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Analysis of Glacial Meltwater in Bagrot Valley, Karakoram

Based on Short-term Ablation and Debris Cover Observations on Hinarche Glacier

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People in the Karakoram use discharge from glaciers during summer for irrigation and other purposes. While the glacial meltwater supply during hot and dry periods will vary as a result of climate change, Karakoram glaciers so far

have not shown a consistent reaction to climatic change, although climate scenarios indicate severe future impacts in the high-elevation regions of the Himalaya and Karakoram. Field measurements on Hinarche Glacier in Bagrot Valley are combined with remote sensing information and climate observations to investigate the meltwater production of the glacier and estimate the meltwater discharge in the valley.

Special emphasis was placed on ice melt beneath supraglacial debris, which is the common process on the glacier tongues in the region. The calculated annual meltwater production of about 135 million m³ for Hinarche Glacier shows the order of magnitude for glacier runoff in such environments. Glacial meltwater production is about 300 million m³ per year for the entire valley under balanced conditions. This analysis serves as a basis for further investigations concerning temporal meltwater variability and potential water usage by the local population.

Keywords: Climate change; debris-covered glacier; glacierized mountain areas; water resources; Karakoram; monitoring strategies; ice and snow melt; Pakistan.

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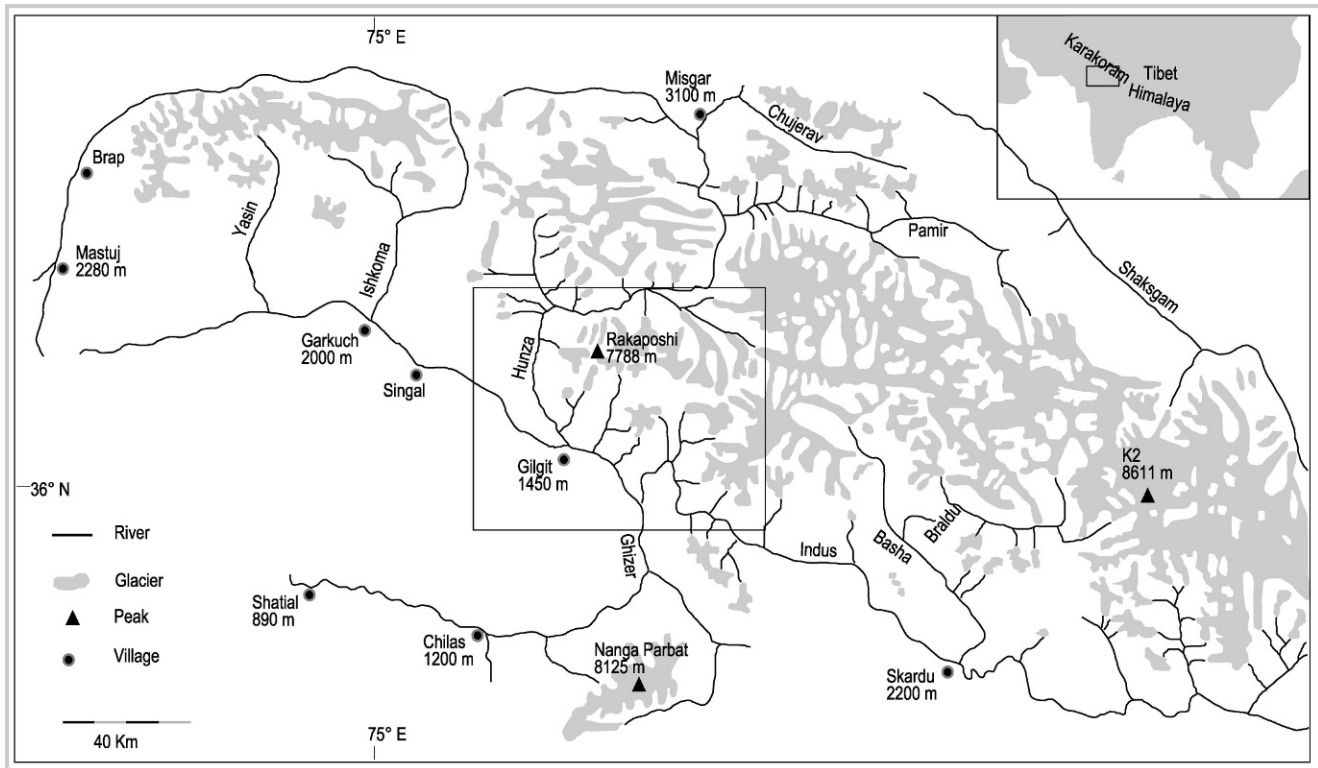
Introduction

The Karakoram stores a huge amount of water in its extensive glacier cover at higher altitudes (about 16,600 km²; Dyurgerov and Meier 2005); the lower reaches are very dry, and people rely on irrigation for agricultural production (Weiers 1995). Especially in the center and north of the Karakoram, the lower elevations receive only occasional rainfall during summer (Winiger et al 2005). With a growing population and intensifying agriculture, a secure water supply becomes more important, and the contribution from snow and ice melt is a crucial issue. Regarding ice, the issue is complicated because the usability of glacial meltwater (eg for irrigation or power generation) depends on certain conditions (eg the stability of discharge and sediment load). The state of the glaciers also plays an important role in future planning: shrinking glaciers initially provide more meltwater, but later their significance is reduced; on the other hand, growing glaciers store

precipitation, reduce summer runoff, and can also generate local hazards.

The meltwater contributions from glaciers are closely related to medium-term mass balance, which is not easily summarized for the Karakoram. Larger glaciers are expanding in several areas of the central Karakoram, accompanied by numerous glacier surges (Hewitt 1998; Campbell 2004; Hewitt 2005; Smiraglia et al 2007). However, other observations indicate that in the Karakoram and adjacent mountain ranges, most glaciers are still losing mass (Ding et al 2006; Haritashya et al 2009). These differences could be caused by increases in precipitation since the 1960s (Archer and Fowler 2004) and a simultaneous trend toward higher winter temperatures and lower summer temperatures (Fowler and Archer 2006). Such a combination, associated with the role of the elevation and elevation range of the glaciers across the Karakoram, may have caused the expansion of large, flat glaciers and probably reduced meltwater production.

FIGURE 1 Map of Northern Pakistan showing Bagrot Valley (see box). (Map modified from Iturrizaga 2008)



Many studies have focused on large glaciers in the Karakoram (eg Batura Glacier Investigation Group [BGIG] 1979; Kick 1964; Mayer et al 2006), whereas smaller glacierized drainage basins have usually not been included in glaciological studies. To initiate a glacier monitoring program and to contribute to an inventory of ice resources in the Central Karakoram National Park, the glaciers of Bagrot Valley were mapped on the basis of remote sensing imagery. In addition, specific melt conditions were studied on the tongue of Hinarche Glacier, a partly debris-covered, medium-sized glacier in the valley.

Bagrot Valley (which is also easily accessible) has already been studied in other projects concerned with the meteorological variability of high Karakoram basins (Winiger et al 2005) and the relationships between climate conditions and effects on human land use at high elevations (Ehlers and Kreutzmann 2000).

Bagrot Valley and Hinarche Glacier

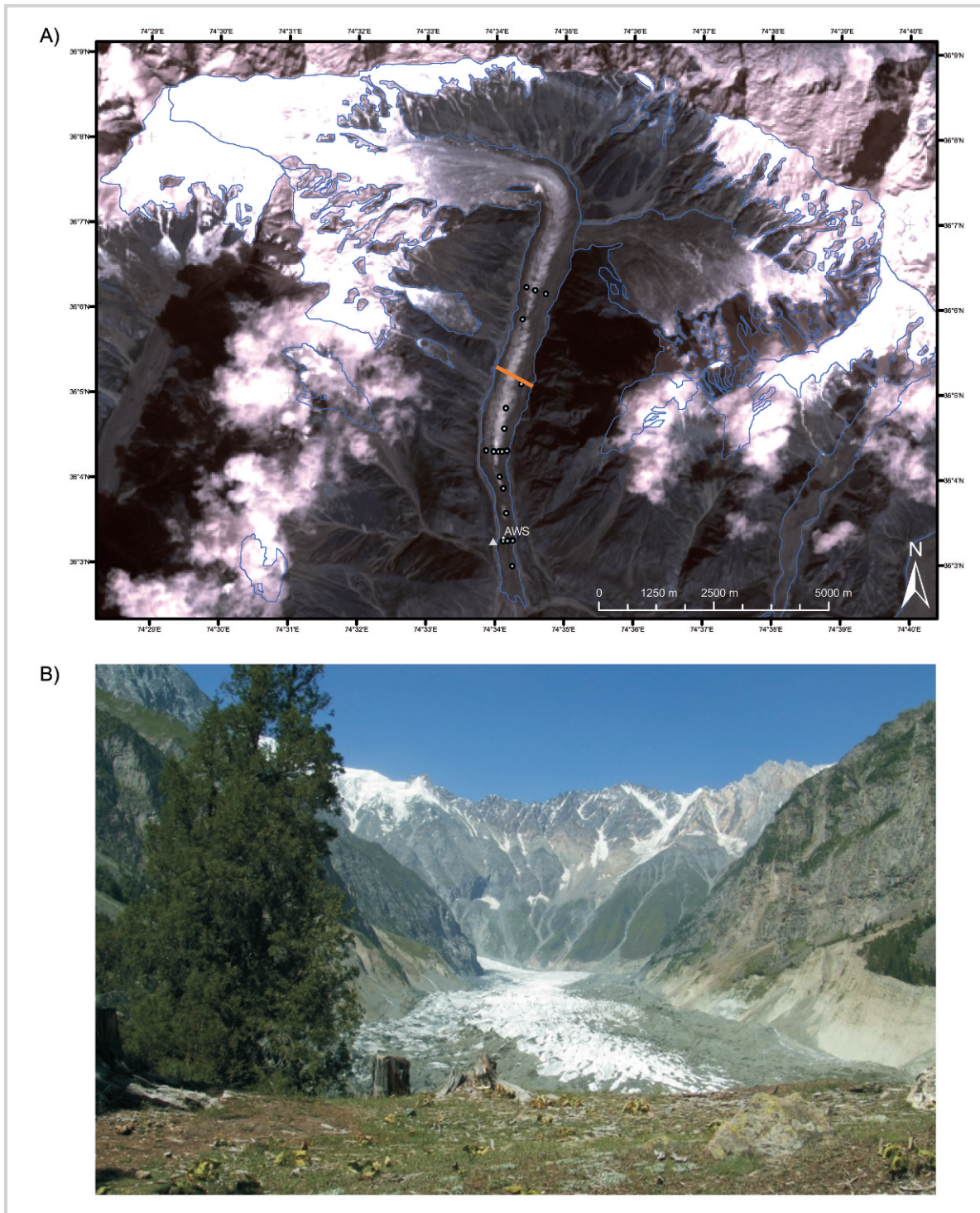
Bagrot Valley (central coordinates 74°43'E, 36°5'N, length: 32 km) covers an area of about 452 km² (Figure 1). It is characterized by extreme relief, from 1500 m up to 7788 m at the summit of Rakaposhi. Local agriculture relies on irrigation for growing crops. Livestock is grazed

on the higher reaches, while downstream of the main villages the valley is only sparsely vegetated due to low precipitation (Ehlers and Kreutzmann 2000). During the summer, meltwater first from snow and later from glaciers is the main source for irrigation and plays a dominant role in the cultivation of land (Reineke 2001).

Precipitation varies greatly with altitude, with dry conditions at low elevations (Gilgit, 1454 m, 135 mm/y; Sinakker in Bagrot valley, 2210 m, 142 mm/y) and more humid conditions at higher elevations (station Diran, 4120 m, 720 mm/y). Investigations on Batura Glacier (Shi and Wang 1980) and Biafo Glacier (Wake 1989) show that precipitation above the regional snow line (about 5000 m) may exceed 2000 mm/y. A detailed study performed in Bagrot Valley by Winiger et al (2005) shows that monsoonal influence is negligible and that at 5000 m, more than 90% of the annual precipitation is deposited as snow. This is in contrast with Wake (1989), who reported high-altitude snowfalls occurring in summer due to the high-altitude penetration of monsoonal air masses into the region.

In Bagrot Valley, the main valley glaciers are Hinarche, Burche, Gutumi, and Yune, while several smaller cirque glaciers exist in the higher reaches. Hinarche Glacier (Figure 2A and 2B) is divided into 2 distinct zones: the rather flat lower tongue (from 2500 m to 3350 m over a

FIGURE 2 (A) Hinarche glacier in the upper Bagrot valley. Glacier boundaries are based on Landsat 7 from 2000. The circles represent ablation stakes, the triangle shows the GPS base, the star the AWS location, and the orange line the cross profile for mass flux calculations. (B) The upper part of the Hinarche Glacier tongue with the crevassed zone in the center. Seasonal settlements reach up to the pastures in the background of the glacier. (Photo by A. Lambrecht, 2008)



distance of 9 km) and the steep icefall stretching from 7788 m down to 3350 m within only 8.5 km. The glacier area is about 42.3 km² and the major part of the lower tongue is covered by supraglacial debris, similar to the other glacier tongues in the valley. Here and throughout the Karakoram, avalanche nourishment and the extent of rock walls in the accumulation zone are critical factors in the amount of supraglacial debris on the lower glacier area. The debris on the glacier reflects the local geology, dominated by basalt and andesite (Pettersen and Treloar 2004). In the greater Rakaposhi/Diran group, Hinarche Glacier can be considered representative of the valley glaciers, with a strong vertical gradient in the accumulation zone, an extensive debris cover on its tongue, and a medium-sized area.

Field activities

Hinarche Glacier was chosen for detailed glaciological investigations from 26 July until 5 August 2008 (see Figure 2A for locations). Information gained from the measurements on the glacier tongue can also be used to characterize the other valley glaciers in the basin. Special attention was given to ice ablation under different conditions. The measured ablation rates were correlated with meteorological data acquired by an automatic weather station (AWS) located on the glacier tongue at 2757 m. The temperatures at the surface and at 2 different depths in the debris layer were also recorded at this site and are used to evaluate the heat flux through the debris layer.

Ablation was measured at 20 bamboo stakes drilled into the ice across the main tongue of the glacier, taking into account both different elevations and different debris thicknesses. The stakes were arranged in 1 longitudinal (mainly N-S) and 3 transversal (W-S) profiles from 2731 m to 3198 m (Figure 2A). Despite the small elevation range covered by the ablation stakes compared with the total elevation extent, this area shows the greatest differences in ice ablation due to the great variability of the surface characteristics. The higher elevations of the ablation zone (from 3200 m up to about 5000 m) are free of supraglacial debris, and ablation can be approximated using our ablation measurements of clean ice, an appropriate lapse rate for temperature, and a simple degree-day model. The debris temperature gradient was measured at several ablation stakes, providing necessary information for ablation modeling.

For steady state conditions, ablation in the lower part is compensated by ice transport from the accumulation zone. This flux is determined by ice velocities and the glacier geometry. To gain insight into the dynamic mass budget of the glacier, the summer surface velocities at the stakes and the surface

topography on a transect (stakes 15, 16, and 17) were measured by differential Global Positioning System (GPS).

Results

As noted, in some parts of the Karakoram (eg Hewitt 2005; Copland et al 2009) there is evidence of glacier expansion or relative stability in the past decade. However, as in much of the rest of the upper Indus Basin, the Bagrot Valley glaciers show stagnant conditions and terminus lowering, based on the analysis of Landsat imagery from 2000 to 2009 (courtesy of the U.S. Geological Survey [USGS]). The supraglacial debris concentration even increased on most glaciers. On the northern flank of Rakaposhi, the glaciers provide even stronger meltdown indications, including shorter glacier tongues.

In general, responses to climate change in Bagrot Valley glaciers are quite complex within the region, as well as in comparison with other areas, such as the Tibetan Plateau (Shi et al 2006).

Although the glaciers in Bagrot Valley are oriented in different directions, large areas of the glacier tongues are rather flat. Thus the influence of the orientation on ice ablation is not too strong and the results from the Hinarche Glacier tongue can be used as a reference to estimate ablation rates on the other glacier tongues as well. The field data are also used for analyzing glacier ablation on the basis of a longer meteorological time series. Mapping of debris extent, concentration, thickness, and composition is required to improve the modeled ablation.

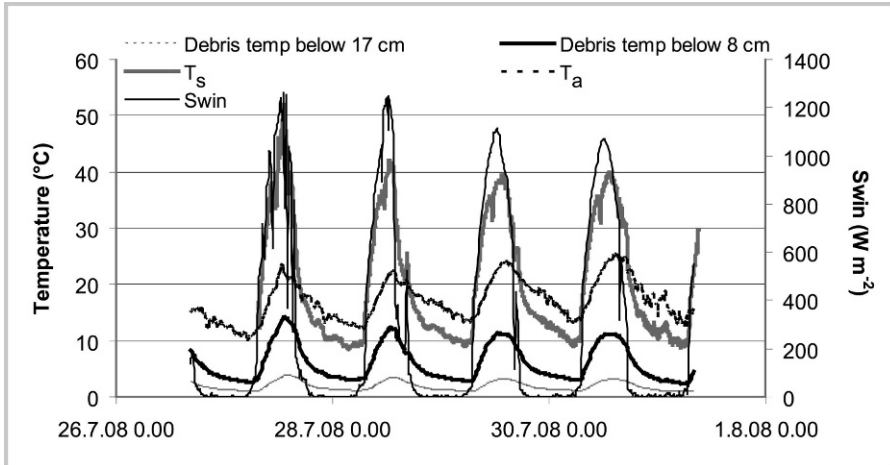
Glacier micrometeorology

Field measurements were performed during stable weather conditions with several almost cloud-free days. Air temperatures at the AWS (2 m above the debris surface) were rather high, typically ranging between +14°C and +24°C, and even during the night the air temperature never dropped below +9.9°C.

The daily average air temperature data from the Gilgit meteo station (30 km distance and 1300 m elevation difference) correlated closely with our AWS measurements ($p: 0.9$). It is therefore justifiable to use Gilgit temperatures to calculate the daily mean air temperature across the glacier. The mean lapse rate from simultaneous measurements was found to be 6.3°C/km. In contrast, precipitation data from the Gilgit record cannot be used because of the more local character of precipitation events and the very strong vertical precipitation gradient on the higher slopes (Weiers 1985).

The mean albedo over the debris cover was determined to be 0.13, thus 87% of the incoming shortwave radiation is absorbed by the debris surface and partly transferred to the debris-ice interface, where it generates ice melt.

FIGURE 3 Incoming shortwave radiation (Swin), air temperature (T_a), surface temperature (T_s), and debris temperatures at different depths.



Supraglacial debris properties and ice ablation

The radiative heating of the supraglacial debris is the main energy source for buried ice melt, and the debris surface temperature is closely correlated to the incoming shortwave radiation (Figure 3). The maximum debris surface temperatures are almost twice the air temperature at 2 m.

The temperature gradients measured in the debris cover were used to calculate subdebris melt rates based on the thermal resistance of the debris cover. Usually a linear vertical temperature profile is a good approximation (with 0°C at the melting ice surface) for calculating daily melt rates.

The stakes cover the major variations in debris thickness (0–40 cm) on the glacier. This enables computations of melt rates for most of the debris-covered glacier tongue and allows extrapolation for the entire range of debris thickness. The maximum ablation was 10.8 cm/d with 1 cm debris cover, while the lowest ablation of 2.3 cm/d was found at 37.5 cm debris cover (Figure 4). It is surprising that even for 37.5 cm of debris cover, the melt rate is substantial. This could be due to the abundance of meltwater on the lower glacier tongue, which is much more effective than nonsaturated debris in transporting heat toward the ice. A large area above the second cross profile is heavily crevassed with a discontinuous thin debris cover. The highest ablation rates were measured in this area, while the ablation rates decreased toward the terminus due to increasing debris cover.

Based on the ablation data and the intradebris temperatures, the thermal resistance was calculated for different debris depths at 14 sites along the longitudinal profile (Table 1). The results show a linear correlation with debris thickness ($p: 0.983$), which allows for a rather simple parameterization of ablation rates with debris cover.

Glacier surface velocity

Ice flux is important for evaluating glacier conditions over a longer time period because ice melt is compensated by ice flux under steady state conditions. Ice melt can, however, outbalance ice flux during periods of increasing temperatures. Estimating the contribution of basal sliding to ice transport requires determining the velocities during the peak season of glacier melt. The short-term velocities measured at the stake positions vary between about 14 cm/d (50 m/y) at the lowermost stake and about 52 cm/d (190 m/y) in the center of the network (Figure 5A), showing a pronounced deceleration toward the glacier tongue. In the upper part of the network, the velocities are rather constant (33–36 cm/d or 120–130 m/y). There is almost no transversal velocity gradient, indicating strong basal sliding, at least during summer. For further analysis of velocity conditions, it is

FIGURE 4 Ablation rate (cm/d) versus debris thickness (cm) at the 20 stakes.

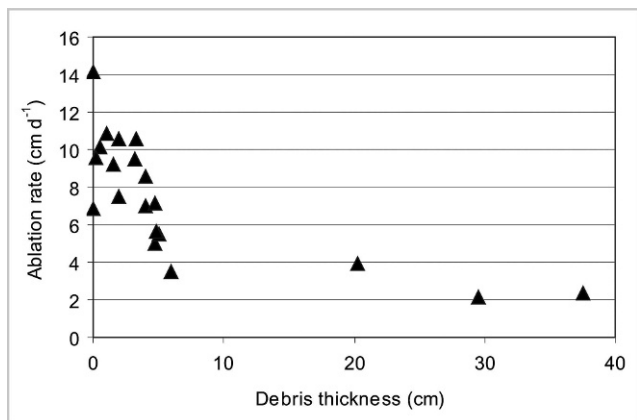


TABLE 1 Total ablation, debris thickness, and thermal resistance at different sites on Hinarche Glacier; Ts: surface temperature.

ID stake	Ts average (°C)	Total ablation (m)	Thermal resistance ($10^{-2} \text{ } ^\circ\text{C m}^2 \text{ W}^{-1}$)	Debris thickness (m)	Elevation (m)
1	20.44	0.39	14.78	0.20	2757
2	15.49	0.69	5.10	0.04	2797
3	14.75	0.40	8.32	0.05	2834
4	12.91	0.76	3.83	0.03	2863
6	9.77	0.85	2.61	0.02	2915
7	11.35	0.74	3.03	0.03	2953
8	9.73	0.71	2.71	0.01	2993
9	1.31	0.67	0.39	0.002 (dust)	3029
10	10.69	0.56	3.26	0.02	3121
11	9.51	0.65	2.48	0.01	3169
13	4.69	0.21	3.78	0.04	3166
14	12.25	0.28	6.28	0.05	2930
15	12.11	0.35	4.88	0.04	2911
19	16.68	0.13	21.71	0.30	2770
20	27.92	0.14	33.76	0.38	2704

also necessary to determine mean annual surface velocities.

Analysis of water production on the Hinarche Glacier tongue

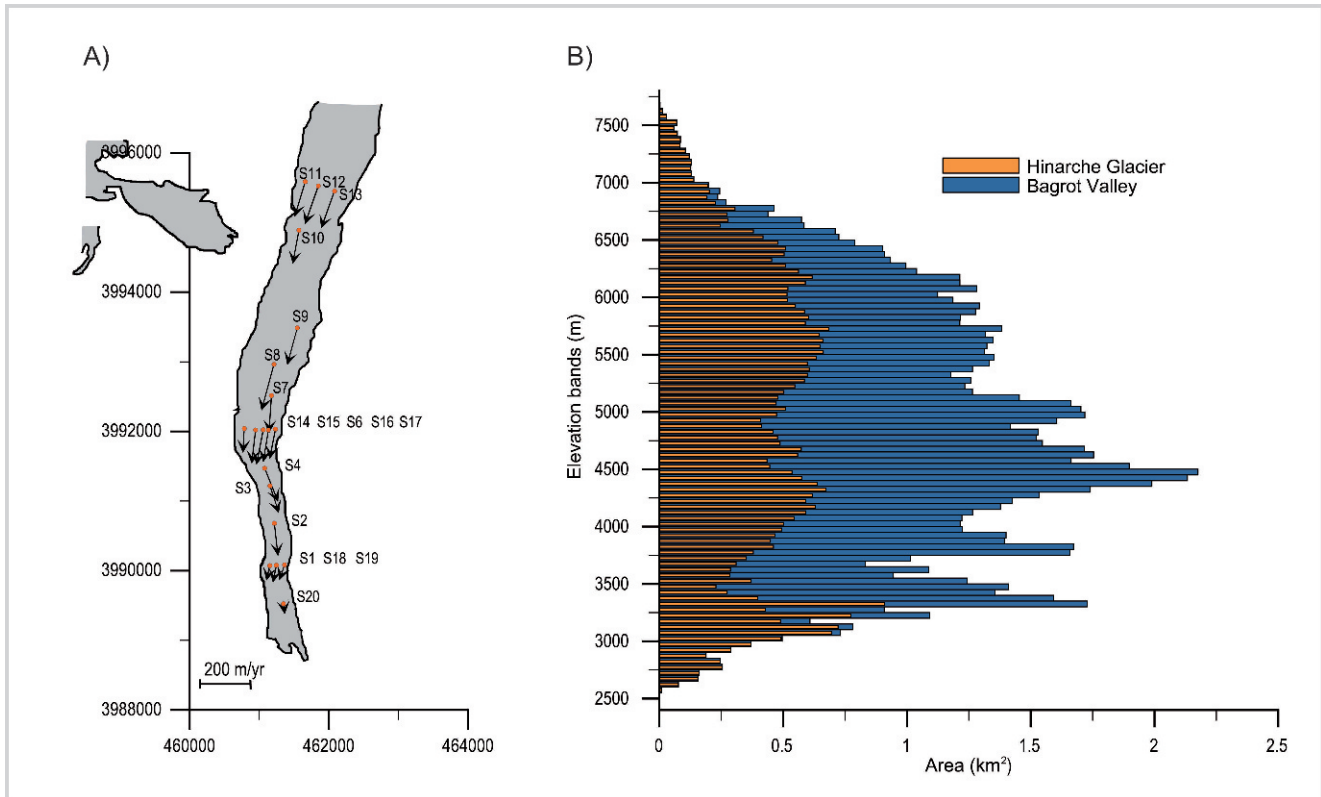
Reliable glacier mapping is necessary for most glacier investigations. In difficult areas such as Bagrot Valley, remote sensing is the most appropriate approach. The Landsat Enhanced Thematic Mapper (ETM) image from 11 November 2000 (orthorectified on the Advanced Spaceborne Thermal Emission and Reflection Radiometer [ASTER] Global Digital Elevation Model [GDEM], a product of the National Aeronautics and Space Administration [NASA], United States of America [USA], and Japan's Ministry of Economy, Trade and Industry [METI]) was chosen to delineate glacier boundaries and supraglacial debris cover because of almost cloud-free conditions and minimum snow cover. Compared with images from 2009, the glacier extent in the valley has not changed since 2000. Hinarche Glacier (42.3 km^2) is covered by supraglacial debris over an area of 6.6 km^2 , or 15.6%. The total glacier area in Bagrot Valley is 99.94 km^2 , and the debris cover accounts for a total of 24.1 km^2 (24%). This higher relative debris cover is mainly due to the extensive debris layer on Burche Glacier (29.8%).

A rough estimate of the mean ice thickness, based on ice dynamic considerations (Mayer et al 2006) and the measured summer velocity, is about 430 m at the center of a chosen cross-section on the glacier tongue (see Figure 2A). Compared to an analysis at Baltoro Glacier (Mayer et al 2006), the mean annual ice velocity should be about 85 m/y at the center line, and the resulting annual ice transport is $17.4 \times 10^6 \text{ m}^3$ through that cross-section. This corresponds to a mean melt rate of about 6.3 m/y over the 2.8 km^2 of the downstream glacier tongue. Compared with the observed short-term melt rates during the peak ablation season, this is a realistic value.

The mean ablation from stake measurements is 7.3 cm/d, while the positive degree-day sum (DDS), also averaged over the tongue area, is 174.4°C . Using a simple degree-day approach, a mean degree-day factor (DDF) of $4.08 \text{ mm}/^\circ\text{C}$ for this area can be inferred. With the observed lapse rate between Gilgit and Hinarche, positive DDSs for the Hinarche Glacier tongue were calculated from Gilgit temperature data. For the last 30 years, the mean annual DDS has been 2819°C , with only minor interannual variations.

The air temperature record also shows that snowfall usually occurs only in the months from November until March at this altitude. The climatic conditions in upper Bagrot Valley (Cramer 2000) will result in a snow cover on

FIGURE 5 (A) Glacier surface velocities measured at the 20 stakes from 2704 m to 3169 m above sea level. The coordinates are given in Universal Transverse Mercator projection (WGS84, zone 34). (B) Area–elevation distribution for the glaciers in Bagrot Valley (blue) and Hinarche Glacier (orange) derived from Landsat 7 imagery and the ASTER GDEM.



the order of 200 mm water equivalent. Considering the melt of this snow cover before ice melt can start, the mean melt rates for glacier ice on the glacier tongue upstream of the flux profile will be about 11.1 m/y. This is higher than the values derived for the lower glacier tongue, with a decidedly thicker and more extensive debris cover. The resulting ice melt of the Hinarche Glacier tongue upstream of the profile (area: 4.3 km²) results in 47.7×10^6 m³ of ice, and the melt volume for the entire tongue up to the beginning of the icefall at an elevation of 3200 m is about 60×10^6 m³ of meltwater (ice density: 910 kg/m³) during a climatically average year. This relates to a continuous discharge of roughly 3.2 m³/s during the ablation season (April until November).

This discharge might seem small compared to the mean discharge of rivers, but it only relates to the glacier tongue below the icefall. The total ablation area of Hinarche Glacier is roughly 12.3 km², where the upper 5.2 km² are almost without debris. This part is included in the analysis, using the measured lapse rate and the determined DDF for bare ice. Together with the elevation–area distribution and appropriate assumptions about snow precipitation (Weiers 1995), we find a mean

ice melt of 83×10^6 m³, or 75.5×10^6 m³ of water. The entire glacier therefore provides about 135×10^6 m³ meltwater, or a continuous discharge of 7.3 m³/s for recent climate conditions. Taking into account all of the simplifications and assumptions, the estimated total error is about 25%.

Glacial meltwater in Bagrot Valley: further perspectives

The comparison of the elevation–area distribution of all glaciers in Bagrot Valley (Figure 5B) shows that Hinarche Glacier is a suitable representative of the distribution of glacier ice in the valley. In a first approximation, the meltwater production for the entire valley results in about 300 million m³/y, which still is a rather rough estimate, especially because the different supraglacial debris distribution of Burche Glacier needs to be mapped in greater detail. Also, the orientation of the individual glaciers will influence the final amount to a certain degree, and the effect of evaporation/sublimation (especially in the higher-elevation bands) has not been

taken into account so far. In relation to the duration of the ablation season, the ice melt provides a continuous water discharge of about $16 \text{ m}^3/\text{s}$.

According to our analysis, the glaciers in Bagrot Valley still show some meltdown. The effect of lower summer temperatures (Fowler and Archer 2006) derived from the climate data of the Gilgit weather station (1978–2008) is rather small if converted to DDSs at the altitudes of the glacier ablation zones. Therefore, we can conclude that the mass balance conditions of the glaciers in Bagrot Valley have been close to equilibrium during the last 3 decades and that the accompanied mean glacial discharge should be rather stable for constant precipitation conditions.

High-mountain areas are frequently labeled “water towers” for the lowlands. The proper management of these water resources requires rather precise knowledge of their characteristics. Here we provide the magnitude of the ice melt contribution to runoff from a high-altitude watershed. Such comparably small watersheds are much more frequent than the limited number of drainage basins dominated by 1 of the large Karakoram glaciers. Usually, these large glaciers are better investigated (eg BGIG 1979; Kick 1964; Mihalcea et al 2006) than the small glaciers, while their role for local communities is usually limited to discharge-related hazards.

Even if the local water supply is often based on high-elevation snow fields and cirque glaciers, the total water discharge in the smaller basins is of great importance for a number of reasons: if the observed trend of slightly

cooler summer temperatures continues, meltwater from high elevations will be reduced and the low-lying glacier tongues could compensate for the missing amount. In the case of a general warming trend, the discharge will increase and potential hazards will play a more important role. At the same time, the runoff characteristics from high-elevation snow fields and small cirque glaciers also will change, and the valley glaciers could again play a compensating role.

Finally, the growing population and higher living standards are demanding more water and more energy production. It is difficult to use glacial meltwater for such purposes, due to the high sediment load and the strong discharge variability. However, modern technology can deal with these difficulties, and studies of runoff characteristics provide an important basis for planning and managing the water resources. This has also been acknowledged by the Government of Pakistan, which is planning to increase the number of hydroelectric power stations in the northern Karakoram areas (Alternative Energy Development Board, Government of Pakistan 2009).

Our study shows that glacial discharge can be estimated to a large degree even with a limited number of observations. These results can also be used for future discharge predictions on the basis of climate scenarios. But there is still room for improvement. In particular, the mapping of supraglacial debris cover needs to be extended, and basin precipitation should be determined as accurately as possible.

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