BILINGUAL PUBLISHING GROUP

Journal of Atmospheric Science Research
https://journals.bilpubgroup.com/index.php/jasr

ARTICLE

Crucial, But not Systematically Investigated: Rock Glaciers, the Concealed Water Reservoirs of the Himalayas: An Opinion

Sheikh Nawaz Ali [1*], ***Pratima Pandey*** [2*]

[1] *Birbal Sahni institute of Palaeosciences, Lucknow, 226007, India*
[2] *Indian Institute of Remote Sensing, Dehradun, 248001, India*

ABSTRACT

The current article is an opinion on the sensitivity of high mountain regions which are the most fragile, sensitive and vulnerable to ongoing climate change. Its impacts are especially severe on the high mountain communities owing to their weak socio-economic profile, limited livelihood resources and agricultural land. The melting of glaciers and changes in the snow cover under the climate change scenario is leading to the scarcity of freshwater supplies, affecting both local and downstream communities. Changes in the precipitation patterns have been suggested to cause droughts, impact restricted agriculture, and limit the availability of water for domestic use. Additionally, the high mountain areas contain distinct flora and fauna, and climate change is not just altering them, but also has resulted in biodiversity loss as species are unable to adapt to the changing climate. Because of its higher altitudes and semi-arid to arid climate, the consequences of climate change are more evident in the higher Himalayas. Climate change is affecting the availability of key resources, such as freshwater and agriculture and pasture lands, resulting in food and water insecurity and their reliance on imports from other regions. As a result, high mountain communities in the Himalayas are progressively shifting to higher glacier valleys in search of suitable cultivable land with adequate irrigation. People are engaging in agro-pastoral activities around thermokarst lakes (Oasis) atop rock glaciers as part of this endeavour. Such actions underscore the crucial role of rock glaciers in dealing with and adjusting to the consequences of climate change. Despite its relevance, rock glacier research in the Himalayan region is still in its infancy. The purpose of this work is to emphasise the significance of these major climate-resilient water resources, as well as the methodology that must be adopted for their systematic and compressive investigations.

Keywords: Climate change; Rock glaciers; Evolving agricultural practices; Systematic study; Higher Himalayas

*CORRESPONDING AUTHOR:
Sheikh Nawaz Ali, Birbal Sahni institute of Palaeosciences, Lucknow, 226007, India; Email: snawazali@gmail.com; Pratima Pandey, Indian Institute of Remote Sensing, Dehradun, 248001, India; Email: pratima@iirs.gov.in

ARTICLE INFO
Received: 14 March 2023 | Revised: 03 April 2023 | Accepted: 04 April 2023 | Published Online: 13 April 2023
DOI: https://doi.org/10.30564/jasr.v6i2.5541

CITATION
Ali, S.N., Pandey, P., 2023. Crucial, But not Systematically Investigated: Rock Glaciers, the Concealed Water Reservoirs of the Himalayas: An Opinion. Journal of Atmospheric Science Research. 6(2): 33-41. DOI: https://doi.org/10.30564/jasr.v6i2.5541

1. Introduction

Rock glaciers are landforms characterized by the presence of rock debris intermingled with ice, resulting in the formation of a frozen mass that moves down-slope due to gravity. They have been referred to as the complex shallow groundwater reservoirs/systems of the high mountain areas due to their hydrological significance [1]. The rock glaciers which are the most characteristic landforms of mountain permafrost, are typically found in high-mountain environments. Rock glaciers are usually found in permafrost areas, where the frozen ground serves as a natural barrier to water movement, forcing it to accumulate and freeze among the rock debris. Ice build-up causes the rock debris to become unstable and slowly flow downhill, producing the distinctive tongue-like morphology. The resilience of these ice-rich bodies to climate change makes them a key water management resource, with implications for future freshwater management if the glacier ice volume shrinks by about 77% (expected) by the end of the century. While there is a lot of data on the effects of climate change on glaciers and snow melt, knowledge concerning the storage and water discharge behaviour of permafrost-influenced landforms such as rock glaciers remains limited [2,3]. The condition is deeply worrying in mid-altitude areas (below 4000 masl), where complete glacier ice loss is predicted by the end of the century [1,4].

The situation become more critical for the High Mountain Asia region, because under the high-end climate model simulations (RCP8.5), the warming is expected to be more than 2 °C (global average) by the end of the 21st century resulting in glacier ice loss of ~95% [5]. **Figure 1** displays the Hindukush-Karakoram-Himalaya region susceptible to climate change. The contemporary glacier ice loss and the decrease in snow cover associated are already being witnessed in a number of catchments in this region, particularly during the spring and early summer [6-8]. This situation creates a strong need for climate adaptation measures in the high mountain area of Himalayas especially the ones that experience a semi-arid to the arid climate and depend largely on the glacier and snow melt for their domestic purposes and livelihoods. People have started engaging in agro-pastoral activities around thermokarst lakes (Oasis) atop rock glaciers as part of this endeavour [9]. Hence a comprehensive understanding of all components of the high-mountain cryosphere and the associated hydrological cycle is required [5,10]. Considering that rock glacier research in the Indian Himalayan region is in its infancy, the most of the studies are related to creating the rock glacier inventories [11-14].

Previously, rock glaciers were classified using a variety of terminologies, and rock glacier research was generally limited to making and compiling inventories, and identifying them as either intact (rock glaciers with permafrost) or relict (rock glaciers without permafrost or ice) using a simple compositional characteristic [15]. Using remote sensing images, however, discriminating between the two (intact and relict) is extremely difficult. As a consequence, the International Permafrost Association (IPA) developed a rock glacier classification system based on morphological and sedimentological criteria [16]. This system should be adhered to. Furthermore, such studies may be insufficient unless the actual amount of water that is stored in these features is estimated. This would help in better comprehending the hydrological support and, consequently, the significance for high mountain communities to deal with the effects of climate change, in addition to evaluating the potential for their variations in the future. This will also increase our knowledge of the behaviour of rock glaciers in response to continuing climate change, which is something that will continue to be very important for future generations. As a result, it is necessary to combine our scientific resources and efforts in order to methodically research and comprehend the Himalayan rock glacier and their resistance to the anticipated climate change.

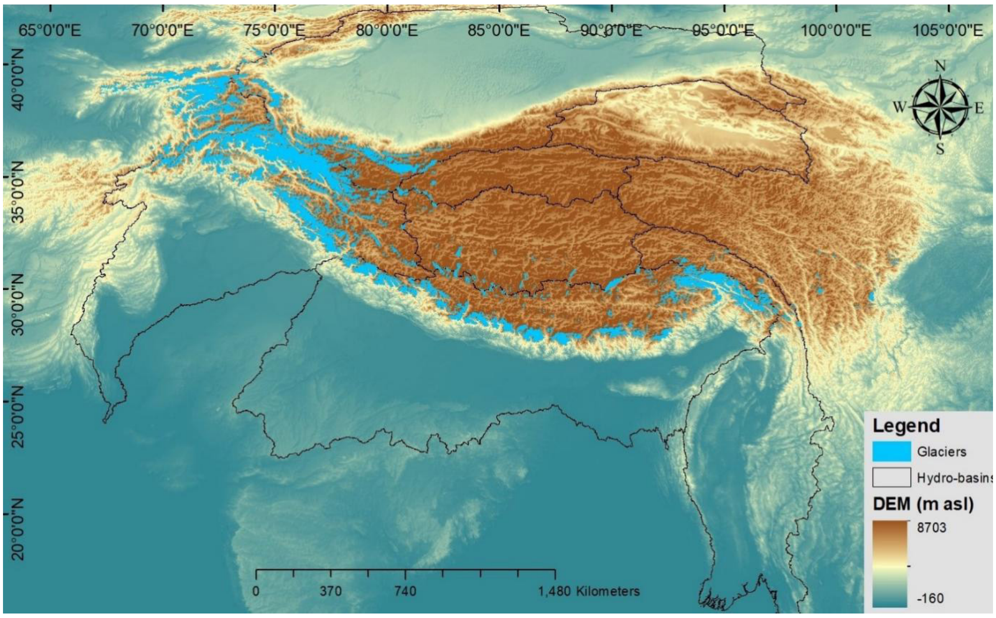

Figure 1. Shuttle Radar Topography Mission (SRTM) digital elevation model (DEM) showing the regional topography and the distribution of glaciers over the Hindukush-Karakoram-Himalaya (HKH) region. The glacier boundaries are derived from the Global Land Ice Measurements from Space (GLIMS) data.

2. Rock glacier classifications

With the recognition of rock glaciers as an integral part of the cryosphere, they have been categorized based on numerous characteristics such as morphology, geometry, activity, topographical association, and origin [17]. A fundamental classification of rock glaciers has been established based on their dynamic activity and the presence of ice [17,18]. Rock glaciers are classified as active, inactive, or fossils/relict based on their dynamic activity and ice presence [15]. Active rock glaciers contain a large volume of ice and creep downslope by a few centimetres to a few metres annually under gravity [19-21]. Inactive rock glaciers also have permafrost but are static, while relict rock glaciers lack both ice and movement, suggesting the existence of permafrost in the past [22]. Intact rock glaciers refer to both active and inactive rock glaciers [15]. Despite some disagreement about their genesis and formation [23], rock glaciers may be characterised based on their origin and ice presence and are divided into the glacial origin and periglacial origin [24]. Rock glaciers are classified into four types based on their morphological and sedimentological characteristics: 1) Tongue-shaped rock glaciers: These are the most common type of rock glacier and are characterized by a steep front and a long tongue-shaped extension. They typically have a well-defined lateral margin and a distinct accumulation area at the top (**Figure 2a**). 2) Lobate rock glaciers: These are similar to tongue-shaped rock glaciers but have a more irregular shape. They are characterized by a broad and lobate front and may have multiple tongues (**Figure 2b**). 3) Rounded rock glaciers: These have a more rounded shape than tongue-shaped or lobate rock glaciers and are typically smaller in size. They are characterized by a smooth front and a more gradual slope (**Figure 2c**). 4) Blocky rock glaciers: These are characterized by a blocky surface and a jagged, irregular front. They typically have a shallow accumulation area and are found in areas with more fractured bedrock (**Figure 2d**).

The International Permafrost Association (IPA) classification seems more robust as it is based on a combination of morphological and sedimentological characteristics, including the shape of the front, the presence of lateral moraines, the presence of permafrost, and the type of sediment present in the rock glacier [16]. We recommend this system be widely used in the field of permafrost and rock glacier studies to classify and describe different types of rock glaciers. The classification of rock glaciers based on their connection to other landforms provides a useful framework for understanding the physical processes that shape these landforms and the environmental conditions under which they form. It also highlights the importance of considering the broader landscape context when studying rock glaciers and their role in mountain environments. Following a standard classification will remove the bias and/or incongruity in the data generated. The IPA classification system categorizes rock glaciers into four types discussed below and displayed in **Figure 3**:

1) Glacier-connected (GC): These rock glaciers are connected to a glacier or ice sheet and are often found at the toe of a glacier. They are characterized by a steep front and a long tongue-shaped extension, similar to tongue-shaped rock glaciers in the IPA classification (**Figure 3a**).

2) Talus-connected (TC): These rock glaciers are connected to talus slopes and are typically found on the lower slopes of mountains. They are characterized by a more irregular shape and a front that is often covered in loose rock debris (**Figure 3b**).

3) Glacier forefield-connected (GFC): These rock glaciers are located in glacier forefields, which are areas of newly exposed terrain at the toe of a glacier. They are characterized by a broad, fan-shaped front and may have multiple tongues (**Figure 3c**).

4) Debris-mantled slope-connected (DC): These rock glaciers are located on slopes covered in loose rock debris and are often found in areas with permafrost. They are characterized by a blocky surface and a more irregular shape than other types of rock glaciers (**Figure 3d**).

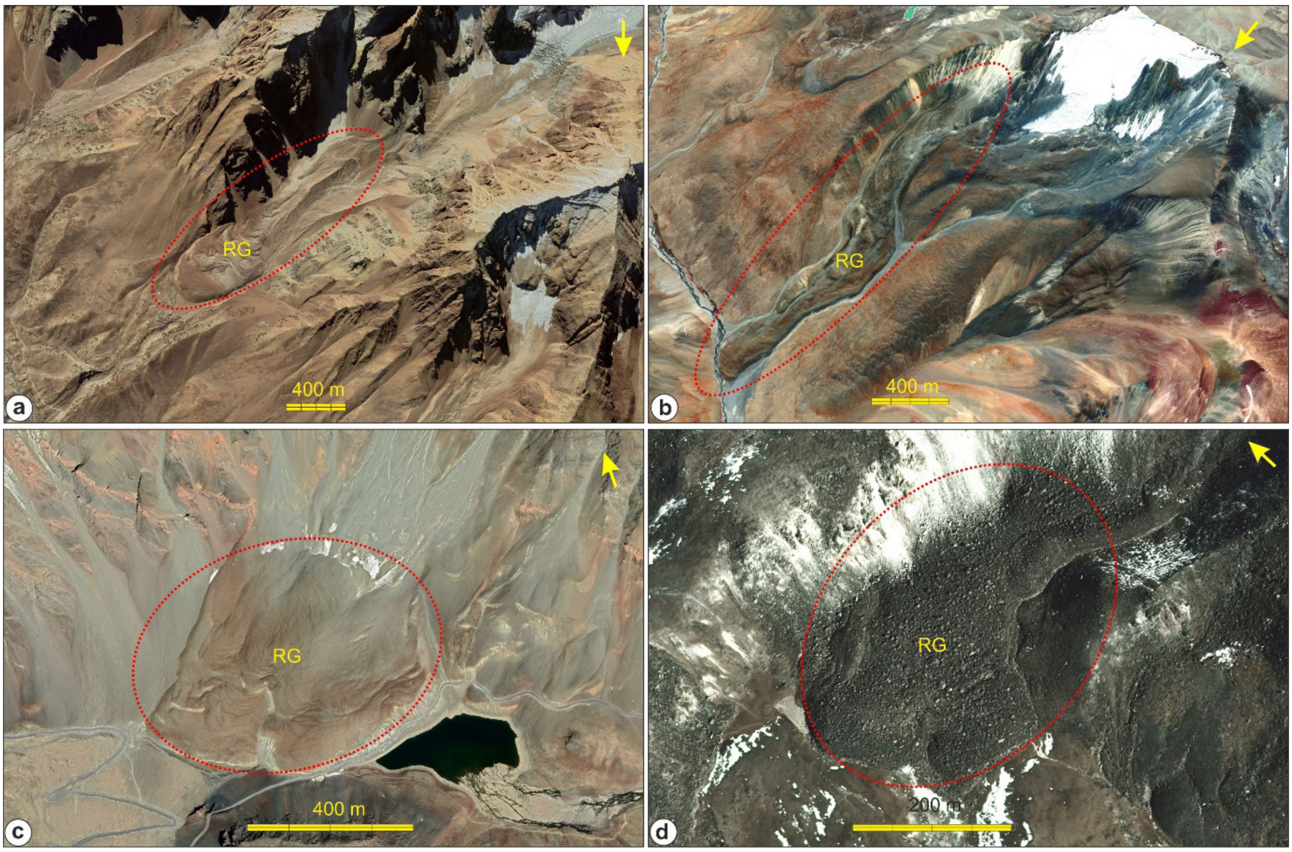

Figure 2. Showing different types of rock glacier (RG) on the Google Earth Pro imagery. a) Tongue-shaped rock glacier; b) Lobate rock glacier; c) Rounded rock glacier, and d) Blocky rock glacier.

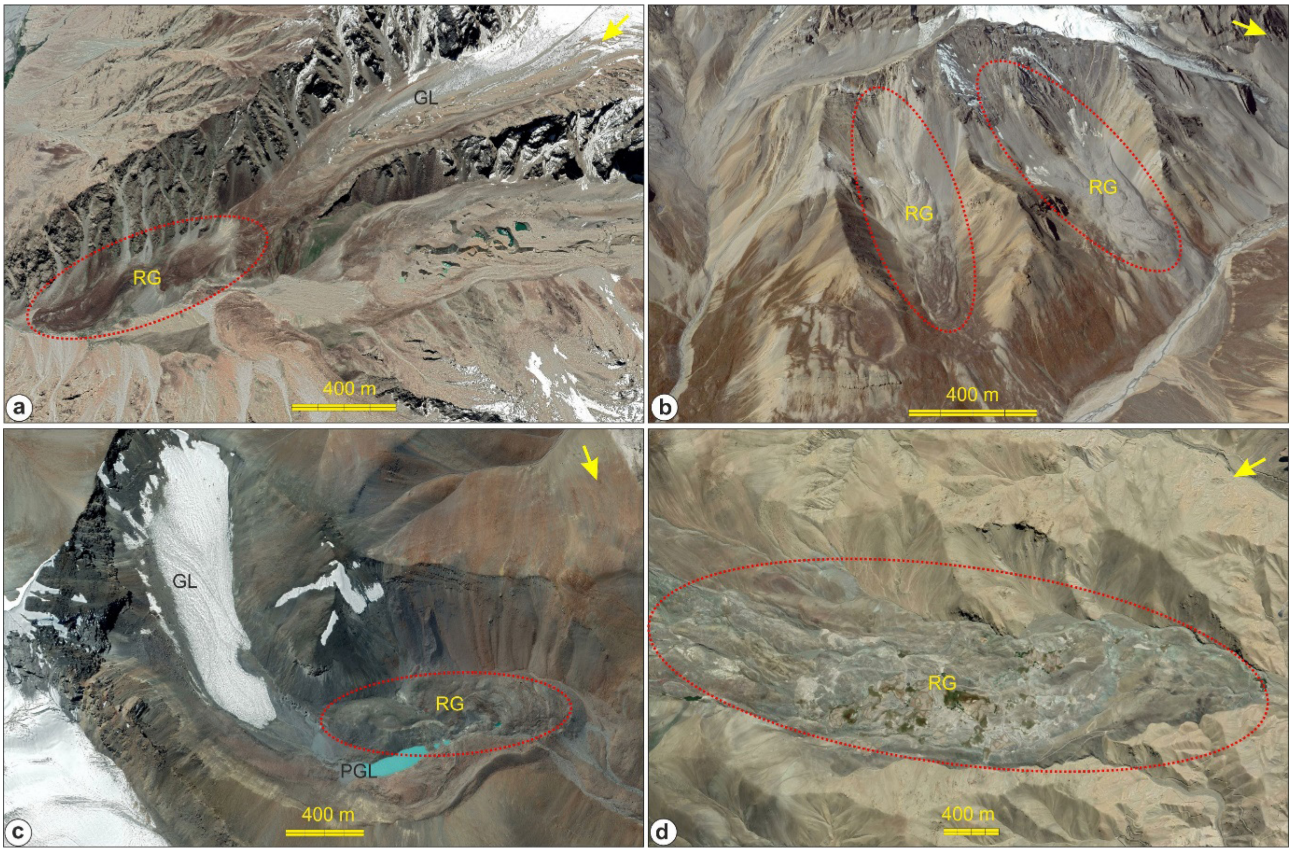

Figure 3. IPA classification is based on different types of rock glacier shown on the Google Earth Pro imagery. a) Glacier-connected rock glacier; b) Talus-connected rock glacier; c) Glacier forefield-connected rock glacier, and d) Debris-mantled slope-connected rock glacier.

Note: RG-rock glacier; GL-glacier and PGL-pro-glacial lake.

3. Systematic rock glacier research

Systematic rock glacier research entails examining the formation, characteristics, hydrological behaviour, and dynamics of rock glaciers at both the local and regional scales, particularly in the context of climate change. As rock glacier research in the Himalayan region is still in its embryonic stage, a properly developed standard strategy for monitoring them, assessing their hydrological behaviour and potential, and evaluating their resilience to climate warming would greatly aid in fostering understanding among policymakers and stakeholders. The characteristics of the rock and ice that make up the glacier, as well as the local geography, geological history, and climate may all be studied in this process. Hence, a multidisciplinary approach is necessary for the proper understanding of these important water reserves (**Figure 4**). The following steps could make up the strategy for investigating rock glaciers:

1) Inventory of rock glaciers: The first and foremost prerequisite for developing understanding is the identification and inventory of the rock glaciers. The ID of rock glaciers, type of rock glacier, origin, and kinematics should all be included in the inventory along with geographical information.

2) Geophysical Investigation: Geophysical investigation is very crucial for comprehending the internal structure and composition of rock glaciers in terms of hydrological perspectives. To ascertain the underlying structure, presence of ice, and depth of bedrock, a geophysical study may be conducted using ground penetrating radar (GPR), electrical resistivity tomography (ERT), and seismic refraction.

3) Topo-climatic characteristics: Rock glaciers are considered as the physical proof or validation of permafrost existence. Permafrost formation is

influenced by a number of topographical factors, including mean annual air temperature (MAAT), sun radiation, and slope aspect. Rock glaciers' topographical climatic and temperature regimes are crucial factors in determining whether or not they can serve as an accurate proxy for permafrost spread. To comprehend the temperature of the subsurface and the composition of rock glaciers, boreholes should be employed extensively.

4) Hydrological significance: A thorough evaluation of the occurrences, characteristics, and internal structure of rock glaciers might also be used to model the percentage of water volume equivalent of rock glaciers for their water reserve capacity in the future.

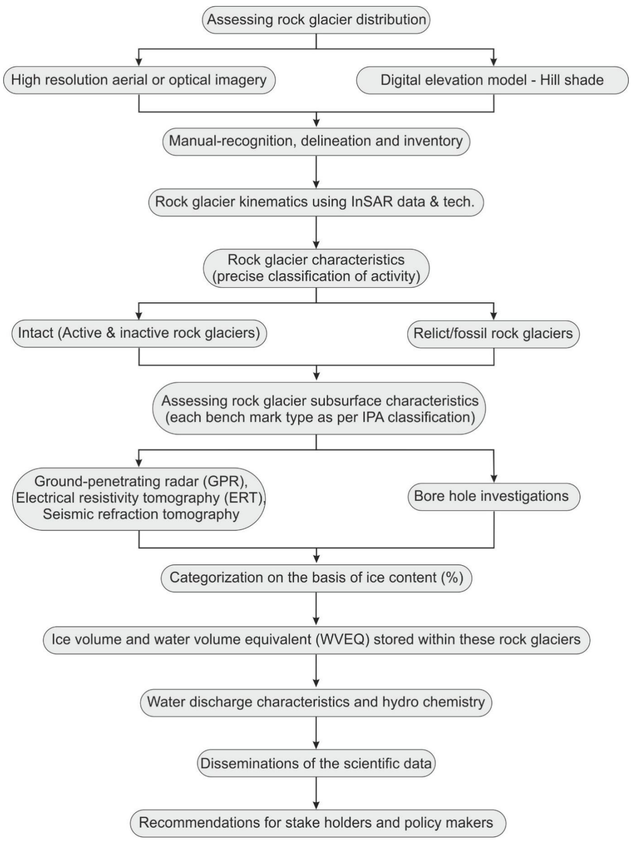

Figure 4. The flowchart shows the strategy and steps required for rock glacier studies.

4. Discussion

Under the ongoing warming scenario, the 0 °C isotherm is and will gradually increase in elevation and result in further melting of the glacier ice, snowpack and permafrost [25]. This is going to affect the mountain hydrology and alter the geo-ecological zones and stress the high mountain areas including communities that generally depend on these water resources. The repercussions of climate change are worrisome in the Himalayas where the future model projections show a warmer and wetter climate, with significant implications for high-mountain glacier cover and glacial lake expansion [26]. In such a situation, the climate-resilient and substantial rock glaciers will act as buffers against these changes. Hence overall, research on rock glaciers is important for comprehending their role in mountain environments, predicting their future behaviour, and managing potential hazards associated with their movement is needed. The key areas of research on rock glaciers in the high mountain Himalayas must include: (1) Mapping and creating rock glacier inventories. Rock glaciers in the Himalayas are often difficult to locate and study due to their remote locations in the rugged terrain and harsh climate. Therefore, researchers need to map and inventory rock glaciers in the region using high-resolution remote sensing imageries and techniques. (2) Understanding the Formation and evolution of rock glaciers because understanding the factors that contribute to the formation and evolution of rock glaciers is important for predicting their future behaviour. Hence the information about the geology, hydrology, and climate conditions that lead to the formation of rock glaciers, as well as the mechanisms that cause them to move needs to be critically investigated. (3) Studying the movement and dynamics of rock glaciers will further help in understanding their behaviour. The rock glacier can move at rates ranging from a few centimetres to several meters per year. Researchers may use various techniques, such as ground-based surveys, remote sensing, and modelling, to monitor the movement and dynamics of rock glaciers. This information is crucial for predicting the potential hazards associated with rock glacier movements, such as landslides and rockfall. (4) Understanding the impacts on water resources is one of the most important factors for societal implications. Rock glaciers will form an important source of water in mountain environments, as they can act as natural reservoirs and release water gradually over time. Research on the hydrological processes of rock glaciers, including water storage and release, must be conducted in order to comprehend their influence on water resources and guide water resource management strategies, and (5) finally the impact on infrastructure development. Rock glaciers can pose a significant hazard to infrastructure development, such as the construction of roads and buildings, due to their potential for movement and instability. High-resolution maps of rock glaciers and permafrost need to be developed for the categorization of potential hazards associated with rock glaciers to inform infrastructure planning and design.

Estimating the water volume stored in rock glaciers is the most crucial and challenging task, particularly in the Himalayas where many of the rock glaciers are located in remote and difficult-to-access areas (**Figure 5**). As a result, there is a lack of accurate water volume estimates for rock glaciers in the Himalayas. One of the primary reasons for the lack of water volume estimates is the limited data on the internal structure of rock glaciers. Rock glaciers are complex structures consisting of a mixture of ice, rock debris, and water, and their internal structure can vary significantly from one location to another. This makes it challenging to estimate the water volume stored in a rock glacier accurately. Rock glaciers can act as natural reservoirs, storing water in the form of ice and releasing it gradually over time. However, the precise mechanisms by which water is stored and released from rock glaciers are not well understood, particularly in the Himalayas. Despite these challenges, efforts are being made to estimate the water volume stored in rock glaciers in the Himalayas. Remote sensing techniques, such as satellite imagery and aerial photography, are being used to map and inventory rock glaciers in the region, providing valuable data for estimating their water storage capacity.

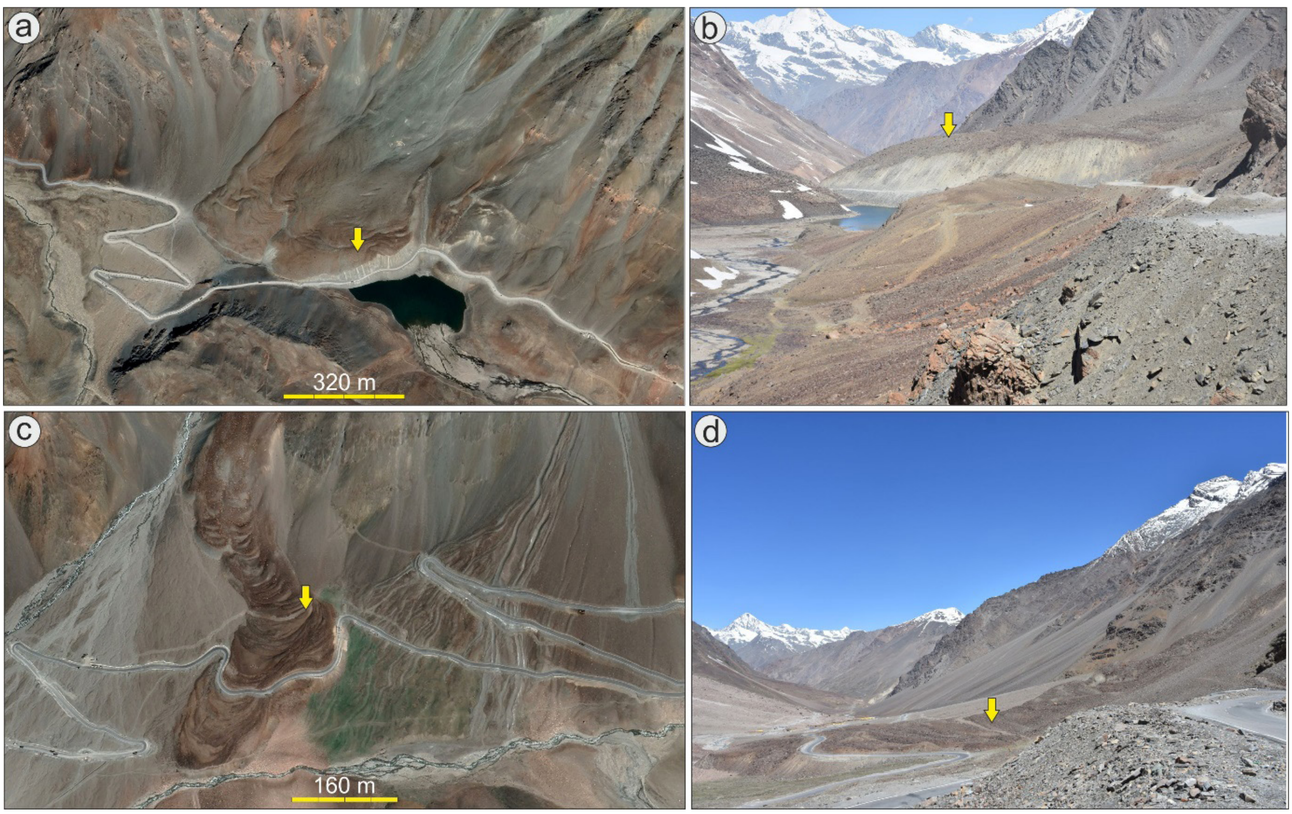

Figure 5. Google Earth images and Filed photographs of two prominent rock glacier in the Bhaga watershed of the western Himalayas, India.

However, ground-based surveys and monitoring programs must be implemented to study the hydrological processes associated with rock glaciers. Till date, the rock glacier water volume equivalent (WVEQ) estimation is being carried out by the empirical thickness-area scaling relations which is a 2-D-area- related statistic [10]. These estimates are crude in nature unless filed-based data are available from different types of rock glaciers discussed in section 2. The volumetric estimates of the ice content in the rock glaciers are also based on assumptions and hence a wide range of ice content is assumed. It ranges from 40%-60% (lowest 40%, mean 50%, and upper limits 60%), but Wagner et al. [1] adjusted the lower bound to 20% to account for the likelihood of less ice content in inactive rock glaciers in the Austrian Alps. This creates a huge difference in the estimation of WVEQ. Therefore, at least some ground-based data on the thickness and ice volume percentages should be made available so that the estimation is genuine. This will include a systematic investigation of different types of rock glaciers like the glacier-connected (GC) rock glaciers, talus-connected (TC) rock glaciers, debris-mantled slope-connected (DC) rock glaciers, and glacier forefield-connected (GFC) rock glaciers.

5. Conclusions

Mountainous regions' cryospheric water supplies are at risk due to climate change. Thus it's important to understand the hydrological cycle as a whole in order to manage these resources. Future global warming may cause rock glaciers to become more significant hydrologically, yet despite their greater climate adaptability than glaciers and potential for beneficial ice accumulation, rock glaciers have received less attention. Systematic investigations of rock glaciers in a changing environment are crucial for improving our knowledge of how to rock glaciers behave in mountain environments and for predicting future behaviour. There aren't many baseline statistics from the Himalayan region, despite it being significant. By studying how climate change impacts rock glaciers, researchers may get a crucial understanding of the potential implications on water supply, natural disasters, and infrastructure. Use of this information is necessary to develop effective management and adaption strategies for the changing climate.

Conflict of Interest

There is no conflict of interest.

Acknowledgements

The authors are thankful to the Directors of Birbal Sahni Institute of Palaeosciences (BSIP), Lucknow and Indian Institute of Remote Sensing (ISRO), Dehradun for providing infrastructure, encouragement and support.

References

[1] Wagner, T., Kainz, S., Helfricht, K., et al., 2021. Assessment of liquid and solid water storage in rock glaciers versus glacier ice in the Austrian Alps. Science of the Total Environment. 800, 149593.

[2] Geiger, S.T., Daniels, J.M., Miller, S.N., et al., 2014. Influence of rock glaciers on stream hydrology in the La Sal Mountains, Utah. Arctic, Antarctic, and Alpine Research. 46(3), 645-658.

[3] Rogger, M., Chirico, G.B., Hausmann, H., et al., 2017. Impact of mountain permafrost on flow path and runoff response in a high alpine catchment. Water Resources Research. 53(2), 1288-1308.

[4] Shannon, S., Smith, R., Wiltshire, A., et al., 2019. Global glacier volume projections under high-end climate change scenarios. Cryosphere. 13, 325-350.

[5] Jones, D.B., Harrison, S., Anderson, K., et al., 2021. Rock glaciers represent hidden water stores in the Himalaya. Science of The Total Environment. 793, 145368.

[6] Ming, J., Wang, Y., Du, Z., et al., 2015. Widespread albedo decreasing and induced melting of Himalayan snow and ice in the early 21st

century. PLoS One. 10(6), e0126235.

[7] Gurung, D.R., Maharjan, S.B., Shrestha, A.B., et al., 2017. Climate and topographic controls on snow cover dynamics in the Hindu Kush Himalaya. International Journal of Climatology. 37, 3873-3882.

[8] Smith, T., Bookhagen, B., 2018. Changes in seasonal snow water equivalent distribution in High Mountain Asia (1987 to 2009). Science Advances. 4, e1701550.

[9] Pandey, P., Ali, S.N., Allen, S., 2022. Rock glacier Oasis: An alternative for agro-pastoralism in a changing environment in the Himalayan cold desert. The Geographical Journal. 188(4), 585-590. DOI: https://doi.org/10.1111/geoj.12468

[10] Jones, D.B., Harrison, S., Anderson, K., et al., 2021. Rock glaciers represent hidden water stores in the Himalaya. Science of The Total Environment. 793, 145368.

[11] Baral, P., Haq, M.A., Yaragal, S., 2019. Assessment of rock glaciers and permafrost distribution in Uttarakhand, India. Permafrost and Periglacial Processes. 31, 31-56.

[12] Pandey, P., 2019. Inventory of rock glaciers in Himachal Himalaya, India using high-resolution Google Earth imagery. Geomorphology. 340, 103-115.

[13] Majeed, Z., Mehta, M., Ahmad, M., et al., 2022. Active rock glaciers of Jhelum basin, Kashmir Himalaya, India. Indian Journal of Geosciences. 76(1), 107-124.

[14] Chakravarti, P., Jain, V., Mishra, V., 2022. The distribution and hydrological significance of intact rock glaciers in the north-west Himalaya. Geografiska Annaler: Series A, Physical Geography. 104(3), 226-244.

[15] Barsch, D., 1996. Rock glaciers: Indicators for the present and former geoecology in high mountain environments. Springer-Verlag: Berlin. pp. 331.

[16] RGIK, 2021. IPA Action Group Rock Glacier Inventories and Kinematics [Internet]. Towards Standard Guidelines for Inventorying Rock glaciers: Baseline Concepts (version 4.2.1). Available from: https://bigweb.unifr.ch/Science/Geosciences/Geomorphology/Pub/Website/IPA/Guidelines/V4/210801_Baseline_Concepts_Inventorying_Rock_Glaciers_V4.2.1.pdf

[17] Martin, H.E., Whalley, W.B., 1987. Rock glaciers: Part 1: Rock glacier morphology: Classification and distribution. Progress in Physical Geography. 11, 260-282.

[18] Wahrhaftig, C., Cox, A., 1959. Rock glaciers in the Alaska Range. Geological Society of America Bulletin. 70, 383-436.

[19] Kääb, A., Kaufmann, V., Ladstadter, R., et al., 2003. Rock glacier dynamics: Implications from high-resolution measurements of surface velocity fields. Eighth International Conference on Permafrost. 1, 501-506.

[20] Berger, J., Krainer, K., Mostler, W., 2004. Dynamics of an active rock glacier (Otztal Alps, Austria). Quaternary Research. 62, 233-242.

[21] Necsoiu, M., Onaca, A., Wigginton, S., et al., 2016. Rock glacier dynamics in Southern Carpathian mountains from high resolution optical and multi-temporal SAR satelliteimagery. Remote Sensing of Environment. 177, 21-36.

[22] Haeberli, W., 1985. Creep of mountain permafrost: Internal structure and flow of Alpine rock glaciers. Mitteilungen der Versuchsanstalt fur Wasserbau. Hydrologie und Glaziologiean der ETH Zurich. 77, 5-142.

[23] Berthling, I., 2011. Beyond confusion: Rock glaciers as cryo-conditioned landforms. Geomorphology. 131(3-4), 98-106.

[24] Haeberli, W., Hallet, B., Arenson, L., et al., 2006. Permafrost creep and rock glacier dynamics. Permafrost and Periglacial Processes. 17(3), 189-214.

[25] Iribarren, P.A., Kinney, J., Schaefer, M., et al., 2018. Glacier protection laws: Potential conflicts in managing glacial hazards and adapting to climate change. Ambio. 47(8), 835-845.

[26] Ali, S.N., Pandey, P., Singh, P., et al., 2023. Intimidating evidences of climate change from the higher Himalaya: A case study from Lahaul, Himachal Pradesh, India. Journal of the Indian Society of Remote Sensing.