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# Climate change impacts and adaptation to permafrost change in High Mountain Asia: a comprehensive review

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## Abstract

Changing climatic conditions in High Mountain Asia (HMA), especially regional warming and changing precipitation patterns, have led to notable effects on mountain permafrost. Comprehensive knowledge of mountain permafrost in HMA is mostly limited to the mountains of the Qinghai-Tibetan Plateau, with a strong cluster of research activity related to critical infrastructure providing a basis for related climate adaptation measures. Insights related to the extent and changing characteristics of permafrost in the Hindu Kush Himalaya (HKH), are much more limited. This study provides the first comprehensive review of peer-reviewed journal articles, focused on hydrological, ecological, and geomorphic impacts associated with thawing permafrost in HMA, as well as those examining adaptations to changes in mountain permafrost. Studies reveal a clear warming trend across the region, likely resulting in increased landslide activity, effects on streamflow, soil saturation and subsequent vegetation change. Adaptation strategies have been documented only around infrastructure megaprojects as well as animal herding in China. While available research provides important insight that can inform planning in the region, we also identify a need for further research in the areas of hazards related to changing permafrost as well as its effect on ecosystems and subsequently livelihoods. We suggest that future planning of infrastructure in HMA can rely on extrapolation of already existing knowledge within the region to reduce risks associated with warming permafrost. We highlight key research gaps as well as specific areas where insights are limited. These are areas where additional support from governments and funders is urgently needed to enhance regional collaboration to sufficiently understand and effectively respond to permafrost change in the HKH region.

## 1. Introduction

Evidence from multiple studies indicates that mountain permafrost is degrading because of a warming climate (IPCC 2019). Due to rising air temperatures and increased insolation, the extent of frozen ground will continue to reduce, and alpine permafrost will continue warming, thus affecting mountain livelihoods, regional economies, and alpine ecosystems (Huss *et al* 2017). Consequently, climate change is expected to evoke significant impacts on regional hydrology, geomorphology, and ecology across the high mountains of Asia. Unlike glaciers that can be easily detected, permafrost is a subsurface phenomenon and hence observation and analysis is often difficult. This aggravates the problem of understanding the distribution of and changes occurring, especially for the case of discontinuous permafrost. This has led to relatively insufficient knowledge about permafrost dynamics in the region. Although permafrost in different mountain ranges in China, especially the Qinghai-Tibetan Plateau (QTP) are relatively well investigated (Ran *et al* 2012, Zhang *et al* 2021), permafrost in the mountains of Hindu Kush

Himalaya (HKH, (Gruber *et al* 2017)) and Central Asia (Barandun *et al* 2020) need further consideration to understand the degree and extent of climate change impacts.

Climate change is expected to cause increasing active layer depths due to permafrost thaw in the HKH (Wester *et al* 2019). While observations are limited, changes in the continuously warming permafrost regime are expected to generate several hydrologic, geomorphic, and ecological impacts in the region (Gruber *et al* 2017, Wester *et al* 2019). Managing water resources is going to be a major challenge for regions in Central Asia where populations living downstream depend heavily upon meltwater from glaciers and permafrost which nourish perennial rivers even during the dry seasons (Huss *et al* 2017). On the QTP, effects of a warming climate on dynamics of low flows are expected in the high elevation regions but remain mostly uninvestigated (Wang *et al* 2019).

The negative impacts are diverse and wide-ranging and have received considerable attention in international climate policy (Huggel *et al* 2019). Changes associated with climate, which includes thawing permafrost, affect mountain livelihoods and adaptation in mountain regions is crucial to alleviate the considerable socio-ecological impacts brought on by climate change (McDowell *et al* 2019). Nevertheless, insufficient knowledge about the present and future impacts and corresponding appropriate adaptation measures will severely restrict the capacity to assess, prepare for, and to mitigate the adverse effects of climate change.

It is expected that future changes of permafrost will be more rapid than what has been witnessed in the recent past (Gruber *et al* 2017). To anticipate these changes and potential strategies for adaptation, measurement programmes are being carried out in various regions of the globe to evaluate and record the distribution, present condition, and potential future variations of mountain permafrost. These measurement activities have been increasing on the Tibetan Plateau and Central Asia (Haeberli *et al* 2011) yet are lacking elsewhere in High Mountain Asia (HMA).

This comprehensive review attempts to contribute towards a deeper understanding about the present status of knowledge regarding climate change impacts and adaptation associated with warming permafrost in the high mountains of Asia. The specific questions we set out to answer in the study are:

- What are the major impacts and adaptation issues associated with climate-driven changes in mountain permafrost in HMA, how are they manifesting across the vast region and what gaps in impact documentation and adaptation measures can be identified?
- Are definite trends of change visible and if so, how homogenous are they across the region?

Considering our knowledge and identified observation gaps, we aim to propose future research protocols as well as baseline strategies for regional stakeholders to strengthen understanding of changing permafrost and its implications as well as potential adaptation for the future.

## 2. Methods

### 2.1. Comprehensive review

The study is based on a comprehensive review of peer reviewed articles obtained from the Web of Science database (Web of Science 2015) and Google Scholar, spanning the years from 1970 to 2021. Specific details on the review process are provided in the supplementary material (section S1). We consider the geographic definition of HMA as used in Bolch *et al* (2019). The initial literature search resulted in a total of 1505 studies, of which 1308 were removed after initial screening, resulting in a total number of 197 to be reviewed in detail (see section S1). The screening of literature resulted in publications that included studies with original data, those that discuss permafrost in the region but do not present new data, and global reviews that include the region. An overview of all studies included in this review is accessible at https://github.com/fidelsteiner/HMAPermafrost.

### 2.2. Information classification

Documented climate change impacts were broadly classified under three categories: hydrological, ecological and geomorphological impacts. After full text review, the respective key themes were identified in each publication (which can be more than one).

Geomorphological impacts crucially include the thermal state of permafrost as well as subsequent impacts related to slope instability and related hazards. Existing cases and possible consequences of land surface subsidence and slope failures on infrastructure were identified.

For hydrological impacts, hydrological responses to permafrost thaw were analysed. This included both quantitative knowledge (e.g. discharge or surface runoff) as well as qualitative information (e.g. sedimentation, presence, or absence of solutes).

To understand ecological responses, variations in frozen soil depths, soil moisture, soil organic carbon, dissolved organic carbon, and release of greenhouse gases due to permafrost degradation were analysed.

The classification process is detailed in the supplementary material (S2).

## 3. Results

### 3.1. Comprehensive review

From the 197 studies that were closely reviewed, 24 studies were reviews that included non-original data on permafrost in the region and a further 42 studies only referred to permafrost in the conclusions,

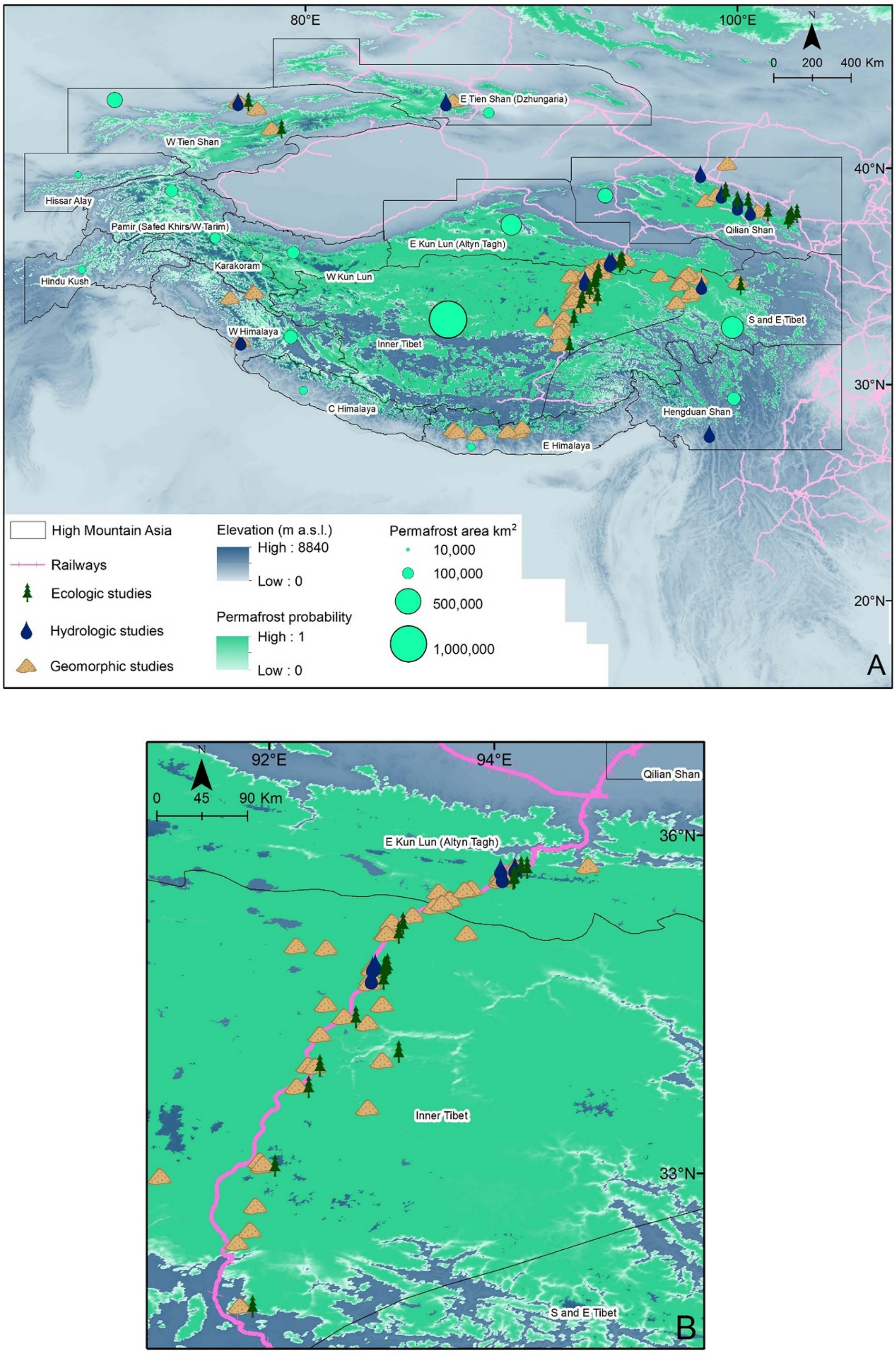


**Figure 1.** (A) Overview of studies with original data from specific field sites across HMA ($n = 95$). Permafrost map for the Northern Hemisphere (Obu *et al* 2019) and Chinese railways (https://download.geofabrik.de/asia/china.html) shown in the background. (B) Focus on the QTEC area in the central Tibetan Plateau, showing a cluster of studies.

with the focus of the investigation being on another topic that had only some relation to permafrost. Data from the remaining 131 studies were investigated to understand regional patterns and trends (figure 1).

Studies on permafrost were sparse until 2005 (∼1 per year), rose steeper than the global average of papers on science and technology until 2019 to nearly 40 per year but have since stagnated (figures S1 and S2). Of all 197 studies we consider here for review, 93 were focused on the QTP, of which 30 covered the whole plateau, 23 focused on the mountainous Qilian Shan to the North and 40 looked at some local field site (figure S3). Of the latter, 16 focused specifically on permafrost change affecting the Qinghai Tibet Economic Corridor (QTEC, figure 1(B)). 39 studies focused on the HKH, and 18 covered Central Asian Mountain ranges, predominantly the Tien Shan (12, figure S3).

Studies are visibly clustered in both elevation as well as latitude around the centre due to the focus of research around the QTEC, with further smaller clusters across the mountain ranges of HKH, Qilian Shan and Tien Shan (figure 2(B)).

More than 90% of all reviewed articles mention climate change impacts, but only about 40% refer to climate change adaptation actions (figure S7(A)), predominately related to infrastructure development and changing herding practices. Less than a quarter of reviewed publications indicate measures taken to avoid risks due to changing permafrost conditions (figure S7(B)), with most of these studies focusing on the QTEC. The academic sector is identified as the actor most engaged in adaptation action (figure S7(D)), followed by government entities, providing some evidence of a potential disconnect between those able to identify actions and those with a capacity to implement them.

### 3.2. Permafrost presence and impacts of climate change

Evidence from different field studies show that the warming climate has continuously increased the active layer depths of mountain permafrost (Jin *et al* 2000, Zhao *et al* 2010, Liu *et al* 2017, Yin *et al* 2017) and shifted the lower limit to higher elevations (Fukui *et al* 2007, Li *et al* 2008). These transformations are affecting the soil moisture content, ground thermal regime, cryopedogenic mechanisms, active-layer detachment slides and different mass movement processes (Bockheim 2015, Yuan *et al* 2020). Possibilities of widespread mass wasting activities (figure 3) as a result of weakened mountain slopes are anticipated to increase due to changes in climate conditions (Fort *et al* 2009, Huggel 2009, Kalvoda and Emmer 2021).

Below we recapitulate on our state of knowledge on permafrost and climate chanage from a hydrological, geomorphological and ecological angle, and identify impacts of permafrost change.

#### 3.2.1. Geomorphological impacts

Climate change largely governs processes occurring in the active layer of permafrost regions in China which has subsequent effects upon engineering practices and geohydrological properties (Jin *et al* 2000, Hu *et al* 2015). Numerous studies have investigated ground temperatures at a variety of depths, including in boreholes (Zhao *et al* 2010). Wang and French (1994) found a 0.2 °C–0.3 °C increase over 15 years (∼0.013 °C–0.02 °C $yr^{-1}$) at 20 m depth starting in the late 1970s next to the QTEC. Between 2003 and 2015 somewhat lower accelerations were found in the same region at 0.011 °C $yr^{-1}$, with rates of 0.014 °C $yr^{-1}$ at 10 m and 0.009 °C $yr^{-1}$ at 30 m (Zhangqiong *et al* 2020). Permafrost depths were estimated between 0.8 and 2.1 m during this time. Between 1996 and 2006 Wu and Zhang (2008) found an increase of 0.043 °C $yr^{-1}$ at 6 m, while mean annual air temperatures increased at 0.1 °C $yr^{-1}$. Data between 2014 and 2016 in the same area at 15 m depth aligns with all previous measured rates, with rates up to 0.02 °C $yr^{-1}$ (Yin *et al* 2017). Within a 60 m borehole further north in the Tien Shan, rates of increase varied between 0.042 °C $yr^{-1}$ at 1 m depth and 0.018 °C $yr^{-1}$ at 58.5 m between 1992 and 2011 (Liu *et al* 2017), matching with much older measurements further West at 20 m (Severskiy 2018). These data suggest regionally different gradients with depth between the QTP and the Tien Shan (figure S6). There are no observations available for other regions in HMA.

Few sites have been instrumented with sensors in the shallow soil layer (10–20 cm), including along QTEC with measured and modelled data (Yin *et al* 2018) and measurements in the Central (Steiner *et al* 2021) and Western Himalaya (Wani *et al* 2020). Surface and thermal offsets are comparable between the QTEC site (3.5 °C and −0.3 °C respectively, (Luo *et al* 2018a)) and in Ladakh (−1.1 °C–3.9 °C and −0.9 °C–0 °C, (Wani *et al* 2020)). Temperature data eventually allowed to make estimates of active layer thickness (ALT), which on the QTP reached 1.7 m by 2011, increasing by 2 cm $yr^{-1}$ since 1992 at 3500 m (Liu *et al* 2017) to 3.4 m at 4628 m between 2014 and 2016, with a rate of change of 21 cm $yr^{-1}$ (Yin *et al* 2017). At different boreholes across the plateau, ALT ranged from 1.05 to 3.22 m in 2007 and 2008, decreasing with elevation (Zhao *et al* 2010). In the Tien Shan the ALT was already up to 4 m thick in the 1970s, reaching up to 5.2 m by 2009 at 3300 m (Gorbunov *et al* 2004, Zhao *et al* 2010). In the Western Himalaya ALT between 2016 and 2017 was found to be between 0.1 and 4.2 m at an elevation between 4700 and 5600 m (Wani *et al* 2020). There is less data on other geomorphological variables across HMA.

Sorg *et al* (2015) show synchronous activity of rock glaciers at decadal scale in Central Asia. Li *et al* (2013) show the formation of patterned ground in line with an expansion of soil moisture, most prevalent in the first 25 cm of soil. Zhong *et al* (2021) show deformation of thermokarst landforms around 3600 m between April 2016 and June 2018, finding a 3.4 m vertical change and 10.7 m wall retreat.

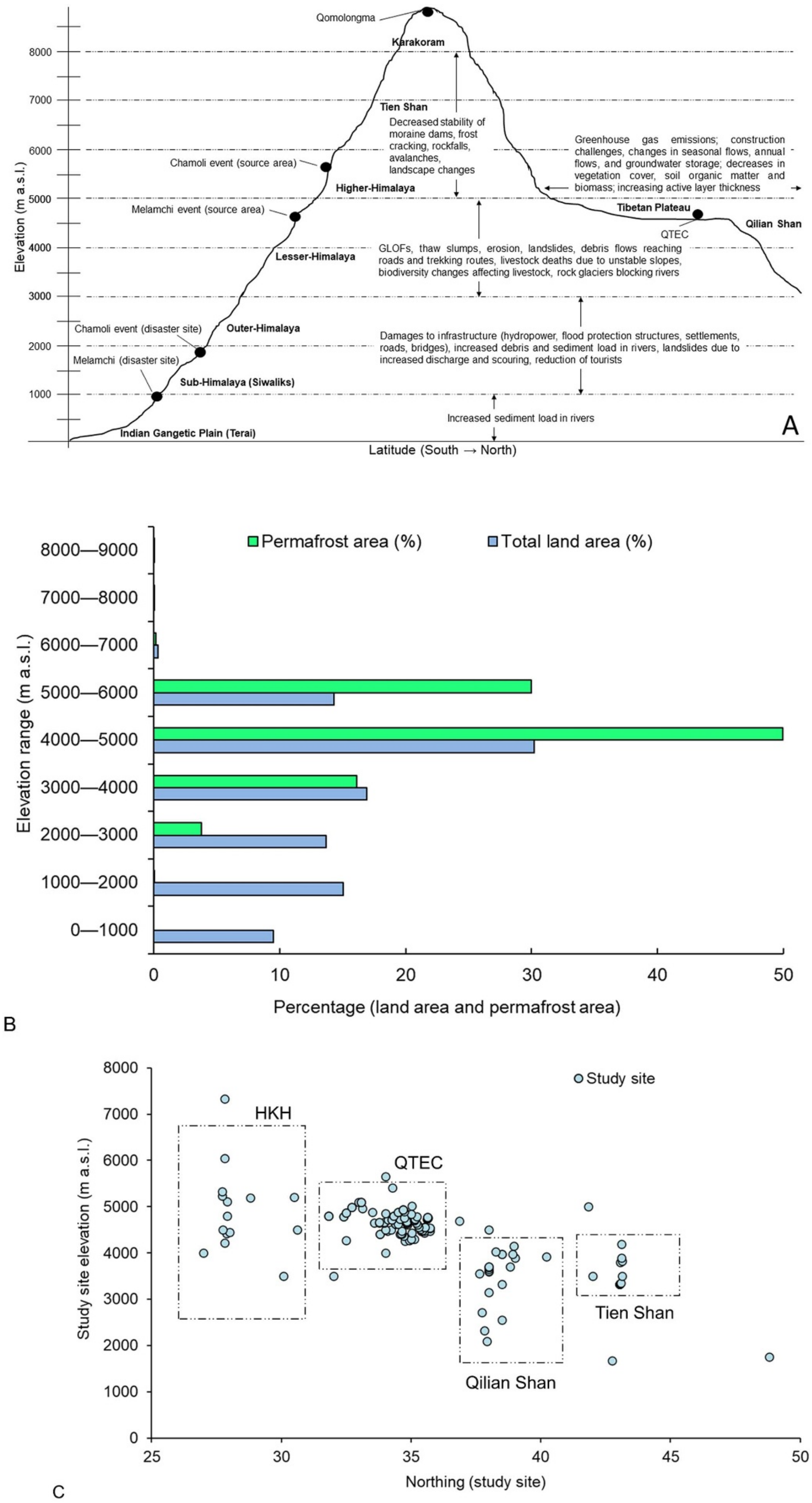


**Figure 2.** (A) Conceptual north–south cross section across HMA with main interests of published studies across elevation ranges described in the centre. (B) Relative total land area and total area covered by permafrost for each elevation band. (C) Location of the studies across the north–south transect.

Related to a changing permafrost, Li *et al* (2021) find increased sediment loads in the Tuotuo He headwater on the Central Tibetan Plateau.

A number of studies have investigated ground movements as a result of permafrost change, relying on remote sensing, including radar data in more recent years. Ground deformation along the QTEC was already found to be $\pm 5$ mm $yr^{-1}$, increasing to $+10/-20$ mm $yr^{-1}$ between 2004 and 2018 (Zhang *et al* 2019b). In the more mountainous parts of the

**Figure 3.** Examples of surface changes attributed to a change in permafrost ranging from patterned ground (A), (B), thaw slumps (D), (E) to landslides (F), (H) and debris flows (H), (I). Permafrost landscape near China-Nepal border, Humla, Nepal (A), Hidden Valley, Mustang, Nepal (B). Tsho Rolpa lake situated below steep permafrost head walls, Nepal (C). Thaw slumps on the trekking route to Yala Glacier in Langtang, Nepal (D). Yaks grazing near a thaw slump near Limi Lapcha road in Humla, Nepal (E). Permafrost slope failures near Kyangjing Village in Langtang, Nepal (F). Landslide due to floods near Melamchi, Nepal (G). Settlement destroyed (H) and bridge damaged (I) due to flood event in Melamchi, Nepal.

Northeastern Plateau subsidence rates have increased 2–5-fold from $\sim$2 cm yr$^{-1}$ between 2003 and 2019 (Daout *et al* 2020). Similarly, Dini *et al* (2019) find 10 mm of slope movement due to active layer change in Bhutan between 2007 and 2011. On the plateau, thaw slumps were also found to increase with ever larger rates both below 4000 (Mu *et al* 2020) as well as between 4400 and 5300 m a.s.l. (Luo *et al* 2019).

In the Tien Shan rising temperatures and soil moisture content in permafrost soils have caused *upfreezing*, a phenomenon where freezing leads to the movement of deposited materials towards the soil surface, and the development of sorted circles (Li *et al* 2013).

An inventory of rock glaciers compiled for the Karakoram region, Tien Shan and Altai shows that rock glacier bodies are able to partially cover, obstruct, narrow down or reroute several segments of mountain rivers (Blöthe *et al* 2019). These rock glaciers are a potential outcome of permafrost in non-equilibrium conditions. Increased warming is predicted to boost the degree of activity of rock glaciers and support faster movement of rock glaciers (Hartl *et al* 2023), increasing the potential for such events, however investigations into this direction in HMA are lacking.

*3.2.2. Hydrological impacts*

Two separate studies suggest that the contribution of permafrost thaw in headwaters of catchments on the northern fringe of the QTP make up more than one third of total discharge, with half of it made up of precipitation in a lower catchment with limited ice and snow melt (3367 m a.s.l.), but only 6% from precipitation in a catchment at 4500 m a.s.l., where glacier melt accounts for more than 50% (Yang *et al* 2016, Zongxing *et al* 2016). For other mountainous parts of HMA such partitioning is not available.

A significant contribution of glaciers and thawing permafrost to river discharge of mountain rivers on the QTP indicates that volume and seasonal variability of river discharge will be considerably affected due to future warming in the region (Yang *et al* 2016). For example, in northwest China, statistical analyses of climate variables and river runoff in a mountain permafrost catchment showed a significant rise in winter air temperatures and subsequent increase in monthly flows during winter months (Liu *et al* 2007). This was also found for long term data between 1960 and 2014, due to an increase in baseflow as precipitation increased and maximum thickness of the seasonally frozen ground decreased (Qin *et al* 2016). The increase in the contribution from groundwater during freezing days was also found in the far southeastern part of the Plateau (Luo *et al* 2020). However, an increase in ground temperatures has also resulted in a decrease in winter runoff elsewhere (Gao *et al* 2016) as well as an increase in spring and decrease in summer (Tian *et al* 2016). Local field studies have also investigated the link between thawing permafrost and resulting decrease in soil moisture and desiccation providing an important link between cryosphere change and its direct impact on ecology (Wang and Wu 2013, Sun *et al* 2019).

Regional observations of climate conditions in the Central Asian region predict a continuous increase in warming leading to retreat of glaciers and permafrost (Shahgedanova *et al* 2018). As a result, future mountain river discharge will experience an initial increase followed by reduction.

#### *3.2.3. Ecological impacts*

Changing permafrost has varied impacts on ecosystems on the QTP, with swamps and cold meadows suffering the most negative impacts between the Kunlun Pass and the Tanggula Shan (Wang *et al* 2006). Similar reductions were also observed for mountain vegetation cover in the Yangtze and Yellow Rivers region of the Tibetan Plateau (Yang *et al* 2006). One explanation could be an increase of evapotranspiration from rapid decreases in frozen soil, negatively affecting vegetation growth (Wang *et al* 2020). A general decrease in soil moisture due to permafrost thaw was already observed in a number of studies (Wang and Wu 2013, Xu *et al* 2018, Sun *et al* 2019). In the Qilian Shan, Qin *et al* (2016) found an increase in leaf area index and earlier start of the growing season as permafrost thaws. A similar increase in vegetation cover was also found further inland on the Plateau resulting in a 65% increase of organic carbon in the topsoil between 1986 and 2000 (Genxu *et al* 2008). There is some field evidence on the QTP for dissolved organic carbon increasing in relation to a thawing permafrost where snow melt does not play a significant role (Zhu *et al* 2020).

#### *3.2.4. Natural hazards*

As the active layer changes, shallow slope movement has been shown to increase (Dini *et al* 2019, Daout *et al* 2020), while deeper and slower warming of permafrost is expected to result in increasing large bedrock failures (e.g. Shugar *et al* 2021). If these movements occur close to infrastructure or adjacent to lakes, they can pose hazards for downstream areas. High elevation lakes formed by natural dams are likely to increase in number under the influence of climate change (Zheng *et al* 2021) and the potential threat from surrounding unstable slopes has been indicated at the regional scale (Furian *et al* 2021). As a result of the potential threat of rising temperatures on moraine stability, existing strength and potential disintegration of natural dams are uncertain (Korup and Tweed 2007), but dam stability in light of potentially thawing permafrost and ice cores remains a concern.

Due to regional warming, the lower limit of mountain permafrost has been gradually shifting to higher elevations in China (Li *et al* 2008), although documentation of the lower limit is so far lacking for most other regions in HMA. In addition to that, ground temperatures are rising, depths of thawing permafrost are increasing, permafrost islands are appearing, and taliks are expanding (Jin *et al* 2000). Ongoing changes clearly indicate that the stability of infrastructures are under great risk as the extent of permafrost cover on the QTP will decrease and permafrost areas will shift upward (Li *et al* 2003). However, studies investigating permafrost related threats to infrastructure and livelihoods beyond QTEC remain lacking so far in HMA.

### 3.3. Adaptation

Climate and related cryospheric change, together with other anthropogenic pressures, is expected to further impact regional geomorphology, hydrology, ecology and economy in future, calling for appropriate adaptation responses. This has been recognized in the western Himalaya, where studies highlight that permafrost has a strong scientific as well as societal significance (Ali *et al* 2018) as well as along the QTEC, where monitoring has been in line with concerns about the sustainability of both road and train infrastructure. For other infrastructure spanning HMA, such dedicated appraisal of permafrost does not exist. We argue that future adaptation should be built on dedicated monitoring and awareness of linkages between permafrost change and hydrology, ecosystems as well as natural hazards, which we review below. Furthermore, although not a focus of this review, we call attention to the importance of recognizing and addressing underlying socio-economic factors that can constrain adaptation across the region (e.g. (McDowell *et al* 2020)).

#### *3.3.1. Permafrost monitoring*

To date, intermittent observations, irregular monitoring, and insufficient field-based observations have been a major constraint to effective understanding of the interrelationship among ecological, hydrological and geomorphological attributes in permafrost environments of HMA (Luo *et al* 2018b). Permafrost monitoring across the HKH in Nepal, India, and Pakistan has received some attention in most recent years, including mapping of rock glaciers (Schmid *et al* 2015, Stumm *et al* 2020) as well as ground temperature measurements (Steiner *et al* 2021). Similar efforts were made in Ladakh (Wani *et al* 2020), and in September 2015 an initial workshop was held in Gilgit, Pakistan.

#### *3.3.2. Adaptation in the hydrological sector*

To minimize the risks from slope failures and GLOFs associated with warming permafrost, well defined frameworks for hazard and risk assessment have been proposed (e.g. (GAPHAZ 2017, NDMA 2020)) including specifically for thermokarst lakes in Central Asia (Falatkova *et al* 2019) and the hydropower sector (Li *et al* 2022). Such frameworks recommend monitoring of mountain lakes that are susceptible to outbursts, evaluation of the magnitude and impact of potential hazard events and implementation of proper risk reduction measures, including Early Warning Systems, and related land-use zoning (Ives *et al* 2010, NDMA 2020).

In China, several research initiatives to explore different aspects of geocryology as well as hydrogeology have been carried out since the early 1960s, including the development of regional maps. Such studies have focused on processes and interactions related to permafrost and groundwater and contributed to the knowledge of impacts of climate change on cold region hydrology (Cheng and Jin 2013). These investigations provide important baseline information to develop national plans and policies in the past up to today to adapt to changing climate conditions and understand subsequent impacts upon the hydrological cycle in cold and arid regions.

#### *3.3.3. Ecosystem protection and adaptation*

In China, there has been a gradual shift in the focus of national grassland policy from sustainable socio-economic development towards conservation (Fang *et al* 2011). In this context, one adaptation option is to focus on compensation mechanisms as land for cultivation is lost as well as the provision of vocational training and livestock replacement to provide a broader scale of potential employment in affected regions. Wang *et al* (2020) suggest that changed grazing patterns, following directives by the government resulted in positive effects for the ecosystems from 2000 onwards compared to negative contributions in the two decades prior, however these actions were not able to offset the degradation of vegetation caused by a decrease in the depth of frozen soil over the same period.

#### *3.3.4. Reducing risk of natural hazards*

Appropriate applications of hazard and risk management principles, in the context of glacial and permafrost mountain areas, need to be planned in such a way that probable future climate conditions are taken into account, along with changing socio-economic conditions (GAPHAZ 2017). Research to investigate the effect of permafrost change on infrastructure as well as the spatiotemporal effects of infrastructure such as roads on thermal regimes in permafrost areas, have developed from early studies monitoring ground temperatures (Wang and French 1995) to using state of the art remote sensing techniques (Zhang *et al* 2019a). This assists in designing operational frameworks for planning of construction programmes and selection of appropriate locations to avoid potential threats to the environment due to future operations. The national project 'Research on a series of technologies for highway constructing in the permafrost regions' was launched by the Chinese Ministry of Communication in 2002 to cope with the difficulties related to climate induced warming of permafrost. The project was designed to investigate aspects of construction, management, and protection of engineered structures, especially roads, in high altitude permafrost regions (Wang *et al* 2009). Field based investigations and mathematical simulations of an unusual and natural permafrost location within a scree slope in northern China have led to the conclusion that thermal conductivity of peat is essential to preserve permafrost even under warm climate conditions (Niu *et al* 2016). This discovery has helped ensure the effectiveness of using crushed rock layers as slope cover in recent constructions of the Qinghai-Tibet Railway.

In China, to ensure safe operation of engineering corridors that exist on permafrost areas, appropriate management practices are followed which include quantitative as well as qualitative analysis (Luo *et al* 2017). These management practices include continuous monitoring through surveying using high precision GPS, borehole drilling, microwave remote sensing techniques, terrestrial photogrammetry, electrical resistivity tomography and terrestrial laser scanning.

## 4. Discussion

### 4.1. Impacts of changing permafrost

Water from thawing permafrost has been found to contribute one third of total discharge of a single catchment, but such data is lacking elsewhere. Increasing temperatures found an increase in contribution to baseflow from permafrost in winter over a limited number of sites, an effect elsewhere recorded especially for discontinuous permafrost (Walvoord and Kurylyk 2016), with some evidence also of the contrary. This follows the generally heterogenous response of streamflow to a changing permafrost also observed in the Arctic (Walvoord and Kurylyk 2016). The formation of ice layers as groundwater discharges in winter (Woo 2012) has been seen in

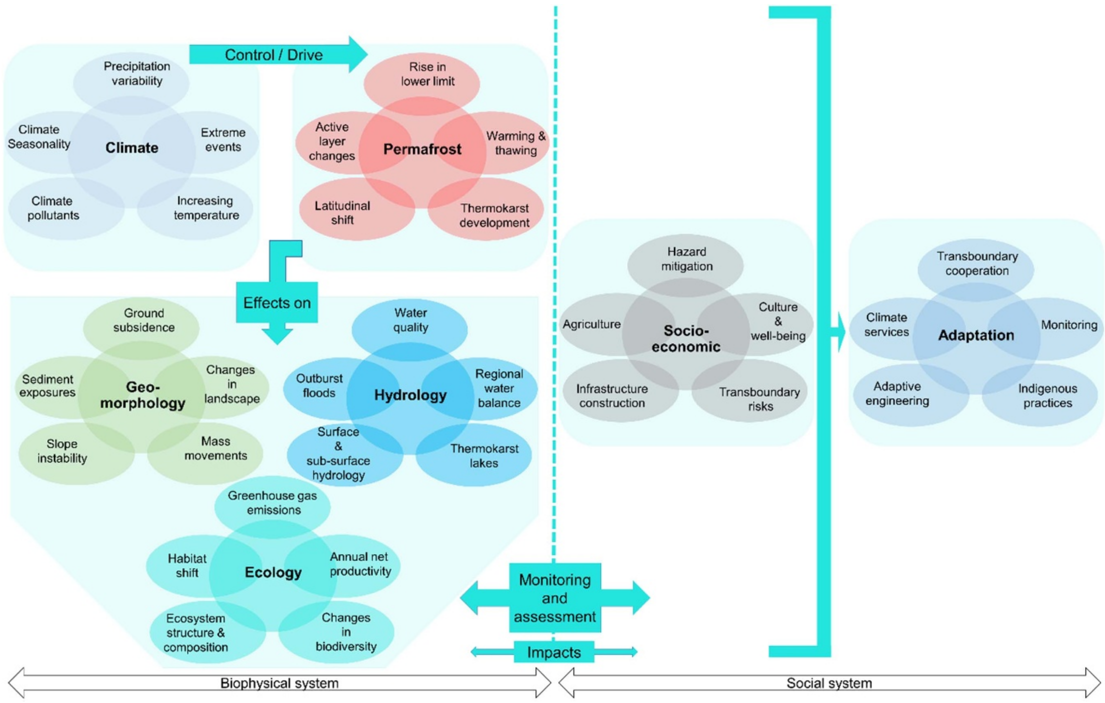


**Figure 4.** Schematic representation of climate system, permafrost processes, impacts of permafrost change on biophysical and social systems, and adaptation measures to minimize the impacts of permafrost change in HMA. Continuous monitoring and assessment of biophysical and social systems is necessary to address the impacts which are bidirectional as changes in biophysical system affects the social system and vice-versa.

different sites in HMA but so far only documented in Ladakh (Brombierstäudl *et al* 2021). Like in the Arctic (Hayashi 2013), the relevance of a changing hydrology for ecosystems and nutrient transport is however well documented on the QTP, resulting in concerns over desiccation of soils and impacts on herding and plant species. What is so far largely lacking is a detailed description of subsurface processes affecting hydrology, either through observations or modelling. As snow cover is changing across HMA, with heterogenous trends but expected significant impacts on hydrology (Kraaijenbrink *et al* 2021) we also expect impacts on permafrost (Zhang 2005), but so far lack in depth analysis in the region. It is projected that even though discharge in river basins with thawing permafrost areas may be gradually increasing, in future, river runoff will reduce and become largely dependent upon precipitation distribution and seasonality. Similarly, an increase in winter base flows and surface runoff could be considered beneficial as they ensure availability of more than anticipated discharge in mountain rivers that could be utilized for increasing hydropower capacity and strengthening irrigation management systems for cultivated lands downstream. However, these benefits are anticipated to be only temporary.

Geomorphic impacts resulting from fragile mountain slopes such as outburst floods, landslides, debris flows, rock falls, ice and rock avalanches, ground subsidence and other mass wasting events can have catastrophic consequences that extend far downstream. Studies have indicated a potential link between large scale, highly mobile mass movements and changes in permafrost in the upstream catchment, however such links remain largely speculative owing to a lack of in situ observations (Maharjan *et al* 2021, Shugar *et al* 2021, Sattar *et al* 2023). A slow onset hazard related partially to a thawing permafrost is the constant rise of sediments in river discharge, posing challenges especially to hydropower infrastructure (Li *et al* 2022). More recently the potential costs to mitigate risks associated with permafrost thaw on the QTP have been quantified at $6.31 billion by 2090, with ample potential of reduction when warming is limited (Ran *et al* 2022a).

Continuous monitoring and assessment of biophysical and social systems affected by permafrost change is challenging. Understanding impacts of global changes in climate on permafrost in HMA requires knowledge about changes in each climate variable that control permafrost processes, many of which have been discussed in literature on HMA (figure 4). However, a major challenge lies in the integration of different methods to monitor and to understand changes in components and processes (Bugmann *et al* 2007). While numerous individual aspects of permafrost have been investigated in HMA over the last years, including a combination of multiple datasets and multi-disciplinary approaches to aid in adaptation as along the QTEC, this integrated approach is still lacking across the region.

### 4.2. Research gaps and recommendations

There have been a number of calls for more long-term monitoring of permafrost globally (Haeberli and Gruber 2008) and regionally for the QTP in 2000 (Jin *et al* 2000), the Tien Shan seven years later (Marchenko *et al* 2007) and another decade later for the HKH (Gruber *et al* 2017). A large amount of evidence followed with research studies increasing markedly from around 2015 (figure S1), especially for the relatively flat QTP (figures 1 and 2). For the more mountainous HKH to the south this has so far not translated into concerted efforts for long term monitoring and the sustainability of efforts in the Tien Shan and Altay established during the Soviet Union are unclear. However, the large number of studies in the equally mountainous Qilian Shan (figure 2) provides some basic understanding of potential impacts of changing permafrost outside of the Plateau.

The steadily increasing numbers of scientific publications in recent years are indicators of increasing scientific attention being given to climate change impacts and adaptation related to mountain permafrost in the region. A majority of these publications identify that the current status of research is insufficient and recommend additional research efforts. Nevertheless, a growing number of scientific investigations confirm the presence of significant climate change impacts and point to the urgent need for appropriate adaptation action in the region. Hence, an incomplete scientific knowledge base should not prevent moving forward with adaptation action.

Studies investigating future projections of permafrost and its consequence in HMA are relatively rare, limited to the Tibetan Plateau, vary in range and across different regions. There is some consensus that projected areal extents will be reduced by approximately 40% after mid-century (Guo *et al* 2012, Ni *et al* 2021), with projections till end of century varying between a 40% and an 80% reduction. ALT is projected to increase between 5 and 30 cm and will be greater than 30 cm, irrespective of concentration pathways, with an increase from south to north (Zhao and Wu 2019). A recent study suggests that soil water contents need to be accounted for in ALT change projections to avoid overestimations, but nevertheless project an average ALT on the QTP of 4 m by end of century (Ji *et al* 2022). This certain ALT increase is expected to eventually lead to a decrease in surface runoff (Guo *et al* 2012), suggesting that peak flow is also imminent for permafrost thaw and can have drastic consequences for ecosystems as alpine meadows dry out (Zhao and Wu 2019). It is expected that in the long run, although richness of certain species may increase, the diversity of species would gradually decrease (Jin *et al* 2021). Consequences are dire for infrastructure with projected hazards for one third of the settlement area along QTEC by mid-century (Guo and Sun 2015), a value similar to projected risks for circumpolar infrastructure (Hjort *et al* 2022).

We show that field-based investigations and monitoring are the most applied method for mountain permafrost assessment, while modelling studies are rare. However, permafrost across the region covers extensive areas and therefore, field-based investigations offer only limited knowledge. Here, remote sensing methods and numerical simulations are more feasible procedures for extensive regional analysis. A preliminary mapping of rock glaciers (Schmid *et al* 2015) has been a benchmark and paved the way for multiple recent studies on rock glaciers (Jones *et al* 2018, Haq and Baral 2019, Pandey 2019), initial discussions of the impact of permafrost change on infrastructure (Streletskiy *et al* 2012), and has led to quantifications in HMA even considering future projections (Guo and Sun 2015, Hjort *et al* 2022). Although permafrost maps especially for the plateau have existed for a long time (Ran *et al* 2012), more recent studies have improved upon their granularity (Gruber *et al* 2017, Obu 2021, Ran *et al* 2022b), while still leaving room for improvement, especially in mountainous regions. Such benchmark studies are central to generating an interest in the scientific community and guide the way for future research, and regional studies that link ecology and hazards to permafrost should be attempted to provide groundwork for these relatively underrepresented topics.

Extensive areal coverage of permafrost makes it a regional phenomenon and therefore, transboundary rather than localized national initiatives seem essential for effective adaptation, particularly concerning hydrological impacts. Building on documented investigations and well-built infrastructure in response to climate change related impacts on mountain permafrost (especially on the QTP) could assist in developing regional programmes to address the issue (see Schmid *et al* (2015) and Allen *et al* (2016) as examples). Such collaboration can extend beyond the region, to build on experiences with permafrost science, impacts and adaptation in Europe and North America, and provide a fertile ground for future permafrost research programs that are not confined to specific locations but affect most mountain regions globally.

Mountain water resources are highly likely to be impacted due to changes in climate conditions. Water management under such conditions should comprise of well-defined policies for water allowance, reservoir installation, irrigation management, responses to low and high flows and prevention of unnecessary loss of distributed water through different mechanisms (Beniston and Stoffel 2014). Ecological impacts such as growth in richness and diversity of herbs, shrubs and tree communities are valuable for ecosystem services. Their role and interconnectedness with a changing permafrost needs to be appreciated to be able to better anticipate potential cascading risks that are currently difficult to project (Ehlers *et al* 2022). Based on the available knowledge on permafrost, local policies regarding water, ecosystems, livelihoods, and hazards should include the role and impact of permafrost in future.

## 5. Conclusions

In this study we have reviewed the state of knowledge on permafrost, its change and existing or envisioned adaptation measures across HMA. Insights from a total of 197 studies show an increasing interest in the recent past, from five studies per year around 2010 to more than 20 only 10 years later. While initial studies focused mainly on ground temperatures, recent research has become more diverse investigating impacts on hydrology, surface displacement and ecology using both field data as well as remote sensing and modelling approaches. Direct information on permafrost presence relying on field data remains however limited to the central QTP, with only three field monitoring sites in the HKH and three borehole locations in the Tien Shan.

The majority of impacts documented include a continuing increase of ground temperatures across all monitored sites from which an increase in ALT follows, as well as indications of a decrease in winter runoff and drying of soils as permafrost thaws. These observed changes are projected to continue to increase unabated into the future. The documented impact on hydrology is confined to few catchments in the northwestern QTP, and responses vary with different elevations and contributions of other water sources. More studies across HMA are required to assess the impact of permafrost hydrology and potentially develop estimates of peak water, as has been done for glacier and snow melt before. Additionally, there is evidence that permafrost change has led to slope movements and increased mass wasting. What is less clear is how such changes are affecting existing or infrastructure under development and how compound drivers, e.g. an increase in liquid precipitation at altitude or the impact from road construction further exacerbate or otherwise influence these hazards.

While global maps of permafrost extents exist, an accurate understanding of the lower permafrost limit as well as high resolution (<1 km) maps remain absent. Present as well as anticipated future direct impacts of permafrost change on livelihoods and potential migration due to changes in vegetation or evolving hazards remain largely unstudied. This includes anticipated risks for major transboundary infrastructure like the two main road (and possibly future road) corridors linking China and Nepal, China and Pakistan (the Karakoram Highway) as well as the Pamir Highway linking China, Kyrgyzstan, Tajikistan, and Afghanistan. Considering the lack of knowledge on permafrost extent, its interrelation with ecosystems as well as the cascading nature of expected changes, we also foresee unanticipated risks that are difficult to prepare for, calling for adaptation strategies that are flexible enough to account for unknown future developments. The direct effect of permafrost change on sediment loads in rivers, and subsequent risks for hydropower and other adjacent infrastructure to waterways remains largely underappreciated. Finally, local and Indigenous knowledge regarding permafrost distribution, impacts of warming and related adaptation does not surface in any of the peer reviewed literature to date. In the Arctic the need for appreciation and integration into conventional research practice of the same has been emphasized very recently with respect to permafrost (Ulturgasheva 2022, Gruber *et al* 2023) as well as on a global level for climate science in general (Miner *et al* 2023). For HMA in a climate or cryosphere context this has been highlighted in the context of hazards (Emmer *et al* 2022, Acharya *et al* 2023) but needs to be documented and integrated in future studies on permafrost.

The increasing volume of literature focusing on multi-disciplinary research is already a positive indication that awareness around the wide-ranging impacts of permafrost degradation is advancing, while there has been relatively less focus on adaptation options in mountain regions. There remain few holistic approaches beyond the central QTP, that would allow for strong recommendations for adaptation. We argue this is due to a combination of factors, namely a lack of continuous monitoring, difficulty in identifying clear trends as has been done for glacier ice as well as a lack of communicating the (potential) effects of a changing permafrost in the region. We therefore recommend that successful practices of permafrost monitoring already present for decades in a few locations should be replicated elsewhere and knowledge needs to be exchanged on the topic in regional exchange forums. Modelling and field studies investigating the high mountain water balance need to add the permafrost component, in order to evaluate its role. Including the effects of enhanced nutrient cycling and lateral carbon flux in future projections will inform the risks of climate-induced permafrost thaw on hydrologic, geomorphologic, ecological, and infrastructure systems. Finally, following the successful focus of research and subsequent adaptation recommendations for critical infrastructure along the QTEC, other infrastructure development across the region should learn from this process and integrate monitoring and modelling approaches into their planning. This could also include an estimate of the economic costs of potential non-action to adapt and a quantification of any other associated risks. Due to the transboundary nature of the observed and anticipated impacts an increase in scientific collaboration, especially focused on less represented mountain regions remains necessary. This needs to be accompanied by active participation of local authorities and young researchers thus contributing towards capacity building on a regional scale.

## Data availability statement

The data that support the findings of this study are openly available at the following URL/DOI: https://github.com/fidelsteiner/HMAPermafrost.

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## Conflict of 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.

## Disclaimer

The views and interpretations in this publication are those of the authors and are not necessarily attributable to ICIMOD.

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