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STATISTICAL APPROACH TO ANALYSING STREAM DISCHARGE IN RESPONSE TO CLIMATE CHANGE AND GLACIER SHRINKAGE

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Key words: river runoff, climate change, glacier shrinkage, Karatal river basin, Mann-Kendall test.
Abstract. Based on runoff, air temperature, and precipitation data from 1960 to 2012, the effects of climate change and glacier shrinkage on water resources in the western part Zhetysu Alatau were investigated. The long-term trends of hydroclimatic variables were studied by using Mann-Kendall test. Analyzing weather station climatic data, we found a significant increase in temperature and quite stable trends for precipitation during study period. Positive trends in annual discharge were detected in almost all glacierized tributaries of Karatal river. This obvious upward trend in river runoff is likely connected with a general trend of increasing temperatures and intensive melting of glaciers in Tien-Shan.

Introduction. Water resources play the most important role in the sustainable development of society and economy in arid region, and they determine the evolution of ecological environment in the arid regions, including the two contrary processes of oasis formation and desertification.

Only a limited number of studies currently address the timing and evolution of expected glacier shrinkage and related changes in runoff [1]. Although glacier changes of Zhetysu Alatau (Eastern Tien Shan) in this region have been investigated [e.g. 2; 3;4), little is known about the whole variation characteristics of glaciers and glacier runoff in the KRB basin during recent decades.

In this paper, the long-term trends of the air temperature, precipitation and runoff time series are analyzed. To further understand the spatial distribution of the trends in the hydrometeorological variable, we divide the Karatal river into 5 sub-basins. The purposes of this study are to detect the trends of major hydroclimatic variables at annual and seasonal scales, and reveal association between climate change, glacier shrinkage and the variability of hydrological process response.

Study area. The Karatal river basin, which is the largest basin in Zhetysu Alatau, covers an area of 19,100 km^2, with acatchment areaof 5,300 km^2[5]. The Karatal river originates on the north-western slopes of the Zhetysu Alatau central ridge. It isformed by the confluence of the Kora, Chizhin and Tekeli rivers [4], while further on the plain, it meets with its largest tributary, the Koksu river to form a united stream [6].

The mean annual air temperature is -5 -7 °C in the high-altitude zone of Zhetysu Alatau; January is the coldest month, with -13 -14 °C. The spatial distribution of precipitation is controlled by altitude and varies from 1,000 to 1,600 mm a^{-1}, with maximum amountsoccurring at elevations of 1,800-2,200 ma.s.l. [6].

Hydro-meteorological data and trend analysing methods. We acquired data from the Taldykorgan weather station, which was the closest weather station available to our study area. This station is situated in the foothills, and provided long-term temperature and precipitation records since 1960.

In order to determine and analyse the potential drivers of glacier changes and investigate the changes in river runoff over the past decades a trend analysis using the Mann-Kendall test [7] was carried out for the time series of air temperature, precipitation and runoff at selected climate and hydrological stations. For more detailed analyses the impact of dramatically decreasing glacier to the runoff variation, we used hydrological data from four station for each glacierized sub-basin (Kora, Koksu, Koktal and Chizhin) and one station from non-glacierized catchment Tekeli (see Fig. 1).

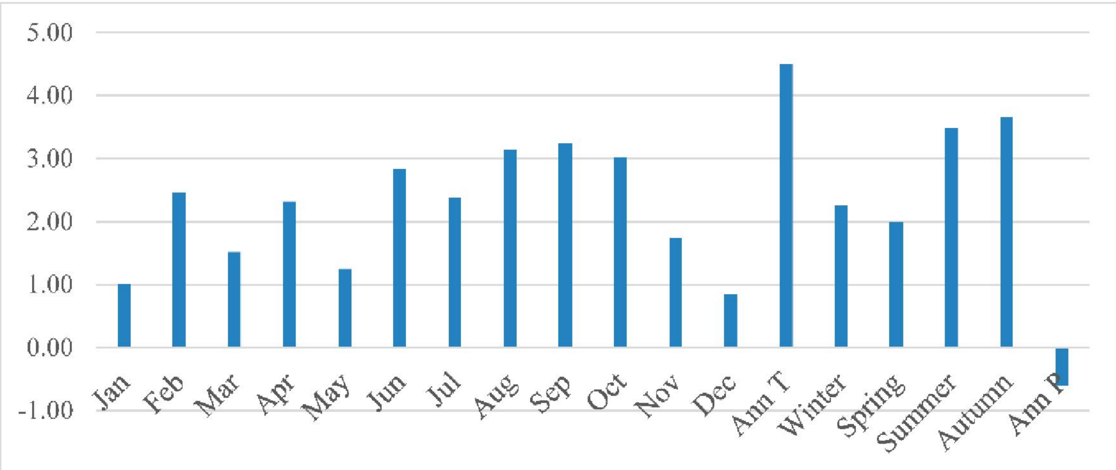

Figure 1 – Kendall test Z statistics for trends of monthly, annual and seasonal temperature and for annual precipitation of Taldykorgan station (Significant atP< 0.05; critical value of Z <-1.96and >+1.96(two-sided))

The accumulative deviation test was applied to detect trends in air temperature at the Taldykorgan weather station. Test results showed that the temperature had step change point occurrence in 1977. Therefore, the data series was divided into two periods before and after 1977. Both periods included data series of more than 20 years, which is acceptable for the nonparametric Mann-Kendall test.

The rank-based nonparametric Mann-Kendall test is commonly used to assess the significance of monotonic trends in hydrometeorological time series (e.g., 8; 9; 10; 11; 12). In this test, the standard normal statistic Z is estimated and compared with the standard normal deviate $Z_{\alpha/2}$. The test statistic Z is not statistically significant if $-Z_{\alpha/2} < Z < Z_{\alpha/2}$. Correspondingly, this test shows a statistically significant trend if $Z < -Z_{\alpha/2}$ or $Z_{\alpha/2} < Z$ [9]. The confidence level fixed at α = 0.95 and critical z values for two-sided test are −1.96 and +1.96. The standard normal statistic Z is estimated by the following formula as [8; 9].

$$Z_c = \begin{cases} \frac{S-1}{\sqrt{Var(S)}}, S > 0 \\ 0 \quad , S = 0 \\ \frac{S+1}{\sqrt{Var(S)}}, S < 0 \end{cases} \tag{1}$$

Where

$$S = \sum_{i=1}^{n-1} \sum_{k=i+1}^{n} \operatorname{sgn}(x_k - x_i) \tag{2}$$

$$\operatorname{sgn}(\theta) = \begin{cases} 1 \ , \theta > 0 \\ 0 \ , \theta = 0 \\ -1, \theta < 0 \end{cases} \tag{3}$$

$$\operatorname{var}[S] = [n(n-1)(2n+5) - \sum_t t(t-1)(2t+5)]/18 \tag{4}$$

In which the x_k, x_j are the sequential data value, n is the length of the data set, t is the extent of any given tie. The magnitude of the trend is given as

$$\beta = Median(\frac{x_i - x_j}{i-j}) \ , \forall j < i \tag{5}$$

In which $1 < j < i < n$. A positive value of β indicates an 'upward trend', and a negative value of β indicates a 'downward trend'.

In addition, the relationship between hydrological and meteorological variables was explored by using Pearson's correlationcoefficient. The correlations calculated were tested for statistically validity at the 95% significance level.

RESULTS. Changes in temperature and precipitation. Annual mean temperature and total precipitation over the 47 year period of 1960–2007 were analyzed from the Taldykorgan weather station, situated close to the study area. The linear trend analysis of mean temperature indicated that the average rate of temperature increase was 0.43 °C $(10a)^{-1}$, while the summer (JJA) temperature rose 0.28 °C $(10a)^{-1}$. From 1960 to 2007, records at the same station displayed a slight decrease in annual precipitation. The results of Mann-Kendall test applied to annual and seasonal data series showed statistically significant trends during the period 1960-2007. Trend in Summer and Autumn seasons were higher than those in Winter and Spring. Monthly highest positive trend was for August, September and October months (Fig. 1).

Trends of runoff. Trends in monthly and annual runoff for the sub-basins of Karatal river were analysed. Discharge trend analysis was calculated for three periods: full-observed time and for periods before and after 1977 (step change year) for each hydrological station. Annual runoff of the almost all sub-basins showed increasing trend for annual, melting and frozen seasons for entire observed time (see Fig. 2 A). Increasing discharge trend was statistically significant in more glacierized catchments (Kora, Koksu and Koktal). Trends of runoff for the melting season were similar to those in the annual cycle. However, runoff for the frozen season exhibited higher changes during entire observed time for all sub-basins, but the absolute changes remained small. Less glacierized (Chizhin) and non-glacierized sub-basins (Tekeli) show lower increasing trend in the melting season and annual time.

The discharge trend for the first period, before step change year (1977), showed slightly negative trend in annual and melting cycle. Positive trend was only for two stations, Chizhin and Tekeli. Neither positive nor negative trend were statistically significant during first period for annual and melting cycles. However, trend for cold months and frozen season was different. Discharge trend was increased in Koktal and decreased in Chizhin and both trends were statistically significant (Fig. 2 B).

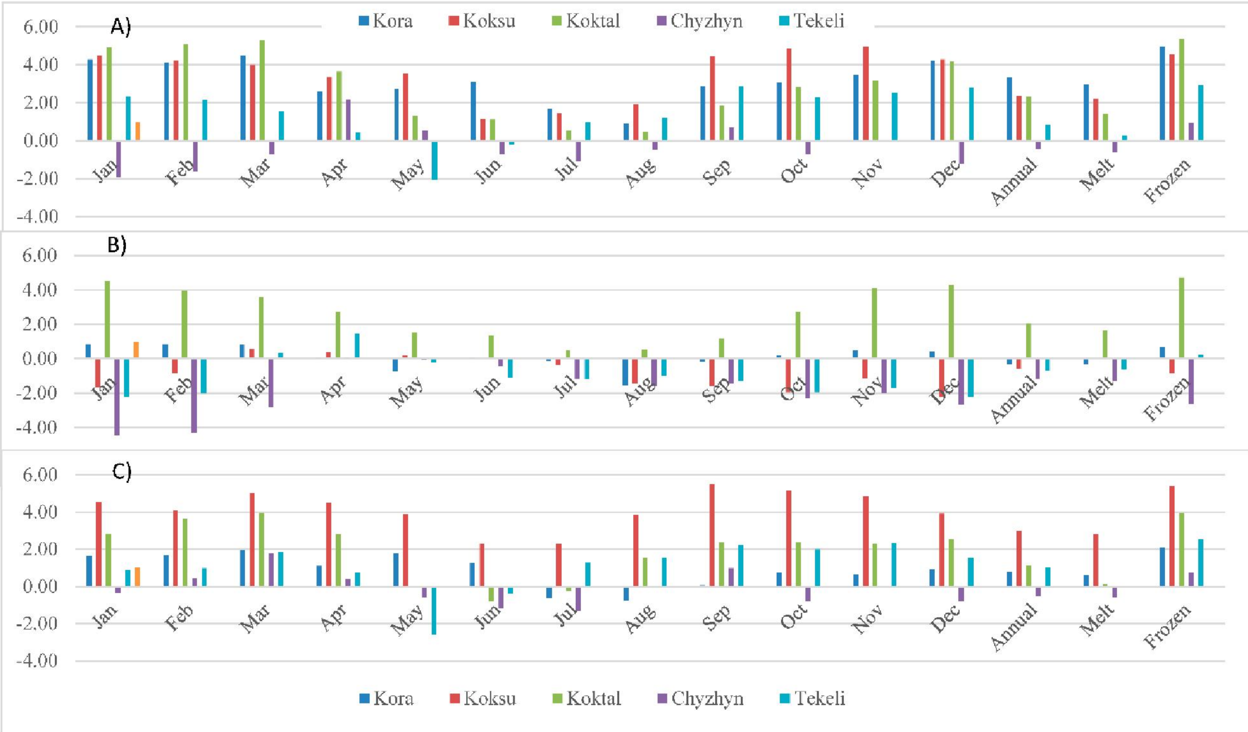

Figure 2 – Kendall test Z statistics for trends of monthly, annual and seasonal runoff for the Sub-basins of Karatal river. (A) for entire period, (B) and (C) for the periods before and after the 1977 (step change) year, respectively; (Significant at P< 0.05; critical value of Z <-1.96and >+1.96(two-sided))

Runoff data for the second period (after 1977) indicated trends that are more positive. In the Koksu sub-basin, where the most glaciers were located (108.6 km^2 in 1956), trend analysis exhibited statistically significant increasing for melting, frozen and annual cycles. Three sub-basins, which were more glacierized, showed the slight increasing trend, while less glacierized had small decreasing trend during melting season (Fig.2 C).

Surprisingly, the runoff trend in the Kora sub-basin showed the decreasing trend for July, August and September months, in spite of relatively intensive glaciation (14%), and statistically significant increasing temperature in these months. Detailed analysis of year-to-year variation of runoff from this station showed the anomaly increasing discharge for the 1988-2000 period. Mean discharge for this months during 1988-2000 were two times higher than mean level during 1940-2014. This is the anomaly impact to the trend analysis for the second period. Thus, despite the fact that statistically significant positive trend during 1940-2014 for annual and melting season, trend for those was negative and positive during 1940-1977 and 1978-2014, respectively. This high runoff phenomenon during 1988-2000 might be technical mistakes during observation in the stationor human factor impact. Neighbouring sub-basins showed the quite stable trend during this period.

Discussion. The Pearson's correlation coefficient values (Table) show that the runoff of the lower glacierized sub-basins, such as Tekeli, Chizhin and Koktal, has a strong and significant correlation with the precipitation. For the temperature, the correlations are much weaker and less significant, even for the comparatively the most glacierized Kora.

The Correlation Coefficients between the Annual Temperature Precipitation and the Runoff. Statistically significant trends are indicated in bold

	Kora	Koksu	Koktal	Chizhin	Tekeli
Temp.	-0.05	0.15	-0.17	-0.06	-0.15
Prec.	0.00	0.12	**0.27**	**0.33**	**0.47**
Significant at P < 0.05.					

The absence of significant positive trends in summerseason discharge can be explained by the low glacierized catchments (less than 15%) [13]. In addition, the evapotranspiration has negative effect on river runoff, but their role are limited [14]. Estimated changes in potential evaporation based on the empirical approach of [15, 16], which solely relies on temperature, suggest that evaporation changes are insignificant during the ablation season, mainly due to small changes in air temperature. However, due to increasing trend in spring and autumn months, trend showed statistically significant positive increasing for the melting and annual cycle in glacierized catchments. The effect on runoff changes was different in glacierized sub-basins of Karatal river. Relatively highest glacierized Kora (14% glaciation) showed highest positive trend, while smaller glacierized Koktal (5%) demonstrated smaller trend, with the statistically significant magnitude of 3.32 and 2.31, respectively. In the catchment with only 2% glaciation (Chizhin) trend was even negative with magnitude of -0.43. Apparently, the tipping point (peak water) for this catchment might be already passed [17, 18]. The tipping point is a phenomenon when runoff during warming climate will at first increase owing to higher temperatures and more meltwater, while this effect is gradually reduced when the glacier area begins to decline as a result of continued glacier mass loss [19-21]. Tekeli sub-basin without glacier showed slight increasing trend, but absolute water volume of rising trend was very small.

Summary. Based on runoff trend analysis, runoff in sub-catchments was controlled by temperature provoking the glacier melting stored for previous decades and centuries. River runoff demonstrated significant increasing trend during last half century at the expense of glaciers' melting intensification against a background of slight decreasing precipitation in the same time.

Even small glacierized areas (5% - 14% of total basin) had significant impact on the river runoff fluctuations in condition of global temperature increasing.

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КЛИМАТТЫҢ ӨЗГЕРУІ МЕН МҰЗДЫҚТЫҢ ҚЫСҚАРУЫНЫҢ ӨЗЕН СУЫНА ӘСЕРІН СТАТИСТИКАЛЫҚ ӘДІС АРҚЫЛЫ ТАЛДАУ

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Тірек сөздер: өзен суы, климаттың өзгеруі, мұздықтардың қысқаруы, Қаратал өзенінің бассейні, Манн-Кендалл тесті.

Аннотация. 1960–2012 жылдар аралығындағы өзен суы, ауа температурасы мен жауын-шашын мәліметтеріне негізделе отырып Жетісу Алатауының батысындағы су ресурстарына климаттың өзгеруі мен мұздықтардың қысқаруының әсері зерттелді. Гидроклиматтың ұзақ уақыттық ауытқуының тренді Манн-Кендалл тесті арқылы қарастырылды. Климаттық мәліметтерді талдай отырып, зерттеліп отырған уақыт аралығында температураның едәуір жоғарылауы мен жауын-шашынның тұрақтылығы байқалды. Жылдық өзен суының көбейуі Қаратал өзенінің барлық мұзды салаларында анықталды. Өзен суының артуы температураның жалпы жылынуымен және мұздықтардың белсенді қысқаруымен байланысты.