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FIELD BASED EVALUATION OF IMPACT OF SUPRA-GLACIAL DEBRIS THICKNESS ON THE MELTING OF GLACIERS IN KARAKORAM

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Abstract

Large numbers of glaciers in the Karakoram region are covered with debris (boulders, rocks & sand) in the ablation zone, which are accessible in the lower elevations but are rarely observed in the field. The supra-glacial debris transported over the melting glacier surface acts as an insulating barrier between the ice and atmospheric conditions and has a strong influence on the spatial distribution of surface ice melt. We conducted in-situ measurements of point-wise ablation rate, supra-glacial debris thickness and its influence on ablation over two glaciers (Hispar and Yashkuk Yaz) in Hunza Basin of Karakoram during the ablation period (July - October 2021) and (May – September 2018). Hunza River basin with drainage area of 13,713 km^2 located in the high-altitude central Karakoram region, Pakistan. Total numbers of glaciers in Hunza basin are approximately 1,384 covering an area of 2,754 km^2 and about 15% of glacier area rages from 2,409 – 5,297 m.a.s.l. are covered by debris with varying thicknesses. The stake wise debris thickness measured at Hispar glacier ranges from 5cm to 20cm, while 5cm to 80cm was measured at Yashkuk Yaz glacier. Surface velocities for both glaciers have been calculated by using a distance-weighted average method. Our results demonstrate the importance of accounting for debris on glacier and measurements taken at the surface of glaciers shows strong relationship between the thickness of debris and the rate of ice melting which plays an important role in surface energy balance and the rate of glacier ablation. Emaciated debris cover enhances the melting of glacier ice while substantial layer of debris reduces the melt rate exponentially. This type of analysis is useful for the empirical parameterization of numerical models and understanding the relationships between surface debris and glacier melting for accurately predicting how debris-covered glaciers in Karakoram region will react to climate change, and whether changes in the patterns of ice melting will threaten communities living downstream (e.g. GLOFs & flooding).

Keywords: Supra-glacial, Ablation rate, Debris thickness, Empirical parameterization, In-situ measurements

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Introduction

Understanding of the hydrological regime of Karakoram glaciers to climate change is critical, since their meltwater contributes to freshwater resources in this highly populated region of South Asia (Kaser et al., 2010; Lutz et al., 2014). However, due to logistical constraints and political instability, field observations of glaciological and meteorological conditions in the Karakoram are not as much of in space and time, in particular at high altitudes (Mihalcea et al., 2006, 2008a; Mayer et al., 2014).

Like many glaciers around the world the glaciers of Karakoram Range in Pakistan have a deposit of debris (boulders, rocks, and sand) covering the underlying ice over much of the glacier surface; however global glacier models do not account for debris because the debris thickness is anonymous. The depth of supraglacial debris will manage how glaciers react to climate change, since a emaciated layer (less than a few centimeters) will increase melting, while a deep layer will protect the underlying ice and suppress melting (Østrem, 1959). While this effect is well known at the point scale, recent studies in High Mountain Asia found similar elevation change rates for debris-covered and clean-ice glaciers (Gardelle et al., 2013; Kääb et al., 2012), a phenomenon referred to as the "debris-cover anomaly" (Pellicciotti et al., 2015). A regional study (Kraaijenbrink et al., 2017) concluded that on High Mountain Asia glaciers debris delays projected mass loss. On the other hand, the effects of debris on regional and global projections of glacier mass change are largely unknown due to a lack of correct debris thickness estimates. Given debris covers ~4%–7% of the global glacier area (excluding the ice sheets), and up to 23% regionally (Herreid & Pellicciotti, 2020; Scherler et al., 2018), exact debris thickness estimates are immediately desired to enumerate the impact of debris on glacier mass balance from local to global scales.

Although the significance of debris thickness for glacier evolution, in-situ measurements of debris thickness and sub-debris melt rates are quite scarce and primarily inadequate to glaciers in High Mountain Asia. Even in-situ measurements from well-studied debris-covered glaciers are typically spatially and/or temporally limited. However, these measurements have been used to build up empirical relationships to estimate debris thickness (Kraaijenbrink et al., 2017; Mihalcea et al., 2008), or to validate debris thickness estimates from physically-based surface temperature inversion (Foster et al., 2012; Rounce & McKinney, 2014) or sub-debris melt inversion (Rounce et al., 2018) methods. At present, the sub-debris melt inversion method is the only physically-based method that can accurately estimate debris thicknesses greater than 0.5 m. However, the method is currently limited to elevation bins and requires accurate estimates of the climatic mass balance, which must be derived from limited in-situ measurements or remotely-sensed elevation change data.

The thickening or lateral expansion of supra-glacial debris cover correlates with a reduction of glacier ablation and, consequently, runoff generation, which is also considered to be an influential factor on the rheology and dynamics of a glacierized system. Studies on supra-glacial debris cover have recently attracted wide attention especially for glaciers in the Himalayas and Karakoram, where the glaciers have heterogeneously responded to climate change.

The increase in ice or snow avalanche activity at high altitudes may be responsible for the rising development of supra-glacial debris cover in the Hunza Valley, which is attributed to the combined effect of temperature decrease and precipitation increase in the study area.

Study Area

Hunza Basin

The Hunza Valley is an area measuring ~11,000 km^2, located in the western Karakoram, northern Pakistan (36°00'15" ~ 37°05'23" N, 74°02'57" ~ 75°46'48" E). The topography across the Hunza Valley is characterized by large altitudinal variations, from 1,341 to 7,831 m.a.s.l. The valley is home to glaciers with a total area of ~3,600 km^2 (1,878 glaciers, with ~12% of them being larger than 0.5 km^2) that accounts for ~33% of the basin area based on the Randolph Glacier Inventory (RGI) 6.0 dataset (RGI Consortium, 2017). Most of the glaciers (e.g., Hispar, Yashkuk Yaz, Batura, and Barpu) are debris-covered and in a state of surging and advancing (Bhambri et al., 2017). Debris-covered glaciers are potential factors driving glacial lake outburst floods (Bhambri et al., 2020), which represent a major threat to local people, their property, and infrastructure such as the Karakoram Highway in the Hunza Valley. Climatologically, the study area is arid to semi-arid, situated in the subtropical climate zone and experiences significant variations in precipitation and temperature (Immerzeel et al., 2012). The present study specifically focuses the two major glaciers in this basin that are Hispar and Yashkuk Yaz.

a) Hispar Glacier

Hispar Glacier is located in the central Karakoram and drains into the Hunza catchment. Its main trunk is a nearly 50 km long (area about 500 km^2) linear stream of ice, flowing towards WNW from Hispar pass at 5150 m a.s.l. down to 3100 m. It is the dominant glacier in the near-linear main valley but other large surge-type glaciers (Trivor, Bualtar) drain further to the west into the main valley. A high mountain range (up to 7000 m) is protecting the ESE-WNW orientated valley in the south and the Hispar Muztagh (up to 7800 m) in the north. At Hispar pass, Hispar Glacier is connected to the third longest glacier in the world, the 65 km long Biafo Glacier, flowing to the East. Hispar glacier has a comparably tiny accumulation area that is not much wider than the tongue in the ablation region and is composed of three small basins. However, from the south about a dozen small tributaries nourish the tongue and from the north, three large tributary glaciers feed the main glacier trunk (Kunyang, Yutmaru and Khani Basa) (Figure.1). The tributaries collectively contribute about a half of the total width of the main tongue and the looped/distorted medial moraines on the main glacier indicate former surge or fast flow events. The three northern main tributaries of Hispar Glacier are complex glacier systems with multiple tributaries nourishing their respective main tributaries, i.e., their shape has a sort of fractal self-similarity. Due to the high relief of their surrounding ice-free rock walls, the ablation areas of the three tributaries are also debris-covered (with decreasing amounts from Kunyang in the west to Khani Bassa in the east). The lower part of the main tongue of Hispar Glacier is completely debris covered and characterized by numerous supra-glacial melt ponds as well as circular collapse structures, indicating the widespread down-wasting of the tongue.

Catchment Area & Altitudinal Zones

The Shuttle Radar Topographic Mission (SRTM) digital Elevation Model (DEM) data was used to delineate the catchment boundary and altitudinal zones of the glacier and its catchment (Figure 2). Hypsometric curve show the area–altitude distributions of the Hispar Glacier at the different elevations (Figure 3). The total area of Hispar Glacier is 495.87 km^2. The elevation bands were divided into an equal interval of 500 m (Table-1). The snout of the glacier falls between an elevations ranges from 3,117 to 3,500 m.s.a.l. About 68.8% of the glacier falls within a range of 4,000-5,500 m.a.s.l making it the major part of the glacier.

Table-1: Characteristics of Different Elevation Bands of Hispar Glacier.

Elevation Zones	Elevation	Mean	Area Km^2	%Age
1	3117-3500	3308	8.54	1.7
2	3501-4000	3750	40.82	8.2
3	4001-4500	4250	100.12	20.2
4	4501-5000	4750	138.54	27.9
5	5001-5500	5250	101.54	20.5
6	5501-6000	5750	49.15	9.9
7	6001-6500	6251	30.76	6.2
8	6501-7000	6750	18.58	3.7
9	7001-7500	7251	6.38	1.3
10	7501-8000	7750	1.43	0.3
Total			495.87	100%

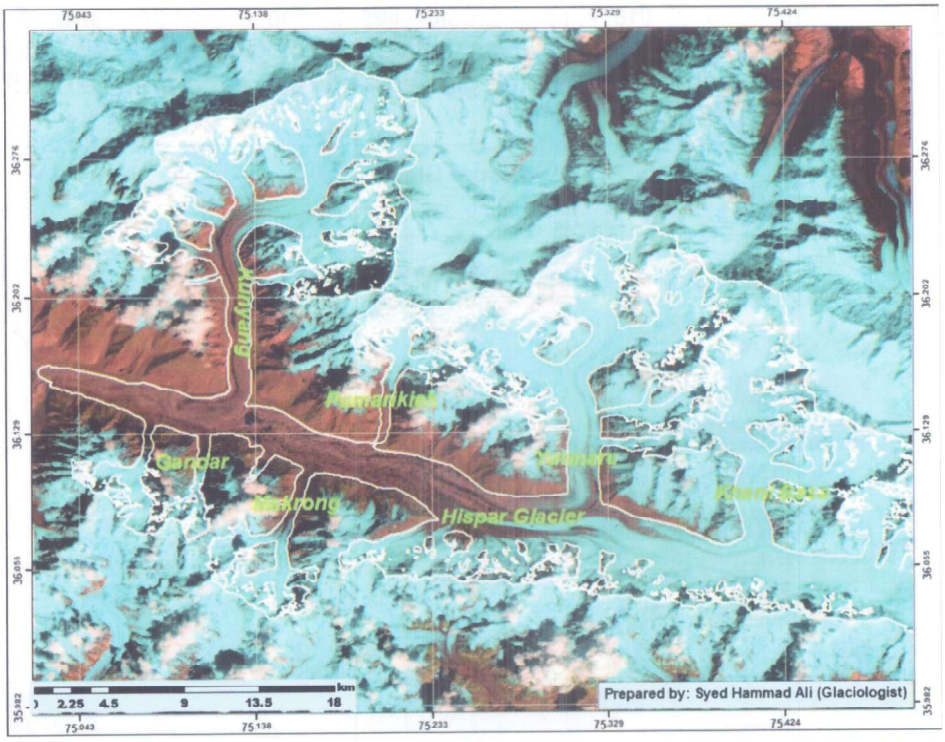


Figure-1: Location of Hispar Glacier and Glacier Boundaries.

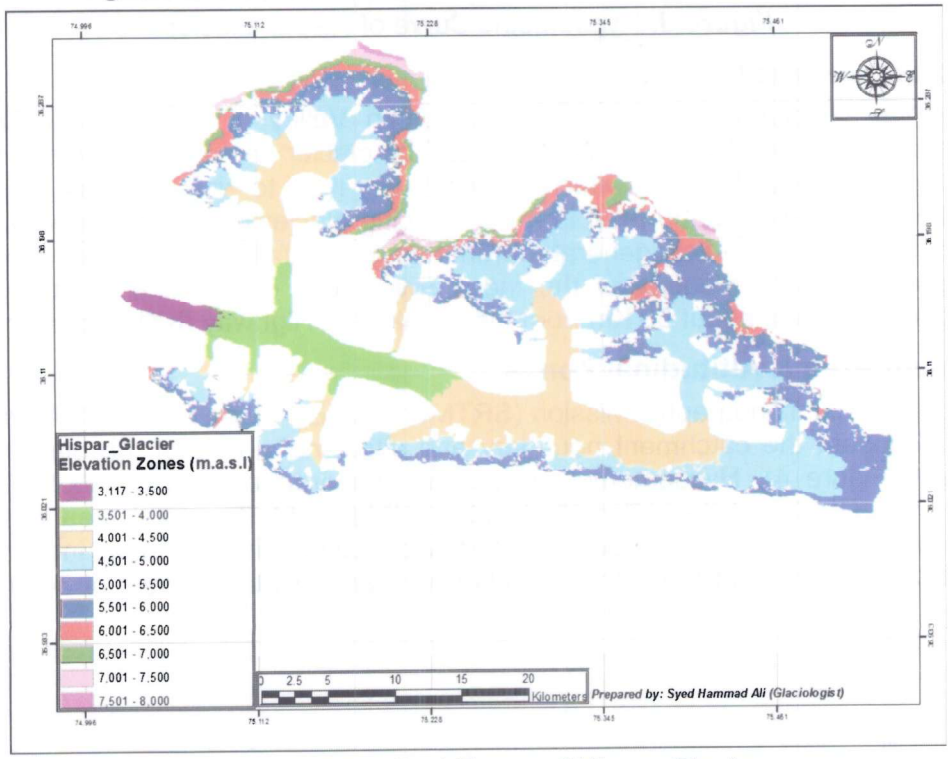


Figure-2: Altitudinal Zones of Hispar Glacier.

About 78.5% of the area of the Hispar glacier lies in the elevation zone of 3,000 to 5,500m.a.s.l. This region is considered as active hydrologic zone. This zone mainly contributes to the flows generated from the glacier. The rest of the area i.e. 21.5% lies at higher elevation of 5,501-8,000.

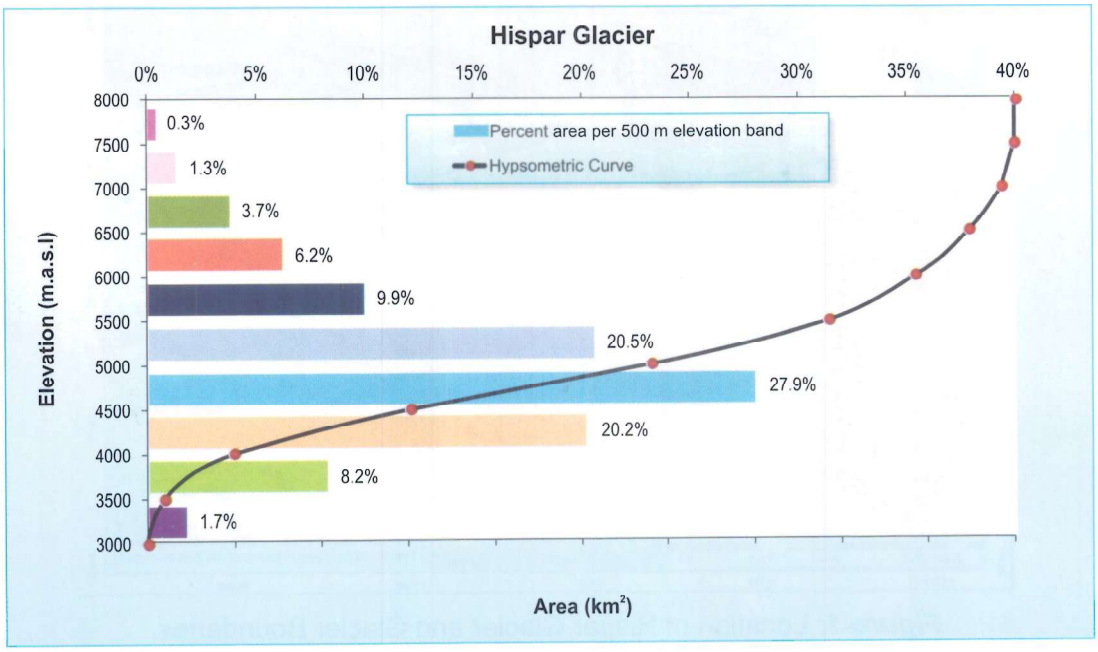


Figure-3: Hypsometric Curve of Hispar Glacier

b) Yashkuk Yaz Glacier

Yashkuk Yaz Glacier is located in the Chipursan Valley of Hunza River Basin. Its coordinates are 36° 45'13" N and 74°18' 8" E. The glacier has a very thick debris cover comprising of massive boulders which makes it very hard to walk or cross. The glacier has total width of about 2000 m. It is a north facing glacier having a number of glacial lakes on its surface. The flow generated from this glacier falls in the Hunza River which is a major right bank tributary of the Indus River. The glacier can be accessed by covering a distance of about 55 Km from the Karakoram Highway (KKH) near Sost.

Catchment Area & Altitudinal Zones

The Shuttle Radar Topographic Mission (SRTM) digital Elevation Model (DEM) data was used to delineate the catchment boundary and altitudinal zones of the glacier and its catchment (Figure 4). Hypsometric curve show the area–altitude distributions of the Yashkuk Yaz Glacier at the different elevations (Figure 5). The total area of Yashkuk Yaz Glacier is 76.02 km^2. The elevation bands were divided into an equal interval of 347 m (Table 2). The snout of the glacier falls between an elevation ranges of 3450 to 3754 m.s.a.l.

Table-2: Characteristics of Different Elevation Bands of Yashkuk Yaz Glacier

Elevation Zones	Elevation	Mean	Area of Each Zone	%Age
1	3443-3790	3616.5	5.92	7.79
2	3790-4137	3963.5	11.13	14.64
3	4137-4484	4485	7.45	9.80
4	4484-4831	5005.5	7.45	9.80
5	4831-5178	5351.5	12.35	16.24
6	5178-5525	5698.5	7.42	9.77
7	5525-5872	6045.5	9.70	12.76
8	5872-6219	6392.5	8.76	11.52
9	6219-6566	6739.5	4.33	5.69
10	6566-6913	6913	1.52	1.99
Total			76.02	100.00

About 16.24% of the glacier falls within a range of 4831-5178 m.a.s.l making it the major part of the glacier. About 68% of the area of the Yashkuk glacier lies in the elevation zone of 3443 to 5525m.a.s.l. This region is considered as active hydrologic zone. This zone mainly contributes to the flows generated from the glacier. The rest of the area i.e. 32% lies at higher elevation of 5526-6913. The melting is very minimal and very less melting occurs in the higher melting period (June-September).

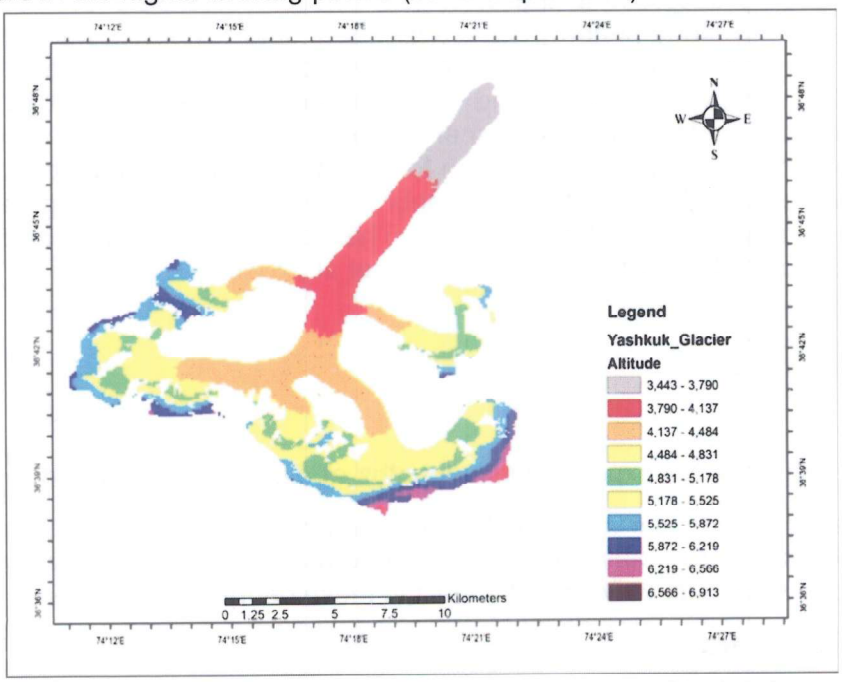


Figure-4: Altitudinal Zones of Yashkuk Yaz Glacier

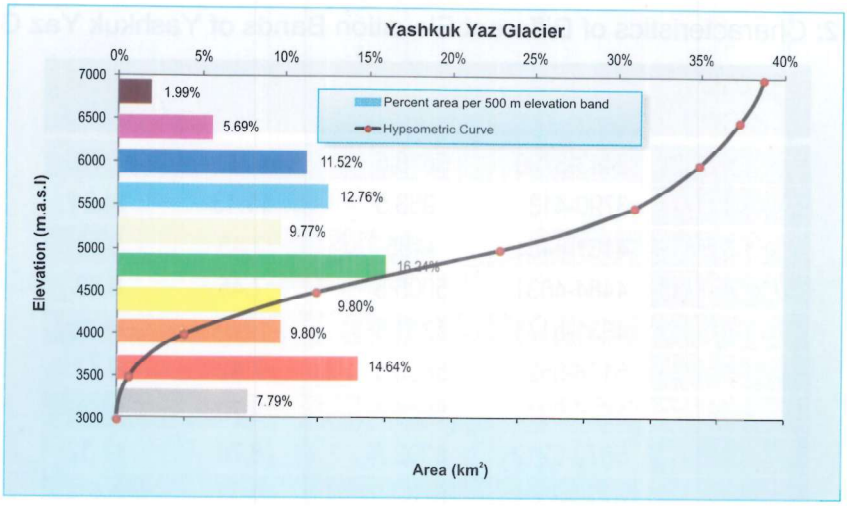


Figure-5: Hypsometric Curve of Yashkuk Yaz Glacier

Methodology

In-Situ Measurements of Debris Thickness

Supraglacial debris is extensive, and covers an estimated 18–22 % of the glacierized area of Karakoram region. Surface debris exerts a strong control on glacier surface-energy and mass fluxes and has the likely to change atmosphere glacier feedbacks. Massive debris-covered glaciers in the Karakoram are reachable in the lower elevations but are infrequently observed in the field. The ablation rates were estimated by stake observations for the study period (measurements at time t° and t^1). By using the direct glaciological method the ablation rate for a specific point was estimated (Cuffey and Paterson, 2010). Network of nine and six bamboo stakes were established using a Heucke steam drill system over the Hispar and Yashkuk Yaz glacier surface on debris-covered ice from 5 cm to 20 cm and 5 cm to 80 cm respectively to understand the melt characteristics of the glaciers at various debris cover. The stakes heights and debris thicknesses were measured after installation. The glacier melt rate was estimated using following equation 1 (Patel et al., 2016; Sharma et al., 2016).

$$\frac{\Delta h}{\Delta t} = \frac{(h^{12} - h^{t^o})}{(t^1 - t^o)} \qquad (1)$$

Where h^{t° and h^{t1} are the exposed stake lengths at different periods and $\frac{\Delta h}{\Delta t}$ represents the melt rate for a particular location. The obtained melt rates were multiplied by an ice density of 900 kg/m^3 to obtain meters water equivalent (m.w.e.). Snow cover was not accounted for owing to its very limited impact in these debris covered areas.

Velocity of Glaciers

Glacier flows under its own weight, fleeting ice across the equilibrium line to sustain an equilibrium slope. How the glacier does this is well presented in the schematic view in Figure-6.

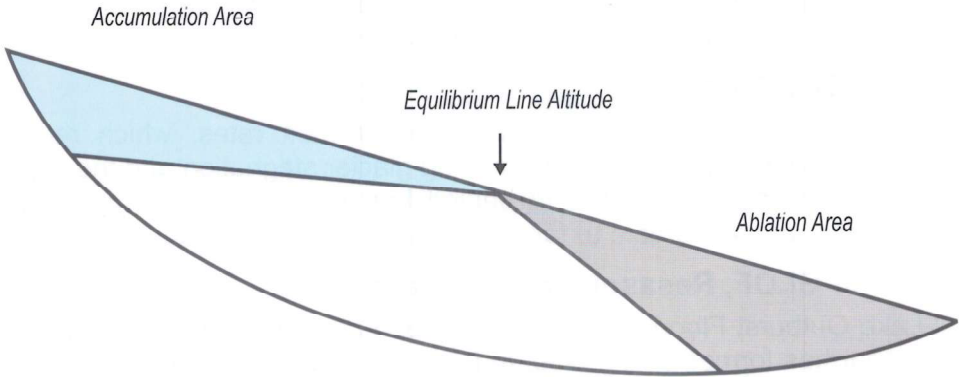


Figure-6: Schematic View of Glacier Accumulation and Ablation

Glacier doesn't move fast enough to be noticeable directly to the eye, although in some cases speeds are up to several tens of meters per day, so you could almost see it moving. Surface velocities on a valley glacier can be measured easily by putting a straight row of stakes across the glacier, surveying their positions relative to fixed points, and then coming back at a later time to resurvey the positions to see how far the glacier has moved down valley.

Ablation processes are all processes that remove snow or ice from a glacier. The most important ablation processes are listed below in order of their relative importance:

- **Melt and runoff**

  Melt and runoff account for most glacier mass loss and are driven by the net energy imbalance between the atmosphere and the glacier surface. The most important contributors are the net radiation and the turbulent fluxes of sensible and latent heat. Once the temperature of the glacier surface is at the melting point, i.e. the glacier surface was sufficiently heated, melts rates increase in proportion to the net energy flux.

- **Sublimation**

  Sublimation refers to the phase change from solid state to gaseous state, e.g. the direct transition of snow and ice to water vapor. It is the dominant source of mass loss in environments where surface temperatures hardly reach the melting point. Sublimation increases with increasing surface temperature and wind speed and with decreasing humidity, hence, it is strongest in dry and warm environments. Melt and sublimation can counteract each other: as sublimation consumes energy and transforms it to latent heat, the energy available for melt decreases.

- **Calving**

  Calving is the separation of ice blocks from a glacier's margin. Most calving occurs at margins of glaciers that stand or float in water. Calving of glaciers terminating in the ocean, so called *tidewater* glaciers, accounts for much of the mass loss, e.g. for more than 90% of the ablation from Antarctica and about half

of the ablation from Greenland. The process is also significant for mountain glaciers that terminate in deep lakes or the ocean.

Ablation and GLOF Risk

The varied debris cover frequently causes higher melt rates, which reducees the glacier's topographic gradient thereby promoting glacier stagnation and the expansion of glacial lakes. These glacial lakes form behind terminal moraines comprising soil and loose boulders that are vulnerable to fail causing a glacial lake outburst flood (GLOF).

Phenomena of GLOF, Resasons and Prevention

A Glacial Lake Outburst Flood, or GLOF, is sudden release of water from a lake fed by glacier melt that has formed at the side, in front, within, beneath, or on the surface of a glacier. GLOF can be impounded by moraine complexes, glacial ice or even bedrock and, as a result of breaching, slope failure, overtopping or other failure mechanisms, lead to catastrophic phenomena in the high mountains that threaten people's lives, livelihoods and regional infrastructure. Fragmentation of the source glacier, landslides and other processes can trigger displacement waves in the lake, potentially compromising the stability of the dam and resulting in a GLOF. Failure of the dam can also occur due to internal processes, such as water seeping through the structure.

There are several possible methods for mitigating the impact of Glacial Lake Outburst Flood (GLOF) surges, for monitoring, and for early warning systems. The most important mitigation measure for reducing GLOF risk is to reduce the volume of water in the lake in order to reduce the peak surge discharge.

Possible peak surge discharge from a GLOF could be reduced by reducing the volume of water in the lake. In general any one or combination of the following methods may be applied for reducing the volume of water in the lake:

- Controlled breaching,
- Construction of an outlet control structure,
- Pumping or siphoning out the water from the lake, and
- Making a tunnel through the moraine barrier or under an ice dam.

Downstream in the GLOF prone area, measures should be taken to protect infrastructure against the destructive forces of the GLOF surge. There should be monitoring systems prior to, during, and after construction of infrastructures and settlements in the downstream area.

Careful evaluation by detailed studies of the lake, mother glaciers, damming materials, and the surrounding conditions are essential in choosing an appropriate method and in starting any mitigation measure. Any measure taken must be such that it should not create or increase the risk of a GLOF during and after the mitigation measures are in place. Physical monitoring systems of the dam, lake, mother glacier, and surroundings are necessary at different stages during and after the mitigation process.

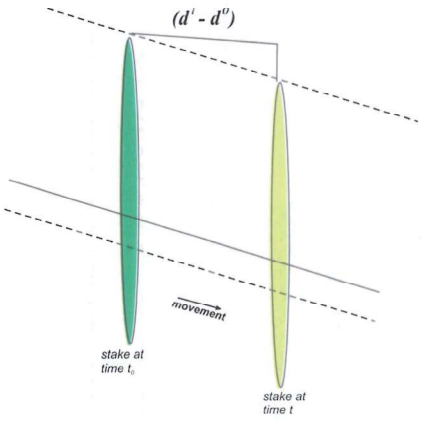


Figure-7: Sketch for analysis of the surface velocity of a glacier

We insert vertical stakes in the surface of the glacier at representative positions in the ablation area (Sketch for analysis of glacier movement figure 7), wait a time Δt, while the stake moves some distance $d^1 - d^0$ down glacier. Glacier velocity was calculated by using the following equation 2.

$$V_e = \frac{(d^1 - d^0)}{\Delta t} \qquad (2)$$

The layout and movement of the stakes between July to November 2021 and May to October 2018 installed at different location on Hispar and Yashkuk Yaz glaciers respectively are shown in figure 8 and 9.

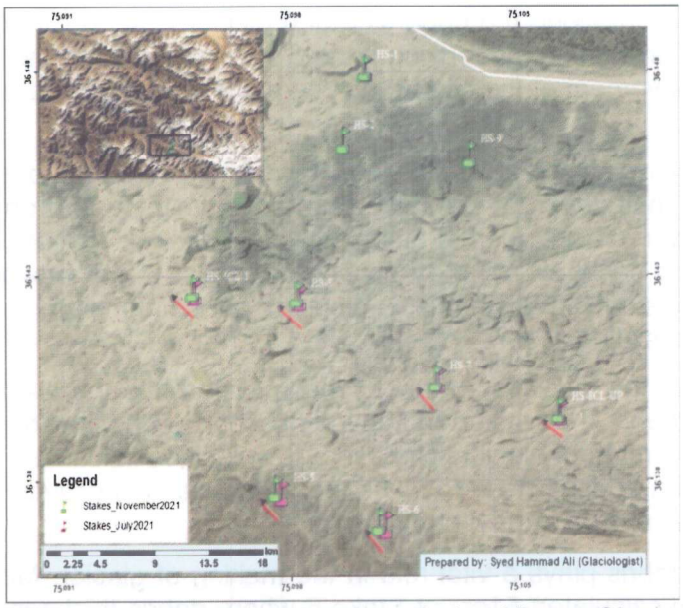


Figure-8: Layout of stakes installed at Hispar Glacier

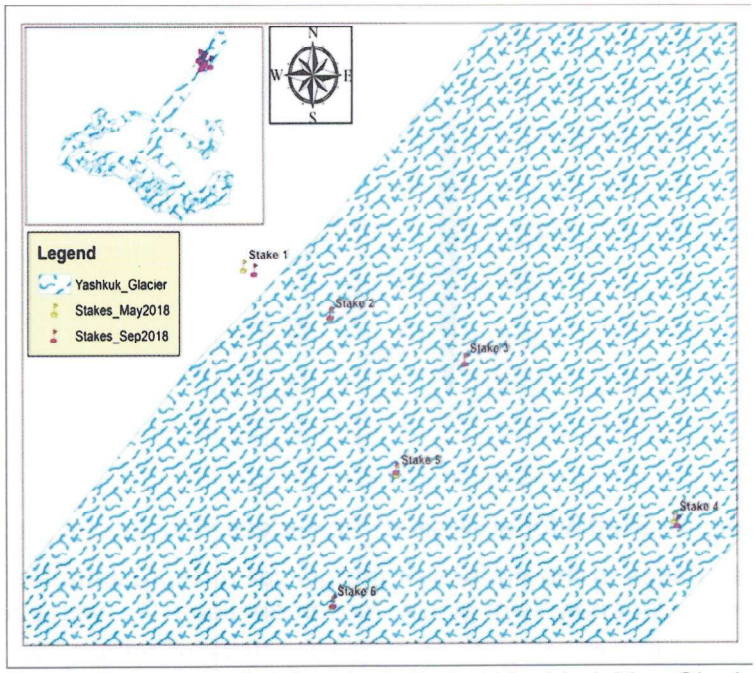


Figure-9: Layout of stakes installed at Yashkuk Yaz Glacier

Observations & Conclusions

As it is clear from the layout of stakes (Figures 8 & 9), all the stakes on the Hispar and Yashkuk Yaz glaciers are moving. The sheer weight of a thick layer of ice, or the force of gravity on the ice mass, causes glaciers to flow very slowly. Ice is a soft material, in comparison to rock, and is much more easily deformed by this relentless pressure of its own weight. Movement along the underside of a glacier is slower than movement at the top due to the friction with the underlying ground's surface. Where the base of the glacier is very cold, the movement at the bottom can be a tiny fraction of the speed of flow at the surface.

Sometimes a glacier slides over a thin water layer at the glacier's base. The water may result from glacial melt driven by pressure of the overlying ice, or from water working its way through glacier cracks to the base. Glaciers can also slide on a soft, watery sediment bed. This basal sliding may account for most of the movement of thin, cold glaciers on steep slopes. Warm, thick glaciers on gentle slopes owe less of their movement to basal sliding.

Rock that falls onto the glacier's surface is incorporated into the glacier and erodes the bed, forming sediment. The glacier and its load of rock debris flow down-valley is also a reason for the movement of glacier. The average velocities calculated were 0.095 m/day and 0.08 m/day on Hispar and Yashkuk Yaz glaciers respectively while stake wise velocities ranges from 0.03 m/day to 0.22 m/day.

The thickness of debris plays a vital role in the melting of glacier. Minimum ablation on Hispar glacier was calculated 51cm at Stake 6 where debris thickness was 20 cm while the maximum ablation 375cm was calculated at stake 1 where debris thickness was only

5cm. On the other hand minimum ablation on Yashkuk Yaz glacier was calculated 75cm at Stake 1 where debris thickness was 80 cm while the maximum ablation 427cm was calculated at stake 6 where debris thickness was only 5cm. From the figures 10 and 11 it is clear that the ablation rate is inversely proportional to the thickness of debris cover. The more debris cover the less is the ablation and vice versa.



Figure-10: Impact of Debris Thickness on ablation at Hispar Glacier



Figure-11: Impact of Debris Thickness on ablation at Yashkuk Yaz Glacier

Such kind of field based data would serve as valuable addition to for batter understanding the melting process affected by debris cover thickness. This type of analysis is constructive for the empirical parameterization of numerical models and understanding the relationships between surface debris and glacier melting for accurately predicting how debris-covered glaciers in Karakoram region will react to climate change. Beside to recognize the role of debris cover on glacier melt inconsistency, it is valuable to examine glacier melting with debris cover for the whole ablation area, including consideration of a very fine debris layer, the role of cliffs, and supra-glacier ponds over the debris cover. In addition to that subsurface temperature and thermal resistance variability are important to understand the underlying processes and debris behavior.

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