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Rock glaciers represent hidden water stores in the Himalaya

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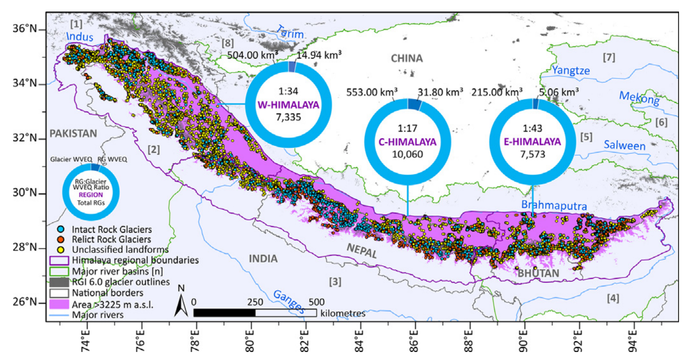
HIGHLIGHTS

- We present the first Himalayan rock glacier inventory, derived using Google Earth.
- Approx. 25,000 rock glaciers, covering an estimated 3747 km^2, were identified.
- Himalayan rock glaciers contain an estimated water volume equivalent of 51.80 km^3.
- Himalayan rock glacier to ice glacier water storage ratio is 1:25.
- Under future climate warming, Himalayan rock glaciers are hydrologically valuable.

GRAPHICAL ABSTRACT



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ABSTRACT

In the high mountains of Asia, ongoing glacier retreat threatens human and ecological systems through reduced water availability. Rock glaciers are climatically more resistant than glaciers and contain valuable water volume equivalents (WVEQ). Across High Mountain Asia (HMA) the WVEQ of rock glaciers is poorly quantified, and thus their hydrological significance versus glaciers is unknown. Here we present the first systematic assessment of Himalayan rock glaciers, totalling ~25,000 landforms with an areal coverage of ~3747 km^2. We calculate the WVEQ of Himalayan rock glaciers to be 51.80 ± 10.36 km^3. Their comparative importance versus glaciers (rock glacier: glacier WVEQ ratio) is 1:25, which means that they constitute hydrologically valuable long-term water stores. In the context of climate-driven glacier recession, their relative hydrological value will likely increase. These cryospheric stores should be included in future scenario modelling to understand their role in sustainable water management for HMA.

1. Introduction

The cryosphere of High Mountain Asia (HMA), which comprises the Tibetan Plateau and its surrounding mountain ranges (including the Himalaya, Karakoram, Tien Shan, and Pamir), forms water towers that are integral for ecosystem services provision, and for servicing the multiple societal needs of ~800 million people living in the mountains and

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surrounding lowlands (Pritchard, 2019). These mountain water towers (e.g., Indus and Ganges-Brahmaputra) are among the most important globally. However, most are also highly vulnerable as they are "transboundary, densely populated, heavily irrigated basins and their vulnerability is primarily driven by high population andeconomic growth rates and, in most cases, ineffective governance" (Immerzeel et al., 2020). Furthermore, considerable and continued glacier mass loss is projected throughout this century (Kraaijenbrink et al., 2017; Hock et al., 2019; Shannon et al., 2019). A high-end climate change scenario (Representative Concentration Pathways [RCP] 8.5) is projected to lead to a HMA glacier volume loss of ~95% relative to the present-day (Shannon et al., 2019). Volume losses are driven by an average temperature change of +5.9 °C and a +20.9% rise in average precipitation, the latter increasingly of rain rather than snow (Fig. 1). Indeed, reductions in snow water equivalent have been reported for a number of catchments in HMA, particularly during spring and summer (Smith and Bookhagen, 2018). For the RCP4.5 scenario, most basins fed by HMA glaciers are projected to reach peak water by ~2050: 2045 ± 17 years (Indus), 2044 ± 21 years (Ganges) and 2049 ± 18 years (Brahmaputra), for example (Huss and Hock, 2018).

Given the need for strong climate adaptation in HMA, a clearer understanding of all components of the hydrological cycle in the high-mountain cryosphere is required (Jones et al., 2019). Recent research shows that rock glaciers constitute globally significant long-term water stores (Jones et al., 2018a). Rock glaciers are masses of poorly sorted, angular-rock debris bound together by massive ice or an ice-cemented matrix, which creep slowly downslope (Martin and Whalley, 1987; Barsch, 1996; Haeberli et al., 2006; Berthling, 2011). Typically, rock glaciers are characterised by distinctive flow-like morphometric features, including spatially organised transverse and longitudinal ridge-and-furrow assemblages, and steep (approx. >30–35°; gradients of >40° have been observed [Krainer et al., 2012]) and sharp-crested frontal and lateral slopes (Wahrhaftig and Cox, 1959; Baroni et al., 2004; Kääb and Weber, 2004) (Fig. 2). They are further characterised by a continuous, thick seasonally frozen debris layer (known as the active layer [AL]) – owing to the insulating and damping properties of the AL, rock glaciers are considered to be climatically more resistant than debris-free and debris-covered glaciers. Consequently, their relative hydrological importance vs glaciers will increase under future climate warming (Jones et al., 2018a; Jones et al., 2019).

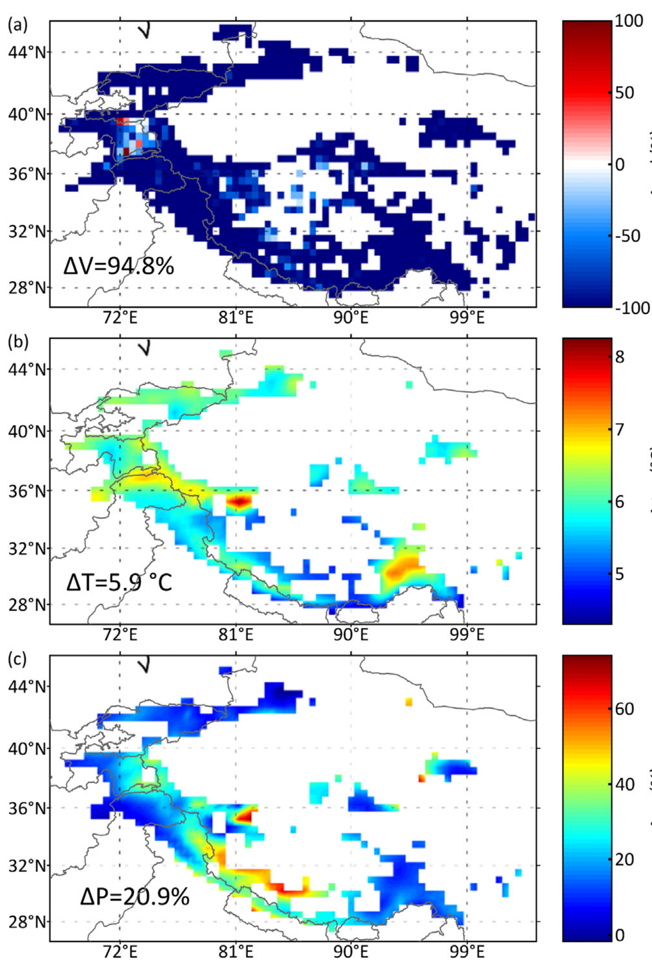

Fig. 1. (a) Ensemble glacier mean glacier volume loss, (b) air temperature change, and (c) precipitation change between the historical period (1980–2010) and the end of this century (2067–2097) over glaciated grid points in the high mountains of Asia. See the Supplementary methods for the description of the climate modelling implemented here.

Yet, to date, with a few notable exceptions (Jones et al., 2019; Schaffer et al., 2019), the hydrological role of rock glaciers globally has been afforded little attention compared to both debris-free glaciers (Fountain and Walder, 1998; Jansson et al., 2003; Irvine-Fynn et al., 2011) and debris-covered glaciers (Fyffe et al., 2019, and references therein). In the Himalaya, a recent impactful report synthesised and evaluated the state of current scientific knowledge regarding changes in the high-mountain cryosphere; however, rock glaciers received no critical attention (Bolch et al., 2019). Furthermore, while systematic rock glacier inventory coverage has increased globally, HMA is comparatively data-deficient (Jones et al., 2018a). Across HMA, with few exceptions (Jones et al., 2018b; Blöthe et al., 2019; Pandey, 2019; Baral et al., 2020), rock glacier inventories have been conducted at localised sites, over relatively small spatial scales or using non-spatially explicit methods (Regmi, 2008; Bolch and Gorbunov, 2014; Schmid et al., 2015). As a result, the distribution and hydrological value of rock glaciers remains unknown. In HMA, Pritchard (2019) notes that "detailed and comprehensive assessments of the future water availability in the region are only possible once the present hydrological regime is better quantified (Miller et al., 2012)". Therefore, we argue that quantifying rock glacier WVEQ across HMA is a critical requirement to quantify the present, and future, hydrological regime of the region.

Consequently, our primary objective was to calculate the first estimation of rock glacier WVEQ across the Himalaya. To do this we compiled the first systematic rock glacier inventory for the Himalaya, from which rock glacier WVEQ was quantified. Subsequently we assessed their comparative importance vs glaciers (i.e. rock glacier: glacier WVEQ ratio) across a range of spatial scales – west Himalaya, central Himalaya, and east Himalaya.

2. Materials and methods

2.1. Rock glacier inventory compilation

In the Google Earth Pro platform (version 7.1.8.3036), we used publicly available current and archived satellite image data, including fine spatial resolution CNES/Airbus (e.g., SPOT and Pleiades) and DigitalGlobe-derived imagery (e.g., Worldview-1 and 2, and QuickBird), to generate a systematic rock glacier inventory for the Himalaya region. Large-scale geomorphological surveys have been facilitated by the Google Earth Pro platform, including several systematic rock glacier inventories (e.g., Rangecroft et al., 2014; Schmid et al., 2015; Charbonneau and Smith, 2018; Jones et al., 2018b; Pandey, 2019). Therefore, there is precedent for the use of the Google Earth Pro platforms for the primary objective stated above.

A gridded search methodology approach was employed to ensure inventory compilation was systematic and exhaustive. In ESRI ArcGIS (version 10.6.0.8321), a gridded overlay of 40 km^2 grid squares covering the study region was created. This shapefile was subsequently imported into Google Earth Pro and each grid square was visually surveyed on an individual basis. Here, the geomorphic indicators outlined in Table 1

Fig. 2. Typical examples of active [a, b], inactive [c, d] and relict [e, f] rock glaciers from around the world including the Himalaya: (a) active rock glacier, west Himalaya (32°46′N, 78°10′E); (b) Caquella rock glacier, Bolivian Andes of South Lipez, Bolivia (21°29′S, 67°55′W); (c) Liapey d'Enfer rock glacier, Hérens valley, Swiss Alps, Switzerland (46°05′N, 7°32′E); (d) rock glaciers in the Niggelingtälli, Turtmann Valley, Swiss Alps, Switzerland (46°13′N, 7°45′E); (e) Hoelltal rock glacier, Niedere Tauern Range, Central Eastern Alps, Austria (47°22′N, 14°39′E); and (f) rock glaciers beneath Le Mourin mountain, Valais, Swiss Alps, Switzerland (45°56′N, 7°10′E). On the photographs, dashed lines correspond to the approximate rock glacier boundary. Images [a–f] from Google Earth. Modified after Jones et al. (2019).

Table 1
Geomorphic indicators used to identify rock glaciers and their activity status.

Geomorphic indicator	Active	Relict
Surface flow structure	Defined furrow-and-ridge topography (Kääb and Weber, 2004)	Less defined furrow-and-ridge topography (Kääb and Weber, 2004)
Rock glacier body	Swollen body (Baroni et al., 2004)	Flattened body (Baroni et al., 2004)
	Surface ice exposures (Potter et al., 1998)	Surface collapse features (Barsch and King, 1975 as cited in Janke et al. [2013])
Front slope	Steep (~>30–35°) (Baroni et al., 2004)	Gently sloping (~<30°) (Baroni et al., 2004)
	Abrupt transition (i.e. sharp-crested) to the upper surface (Wahrhaftig and Cox, 1959)	Gentle transition (i.e. round crested) to the upper surface (Wahrhaftig and Cox, 1959)
	Light-coloured (little clast weathering) frontal zone and a darker varnished upper surface (Bishop et al., 2014)	

were used to identify rock glaciers. Nota bene, notwithstanding the semantic connection between them, rock glaciers and debris-covered glaciers constitute distinct landforms (Hambrey et al., 2008; Benn and Evans, 2010; Cogley et al., 2011; Kirkbride, 2011). Distinguishing between rock glaciers and debris-covered glaciers is therefore important, particularly when reviewing the hydrological significance of the former; grouping these features would erroneously inflate the hydrological significance of rock glaciers (Jones, 2020, p. 46). Debris-covered glaciers characteristically have a discontinuous or continuous mantle of surface debris (typically less than several-decimetres thick) in their ablation zones, and a topographically complex, spatially-chaotic mosaic of surficial features; hummocks, depressions, supraglacial melt ponds and frequent ice exposures (e.g., ice cliffs), for example. In this study, the above-described characteristics were used to exclude debris-covered glaciers from the systematic rock glacier inventory.

Rock glaciers were pinned within Google Earth Pro, and an initial point-based inventory was created for the Himalaya. In ArcGIS, the point-based inventory was organised according to the sub-regions originally defined by Bolch et al. (2012): west Himalaya, central Himalaya, and east Himalaya (Fig. 3). Note that the Nepalese Himalaya, which constitutes a considerable portion of the central Himalaya, has previously been surveyed by the present authors using the methodology described here (see Jones et al., 2018b). In Jones et al. (2018b), for the Nepalese Himalaya a ~20% randomly selected sample was digitised (1137 of 6239 total inventoried rock glaciers). Due to the large size of the additional inventory presented in the present paper (18,729 additional rock glaciers), the sample size was set to ~5% in order to keep a reasonable sample size. Consequently, for each region a ~5% sample of the point-based inventory was randomly selected within ArcGIS using the Subset Features tool and digitised: west Himalaya ($n = 363$); central Himalaya ($n = 192$); and east Himalaya ($n = 378$).

The geographic boundaries of rock glaciers selected for the ~5% regional samples were digitised within Google Earth Pro, forming a polygonised inventory within which the 2-D spatial attributes (e.g., area) were measured. Multi-temporal satellite image data (2000–2019) was used to effectively reduce the mapping uncertainty associated with poor image quality data affected by long-cast shadows on steep north-facing slopes, cloud cover, and snow cover, for instance (Jones et al., 2018b). Here, the methodology of Scotti et al. (2013) was adopted for rock glacier digitisation. The outline of the entire rock glacier surface was delineated, extending from the rooting zone (i.e. uppermost extent) to the foot of the front slope (i.e. lowermost extent). Where multiple landforms coalesce into a single body, digitisation was challenging. In this study, "when the frontal lobes of two (or more) rock glaciers originating from distinct source basins join downslope, we consider the two components as separate bodies. Where the limits between lobes are unclear and the lobes share other morphological characteristics (see Table 1), we classify the whole system as a unique rock glacier" (Scotti et al., 2013). Occurrences where rock glaciers grade into upslope landforms, for instance where a rock glacier is gradually developing from a terminal or lateral moraine, "a clear distinction between the two landforms cannot be set and we delineated the whole

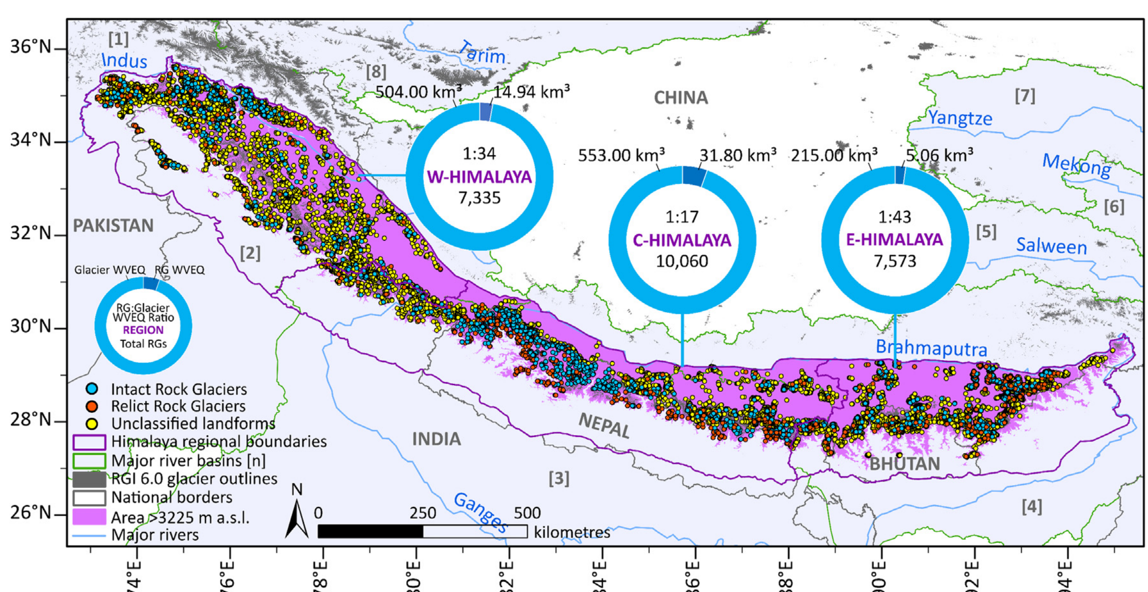

Fig. 3. Map depicting the distribution of rock glaciers across the Himalaya. Rock glaciers with unclassified dynamic status (i.e. landforms not digitised as part of the sampling strategy) are included here for completeness. The total rock glacier number, rock glacier and glacier WVEQ and rock glacier: glacier WVEQ ratios for the west, central and east Himalaya regions are shown. These regional outlines were derived from Bolch et al. (2012). Note that rock glacier WVEQ values presented here assume 50% (average) ice content by volume. The area >3225 m a.s.l. represents the terrain above the minimum elevation at which rock glaciers were found. The major river basin boundaries are also shown: [1] Amu Darya, [2] Indus, [3] Ganges, [4] Brahmaputra, [5] Salween, [6] Mekong, [7] Yangtze, and [8] Tarim.

body (i.e. moraine plus rock glacier)" (Scotti et al., 2013). In ArcGIS, the present study used the Universal Transverse Mercator (UTM) WGS 84 projected coordinate system – UTM Zone 43N to 46N – in order to quantify rock glacier area [and thus WVEQ]. In Google Earth Pro the dynamic status of landforms was determined considering their presumed ice content and movement, according to an existing morphological classification (Barsch, 1996), established using geomorphic indicators (Table 1). The sampled rock glaciers were categorised as: (i) active landforms, containing ice and displaying proxies for movement; (ii) inactive landforms, containing ice and not displaying proxies for movement; and (iii) relict landforms, not containing ice nor displaying movement characteristics (Haeberli, 1985; Barsch, 1996). Note, as the geomorphic indicators represent a surficial expression of the presence of abundant ice (Table 1), relict rock glaciers or those transitioning towards relict activity status (i.e. inactive landforms) have a more subdued surface micro-topography. Typically, inactive rock glaciers have gentler, dark-coloured rock-varnished frontal slopes with partial to full vegetation and/or lichen cover (Ikeda and Matsuoka, 2002). For simplicity, due to the difficulty of differentiating between active and inactive forms, particularly through photogeomorphology, these are collectively termed "intact landforms" in the present study. Relict rock glaciers characteristically have surface collapse features including thermokarst ponds (i.e. water-filled depressions resulting from melting of stagnant glacial ice) and have much gentler (~<30°) and round-crested frontal and lateral slopes, a dark-coloured rock-varnished frontal slope, and extensive vegetation and/or lichen cover (Fig. 2).

As a consequence of the paucity of detailed subsurface information for rock glaciers, 2-D-area-related statistics (i.e. empirical H-S relations) were applied in this study to predict rock glacier thickness and derive volume. Empirical H-S relations can be expressed as $\overline{h} = c \cdot S^{\beta}$, where mean feature thickness $\overline{h}$ (m) is calculated as a function of surface area S (km^2) and a scaling parameter c (50) and scaling exponent β (0.2) (Brenning, 2005). Feature volumes were determined by $V = \overline{h} \cdot S$. WVEQ was subsequently estimated through the multiplication of V and estimated ice content (% by vol.) and assuming an ice density conversion factor of 900 kg m^{-3} (Paterson, 1994). Here, a volumetric rock glacier ice content of 40–60% vol. (i.e. lower [40%], mean [50%], and upper bounds [60%]) was assumed based upon previous studies (Brenning, 2005; Bodin et al., 2010; Rangecroft et al., 2015; Jones et al., 2018a; Jones et al., 2018b). This is consistent with in situ data derived from different climatic regions worldwide (Elconin and LaChapelle, 1997: >50%; Arenson et al., 2002: 40–70%; Croce and Milana, 2002: ~55%; Hausmann et al., 2007: 45–60%; Hausmann et al., 2012: 40–60%). In the present study, the dataset generated through the application of the above-described methodology and pre-existing rock glacier inventory of the Nepalese Himalaya were amalgamated, creating the first systematic inventory of rock glaciers in the Himalaya. In order to estimate rock glacier area and WVEQ in the Himalaya, the digitised random sample (n = 2070 – i.e. this study [n = 933] + Jones et al., 2018b [n = 1137]) was extended to the entire population (n = 24,968) on a regional basis through the upscaling (extrapolating) procedure (Fig. S1).

2.2. Glacier data

Here, the glacier data were derived from Frey et al. (2014). Note that the original sources for the glacier boundaries are described in Fig. 1 in Frey et al. (2014), The estimated ice volumes, upon which the glacier WVEQs are based, were calculated using the GlabTop2 ice-thickness distribution model (Frey et al., 2014). The regional glacier data were presented for the west Himalaya, central Himalaya, and east Himalaya using the same geographic regional boundaries (i.e. Bolch et al., 2012) as used in this study, enabling the direct comparison of rock glacier and glacier results.

3. Results

A total of 24,968 rock glaciers were identified across the Himalaya. Intact (features containing ice) and relict (features not containing ice) rock glaciers accounted for ~65% (n = 16,334) and ~35% (n = 8, 634) of the total, respectively. Most are located within the central Himalaya (~40%, n = 10,060) with ~30% situated in the east Himalaya and ~29% in the west Himalaya (Fig. 3). Across the Himalaya, rock glacier estimated areal coverage is 3747 km^2 (i.e. intact and relict), representing ~16% of that covered by glaciers (22,829 km^2). Regionally, rock glacier vs glacier areal coverage ranges between 12 and 21% (Table 2).

We have shown that the sampled rock glaciers (n = 2070) have an estimated WVEQ of 5.19 ± 1.04 km^3 (Table S1), with statistically upscaled estimates for the entire population of 51.80 ± 10.36 km^3 (Fig. 3). The WVEQ of glaciers in the Himalaya was estimated to be 1272 km^3, which translates to a rock glacier: glacier WVEQ ratio of 1:245 (Table 2). Importantly, however, the rock glacier: glacier WVEQ ratio reduces to 1:25 when statistically upscaled rock glacier WVEQs are considered (Fig. 3, Table 2). This implies that glacier WVEQ is twenty-five times larger than rock glacier WVEQ. Regionally, when considering statistically upscaled rock glacier WVEQs, this ratio ranges between 1:17 and 1:43 in the central Himalaya and east Himalaya, respectively. Rock glacier WVEQ are 1:34 in the west Himalaya.

In this study, the estimated glacier ice volumes subsequently used to calculate WVEQ were calculated from the GlabTop2 ice-thickness distribution model (Frey et al., 2014). However, in the Himalaya, glacier WVEQ ranges from 1237 to 1909 km^3 depending upon the choice of method used to estimate glacier volume (Table S2). The resultant rock glacier: glacier WVEQ ratios for the Himalaya varied between 1:24 (slope-dependent thickness estimation) and 1:37 (V-S scaling relation [LIGG et al., 1988 as cited in Frey et al. (2014)]) (Table S2).

The systematic rock glacier inventory presented in this study was generated using expert photomorphic mapping from remote sensing image data, with landforms manually identified, digitised, and categorised based upon geomorphic indicators (see Methodology). Inevitably, therefore, there is a degree of subjectivity regarding the mapping outcome (see Brardinoni et al., 2019). In this study, we apply the Certainty Index methodology developed by Jones et al. (2018b; Table 3) to detail the degree of uncertainty. Here, Certainty Index scores, listed in order of occurrence, are as follows for the digitised sample: high certainty (~81%), virtual certainty (~15%), and medium certainty (~5%). Those rock glaciers categorised as "virtual certainty" are

Table 2
Areal coverage (upscaled) and WVEQs (samples and upscaled) for rock glaciers and glaciers, regionally and for the Himalaya (i.e. total). Additionally, the rock glacier: glacier WVEQ ratios are directly compared. Rock glacier WVEQs assume 50% (average) ice content by volume. Values are reported to two decimal places. Glacier WVEQ data are derived from Frey et al. (2014). N.B. Rock glaciers WVEQs based on the expected range of ice content by volume (40–60%) are available in Table S1.

Region	Rock glacier			Glacier		Rock glacier: glacier WVEQ ratio	
	Area (km^2)	Sample WVEQ (km^3)	Upscaled WVEQ (km^3)	Area (km^2)	WVEQ (km^3)	Sample ratio	Upscaled ratio
E-Himalaya	550.87	0.25	5.06	3946.00	215.00	1:851	1:43
C-Himalaya	2109.63	4.20	31.80	9940.00	553.00	1:132	1:17
W-Himalaya	1086.27	0.74	14.94	8943.00	504.00	1:682	1:34
Total	3746.77	5.19	51.80	22,829.00	1272.00	1:245	1:25

Table 3
Certainty Index applied to each rock glacier. Table after Jones et al. (2018b).

Parameter	Parameter options (index code)		
	1 point	2 points	3 points
External boundary	None (ON)	Vague (OV)	Clear (OC)
Snow coverage	Snow (SS)	Partial (SP)	None (SN)
Longitudinal flow structure	None (LN)	Vague (LV)	Clear (LC)
Transverse flow structure	None (TN)	Vague (TV)	Clear (TC)
Front slope	Unclear (FU)	Gentle (FG)	Steep (FS)
Certainty Index score	Medium certainty (MC) ≤5	High certainty (HC) 6 to 10	Virtual certainty (VC) ≥11

predominantly intact features (~96%), whereas relict rock glaciers feature more prominently in the "medium certainty" category (~68%). This is to be expected. Considering that the morphological characteristics (Table 1) used for rock glacier identification and determining dynamic status (active, inactive, or relict) generally become less well-defined and subdued in relict features or those transitioning towards relict dynamic status, uncertainty will likely increase with respect to (i) clear external boundaries (i.e. outline); (ii) distinct longitudinal flow structure; (iii) distinct transverse flow structure; and (iv) steepness of the frontal slope (Table 3).

Active (relict) rock glaciers have previously been used to indicate the presence (absence) of permafrost (Janke, 2005; Sattler et al., 2016; Deluigi et al., 2017; Esper Angillieri, 2017). Indeed, within the Hindu Kush Himalaya Schmid et al. (2015) demonstrated relatively good agreement between the Global Permafrost Zonation Index (PZI) (see Gruber, 2012) and mapped rock glaciers. Therefore, to further validate the systematic rock glacier inventory presented here we compare the spatial distribution of the ~5% sample within the Himalayas to the PZI. PZI values ≥0.1 form the permafrost region (PR), with PZI values <0.1 attributed to the PZI fringe of uncertainty –"the zone of uncertainty over which PZI could extend under conservative estimates" (cf. Table 1 in Gruber, 2012). Across the Himalaya, ~86% of rock glaciers are situated in the PR. These rock glaciers are predominantly intact (~68%). The frequency of relict rock glaciers decreases towards PZI = 1 (i.e. increasingly suitable for rock glacier development and persistence). Further, the median PZI values for relict (0.37) and intact (0.53), potentially indicating lower ice volumes in the former. Finally, Certainty Index scores and the median PZI values concurrently increase; "medium certainty" (0.31), "high certainty" (0.46), and "virtual certainty" (0.53). Given the aforementioned association between "virtual certainty" and intact rock glaciers (i.e. landforms displaying morphological characteristics [Table 1] assumed to reflect the presence of abundant ice), this result lends confidence to the mapping output presented in this study. To summarise, both the identification and mapping, and classification of activity status are in good agreement with the PZI.

4. Discussion

We have developed the most extensive systematic rock glacier inventory generated to date, addressing the need for information in critical data-deficient regions (Central Asia, South Asia East, and South Asia West) previously defined as research priorities (Jones et al., 2018a). The previous estimate of rock glacier WVEQ across HMA (Randolph Glacier Inventory [RGI] regions: South Asia East, South Asia West, and Central Asia) significantly underestimated rock glacier WVEQ in this region (see Jones et al., 2018a). Considering that the Nepalese Himalaya was already included in the previous near-global estimate, the Himalaya-wide assessment presented in the present paper would add ~30 km^3 WVEQ to the current estimate. The Himalaya-wide and regional rock glacier: glacier WVEQ ratios illustrate that rock glaciers constitute hydrologically valuable long-term water stores (Table 2; Fig. 3). Notably, rock glacier water stores are shown to be hydrologically valuable irrespective of the choice of method used to estimate glacier volume (Table S2). Importantly, at decadal and longer timescales, under future climate warming and thus continued glacial mass loss (e.g., Fig. 1), the relative hydrological value of Himalayan rock glaciers will become increasingly important (Jones et al., 2019).

The headline rock glacier: glacier WVEQ ratios suggest that rock glacier water stores are most hydrologically valuable in the central Himalaya (1:17). However, the runoff contribution of glacial melt is highest in heavily glacierized basins with relatively wet winters and dry summers – conditions particularly common in the western Himalaya (e.g., Indus basin) (Pritchard, 2019). Indeed, glacial melt inputs [and presumably rock glacial melt inputs] are relatively insubstantial in the wetter monsoonal central Himalayan basins (Ganges and Brahmaputra) but more significant in the drier westerly dominated basins of the western Himalaya (Indus) (Immerzeel et al., 2010; Kaser et al., 2010). Therefore, although rock glaciers in the central Himalaya (31.80 ± 6.36 km^3) and east Himalaya (5.06 ± 1.01 km^3) constitute considerable long-term water stores, their relative hydrological contribution vs other hydrological inputs (i.e. precipitation) diminishes their hydrological significance when considered at the sub-regional spatial scales considered in this study.

The proportional contribution of glacial [and rock glacial] melt inputs to runoff generally increases with proximity to the source (i.e. water inputs are less diluted by precipitation), the importance of which is influenced by the distribution of water demand and pre-existing levels of water stress (Pritchard, 2019). Therefore, in basins with higher population densities in their upper ranges (e.g., Indus) glacial melt has greater comparative hydrological value than basins where the populations predominantly occupy lowland plains (e.g., Ganges and Brahmaputra) (Table 4). In the present study, the headline rock glacier: glacier WVEQ ratios, although an important step in quantifying rock glacier water stores across the Himalaya, mask their *actual* hydrological significance. Arguably, rock glaciers located in the western Himalaya (1:34) are the most hydrologically significant. Additionally, as has been argued by the present authors (Jones et al., 2018a; Jones et al., 2018b), the regional-extent rock glacier: glacier WVEQ ratios are not reflective of rock glacier hydrological significance at smaller spatial scales; for example, 1:3 and 1:5 in the West and Far-west regions of Nepal, respectively (Jones et al., 2018b). We therefore argue that assessment of the hydrological significance of rock glaciers requires development of a more nuanced approach and is deserving of greater study.

5. Conclusion

Here, we present the first systematic assessment of rock glacier WVEQ across the Himalaya range. Our Himalayan-wide analysis illustrates that the ~25,000 rock glaciers identified constitute hydrologically valuable long-term water stores. The ongoing climatically-driven glacier recession and mass loss across the high mountains of Asia has rightly attracted much research attention due to the potential impacts upon ~800 million people living downstream. Yet, mountain water

Table 4
Population of the three major river basins originating in our study area. Population data (2020) are based on the GPWv4 dataset adjusted to United Nations estimated national-level population counts [https://sedac.ciesin.columbia.edu/data/collection/gpw-v4 (1 June 2020)]. Upstream refers to the area >2000 m a.s.l.

Parameter	Indus	Ganges	Brahmaputra
Total population (10^3)	277,567	499,236	67,602
Upstream population (10^3)	16,979	4221	2099
Upstream population (%)	6.1	0.8	3.1

resources are nuanced and more varied than simply snow and debris-free or debris-covered glaciers. Our work evidences that rock glaciers with a WVEQ of 51.80 ± 10.36 km^3 (41–62 trillion litres) and a WVEQ ratio versus glaciers of 1:25 are a critical component of the Himalayan water system; yet, to date, have been largely overlooked as hydrologically valuable long-term water stores. We argue that future analysis of the Himalayan cryosphere [and beyond] should include rock glaciers so that a more complete understanding of the response of the Himalayan water system to climate change can be delivered.

CRediT authorship contribution statement

D.B. Jones: Methodology, Data curation, Formal analysis, Writing – original draft. **S. Harrison:** Conceptualization, Writing – review & editing, Supervision. **K. Anderson:** Writing – review & editing, Supervision. **S. Shannon:** Writing – review & editing, Visualization. **R.A. Betts:** Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2021.145368.

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