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Mountain rock glaciers contain globally significant water stores

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Glacier- and snowpack-derived meltwaters are threatened by climate change. Features such as rock glaciers (RGs) are climatically more resilient than glaciers and potentially contain hydrologically valuable ice volumes. However, while the distribution and hydrological significance of glaciers is well studied, RGs have received comparatively little attention. Here, we present the first near-global RG database (RGDB) through an analysis of current inventories and this contains >73,000 RGs. Using the RGDB, we identify key data-deficient regions as research priorities (e.g., Central Asia). We provide the first approximation of near-global RG water volume equivalent and this is 83.72 ± 16.74 Gt. Excluding the Antarctic and Subantarctic, Greenland Periphery, and regions lacking data, we estimate a near-global RG to glacier water volume equivalent ratio of 1:456. Significant RG water stores occur in arid and semi-arid regions (e.g., South Asia East, 1:57). These results represent a first-order approximation. Uncertainty in the water storage estimates includes errors within the RGDB, inherent flaws in the meta-analysis methodology, and RG thickness estimation. Here, only errors associated with the assumption of RG ice content are quantified and overall uncertainty is likely larger than that quantified. We suggest that RG water stores will become increasingly important under future climate warming.

In semi-arid and arid high mountain systems glaciers and seasonal snowpack form natural buffers to hydrological seasonality, as seasonal meltwater contributions smooth the effects of highly variable summer precipitation and associated irregular runoff[1–3]. Described as the world's natural "water towers"[4], glacier- and snowpack-derived meltwater are critical to ecological, social and economic systems in these regions. Additionally, mountain water stores provide buffering capacity for surrounding lowlands[5]. Elevation dependent warming (i.e. an amplified rate of warming with altitude) suggests that high-altitude environments will likely experience comparatively faster warming than lower altitude areas[6]. Furthermore, high-altitude hydrological resources are highly sensitive to environmental change[3,7]. Indeed, between 2003 to 2009 glacier volume loss globally was estimated to be -259 ± 28 Gt yr^{-1} [8]. With projected atmospheric warming, long-term glacier and seasonal snowpack changes are expected to impact significantly hydrological resources stored within high mountain systems[9]. Small and low-lying glaciers are particularly likely to be sensitive to warming, with many disappearing[10–12]. In the short-term glacier shrinkage results in increased runoff. However, following "peak non-renewable water"[13], summer runoff will significantly reduce in semi-arid and arid regions[14,15]. Additionally, a warming-induced precipitation shift from snowfall to rainfall[16] combined with a temporal shift towards earlier snowpack melt[17], will further lead to runoff reduction.

Consequently, effective water resource management in terms of climate change adaptation strategies is critical. However, this is hampered by an incomplete understanding of all components of the hydrological cycle in high mountain systems. Whilst much has been written on the hydrological role of glaciers[18], that of rock glaciers (RGs) has received comparatively little attention[19]. RGs are cryospheric landforms that are formed by gravity-driven creep of accumulations of rock debris supersaturated with ice. They are characterised by a seasonally frozen, clastic-blocky surficial layer ~0.5 to 5 m thick that thaws each summer (this is known as the *active layer*)[20]. RGs are described as active or inactive if they contain ice beneath the active layer. These are described collectively as intact RGs. Those containing no or minimal ice content are termed relict RGs[21]. RGs are thermally decoupled from external micro- and meso-climates because of the insulating effect of the active layer, which is shown to slow the rate of ice melt within RGs[20]. Consequently, RGs respond to climate change at comparatively longer time scales than glaciers[22]. Therefore, RGs are more climatically resilient than glaciers and form frozen water stores

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