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Research Article

DISTRIBUTION OF ROCK GLACIER AND ESTIMATION OF PERMAFROST ZONE IN API NAMPA CONSERVATION AREA

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ABSTRACT

Rock glaciers are periglacial landscapes that incorporate surface rock debris insulating ice-core or ice-cemented debris mixture. Rock glacier status can indicate the impact of the global warming in the region along with water reserves state, permafrost zone and the potential related hazards. However, its study in the Nepali Himalaya is very limited. This study presents rock glaciers inventory plus its activity accompanied by Lower Limit of Permafrost (LLP) in Api Nampa Conservation Area. Freely available and accessible Google Earth Pro's images were used to identify the rock glaciers. A total of 116 Rock Glaciers (RGs) of 28.11 km^2 area were identified between 3893 to 5446 masl (meter above sea level). The highest rock glacier accumulation was found between elevation of 4600-4900 masl. Mean elevation of rock glacier in the study area is 4704 masl. As altitude increases, area of Talus Rock Glacier also increases while the area of Debris Rock Glacier peaked at 4600-4900 masl and decreases along with elevation. In the case of activity, Relict Rock Glacier's area decreases as elevation increases, whereas the Intact Rock Glacier area increases correspondingly with altitude. North-facing slope have maximum rock glaciers while south-facing slope have few rock glaciers. Rock glaciers are found in higher elevation in Southern facing slopes while mean elevation of north facing slopes is low. Maximum rock glaciers having a northern aspect are talus-based rock glaciers and maximum rock glaciers facing southern aspect have debris as its origination. Permafrost Zone Index (PZI) map is valid in the study area and using mapped rock glacier as a proxy for Permafrost and PZI as valid indicator it was estimated that the LLP in the Api Nampa Conservation Area is 4630 masl in Northern facing slope and 4692 masl in southern facing slope.

Keywords: *Rock Glacier, Api Nampa Conservation Area, Permafrost, Permafrost Zonation Index (PZI), Lower Limit of Permafrost (LLP), Talus, Debris, Intact, Relict*

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). Rock glaciers are cryogenic landforms of cold mountain landscapes formed by downslope creeping, perennially frozen debris (Haeberli *et al.,* 2006). Rock glaciers are also the important water reservoir; they can store water in solid as permafrost ice and in liquid form as groundwater within the unfrozen base layer (Wagner, 2021). Rock glaciers are climatically more resilient than glaciers potentially containing hydrologically valuable ice volumes (Jones *et al.*, 2018). Rock glaciers can significantly contribute to hydrological contribution and water management planning. Rock glaciers constitute hydrologically valuable long-term water stores and with continued climatically-driven glacier recession and mass loss, their value is likely to become increasingly important (Harrison *et al.,* 2024). Ice presence in rock glaciers is a topic that is likely to gain importance in the future due to the expected decrease in water supply from glaciers and the increase of mass movements originating in periglacial areas thus making it important to have at ones disposal inventories with complete information on the state of rock glaciers (Kofler *et al.,* 2020). However, in the Nepalese Himalaya, there is little information on rock glacier's number, spatial distribution and morphometric characteristics (Jones *et al.*, 2018). Along with water reservoir, they are also important indicators of discontinious Permafrost which permits them to be used in the reconstruction of the development of mountain permafrost (Urdea, 1998).

Rock glaciers are important hydrological reserves and their activity status can indicate the existence of Permafrost (Li, 2022). Intact rock glaciers are common periglacial landforms that occur in cold alpine mountains and are often considered indicators of alpine Permafrost (Chakravarti, 2022). Rock glacier 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 is a perennially frozen ground, a naturally occurring material with a temperature colder than 0º C (32º F) continuously for two or more years (Pewe, 2024). 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). The mean lower limit of permafrost and the size of rock glacier indicate a decreasing trend of the permafrost limit from the eastern, 5239 masl, to the western part of Nepal 4513 masl (Chauhan & Thakuri, 2017).

Around 25,000 rock glacier exists in Himalaya region with a total estimated areal coverage of 3747 km^2 (Harrison *et al.,* 2024). In Nepali Himalaya, rock glaciers are situated between 3225 and 5675 masl, with minimum elevation at the front estimated to be 4977 ± 280 masl for intact landforms and 4541 ± 346 masl for relict landforms (Jones *et al.,* 2018). Across the entire Himalayas, intact rock glaciers are predominantly found above 4800 masl (65%) with relict rock glaciers found below 4800 masl (67%). Furthermore, rock glaciers are clustered between 4400 and 5400 masl (84%) and relict rock glaciers between 4200 and 5200 masl (Harrison *et al.,* 2024). 49% of rock glaciers are highly active in the central Himalayas (Zhang, 2021). Rock glaciers are the cryospheric reserves that store between 16.72 and 255.08 billion m^3 of water in the Nepali Himalayas (Jones *et al.*, 2018). Rock glacier plays vital role in the Himalayas, but are very few research has been done in the issue, the science of permafrost and rock glaciers remains under-researched in the Himalayan region (Remya, 2024).

The Far Western Region of Nepal is remote and developmentally challenged. The region has limited access to essential services and increasing the number of services is challenging due to the difficult topography (UNFCO Nepal, 2009). It is also the region where very few scientific researches have been carried. Thus, this paper tries to facilitate in the study of rock glacier in western part of Nepal by inventorying the rock glacier of the Api Nampa Conservation Area. It is the newest conservation area of Nepal in far western region. Small-scale assessments are important to validate the studies done in whole Hindu Kush Himalayan (HKH) Range (e g., Chauhan & Thakuri, 2017; Jones *et al.*, 2018; Harrison *et al.*, 2024).

MATERIALS AND METHODS

2.1. Study Area

Api Nampa Conservation Area was selected as study area as no research specifically on rock glacier in particular area has been conducted. Geographical location of study area has been presented in Fig 1.

Api Nampa Conservation is the newest conservation area of Nepal as it was created in July 12, 2012 A.D and is named after two mountains of the region, Api and Nampa. It is located in Darchula district of Sudurpashchim province. It covers 1903 km^2 of Area and lies between 29º 30’ to 30º 15’ North latitude and 80º 22’ to 81º 09’ East longitude.

2.2. Climatic Zone of Study Area

The Himalayan region has a tundra climate mostly covered by ice and glaciers, where snow line elevations are lower in the west than in the east (Shrestha & Joshi, 2009). The Koppen climate classification scheme divides climates into five main climate groups: A (tropical), B (arid), C (temperate), D (continental) and E (polar). Fig 2 presents the climatic division in study area. Table 1 shows the each zone coverage area in Api Nampa Conservation Area.

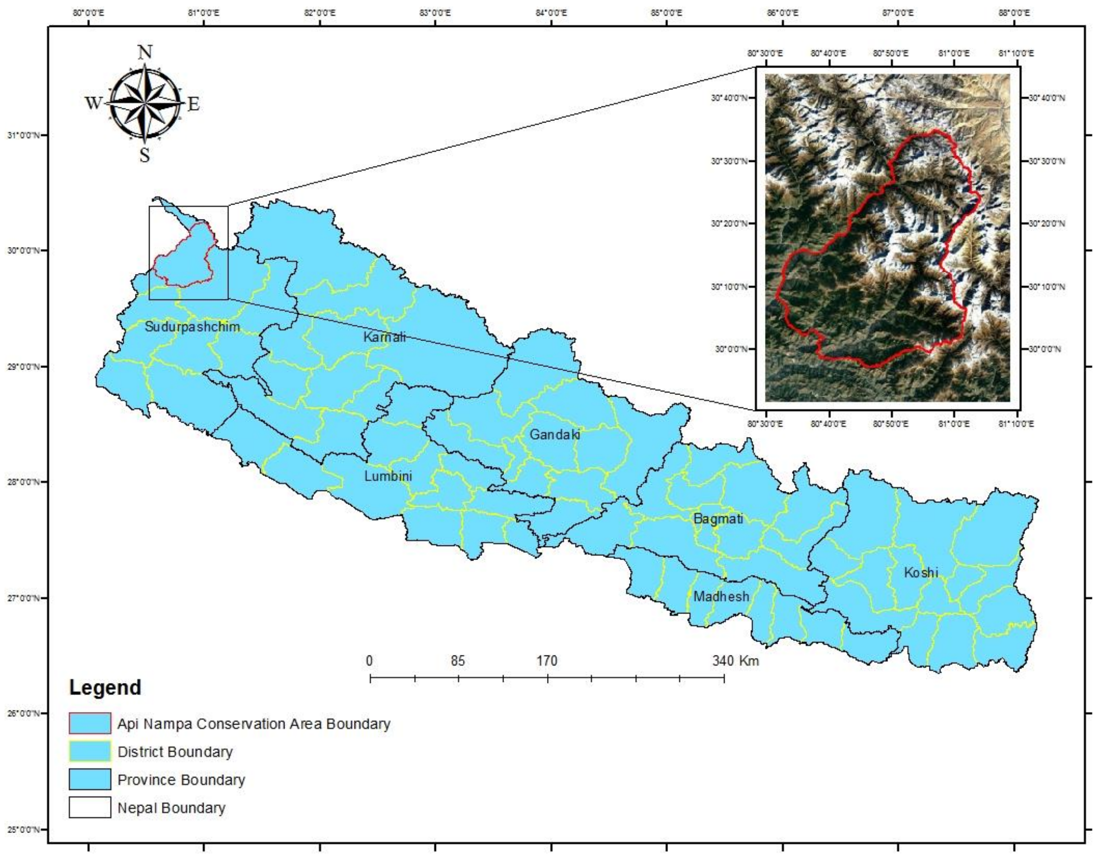

Fig 1: Study Area

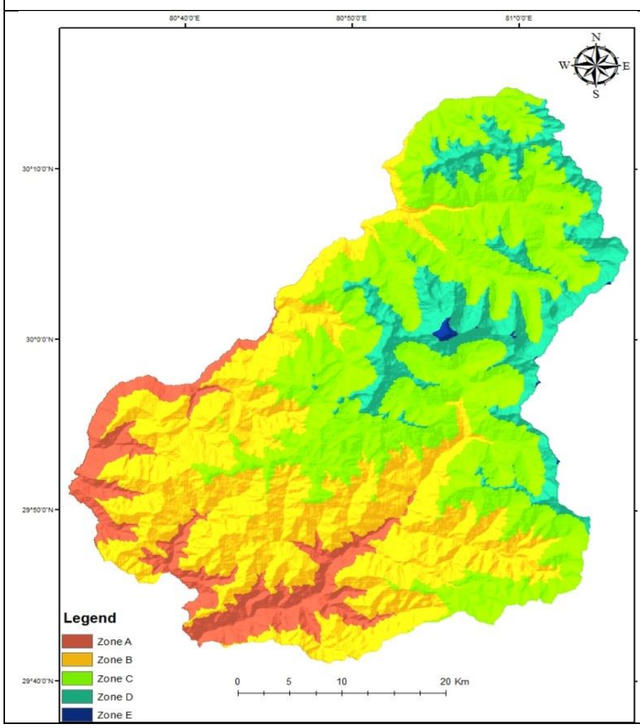

Fig 2: Climatic division of Study Area

Table 1: Study Area's elevation range and climatic zone

Zones	Elevation Range (m)	Area (Km^2)	Area Coverage %
Zone A	855 - 2000	199.24	10.47
Zone B	2000 - 3500	704.5	37.02
Zone C	3500 - 5000	754.73	39.66
Zone D	5000 - 6500	240.73	12.65
Zone E	6500 - 7106	3.8	0.2
Total	-	1903	100

Highest percentage of study area lies under Zone C followed by Zone B. Zone E has least area as it only covers 0.2% of total area. Table 2 describes the features of each climatic Zone.

Table 2: Climatic zone's features

Zones	**Features**
Zone A	Warm Temperature with every month averaging 18ºC. Abundant precipitation, approximately 150cm/year.
Zone B	Hot summer and cold winters. Irregular precipitation.
Zone C	Winter months between -3ºC to 18ºC and summer months warmer than 10ºC. Plentiful annual precipitation.
Zone D	Monthly summer temperature averages over 10ºC and winter month can drop below -3ºC. Winter is cold and stormy and snowfall stays in the ground for extended period.
Zone E	Cold winter and cold summer. Average temperature of warmest month is below 10ºC. Annual precipitation less than 25cm.

2.3. Research Method
Rock Glaciers (RGs) were identified and mapped in Google Earth Pro. To Map the RGs, the shapefile data of Api Nampa Conservation Area was downloaded from an online portal http://geoportal.ntnc.org.np/layers/ntnc:Api_Nampa_Conservation_Area. Then the designated study area was mapped by taking four major steps: (1) Identification of Rock Glacier, (2) Recognition of Status, (3) Manual Mapping of Rock Glaciers, (4) Regional Aggregation. All four steps are described in following subchapters.
There are two permafrost distribution map; IPA map and PZI map for the HKH region, IPA map falls short in adequately representing local permafrost conditions while PZI indicate area where no permafrost can be expected rather well and currently is best prediction map (Schmid *et al.*, 2015). Thus, after identifying RGs, we checked their location with Permafrost Zonation Index (PZI) developed by Stephan Gurber in 2012. PZI is an estimate of to what degree permafrost exists in a region nearly everywhere, or only in the most favorable condition. This process was carried out to validate the PZI map of the study area and also to estimate the permafrost zone. PZI map was downloaded from https://datashare.ed.ac.uk/ .

2.3.1. Identification of Rock Glacier: Rock Glaciers were visually identified in Google Earth Pro based on Flow Structure and Front. Since the maximum area lies in Zone B, C and D, the surrounding region is covered with snow for most of the months, thus to identify the Rock Glacier, images of different months and years were analyzed. Identified Rock Glaciers were named as RG_1, RG_2, …… to get the total count number.
The movement of the Rock Glacier creates the flow structure of either longitude or transverse or even both at same time thus only the bodies showing either of three patterns were only selected. Along with the flow structure, the front of the body makes it more evident either the formation is rock glacier or not.

Front of the rock glacier were characterized as Steep or Gentle. Steep front are those RG which front slope are at steep angle relative to the horizontal plane and is indicated by the presence of loose material along the front slope which has a lighter color than the material on the rock glacier surface (Stumm *et al.*, 2015). Fig.3 shows these attributes.

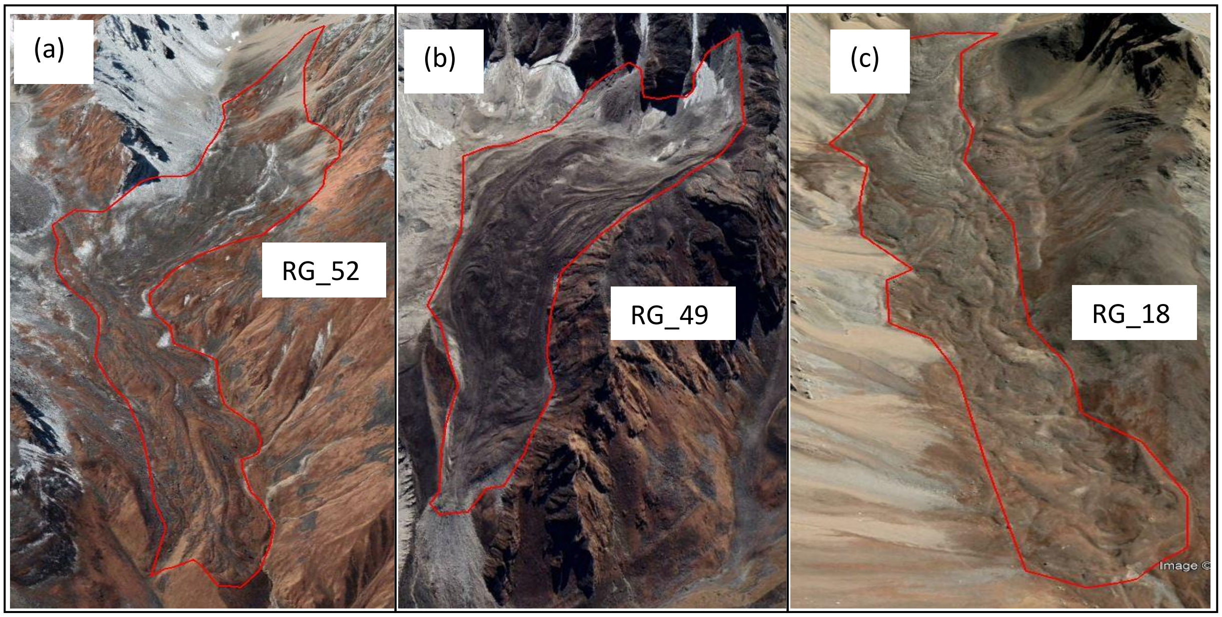

Fig 3: Examples of identified Rock Glaciers. (a) Longitudinal flow structure with Gentle front. (b) Transverse flow structure with Steep front (c) Both flow structure with Gentle front. (d).

2.3.2. Recognition of Status: To identify the activity status of the Rock Glacier, two different bases were selected on the basis of:
(a) upslope boundary (b) activity

(a) On the basis of upslope boundary

Head or the originations of the RGs are mainly of two types, Talus and debris. Those RGs which upslope boundary is directly connected with the glacier are called Talus Rock Glacier while those RGs which origination point are the debris from the surrounding environment or directly not connected to the glacier are recognized as the Debris Rock Glacier. Upslope boundary plays critical role to identify the RG as Ice-cored Rock Glacier or Ice-Cemented Rock Glacier. Fig 4 shows the example of Talus and Debris Rock Glacier.

On the basis of activity Rock Glaciers can be divided into two types, Intact and Relict Rock Glacier. Both active and inactive Rock Glaciers are categorized as intact meaning that they contain ice. Conversely, relict rock glacier contains little to no ice (Barsch, 1992; Jones *et al.*, 2018). Intact rock glaciers are containing ice whether or not they are moving, whereas relict rock glaciers do not contain ice and do not display the movement characteristics (Harrison *et al.,* 2024). Activity of rock glacier is important to identify the permafrost area. Furthermore, to identify the activity of the rock glacier in Google Earth Pro, the indicators listed in Table 3 were used and it has been derived from the article "Rock glacier distribution across the Himalaya" (Harrison *et al.*, 2024). Examples of both type of RG are shown in Fig 5.

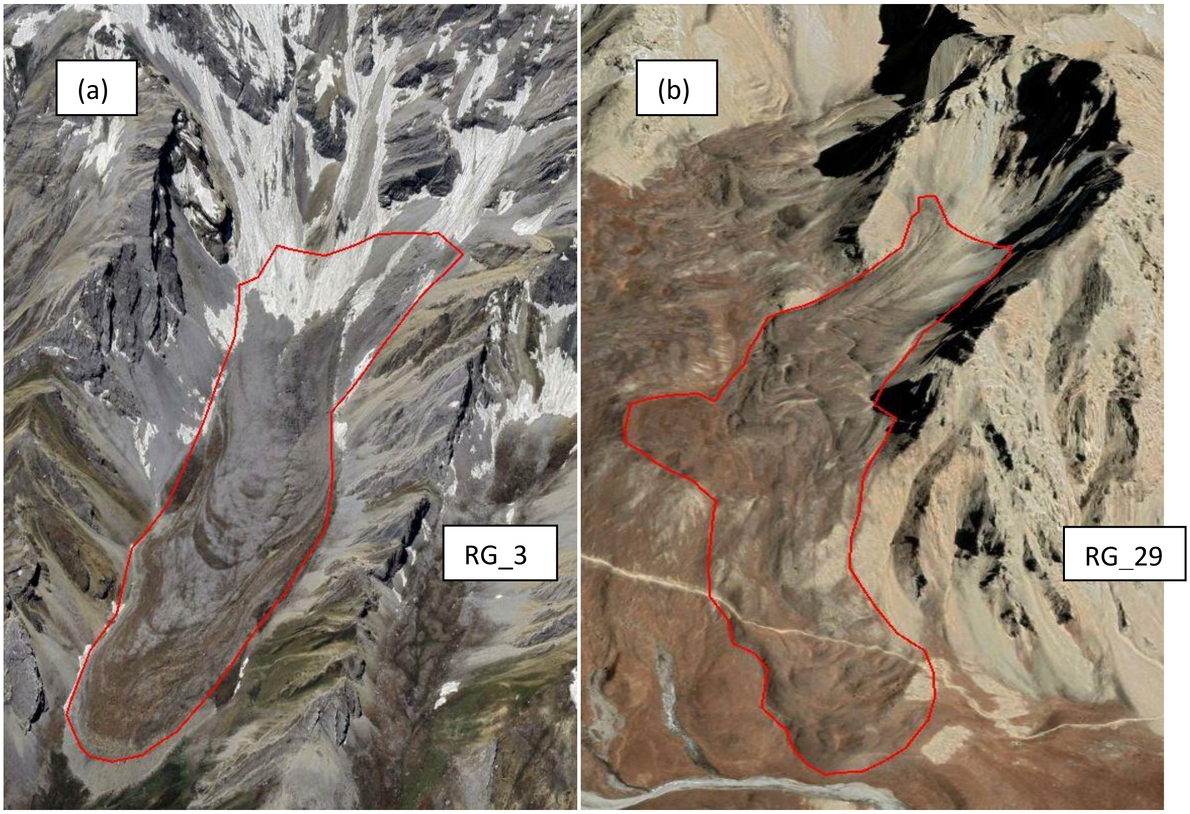

Fig 4: Examples of Rock Glacier on the basis of Upslope Boundary. (a) Talus Rock Glacier (b) Debris Rock Glacier

(b) On the basis of activity

Table 3: Geomorphic indicators used to identify rock glacier's activity

Geomorphic indicator	**Intact rock glacier**	**Relict rock glacier**
Surface flow structure	Well-defined furrow and ridge topography (Kääb and Weber, 2004)	Less defined furrow and ridge topography (Kääb & 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 (30–35°; 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 (<30°) and gentle transition to surrounding slopes and upper surface (Janke and Bolch, 2021).

Source: "Rock glacier distribution across the Himalaya" (Harrison et al., 2024)

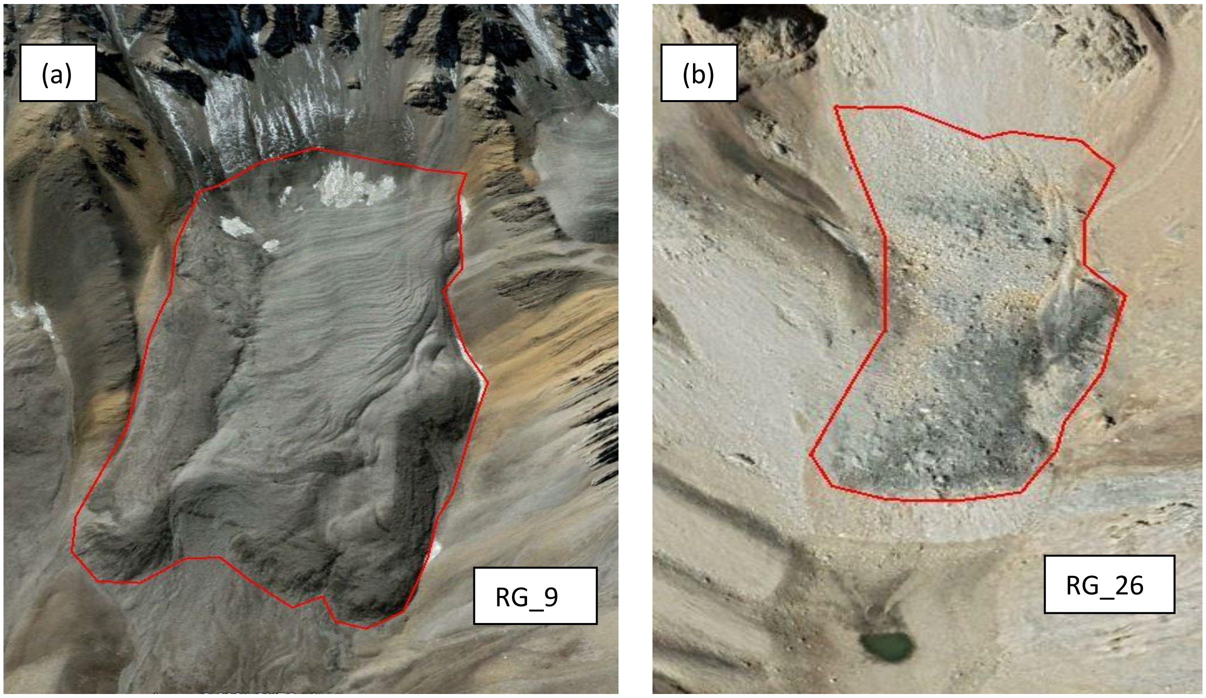

Fig 5: Examples of Intact and Relict Rock Glacier. (a) Intact Rock Glacier (b) Relict Rock Glacier

2.3.3. Manual Mapping of Rock Glacier: Rock Glaciers were mapped in Google Earth Pro following the standard guidelines for inventorying rock glaciers issued by IPA Action Group Rock Glacier inventories and kinematics in 2022 (RGIK, 2022). The accuracy of Google Earth is sufficient for this projects purpose as the inaccuracy arising from horizontal misalignment between imagery and DEM is likely to be smaller than 100m vertically (Schmid *et al.,* 2015). Google Earth has been used as the main data source for this research. Manually RGs having area of atleast 0.01 Km^2 has been mapped. Mapping was done by a single researcher which nullifies the uncertainty of different standards for different rock glaciers. Red Boundary line in Fig 3, Fig 4, Fig 5 and Fig 6 are the example of the mapped rock glaciers.

2.3.4. Regional Aggregation: NASA Shuttle Radar Topography Mission (SRTM) Global 1 arc second V003's ~30 meter resolution images were downloaded from earthdata.nasa.gov to clip the study area's Digital Elevation Model (DEM) map in Arcmap 10.3. Then, the elevation properties of the mapped rock glaciers were extracted from it. Resulting elevation characteristics were further rechecked in the Google Earth Pro to reduce the any possible error. This process ensured much more solid and conservative dataset. The head or the origination point of the RG was taken as maximum elevation and the lowest point of the RG was taken as minimum elevation. Fig 6 shows the example of taking max. and min. elevation.
the study area lie in Northern Hemisphere. In general, for the northern hemisphere, south-facing slopes receive more sunlight and become more xeric and warmer, while north-facing slopes retain moisture and are cold and humid (Maren *et al.*, 2015). Due to the difference of sunlight in different slope, the direction of the mountain plays important role for formation of rock glacier along with its activity. Apart from the slope aspect, the attributes such as area, maximum and minimum elevation, flow structure, front, upslope boundary and activity were interpreted using interpretations elements such as color, tone, location, texture, pattern, shape and association (Table 5). Author's field experience and literature related glacial and periglacial environment in the other parts of the Himalayas in Nepal also aided in identifying the attributes of the rock glacier.

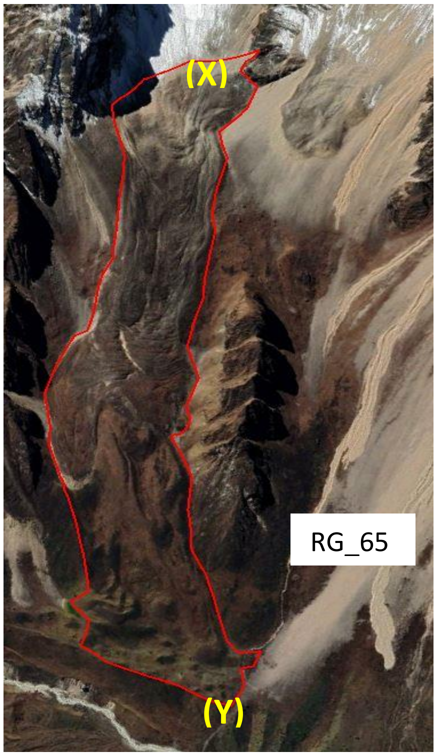

Fig 6: Example of delegating max. and min. elevation. (X) is the max. elevation and (Y) is the minimum elevation.

Table 4: 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 5: Attributes of rock

Name	RG_Count
Flow Structure	Longitudinal
	Transverse
	Both
Front	Gentle
	Steep
Upslope Boundary	Talus
	Debris
Activity	Intact
	Relict
Aspect	North
	NorthEast
	East
	SouthEast
	South
	SouthWest
	West
	NorthWest
Max. Elevation	Eg: Point (X) from Fig 6
Min. Elevation	Eg: Point (Y) from Fig 6
Area	Calculated (km^2)

RESULTS

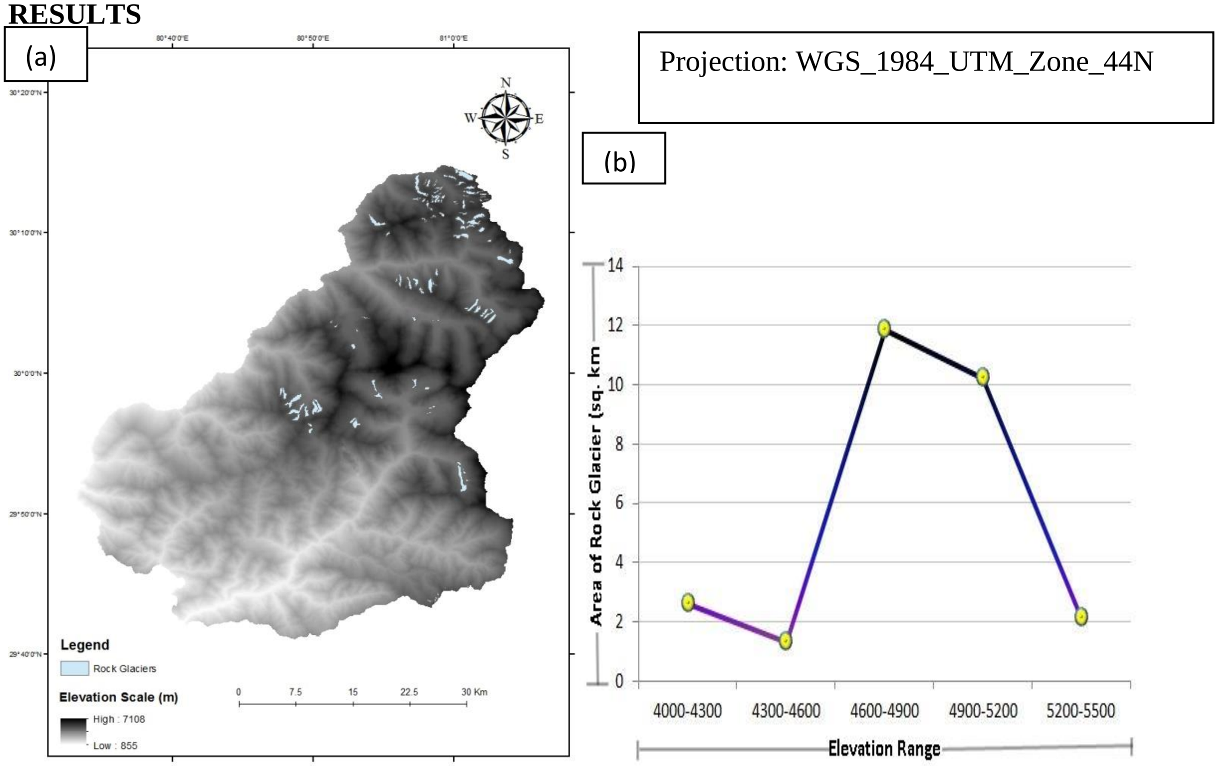

Fig 7: Rock glacier with relation to elevation. (a) Rock glacier represented in map of study area. (b) Rock glacier distribution with respect to elevation in graph line.

Total of 116 Rock Glaciers were identified with the area of 28.11 km^2. All the mapped Rock Glaciers are located within elevation from 3893 to 5446 masl. Mean Elevation of Rock Glacier is 4704 masl. Their distribution in different elevation range is presented in Fig 7Highest area of rock glaciers are between 4600-4900 masl i.e.; 11.86 Km^2 followed by 10.21 km^2 in 4900-5200 masl. Lowest accumulation of rock glaciers were observed in 4300-4600 masl which were 1.3 km^2. The elevation of each rock glacier for this and any elevation related calculation is taken from its max. elevation.

3.1. Inventory of Rock Glaciers and its Distribution

Rock glaciers were only observed in climatic zone C and D while the zone E which covered 0.2% of study area was fully covered in glacier. Rock glaciers were further studied under its status and its aspect and are discussed in following subchapters.

3.1.1 Rock Glacier's status: Rock glacier's statuses were categorized in two categories; on the basis of upslope boundary and on the basis of activity. On the basis of upslope boundary, it was found that among the 116 RGs, 56 originated from glacier or talus and 60 were debris-based rock glaciers. Their distribution is shown in Fig 8. Talus rock glacier has total area of 18.21km^2 and Debris rock glacier had total area of 9.9km^2. Elevation with maximum area (7.51 km^2) of Talus rock glacier was between 4600-4900 masl while lowest (0.32km^2) was between 4300-4600 masl. Elevation with maximum area (4.35km^2) of Debris rock glacier was also between 4600-4900 masl while lowest (0.19km^2) was between 4000-4300 masl.

Based on activity, it was found that 88 were Intact rock glaciers and 28 were Relict rock glaciers. The highest area (8.57km^2) of Intact rock glacier were observed in the elevation between 4900-5200 masl and the lowest area (0.61km^2) were identified between 4300-4600 masl. Largest areas (4.62km^2) of relict rock glacier were identified between 4600-4900 masl whereas the lowest area (0.23km^2) was observed between 5200-5500 masl.

A rock glacier have both upslope boundary and activity status which further divides rock glaciers into (i) Intact & Debris rock glacier (ii) Intact & Talus rock glacier (iii) Relict & Debris rock glacier (iv) Relict and Talus rock glacier. On this division, the calculated area of (i) was 7.49km^2, (ii) was 11.81km^2, (iii) was 2.41km^2 and (iv) was 6.4km^2 .Further its relationship with elevation is presented in Fig 9.

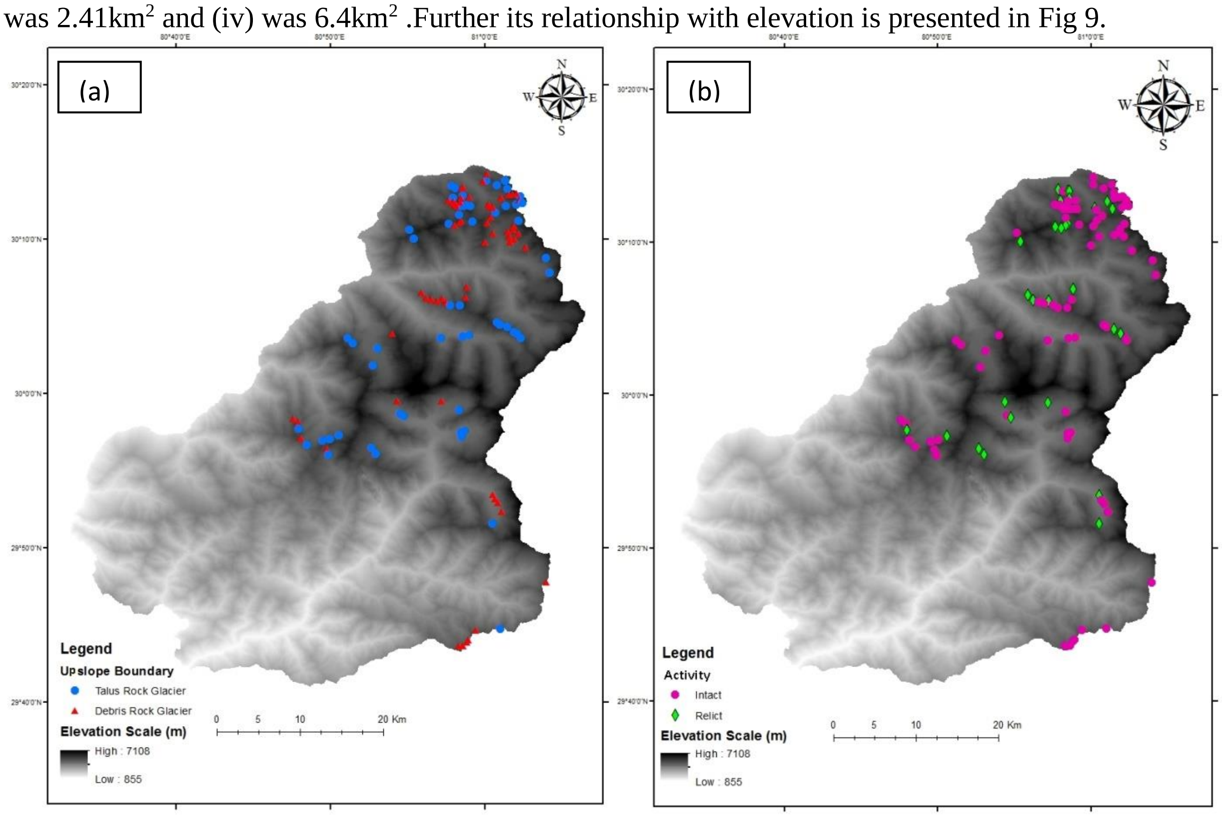

Fig 8: Distribution of Rock Glacier. (a) Distribution of Rock Glacier based on Upslope Boundary.

(b) Distribution of Rock Glacier based on Activity.

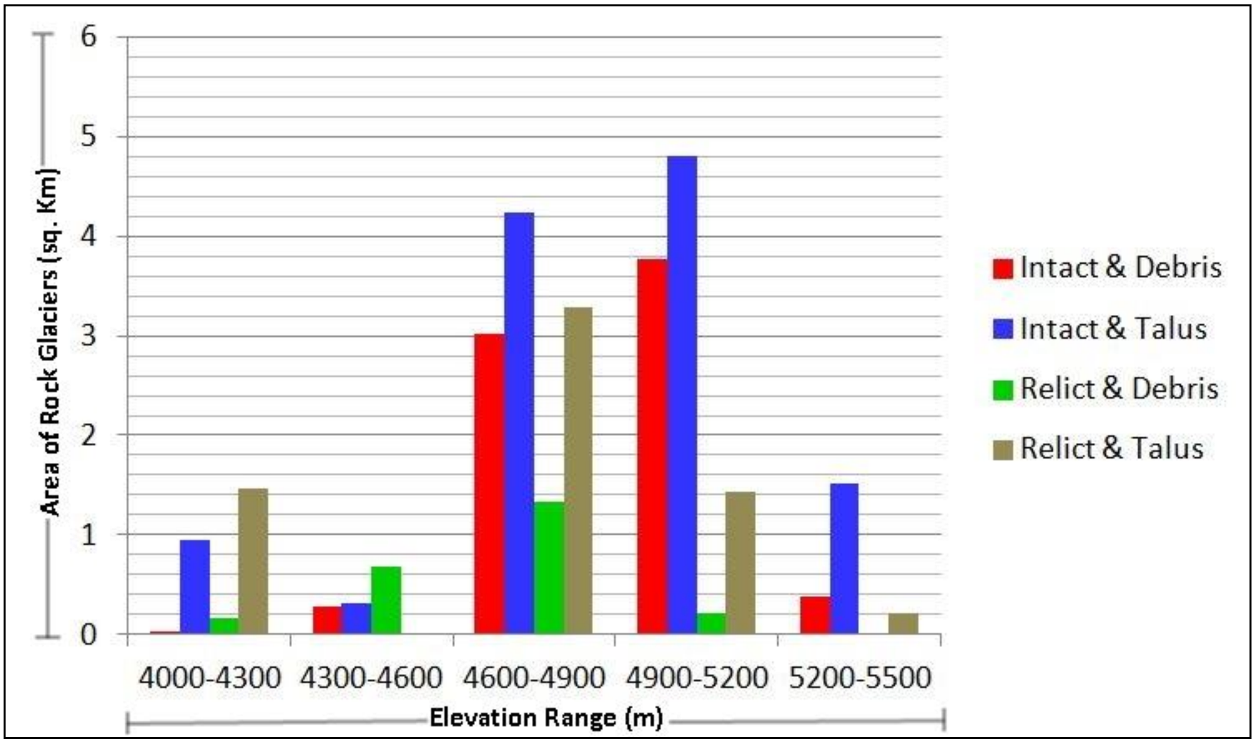

Fig 9: Relation of Rock Glacier with Elevation

We observed that maximum area of rock glacier lies between the elevation range from 4600-5200 masl. With the increase of elevation Relict rock glacier's area decreases while intact rock glacier area increases. In the case of upslope boundary, eventhough the number of debris rock glacier is more, its area is less than Talus rock glacier. Talus rock glacier have an area of 2.42km^2 in the elevation range 4000-4300 masl and 0.32 km^2 in elevation range 4300-4600, this suggests the RGs in 4000-4300 masl may have ice core and have moved down below the permafrost zone. Further observation shows, with the increase of elevation, the area of Talus rock glacier increases. In contrast, debris rock glacier area peaked at 4600-4900 masl and decreases along with the rise in altitude.

3.1.2. Aspect of Rock Glaciers: Among the identified 116 rock glaciers, a maximum of it were found facing NorthWest (292.5º - 337.5º) direction followed by NorthEast (22.5º - 67.5º) direction where 29 and 21 rock glaciers were identified respectively. Lowest number of rock glaciers ie; 8 were recorded in SouthEast (112.5º - 157.5º). All the identified rock glaciers along with it aspects is presented in Fig 9 (a). Along with the number NorthWest followed by NorthEast also contained highest area of rock glacier ie; 8.76 and 6.25 respectively. Rock glacier's aspect was also compared with its upslope boundary and activity which is presented in Fig 9 (b). Fig 9 (c) shows the mean elevation of rock glacier in every aspect.

Highest number of RGs were found in Northwest slope where maximum of rock glacier were Relict & talus. Highest area of Intact and Talus rock glacier were found west facing slope. All the north facing slope have a significant number of rock glaciers while the south facing slope has a very low number.
Eventhough south facing slope have few rock glaciers but it had the highest mean elevation of rock glacier ie; 5001 masl. Rock glaciers are found in higher elevation in Southern facing slopes while mean elevation of northern facing slopes are low and lowest in Northeast (4585 masl). The mean elevation of RGs in eastern facing slopes is low comparatively to the western facing slopes.

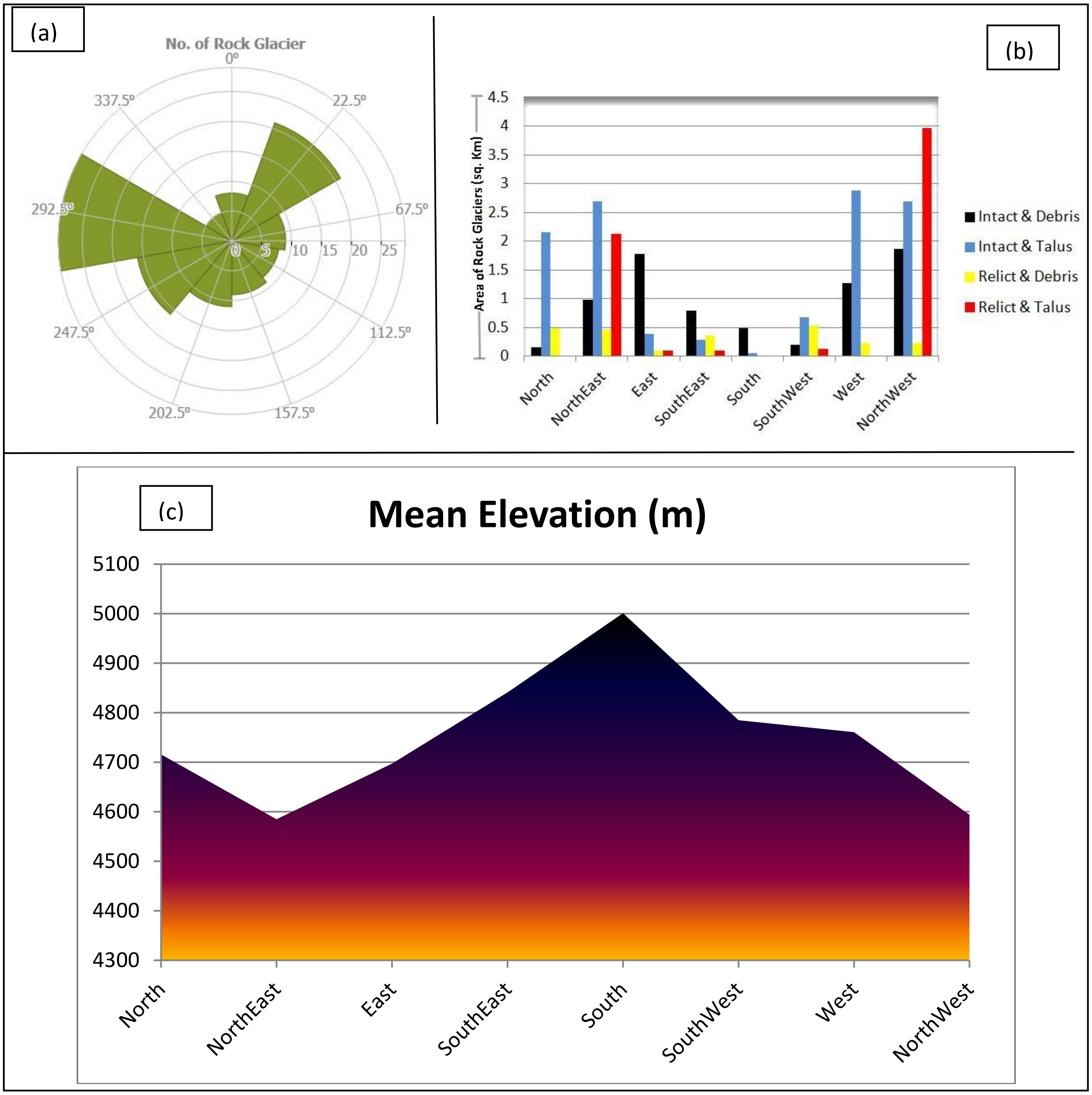

Fig 9: Rock Glacier's relation with aspect and mean elevation. (a) Distribution of RGs with respect to aspect. (b) RGs area with respect to aspect. (c) RGs mean elevation with respect to aspect.

3.2. Permafrost Zonation Index (PZI)

All the identified rock glaciers upslope boundary fell under the PZI map of the study area. Only 4 RGs's front came to the 0 of PZI and their name are: RG_57, RG_80, RG_97 and RG_110, more details of these RGs can be found in Table 6. Fig 10 (a) is the PZI map of the study Area. Fig 10 (b) shows the area of rock glaciers in each PZI.

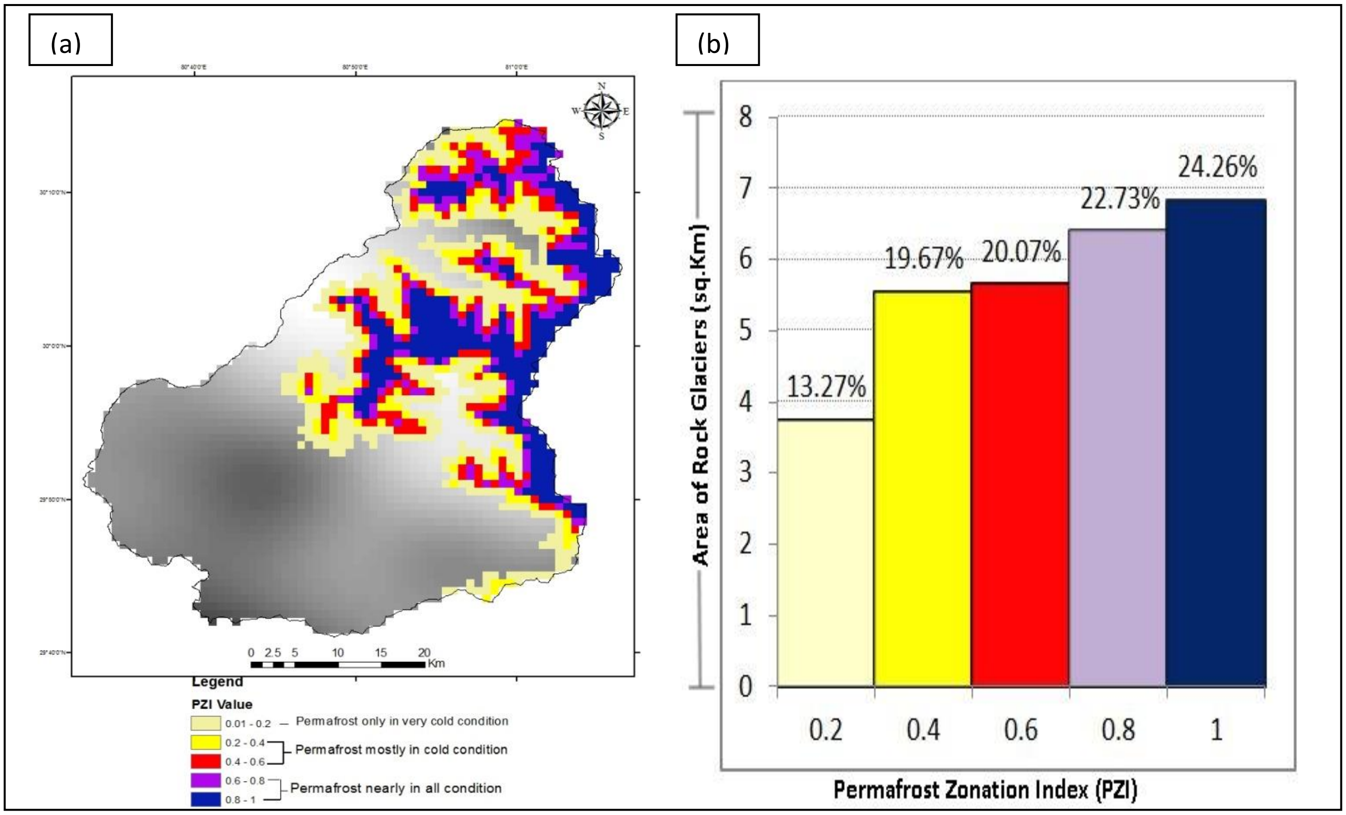

Fig 10: PZI and its relation in Study Area (a) PZI map of Study Area. (b) RG area in relation with PZI.

The relation of color and the index can be seen in Fig 10 (a) legend. Higher the index higher the chances of permafrost availability in all climatic conditions. Highest area of identified rock glaciers are situated in the PZI representing "Permafrost nearly in all condition". Only 13.27% of mapped rock glacier falls under the PZI representing "Permafrost only in very cold condition". None of the mapped RGs origination point comes outside of the PZI.

3.3. Estimation of Permafrost Zone

Fig 10 (b) shows the PZI is in agreement in the study area and thus is valid for identifying the permafrost zone. Furthermore, to limit the permafrost zone from the mapped rock glaciers, we must know that, active rock glaciers are indicators of discontinuous alpine Permafrost (Barsch, 1978). They are visible indicators of permafrost existence in periglacial areas and elevations at the front of rock glaciers are commonly referred to as the lower limit of discontinuous alpine Permafrost. In this study area lower altitude of the observed rock glacier is 3893 masl. This altitude is of RG_58 which upslope boundary elevation is 4705 masl but it is a Relict rock glacier which does not have credibility to identify permafrost zone. Next lowest altitude is 3897 of RG_92. RG_92 is a Talus rock glacier which suggests it having ice core. Distribution of glacier derived rock glacier may cause misinterpretation when determining the lower limit of discontinuous mountain permafrost zone thus we should focus on ice-cemented rock glacier (Ishikawa, 2001). Ice cores are revealed by depressions between rock glacier and headwall cliff (where a former glacier melted), longitudinal marginal and central meandering furrows, and collapse pits but ice cemented rock glaciers ordinarily do not possess these features (White, 1976). Four RGs RG_57, RG_80, RG_97 and RG_110 which front lie in 0 in PZI have min. elevation 4022, 4194, 4032 and 4214 respectively also cannot be selected to limit the lower limit as three of it are relict and one of it is talus rock glacier. RG_46

posses the features of ice-cemented rock glacier with min. elevation of 4034 masl but it lie in the 0.01-0.2 PZI indicating Permafrost only in very cold condition, thus cannot be taken as lower limit.
RG_29 (Fig:4 (b)) shows all the indications of ice-cemented rock glacier and also lie between 0.8-1 in PZI, it have the min. elevation of 4630 masl concluding it as lowest limit for discontinuous permafrost zone. This altitude is for Northern facing slope as RG_29 aspect is NorthWest. RG_42 which face South also possesses all the ice cemented indicators and lie between 0.6-0.8 in PZI, making its min. elevation 4692 masl as lower limit of discontinuous permafrost zone of south sloping face in study area.

DISCUSSION

The study provides essential understating of the rock glaciers' spatial distribution, dynamics and the lower limit of the permafrost (LLP) in Api Nampa Conservation Area. The inventory of rock glaciers created in this study is a valuable dataset for understanding the periglacial area and dynamics of the region. The implications of the findings and the potentiality of the future research are discussed in the following subchapters.

4.1. Rock Glacier Distribution and Dynamics

Our study showed that the total of 116 rock glaciers are present in Api Nampa Conservation Area between 3893 and 5446 masl and cover total areas of 28.11 km^2. The altitude range coincides with the result of Jones et al. (2018), study which stated that the rock glaciers in the Nepali Himalaya are situated between 3225 and 5675 masl.
We found that the highest rock glacier accumulation was between 4600-4900 masl and their mean elevation was 4704 masl. Area of intact rock glacier is high in higher altitude while more relict rock glaciers are found in lower altitude. Talus rock glacier are predominantly in elevation above 4600 masl but significant of it are also found in between 4000-4300 masl. The maximum of the talus rock glacier found in lowest rock glacier zone are relict which indicates that those RGs once had the ice-cored interior but lost it as it moved down from the permafrost zone. Significant area of talus and intact rock glacier are also found between 4000-4300 masl suggesting that it has an ice-cored interior, which is still active. This hypothesis can be checked by using adequate methods and tools in the field. Intact and debris rock glacier area is very low below 4600 masl and increases above 4600 masl, which along with PZI helped to estimate the permafrost zone. In relationship with aspect, it was observed that the north-facing slope have more rock glaciers than the south-facing slope and the mean elevation of RGs in south-facing slope is 5001 masl while lowest mean elevation is 4585 masl in NorthEast aspect.
According to Harrison et al. (2024), across the entire Himalayas, intact roc glaciers are predominantly found above 4800 masl (65%) with relict rock glaciers found below 4800 masl (67%). In our study intact rock glaciers above 4800 masl were 9km^2 (47%) while relict rock glaciers below 4800 masl were 5.87km^2 (67%). We found that intact rock glaciers are predominantly above 4700 masl (60%). Whereas Harrison's study also showed that the much of the RGs are clustered in northern quadrants, 40-57% intact rock glacier and 57-62% relict rock glacier, especially in NorthWest facing slopes. Our study also have the same outcome as much of the RGs are clustered in northern quadrants (63%), especially in NorthWest facing slope where 44% are intact rock glacier and 56% are relict rock glacier. These findings correspond with each other with some errors.

4.2. Permafrost zonation and Aspect factor

Except 4, all other identified RGs were within the PZI. Those 4 RGs had their upslope boundary within PZI but their front fell outside the indicator suggesting them as RGs having ice-cored interior. The hypothesis becomes stronger as two among it have glacier as origination point and other two are relict rock glacier. This puts PZI in agreement with the study area. With the inventory generated for each rock glacier and the available PZI map, LLP in study area was estimated as 4630masl. Chauhan & Thakuri (2017), estimated the LLP as 4513 masl in western Himalayas of Nepal. Our calculated LLP is 117m above the Chauhan's estimation. This difference may be due to the difference in area as Chauhan estimated the LLP in western Nepali Himalaya at Sisne Himal which is in eastern part of our study area.

This reflects LLP of Api Nampa Conservation Area is higher than of the Sisne Himal and is not the LLP of whole western Nepali Himalaya.

LLP of study area is different in different aspects. It is higher in south-facing slope, 4692 masl, than on the north-facing slope, 4630 masl. This may be because the south-facing slopes receive more sunlight than north-facing slopes.

4.3 Implications and Future Research

The findings of the study give a general view of periglacial environment of Api Nampa Conservation Area. The outcomes have various implications for interpretation of rock glaciers and related dynamics. Active rock glaciers are water rich body thus should be linked with potential hazard along with possible water resource. Whereas relict rock glaciers can be used for paleoclimatic reconstructions (Colucci *et al.*, 2019). LLP is an important data for any conservation strategy, land use planning or infrastructure setup in the conservation area. Since, conservation area is rich in biodiversity, the activity of birds and animals below and above the LLP could also be observed to understand the impact of ground ice on the living species.

Chauhan & Thakuri (2017), stated LLP would rise by 188m between 2009 and 2039. (Fukui *et al.*, 2006) predicted that the LLP in Khumbu Himal has risen by 100-300m between 1973 and 1991, thus the LLP should be continuously monitored to understand the impact of global warming in the region. Moreover, future research should also focus on hydrological impact of rock glacier in the area along with potential related hazard in the region. Researchers should also put effort to understand the changing dynamics of periglacial and glacial environment in response to the climate change and its impact on the adaptability of living species in the Api Nampa Conservation Area.

4.4 Inventory of Identified Rock Glaciers

Inventory of all 116 rock glaciers has been created and presented in Table 6.

Table 6: Inventory of rock glaciers

Name	Flow Structure	Front	UpSlope Boundary	Activity	Aspect	Max. Elev (m)	Min. Elev (m)	Area (km^2)
RG_1	Both	Steep	Talus	Relict	NorthWest	5161	4164	1.14
RG_2	Transverse	Steep	Talus	Relict	NorthEast	4788	4544	0.1
RG_3	Transverse	Steep	Talus	Intact	NorthEast	4787	4460	0.24
RG_4	Longitudinal	Steep	Debris	Relict	NorthEast	4788	4278	0.1
RG_5	Longitudinal	Gentle	Debris	Relict	North	4723	4312	0.1
RG_6	Transverse	Gentle	Talus	Relict	NorthEast	5016	4333	0.26
RG_7	Transverse	Gentle	Talus	Intact	NorthEast	5086	4649	0.2
RG_8	Transverse	Steep	Talus	Intact	North	5109	4975	0.1
RG_9	Transverse	Steep	Talus	Intact	North	5156	4967	0.13
RG_10	Transverse	Gentle	Talus	Intact	North	5227	5129	0.1
RG_11	Both	Gentle	Debris	Relict	SouthWest	4832	4612	0.1
RG_12	Both	Gentle	Talus	Intact	North	5035	4792	0.25
RG_13	Longitudinal	Gentle	Talus	Relict	NorthWest	5048	4970	0.03
RG_14	Transverse	Steep	Talus	Intact	NorthWest	5223	5166	0.1
RG_15	Both	Steep	Talus	Intact	West	5340	5161	0.11
RG_16	Longitudinal	Gentle	Talus	Intact	West	5259	4969	0.29
RG_17	Transverse	Steep	Talus	Intact	West	5117	4855	0.2

RG_18	Both	Gentle	Talus	Intact	West	4881	4628	0.29
RG_19	Transverse	Gentle	Talus	Intact	NorthWest	5093	4685	1.15
RG_20	Transverse	Gentle	Debris	Intact	South	5254	5037	0.1
RG_21	Transverse	Gentle	Debris	Intact	SouthWest	5143	4969	0.12
RG_22	Both	Steep	Debris	Intact	South	5240	5112	0.02
RG_23	Transverse	Steep	Debris	Intact	South	5167	4949	0.1
RG_24	Transverse	Steep	Talus	Intact	West	5032	4248	0.83
RG_25	Transverse	Steep	Talus	Relict	SouthWest	5260	4916	0.12
RG_26	Longitudinal	Steep	Debris	Relict	East	5146	5064	0.05
RG_27	Transverse	Steep	Talus	Intact	SouthWest	5124	4849	0.53
RG_28	Both	Steep	Debris	Intact	SouthEast	5080	4634	0.41
RG_29	Transverse	Gentle	Debris	Intact	NorthWest	4976	4630	0.24
RG_30	Both	Gentle	Debris	Intact	West	5033	4885	0.3
RG_31	Both	Gentle	Talus	Intact	West	4817	4360	0.99
RG_32	Transverse	Gentle	Debris	Intact	West	4879	4744	0.1
RG_33	Transverse	Gentle	Talus	Intact	SouthWest	5142	4780	0.1
RG_34	Transverse	Steep	Talus	Intact	NorthWest	4106	3916	0.16
RG_35	Both	Steep	Talus	Intact	NorthWest	4014	3978	0.05
RG_36	Transverse	Gentle	Talus	Intact	NorthWest	4239	4205	0.1
RG_37	Longitudinal	Gentle	Debris	Relict	SouthWest	4567	4277	0.33
RG_38	Both	Gentle	Debris	Relict	SouthEast	4771	4216	0.36
RG_39	Transverse	Steep	Talus	Intact	NorthEast	4753	4539	0.22
RG_40	Longitudinal	Steep	Talus	Relict	SouthEast	5261	4866	0.1
RG_41	Transverse	Gentle	Talus	Intact	NorthWest	4211	4193	0.1
RG_42	Transverse	Gentle	Debris	Intact	South	4957	4692	0.12
RG_43	Transverse	Gentle	Talus	Intact	SouthEast	4601	4508	0.19
RG_44	Longitudinal	Gentle	Debris	Intact	West	4731	4604	0.08
RG_45	Transverse	Gentle	Talus	Intact	NorthWest	5446	5250	0.15
RG_46	Transverse	Steep	Debris	Intact	NorthEast	4720	4270	0.43
RG_47	Transverse	Steep	Debris	Intact	NorthEast	4668	4226	0.27
RG_48	Transverse	Steep	Talus	Intact	NorthEast	4647	4423	0.35
RG_49	Longitudinal	Gentle	Debris	Intact	East	4787	4119	0.82
RG_50	Transverse	Steep	Talus	Intact	North	4702	4149	0.51
RG_51	Transverse	Gentle	Talus	Relict	NorthEast	4808	4001	1
RG_52	Both	Steep	Talus	Intact	North	4908	4206	0.74
RG_53	Both	Steep	Talus	Relict	NorthWest	4751	4050	0.6
RG_54	Transverse	Gentle	Talus	Intact	NorthEast	4439	4405	0.1
RG_55	Transverse	Gentle	Debris	Intact	East	4811	4618	0.21
RG_56	Transverse	Gentle	Debris	Intact	East	4994	4285	0.71
RG_57	Transverse	Steep	Debris	Relict	NorthEast	4457	4022	0.36
RG_58	Transverse	Gentle	Debris	Relict	North	4705	3893	0.39

RG_59	Transverse	Steep	Talus	Intact	NorthWest	5223	4424	0.71
RG_60	Transverse	Gentle	Talus	Intact	SouthWest	4046	4024	0.04
RG_61	Transverse	Gentle	Talus	Intact	West	4462	4331	0.17
RG_62	Both	Steep	Talus	Intact	SouthEast	4871	4805	0.1
RG_63	Longitudinal	Steep	Talus	Intact	North	4815	4718	0.1
RG_64	Both	Steep	Talus	Intact	NorthEast	4877	4682	0.1
RG_65	Longitudinal	Gentle	Talus	Intact	NorthEast	4785	4025	0.59
RG_66	Both	Steep	Talus	Relict	NorthEast	4779	4215	0.41
RG_67	Both	Gentle	Talus	Intact	NorthEast	4838	4248	0.43
RG_68	Both	Gentle	Talus	Intact	NorthEast	4921	4325	0.47
RG_69	Both	Steep	Talus	Relict	NorthEast	4894	4314	0.35
RG_70	Transverse	Gentle	Debris	Relict	SouthWest	4915	4700	0.1
RG_71	Transverse	Gentle	Debris	Intact	West	5048	4785	0.38
RG_72	Transverse	Gentle	Debris	Intact	NorthEast	4818	4622	0.16
RG_73	Transverse	Gentle	Debris	Relict	East	5308	5111	0.03
RG_74	Transverse	Steep	Debris	Intact	SouthWest	5158	4969	0.04
RG_75	Transverse	Steep	Debris	Intact	NorthWest	5096	4726	0.56
RG_76	Transverse	Steep	Debris	Relict	South	5015	4868	0.01
RG_77	Transverse	Gentle	Debris	Intact	NorthWest	4863	4250	0.35
RG_78	Transverse	Gentle	Debris	Intact	East	4863	4725	0.02
RG_79	Transverse	Gentle	Debris	Intact	West	4978	4631	0.11
RG_80	Transverse	Steep	Debris	Relict	NorthWest	4779	4194	0.22
RG_81	Both	Steep	Debris	Intact	NorthWest	5191	4626	0.11
RG_82	Transverse	Gentle	Debris	Intact	North	4540	4427	0.1
RG_83	Transverse	Steep	Debris	Intact	NorthWest	4621	4218	0.07
RG_84	Transverse	Steep	Debris	Intact	NorthWest	4632	4360	0.06
RG_85	Transverse	Gentle	Debris	Intact	NorthWest	4756	4466	0.09
RG_86	Transverse	Steep	Debris	Intact	NorthWest	4608	4428	0.02
RG_87	Transverse	Steep	Talus	Intact	NorthWest	4379	4190	0.05
RG_88	Both	Steep	Debris	Intact	NorthEast	4741	4585	0.1
RG_89	Transverse	Gentle	Talus	Relict	NorthWest	4802	4488	0.59
RG_90	Transverse	Gentle	Talus	Relict	NorthWest	4670	4464	0.23
RG_91	Transverse	Steep	Talus	Intact	North	4202	4133	0.12
RG_92	Transverse	Gentle	Talus	Relict	NorthWest	4288	3897	1.38
RG_93	Transverse	Gentle	Debris	Relict	West	4015	3918	0.16
RG_94	Transverse	Gentle	Debris	Intact	SouthWest	4159	4055	0.03
RG_95	Longitudinal	Gentle	Debris	Intact	West	4310	4057	0.11
RG_96	Longitudinal	Gentle	Debris	Intact	NorthWest	4456	4196	0.08
RG_97	Longitudinal	Gentle	Talus	Intact	East	4220	4032	0.38
RG_98	Longitudinal	Gentle	Talus	Relict	East	4144	3985	0.09
RG_99	Transverse	Steep	Debris	Intact	SouthEast	5230	4870	0.19

RG_100	Transverse	Steep	Debris	Intact	SouthEast	4870	4757	0.06
RG_101	Transverse	Steep	Debris	Intact	West	5060	4614	0.19
RG_102	Transverse	Steep	Debris	Intact	South	5255	5126	0.02
RG_103	Transverse	Gentle	Debris	Intact	East	5205	5127	0.02
RG_104	Transverse	Gentle	Debris	Intact	NorthWest	5017	4713	0.04
RG_105	Transverse	Gentle	Debris	Intact	West	5429	5188	0.06
RG_106	Longitudinal	Gentle	Talus	Intact	South	5314	5195	0.05
RG_107	Longitudinal	Gentle	Debris	Intact	SouthWest	5450	5331	0.01
RG_108	Longitudinal	Steep	Talus	Intact	North	5190	4954	0.1
RG_109	Both	Gentle	Debris	Intact	SouthEast	5158	4962	0.13
RG_110	Transverse	Steep	Debris	Relict	NorthWest	4601	4214	0.07
RG_111	Transverse	Steep	Talus	Intact	NorthWest	4891	4643	0.12
RG_112	Transverse	Gentle	Debris	Intact	NorthWest	4957	4652	0.19
RG_113	Transverse	Gentle	Debris	Intact	South	4871	4710	0.04
RG_114	Transverse	Steep	Debris	Intact	South	4675	4574	0.08
RG_115	Transverse	Gentle	Debris	Intact	North	4880	4759	0.05
RG_116	Transverse	Gentle	Debris	Intact	NorthEast	4967	4846	0.02

CONCLUSION

Rock glaciers are important cryogenic landform; they store water both in solid and liquid form. Due to the expected decrease of supply of water from glacier in future, their significance is anticipated to grow. Rock glaciers also act as a proxy to delineate Permafrost zone. Eventhough researches in the topic are being conducted but still there are not sufficient morphometric and spatial information about it in the Nepali Himalaya. Thus, this study facilitates researchers and every other parties to understand the scenario of rock glacier and lower limit of permafrost in Api Nampa Conservation Area.

In this study, successfully 116 rock glaciers were mapped and inventoried in the study area using Google Earth Pro, SRTEM DEM map and Arcmap 10.3. The Total area of rock glacier was calculated as 28.11 km^2. The largest rock glacier area is found on elevation between 4600-4900 masl where most of it are intact and talus. The location of talus rock glacier are higher than the debris rock glacier and the area of intact rock glacier are bigger than the relict rock glacier. Mapped rock glaciers are situated between the elevations of 3893 to 5446 masl. The calculated mean elevation for Rock Glacier is 4704 masl. With respect to aspect, the highest mean elevation as 5001 masl is calculated in south-facing slope while lowest mean elevation was calculated in NorthEast-facing slope as 4585 masl. It was clearly visible that the north-facing slope had more number and area of rock glaciers than the south-facing slope. PZI map is valid for the study area. Using PZI and the features of mapped rock glacier, the lower limit of permafrost zone in the study area was estimated at 4630 masl in Northern facing slope and 4692 masl for the southern facing slope.

With the rise of temperature, lower limit of permafrost is expected to rise and the activity of rock glacier is awaited to increase. Thus their status need to be monitored either for planning of any hydrological management or assessment of potential hazard in the region. The inventory created in this research will help researcher and policymaker to understand the present scenario of rock glacier's spatial distribution and the permafrost zone in the Api Nampa Conservation area.

Ethics Declarations

Data were collected in accordance with the code of conduct of research with Tribhuvan University Central Department of Geography. The data were mapped according to the standard guidelines for inventorying rock glaciers issued by IPA Action Group Rock glacier inventories and kinematics. This study was approved by the ethical committee of Geography Department.

Conflict of Interest

The author declare that they have no conflict of interest.

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