

Article

Major Controls on Streamflow of the Glacierized Urumqi River Basin in the Arid Region of Northwest China

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Abstract: Understanding the main drivers of runoff availability has important implications for water-limited inland basins, where snow and ice melt provide essential input to the surface runoff. This paper presents an analysis on the runoff response to changes in climatic and other controls of water-energy balance in an inland glacierized basin, the Urumqi River basin, located in the arid region of northwest China, and identifies the major control to which runoff is sensitive across the basin's heterogeneous subzones. The results indicate that the runoff is more sensitive to change in precipitation in the mountainous headwaters zone of the upper reach, and followed by the impact of basin characteristics. In contrast, the runoff is more sensitive to changes in the basin characteristics in the semiarid and arid zones of the mid and lower reaches. In addition, the change in basin characteristics might be represented by the distinct glacier recession in the mountainous upper reach zone and the increasing human interferences, i.e., changes in land surface condition and population growth, across the mid and lower reach zones. The glacier wasting contributed around 7% on average to the annual runoff between 1960 and 2012, with an augmentation beginning in the mid-1990s. Findings of this study might help to better understand the possible triggers of streamflow fluctuation and the magnitude of glacier wasting contribution to runoff in inland glacierized river basins.

Keywords: runoff; climatic factors; basin characteristics; glacier; the Urumqi River; Budyko framework

1. Introduction

Facing a warming climate, unraveling the dominant factors responsible for streamflow change is an important step for water resource management [1,2]. In general, the prevailing climatic factors (e.g., precipitation) and the integrative factors (e.g., the landform features) that exclude climatic factors (referred as other factors hereafter) are two types of factors that trigger streamflow changes, and many efforts have been made to assess their effects on streamflow [3,4]. For climatic factors, precipitation (P) and potential evapotranspiration (E_0) are considered to be two major factors that cause fluctuations in the hydrological cycle [5,6]. Integrative other factors consist of a wide range of controls, and the components often vary across regions characterized by different climatic conditions [7]. A correct assessment of the effects of the two types of factors on runoff requires a good understanding of the physical nature of the water and energy balance between the Earth's surface and the atmosphere, which accounts for the partition of precipitation into evaporation (E) and runoff (Q) [8,9].

Budyko frameworks couple the water and energy balances [10], estimating that the long-term annual average E is primarily controlled by available water, i.e., P , and energy, i.e., E_0 [11,12]. This framework quantifies impacts of changes in climatic and other factors on runoff [1–9]. Particularly, the parametric Budyko frameworks [13–15] that integrate the elasticity method [16] are often used

to assess the climate elasticity and joined influence of other factors on runoff [1–6]. A vast amount of applications has shown that the Budyko frameworks are efficient and robust in assessing the water-energy balance problems and hydrological responses at various scales of time and space [6–11].

Alpine glaciers are important natural solid reservoirs because they contribute considerably to the water supply in many catchments across the world [17]. However, global warming seems to have enhanced glaciers' melting [18] and their contribution to a rise in global sea level [19] and runoff [20]. At a basin scale, the enhanced glacier melting may change the water-energy balance by lowering the ice surface albedo, which in turn induces faster melting and snow to rain transitions [21]. This makes ice caps in glacierized basins further vulnerable to warming. One of the anticipated trends is that shrinking glaciers augment runoff in the first instance, then induce water deficiency, if water from other sources remain unchanged [22]. Enhanced glacier wasting thus challenges the water resources sustainability in the long term [23] and raises a strong concern about the future function of glaciers as a source of freshwater [22].

The arid regions in northwest China are characterized by fragile ecosystem and scarce water resources [23]. Warming-induced water issues are very distinct in these regions [24,25], especially across basins where glacier and snow melt provide important input to surface runoff. Remarkable shrinking in alpine glaciers and associated changes in water resources have been reported [18,22]. For example, glaciers in the Tianshan Mountains have been retreating since the mid-nineteenth century [22], resulting in significant changes in runoff in many inland rivers across Central Asia [26,27]. Moreover, changes in water availability caused by other factors cannot also be ignored [23,25]. With the impact of warming, the effect of precipitation, glacier melting, and other factors on runoff tend to be amplified [28]. Therefore, it is crucial to identify runoff response to warming and understand the local effects of glacier wasting on river flow.

The objective of this study is to examine the spatial heterogeneity of factors responsible for runoff availability in arid water tense regions, where the water resource system relies on precipitation and meltwater from glacier and snowpack. Toward this end, this study selected the Urumqi River basin located in the arid region of northwest China as the study area. The Urumqi River is the lifeblood of many communities in this region, and a good case where basin characteristics differ significantly spatially and where management strategies need to be carefully issued. In addition, the distinct glacier wastage, i.e., the wastage of the Glacier No.1 at the headwaters of the Urumqi River basin, has received much attention [29], and understanding its implication for water resources in the water scarce glacierized basin is essential [30]. Such an investigation can help us to see clearly the situations in the past and serve the water management strategies in the future.

2. Methods and Materials

2.1. Water Balance Equation

Over a long-term scale, water–energy balance in a catchment can be expressed as:

$$P = E + Q + \Delta S \quad (1)$$

where ΔS is the change in moisture storage of glacier, snow, and groundwater.

Hydrological attributes of the glacierized basins vary from that of the non-glacierized basins because the existence of ice and snow [31]. In the glacierized upper reach zone of the Urumqi River basin (Figure 1a), the contribution of the glacier melting to runoff should be considered, which is represented by ΔS in Equation (1). In the non-glacierized mid and lower reach zones (Figure 1a), water balance depends mainly on the partition of precipitation into E and Q , ΔS can be assumed to be zero on a long-term basis [11].

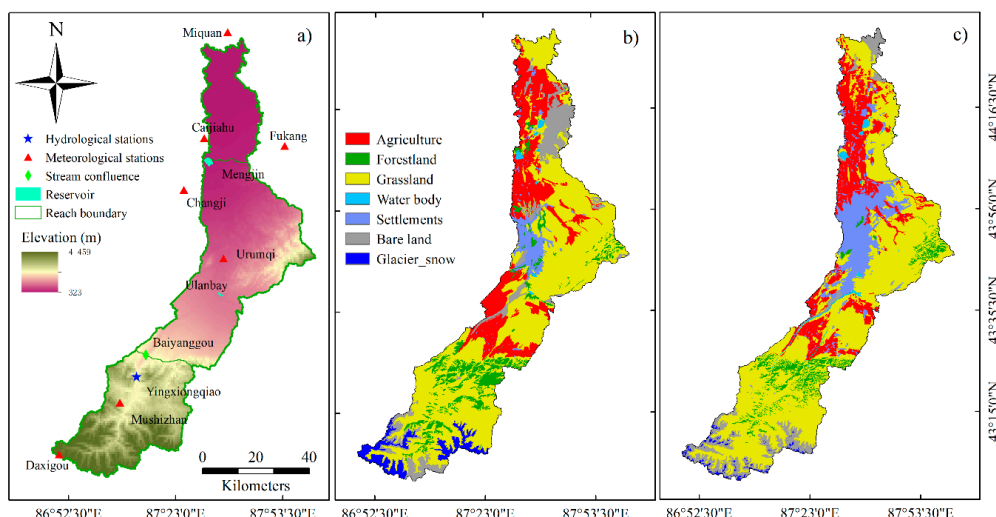


Figure 1. (a) Location of the Urumqi River basin and spatial layout of land surface condition in (b) 1980 and (c) 2015.

2.2. Budyko Framework

Assume that the available water is represented by P and the energy is measured as E_0 , the functional relationship between E and P can be expressed as:

$$E = E_0 \left(1 + \frac{P}{E_0} - \left(1 + \left(\frac{P}{E_0} \right)^m \right)^{1/m} \right) \quad (2)$$

where m represents the watershed properties, including all factors other than the climatic variables of P and E_0 , such as vegetation cover [32,33], soil water [34], topography [35], temperature [36], effects of CO_2 on plant water use [37], population density [8], irrigation [38], and construction of reservoirs [4,38].

The Budyko framework estimates the impacts of climate change and other factors on runoff regime by the partial derivatives of streamflow with respect to the target variables, which is generally referred to as elasticity [16]. Combining water balance equation, Equation (1), and the Budyko curve, Equation (2), the streamflow of a watershed can be expressed as:

$$Q(P, E_0, m) = P \left(-\frac{E_0}{P} + \left(1 + \left(\frac{E_0}{P} \right)^m \right)^{\frac{1}{m}} \right) \quad (3)$$

Berghuijs et al. (2017) derived the elasticity of streamflow to climatic variables and watershed properties as follows [1]:

$$\xi(Q, P) = \frac{\partial Q}{\partial P} \frac{P}{Q} = \frac{((E_0/P)^m + 1)^{\frac{1}{m}-1}}{-E_0/P + (1 + (E_0/P)^m)^{1/m}} \quad (4)$$

$$\xi(Q, E_0) = \frac{\partial Q}{\partial E_0} \frac{E_0}{Q} = \frac{(E_0/P)^m ((E_0/P)^m + 1)^{\frac{1}{m}-1} - E_0/P}{-E_0/P + (1 + (E_0/P)^m)^{1/m}} \quad (5)$$

$$\xi(Q, m) = \frac{\partial Q}{\partial m} \frac{m}{Q} = \frac{(1 + (E_0/P)^m)^{1/m} \left(\frac{(E_0/P)^m \ln(E_0/P)}{1 + (E_0/P)^m} - \frac{\ln(1 + (E_0/P)^m)}{m} \right)}{-E_0/P + (1 + (E_0/P)^m)^{1/m}} \quad (6)$$

Equations (4)–(6) account for the relative change in runoff due to relative changes in P , E_0 , and other factors, respectively.

Obviously, to calculate the change in runoff due to shifts in climate and other factors, the basin characteristic parameter, i.e., m , must be estimated first. Usually, the basin characteristic parameter is estimated using a nonlinear least square regression model, e.g., Equations (2) or (3). In this paper, calibration of the regression is made by minimizing the difference between water balance based and simulated E [39], and the accuracy was tested using the coefficient of determination (R^2), the Nash–Sutcliffe efficiency (NSE) and the root mean square error ($RMSE$).

After clarifying the elasticity of runoff to climatic and other factors, the most important control on runoff can be distinguished from those having the least importance by evaluating the relative importance of each factor to runoff as:

$$\varepsilon_x = \frac{|\xi(Q, x)|}{|\xi(Q, P)| + |\xi(Q, E_0)| + |\xi(Q, m)|} \quad (7)$$

where ε_x is the relative sensitivity of runoff to a given factor, and varies from zero to one; the ε_p , ε_{E_0} , and ε_m are summed up to a unity. The higher the value of the relative importance, the stronger the influence from an investigated factor on runoff [1].

2.3. Glacier-Melt Contribution

Change in glacier mass balance can be used to explain glacier wasting contribution to runoff [40,41]. Among all existing glaciers in the mountainous catchment of the Urumqi River basin, the Glacier No.1 has the longest continuing series of mass balance measurements starting in the 1950s. It is a northwest-facing valley glacier, with elevations ranging between 3740–4486 m [42], and representative among the existing glaciers in the arid region of northwest China [43]. We use the mass balance measurements of the Glacier No.1 to estimate the melting of entire glaciers in the basin. For this purpose, the mass balance of the Glacier No.1 [44–47] is extrapolated to the entire glaciers in the mountainous catchment using an area proportion method [48]. The area of the Glacier No.1 [29,47,49–51] and that of the entire glaciers in the Urumqi River basin [52] are collected from the existing literature, and time series glacier areas are interpolated using the rate of area change between two given time periods. Finally, the estimated mass balance of the entire glaciers was converted into runoff depth, and its contribution to the runoff at the river outlet is estimated.

2.4. The Urumqi River Basin

The Urumqi River basin is located in the northern slopes of the Tianshan Mountains in China and covers 4684 km² (Figure 1). The Urumqi River originates from the Glacier No.1 in the Tianshan Mountains in China and flows northward through the city of Urumqi. It has a total length of 214 km before disappearing in the northwestern Gurbantunggut Desert [53]. With respect to the climatic and hydrological conditions, the basin can be divided into three zones: the upper, mid, and lower reach zones (Figure 1a) [54,55]. The upper reach zone, Daxigou, spreads from the river heads to the Baiyanggou confluence and has a total area of approximately 1488 km². The mid reach, named the Urumqi River, starts from the Baiyanggou confluence, flows through the city of Urumqi, and ends near the Mengjin reservoir. This zone covers an area of 2437 km². The lower reach, named the Laolong River, refers to the section to the north of the Mengjin Reservoir. This section has an area of 773 km².

To date, the mountainous upper reach zone has been minimally affected by human activities, while the mid and lower reach zones are highly impacted by urbanization, agricultural, and industrial activities. For example, the streams in the mid and lower reach zones are now maintained as irrigation channels and supply water to a number of small reservoirs. It should also be noted that the segmentation of the basin reaches considers both the natural boundaries of the catchments and the practical segmentation of the three reaches in the Urumqi River basin [54,55]. By doing so, the basin segmentation has practical meaning, and the subsequent results will be more applicable to water resources management in this basin.

2.5. Hydrometeorological Data

The runoff data were collected from the Yingxiongqiao hydrological station and spanned from 1962 to 2012. Since there are no regular hydrological stations in the mid and lower reach zones, river runoff for the mid and lower reach zones are extrapolated using the observed runoff from the upper reach zone. The relevant long-term average annual runoff records at the mid and lower reach zones are obtained from “The Urumqi River Basin Chronicles” [55]. A detailed description of the extrapolation method is described in Appendix A.

The meteorological data from seven national meteorological stations scattered along the river course were provided by the National Meteorological Information Center of China. These meteorological stations are as follows: (1) Daxigou and Mushizhan, located in the upper reach zone; (2) Urumqi and Changji in the mid reach zone; and (3) Caijiahu, Fukang, and Miquan, located near the lower reach zone. Based on the collected meteorological data, daily E_0 at the Daxigou, Mushizhan, Urumqi, Caijiahu and Miquan stations is estimated using the FAO Penman–Monteith method. Given the lack of observed wind speed and humidity at the Fukang and Changji stations, the temperature-based method [56] is employed to estimate daily E_0 at these two stations. Daily E_0 is aggregated to obtain annual values for analysis. The mean annual E is estimated considering the glacier ablation in the upper reach zone and as the difference between P and Q in the mid and lower reach zones. A summary of the hydrometeorological variables used in this study is presented in Table 1.

Table 1. Hydrometeorological characteristics of the Urumqi River basin.

Basin Zones	Area /km ²	Mean Elevation/m	Temperature /°C	P /mm	E_0 /mm	φ	Meteorological Station	Data Extension
Upper reach zone	1488	2922	−1.6	458	665	1.5	Daxigou Mushizhan	1960–2012 1978–2012
Mid reach zone	2437	1163	7.2	228	1091	4.8	Urumqi Changji	1960–2012 1960–2012
Lower reach zone	773	448	7.5	196	1205	6.1	Caijiahu Fukang Miquan	1960–2012 1963–2012 1962–2012

Temperature, P , E_0 , and φ at each zone are calculated by averaging the mean of a variable from the available stations over the given time scale.

2.6. Basin Characteristics

For a given region, aridity index (φ) can be related to the characteristics of regional climate types [13,50]. Regions where φ is greater than unity (water limited) are generally classified as dry since the atmospheric evaporative demand cannot be met by precipitation [8,11]. Conversely, regions where φ is less than unity (energy limited) are described as wet since the available energy is insufficient for evaporating all coming precipitation [8,11]. Thus, studies have proposed that aridity can reflect the characteristics of regional climate types and that the aridity within the range of $12 > \varphi \geq 5$, $5 > \varphi \geq 2$, $2 > \varphi \geq 0.75$, and $0.75 > \varphi \geq 0.375$ can represent the arid, semiarid, subhumid, and humid regions, respectively [11]. Table 1 shows that the Urumqi River basin is characterized by a semiarid climate with a basin-wide average aridity of 4.1. However, there are noticeable differences in aridity index among different subzones, which vary between 1.5 and 6.1. Based on the aforementioned classification criteria, the upper, mid, and lower reach zones of the Urumqi River basin can be characterized as subhumid, semiarid, and arid zones, respectively. Thus, the runoff sensitivity to changes in climatic and other factors can be separately analyzed. These three reaches, by their up-to-date characteristics, can be described as mountainous zone, urban areas, and near-desert zone.

3. Results

3.1. Simulation of Water-Energy Balance

The basin characteristic parameter m was estimated for each climatic station and spatially averaged across each zone to evaluate the zonal value (Table 2). Within the Budyko framework, the parameter m is essential to accurately assessing the water balance, and spatial variation in this parameter is affected by the properties of underlying surface [57]. Our results show that the basin parameter m varies noticeably between 1.86 and 2.49 across the three subzones, suggesting that the underlying surface and climatic conditions differ across space in the Urumqi River basin.

Table 2. Simulation accuracy of E and elasticity of runoff to changes in climatic and other factors across the Urumqi River basin.

Indices	Upper Reach Zone	Mid Reach Zone	Lower Reach Zone
m	1.86	1.95	2.49
R^2	0.84	0.99	0.99
NSE	0.54	0.95	0.99
$RMSE$	53.00	12.77	4.58
$\zeta(Q,P)$	1.64	1.96	2.48
$\zeta(Q,E_0)$	−0.64	−0.96	−1.48
$\zeta(Q,m)$	−1.35	−4.08	−5.21

The Budyko framework with the zone-specific m values simulates the water-balance based evaporation with considerably high accuracy (Figure 2 and Table 2). It can be seen that the evaporation derived, respectively, from the water balance equation and Budyko framework exhibits good agreement with R^2 ranging from 0.80 to 0.99, NSE from 0.54 to 0.99, and $RSME$ from 4.58 to 53.00 mm. However, compared with the upper reach mountainous watershed, the mid and lower reach zones have higher simulation accuracies with greater R^2 and NSE , and smaller $RSME$.

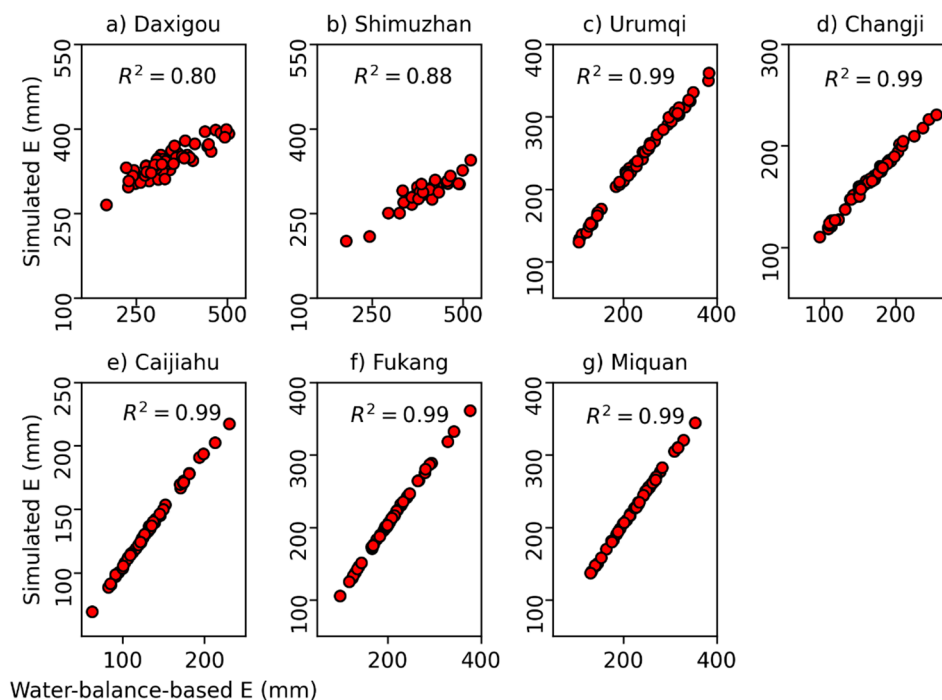


Figure 2. Comparison of the water-balance-based evaporation (x-axis) and simulated evaporation (y-axis) using Budyko framework across the representative climate stations in the basin.

3.2. Major Controls on Runoff across Heterogeneous Subzones

Table 2 shows the elasticity of runoff to climatic and other factors. It can be seen that in the headwaters of the Urumqi River basin, the elasticity of runoff to P and E_0 is 1.64 and -0.64 , respectively, implying that a 10% increase in mountain precipitation would increase runoff by 16.4% on average, while a 10% increase in E_0 would decrease streamflow by 6.4%. In the mid reach zone, the average elasticity of runoff to P and E_0 is 1.96 and -0.96 , respectively, indicating that a 10% increase in P would increase runoff nearly by 20%, while a 10% increase in E_0 would decrease runoff approximately by 10%. When compared with those of the upper and mid reach zones, the lower reach zone has greater P and E_0 elasticity, which are 2.48 and -1.48 , respectively. Regarding the impacts of other factors, the elasticity of runoff to other factors is higher than that of the climatic factors, especially in the mid and lower reach zones where the climate is drier. As shown in Table 2, for each 10% change in other factors, the runoff decreases by 13.5%, 40.8%, and 52.1% in the upper, mid, and lower reach zones, respectively.

To discern the major controls on runoff in different zones, the relative importance was calculated using Equation (7), and the results are shown in Figure 3. It can be seen that both P and other factors play important roles in the runoff regime in the glacierized headwaters with greater impact from P . For example, the relative sensitivity of runoff to changes in P and other factors are 45% and 37%, respectively. For the mid and lower reach zones, the impact of other factors is stronger than that of P and E_0 . Noticeably, in the mid and lower reach zones, changes in other factors account for major variation, i.e., nearly 60%, in runoff, and the variation in climatic variables becomes less significant. In particular, the relative importance of E_0 is small across the basin, which is less than 20%, indicating that the effect of change in E_0 on runoff may not be significant.

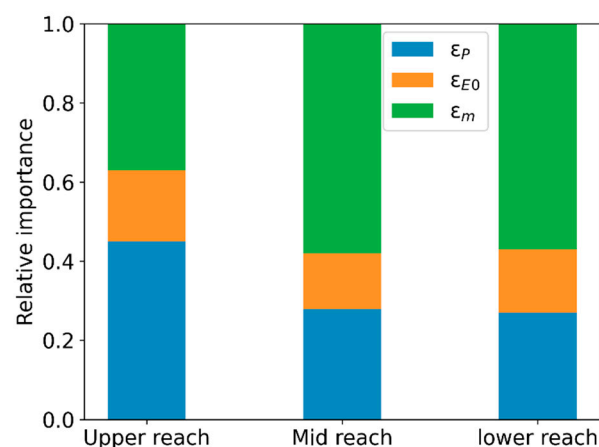


Figure 3. Relative importance of P (stacks at the bottom), E_0 (stacks at the middle), and other factors (stacks at the top) across the subzones of the Urumqi River basin.

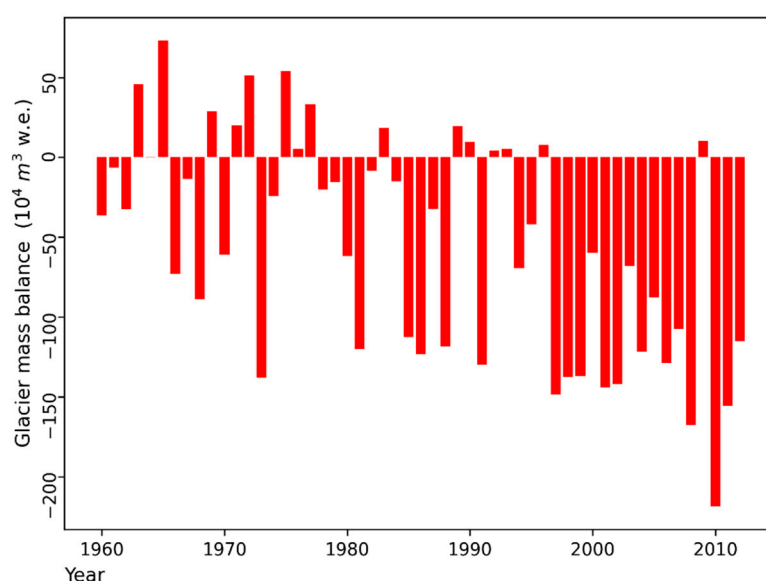
3.3. Glacier Wasting Contribution to Runoff

There was a total of 155 glaciers at the headwaters of the Urumqi River basin in the 1960s [52]. However, the glacier area decreased from 48.04 km² to 23.61 km², for the entire basin, and from 1.95 km² to 1.59 km², for the Glacier No.1 at the headwaters, between 1960s and early 2010s (Table 3). The consecutive retreat of the Glacier No.1 has been observed, with a faster shrinkage beginning in 1990s, resulting in the glacier body completely separated into two small glaciers, the west and east branches, in 1993 [29]. In addition, most pronounced shrinkage or disappearance is found on smaller glaciers due to the greater sensitivity of small and fragile glaciers to warming [22].

Table 3. Summary of the changes in glaciers in the Urumqi River basin.

Year	Glacier Area/km ²	Retreated Glacier Area/km ²	Rate of Area Change/km ² a ^{−1}	References
Glacier No.1 at the headwaters of the Urumqi River basin				
1921–1962	1.950	−0.030	−0.0007	[47,49,50]
1963–1973	1.872	−0.078	−0.0071	
1974–1980	1.858	−0.014	−0.0020	
1981–1988	1.828	−0.030	−0.0038	
1989–1993	1.800	−0.028	−0.0056	
1994–2000	1.733	−0.067	−0.0096	[29]
2001–2009	1.646	−0.087	−0.0097	
2010–2012	1.590	−0.056	−0.0280	[51]
Glaciers at the mountainous upper reach catchment of the Urumqi River basin				
1964	48.04			[52]
1964–1989	34.42	−13.62	−0.5448	
1990–2005	28.00	−6.42	−0.4013	
2006–2014	23.61	−4.39	−0.4878	

The changes in glacier mass balance shows a mostly negative balance in the Urumqi River basin (Figure 4), suggesting a glacier wastage. According to the records on the Glacier No.1, nearly 70% of observed values revealed glacier mass losses, which began to augment in mid-1980s, especially pronounced after mid-1990s, and largest in 2010, when the mass balance for the Glacier No.1 was $-219 \times 10^4 \text{ m}^3$ water equivalent (w.e.).

**Figure 4.** Mass balance of the Glacier No.1 in the Urumqi River basin.

Certain proportion of the surface streamflow is fed by glacier melting in the Urumqi River basin [48]. Our results showed that the annual glacier mass loss contribution to the runoff at the river outlet does not exceed 15% between 1960 and 2012 (Figure 5a), with an average of nearly 7% each year (averaged for the years with negative mass balances). Particularly, the contribution of glacier wasting to runoff has augmented since mid-1990s (Figure 5a), and the decadal average contribution reached its highest value, which is 9.5%, in the 2000s (Figure 5b).

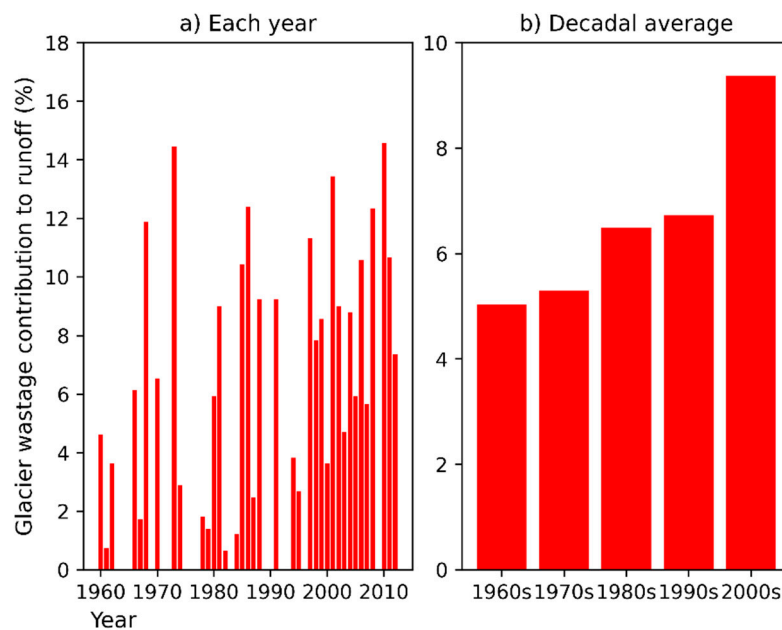


Figure 5. Glacier wasting contribution to the runoff at the river outlet: (a) in each year, and (b) decadal average.

4. Discussion

Climatic factors (i.e., P) are the dominant controls on runoff in the mountainous catchment of the Urumqi River basin. This is consistent with the findings of Chen et al. (2012) and Ma et al. (2008) for mountainous catchments in arid settings which are close to the Urumqi River basin [58,59]. The significance of P and other factors were also stressed by He et al. (2019), indicating that P and changes in basin characteristics have the strongest control on the runoff availability in northwest China [60]. Existence of glaciers is one of the important features of basin characteristics across the mountainous catchment in the arid regions of northwest China. In addition to climate variables, one of the most important factors which might influence runoff is the change in glacier melting. Previous studies have shown that change in glaciers melting affects river flow [30], and has become one of the critical controls on runoff perturbations in the Urumqi River basin [25]. However, mountain glaciers across the world have experienced a general recession under warming since the early twentieth century, due to their strong dependency on climatic conditions [18]. The observed drastic warming in the arid regions of northwest China [24] also exacerbated the fragility of mountain glaciers in this region. For example, an intensive glacier retreat was found in the southeast Tibetan Plateau and Karakorum Mountains in the northwest China [30]. Sun et al. (2013) found that the Glacier No.1 in the headwaters of the Urumqi River basin shrank by approximately 15% during last five decades [29]. Li et al. (2011) reported that smaller glaciers in an area of 0.5 km² on the Eastern Tianshan Mountains had shrunk or even disappeared at the same time period [61]. Particularly, the impact of warming on the glaciers is pronounced after 1990s in the northwest China and has led to a great amount of glacial volume loss [30,41]. We found that ablation of the Glacier No.1 has accelerated since mid-1980s and especially pronounced after mid-1990s. Li et al. (2011) also found that the acceleration of the mass loss for the Glacier No.1 commenced first in 1985 and further augmented in 1996 [62]. Such a phenomenon may be related to the albedo reduction at the ice surface caused by the augmentation of mineral and organic dust [63] and/or warming in the melting season [22,30]. In addition, Braithwaite and Raper (2007) argued that [19] glaciers in dry-cold climate have lower mass balance sensitivity to changes in precipitation and air temperature than those in warm-wet climate. The acceleration of glacier ablation in the Urumqi River basin thus might reflect the observed climate shift from warm-dry to warm-wet in the arid regions of northwest China [64]. However, due to the enhanced glacier melting, the glacier wasting contribution to runoff has increased by more than 5.5% since the 1990s in the

northwest China [30]. In the Urumqi River basin, we found that the glacier wasting contribution to runoff has increased considerably since mid-1990s, i.e., 1996, which concurs with the findings of Sun et al. (2013) [29]. As to the magnitude of this contribution, Shi et al. (1992) estimated that glacier melting in the Urumqi River basin contributes approximately 8.7% to the total runoff, which is close to our results [48].

In the mid and lower reach zones, impacts of changes in basin characteristics, which is represented by the parameter m in the Budyko framework, plays an important role in runoff fluctuation. Changes in basin characteristics, to some degree, can be explained by the changes in land use and land cover, since surface conditions reflect basin properties [2], and some other factors, such as population growth [8]. Land surface conditions in the Urumqi River basin have experienced drastic changes (Figure 1b,c) over the last few decades [65]. For example, the expansion of settlements was evident in the mid and lower reach zones [66]. Especially, the areal extensions of settlements, water body, and glacier had exhibited remarkable variations. The settlements were mainly distributed in the urbanized mid reach zone before 1980; however, over the recent 35 years, the area of settlements in the mid reach zone expanded while new settlements were also developed in the lower reach zone; the total area of settlements in Urumqi River basin, therefore, increased by around 200% in comparison to the areal extension in 1980 (Table 4). The expansion of settlements implies, undoubtedly, that human interferences and their impacts on the surface condition had been growing. For example, without much increase in total available runoff in the basin, there is nearly 23 times more population in the Urumqi River basin in the early 2010s than it was in early 1950s [67,68], implying huge increase in water consumption due to a larger population. This can support our results that the influences of non-climatic factors are dominant on water availability in the mid and lower reach zones. Other studies also found that human interferences are the major cause of streamflow perturbations in the downstream of water tense arid inland river basins [69–71].

Table 4. Changes in land use/land cover during 1980 and 2015.

Land Use Class	Proportion (%)		Relative Change (%)	Trend
	1980	2015		
Agriculture	18.7	16.7	−10.8	decreasing
Forestland	8.0	4.8	−39.8	decreasing
Grassland	54.9	56.7	3.3	increasing
Water body	0.5	0.9	75.0	increasing
Glacier and snow	4.1	0.8	−80.1	decreasing
Settlements	4.0	12.2	204.0	increasing
Bare land	9.7	7.9	−18.8	decreasing
Total	100	100	−	−

The data shown in this table is driven from the dataset, which is specified in the reference [65].

5. Conclusions

Surface runoff across the glacierized inland river basins are extremely fragile to variation in climatic and other factors. Identifying the major controls on runoff has important implication for water resources management in these regions. In the glacierized mountainous catchments of the Urumqi River basin, runoff variation is most sensitive to change in P , and followed by the impact of change in basin characteristics. Across the drier mid and lower reach zones, variation in basin characteristics plays a dominant role and accounts for nearly 60% of the change in runoff alteration. In addition, the enhanced glacier recession represents the most pronounced change in basin characteristics in the mountainous upper reach zone, whereas human interferences are dominant in the mid and lower reach zones. In the long term, the enhanced glacier wasting contributes around 7% to the annual runoff in the Urumqi River basin. Our results highlight that the major control on runoff varies noticeably over the heterogeneous basin surface, and is needed to be identified separately. In addition, the importance of

change in glacier melting and intensity of human interferences should be considered in water resources management over the arid inland glacierized river basins.

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Appendix A. Extrapolation of Runoff across the Three Reaches

Hydrological stations are sparse in the inland river basins in the northwest China. Usually, there is one hydrological station available at the river outlet, and calculating the runoff depth at the remainder of the basin is challenging. In the Urumqi River basin, the Yingxiongqiao station is available at the upper reach. Thus, for the upper reach, the below equation is used to calculate the runoff depth by spreading the observed runoff at the hydrological station over the contributing area as:

$$Q_u = \frac{Q}{A_u} \quad (\text{A1})$$

where Q_u is the runoff depth at the upper reach (mm), Q is runoff observation at the hydrological station (mm^3), and A_u is the runoff contributing area of the upper reach (mm^2).

In the mid and lower reach zones, a number of seasonal streams contribute to the streamflow. Because observations are scarce, streamflow for the mid and lower reach zones are extrapolated, respectively, using the observed runoff from the upper reach zone. For this purpose:

First, the ratio of long-term average annual runoff at the upper reach over the long-term average annual runoff at the mid and lower reaches are calculated respectively as:

$$C_m = \frac{\bar{Q}_m}{\bar{Q}} \quad (\text{A2})$$

$$C_l = \frac{\bar{Q}_l}{\bar{Q}} \quad (\text{A3})$$

where \bar{Q} , \bar{Q}_m , and \bar{Q}_l are, respectively, long-term average annual runoff at the upper, mid, and lower reaches of the Urumqi River basin (mm).

Second, the annual runoff at the upper reach was multiplied by the runoff ratio of mid and lower reaches to estimate the annual runoff at mid and lower reaches respectively as:

$$Q_{m_i} = C_m Q_i \quad (\text{A4})$$

$$Q_{l_i} = C_l Q_i \quad (\text{A5})$$

where Q_i is the given annual runoff at the upper reach (mm). Q_{m_i} and Q_{l_i} are, respectively, the annual runoff at the mid and lower reaches (mm).

Finally, the annual runoff depths of mid and lower reach zones were calculated, respectively, by multiplying the annual runoff and the areal ratio, which is the ratio of the runoff contributing area over the zone area as:

$$R_{m_i} = Q_{m_i} A_m \quad (\text{A6})$$

$$R_{l_i} = Q_{l_i} A_l \quad (\text{A7})$$

where R_{m_i} and R_{l_i} are annual runoff depth for the mid and lower reaches (mm), and A_m and A_l are the areal ratios for the mid and lower reaches, respectively, without unit.

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