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Article

Multi-Earthquakes in 1974 Induced Hydrological Anomaly in a Large Glacier-Fed River, the West Tibet, China

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Abstract: Future climate change is expected to affect components of the hydrological cycle. However geologic factors can sometimes be more important than the climate with regarding to change hydrological processes. The Keriya River is a large glacier-fed river in the western Tibet Plateau, its upper reaches flow across active fault zones, which have experienced four medium-sized earthquakes within four months 1974. These active faults have made difficult to identify normal meltwater changes using a snow-ice melt model. Because of the seismic events, the river has experienced substantial changes in their drainage systems and complex hydrological processes. Both the Mann-Kendall trend test and a correlation analysis were applied to detect the monthly patterns of stream flows, the change points and the correlations among both summer discharge and air temperature before and after seismic events. We found significant correlations between monthly air temperature and meltwater flow in the summer June during the pre-earthquake of 1958-1974, but none in July and August in the post-earthquake of 1975-1980, and we found no correlation following the earthquake. The correlations were the inverse by losing the former and setting up the latter alternately since the multiple earthquakes. Clearly, the earthquakes and changes in the faults can greatly induce hydrological processes.

Keywords: active fault; earthquake; meltwater flow; hydrological anomaly; correlation

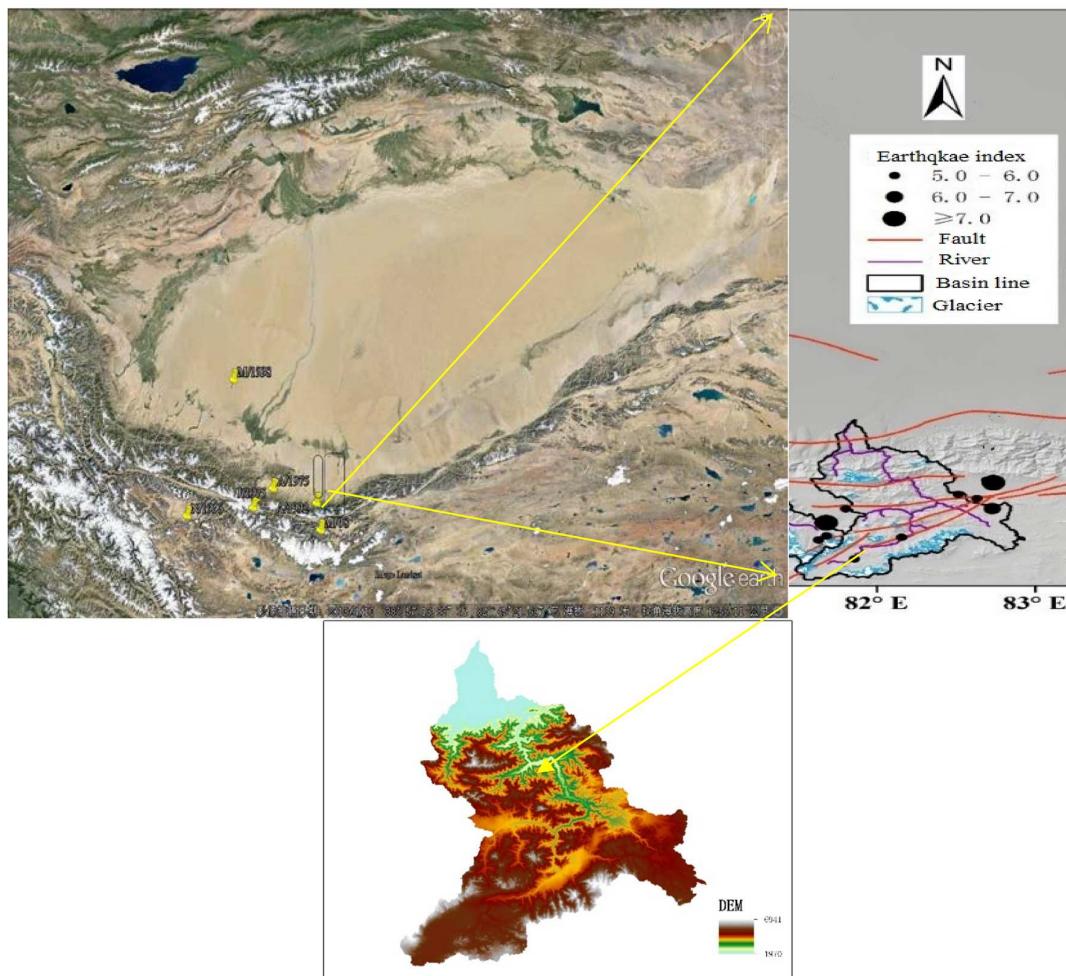
1. Introduction

Future climate change is expected to affect components of the hydrological cycle [1], these changes have significant implications for water resources in the cold, arid parts of northwest China [2–4]. These predictions and analyses are based on the regional climate and observed land surface, without considering changes in geologic structures, such as fault activity. The neighbouring glacier-fed Keriya River is located on the West Kunlun Mountains of the western Tibetan Plateau, and drains across two tectonically active Altyn-Tagh fault and the West Kunlun fault in their upper reaches of western Tibet. The river has a high meltwater contribution of 70%–75% [5].

The glaciers of the Kunlun Mountains act like efficient reservoirs, allowing a large amount of meltwater to be transferred into a few oases and the Keriya River system, including the Cera River (Figure 1a). With an annual runoff of $10.2 \times 10^8 \text{ m}^3$, the rivers have created an extensive valley fills in its alluvial reaches. The large altitude dynamics of the Keriya River has been fascinated glacial-hydrologists from around the world for the last three decades. However, only a few numbers of studies, particularly in the upper streams, bear testimony to the international attention these rivers have received [6–8]. The results of investigations on the glacier- fed rivers surrounding the Tarim Basin suggest that flows of the Kunlun Rivers have been underestimated and lack a statistical analysis to date [2]. The rivers are predicted to increase with further global warming, and the glaciers in the West Kunlun Mts. were predicted in retreating or stabilizing as evidenced by both hydrometeorological records and satellite images [9–11]. However, these predictions did not include the geologic structures and possible tectonic activity in the region. Rivers of the Kunlun flow through



one of the largest faults in the world, the Altyn-Tagh Fault which is known for its unique geologic impacts apart from its hydrological significance.



<http://www.csi.ac.cn/publish/main/848/100080/index.html>

Figure 1. Location map of study area (top map: the black circles represent the Keriya River in the southern Tarim) and the fault distribution in western Tibet. Large earthquakes are marked with yellow pin. (Bottom map: white lines represent the fault length and direction; red color represents high mountains and plateau >4000 m, asl.; the green represents low mountains <2000 m, asl.). The mediun intensity earthquake of four times occurred in the West Kunlun-the Altyn fault: Ms 5.0 - 4.0 on 3ed. and on 16th. August, Ms 4.0 on 16th. October and on 16th November 1974, respectively.

The Keriya River shows a significantly hydrological diversity with the small winter and spring flows in the Tarim Basin [12,13]. This is strongly manifested by the geodynamics of the river across the faults as shown in Figure 1b. Moreover, the behavior of the river is quite different in terms of its neighboring river, the Yarkand which shows evidence of advancing glaciers in the Karakoram [14–17]. This study documents the altering of the drainage systems of the river along the upper fault valleys and the transformations between surface and subsurface water. We argue that previous studies only attribute the variability of the river to the strong influence of climatic and glacial changes, we propose that changes in the multiple transfer patterns between surface water and air temperature are due to tectonic activity triggered by frequent large earthquakes, and that various melt models should be taken an account for these of glacier-fed rivers. This is very important not only for correctly understanding, assess and managing the water resources for the river, but also for understanding

how the hydrological anomaly of rivers such as those in the Tarim Basin, the Indus Basin region and Central Asia, are affected by geologic factors.

2. Material

The study area covers an area of 9390 km² that is sandwiched between the EW-SW trend of the Altyn-Tagh Fault, the Ashkul Fault to the south and the West Kunlun Fault to the north. The Keriya River in hydrogeologic history is one of the largest tributaries of the Tarim River from the West Kunlun Mountains in western Tibet (Figure 1a). The Keriya River in the east is a large glacier-fed watershed, its hydrometric station is at the Keriya village (the former Nunu maimatlangan, 36°28'N, 81°28'E, 1880 m, asl.). The climatic data are from station Keriya and adjacent Heishan (36°15'N, 79°46'E, 2460 m, asl.) in the river respective upper reaches. The glacio-hydrological parameters of the river are listed in Table 1.

Table 1. Glaciological and hydrological parameters of the studied watersheds .

S-Height	R-Length	D-Area	G-Area	A-Height	G-Height	Runoff	A-P
m, asl.	km	km ²	km ²	m, asl	m, asl	mm	mm
1880	192	7358	685.3	4600	4000-6995	101.5	125-450

S-height means station altitude; R-length means river length; D-area means drainage area; G-area means glacier area; G-Height mean height of glacier terminus; Runoff is the annual runoff depth; A-P is the ranges of annual precipitation.

The Keriya River encompass a wide variety of climatic conditions including the periglacial and desert zones shown in Figure 1. Glaciers and patterned ground features associated with continuous and dis-continuous permafrost are found in the south [18]. A great number of glaciers are present above 4000 m, and have a total area of 985.15 km². We used hydrological data of monthly discharge at the Keriya hydrometric station, and air temperature data from Heishan station between year 1958 to 2014. The hydrometeorological records indicate a simple pattern of streamflow under an extremely continental climate. The surface flow from glacier meltwater is the dominant contribution to the streamflow as shown in Figure 2. The alpine precipitation varies from 70 mm in the valleys to 450 mm in the glaciated areas and increases with altitude up to 5800 m, asl [5]. The average annual air temperature at the Keriya station is 12.5 °C, and the estimated annual air temperature over the periglacial areas above 4200 m, asl. is below -3.6°C, according to a lapse rate of air temperature at 0.65°C/100m.

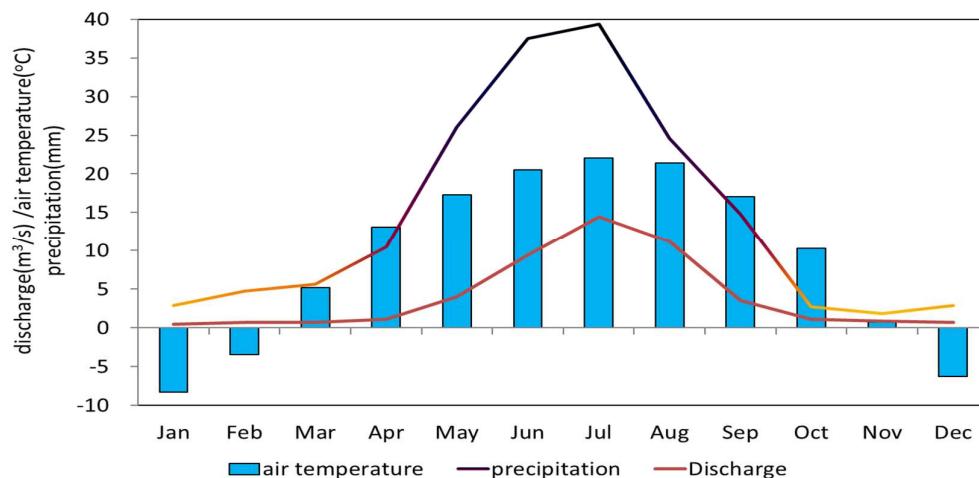


Figure 2. Hydro-meteorological graph of the Keriya River at Keriya hydrometric station (red line - stream flow, blue bar-T represent air temperature and precipitation).

The ablation period of the large glacier Ghoza near the Keriya River headwater in 1987 was approximate 110 days from June to September, according to an investigation at 5200 m, asl.[19]. Hence, the seasonal distribution of runoff is quite variable because the runoff is composed mainly of summer meltwater and rainfall, which account for approximately 60% to 70% of the annual runoff. The maximum runoff is in July comprising 26% to 28% of the annual runoff, and the minimum is in March with only 0.9% of the annual runoff.

With global climate change, the annual air temperature has risen by 0.9°C since 1989, and precipitation has increased by 35% since the late 1990s in the West Kunlun Mountains, as shown in Figure 3. As is well known, the warming is significant in the winter and spring, instead of in the summer, but wetter conditions are occurring in the summer. However, the summer flow of Keriya River is not sensitive to warming and wetting as that as other glacier-fed rivers which are surrounding the Tarim Basin.

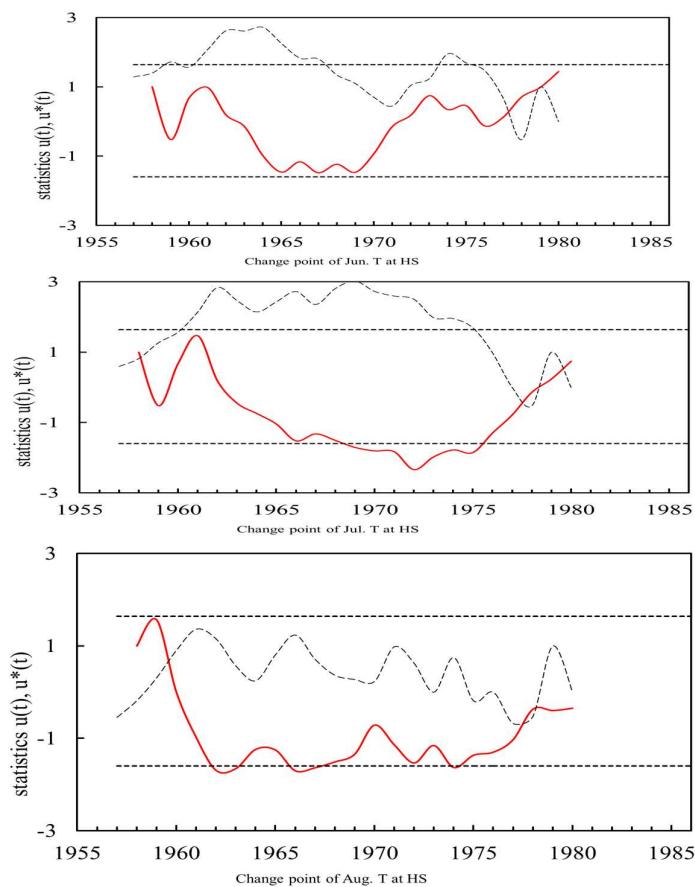


Figure 3. Graph of climatic changes from 1958 to 1980 for the Keriya River (with a slight cooling in 1972-1974). Change points of summer monthly air temperatures in station Heishan (marked with red line).

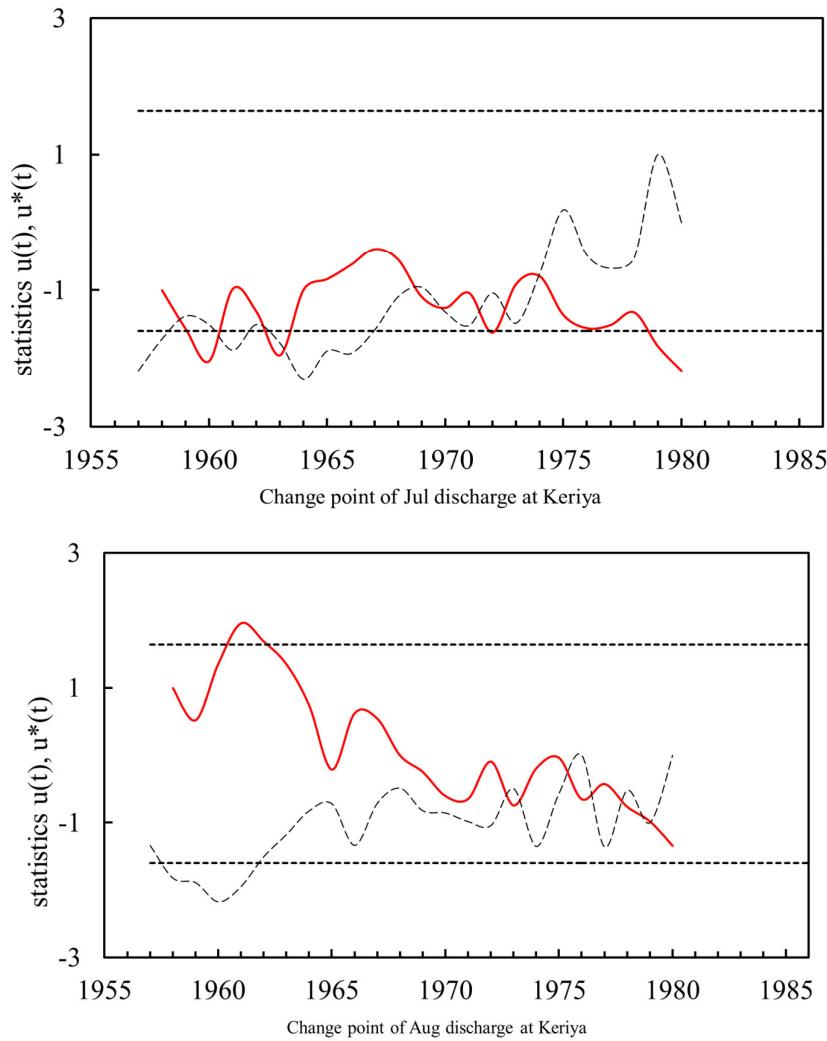


Figure 4. Change point of summer streamflow (July to August) for Keriya River (No trend in June no shown). The red line (top graph) shows that a gradual decrease of July discharge occurs with change point in year 1976 at a significance of 0.1 (90% probability), as same as that in August discharge (bottom graph).

Figure 1b shows the West Tibetan Plateau, one of the most remarkable topographic features on Earth and a classic example of continent-continent collision. In northwestern Tibet, the Altyn Fault is over 2000 km in length and the longest left lateral strike-slip fault in Asia. The fault accommodates sinistral motion between Tibet and the Tarim block within the India-Eurasia collision zone. The West Kunlun Fault are 700 km long, forming the western segment of the Altyn-tag Fault, and are associated with the many Kunlun rivers [20–25].

The Kunlun River penetrates along surface rupture zones that are 200 km long in the North-South direction, these zones were produced by the most recent large seismic events ($M_s > 6.0$) in upper reaches of the rivers, including multiple earthquakes with M_s . 6.1 in May and June of 1975, an M_s . 6.0 in April 1992, M_s . 7.3 in March 2008 and 7.1 in March 2014, as recorded by the China Earthquake Network Center (www.cenc.ac.cn) (Figure 1a).

Table 3 illustrates the hydrograph of daily discharge of the Keriya River and the effect of the 1974 earthquakes in the West Kunlun. The discharge suddenly and significantly increased on May 29 (○ marked on yellow point) following the earthquakes, with only a gradual increase in air temperature. There was a little rainfall 4.4 mm in April and 6.4 mm in May at gauge station. The daily and monthly discharge data indicate three hydrological responses to the three mega earthquakes in

shortly daily and mid-period of monthly increase, as well as the annually decrease shown in Figure 5. The river discharge suddenly and significantly increased by four times from 11.9 m³/s during base flow on May 27th. to a peak flow of 47.1 m³/s on May 28th following the earthquakes. Clearly the peak flow was not a meltwater flow resulting from a gradual rise in air temperature. These earthquakes caused a series of geologic and geomorphic changes, such as systematically offset streams, displaced fluvial fans and terrace risers, pull-apart grabens, and pressure ridges or pushups which are well developed along the surface rupture zone [25,26]. It is not by chance that the rivers flow northward from the headwaters and then flows across a few fault zones until reaching its outlet station.

Table 3. Daily discharge anomaly (m³/s) of streamflow in post-earthquake periods in 1974.

Aug/date	2	3	4	5	6	7	8	9	10	11	15	16	17	18	19
Discharge	127	141	138	171	115	132	177	162	164	116	129	174	86	66	75
Oct/date	4	5	6	7	8	9	10	11	12	13	14	15	16		
Discharge	11.5	12.5	11.5	11.5	12.5	11.9	11.5	11.9	11.9	11.9	11.9	11.9	11.9	10.6	
Nov/date	15	16	17	18	19	20	21	22	23	24					
Discharge	8.8	8.5	7.6	7.6	7.6	8.5	9.1	8.5	8.8	8.5					

In first earthquake on 4th and 16th August, the river discharge on the 5th and 17th at gauge station significantly increased by 33 m³/s and 45 m³/s on 8th, then abruptly decreased by 88 m³/s on the 17th. In second earthquake on the 4th. October, the discharge at gauge station slightly increased twice by 1 m³/s on the 5th and 8th at the base flow of the recessive curve without meltwater and rainfall, In third earthquake on 16th. November, the discharge at gauge station slightly decreased by 0.9 m³/s in 3 days of the 17th – 19th., then recovered to the base flow of the recessive curve in winter without meltwater flow.

3. Data Analysis and Methods

3.1. Trend and change point test

The Mann–Kendall trend and change point test were used to explore hydro-meteorological trends and variability [28,29]. The Mann–Kendall test is a rank-based method that has been used in many previous studies to identify trends in hydro-meteorological variables [30–32], and begins by evaluating the trends in the hydrological variables of a station. All trend results have been evaluated at the 95% significance level or better, to ensure an effective exploration of the trends and change point in this study.

3.2. Correlation analysis

The air temperature index and snow melt models rest upon an assumed relationship between snow-ice meltwater and air temperature usually expressed in the form of positive correlation. Because air temperature is generally the most readily available data, such models have been the most widely used method of snow-ice melt computations for many purposes, such as hydrological modelling, ice dynamic and the climate sensitivity studies [2,31].

Additionally, the moving correlation analysis were used to explore the relationships between hydrometeorological variables. Data associated with a group were investigated to identify significant trends after applying the Mann-Kendall test based on a harmonic analysis, while the strength of the relationships between both meteorological and hydrological variables were evaluated by a linear correlation, the calculated correlations were tested for statistical validity at the 90% significance level.

4. Results

The results of the Mann–Kendall trend and change point test for monthly air temperature and discharge during the summer are shown in Figures 5 and 6 and summarized in Table 2 for those trends at the 95% of significance level or better. The change point test reveals, a steady rise in the

summer air temperature is not the only feature of the data, the time series for monthly temperatures exhibits fluctuations occurring in various years between 1956 and 1980, June air temperatures feature a significantly rise ($P<0.05$) since 1986, while July and August air temperatures have risen from 1976 and 2001 respectively, but without significance, implying there is considerable variability.

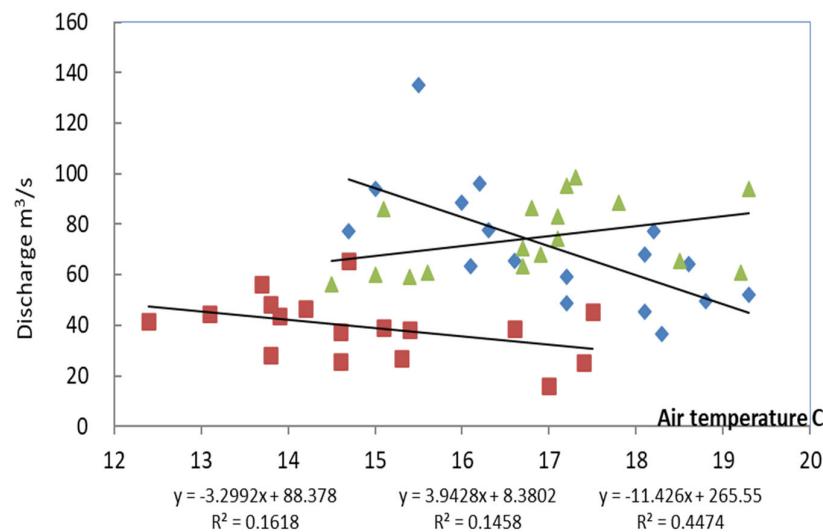
Table 2. Seismological parameters of major earthquakes in 1974 in the Keriya River Basin.

Date	Latitude (°)	Longitude (°)	Epicenter depth(km)	Earthquake (Ms)
03-Aug. 74	35.70	80.60	24	5.0
16-Aug. 74	36.32	81.30	33	4.0
16-Oct. 74	36.30	81.30	30	4.1
16-Nov. 74	36.33	81.30	30	4.0

Due to the earthquakes in 1974,

However, the monthly discharge of the Keriya River did not show any increasing trends to respond to the warmer and wetter climate (not shown in Figure 5), which can be attributed to a triggering flow of the meltwater flowing through the fault drainage systems.

To understand the lack of a response of summer meltwater to air temperature, we calculated the correlation between the monthly air temperature and the meltwater discharge for different periods. For the river, these periods included 1958 to 1980 as a whole; 1958 to 1974 because of the multi earthquakes in 1974, and 1975 to 1980 as a period without earthquake as shown in Figure 7 (red □ - June, blue □ - July and green ▲-August). There are significantly negative correlations between monthly air temperature and discharge in June ($R=0.40$, $P=0.12$) and August ($R=0.46$, $P=0.003$) at a significance of 0.1 (90% probability), but a significantly positive correlation in July ($R=0.65$, $P=0.06$). Subsequently, there is a weakly positive correlation in June only ($R=0.34$, $P=0.21$), but none in July and August in period of 1975 to 1980 (●, ○ and ▲ for June, July and August, respectively), following the earthquakes in 1974.



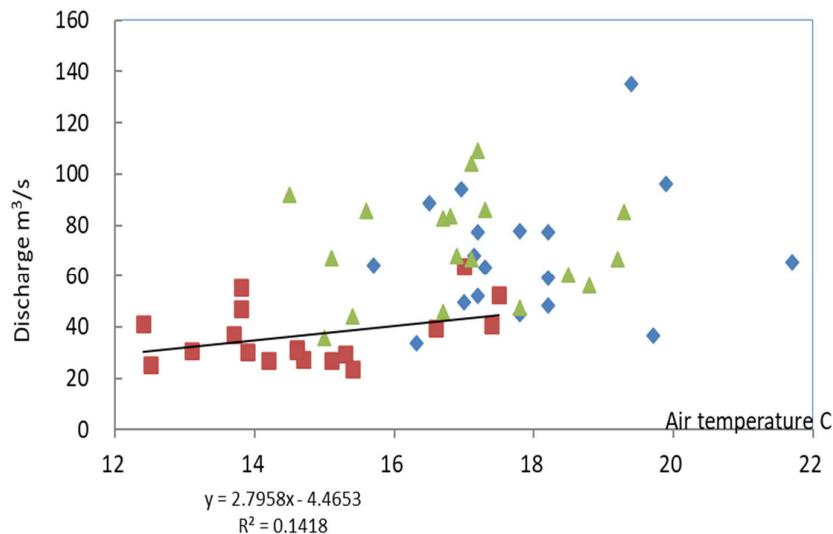


Figure 5. (a) Monthly correlations between monthly air temperature and discharge in summer during 1958 to 1974 (red □ - June, blue □ - July and green ▲ - August). There is a significantly negative correlation between monthly air temperature and discharge in June and August at a significance of 0.1 (90% probability), but a positive correlation in July. (b) Correlations between summer monthly air temperature (June to August) and discharge for the Keriya River from 1975 to 1980, there is a weakly positive correlation in June only, but none in July and August, respectively.

As that as relationships between runoff and rainfall in rainy south China, correlation between meltwater discharge and air temperature are positive on ice-snow hydrology. Therefore it is clear that upper stream in drainage systems of the river have been modified by these seismic events, thus changing the relationship between the air temperature and meltwater flow. This observation is critical to obtaining a real picture of snow-ice melt. The inverse relationships may imply that the higher air temperatures lead to a greater loss of the meltwater because more water is transferred to the subsurface flow due to complete thawing of frozen ground which open deep drain channels. Therefore, the maximum air temperatures and high degrees of melting contribution to the poor and unsteady correlations in July.

5. Discussion

The 400 km-long Kunlun-Karakax left-lateral strike-slip fault is the westernmost segment of the ATF, which separates northwestern Tibet to the south from the Tarim Basin to the north. The western section of the Kunlun Fault exhibits clear co-seismic surface ruptures from past major earthquakes [27–29]. Earthquakes have been observed to affect hydrological systems in a variety of ways. For example, the spring water, well levels can change dramatically, streams can become fuller and spring discharges can increase at the time of the earthquake [21,24,25], distant earthquakes may even increase the permeability in faults, usually involving increases in the stream and spring discharges in response to large earthquakes. In contrast this study illustrates that water draining into the crust may trigger earthquakes. This relationship is positive feedback between earthquakes and deep drainage systems.

Understanding how the river water flows through the faults and where it enters and exits the fault poses interesting and challenging questions. It has been suggested that the water for certain lakes seeps out from the deep and extensive Xigaze- Langshan Fault zone and is transported to the Badain Jaran Desert in Inner Mongolia, 1200 km from the source lakes [22]. In more recent studies, a significant amount of groundwater is assumed to flow from the Tibetan Plateau recharge into desert areas to the valleys and fault zones on the plateau and to the Taklimakan Desert northwest of the plateau [11,22]. There are the number of faults in the Kunlun catchments, especially in the southern

part of our catchments. It is likely that the Kunlun rivers repeatedly drain into and out of these fault systems, though the pathways of the river water remain unknown.

The abrupt and frequent changes in the correlations between summer temperature and meltwater discharge since 1975 and 1997 is attributed to fault activity related to major earthquakes, instead of to climatic change, which should increase the contribution of summer meltwater and enhance the correlation. The meltwater percolates into the mountain's large deep fault system and travels along deep carbonate layers that extend from the mountain to the desert. Increases or decreases in streamflow, groundwater and well levels are commonly observed following earthquakes [23–25], the variability in the water budget of excess flow in different regions following different earthquakes, as cited earlier, may reflect the differences in the regional mechanisms of runoff generation.

Our evidence clearly supports this hypothesis and shows multiple alternations in the relationship between summer meltwater and the air temperature following seismic events. We suggest that the altering of the river regime is caused by the activities of the faults after frequently huge earthquakes which opened and closed river channels in upstream areas in 1974 and 1975, respectively. Furthermore, earthquake-induced changes of the drainage systems are responsible for percolation of summer surface water which disrupts the classical relationship between air temperature and meltwater in snow and ice melt models. We found no extraordinary increase in summer runoff despite the increasingly warmer and wetter climate in this region. This suggests that streamflow from mountain rivers, many of which discharge directly into active faults, have greatly underestimated the basin water and glacier mass budgets by amounts that are comparable to the contribution of human activity and climate change. Similarly, the water resources of the Kunlun rivers, and the rivers flowing through the surrounding faults of the Tarim Basin have been greatly under estimated in previous regional water budgets that did not consider the geologic changes.

Periodic geological events are rare. When two very different events occur closely spaced in time, it is natural to wonder whether there is a causal relationship. In the case of major earthquakes and changes in flow regimes of the rivers triggered by the multi earthquakes in 1974, a causal relationship might be expected because the drainage requires a change in stress, and earthquakes cause rapid and sometimes large changes in stress. Moreover, a spatial relationship exists, when more meltwater percolates into the fault zones, earthquakes occur more frequently.

6. Conclusions

This study highlights two statistical methods of hydrologic correlation of surface waters versus air temperature and changes in daily flow in response to the fault activity induced by multi-earthquake. Our study reveals complex indirect processes that are influenced by the seismic events and fault activity and that lead to the transformation of surface flow into subsurface. Following these earthquake-induced changes, the pattern recovers the original direct relationship between air temperature and meltwater in snow and ice hydrology that was disrupted by the event. The variety of interactions between the hydrogeologic processes provides opportunities for insight into the factors controlling on the changes in both surface and subsurface water resources that are occasionally dominated by changing geologic conditions, rather than climate. The active faults not only ultimately control the periglacial, geomorphic and hydrological processes of the Kunlun Rivers, but also may control and hide the real surface flow in the Karakoram, the Pamir, the Tien Shan Mountains and other alpine rivers of the Himalayas. Therefore, the faults exert a major influence on the long-term evolution of the entire river system.

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