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Suspended sediment and total dissolved solid yield patterns at the headwaters of Urumqi River, northwestern China: a comparison between glacial and non-glacial catchments

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ABSTRACT:

In order to understand the differences in the suspended sediment and total dissolved solid (TDS) yield patterns between the glacial and non-glacial catchments at the headwaters of Urumqi River, northwestern China, water samples were collected from a glacier catchment and an empty cirque catchment within the region, during three melting seasons from 2006 to 2008. These samples were analyzed to estimate suspended sediment and TDS concentrations, fluxes and erosion rates in the two adjoining catchments. There were remarked differences in suspended sediment and TDS yield patterns between the two catchments. Suspended sediment concentrations were controlled mainly by the sediment source, whereas TDS concentrations were primarily related to the hydrologic interaction with soil minerals. Generally, the glacial catchment had much higher suspended sediment and TDS yields, together with higher denudation rates, than the non-glacial catchment. Overall, glacial catchment was mainly dominated by physical denudation process, whereas the non-glacial catchment was jointly influenced by physical and chemical denudation processes. The observed differences in material delivery patterns were mainly controlled by the runoff source and the glacial processes. The melting periods of glacier and snow were typically the most important time for the suspended sediment and TDS yields. Meanwhile, episodic precipitation events could generate disproportionately large yields. Subglacial hydrology dynamics, glaciers pluck and grind processes could affect erodibility, and the large quantities of dust stored on the glacier surface provided additional sources for suspended sediment transport in the glacial catchment. These mechanisms imply that, in response to climate change, the catchment behaviour will be modified significantly in this region, in terms of material flux.

KEY WORDS suspended sediment and total dissolved solid (TDS); delivery patterns; climate condition; runoff source; Urumqi Glacier No. 1; glacial and non-glacial catchments; Urumqi River

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INTRODUCTION

Glaciers have an important role in shaping some of the most spectacular landscape on earth, ranging from deep fjords to rugged alpine terrain characteristic of high mountain ranges and to broad valleys that drain vast volumes of ice from polar ice sheets (Hallet *et al.*, 1996). Glaciers also produce prodigious quantities of sediments ranging from house-size boulders to fine silt readily entrained by winds (Hallet *et al.*, 1996). Therefore, the temporally changing characteristics of sediment concentrations and solute loads provide insight into the role of glacier dynamics in the production and transport of sediments in a glacierized environment. Suspended sediment is especially sensitive to glacial environment change, due to interactions of the glacier, climate and landscape changes (Hodgkins *et al.*, 2003).

Researches about river loads and modern denudation of the Alps showed that sediment yield and glacial cover are positively correlated, and sediment yields of extensively glaciated basins with glacial cover >50% are nearly one order of magnitude higher than those of non-glaciated or weakly glaciated (Hinderer *et al.*, 2013). A general tendency exists that dissolved load increases with sediment load because chemical weathering is more efficient when mechanical weathering supplies more fresh rock particles (Bluth and Kump, 1994; von Blanckenburg, 2005). However, other studies have shown that a glacier has a strong impact on the mechanical erosion in the glacial catchment, yet such influence on chemical weathering has not been found for the same

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catchment (Anderson, 2005; Gislason *et al*., 2009). These suggest that glaciers have different influence on the river material transport in different alpine catchments.

Strong glacial impact on the sediment yield is due to glacier recession since the 19th century as well as due to glacial conditioning during repeated Quaternary glaciations that have produced the strong transient state of the Alpine landscape (Hinderer *et al*., 2013). Studies also have indicated that enhanced air temperature and the presence of glacial cover over a watershed can cause an increase in suspended sediment flux, compared with lower temperature, non-glacier catchments (Anderson, 2005, 2007; Gislason *et al*., 2009). Another study (Syvitski, 2002) about sediment discharge variability in Arctic rivers showed about 22% increase in the sediment flux carried by river for every 2 °C warming through the model prediction, indicating the effect of climate change on the sediment yield in the alpine catchment (Lu *et al*., 2010). Glacial and snowmelt-fed rivers may have different runoff responses to climate change in alpine areas (Lafreniere and Sharp, 2003). Thus, under the condition of climate change, a comparison study of suspended sediment and dissolved solid yield patterns between glacial and non-glacial catchments is necessary for the evaluation of the river material delivery patterns and glacial environment changes in alpine regions.

Urumqi River (Figure 1), located in the eastern Tianshan Mountain and an interior area of arid and semi-arid Central Asia, is the main water supply for the city of Urumqi, the provincial capital city of the Xinjiang Uyger Autonomous Region, China. In recent years, the water quality at the headwaters of Urumqi River has drawn wide attention (Li *et al*., 2010). Investigations have been carried out to investigate the solute characteristic and glacier runoff change in glacial catchment (Luo, 1983; Woo *et al*., 1994; Williams *et al*., 1995; Kang *et al*., 1997; Liu *et al*., 1999a,b; Li *et al*., 2003, 2007, 2010, 2012; Ye *et al*., 2005; Han *et al*., 2007). In this study, we attempt to compare the differences of the suspended sediment and dissolved solid yield patterns between glacial and non-glacial catchments from the headwaters of Urumqi River based on the measurements in the 3-year melting seasons and discuss about the related hydrological processes and river material delivery mechanisms.

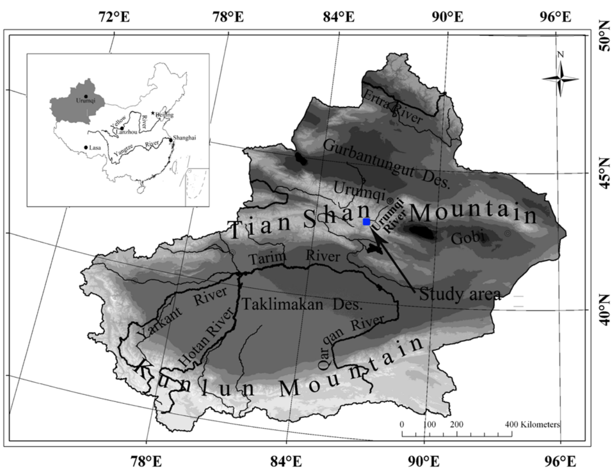

Figure 1. Location and the surrounding geographic environment of the study area (from Li *et al*., 2012)

SITE DESCRIPTION AND METHODS

Sampling site description

Urumqi River (Figure 1) is located in eastern Tianshan Mountain, surrounded by the three deserts, that is, the Takimakan to the south, the Junggar Basin to the north and the Gobi Desert to the east. The river is 214-km long and has a 4684 km^2 drainage basin, of which 1070 km^2 belongs to mountainous terrain (Liu *et al*., 1999a). There are two catchments at the headwater of Urumqi River, which are referred to as the Urumqi Glacier No. 1 (UG1) catchment (43°06′N, 86°49′E) and the Empty Cirque (EC) catchment (43°07′N, 86°49′E), respectively, by the local researchers (for locations, see Figure 2). The UG1 catchment is the glaciated catchment that contains the largest northeast-facing valley glacier (UG1) in the drainage basin. UG1 is composed of east and west tributaries, which became separated into two small independent glaciers in 1993 attributable to continued glacier shrinkage (Li *et al*., 2003; Ye *et al*., 2005). The EC catchment is a small non-glacierized catchment, only seasonally snow-covered.

The UG1 catchment is approximately 3.34 km^2 in area, as measured at a gauge station, located approximately 300 m from the present front of the Glacier No. 1, with a

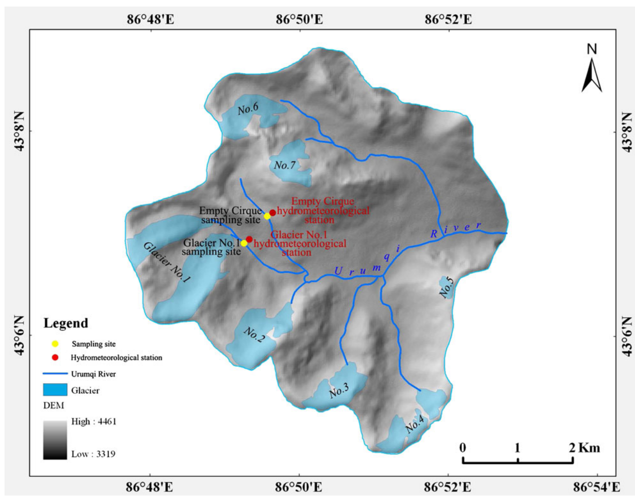

Figure 2. Locations of the gauging/sampling sites and the hydrometeorological stations at the headwaters of the Urumqi River (with the shaded areas designating glaciers) (from Li *et al*., 2012)

glaciated area of 1.646 km^2 (49% of the basin) and the terminus elevation of 3693 m above sea level (Figure 2 and Table I). Mean annual temperature and precipitation are −5.9 °C and 504 mm, respectively. Meanwhile, mean annual runoff is 241.81×10^4 m^3. This catchment consists mainly of bare rock, glacial deposits and permafrost, and the valley floor is characterized by barren rock with sparse vegetation. The lithology of moraine is primarily siliceous crystalline schist, with liberal amounts of gneiss, gabbro, granodiorite, granite and quartzite; occasionally, there are deposits consisting of limestone debris. The minerals mainly include hornblende, biotite, dolomite and quartz, with a small amount of carbonate, gypsum and pyrite (Wang and Zhang, 1981).

The EC catchment (1.68 km^2) consists mainly of bare rock and gravel on the steep slopes of the upper valley floor, with vegetation being found only on the tundra soil and over the peaty low-lying land, accounting for less than 10% of the basin area (Figure 2 and Table I). This catchment is a non-glacierized catchment, only seasonally snow-covered. The terminal elevation is 3805 m above sea level. Mean annual temperature and precipitation are −6.3 °C and 528 mm, respectively. Mean annual runoff is 70.69×10^4 m^3. In EC catchment, the bedrock is composed primarily of crystalline granite, diorite and gabbro-diabase, with some sedimentary outcrops, mostly limestone and shale. The surface ground materials in the basin permit much storage, rapid drainage and easy transmission of water (Woo *et al.*, 1994).

Measurement of water discharge, daily mean temperature and daily precipitation

Streamflow discharge and meteorological parameters were measured at two hydrometeorological stations at the headwaters of Urumqi River (Table I). These stations are operated and maintained by the Tianshan Glaciological Station, the Chinese Academy of Sciences. Streamflow discharge observation at both gauging stations was carried out from May to September in 2006–2008. The observed water level records were converted to water discharges, based on rating curves, and total daily volumes in cubic meters or daily runoff depths (for the related catchment areas) in millimeters (Li *et al.*, 2010). Over 95% of the annual runoff at both stations occurred during the observation period, whereas in the rest of the year, the streams were mostly frozen. Daily air temperature and precipitations were recorded at both hydrometeorological stations during the study.

Sample collection and analysis

Surface water samples were collected on a daily basis for the two catchments during the melting season (i.e. May to September) of 2006–2008, using pre-cleaned polyethylene bottles. Water depth of the present sample sites is shallow, and riverbed is covered by the large numbers of bare rocks. Sometimes, bare rocks cannot be submerged by the water flow, so bed load would not be considered in the present study. One water sample on a daily basis was used to determine the amount of the suspended sediment and dissolved solid. More than one hundred surface water samples were collected from the glacial and non-glacial catchments every year. The water samples were stored in polyethylene bottles and then transported frozen from the sampling sites and stored at −18 °C until further analysis.

Suspended sediment samples were obtained through filtration of the water samples. Grain size analysis of these samples was undertaken using an Accusizer 780A counter, which uses the single particle optical sensing principle, equipped with a 120 orifice (Zhu *et al.*, 2006). Measurements were performed under class 100 conditions on sample aliquots diluted with a pre-filtered NaCl solution to give a 2% vol. electrolyte concentration. The data were acquired for a size range of 0.57–400 μm equivalent spherical diameter. This particular operation process has been described in detail by Zhu *et al.* (2006). Suspended sediment concentration (SSC) was calculated using the raw count data. Total dissolved solid (TDS) concentration was determined by a Conductivity Meter (Shanghai REX Instrument Factory, Shanghai, China) (DDSJ-308A). Suspended sediment flux was calculated by multiplying the SSC by the water discharge. Similarly, TDS flux was also calculated by multiplying the TDS concentration by the water discharge. Finally, the total flux was calculated by

Table I. Main geographical and hydrometeorological feature of the two catchments (from Sun *et al.*, 2012)

Particulars	The Glacier No. 1 catchment	The Empty Cirque catchment
Total area (km^2)	3.34	1.68
Glacierized area (km^2)	1.646	0
Elevation range (m, a.s.l.)	3693–4486	3805–4301
Elevation of gauging station (m, a.s.l.)	3693	3805
Mean annual runoff (10^4 m^3)	241.81	70.69
Mean annual temperature (°C)	−5.9	−6.3
Mean annual precipitation (mm)	504	528

adding suspended sediment flux and TDS flux. The rates of denudation were estimated by using the relationship given by Singh *et al*. (2008) and Hinderer *et al*. (2013):

$$DR_{\text{phy}} = \text{SSC}{*}Q/(A{*}\gamma) \tag{1}$$

$$DR_{\text{che}} = \text{TDS}{*}Q/(A{*}\gamma) \tag{2}$$

$$DR_{\text{t}} = DR_{\text{phy}} + DR_{\text{che}} \tag{3}$$

where DR is the denudation rate, DR_{phy} is the physical denudation rate, DR_{che} is the chemical denudation rate, DR_{t} is the total denudation rate, Q is the discharge, A is the catchment area and γ is the bulk density of the strata. The denudation rate is expressed in 10^{-3} mm year^{-1} or in m^3 km^{-2} year^{-1}. In this study, the bulk density of the rock was taken as 2.65 kg m^{-3}, which is the value for the average crustal material (Hicks, 1990; Andrews *et al*., 1994; Wake *et al*., 1994; Liu *et al*., 1999; Dong *et al*., 2011; Li *et al*., 2012).

RESULTS

Climate conditions

According to the previous research (Sun *et al*., 2012), annual average temperature and annual precipitation at the headwaters of Urumqi River increase significantly since the middle 1990s. For UG1 catchment and EC catchment, air temperature in 2006 and 2008 was relatively high, compared with the long-term climate record from the hydrometeorological station. The range of the average air temperature from UG1 hydrometeorological and EC hydrometeorological stations during the melt season varied from −5.0 to 11.9 °C day^{-1}. The high average air temperature usually occurs during late July and early August. Generally, mean air temperature with the UG1 catchment is about 1.24 times higher than that of the EC catchment (Li *et al*., 2012).

Significant rainfall events are not common in this region. Total precipitation during the melt season ranged from 271 mm (2007) to 376 mm (2008) in the UG1 catchment, and varied from 223 mm (2007) to 339 mm (2006) in the EC catchment (Figures 3–5). Generally, most rainfall occurs in July in the study area. More than 100 mm of precipitation was recorded in July of 2006 in both catchments, although the most intense precipitation event was on 4 July, when 18.3 and 15.3 mm of rain fell in the UG1 catchment and the EC catchment, respectively. Substantial rainfall occurred on 5–18 July 2007, and total precipitation was 98.9 mm in the UG1 catchment and 95.5 mm in the EC catchment in these 14 days. The July of 2008 was also wet and characterized by higher rainfall intensity than observed in 2006 and 2007. One hundred eighty millimeters of rainfall in the UG1 catchment and 126 mm of rainfall in the EC catchment were recorded, which occurred in about 21 days.

Water discharge and suspended sediment transport

For both catchments, the variations of discharge and SSC in the different years are quite different, which finally lead to the large difference for the suspended sediment flux.

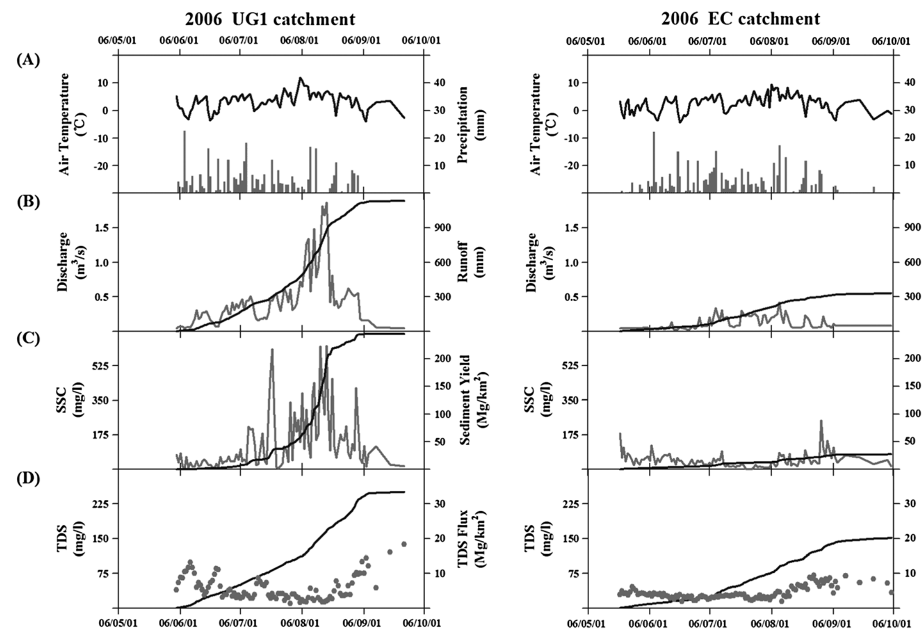

Figure 3. Hydrometeorological and river material conditions in the Urumqi Glacier No. 1 (UG1) catchment and the Empty Cirque (EC) catchment in 2006. (A) Daily air temperature and precipitation from the Glacier No. 1 hydrometeorological station and the EC hydrometeorological station. (B) Discharge and cumulative runoff. (C) Suspended sediment concentration (SSC) and cumulative sediment flux. (D) Total dissolved solid (TDS) concentration and cumulative TDS flux

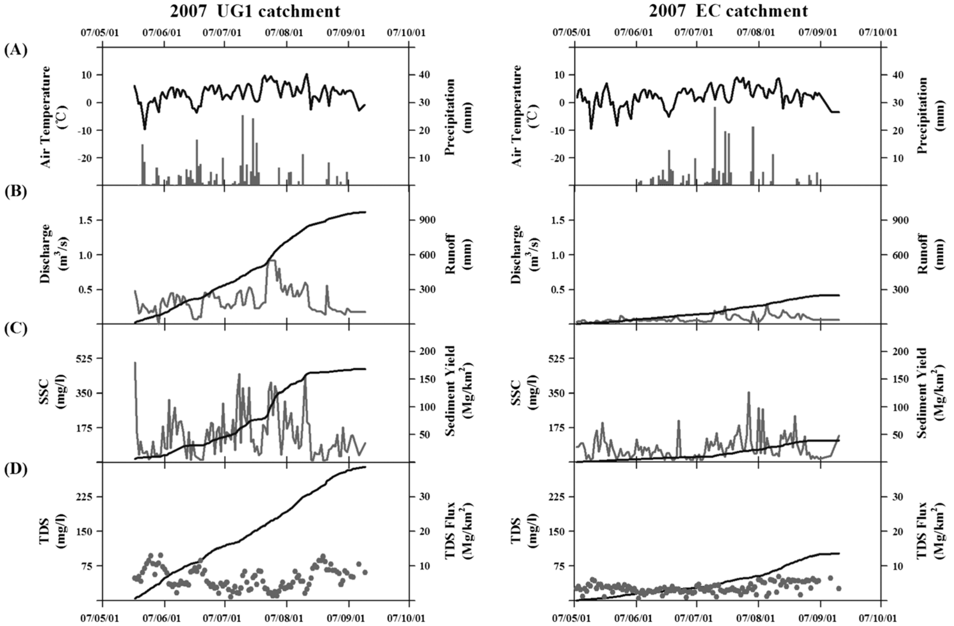

Figure 4. Hydrometeorological and river material conditions in the Urumqi Glacier No. 1 (UG1) catchment and the Empty Cirque (EC) catchment in 2007. (A) Daily air temperature and precipitation from the Glacier No. 1 hydrometeorological station and the EC hydrometeorological station. (B) Discharge and cumulative runoff. (C) Suspended sediment concentration (SSC) and cumulative sediment flux. (D) Total dissolved solid (TDS) concentration and cumulative TDS flux

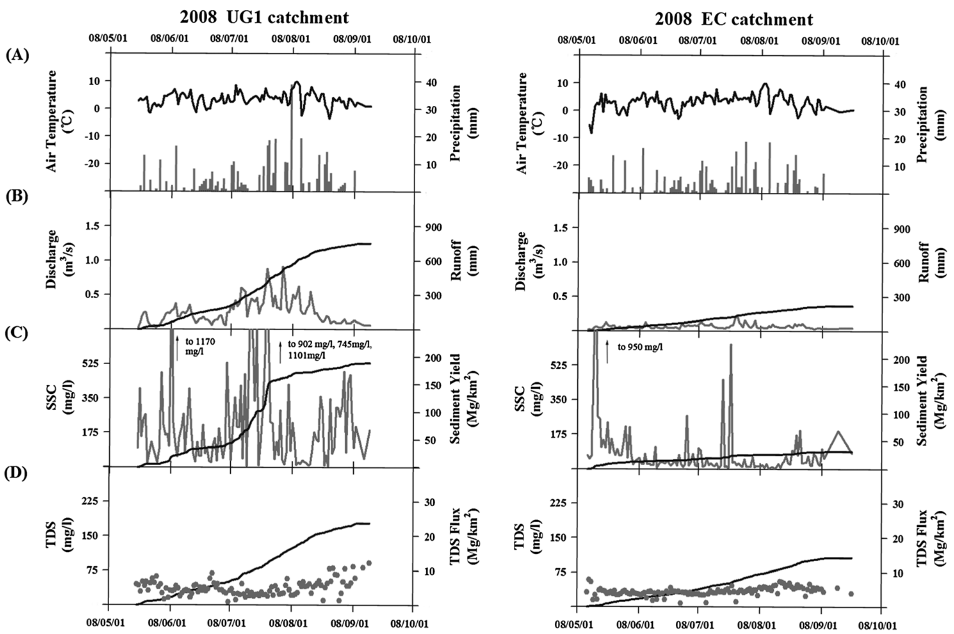

Figure 5. Hydrometeorological and river material conditions in the Urumqi Glacier No. 1 (UG1) catchment and the Empty Cirque (EC) catchment in 2008. (A) Daily air temperature and precipitation from the Glacier No. 1 hydrometeorological station and the EC hydrometeorological station. (B) Discharge and cumulative runoff. (C) Suspended sediment concentration (SSC) and cumulative sediment flux. (D) Total dissolved solid (TDS) concentration and cumulative TDS flux

Discharge during the melt season was the highest in 2006 in both catchments, which was mainly controlled by the high air temperature and moderate precipitation (Sun *et al.*, 2012). Discharge increased from May and reached its peak in the early August, and then decreased until the end of the melting season. With the transport of discharge, the majority of suspended sediment was also delivered by the river (Figure 3). During the melting season of 2006, SSC in the UG1 catchment increased gradually with increasing water discharge from May, reaching its peak value (c. 625 mg l^{-1})

on 13 August, and then decreased and remained below c. 175 mg l^{-1}. Because of the synchronous variation between SSC and water discharge, suspended sediment flux in the UG1 catchment was transported (818.77 Mg), which was the highest flux in the three study years (Table II). Ninety per cent of sediment was carried in July and August, and the largest amounts of discharge and suspended sediment both occurred in August (Figure 6). Meanwhile, discharge in the EC catchment showed the same variation with the discharge in the UG1, although it was quite lower than that of the UG1. SSC in the EC catchment exhibited the higher value (c. 181 mg l^{-1}) in the early stage of melting season and then decreased gradually until the late stage of August, reaching the highest concentration (c. 247 mg l^{-1}), and eventually decreased with the low discharge (Figure 3). Because of the variations of SSC and discharge in the EC catchment, sediment flux in this catchment was about 45.65 Mg in 2006, and nearly half of suspended sediment flux was carried in August in this year (Figure 6).

Table II. Water yield, runoff, suspended sediment concentration (SSC) and total dissolved solid (TDS) of the Urumqi Glacier No. 1 (UG1) catchment and Empty Cirque (EC) catchment

Year	Water yield ($\times 10^5$ m^3)	Runoff (mm)	SSC (mg l^{-1})	TDS (mg l^{-1})	Sediment flux (Mg)	TDS flux (Mg)	Specific sediment yield (Mg km^{-2})	Specific TDS yield (Mg km^{-2})
UG1 catchment								
2006	37.51	1123.05	131.07	43.12	818.77	111.79	245.14	33.47
2007	22.13	662.58	135.36	47.76	561.99	129.06	168.26	38.64
2008	25.21	754.79	207.30	37.34	630.66	79.59	188.82	23.83
EC catchment								
2006	6.81	405.36	44.96	32.78	45.65	34.04	27.17	20.26
2007	8.27	492.26	73.59	26.94	66.58	22.85	39.63	13.60
2008	7.17	426.79	75.54	33.65	53.54	23.99	31.87	14.28

Values of sediment and TDS are listed as average concentration (mg l^{-1}), flux (Mg) and specific yield (Mg km^{-2}).

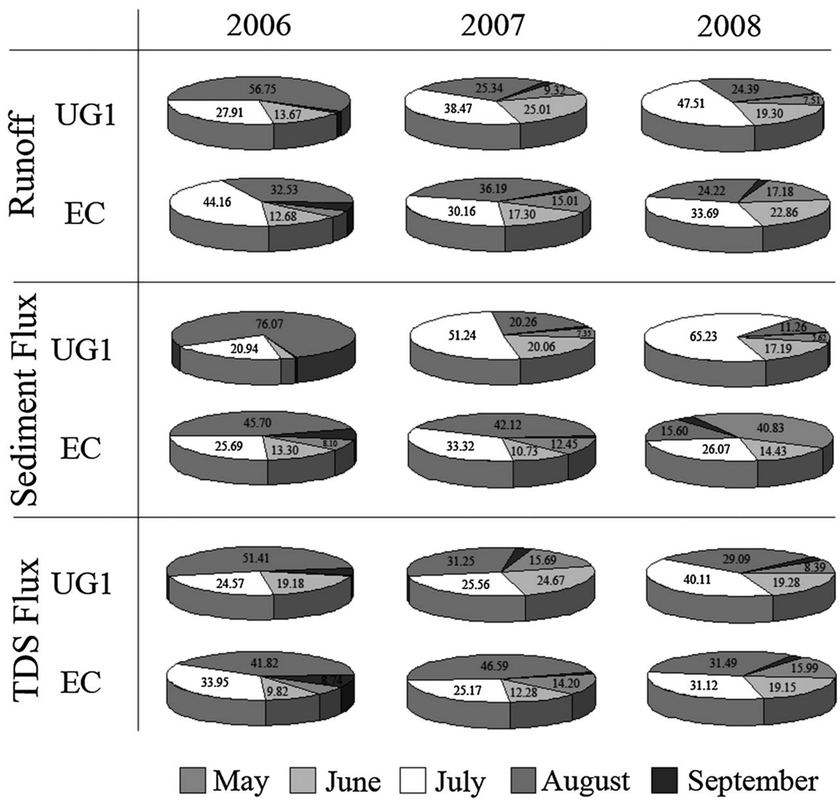

Figure 6. The different proportion of runoff, sediment flux and total dissolved solid (TDS) flux in different months between the Urumqi Glacier No. 1 (UG1) catchment and Empty Cirque (EC) catchment from 2006 to 2008

Moderate air temperature and precipitation during the 2007 melting season resulted in discharge that lacked the large diurnal hydrograph peak and produced the low runoff intensities in both catchments (Figure 4). SSC in both catchments in this year showed similar variations with the SSC of 2006, except for the early stage of melt season. In a few days during the early melting season in this year, SSC exceeded c. 100 mg l^{-1} in both catchments, whereas this phenomenon did not occur in 2006. During the intense melting season of this year, persistent and substantial precipitation from 5 to 18 July (98.9 mm) and high air temperature in July (5.06 °C) that was the highest air temperature of three study years generated the notable high SSC in the UG1 catchment and transported 51.24% of sediment in this period. However, for the EC catchment, intensive precipitation did not lead to high SSC immediately. With the end of precipitation and increase of air temperature, SSC reached its peak value c. 353.76 mg l^{-1}. Suspended sediment flux was 561.99 Mg for the UG1 catchment and 66.58 Mg for the EC catchment in this year (Table II). The largest sediment discharges occurred in July (51.24%) for the UG1 catchment and August (42.12%) for the EC catchment (Figure 6).

Streamflows in both catchments were also generally low during the melting seasons in 2008, although intensive and substantial precipitation occurred in this year (Figure 5). There is the similar variation for discharge between 2007 and 2008 in both catchments. However, SSC in 2008 was apparently higher than that of 2007, or even in 2006. In the early stage of melting season, most of SSC kept above c. 150 mg $\cdot$ l^{-1} in both catchments, especially in the UG1 catchment. High SSC in the EC catchment resulted in high sediment flux (40.83 %) during this period (Figure 6). During the intensive melting season, SSC also generated the extreme values (e.g. 1101 mg l^{-1} for UG1 and 635 mg l^{-1} for EC), and about 76.49% (UG1) and 41.67% (EC) of sediment flux were carried in this time. During recession and baseflow, SSC remained above c. 175 mg l^{-1} for the UG1 catchment but was comparatively low for the EC catchment. However, because of the comparatively low runoff in this year, only about 630.66 Mg (UG1) and 53.54 Mg (EC) of suspended sediment were carried in this period (Table II).

Total dissolved solids transport

For both catchments, there were similar variations for TDS concentrations in different years (Figures 3–5). At the early (May) and later (September) stages of the melting season, higher TDS concentrations were observed, especially towards the later stage of ablation season. Meanwhile, TDS concentrations were relatively low during the intensive melting season (July). Yet, despite low TDS concentrations in the intensive melt season, the majority of the TDS flux usually occurred during this period.

In 2006, TDS concentrations were comparatively high and showed large variation throughout the melting season in the UG1 catchment (Figure 3). In the intensive melting season, most TDS concentrations were approximately c. 30 mg l^{-1} and even were only c. 10 mg l^{-1}. Yet, in the late melting season, TDS concentrations could increase to more than c. 100 mg l^{-1}, reaching its peak value c. 137 mg l^{-1} on 21 Sept. Such variations of TDS concentration led to the high TDS flux (111.79 Mg) in this year, despite low TDS concentrations in the intensive melting season, and 86% TDS flux was transported in this period (Table II and Figure 6). For the EC catchment, TDS concentrations showed a similar variation with the ones of the UG1 catchment and remained below c. 75 mg l^{-1} during the melting season. Only about 34.04 Mg TDS flux was carried in this year in the EC catchment, which was still the largest amount in these three years (Table II).

In 2007, TDS concentrations in both catchments were similar to 2006 (Figure 4). TDS concentrations kept below c. 100 mg l^{-1} for the UG1 catchment and c. 50 mg l^{-1} for the EC catchment. The UG1catchment and the EC catchment transported about 129.06 and 22.85 Mg during the melt season in this year (Table II), respectively, and carried maximum TDS flux in August in both catchments. Although the largest runoff did not occur in the UG1 catchment in 2007, the river carried the largest TDS flux in this year. Although the EC catchment runoff in 2007 was the maximum value, the watershed did not transport the largest TDS flux.

In 2008, TDS concentrations in both catchments showed little variations throughout the melting season, even though high TDS concentrations still presented at the onset and late stages of melting season (Figure 5). This year, both catchments carried the lowest TDS flux (79.59 UG1; 23.99 EC), compared with the other two years.

Inter-catchment differences

The inter-annual variability of TDS concentrations in both catchments is similar. They exhibit the higher concentrations in the intensive melting season and lower concentrations in the early and later stages of melting season, whereas TDS concentrations in the UG1 catchment are generally higher than that of the EC catchment, as showed by the mean monthly distribution of SSC and TDS observed at the gauging sites of the UG1 and EC catchments (Figure 7). In contrast, SSC has different inter-annual variability in both catchments, and the distribution tendencies of SSC between the UG1 and EC catchments also show different patterns. For the UG1 catchment, the intensive ablation season is mostly associated with higher SSC than early and later stages of the melting season. However, SSC in the EC catchment is higher at the early stage of the ablation period than at the intensive and later stages of the melting season. Additionally, the UG1 catchment also has the higher SSC than the EC catchment (Figure 7).

Moreover, runoff, water yield, specific sediment yield and specific TDS yield are consistently higher in the UG1 catchment (Table III). Higher water flux ratio between the UG1 catchment and the EC catchment leads to the higher sediment yield ratio and low TDS yield ratio. The total denudation rates were 0.08 mm year^{-1} for the UG1 catchment and 0.018 mm year^{-1} for the EC catchment, suggesting that the glacial catchment is eroding more intensively than the non-glacial catchment. Physical denudation rates in the UG1 and EC catchments are 0.07 and 0.012 mm year^{-1}, respectively. Meanwhile, chemical denudation rates are 0.01 mm year^{-1} (the UG1) and 0.006 mm year^{-1} (the EC). These results show that the physical denudation rate in the UG1 catchment is about seven times higher than the chemical denudation rate, while the physical denudation rate in the EC catchment is just two times higher than the chemical denudation rate. This indicates that glacial catchment is mainly dominated by physical denudation process, whereas the non-glacial catchment is jointly influenced by physical and chemical denudation processes.

Further, there are different transport patterns of river materials between the UG1 catchment and the EC catchment (Figure 6). In terms of the average proportion of the runoff and materials, only 5.69% of water, 4.34% of sediment flux and 8.16% of TDS flux were transported in May in the UG1 catchment. However, in the EC catchment, the water accounted for 12.50% of the annual total in May, which transported 20.46% of sediment flux and 11.95% of TDS flux. In June, the water, sediment flux and TDS flux in the UG1 catchment accounted for 19.33%, 13.25% and 21.04% of the annual total, and yet, the corresponding ratios in the EC catchment became 17.61%, 12.82% and 13.75%, respectively. During the early stage of melting season, the majority of sediment, which was stored in the channel during the non-melting season, is washed out in May and also leads to the high delivery ratios of water discharge and river materials in the EC catchment in May. With the increase of melting, water runoff and river materials also increase, as demonstrated by the ratios of runoff and river materials in the UG1 catchment in June, whereas in the EC catchment, higher delivery of sediment in May causes the amount of sediment transport to decrease in June.

During the intensive melting season, the water discharge in the UG1 catchment in July accounted for 37.97% of the annual total, together with approximately 45.80% for sediment flux and 30.08% for TDS flux, and in August, the values were 35.49%, 35.86% and 37.25%, respectively. This suggested that the sediment flux declined faster than the water discharge because of the exhausted sediments in the channel, while the TDS flux had an opposite trend.

Table III. The Urumqi Glacier No. 1 catchment to the Empty Cirque catchment ratios of runoff (mm), water flux ($\times 10^5$ m^3) and specific fluxes (Mg km^{-2}) for sediment and total dissolved solid (TDS) flux

Year	Runoff	Water flux	Sediment	TDS flux
2006	2.77	5.51	9.02	1.65
2007	1.35	2.68	4.25	2.84
2008	1.77	3.52	5.93	1.67

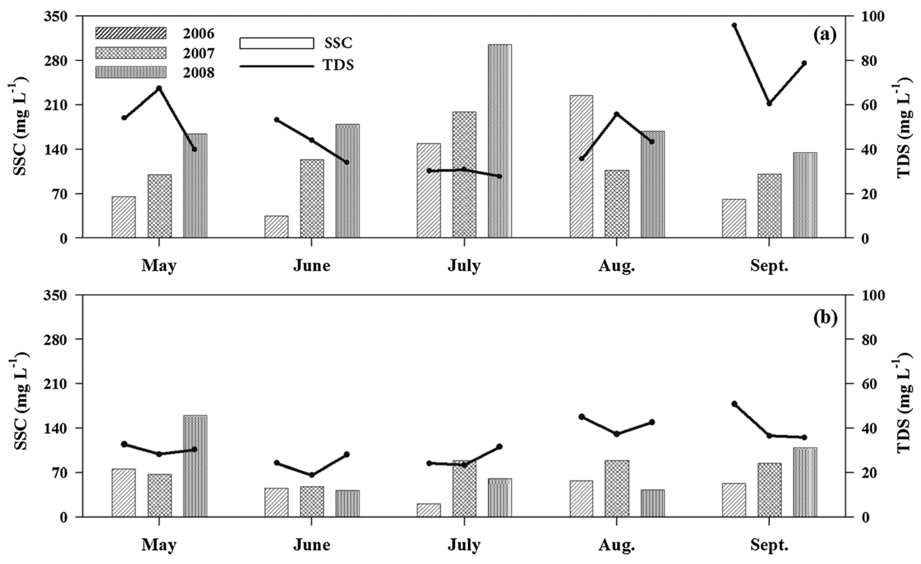

Figure 7. Mean monthly suspended sediment concentration (SSC) and total dissolved solid (TDS) observed at the gauging sites of (a) Urumqi Glacier No. 1 and (b) Empty Cirque during the melting seasons 2006–2008. (In both figures, the line graph represents TDS, whereas the bar graph represents SSC.)

Correspondingly, in the EC catchment, water discharge, sediment flux and TDS flux in July accounted for 36.01%, 28.35% and 30.08% of the annual total, respectively. In August, the water discharge accounted for 30.98%, but it carried 34.47% of sediment flux and 39.97% of TDS flux, representing a sharp increase.

Entering the late stage of the melting season (September), the water discharge in the UG1 catchment accounted for only about 1.53%, and the sediment flux and TDS flux accounted for 0.74% and 3.4%, respectively. For the EC catchment, the percentages decreased to 2.91%, 3.89% and 4.25% for water, sediment flux and TDS flux. Lower water discharge also generates the lower sediment flux and TDS flux.

DISCUSSION

Influencing factors of river material transport

There are apparently different variations in material delivery patterns between the UG1 and EC catchments. Suspended sediment and dissolved solid yields of the UG1 catchment are about 2.08 and 6.03 times higher than that of the EC catchment. Furthermore, the total denudation rate for the UG1 catchment is considerably (i.e. four times) higher than that of the EC catchment. The observed differences between glacial catchment and non-glacial catchment may be caused by a number of factors, such as climate influences, lithological characteristics of the catchment, and vegetation and glacier cover.

The environments of the UG1 and EC catchments are quite similar to each other, in terms of lithology and vegetation. They both consist mainly of bare rock, gravel and permafrost on the valley floor, with sparse vegetation being found only on the tundra soil and the peaty bottom land.

Moreover, there was no much difference in the climate patterns between the two catchments. Figures 3–5 present variations of daily average temperature and precipitation observed at the gauging sites for the UG1 and EC catchments during the 2006–2008 melting seasons. Although the values of precipitation for the EC catchment in May were missing, the overall results showed that the variation patterns of air temperature and precipitation of the UG1 and EC catchments have no much difference. The average values of air temperature for the UG1 and EC catchments were 3.38 and 2.76 °C, and the annual average precipitations of these catchments were 333 mm (UG1) and 291 mm (EC), respectively. The observed minor differences in climate characteristics are mainly influenced by the different elevations. Because the UG1 catchment (3693 m above sea level) has a slightly lower elevation than the EC catchment (3804 m above sea level), the air temperature and precipitation in the UG1 catchment are both a little higher than those of the EC catchment. Even though both catchments have similar climate patterns, the effects of climatic conditions on the variation of suspended sediment and dissolved matter are different between the UG1 catchment and the EC catchment (Li *et al.*, 2012), and yet, the influence of climate to the river materials is due to runoff; thus, runoff contributions from glacier meltwater, snowmelt water and stormflow are of importance to the river material transport and will be discussed in the next section.

According to Hallet *et al.* (1996), effective rates of glacial erosion vary by orders of magnitude from 0.01 mm $year^{-1}$ for polar glaciers and thin temperate plateau glaciers on crystalline bedrock to 0.1 mm $year^{-1}$ for temperate valley glaciers over resistant crystalline bedrock (e.g. those in Norway), to 1.0 mm $year^{-1}$ for small temperature glaciers on diverse bedrock (e.g. those in the Swiss Alps) and to 10–100 mm $year^{-1}$ for large and fast-moving temperate valley glaciers in the tectonically active ranges (e.g. those of southeast Alaska). The erosion rate of the present glacial catchment is 0.08 mm $year^{-1}$, which is the same order of magnitude for the erosion rate variation of the thin temperate plateau glaciers on crystalline bedrock. However, it is apparently lower than the average erosion rate of Central Asia (2.25 mm $year^{-1}$) (Hallet *et al.*, 1996). Therefore, the present glacial erosion can be used to represent the thin temperate plateau glacier erosion; meanwhile, it is also different from other glacial erosions of Central Asia. Further, we propose here that the differences in material flux variation between the UG1 catchment and the EC catchment are related to the presence or absence of the glacier cover. This effect of glacier on the river material transport also would be discussed in a later section.

Runoff contributions from glacier, snowmelt and precipitation: importance to river material delivery and transport

Godsey *et al.* (2009) have proposed that if river system keeps material concentrations constant as discharge varies, that means the catchment behaves chemostatically. According to our results, the present study catchments are not chemostatic watersheds. The effect of runoff on the suspended sediment is mainly through the physical erosion process. Water dynamic condition plays a pivotal role in this process. Physical erosion will increase with the larger water dynamic condition. Inversely, erosion intensity will decrease. For water dynamic condition, it is strongly related to the amount of discharge and the energy of runoff. Different runoff sources and different time will lead to the different amounts of discharge and energy of runoff, which further influence the physical erosion process and sediment variation.

For dissolved solid, runoff influences though the chemical denudation process, which is mainly controlled by the interaction between water and rock. Because of different water sources, water retention time is also different, which strongly influences the interaction between water and rock. In the early and later stages of melting season, the relatively low discharges are observed and associated mainly with the water mass stored in the aquifer, which has a high solute content; however, during the intensive melting season, the water discharge is contributed by the glacier meltwater, snow meltwater and precipitation, which all contributed to the dilution of the total flow. So at the early (May) and later (September) stages of the melting season, higher TDS concentrations were observed, especially towards the later stage of the ablation season. Meanwhile, TDS concentrations were relatively low during the intensive melting season (July).

The difference between the glacierized and non-glacierized catchments is that the runoff derived from the non-glacierized catchment is precipitation-dominated, whereas the glacierized catchment is energy-dominated (Chen and Ohmura, 1990; Liu *et al*., 2010). The main contributions to runoff in the study area are glacier or snowmelt and rainfall. According to the previous study (Sun *et al*., 2012), the runoff at EC is mainly derived from rainfall after depleting snowmelt in late May or early June, and a 1-mm increase of precipitation during the melting season could lead to an increase of $0.146 \times 10^4\,m^3$ runoff; thus, precipitation is the important factor for the non-glacierized EC catchment. For the Glacier No. 1 catchment, there is a substantial increase in the area of exposed ice, which would reduce the albedo and increase melting rate, and also produce a large increase in the amount of glacier meltwater. Moreover, research showed that air temperature is higher than 2 °C, the runoff would increase at an accelerated rate, indicating that runoff in the glacierized area is quite sensitive to temperature change (Sun *et al*., 2012), and glacier runoff accounts for 72.1% of the total river flow in the UG1 catchment.

According to the water balance model (Sun *et al*., 2012), the glacier runoff contribution rate in the UG1 catchment shows more than 80% higher in 2006, and yet, it presents the lowest contribution rate (60%) in 2007. Thus, in the UG1 catchment, the runoff in 2006 is entirely dominated by the glacier meltwater, but in 2007 and 2008 glacier meltwater, snow meltwater and precipitation all control the runoff. For the EC catchment, precipitation and snow meltwater both supply and dominate the runoff.

The majority of runoff occurred in August when the glacier meltwater dominated in the 2006 season, and the water flow increased rapidly and reached its peak value from 31st July to 14th August because of the higher air average temperature (7.16 °C), which was about 2.72 times higher than other periods. Rapid water flow and limited storage led to increase erosion and slow the hydrologic interaction with mineral in the soil, which resulted in high SSC and low ionic concentrations. Fluxes of sediment and TDS are high because the glacier meltwater is the source responsible for the vast majority of sediment and dissolved matters. Thus, half of the total runoff transported 76% of sediment and 51% of dissolved flux in August of this year. Similar phenomenon also occurred from 19 July to 12 August 2007. There were low precipitations in this period, and average air temperature was 6.4 °C. Higher runoff was mainly derived from the glacier meltwater. Similarly, higher SSC and lower TDS concentrations also occurred in this period, and river transported 37% of water flow, 50% of sediment flux and 26% of the TDS flux.

The snowmelt-dominated period generally occurs in the early stage of melt season, and the water flow is comparatively low in this period. Slow runoff can enhance hydrological interaction with mineral in the soil and increase the TDS concentrations, but low discharge cannot transport large TDS flux (10%) in this period. However, for the suspended sediment, snow meltwater-generated runoff does not necessarily generate high SSC and sediment flux. In the early stages of melting season in 2007 and 2008, there are high SSCs in the UG1 catchment, and water flow transports about 6% of sediment in this period. Yet, when snow meltwater supplied the runoff in 2006, it could not produce the high SSC and only carried about 0.1% of sediment flux in this period. This phenomenon is likely due to the snow meltwater dynamic and sediment storage conditions. Comparatively high SSCs were showed in the early stage of the melting season in the EC catchment, and the runoff of this period was mainly controlled by the snow meltwater. In general, water flow in this period can transport about 10% of sediment flux and TDS flux in river, except that the sediment, which was stored in the channel in winter, is affluent, which can lead to a major delivery of sediment (e.g. 40% of sediment was transported in the early stage of melt season in 2008).

Besides glacier meltwater and snow meltwater, rainfall is another major water source capable of generating hydrologic, sediment flux and TDS flux in the alpine catchment. The occurrence of rainstorm has a significant impact on the runoff as well as the sediment flux and TDS flux. According to Tempany and Grist (1958), heavy rain that occurred in a short period influences the increase of sediment in meltwater more than the increase in melt runoff. Significant rainfall events were recorded in 2008 (Figure 8). In 2008, a large amount of rain fell in the late July event, and intensity was high. Between 14 July and 31 July, 141.3 mm of rain was recorded in the UG1 catchment, and rain fell on 13 of 18 days in this period. During the first successive storm (from 14 and 23 July, maximum precipitation is 18.6 mm), sediment flux and TDS flux rapidly reached 84 and 1.69 Mg. Meanwhile,

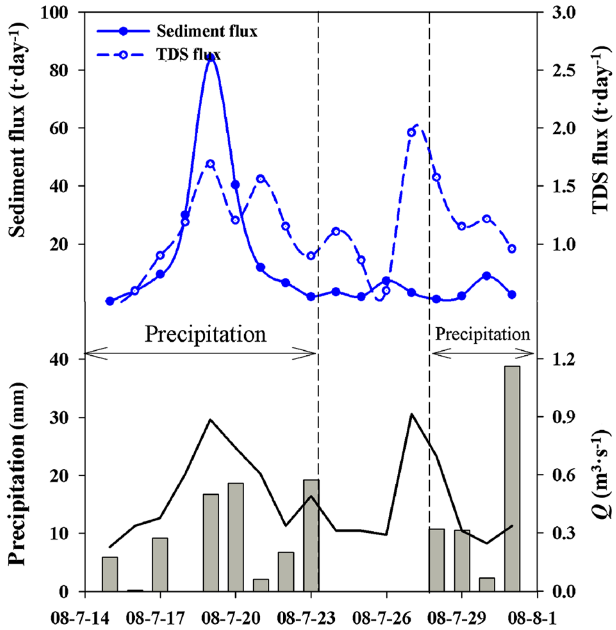

Figure 8. Daily discharge, suspended sediment flux and total dissolved solid (TDS) flux observed in the Urumqi Glacier No. 1 (UG1) catchment during the storms in July of 2008

sediment flux and TDS flux increased about 14 times and 3 times, whereas discharge increased only 3.8 times. This storm provided total rainfall of 79 mm and carried 1% of discharge, 35% of sediment flux and 13% of TDS flux. However, research suggested that it is important to note that local storms lead to both increased discharge and river materials, but timing of the occurrence of storm during the melting season is very important in generating the total sediment in meltwater. For the second storm (from 28 July to 31 July, maximum precipitation is 38.8 mm), it provided a total rainfall of 62 mm and carried 6% of discharge, but only 2% of sediment flux and 6% of TDS flux. The reason is that the large quantities of stored sediment are available for flushing out when the first storm occurred, whereas the second storm occurred again, and the sediment supply was depleted. Consequently, although rainstorm affects the river material evacuation, it depends on the time season of the rain event and the river material supply.

Consequently, water from different sources can lead to the different influences on the river material delivery and transport. For the glacial catchment, in May to June, water discharge was mainly controlled by the water stored in the aquifer and some snow meltwater, resulting in lower sediment flux but higher TDS flux; during the intensive melting of glacier and snow (July and August), most suspended sediment and dissolved solid were transported from the glacier zone; and finally, during the late ablation period (September), there was not sufficient melting in the catchment, and the sediment flux and TDS flux were also reduced because of limited material supply at this stage. Moreover, for the non-glacial catchment, earlier studies carried out for this catchment showed that there were multiple streamflow sources that include rainfall, snowfall and active layer ground ice-melt in summer, but the main contributor of runoff was snowmelt during the spring season (Woo *et al.*, 1994). The multiple sources of flow discharge in the EC catchment may have resulted in the observed particular sediment supply and delivery patterns.

Functioning of glacier on river material delivery patterns

With an accelerated shrinking trend, the UG1 length shortened by about 215.2 m (9.7%), and its area diminished by 0.304 km^2 (15.6%). The cumulative mass balance of the glacier was −13 693 mm, equivalent to 15.2 m of glacier ice (Sun *et al.*, 2012). Presently, approximately only 49% of the UG1 catchment area is still covered by glacier. In response to these changes, annual glacier meltwater and river runoff at gauging site also exhibited increasing trends. A noticeable increase occurred in 1994. Before 1994, glacier meltwater accounted for 62.8% of the total river flow, but it rose to 72.1%, probably because of the strong warming and increased precipitation. About 69.7% of the increased river runoff was derived from the increased glacier meltwater caused by loss of ice mass (Sun *et al.*, 2012). These records suggest that glacier melting can greatly influence the runoff of the glacial catchment. The increased runoff can, in term, transport more river materials downstream and modify the river materials delivery patterns.

Some researches have proposed that vigorous water discharge may strip the surficial debris layers, allowing underlying bedrock to be eroded more rapidly by sliding ice than if the bedrock surface remains around by debris (Herman *et al.*, 2011). Moreover, variable water discharge may lead to water and ice pressure variations on the bed that fatigue and crack bedrock, thereby hastening quarrying (Cohen *et al.*, 2006). Hydraulic potential gradients in the bed exert body forces on basal sediments and cracked bedrock, thereby helping to mobilize them (Alley *et al.*, 1997). Furthermore, in summer, there is increased subglacial meltwater compared with the winter season, and drainage efficiency is enhanced accordingly. Therefore, there is a period in a year when drainages shift from slow to fast to discharge subglacial meltwater. During that period, subglacial water pressure is large, and effective pressure is low, which promotes sliding and erosion (Herman *et al.*, 2011). These functions and processes all enhance the erosion rate, increasing the content of suspended matters in the river; these mechanisms are responsible for larger material discharges in a glacial catchment than in a non-glacial catchment.

Moreover, dust storms are an important phenomenon in eastern Tianshan Mountain, because this region is located in an arid and semi-arid region of Central Asia, at the source region for Asian dust (Dong *et al*., 2009). An analysis about the deposition of atmospheric dust in the fresh snow on UG1 suggested that the number of concentration of dust particle is significantly high from April to June (Dong *et al*., 2010). Meanwhile, the dust concentration in the precipitation in this area increased significantly during winter and springtime, but decreased during summer and autumn (Dong *et al*., 2011). Thus, in the UG1 catchment, the accelerated ablation of glacier can carry the dust, which is deposited and stored in the glacier, enhancing the content of suspended matter in the river flow. By using the Hysplit model, backward trajectories of air mass of different times to the Glacier No. 1 catchment are shown in different colours (i.e. blue and red) in Figure 9. The results show that when backward trajectories of air mass are across the desert, the suspended sediment has higher fine particle materials in the glacial catchment, compared with the air mass that has not passed the desert (Figures 4, 5 and 6). This indicates that dust storms are important to the variation of suspended sediment, especially for the fine particle materials. A previous study also demonstrated that glacier meltwater had relatively high SSCs (Li *et al*., 2012). However, in the EC catchment, the dust deposits mainly over the bare rock and gravel/tundra soil because of the absence of glacier cover; thus, fewer dust particles can be washed into the river. Furthermore, because of the influence of winter monsoon, the physical weathering of bedrock is more intensified in the UG1 than in EC. A combination of these processes, together with glacier plucking and grinding across the full width of the valley bottom, would be able to produce a sediment yield that is higher than that of the non-glacial catchment environments.

CONCLUSIONS

The present study shows that there are remarked differences in suspended sediment and TDS transport patterns between a glacial catchment (represented by the UG1 catchment) and a non-glacial catchment (represented by the EC catchment). In the UG1 catchment, higher SSCs occurred in the intensive stage of the melting season, whilst in the EC catchment, they were found at the beginning of the melting season. However, the TDS concentrations exhibited a similar variation in both catchments; that is, they are relatively low during the intensive ablation period, compared with the early and later stages of the melting season. SSCs were mainly controlled by the sources of sediment. The coaster sediments from local environment generated the high SSC in river, whereas TDS concentrations were primarily related to the hydrologic interaction with soil minerals.

Likewise, about 82% of suspended sediment flux and 67% of TDS flux in the UG1 catchment were transported in the intensive stage of melting season, whereas in the EC catchment, the river carried approximately 63% of suspended sediment flux and 70% of TDS flux in this period. In addition, in terms of overall suspended sediment and TDS fluxes, the UG1 catchment had much higher values than the EC catchment. Similarly, the denudation rate was also higher in the UG1 than in the EC. Overall, glacial catchment was mainly dominated by physical denudation process, whereas the non-glacial catchment was jointly influenced by physical and chemical denudation processes.

The source of runoff and the glacial processes were responsible for the observed differences of suspended sediment and TDS delivery patterns between the glacial catchment and the non-glacial catchment. The melting periods of glacier and snow were typically the most important time for the suspended sediment yield and TDS yield. Meanwhile, substantial precipitation events generated

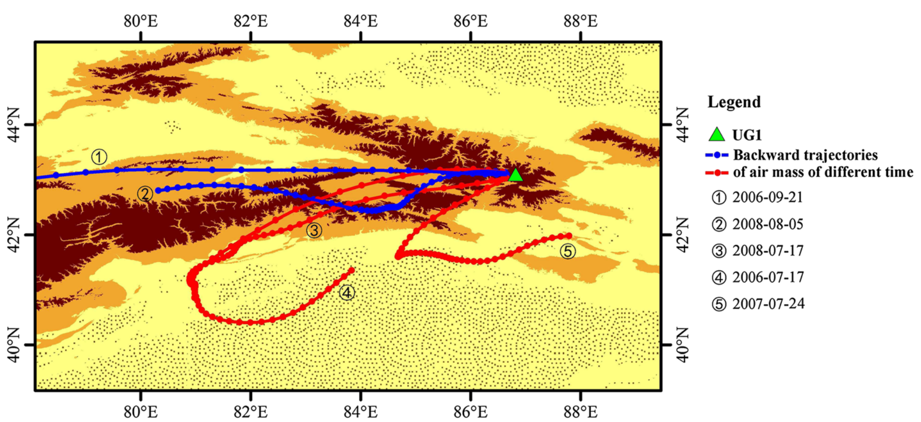

Figure 9. Backward trajectories of air mass of different time to the Urumqi Glacier No. 1 (UG1) catchment. (Blue line represents the backward trajectories of air mass that has not passed the desert, whereas red means air mass has passed the desert.)

disproportionately large yields, and this influence was also controlled by the sediment supply. Subglacial hydrology dynamics (i.e. variation in water discharge and the resultant surficial debris mobilization and changes in water or ice pressure that enhances the erosion of bedrock), and glacier pluck and grind processes could affect erosion rate for the glacial catchment. Furthermore, the large quantities of stored dust in the glacial catchment might generate additional sources of suspended sediment transport by melted water. The existence of these mechanisms implies that climate change will significant modify the catchment behaviour in terms of material flux in this region.

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