which influenced the water cycle and hydrological process in the Kofarnihon River. The effect of climate variability on runoff variations between 1992 and 2016 was computed to be 20.06% in the upstream and 7.53% in the downstream regions of the Kofarnihon River Basin in Central Asia.

4. DISCUSSION

The study of climate variability in historical context is important to evaluate the economic, ecological, and potential social feedback of the region to climate change. The influences of climate variations and anthropogenic disturbances on the hydrological alterations influence all living things, including humans (Lioubimtseva and Henebry, 2009).

The Kofarnihon River Basin is one of the major water arteries in the Amu Darya River Basin. This river accounts for more than 9% of its whole runoff (Dukhovniy and Makhramov). The Amu Darya River is the second major inflow of Aral Sea in Central Asia and it is characterized with the arid and semi-arid weather condition with limited water resources due to the increase in water demand as a result of the demographic expansion and the larger change in water resources arising from the climate variation and severe anthropogenic disturbances. The terrestrial exploitation and residential land have strongly impacted the provision of water and water demand patterns in this region (Yin et al., 2016). The Kofarnihon River Basin also accounts several small run-of-river hydropower schemes, notably in the Varzob River close to Dushanbe in Tajikistan. In the KRB within the Tajikistan's territory are located several cities and districts such as Dushanbe, Varzob, Hisor, Vahdat, Rudaki, Tursunzoda, Faizobod, Shahrinav, N. Khusrav, Qubodiyon and Shaartuz where is population growing year after year. The climate of the KRB is continental under the impact of the westerlies direct to highly seasonal variations of precipitation and temperature. These variabilities are indicated because of the mountainous terrain of the catchment, which has a too strong local contrast and most assailable area in Central Asia to hydro-climatic variability (Duan et al., 2019). The south-western parts of the basin in summer are significantly influenced with the dry heat, which waves from the Afghanistan, Uzbekistan, and Turkmenistan deserts.

Based on the geological developments, the Kofarnihon River Basin associated to Central (Southern Tien Shan and Gissaro-Alai) and South-Western Tajikistan. The geological structure of the latter part essentially comprises Middle and Upper Paleozoic and, to a limited degree, Precambrian, Lower Paleozoic, Mesozoic, and Cenozoic deposits. The paper used the Harmonized World Soil Database (HWSD) version 1.2 with a scale of 1:5,000,000 to identify the soil type for the Kofarnihon River Basin. On the website of the Food and Agriculture Organization of the United Nations, the HWSD is freely available. The most notably soil categories were cambisols (48.69%), leptosols (26.60%), calcisols (9.79%), anthrosols (8.37%), shifting sand dunes (3.53%), and arenosols (3.02%) (FAO and ISRIC, 2012).

As for anthropogenic intervention, construction land and agricultural irrigation are the respective factors that can confirm the expansion of human influences on water resources in the KRB. The construction land increased heavily and forest land rised insignificantly while agricultural land tend declined and it implies that some areas of agricultural land altered into residential land.

[Insert Table 6]

In the KRB, compared with 1990, the area of forest land, grass land, water body and construction land increased by 0.13%, 1.08%, 17.57% and 175.69% in 2015, respectively (Table 6). At the same time, the area agricultural land and bare land decreased by 19.63% and 4.07%. The dramatic changes showed that the population is growing and demand for construction land is increasing. This could cause high water consumption in the KRB and for water managers is necessary to implement the gradually improved water use efficiency. Figure 7 demonstrated the land use type in the KRB based on the data which were derived from the Institute of Ecology and Geography Chinese Academy of Sciences.

[Insert Figure 7]

The application of trend approach to analyze the impact of climate or other factors on runoff is a common practice implemented by many researchers (Jha and Singh, 2013; Tan et al., 2019; Yagbasan et al., 2020). The result of modified MK test indicated that the trend of annual temperature and annual potential evapotranspiration significantly increased, while precipitation showed insignificant decreasing trend in the upstream and downstream of the KRB. These findings are in line with the previous studies which were done in Central Asia as well as agreed with IPCC reports (Hu et al., 2017; Li et al., 2017; Pachauri et al., 2014b). Our result of the trend analysis showed that annual runoff significantly increased in upstream and downstream areas of the KRB. Previous studies showed that temperature, precipitation, and potential evapotranspiration effect land-use transformation and could lead to larger variations in runoff (Wang et al., 2013). The land-use variability may induce significant variations in temperature and evapotranspiration, thus affecting the hydrological process of the catchment.

The combination of the Pettitt test and Double Cumulative Cure method demonstrated the abrupt change in 1991 in the upstream and downstream basin, which was agreed with the study of Bissenbayeva et al. (2019) in the Arys River Basin in Central Asia. Dong et al. (2017) studied the influences of climate variation and anthropogenic intervention based on precipitation, potential evapotranspiration and runoff data between 1975 and 2015 in the Nenjiang River Basin. Their results showed that in the upstream where is mountain area, the anthropogenic activities was less, and in the downstream area the effect of anthropogenic activities was greater. Since the 1990s human disturbances have had a rising effect on runoff changes due to the fast population growth, economic development, building of water conservancy plan facilities and grow in the planting zone for agricultural products. Zhou et al. (2018) used the climate elasticity method in the Dongjiang River Basin (DRB) and results presented that the influences of anthropogenic interventions on runoff variability in the lower parts is greater than in the upper parts in the catchment. The effect caused by anthropogenic activities on runoff variability was 37% in the upstream and 84% in the downstream of the DRB. In our study, the result of the climate elasticity method presented that the variation in runoff induced by climate variability and anthropogenic intervention is 20.06% and 79.94% in the upstream and 7.53% and 92.47% in the downstream of the KRB during the 1992–2016 time period compared to the period of 1950–1991. It shows that in both upstream and downstream areas the impact of human activities is a dominant factor to runoff changes. These findings in line with the result of previous investigations in the region of Central Asia including Arys River Basin, Keles River Basin, Buqtyrma River Basin, and Tarim River Basin (Bissenbayeva et al., 2019; Rakhimova et al., 2020; Xue et al., 2017).

It should be pointed out that there are uncertainties in the outcomes due to the assumption that runoff changes caused by precipitation–runoff variations due to climate change and human activities are independent from one another. In this study area (KRB) the meteorological data from presented climate stations might not be sufficient coverage of basin.

The climate change and human activities effects can be disregarded may also generate certain uncertainties due to data limitations. The simulation preciseness of hydro-climatic including precipitation and potential evapotranspiration may be influenced because of the limited number and distribution of the discharge gauging stations and climate stations. Hence, climate change may impact anthropogenic activities including land use, increasing urbanization and growing population may induce variations in water resources. In spite of negligible limitations and uncertainties, this analysis led to the comprehension of the quantitative investigation of the effects of climate variability and anthropogenic intervention on the runoff variations in the KRB. Further investigations could focus on the reduction of uncertainties and combining the climate measured data along with global climate model (GCM) data linked with a hydrological model of Soil and Water Assessment Tool (SWAT) and climate elasticity method to project the effects of climate variability and anthropogenic disturbances on water resources in the Kofarnihon River Basin.

5. CONCLUSIONS

The purpose of current work was to quantitatively identify the contributions of climate variability and anthropogenic activities on runoff variation in the upstream and downstream regions of the Kofarnihon River Basin in Central Asia. In accordance with the long-term data the trend of precipitation, temperature, and potential evapotranspiration were identified by using original and modified Mann-Kendall tests. The breakpoint change of the hydro–climatic series was computed by applying the Pettitt test and Double Cumulative Curve methods during the 1950–2016 time period. After splitting the study time series into prior impacted period (1950–1991) and post impacted period (1992–2015) the climate elasticity method was used to evaluate the contribution to runoff variation caused by climate variability and human activities. The main findings of this paper can be concluded as follows:

(1) Result of trend analysis showed a rising trend in annual temperature at a rate of 0.023 °C/year in the downstream and at a rate of 0.0108 °C/year in the upstream of the Kofarnihon River Basin during the 1920–2016 time period. The trend of annual potential evapotranspiration raised at a rate of 0.4142 mm/year and at a rate of 0.3899 mm/year in the downstream and upstream. The annual runoff exhibited a rising trend by 1.3361 and 2.4674 mm/year in the downstream and upstream of the basin respectively. The result of original and modified MK test confirmed a statistically significant increasing trend in annual runoff, potential evapotranspiration, and temperature throughout the period of

1950–2016 in the KRB. Annul precipitation demonstrated slightly a decreasing trend in both downstream and upstream at a rate of –0.0124 mm/year and –0.2134 mm/year, however the trend insignificantly decreased. The breakpoint change for the annual mean temperature occurred around in 1976 and 1996 in the downstream and upstream regions during the 1950–2016 time period. For the precipitation breakpoint change occurred in 1969 and for potential evapotranspiration in 1998 in the downstream and upstream. The result both Pettit test and DCC indicated the breakpoint change for annual runoff series in 1991 in the upstream and downstream of the catchment.

(2) The area of the construction land or residential land in 1990 during the prior impacted period, which was 248.63 km^2, increased to 685.45 km^2 in 2015 during the post impacted period. The area of agricultural land in 1990 was 1900.11 km^2, which decreased to 1527.16 km^2 in 2015. These discrepancies show that land use in the middle and downstream areas changed from agriculture to residential due to the growing population in the Kofarnihon River Basin in Central Asia.

(3) The climate elasticity method result exhibited that the effect of climate variability on runoff changes in the post impacted period (1992–2016) is 19.99 mm (20.06%) in the upstream and –11.09 mm (7.53%) in the downstream of the Kofarnihon River Basin in Central Asia. The change in runoff caused by anthropogenic activities is 79.65 mm (79.94%) in the upstream and 136.22 mm (92.47%) in the downstream in the post impacted period. Among the six divided periods of the post impacted period our result exhibited that the most significant impact of climate change 245.98 mm (97.78%) occurred between 2002 and 2006 in the upstream and 82.87 mm (49.66%) between 1992 and 1996 in the downstream areas. The most significant impact of human activities 111.76 mm (58.93%) presented in the upstream between 1992 and 1996, in the downstream 120.42 mm (84.11%) between 1997 and 2001. In this study, the effect of anthropogenic activities was a dominant factor in the runoff changes in both upstream and downstream of the KRB, while upstream was relatively less exposed to human activities due to a mountainous area. The constant global warming might induce rapid snowmelt in the KRB which also affected the hydrological process and climate influences in runoff changes in the upper part were greater than in the lower part of the catchment.

The runoff is an essential part of the hydrological cycle, the runoff variability can significantly influence human's safety, ecosystem well-being, and water resources. This study can provide suggestions for decision-makers and researchers to restrict human intervention to a reasonable range in the degrading agricultural land which is transferring into construction lands. To create relevant adaptation measures for mitigation of climate variations impacts on the water resources and reasonable allocation of water resources in the upstream and downstream of the Kofarnihon River Basin in Central Asia.

AUTHOR CONTRIBUTION STATEMENTS

N. G. and Y. C. proposed the idea and designed the study. A.G. contributed to results analysis. M.R. contributed to model development. M.G. contributed to data collection. All authors approved the final version of the manuscript.

DATA AVAILABILITY STATEMENT

Research data are not shared.

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APPENDIX A

Software Package, "Modifiedmk"

The modified MK test initiated by Hamed and Rao (1998) was applied to estimate the trends of serialcorrelation data. Afterward, Yue et al. (2002) initiated a nonparametric modified MKtrend method, that is appropriate for autocorelated data in accordance with the modified value in the difference of the test statistc. The correctness of this modified test in terms of its empirical significance was revealed to be superior to the original Mann–Kendall trend test absence from any loss of power. The open-course librarypackage named "modifiedmk" was developed in the R-language (Team). In this study the nonparametric Mann–Kendall tests and all modified versions of the Mann–Kendall tests was calculated by using the "modifiedmk" package. The "modifiedmk" package is now freely accessible via the CRANsource and Github version control platform (Patakamuri and O'Brien, 2019). Fixed modification indication is figured out as below, and from Equations (A.1) and (A.2) the *Z* values are identified (Yue et al., 2002):

$$V(S) = Var(S) \times \frac{n}{n_s^*} = \frac{n(n-1)(2n+5)}{18} \times \frac{n}{n_s^*} \tag{A.1}$$

$$\frac{n}{n_s^*} = 1 + \frac{2}{n(n-1)(n-2)} \times \sum_{i=1}^{n-1} (n-i)(n-i-2)\rho_s(i) \tag{A.2}$$

where n/n_s* indicates a modification dueto autocorrelation in the data, *"n"* is the actual value of measurementpoint, and ρ_s(i) is the autocorrelation of the measurement ranks. The RStudio software, version 3.5.3 were used to compute all MK, MMK, and Pettitt's tests resultsof the current research.