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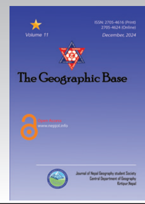

Comparative Inventory of Rock Glaciers and Permafrost Lower Limits in Api Nampa, Manaslu and Kanchenjunga Region

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Abstract

Rock glaciers are cryogenic landforms consisting of surface rock debris that conceals either an ice-core or an ice-cemented debris mixture. A study of rock glacier dynamics is useful to understand the effect of global warming. This study provides inventories of rock glaciers, along with their status, and delineates the Lower Limit of Permafrost in three areas in Eastern, Central, and Western Nepal. Those are the Api Nampa Conservation Area (ANCA), Manaslu Conservation Area (MCA) and Kanchenjunga Conservation Area (KCA). Freely accessible Google Earth Pro's images were used to map the rock glaciers. A total of 340 Rock Glaciers (RGs) with a total area of 76.21 km2 were identified between elevations of 3821 to 5667 meters above sea level (masl). The highest rock glacier concentration was identified between 4800 – 5200 masl. Mean elevations of RGs are 4703.93 masl, 4903.79 masl, and 4928.14 masl in ANCA, MCA, and KCA, respectively. There is a downward trend in the elevation of the rock glacier while moving from the Eastern Nepal Himalaya to the Western Nepal Himalaya. Comparing all three conservation areas, it has been seen that intact RGs are predominantly found above 4800 masl *and relict RGs below it. Northern slopes have more RGs in ANCA, while southern slopes have much of it in MCA and KCA. RGs in the South-facing slope area are found at much higher altitudes, with most being debris and intact. In contrast, the majority of RGs from northern aspects are intact and the talus. Using RGs as a proxy for permafrost, it is estimated that the Lower Limit of Permafrost (LLP) of ANCA, MCA, and KCA were 4630 masl, 4324 masl, and 4417 masl, respectively. The mean elevation of RGs is high in MCA and KCA, but LLP is lower than ANCA. This difference may be attributed to the presence of sporadic permafrost or isolated patches.*

Introduction

A rock glacier is a lobate or tongue-shaped landform consisting of rock debris and either an ice core or an ice-cemented matrix (Giardino, 2011). Active rock glaciers are viscous flow features embodying ice-rich permafrost and other ice masses (Hu et al., 2023). Rock glaciers act as water reservoirs, storing water in both solid and liquid forms, such as permafrost ice and groundwater within the unfrozen base layer, respectively (Wagner et al., 2021). Rock glaciers are climatically more resilient than glaciers and contain potentially hydrologically valuable ice volumes (Jones, 2019). Studying the changing dynamics in rock glaciers on seasonal to decadal timescales, which are linked to ground temperature variations, helps to understand the degradation due to climate warming (Muller et al., 2016; Rai et al., 2020). RG's ice content is a subject that is likely to gain importance in the future due to the anticipated decrease in water supply from glaciers and the increase of mass movements originating in periglacial areas, thus making it important to have at one's disposal inventories with complete information on the state of rock glaciers (Kofler et al., 2020). However, the detailed knowledge about RG's distribution, characteristics and dynamics in the Himalayan region is scarce (Abdullah & Romshoo, 2024). RGs are also important indicators of discontinuous permafrost, which allows them to be used in the reconstruction of the development of mountain permafrost (Urdea, 1998). RG's activity represents a critical indicator of water reserves state, permafrost distribution, and landslide disaster susceptibility, but their dynamics are poorly quantified, especially in the central Himalayas (Zhang, 2021).

Permafrost refers to soil or rock whose temperature has been maintained at or below 0°C for at least two consecutive years (Guo & Wang, 2017). Due to the steepness of the southern flank of the Greater Himalaya and potential large-scale rock failures, permafrost evidence manifests itself best in inner valleys and on the northern, arid side of the Himalayas, elevation >4000m (Fort, 2015). A decreasing trend of the permafrost limit can be witnessed from eastern, 5239 masl, to the western part of Nepal, 4513 masl (Chauhan & Thakuri, 2017).

Around 25,000 RG exist in the Himalaya region with a total estimated area coverage of 3747 km^2 (Harrison et al., 2024). In the Nepal Himalayan region, RGs are found between 3225-5675 masl, with minimum elevation at the front estimated to be 4977 ± 280 masl for intact landforms and 4541 ± 346 masl for relict landforms; intact RGs are the cryospheric reserves that hold between 16.72 and 255.08 billion m^3 of water (Jones et. al., 2018). Across the entire Himalayas, intact RGs are mostly found above 4800 masl (65%) while relict RGs are concentrated below 4800 masl (67%) (Harrison et al., 2024).

To understand the spatial distribution of RGs in the Nepal Himalaya and to investigate the results of Harrison et al. (2024), this paper studies and inventories RGs from ANCA, MCA and KCA. These specific CAs were selected because ANCA lies in the far western region, representing the Western Himalayan region; MCA is in the center of the Nepal Himalaya; and KCA is in the easternmost part of Nepal, representing the Eastern Nepal Himalayan region. This paper aim to understand the changing dynamics of RGs in the Nepal Himalayas concerning elevation and aspect. This study also sets the LLP in three CAs to understand the area of permafrost in different regions of the Nepal Himalaya.

Methods and Materials

Study area

Three Conservation Areas (CAs) were taken as the study area (Figure 1). Api Nampa Conservation Area lies between 29º 30' to 30º 15' north latitude and 80º 22' to 81º 09' East longitude. It is located in the Darchula district of Sudurpaschim province and covers a 1903 km^2 area.

Manaslu conservation area lies in Gorkha district of Gandaki province and geographical coordinates between 28º 20' to 28º 41' north latitude and 84º 29' to 85º 11' east longitude covering an area of 1663 km^2. Kanchejunga conservation area lies between 27º 26' to 27º 57' north latitude and 87 39' to 88º 11' east longitude, which falls in Taplejung district of Koshi province and has an area of 2035 km^2.

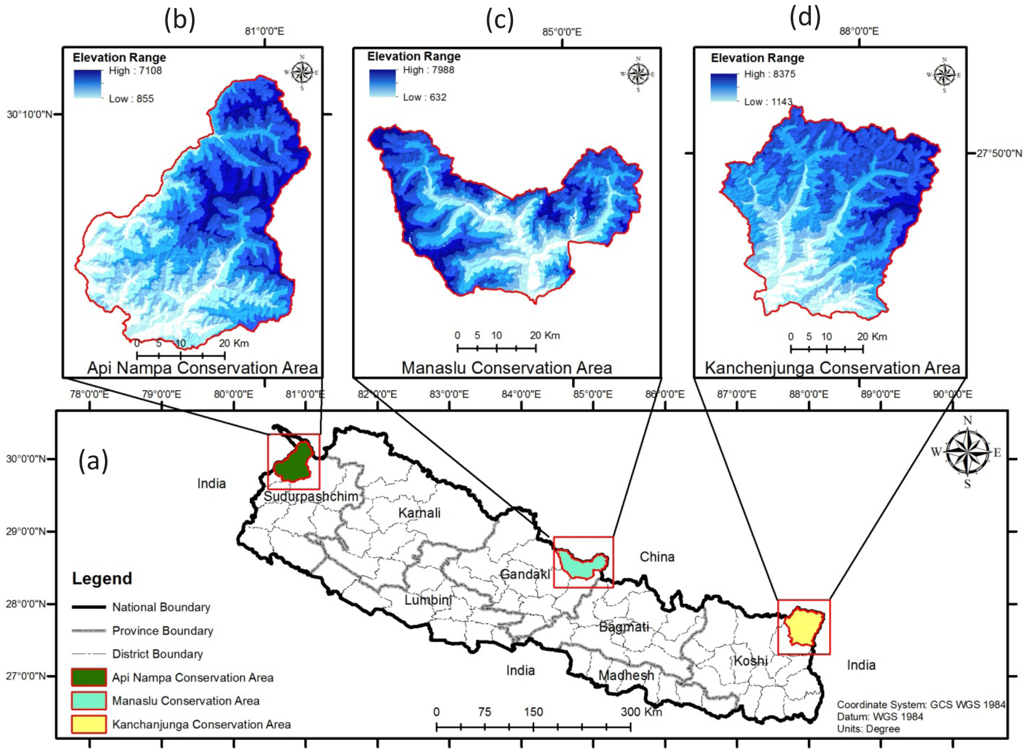

Figure 1. Study Area (a) Location of CAs in Nepal's map (b) ANCA (c) MCA (d) KCA

Research method

RGs were identified and inventoried in Google Earth Pro. To map the RGs in the study area, shapefiles of all three CAs were downloaded from the National Trust for Nature Conservation (NTNC) http://geoportal.ntnc.org.np/. Four major steps were taken for mapping the RGs: (1) Identification of rock glaciers, (2) recognition of status, (3) manual mapping & (4) regional aggregation.

Identification of rock glaciers

The movement of RG generates flow patterns within its body - transverse, longitudinal or a combination of both- that serve as distinguishing features separating RG from the surrounding landscape. Along with the flow pattern, the front body makes it more perceivable and can be visually identified in Google Earth Pro. RGs' front was categorized as either steep or gentle. Steep fronts are those rock glaciers whose front slope is at a steep angle relative to the horizontal plane and are indicated by the presence of loose material along the front slope, which has a lighter colour than the material on the rock glacier surface (Stumm et al., 2015). Flow pattern and front are indicated (Figure 2).

Recognition of status

RGs statuses were categorized on two different bases: (i) upslope boundary, (ii) activity.

Based on the upslope boundary

RGs either originate from the glacier or the rock debris in the periglacial area. RGs whose head is directly connected to the glaciers are called talus rock glaciers, and those which have originated from the surrounding debris are mapped as debris rock glaciers.

Based on activity

Activities of RGs are vital to identify the lower limit of permafrost (LLP). The activity in RGs is due to the ice-rich interior. Those RGs that have the presence of ice in their body are intact rock glaciers, while they are characterized as relict rock glaciers if the ice from the interior has melted. Relict RG contains little to no ice (Barsch, 1992; Joes et al., 2018). To spot intact and relict RGs in Google Earth Pro, the indicators listed in Table 1 were used.

Table 1. Indicators used to identify RG's Activity

Geomorphic Indicator	Intact Rock Glacier	Relict Rock Glacier
Surface flow structure	Well-defined furrow and ridge topography (Kaab and Weber, 2004)	Less defined furrow and ridge topography (Kaab & Weber, 2004)
Rock Glacier body	Swollen body (Baroni et al., 2004). Surface ice exposures (Potter et al., 1998)	Flattened body (Baroni et al., 2004). Surface collapse features (Janke and Bolch, 2021)
Frontal Slope	Steep (30-35º; Baroni et al., 2004). Abrupt transition to surrounding slopes and to the upper surfaces; light coloured with little surface weathering compared to surrounding stable slopes (Wahrhaftig and Cox, 1959; Janke and Bolch, 2021).	Gentle frontal slopes (<30º) and gentle transition to surrounding slopes and upper surface (Janke and Bolch, 2021).

Source: Harrison et al., 2024

Manual mapping

RGs were mapped following the standard guidelines issued by IPA Action Group Rock Glacier Inventories and Kinematics in 2022 (RGIK, 2022) in Google Earth Pro. The accuracy of Google Earth is sufficient for this project's purpose, as the inaccuracy arising from horizontal misalignment between imagery and DEM is likely to be smaller than 100 meters (Schmid et al., 2015). To avoid the variation of standards in rock glacier mapping, all the inventories were created by a single researcher.

Regional aggregation

NASA Shuttle Radar Topography Mission (SRTM) Global 1 arc second V003's ~ 30m resolution images were downloaded from earthdata.nasa.gov to analyze and generate Digital Elevation Model (DEM) map in ArcMap 10.3. Map was used to study and develop elevation profile of RGs. They were further retraced in Google Earth Pro to eliminate any possible inaccuracy. The head of RG was taken as maximum elevation, and tip of the front was taken as minimum elevation.

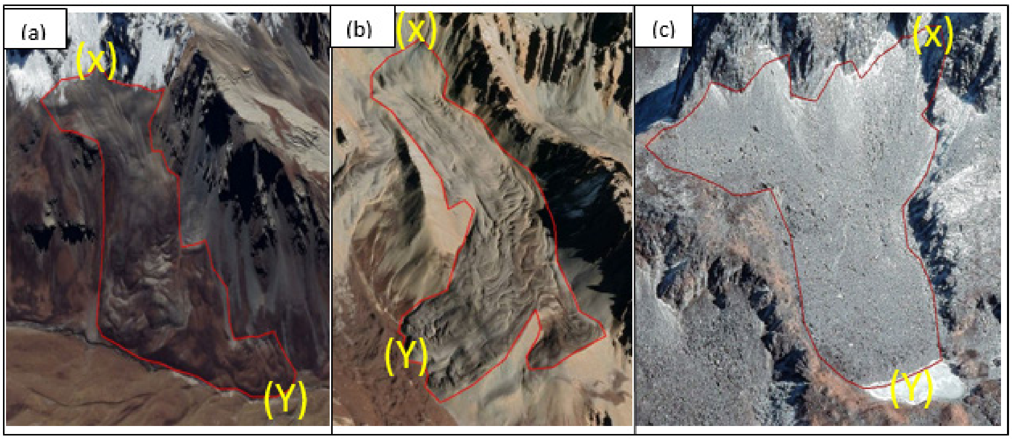

Figure 2. Examples of rock glaciers. (a) Talus-based intact Rock glacier with a gentle front and both longitudinal and transverse flow patterns. (b) Debris-based intact Rock glacier with a steep front and a transverse flow pattern. (c) Debris-based relict Rock glacier with a gentle front. (X) is maximum and (Y) is minimum elevation.

DEM map was processed in ArcMap 10.3 using the aspect tool to recognize the aspect of RGs (Table 2). Along with other attributes, such as maximum and minimum elevation, flow pattern, front, upslope boundary, and activity, were also identified (Table 3).

Table 2. Degree range of aspects

Degrees	Aspect
0^o - 22.5^o	North
22.5^o - 67.5^o	NorthEast
67.5^o - 112.5^o	East
112.5^o - 157.5^o	SouthEast
157.5^o - 202.5^o	South
202.5^o - 247.5^o	SouthWest
247.5^o - 292.5^o	West
292.5^o - 337.5^o	NorthWest
337.5^o - 360^o	North

Table 3. Check-list for generating data on rock glaciers.

Flow Pattern	Longitude
	Transverse
	Both
Front	Gentle
	Steep
Upslope Boundary	Talus
	Debris
Activity	Intact
	Relict
Aspect	North
	NorthEast
	East
	SouthEast
	South
	SouthWest
	West
	NorthWest
Maximum Elevation	Point (X) from Figure 2.
Minimum Elevation	Point (Y) from Figure 2.
Area	Calculated (km^2)

Results and Discussion

The total of 340 rock glaciers were identified, comprising 116 within the Api Nampa conservation area (28.11 km^2), 121 within the Manaslu conservation area (29.42 km^2), and 103 within the Kanchenjunga conservation area (18.68 km2). All mapped RGs are located within 3821 masl to 5667 masl. The lowest elevation point is from Manaslu Conservation Area's relict RG, which has a talus head. The highest elevation point is located within an RG of the Kanchenjunga conservation area. Their distribution in different elevations is presented (Figure 3).

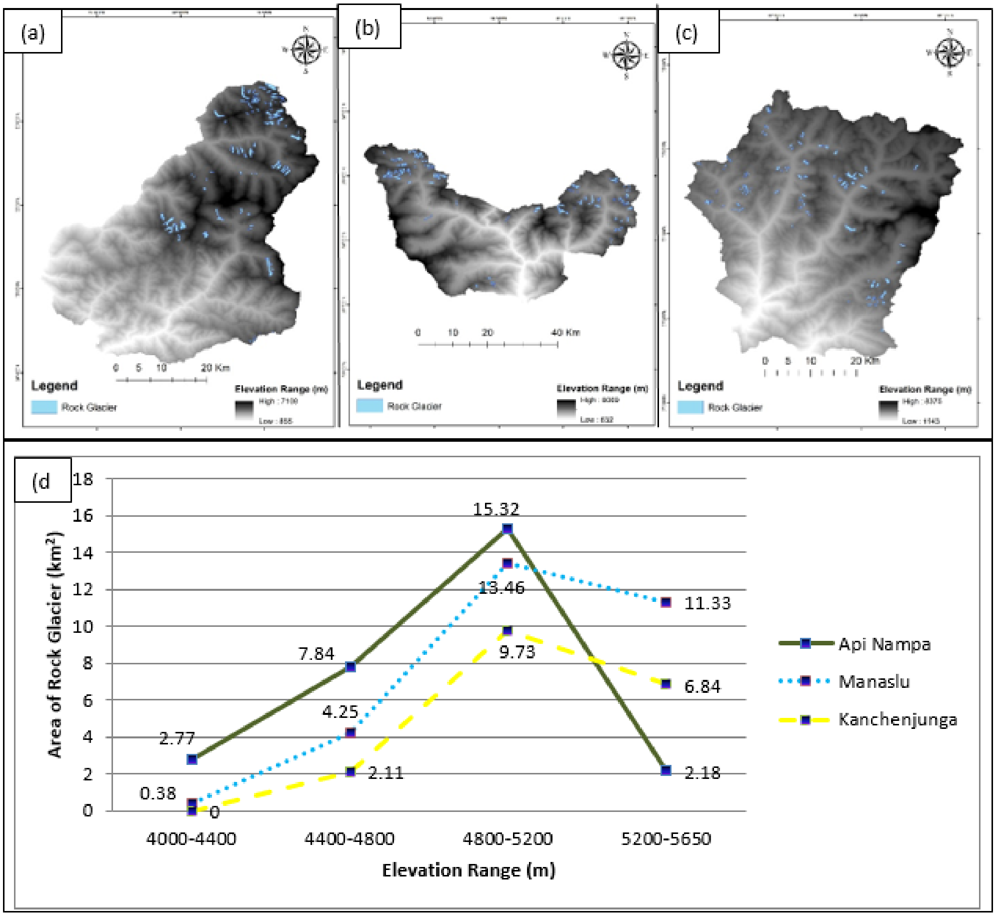

Figure 3. Rock glacier and its relationship with elevation (a) Rock glacier in ANCA (b) Rock glacier in MCA (c) Rock glacier in KCA (d) Graphic representation of the relation between total Rock glacier area and the elevation range from all three CAs

Across all three conservation areas, the greatest concentration of rock glaciers was observed within the 4800–5200 masl range, where APCA exhibited the largest extent (15.32 km²), followed by MCA (13.46 km²). In APCA, the volume of RGs, along with density, declined and reached its lowest between 5200-5650 masl. In contrast, the mass and density of RGs were highest in the same elevation range after 4800-5200 masl in the other two protected areas. No RGs were found in KCA, and the lowest accumulation of RGs, i.e., 0.38 km², was observed in MCA between 4000-4400 masl. The elevation of each RG was taken from their head.

Inventory of Rock glaciers and their distribution

RGs were studied based on their activity, origin point and their aspect. Those characteristics are discussed in the following subheadings.

Rock glacier status

RG's statuses were studied under its upslope boundary and type. Based on the upslope boundary, it was found that ANCA hosts the highest number of talus-derived RGs (56), covering an area of 18.21 km², whereas Manaslu contains the largest number of debris-derived RGs (83), extending across 17.92 km². In contrast, Kanchenjunga has the lowest count of talus-derived RGs (26; 6.85 km²) but a relatively high number of debris-derived RGs (77; 11.83 km²). Overall, the results indicate substantial variation in both the abundance and area of RGs among CAs, with debris-derived RGs being more numerous in all regions, while talus-derived RGs tend to occupy a larger area in ANCA compared to the other two CAs (Table 4).

Table 4. Rock glacier based on the upslope boundary

Conservation Area	Talus		Debris	
	RG Count	Area (km^2)	RG Count	Area (km^2)
Api Nampa	56	18.21	60	9.9
Manaslu	38	11.5	83	17.92
Kanchenjunga	26	6.85	77	11.83

Source: Data derived from Google images, 2024

Relict and Intact activities were another factor to understand the status of RGs. It was observed that Manaslu hosts the highest number of intact RGs (104), covering 25.48 km², followed by Api Nampa (88; 19.33 km²) and Kanchenjunga (84; 16.17 km²). Relict RGs are most abundant in Api Nampa (28; 8.78 km²), while Manaslu (17; 3.94 km²) and Kanchenjunga (19; 2.51 km²) contain fewer and smaller relict features. Overall, intact RGs dominate both in number and area across all three regions, whereas relict RGs are relatively scarce and cover substantially smaller extents (Table 5).

Table 5. Rock glacier based on activity

Conservation Area	Intact		Relict	
	RG Count	Area (km^2)	RG Count	Area (km^2)
Api Nampa	88	19.33	28	8.78
Manaslu	104	25.48	17	3.94
Kanchenunga	84	16.17	19	2.51

Source: Data derived from Google images, 2024

Debris based intact RGs and talus based intact RGs are dominant in all three CAs, while relict forms occur less frequently. The clustering of RGs is in high-elevation zones, with ANCA and KCA showing dense distributions along north-facing slopes, whereas Manaslu exhibits a more scattered pattern (Figure 4).

RG's status relation with elevation can be seen in Figure 4 and its detail is presented in Figure 5.

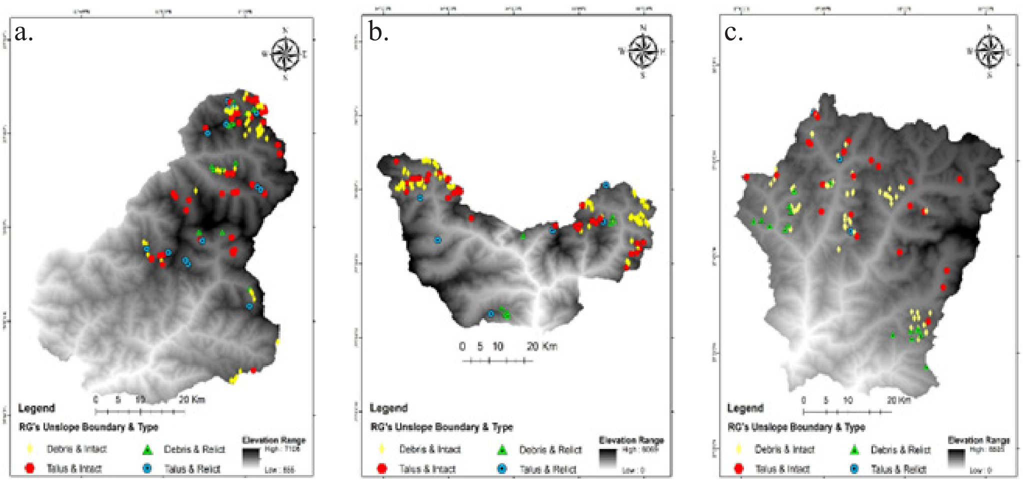

Figure 4. Rock glaciers status and its relationship with elevation (a) Rock glaciers from ANCA (b) Rock glaciers from MCA (c) Rock glaciers from KCA

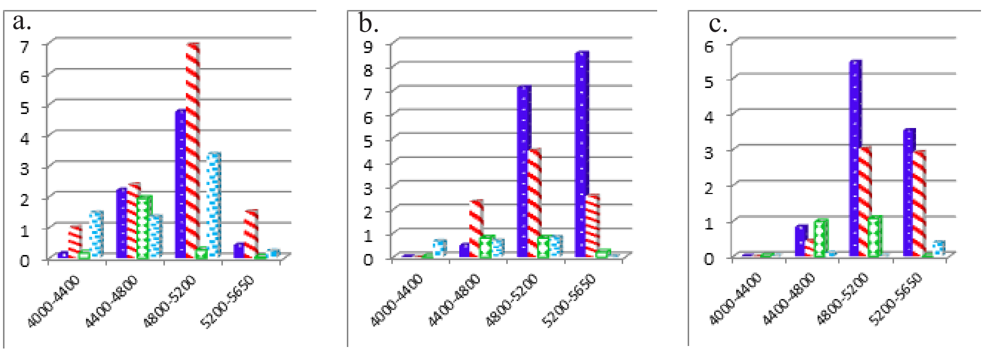

Figure 5. Area of Rock glacier's status and its relationship with elevation (a) Rock glaciers from ANCA (b) Rock glaciers from MCA (c) Rock glaciers from KCA

It was observed that the maximum concentration of RGs was between 4800-5200 masl, with the majority being intact and debris (Fig. 5). Only in ANCA were the maximum RGs in that range intact, specifically the talus. Relict & talus RGs were almost negligible in KCA, as only 0.47 km^2 of RGs had those properties, while they were found in huge numbers in ANCA. 6.4 km^2 area of RG was relict & talus, and most of it was found between 4800-5200 masl in ANCA. The highest area of intact & debris RGs was identified between 5200-5650 masl in MCA, with a total area of 8.55 km^2. Intact & talus RGs were the majority in ANCA with an area of 11.81 km^2, whereas in MCA and KCA, intact & debris were maximum with a total area of 16.14 km^2 and 9.79 km^2, respectively.

Rock glaciers aspect

The majority of RGs on ANCA and KCA were found in the NorthWest-facing slope, even though there was very little margin in total area of RGs found in the Northwest and SouthWest in KCA, i.e., 4.96 km^2 in the NorthWest and 4.78 km^2 in the SouthWest. In MCA, most of the RGs faced the Southwest slope. RGs facing the Southern aspect had higher elevation compared to those facing the Northern aspect; consequently, the mean elevation of Southern aspects is higher and is visualized (Figure 6).

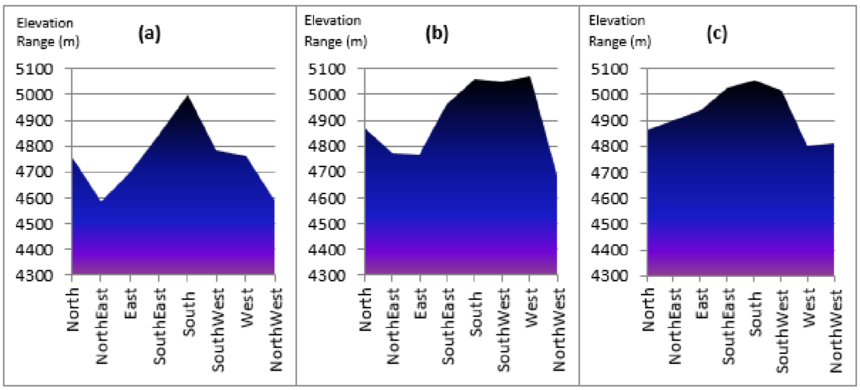

Figure 6. Mean elevation (masl) (a) ANCA (b) MCA (c) KCA

RGs in ANCA are found at lower elevations compared to other CAs, and RGs above the mean elevation of 5050 masl can only be found in MCA. The mean elevation profiles of all three CAs are presented (Table 6).

Table 6. Mean elevation profile

Elevation	**ANCA**	**MCA**	**KCA**
Mean elevation	4703.93	4903.79	4928.14
Mean north aspect elevation	4646.93	4849.35	4858.18
Mean South Aspect Elevation	4875.74	5023.32	5032.93

Source: Data derived from SRTM, 2024

It was observed that the mean elevation decreased as we moved from KCA to ANCA. Both the north aspect and south aspect mean elevation was highest in KCA and lowest in ANCA.

It was also noted that the highest mass of relic RGs was identified in the northern aspect of ANCA, while the lowest was marked in the northern aspect of KCA. Both the highest and lowest accumulation of talus-based RGs were observed in ANCA's northern and southern aspects, respectively. Figurative detail of the relation between aspect and status is presented in Table 7.

Table 7. The relation between the rock glacier's status and aspect

Aspect	ANCA				MCA				KCA			
	Upslope Boundary		Activity		Upslope Boundary		Activity		Upslope Boundary		Activity	
	Debris	Talus	Intact	Relict	Debris	Talus	Intact	Relict	Debris	Talus	Intact	Relict
Northern Aspect	4.18	13.63	10.48	7.33	5.1	4.9	8.04	2.02	4.88	3.36	7.43	0.81
Southern Aspect	2.37	1.23	2.48	1.12	11.48	4.37	14.52	1.33	6.07	3.08	7.67	1.48

Source: Data derived from Google images and SRTM, 2024

Except for ANCA, the upslope boundary in the other two CA is almost equal among their own RGs. The northern aspect had more relic RGs, even though they were very few in KCA. Talus-based RGs were more prevalent in the Northern aspect, while the southern aspect had a high area of debris-based RGs.

RGs status's relation with aspect is presented in Figure 7.

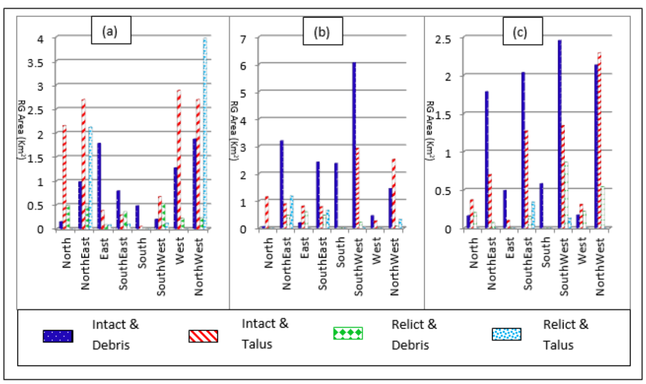

Figure 7. Area of Rock Glacier's status and its relationship with aspect (a) ANCA (b) MCA (c) KCA

It was detected that the relict & talus RGs were almost only present in ANCA as other two CA had very few of it. Intact & debris RGs were present at high numbers in SouthWest facing slope in MCA and KCA but were very few at ANCA. Intact & Talus RGs were very less at SouthWest in ANCA but were high at the other two CA.

Estimation of lower limit of permafrost

Active RGs are indicators of discontinuous permafrost that needs to be understood for estimating the LLP (Barsch, 1978). They are visible indicators of permafrost existence in periglacial areas and elevations at the front of RGs are commonly referred to as the lower limit of discontinuous alpine permafrost (Ghimire, 2024). In the study area, the lowest altitude of RG is 3821 masl in MCA but it has talus upslope boundary and relict activity which suggests that it had once ice-cored interior from glacier and melted as it moved below permafrost zone. Distribution of glacier derived RG could cause misinterpretation when determining the lower limit of discontinuous mountain permafrost zone thus we should focus on ice-cemented RG (Ishikawa, 2001). Following the suggestions of previously done research and researchers, RGs were selected to estimate the LLP. The outcome estimation is presented in Table 8.

Table 8. Lower Limit of Permafrost profile

Conservation Area	LLP in Northern Aspect (masl)	LLP in Southern Aspect (masl)
ANCA	4630	4692
MCA	4324	4543
KCA	4417	4612

Source: Data derived from SRTM, 2024

Ice cores are revealed by depressions between RG and headwall cliff (where a former glacier melted), longitudinal marginal and central meandering furrows, and collapse pits but ice cemented RGs ordinarily do not possess these features (White 1976). The RG indicating of having all the features of ice cemented RG were selected from each CA and the lowest elevation at the front was taken as the estimated LLP. The outcome indicates that LLP in all three CA are higher in southern aspect than in Northern. The LLP is highest at 4692 masl in southern aspect at APCA and lowest as 4324 masl in MCA.

Rock Glacier distribution and dynamics

This study showed that the total of 340 RGs is present between APCA, MCA and KCA with the total area of 76.21 km^2 which lies in the elevation range from 3821 masl to 5667 masl. Jones et al. (2018) had published a study stating that the RG in Nepal Himalaya are situated between 3225 and 5675 masl, our RGs also falls between the same elevation range coinciding both studies.

The mean elevation of RG decreases toward western Nepal Himalaya (Regmi. D, 2008). Our study found that the highest concentration of RG was between 4800-5200 masl and their mean elevation was 4703.927, 4903.75 and 4928.141 in ANCA, MCA and KCA respectively. According to Harrison et al. (2024), in the Nepal Himalayas mean elevation of RG in West is (4503 ± 422 masl), Centre is (4863 ± 372 masl) and East is (4949 ± 256 masl) which shows a decreasing westward trend in RG elevation, our study supports the claim. Harrison also asserts that, across the entire Himalayas, intact RGs are predominantly found above 4800 masl (65%) and relict RGs below 4800 masl (67%). Our study found that the intact RGs above 4800 masl were 84% and relict RGs below 4800 masl were 60%.

It was found that the area of intact RGs is high at higher altitude and more of the relict RGs are found in lower altitude. Most of the talus RG from low elevation are relict which indicates that those RGs previously had ice-cored interior but lost it as it moved down from permafrost zone. In the context of this aspect, it was observed that the north facing slope had more RGs in ANCA while in MCA and KCA south facing slope had more RGs. Harrison's paper stated that intact RGs in north quadrant in Eastern Himalaya was 46%, 40% in Central Himalaya and 57% in Western Himalaya, our study also almost coincides with the result as we found 46%, 36% and 55% of RGs were in northern slopes from KCA, MCA and ANCA respectively. With relation to relict RGs, we found 59%, 34% and 13% of RGs were from KCA, MCA and ANCA respectively were in south quadrant whereas Harrison claimed 13%, 19% and 18% of relict RGs from Eastern, Central and Western Himalaya respectively were in south facing slopes.

Lower limit of permafrost and aspect

RGs are used as a proxy for the permafrost zone because their end melting occurs when they fall below this zone. However, RGs with ice core interiors are expected to survive longer than those with ice-cemented RGs. Thus, RGs with a debris upslope boundary are more reliable for estimating the LLP than talus-based RGs. Following this main principle and studying the type of RGs along with their surrounding environment, LLP for all three CA were estimated and they were: 4630 masl, 4324 masl, and 4417 masl in ANCA, MCA, and KCA, respectively. All three LLPs were located on the northern aspect, while the LLPs in the southern aspect were at 4692 masl, 4543 masl, and 4417 masl in ANCA, MCA, and KCA, respectively. This indicates that permafrost zones are located at higher altitudes on southern aspects compared to northern aspects. This may be because southern aspects receive more sunlight than northern slopes. This result supports the claim of Chauhan & Thakuri (2017) that the LLP has a decreasing trend from Eastern Nepal Himalaya to Western, but the LLP ranges vary. Their study showed LLP in the Western area was 4513 masl and 5239 masl in the East. The difference could be due to the selection of different study areas.

The trend of increasing LLP's elevation is also evident when moving from Central Himalaya to the Western Himalaya, where it appears to decrease slightly as one advances from the East to the Centre.

Conclusion and Implications for future research

Rock glaciers are valuable periglacial landforms that store water in both solid and liquid forms. It is also significantly important for paleoclimatic reconstruction. Rock glaciers are also taken as proxies to outline the lower limit of permafrost. Studies on Rock glaciers are expected to increase due to the shrinkage of glaciers and the reduction of glacier-fed water bodies in the future. However, currently, there is a lack of research in this area, and there is a shortage of extensive morphometric and spatial data on it in the Nepal Himalaya. Thus, this study facilitates researchers and all other parties involved in acknowledging the current state of rock glaciers in the far eastern, central, and far western regions of the Nepal Himalaya.

In this research, 340 rock glaciers were successfully identified and mapped in the study area using Google Earth Pro, SRTEM DEM map, and ArcMap 10.3. The total area of the rock glacier was 76.21 km^2, comprising 28.11 km^2 from the Api Nampa Conservation Area, 29.42 km^2 from the Manaslu Conservation Area, and 18.68 km^2 from the Manaslu Conservation Area. The highest accumulation of rock glacier area is found at elevations between 4800-5200 masl, where most of it is intact and debris-free, except in Api Nampa, where talus and debris are concentrated in the same elevation range. Most talus rock glaciers are located at higher elevations than debris, and the area of intact rock glaciers is significantly larger than that of relict rock glaciers. Inventoried rock glaciers are situated between 3821-5667 masl. The calculated mean elevation for RG is 4703.93 masl, 4903.79 masl, and 4928.14 masl in Api Nampa, Manaslu, and Kanchenjunga, respectively. This shows the rock glaciers' availability in lower altitudes increasing from the East to the West Himalayan region. Mean elevation is higher in southern quadrants, signalling that the sun's radiation plays a significant role in the formation of rock glaciers. The lower limit of Permafrost is located at higher elevations in the Api Nampa Conservation area, indicating that the western Himalayan region has a permafrost region at higher altitudes compared to the central and eastern Himalayan regions.

With the increase in global temperature, the permafrost zone is expected to decrease, leading to rising rock glacier activity. Tracking the status of rock glaciers before any hazard management or assessment, along with other hydrology-related planning in the region, should be a key aspect. The outcomes of this study provide a brief overview of the periglacial environment in three key conservation areas of the Nepal Himalaya. The findings have numerous implications for the exposition of RGs and associated dynamics. Intact RGs are water-rich bodies; therefore, they should be associated with potential water resources and possible hazards. On the other hand, relic RGs can help to reconstruct paleoclimate (Colucci et al., 2019). LLP is an important factor that needs to be taken into account before any infrastructure development, land use strategy and conservation planning in the periglacial region. Studies to understand the response of flora and fauna to the LLP can also be conducted, given that CAs are rich in biodiversity.

Fukui et al. (2006) calculated that the LLP in the Khumbu area has risen by 100-300m between 1973 and 1991. Chauhan & Thakuri (2017), claimed that the LLP would rise by 188m between 2009 and 2039 in Western Himalaya. To understand the impact of global warming in the Himalayan region, LLP should be constantly monitored. Furthermore, future research should also focus on hazards related to RGs, along with hydrological processes, their impact, and opportunities. Researchers should also emphasize RGs while studying the changing dynamics of the periglacial environment in response to climate change.

References

Abdullah, T., & Romshoo, S.A. (2024). A comprehensive inventory, characterization and analysis of rock glaciers in the Jhelum Basin, Kashmir Himalaya, using high-resolution Google Earth data. *Water*. https://doi.org/10.3390/w16162327

Baroni, C., Carton, A., Seppi, R. (2004). Distribution and behavior of rock glaciers in the Adamello-Presanella Massif (Italian Alps). *Permafrost and Periglacial Processes*. https://doi.org/10.1002/ppp.497

Barsch, D. (1978). Active rock glaciers as indicators for discontinuous alpine permafrost: An example from the Swiss Alps. *Proceedings of Third International Conference on Permafrost, 1978.*

Chauhan, R. & Thakuri, S. (2017). Periglacial environment in Nepal Himalaya: Present contexts and future prospects. *Nepal Journal of Environmental Science*. https://doi.org/10.3126/njes.v5i0.22713

Colucci R.R., Forte E., Zebre M., Maset E., Zanettini C. e Guglielmin M. (2019). Is that a relict rockglacier? *Geomorphology*. http://dx.doi.org/10.1016/j.geomorph.2019.02.002

Fort, M. (2015). Permafrost in the Himalayas: Specific characteristics, evolution vs. climate change and impacts on potential natural hazards. *EGU General Assembly 2015*.

Fukui K, Fujii Y, Ageta Y and Asahi K (2006). Changes in the lower limit of mountain permafrost between 1973 and 2004 in the Khumbu Himal, the Nepal Himalayas. *Global* *and Planetary Change*. https://doi.org/10.1016/j.gloplacha.2006.06.002

Ghimire. S. & Ghimire. M. (2024). Distribution of rock glacier and estimation of permafrost zone in Api Nampa Conservation Area. *International Journal of Geology, Earth & Environmental Sciences*. https://cibtech.org/J-GEOLOGY-EARTH-ENVIRONMENT/PUBLICATIONS/2024/JGEE-15-GHIMRE-Rock_Glacier.pdf

Giardono, J. (2011). Rock glaciers. *Encyclopedia of Earth Sciences Series*. https://www.academia.edu/21417637/Rock_Glaciers

Guo, D. & Wang, H. (2017). Simulated historical (1901-2010) changes in the permafrost extent and active layer thickness in the Northern Hemisphere. *Journal of Geophysical Research: Atmospheres*. https://doi.org/10.1002/2017JD027691

Harrison. S., Jones. D.B., Racoviteanu. A.E., Anderson. K., Shannon. S., Betts. R.A, Leng. R., (2024). Rock glacier distribution across the Himalaya*. Global and Planetary Change*. https://doi.org/10.1016/j.gloplacha.2024.104481

Hu. Yan., Harrison. S., Liu. L., Wood. J.L. (2023). Modelling rock glacier ice content based on InSAR-derived velocity, Khumbu and Lhotse valleys, Nepal. *The Cryosphere*. https://doi.org/10.5194/tc-17-2305-2023

Ishikawa. M., Watanabe. T., Nakamura. N. (2001). Genetic differences of rock glaciers and the discontinuous mountain permafrost zone in Kanchanjunga Himal, Eastern Nepal. *Permafrost and Periglacial Processes*. https://doi.org/10.1002/ppp.394

Janke. J.R., & Baloch. T. (2021). Rock glaciers. *Treatise on Geomorphology (Second Edition).* https://doi.org/10.1016/B978-0-12-818234-5.00187-5

Jones. D.B., Harrison. S., Anderson. K., Whalley. W.B. (2019) Rock glaciers and mountain hydrology: A review. *Earth-Science Reviews*. https://doi.org/10.1016/j.earscirev.2019.04.001

Jones. D.B., Harrison. S., Anderson. K., Selley. H.L., Wood J.L., Betts. R.A. (2018). The distribution and hydrological significance of rock glaciers in the Nepalese Himalaya. *Global and Planetary Change*. https://doi.org/10.1016/j.gloplacha.2017.11.005

Kaab. A. & Weber. M. (2004). Development of transverse ridges on rock glaciers: Field measurements and laboratory experiments. *Permafrost and Periglacial Processes.* https://doi.org/10.1002/ppp.506

Kofler. C., Steger. S., Mair. V., Zebisch. M., Comiti. F., Schneiderbauer. S. (2020). An inventory-driven rock glacier status model (intact vs. relict) for South Tyrol, Eastern Italian Alps. *Geomorphology.* https://doi.org/10.1016/j.geomorph.2019.106887

Muller. J., Vieli. A., Gartner-Roer. I. (2016). Rock glaciers on the run-understanding rock glacier landform eolution and recent changes from numerical flow modeling. *The*

Cryosphere. https://doi.org/10.5194/tc-10-2865-2016

Potter. N.Jr., Steig. E.J., Clark. D.H., Speece. M.A., Clark. G.M., Updike. A.B. (2004). Galena Creek rock glacier revisited-new observations on an old controversy. *Geografiska Annaler Series A Physical Geography.* https://doi.org/10.1111/j.0435-3676.1998.00041.x

Rai K, Neupane B.K., Pariyar RK. Climate change vulnerability assessment in the High Mountain Region of Nepal: a case study of Lamjung District. *International Journal of Environment and Climate Change*. https://doi.org/10.9734/ijecc/2020/v10i330187.

Regmi, D. (2008). Rock glacier distribution and the lower limit of discontinuous mountain permafrost in the Nepal Himalaya. *In Proceedings of the Ninth International Conference onPermafrost (NICOP), June 29 - July 3, 2008*. Alaska Fairbanks

RGIK (2022). Towards standard guidelines for inventorying rock glaciers: baseline concepts (version 4.2.2). *IPA Action Group Rock glacier inventories and kinematics*, 13pp.

Schmid. M.-O., Baral. P., Gruber. S., Shahi. S., Shrestha. T., Stumm. D., Wester. P. (2015). Assessement of permafrost distribution maps in the Hindu Kush Himalayan region using rock glaciers mapped in Google Earth. *The Cryosphere.* https://doi.org/10.5194/tc-9-2089-2015

Stumm D, Schmid MO, Gruber S, Baral P, Shahi S, Shrestha T and Wester P (2015). Manual for mapping rock glacier in Google Earth. *International Centre for Integrated Mountain Development (ICIMOD).*

Urdea. P. (1998). Rock Glaciers and permafrost reconstruction in the southern carpathians mountains, Romania. *Conference: Permafrost - Seventh International Conference (June 23-27, 1998), Yellowknife, Canada At: Univ. Laval, Quebec Volume: Collection Nordicana,* 57, 1063-1069.

Wagner. T., Seelig. S., Helfricht. K., Fischer. A., Avian. M., Krainer. K., Winkler. G. (2021). Assessment of liquid and solid water storage in rock glaciers versus glacier ice in the Austrian Alps. *Science of The Total Environment..* https://doi.org/10.1016/j.scitotenv.2021.149593

Wahrhaftig. C. & Cox. A. (1959). Rock Glaciers in the Alaska range. *GSA Bulletin*, 70, 383-436. https://doi.org/10.1130/0016-7606(1959)70[383:RGITAR]2.0.CO;2

White S.E (1976). Rock glaciers and block fields, review and new data. *Quaternary Research*. https://doi.org/10.1016/0033-5894(76)90041-7

Zhang X, Feng M, Zhang H, Wang C, Tang Y, Xu J, Yan D and Wang C (2021). Detecting Rock Glacier Displacement in the Central Himalayas Using Multi-Temporal InSAR. *Remote Sensing*. https://doi.org/10.3390/rs13234738