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Glacier recession, debris cover development and the implications for water resources in Afghanistan

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UNIL | Université de Lausanne
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PhD. Thesis

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Professeure Marie-Elodie Perga

To my parents, Abdul Rasoul Shokory and Atefa Shokory – thank you for your lifetime support and love.

تقدیم به پدر و مادر عزیز و بزرگوارم – تشکر و سپاس از حمایت های معنوی و مادی همیشگی و محبت های تان که ارزشمند ترین اموزگاران زندگی ام بودید.

Summary

Rapid climate change is impacting water resources in Afghanistan, a country in the western Himalayas. It is a semi-arid to arid country of Central Asia where livelihoods and economies have developed to be strongly dependent upon mountain water resources, and where snow and glacier melt deliver 80% of Afghanistan's water supply. It is also poorly-developed in terms of scientific research and environmental monitoring. Average global temperatures are rising and glaciers are shrinking significantly, potentially impacting water supply to a critical degree. This effect is likely hidden for the time being as glaciers are still larger in volume than that associated with a warmer and warming climate. However, once glaciers shrink to a certain size, "peak water" will be reached. Water supply will decline. If winter snowfall declines, or becomes more variable, glaciers are less likely to compensate for the associated water shortage that results. Recent research has emphasized the complexity of identifying when peak water develops, not least because as glaciers retreat they may develop extensive debris cover, which can significantly modify the relationship between climate change and glacier melt. Given the lack of research in Afghanistan on this topic, the primary aim of this thesis is to quantify the impacts of ongoing and future climate change on Afghan glaciers and the associated consequences for water resources in Afghanistan. To this end, a multidisciplinary approach is used, based on the combination of remote sensing, a restricted field campaign, hydrological modeling, archival data, and locally adjusted climate change scenarios. The PhD thesis addressed the following four research questions:

R1: Is it possible to improve remote sensing techniques for glacier monitoring in Afghanistan to allow mapping of not only ice cover but also debris-covered ice at the scale of the entire country?

R2: How have the total, bare ice and debris-covered ice extents of Afghanistan glaciers changed in recent decades with the onset of rapid warming?

R3: Is it possible to develop a glacier-snow melt runoff model suitable for application over large scales in the data poor context of Afghanistan?

R4: How has and how will climate change influence future glacier runoff in Afghanistan?

This study is contextualized through a systematic review of more than 130 scientific articles, reports and data sources to assess the potential impacts of climate change on the cryosphere, streamflow, groundwater and hydrological extremes in Afghanistan and to highlight knowledge gaps. This review shows the importance of the cryosphere for Afghan water resources and identifies the need to develop a better inventory of glacier cover in Afghanistan, notably taking into account debris-cover given the geology and geomorphology of the region. To do this, the thesis develops two new debris-cover mapping indices based on thermal and near Infrared Landsat 8 bands. The indices are calibrated with field data, and validation both within and beyond Afghanistan suggests that they have a high level of accuracy. Principal components analysis was applied to 9 glacier parameters to identify the most influential drivers of debris-covered ice extent. This analysis showed that lower proportions of debris cover were associated with glaciers with a higher elevation range that were larger, longer and wider. However, these patterns were statistically clearer when the dataset was broken down into climate zones and geological regions.

This methodology is then applied to two timespans (2000-2008 and 2008-2020) to assess recent glacier changes in Afghanistan. Three glacier inventories were developed for the years 2000, 2008, and 2020. In 2020, a glacier area of 2684±100.7 km^2 was mapped, split into 75±0.7 % clean ice area and 25±3.0 % debris-covered ice. Total glacier area retreated by -4.5±0.5 km^2 yr^{-1} (-0.15±0.01 % yr^{-1}) between 2000 and 2008 and -12.3±1.5 km^2 yr^{-1} (-0.43±0.05 % yr^{-1}) between 2008 and 2020. However, the analysis revealed substantial spatial variation in these retreat rates based upon geographical region, glacier size and climate region. The results point to the environmental complexity of Afghanistan and suggest that certain regions may pass through peak water much sooner than others. Debris cover changes were also found to be complex, with debris-covered ice extent increasing much more for smaller glaciers <2.5 km^2 than larger ones.

In order to understand the implications of glacier recession now and in the future for Afghan water resources, three representative catchments were selected based on their locations and data availability, the Taqchakhana catchment (264.4 km^2 area with 2.8% glacier cover) in the north; the Sust catchment (4609 km^2 area with 15.6% glacier cover) in the east; and the Bamyan catchment (325.3 km^2 area with 0.7% glacier cover) in the center of Afghanistan. Current glacier retreat rates are different for each catchment on the basis of the glacier change study. These were also catchments with climate and streamflow data from 2012 to 2019 provided by the Ministry of Energy and Water of Afghanistan. To understand the current and future relative contributions of ice, snow and other components to water supply, Hydrobricks, a new semi-lumped, glacio-hydrological modeling framework based on a C++ core with a Python interface, was used. The model was modified to allow a simple representation of the effects of debris cover development on ice melt. The model was individually calibrated for each catchment based on Shuffled Complex Evolution Algorithm (SCE-UA), with the best parameters taken after 30,000 iterations. Eight regional climate models (RCMs) under two scenarios (2.6 and 8.5) were used in the model to simulate future streamflow in the catchments. The RCMs were bias-corrected using non-parametric statistical transformation. Future glacier evolution was introduced to the model using a very simple propagation of current measured glacier recession rates into the future. Validation of the calibrated model produced good values of the Kling-Gupta efficiency (KGE) for simulated daily streamflow (KGE >~0.8). Glacier runoff dominated the Sust catchment (76%); rain and snow runoff the Taqchakhana catchment (50%) and baseflow the Bamyan catchment (61%). Projected streamflow under RCP 2.6 suggests that mean annual glacier runoff for the Sust and Taqchakhana catchments will increase until 2050, following an increase in temperature (0.9 ˚C). Then runoff declines to the end of the 21st century. The Bamyan is predicted to have declining runoff throughout the 21st century. However, under RCP 8.5 glacier runoff increases more markedly in the Sust and Taqchakhana catchments as temperature rises are larger, climate change mitigation measures do not reverse them. These catchments are likely to pass through a phase of peak water not due to temperature limitation on runoff as under RCP 2.6, but due to progressively diminishing glacier size.

Résumé

Le rapide changement climatique a un impact sur les ressources en eau de l'Afghanistan, un pays situé dans l'ouest de l'Himalaya. Il s'agit d'un pays semi-aride à aride d'Asie centrale. En l'Afghanistan, les moyens de subsistance et les économies se sont développés pour dépendre fortement des ressources en eau des montagnes, et la fonte des neiges et des glaciers fournit 80 % de l'approvisionnement en eau. L'Afghanistan est également peu développé en termes de recherche scientifique et de surveillance de l'environnement. Les températures moyennes mondiales augmentent et les glaciers rétrécissent considérablement, ce qui pourrait avoir un impact critique sur l'approvisionnement en eau. Cet effet est probablement caché pour le moment, car les glaciers ont encore un volume plus important que celui associé à un climat plus chaud. Toutefois, lorsque les glaciers auront atteint une certaine taille, le "pic hydrique" sera atteint. Et l'approvisionnement en eau diminuera. Si les chutes de neige hivernales diminuent ou deviennent plus variables, les glaciers sont moins susceptibles de compenser le manque d'eau qui en résulte. Des recherches récentes ont mis en évidence la complexité de l'identification du moment où le pic d'eau est atteint, notamment parce que lorsque les glaciers reculent, ils peuvent se couvrir de débris, ce qui peut modifier de manière significative la relation entre le changement climatique et la fonte des glaciers. Étant donné le manque de recherche en Afghanistan sur ce sujet, l'objectif principal de cette thèse est de quantifier les impacts du changement climatique actuel et futur sur les glaciers afghans et les conséquences associées pour les ressources en eau en Afghanistan. Dans ce but, une approche multidisciplinaire est utilisée, basée sur la combinaison de la télédétection, d'une campagne de terrain restreinte, de la modélisation hydrologique, des données d'archives, et des scénarios de changement climatique ajustés localement. La thèse de doctorat a abordé les quatre questions de recherche suivantes :

R1 : Est-il possible d'améliorer les techniques de télédétection pour la surveillance des glaciers en Afghanistan afin de permettre la cartographie non seulement de la couverture de glace mais aussi de la glace couverte de débris à l'échelle du pays tout entier ?
R2 : Comment les étendues de glace totale, de glace nue et de glace couverte de débris des glaciers d'Afghanistan ont-elles évolué au cours des dernières décennies avec l'apparition d'un réchauffement rapide ?
R3 : Est-il possible de développer un modèle de ruissellement des eaux de fonte des glaciers et des neiges adapté à une application à grande échelle dans le contexte pauvre en données de l'Afghanistan ?
R4 : Comment le changement climatique a-t-il influencé et comment influencera-t-il l'écoulement futur des glaciers en Afghanistan ?

Cette étude est contextualisée par une revue systématique de plus de 130 articles scientifiques, rapports et sources de données afin d'évaluer les impacts potentiels du changement climatique sur la cryosphère, le débit des cours d'eau, les eaux souterraines et les extrêmes hydrologiques en Afghanistan et de mettre en évidence les lacunes en matière de connaissances. Cette revue montre l'importance de la cryosphère pour les ressources en eau afghanes et identifie le besoin de développer un meilleur inventaire de la couverture glaciaire en Afghanistan, notamment en prenant en compte la couverture de débris étant donné la géologie et de la géomorphologie de la région. Pour ce faire, la thèse développe deux nouveaux indices de cartographie de la couverture de débris basés sur les bandes thermiques et infrarouges proches de Landsat 8. Les indices sont calibrés avec des données de terrain, et la validation à l'intérieur et à l'extérieur de l'Afghanistan suggère qu'ils ont un haut niveau de précision. Une analyse des composantes principales a été appliquée à 9 paramètres des glaciers afin d'identifier les facteurs les plus influents de l'étendue de la glace couverte de débris. Cette analyse a montré que des proportions

plus faibles de couverture de débris étaient associées à des glaciers d'altitude plus élevée qui sont plus grands, plus longs et plus larges. Toutefois, ces schémas sont statistiquement plus clairs lorsque l'ensemble des données est décomposé en zones climatiques et en régions géologiques.

Cette méthodologie est ensuite appliquée à deux périodes (2000-2008 et 2008-2020) pour évaluer les changements récents des glaciers en Afghanistan. Trois inventaires des glaciers ont été élaborés pour les années 2000, 2008 et 2020. En 2020, une zone glaciaire de 2684±100.7 km^2 a été cartographiée, divisée en 75±0.7 % de glace propre et 25±3.0 % de glace couverte de débris. La superficie totale du glacier a reculé de -4.5±0.5 km^2 yr^{-1} (-0.15±0.01 % yr^{-1}) entre 2000 et 2008 et de -12.3±1.5 km^2 yr^{-1} (-0.43±0.05 % yr^{-1}) entre 2008 et 2020. Toutefois, l'analyse a révélé des variations spatiales substantielles dans ces taux de recul en fonction de la région géographique, de la taille du glacier et de la région climatique. Les résultats soulignent la complexité environnementale de l'Afghanistan et suggèrent que certaines régions peuvent passer par le pic hydrique beaucoup plus tôt que d'autres. L'évolution de la couverture de débris s'est également révélée complexe avec l'étendue de la glace couverte de débris qui augmente beaucoup plus pour les petits glaciers <2.5 km^2 que pour les plus grands.

Afin de comprendre les implications actuelles et futures du recul des glaciers sur les ressources en eau afghanes, trois bassins versants représentatifs ont été sélectionnés en fonction de leur emplacement et de la disponibilité des données : le bassin versant de Taqchakhana (264.4 km^2 avec une couverture glaciaire de 2.8 %) dans le nord ; le bassin versant de Sust (4609 km^2 avec une couverture glaciaire de 15.6 %) dans l'est ; et le bassin versant de Bamyan (325.3 km^2 avec une couverture glaciaire de 0.7 %) dans le centre de l'Afghanistan. Les taux actuels de recul des glaciers sont différents pour chaque bassin versant, sur base de l'étude sur les changements glaciaires. Il s'agit également de bassins versants pour lesquels le ministère afghan de l'énergie et de l'eau a fourni des données sur le climat et le débit entre 2012 et 2019. Pour comprendre les contributions relatives actuelles et futures de la glace, de la neige et d'autres composants sur l'approvisionnement en eau, Hydrobricks, un nouveau cadre de modélisation glacio-hydrologique semi-lumped basé sur un noyau C++ avec une interface Python, a été utilisé. Le modèle a été modifié pour permettre une représentation simple des effets du développement de la couverture de débris sur la fonte des glaces. Le modèle a été calibré individuellement pour chaque bassin versant sur la base de l'algorithme d'évolution complexe aléatoire (SCE-UA), avec les meilleurs paramètres retenus après 30000 itérations. Huit modèles climatiques régionaux (MCR) selon deux scénarios (2.6 et 8.5) ont été utilisés dans le modèle pour simuler le débit futur des cours d'eau dans les bassins versants. Les MCRs ont été corrigés des biais à l'aide d'une transformation statistique non paramétrique. L'évolution future des glaciers a été introduite dans le modèle en utilisant une propagation très simple des taux de recul des glaciers mesurés actuellement. La validation du modèle calibré a produit de bonnes valeurs de l'efficacité de Kling-Gupta (KGE) pour le débit journalier simulé (KGE>~0.8). Le ruissellement des glaciers a dominé le bassin versant de Sust (76 %), le ruissellement des pluies et de la neige le bassin versant de Taqchakhana (50 %) et le débit de base pour le bassin versant de Bamyan (61%). Les projections de débit dans le cadre du RCP 2.6 suggèrent que l'écoulement glaciaire annuel moyen pour les bassins versants de Sust et de Taqchakhana augmentera jusqu'en 2050, à la suite d'une augmentation de la température (0.9˚C). L'écoulement diminuera ensuite jusqu'à la fin du 21ème siècle. Il est prévu que le ruissellement du Bamyan diminue tout au long du 21ème siècle. Toutefois, dans le cadre du RCP 8.5, l'écoulement des glaciers augmente de manière plus marquée dans les bassins versants de Sust et de Taqchakhana, car les hausses de température sont plus importantes, et les mesures d'atténuation du changement climatique n'inversent pas cette tendance. Ces bassins versants sont susceptibles de passer par une phase de pic hydrique non pas en raison de la limitation de l'écoulement par la température, comme dans le cas du RCP 2.6, mais en raison de la diminution progressive de la taille des glaciers.

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Basic acronyms

a.s.l	**Above Sea Level**
ALOS	**Advanced Land Observing Satellite**
AMD	**Afghanistan Meteorological Department**
APHRODITE	**Asian Precipitation - Highly-Resolved Observational Data Integration Towards Evaluation Of Water Resources**
BCM	**Billion Cubic Meters**
DEM	**Digital Elevation Model**
GCM	**General Circulation Model**
GHG	**Greenhouse Gases**
GLOF	**Glacier Lake Outburst Flood**
HKH	**Hindu Kush Himalaya**
HWMI	**Heat Wave Magnitude Index**
ICIMOD	**International Centre For Integrated Mountain Development**
IDYST	**Institute Of Earth Surface Dynamics (University Of Lausanne)**
IPCC	**Intergovernmental Panel On Climate Change**
ITCZ	**Intertropical Convergence Zone**
KGE	**Kling-Gupta Efficiency**
MEW	**Ministry Of Energy And Water**
MoMP	**Ministry Of Mines And Petroleum**
NDSI	**Normalized Difference Snow Index**
NEPA	**National Environmental Protection Agency**
OBIA	**Object-Based Image Analysis**
RCP	**Representative Concentration Pathway**
SCE-UA	**Shuffled Complex Evolution Algorithm**
SPOTPY	**Statistical Parameter Optimization Tool For Python**
SWAT	**Soil Water Assessment Tool**
UNEP	**United Nation Environmental Program**
UNIL	**Université De Lausanne**

I INTRODUCTION

I.1 Background

About one sixth of the world's population lives in river basins fed by significant melt of snow and/or ice (Schaner et al., 2012). For instance, 1.9 billion people in Asia depend on river basins originating from the Hindu Kush Himalaya (HKH) mountains (Molden et al., 2021). Snow and ice are important because they impart memory effects upon river runoff over different time-scales. At the shortest time-scales, snow- or ice-melt driven by temperature and/or solar radiation can lead to significant river flow even during dry periods. At the annual time-scale, winter-accumulated snow is stored and released as summer runoff, such that the latter is a function of winter (i.e. cryosphere-stored) as well as summer precipitation. Over the longest timescales, snow that accumulates on glaciers forms ice that may sustain summer runoff for years and decades, long after the precipitation that formed the ice. These memory effects render the runoff response of mountain catchments highly sensitive to the history of cryosphere water storage over different time-scales. They also mean that linking runoff to current climate change becomes complex; if we invert the problem, the runoff measured at any one time in a mountain stream is not only a product of temperature and/or precipitation in the hours, perhaps days, before; it is also a function of the historical storage of water as snow (at the annual scale) and ice (at longer time-scales).

In terms of flow extremes, and notably low flows, glaciers may well hide the true sensitivity of a basin to climate warming, because historical ice accumulation provides a "glacial subsidy" (Collins, 2008) until a glacier has become relatively small (Kaser et al., 2010; Sorg et al., 2014; Huss and Hock, 2018) or ice melt declines due to insulation related to debris accumulation (Scheler et al., 2011). At this point, a basin is said to have passed "peak water" (Sorg et al., 2014; Huss and Hock, 2018). Such a transition may substantially increase water scarcity, especially if a basin has developed rapidly during a period of enhanced glacial subsidy and water resource management decision-making has proceeded oblivious to this subsidy.

Human-induced warming had already reached a 1°C (likely range between 0.8°C and 1.2°C) above pre-industrial levels by 2017 (Allen et al., 2018). The increase of global mean surface temperature by the end of the 21st century (2081–2100) relative to 1986–2005 is likely to be 0.3°C to 1.7°C under representative concentration pathway (RCP) 2.6, 1.1°C to 2.6°C under RCP 4.5, 1.4°C to 3.1°C under RCP 6.0 and 2.6°C to 4.8°C under RCP 8.5 (IPCC, 2014). The 2022 IPCC Synthesis Report is not yet formally accepted, but these figures have been updated showing an increases in temperature to 1.1°C above 1850-1900 in 2011-2020. There are very likely ranges of warming for 2081–2100 with respect to 1850–1900 vary from 1.4°C (1.0-1.8°C) in the very low GHG emissions scenario (SSP1-1.9) to 2.7°C (2.1°C– 3.5°C) in the intermediate GHG emissions scenario (SSP2-4.5) and 4.4°C [3.3°C–5.7°C] in the very high GHG emissions scenario (SSP5-8.5) (IPCC, 2022) These global figures hide rates that are higher in mountain regions such as the Alps or the Hindu Kush Himalayas (HKH) (Rangwala and Miller, 2012). Consequently, glaciers are shrinking significantly (Milner et al., 2017), especially in the HKH (Lee et al., 2021). This ice volume loss may impact water resources, which are sometimes critical for countries with semi-arid or arid climates where glaciers provide water for irrigation during the growing season (Pritchard 2019). In addition, ongoing climate warming is enhancing the probability of natural disasters in regions often vulnerable under normal conditions (Rädler 2022). For now, glaciers may still compensate the effects of reduced winter snowfall on subsequent summer runoff by enhanced ice melt (Collins, 2008). However, once glaciers are sufficiently small that peak water passes and this subsidy ends, many regions that have developed during glacial subsidy (population growth, sanitation systems, consumption patterns) may find themselves exposed to severe water shortages driven both by declining water supply and a demand where water supply has not traditionally been limiting. Understanding this effect in semi-arid and arid regions reliant upon mountain water resources is the motivation behind this thesis.

I.2 Thesis context and focus

The context for and focus of this thesis is Afghanistan, a country where issues regarding the role of glaciers in water supply are of crucial importance. Afghanistan is a mountainous country in the western Hindu Kush Himalaya Mountain Area (29°21′N to 38°30′N latitude and from 60°31′E to 75°E longitude, Figure I-1) with an arid and semi-arid continental climate. Its location gives Afghanistan a unique geography that includes glaciated basins extending to over 7,000 m a.s.l. in the Hindukush with non-glaciated basins having a maximum elevation of 250 m.a.sl in the arid deserts in the south-west (NEPA and UNEP, 2016). Nationally, there are extreme seasonal variations in temperature with mean summer temperatures exceeding 33°C and mean winter temperatures of around 10°C. In the glaciated basins to the East, mean winter temperatures are below zero, and the average summer temperature does not exceed 15°C (Savage et al., 2009; NEPA and UNEP, 2016). Some regions of the lowland plains experience very low annual rainfall even below 50 mm per year in the far south-west of the country. However, the glaciated parts of the eastern basins receive substantially higher annual rainfall, which has traditionally fallen mostly as snow between November and April (c. ~1000 mm per year) and linked to winter storms of Mediterranean origin. These rainfall patterns, and their changes, are also made complex due to interactions with the Indian monsoon which can also penetrate across the southern border of Afghanistan. The combination of lower temperatures and higher rainfall in the East of the country sustains both winter snow fall and the historical development of glaciers. Indeed, snow and glaciers contribute 80% of the water resources of Afghanistan, and are of notable importance for summer irrigation (Levedeva and Larin, 1991; Favre and Kamal, 2004). In turn, agriculture supports about 80% of the population, meaning that there is very strong total dependence on natural resources for livelihoods (e.g., small-scale farming, pastures, and forest products).

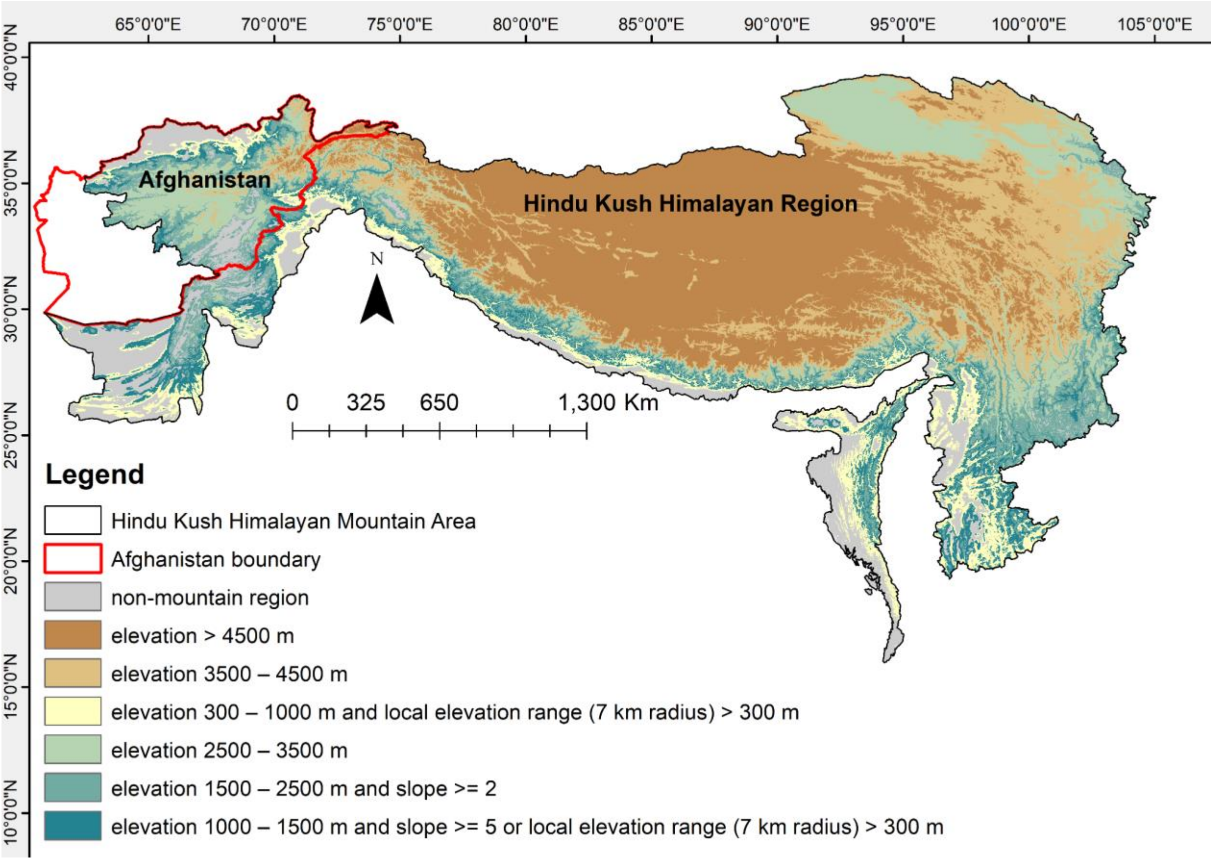

Figure I-1 Shows location of Afghanistan in the Hindu Kush Himalayan Mountain Area. The background image is a classified elevation map.

This dependence on water is of particular concern because there is relatively little peer-reviewed literature and impact studies of climate trends and changes in the water resources of Afghanistan (Savage et al., 2009; Aich et al., 2017). Most research in this region more widely is large scale with a coarse spatial resolution and with a particular focus on the Hindu Kush Himalayan and the Panj Amu regions in central Asia (NEPA and UNEP, 2016). Despite the uncertainty in the scale of the studies, available data and information suggest that temperature has risen significantly in Afghanistan, by between 0.6°C and 1.8°C since 1950 (Savage et al., 2009). Based on climate model projections, the signal be amplified throughout the 21st century (NEPA and UNEP, 2016). Rising temperature is likely to reduce winter snow accumulation with important impacts on summer runoff, notably in basins with no glacier cover or rapidly losing it. However, there are few data that quantify the rapidly evolving state of the cryosphere in Afghanistan because of its history of security and political tensions. Most data are for the period 1965 to 1980. The few data that exist for the more recent period suggest that over a 25 year period (1990-2015), a net 13.4% of glacier area was lost, with an average loss of 5.4% per decade (Maharjan et al., 2018). Rising temperatures may explain this trend. However, these analyses only provide a partial picture of the cryosphere changes that matter for water resources. For instance, retreating glaciers tend to increase their debris cover, so they may mistakenly become labeled as ice free when buried ice remains. Debris cover insulates ice from solar radiation (once a minimum thickness is reached) such that debris-covered ice may still be an important water supply. Scherler et al. (2011) argued that debris cover might be a key missing link in the understanding of the retreat of the Hindukush Himalayan glaciers and its importance has recently been confirmed in Lee et al. (2021). The same may apply to Afghanistan, making existing studies that have failed to include it problematic (Shroder and Bishop, 2010) in water resource terms. Developments in remote sensing (see review in Taylor et al., 2021) may help to improve the quantification of glacier response to changing climate, especially given the growing global availability of high resolution and free datasets.

Future projected climate change over the next century will further affect the rate at which glaciers melt, and the rate of change may be elevated in the Hindu Kush if its mountain climate proves more sensitive to rising greenhouse gas emissions (due to climate feedback) as observed in other Alpine areas (Rangwala and Miller, 2012). The extent to which this will likely impact Afghan water resources is unknown. For instance, it will depend upon both how the subsidy of runoff by glacier melt changes due to glacier retreat and glacier debris cover changes, balanced by changing precipitation patterns. It is probable that, as in Alpine settings, Afghanistan glaciers will go through a state of “peak water” (Farinotti et al., 2014; Huss and Hock, 2018) as they shrink. This could have potentially catastrophic impacts on Afghan agriculture, but there are few data on the current distribution of Afghan glaciers, historical rates of glacier change and how these are and will be moderated by debris cover development. There are also few studies of how such glacier changes might influence water availability in Afghanistan under a future climate.

I.3 Objective and research questions

Given this context, this thesis addresses how glaciers in Afghanistan are currently responding to rapid climate warming and what this might mean for mountain water resources in Afghanistan both now and later in the 21st century. Political instability since the summer of 2021 has rendered scientific investigation of these topics more difficult but has not change their importance. Knowledge of snow and glaciers is critical for water resource policy development in Afghanistan. Its comprehensive management will lead to more sustainable water resources in the country and neighbouring counties with whom Afghanistan shares water.

The main research questions that will be addressed are:

R1: Is it possible to improve remote sensing techniques for glacier monitoring in Afghanistan to allow mapping of not only ice cover but also debris-covered ice at the scale of the entire country? As it is likely that runoff from glaciers in Afghanistan is likely to be influenced by debris cover development, it is vital that methods are developed that can quantify its spatial extent and changes through time.

R2: How have the total, bare ice and debris-covered ice extents of Afghanistan glaciers changed in recent decades with the onset of rapid warming? Afghanistan is in a climatically complex region, notably in terms of precipitation influences, and it is important to revisit the question of how Afghanistan glaciers are responding to climate change in the light of improved mapping (**R1**).

R3: Is it possible to develop a glacier-snow melt runoff model suitable for application over large scales in the data poor context of Afghanistan? Given the paucity of data, understanding the extent to which current runoff from glaciers is responsible for a glacial subsidy is a challenge. One solution to this problem is to take a modelling approach in which the restricted data available are used for model calibration and validation; but then, if the model is deemed valid, model predictions can be used to provide a deeper understanding of the drivers of runoff.

R4: How has and how will climate change influence future glacier runoff in Afghanistan? With a reliable predictive model, it becomes possible to assess future possible climate changes on runoff. Although there have been some attempts to do this at the regional level, their representation of cryosphere-related processes is relatively poor. Such a model will allow two specific questions to be asked: (a) how might melt-driven glacier feedback processes (e.g., debris cover development) condition the future response of Afghan glaciers to climate change?; and (b) how will climate change impacts on Afghan glaciers influence Afghan water resources in the future?

I.4 Structure of the dissertation

After this introduction, the thesis presents five main chapters. The first four of these contain individual research articles, two of which have been published and two of which are in preparation for submission.

Chapter II provides a detailed review of the water resources of Afghanistan under rapid climate warming and has been published in the Hydrological Sciences Journal (HSJ). This chapter presents changes in the climate, cryosphere, streamflow, groundwater, and frequency of hydrological extremes in Afghanistan from the available literature and data. The chapter identifies key research gaps.

- Shokory, J.A., Schaefli, B. and Lane, S.N. (2023). Water resources of Afghanistan and related hazards under rapid climate warming: a review. *Hydrological Sciences Journal*, 68, 1-19. https://doi.org/10.1080/02626667.2022.2159411

Chapter III is methodological and addresses research question **R1** by developing two remote sensing indices for mapping simultaneously bare ice and debris-covered ice for the entire extent of Afghanistan's glacierized zones using Landsat images from 2016. This chapter covers detailed methodological workflow, field campaign, calibration and validation of the methods, and comparison with different inventories from other researchers. The drivers of debris-covered ice extent in Afghanistan were assessed using principal component analysis. The second chapter has been published as an article in the Journal of Glaciology (JOG).

- Shokory, J.A.N. and Lane, S.N. (2023). Patterns and drivers of glacier debris-cover development in the Afghanistan Hindu Kush Himalaya (AHKH). *Journal of Glaciology*, 1-15. doi:10.1017/jog.2023.14

Chapter IV uses these methods to quantify glacier retreat and debris cover evolution in Afghanistan between 2000 and 2020 and so addresses **R2**. The methodology presented in the second chapter is applied to to three dates (2000, 2008, and 2020) for which Landsat images are available. Glacier changes (total area, bare ice extent, debris-covered ice extent) are discussed for all Afghanistan glaciers for two periods (2000-2008) and (2008-2020). This paper will be submitted to Arctic, Antarctic and Alpine Research.

- Shokory, J.A.N. and Lane, S.N. (2023). Glacier retreat and debris cover evolution in the Afghanistan Hindu Kush Himalaya (AHKH), between 2000 and 2020. In preparation for submission to *Arctic, Antarctic, and Alpine Research*.

Chapter V addresses modelling of the glacier-influenced hydrological regimes of Afghanistan using three representative catchments under current and future climates to address questions

R3 and **R4**. This chapter presents a modified glacio-hydrological model that is used for Afghanistan in which a debris cover ice treatment is added to the model. It allows a clear identification of the extent to which these three catchments depend currently on a glacier subsidy (**R3**). By coupling the model to future climate scenarios, it quantifies possible future evolution of these hydrological regimes due to climate change, including the influence of debris cover development (**R4**). This paper will be submitted to Hydrology and Earth System Science.

- Shokory, J.A.N., Horton, P., Schaefli, B. and Lane, S.N. (2023). Glacier-influenced hydrological regimes of Afghanistan Hindu Kush Himalaya (AHKH) under current and future climate. In preparation for submission to: *Hydrology and Earth System Science*.

The final chapter concludes the thesis by providing a synthesis the thesis, identifying weaknesses in the work that has been done and highlighting potential future research

II WATER RESOURCES OF AFGHANISTAN AND RELATED HAZARDS UNDER RAPID CLIMATE WARMING: A REVIEW

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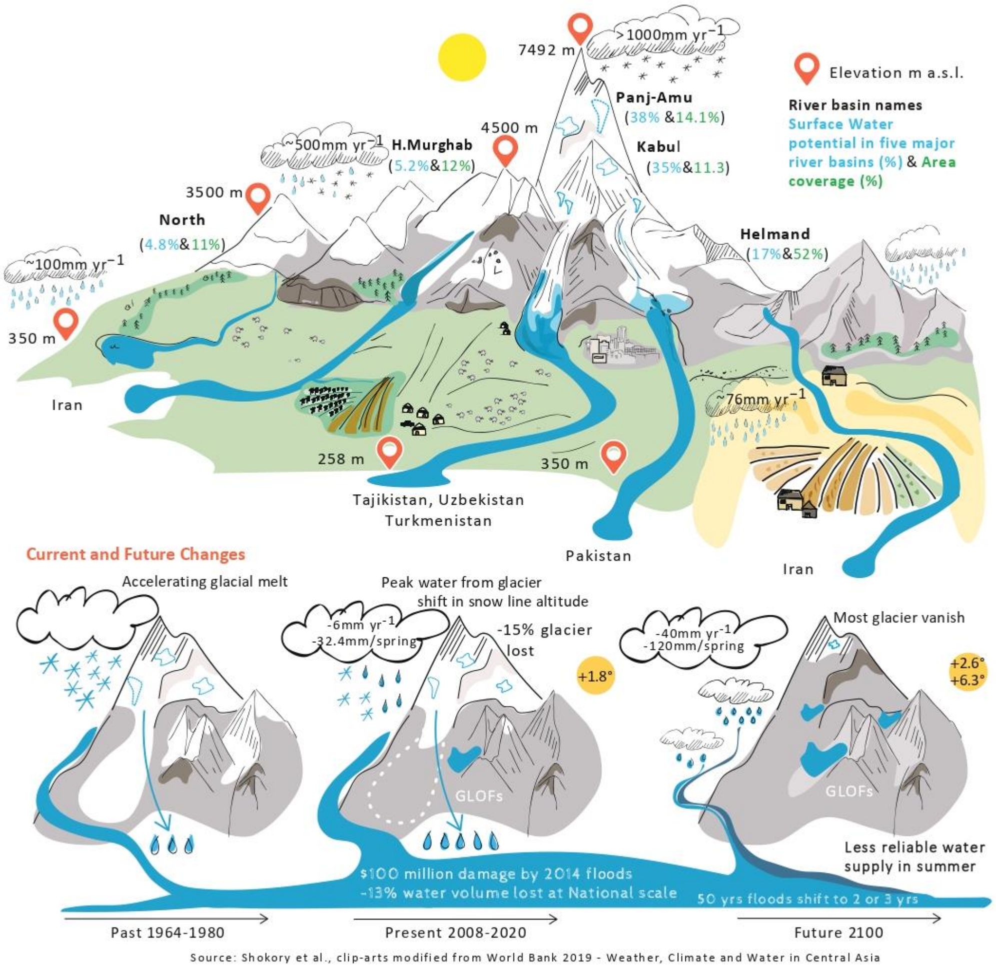
This chapter provides a comprehensive review of water resources of Afghanistan and related hazards from more than 130 scientific articles, reports and data sources. This chapter is organised into seven subsections. We present: (1) an introduction to the geographical and hydro-climatological context of Afghanistan, (2) current knowledge and future projections for changing climate for the country, (3) cryosphere processes in an Afghan context, (4) analyses of streamflow data for glacierised and non-glacierised basins in Afghanistan, (5) changes in groundwater, illustrated using data for Kabul city, (6) the challenge of hydrological extremes and (7) a synthesis of this review and these data to argue that in Afghanistan, glacial subsidy may be hiding the effects of climate changes upon streamflow.

Abstract

Rapid climate change is impacting water resources in Afghanistan. The consequences are poorly known. Suitable mitigation and adaptation strategies have not been developed. Thus, this paper summarizes current status of knowledge in relation to Afghan water resources. More than 130 scientific articles, reports and data sources are synthesized to review the potential impacts of climate change on the cryosphere, streamflow, groundwater and hydrological extremes. The available information suggests that Afghanistan is currently witnessing significant increases in temperature, less so precipitation. There is evidence of shifts in the intra-annual distribution of streamflow, with reduced summer flows in non- glaciated basins and increased winter and spring streamflow. However, in the short-term there will be an increase in summer ice melt in glaciated basins, a “glacial subsidy”, which sustains summer streamflow, despite reduced snow accumulation. The future prognosis for water resources is likely to be more serious when this glacier subsidy ends.



II.1 Introduction

Climate change impacts on water resources have been widely observed and future impacts likely to cause significant harm to water resources at both regional and global scales (Portner et al. 2022). Water shortage, especially when relating to river basins that cross national or international jurisdictions are likely to lead to conflict (Unger-Shayesteh et al. 2013; Atef et al. 2019). Understanding such shortages and how and when they might develop is important to give the time needed to prepare and to adapt (Portner et al. 2022). This is why national-scale water resource assessments under future climate are key to sustainable resource management. Yet, they are crucially lacking in some world regions. In this review we provide a systematic overview of existing climate change impact studies on water resources and related national hazards for Afghanistan, a country in the western Himalaya, which receives 80% of its water resources from as snow and glacier melt (Lebedeva and Larin 1991, Favre and Kamal 2004). Afghanistan is poorly developed in terms of scientific research and environmental monitoring; it is one of those semi-arid to arid countries of Central Asia where livelihoods and economies have developed such as to now be strongly dependent upon mountain water resources (Unger *et al.* 2013) including summer snow- and ice-melt (Ma *et al.* 2015). These resources are potentially threatened through ongoing glacier retreat in this area (Haritashya *et al.* 2009, Shroder and Bishop 2010). Water availability in the catchments without glaciers is strongly related to snowmelt in Afghanistan mainly during spring and early summer season (Hussainzada and Lee 2021; Mahmoodzada et al. 2022). While many Afghans rely on snowmelt for irrigated croplands, and snow drought when it occurs alongside ongoing conflicts, violence, and economic challenges can further stress the country (Huning and AghaKouchak 2020). Such sensitivity can reduce when enough snow at higher elevations is accumulated (Muhammad et al. 2017). Despite this, relatively few studies have assessed the impacts of climate change on water resources in Afghanistan and a clear picture of what we know about Afghan water resources and about possible changes is lacking. There is no national-scale water resource assessment available and this article contributes to this lack by developing an initial baseline.

A key challenge in water resources assessment for Afghanistan is the lack of long-term measurement of hydro-meteorological variables (Savage et al. 2009, Mohanty et al. 2012, Ghulami 2017, Qutbudin et al. 2019, Aawar and Khare 2020, Mianabadi et al. 2020), which hampers model-based projections at the catchment-scale (Hrachowitz et al. 2013). The latter is a key scale for water resources and related hazard management. This lack of in-situ data is especially challenging in areas strongly influenced by glacier melt because historical ice accumulation provides a "glacial subsidy" to streamflow (Collins 2008) until a glacier has become relatively small (Kaser *et al.* 2010, Sorg *et al.* 2012, Huss *et al.* 2018). In the absence of detailed information on incoming precipitation or on outgoing evapotranspiration, assessment of streamflow availability, dynamics and future evolution becomes challenging (Schaefli and Huss 2011) and is further complicated by groundwater storage dynamics (Bookhagen 2012).

Here we review existing literature to summarize known climate change impacts on the cryosphere, streamflow, groundwater, and related hazards at the scale of Afghanistan and complete this review with a small number of additional data analyses at local scales. We attempt to synthesize the existing knowledge to highlight knowledge gaps. Through a comprehensive search terms we have been able to identify 131 scientific papers and reports that relate to Afghanistan's water resources and use these as the basis of our review. The review is organised as follows: We present: (1) an introduction to the geographical and hydro-climatological context of Afghanistan, (2) current knowledge and future projections for changing climate for the country, (3) cryosphere processes in an Afghan context, (4) analyses of streamflow data for glacierised and non-glacierised basins in Afghanistan, (5) changes in groundwater, illustrated using data for Kabul city, (6) the challenge of hydrological extremes and (7) a synthesis of this review and these data to argue that in Afghanistan, glacial subsidy may be hiding the effects of climate changes upon streamflow.

II.2 The Geographical Context of Afghanistan

Afghanistan is a mountainous country located in the subtropical zone, extending from 29°21′N to 38°30′N latitude and from 60°31′E to 75°E longitude (Gopalakrishnan 1982) (Figure II-1). It has an arid and semi-arid continental climate, characterised by temperature and precipitation regimes characteristic of deserts, steppe and highlands (Humlum *et al.* 1959, Shroder *et al.* 2014). Precipitation primarily falls from winter storms that originate as Mediterranean cyclonic systems in winter and that move eastwards, generally affecting Afghanistan between November and April, and notably between January and March (Glantz 2005, Sorrel *et al.* 2007; Shokory et al. 2017). The importance of Mediterranean storms for the lower mid-latitudes of central Asia has been known for some time (Pisharoty and Desai 1956, Syed *et al.* 2006). In the summer season, monsoonal airflows associated with the Intertropical Convergence Zone (ITCZ) may also cross the border between Afghanistan and Pakistan (Shroder 2014; Shokory et al. 2017) causing occasional snowfall during summer in the highest mountain peaks in the northeastern region of the country.

The lowland plains to the west and the north of the country experience low annual rainfall (~50-100 mm yr^{-1}) and extreme seasonal variations in temperature, with mean summer temperatures exceeding 33°C and mean winter temperatures of around 10°C. By comparison, the glaciated parts of river basins in the east receive substantially higher annual precipitation. This has traditionally fallen as snow between November and April (c. ~1,000 mm yr^{-1}) (Figure II-2) linked to eastward movement of Mediterranean cyclonic systems (Savage *et al.* 2009, Meier *et al.* 2013) with mean winter temperatures below 0°C, and average summer temperatures not exceeding 15°C (Savage *et al.* 2009, NEPA and UNEP 2016).

The country is divided into five major river basins: (1) Panj-Amu, (2) North, (3) Harrirud Murghab, (4) Helmand, and (5) Kabul (Mahmoodi 2008) (Figure II-1). The elevation range of these basins is very large; from glaciated basins extending to over 7,000 m a.s.l. in the Hindukush; to non-glaciated basins lower than 250 m a.s.l. in the arid deserts in the South (NEPA and UNEP 2016) (Figure II-1).

These river basins make different contributions to total volume of streamflow (Bromand 2017). By proportion, the Panj-Amu and Kabul river basin produces the highest water volumes (38% and 35% respectively) with respect to the total outgoing flow of Afghanistan despite having smaller percentage basin areas (14% and 11% of the country). The other three basins have lower volumes than expected given their area, with 17% volume but 52% area for the Helmand river basin; 5.2% volume but 12% area for the Harrirud Murghab river basin and 4.5% volume for the Northern river basin but 11% area (Mahmoodi 2008, Bromand 2017) (Figure II-1).

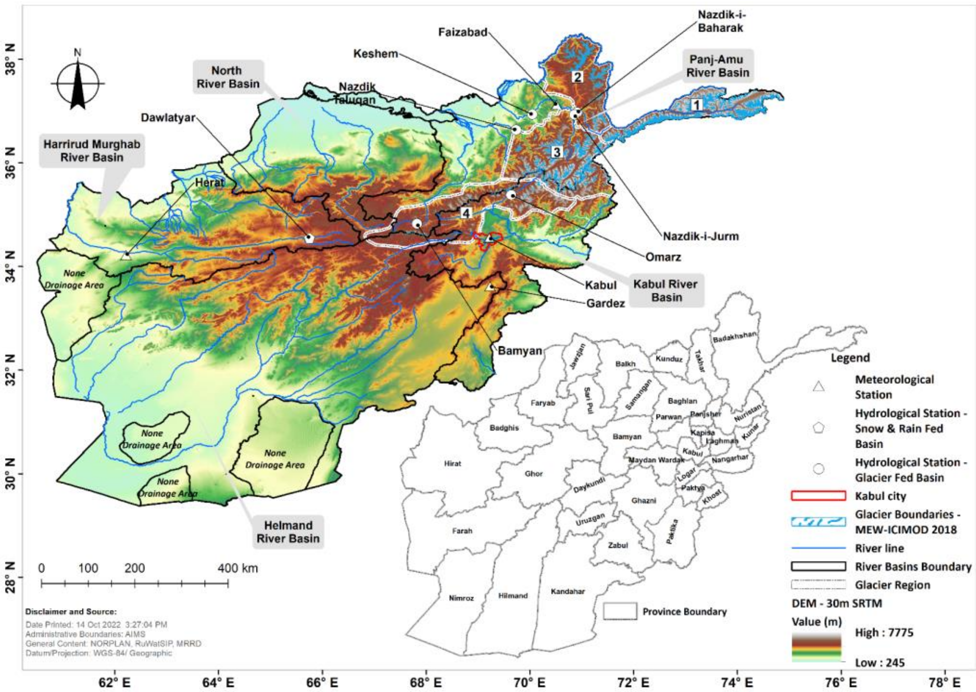


Figure II-1 Geographical map of Afghanistan, showing elevation, river lines, hydro-meteorological *stations, glacier coverage, and identifying the four most glacier- covered regions. The subordinating map shows province boundary of Afghanistan.*

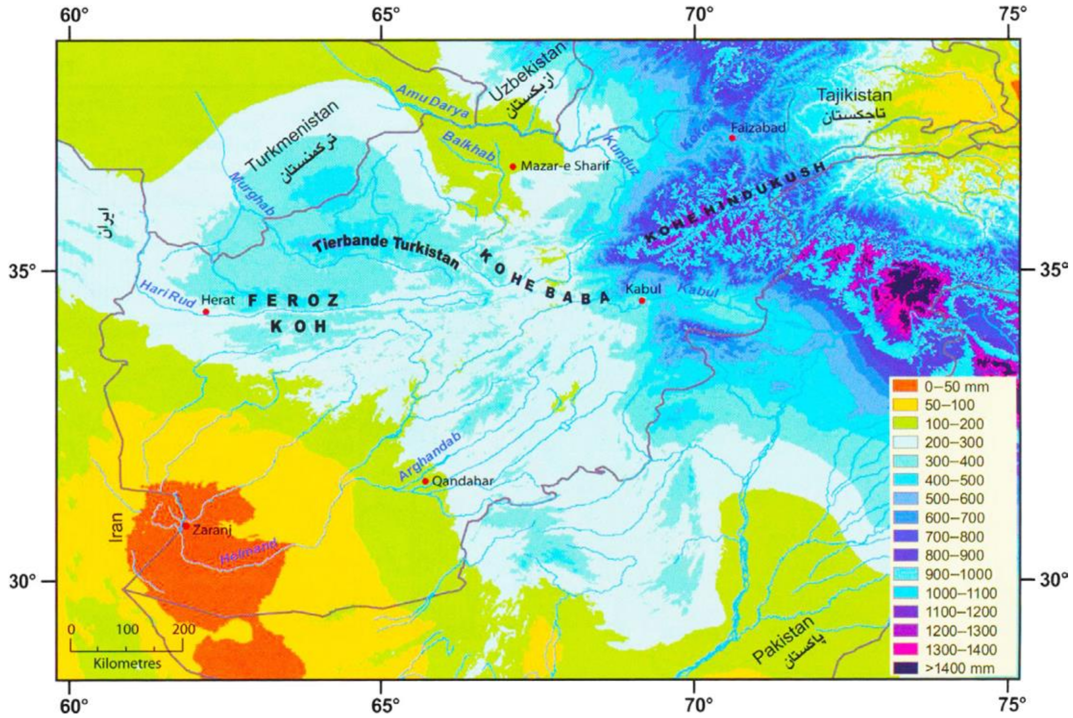


Figure II-2 Precipitation map of Afghanistan and the nearest parts of the neighboring countries (Breckle and Rafiqpoor 2010, Shroder et al. *2014). Source: Natural Resources in Afghanistan, Shroder, J.F., Soil and Vegetation In extremis, 116-137., 2014, with permission from Elsvier.*

II.3 Changes in Climate

There is little peer-reviewed literature concerning climate trends and associated changes in water resources for Afghanistan (Savage *et al.* 2009, Aich *et al.* 2017). Most research is large-scale with a relatively coarse spatial resolution and a particular focus on the Hindukush Himalayan region and the Panj-Amu region in central Asia (NEPA and UNEP 2016). In this context, this section addresses current and future changes in two main climate variables (temperature and precipitation). Other climate variables (e.g. humidity, wind, evapotranspiration etc.) are poorly studied and this remains a serious challenge for obtaining a complete assessment of hydro-climatic drivers of changes in Afghan water resources.

II.3.1 National-scale climate studies

II.3.1.1 Changes in temperature

There are only two studies which have assessed changes in climate for entire Afghanistan. The first regional climate trend and future projection assessment for the country was published in 2009 (Savage *et al.* 2009) (see Table II-1 for a summary of all studies cited hereafter). Savage *et al.* (2009) used the output of global climate models from the Coupled Model Inter-comparison Project (CMIP3) with a 2.5° grid size resolution such that only 19 data cells represented the entire country. Mean annual temperature showed a trend of +0.6°C since the 1960s with a 6.8% increase in the number of both hot days and hot nights per year. The National Environmental Protection Agency (NEPA) and United Nation Environmental Program (UNEP) report (NEPA and UNEP 2016) updated the previous study with a better resolution (0.5° grid size) reanalysis data for 1950 to 2010 and a regional climate model (RCM) and general circulation model (GCM) combinations generated from the CORDEX5 for future projections. This study showed a stronger trend for mean annual temperature, which has increased by 1.8°C since the 1950s (NEPA and UNEP 2016).

Projections suggested that mean annual temperatures are likely to rise by about 1.4°C by the 2030s compared to the baseline 1970-1999, with slightly lower increases in summer and larger increases in winter, notably in the north-eastern part of the country (Savage *et al.* 2009). Increases in mean temperature were predicted to be between 2°C and 6.2°C by the 2090s according to the scenario chosen, with the most rapid rates of change in the north and central plains (Savage *et al.* 2009).

The subsequent study by NEPA and UNEP (2016) estimated that under an “optimistic” (RCP2.6) scenario, mean annual temperature increases of 1.4°C compared to the baseline 1970-2005 are to be expected by the 2050s, although data suggested that current warming has already reached this level of change. By the 2100s, temperature was predicted to increase by 2.6°C. However, with the more “pessimistic” (RCP8.5) scenario, temperature was projected to increase by 2°C to the 2050s and more than 6.3°C to the 2100s.

At the basin scale, Sidiqi *et al.* (2018) predicted future temperature changes for the Kabul River Basin (Figure I-1) using the outputs of three general circulation models (GCMs) varying in resolution (0.4°× 0.4° to 2.8°× 2.8 °) with respect to the baseline 1961-1980. Model outputs projected the mean annual temperature of the basin to increase by 1.8°C, 3.5°C and 4.8°C to the 2020s, 2050s and 2080s respectively as compared with the baseline under RCP 4.5. Azizi and Asaoka (2020) studied future climate change in the Panjshir sub-basin in the north part of the Kabul River basin using eight GCMs (0.7°× 0.7° to 2.5°× 2.0 ° spatial resolution). Their study suggested a higher increase in temperature under the RCP 4.5 of 2.51°C by 2089-2095.

II.3.1.2 Changes in precipitation

According to the work of Savage et al. (2009), mean annual precipitation slightly decreased in Afghanistan at the national scale, by 6 mm yr^{-1} across the period 1960 and 2008, mainly due to decreases in spring precipitation, compensated partially by small increases in summer and autumn precipitation (Savage *et al.* 2009). Likewise, NEPA and UNEP (2016) reported significant trend in seasonal precipitation for the period 1950-2010.

National scale patterns appear to mask some regional-scale and seasonal-scale changes. NEPA and UNEP (2016), for the spring season, reported a reduction of about 30 to 40 % (50-64 mm) in the northern and Central Highlands from 1950 to 2010 (NEPA and UNEP 2016). Aich *et al.* (2017) confirmed that heavy precipitation (defined as the 95th percentile of the annual distribution of daily precipitation, considering those days with more than 1mm of precipitation) has increased in the East of Afghanistan along the border with Pakistan by more than 25% in magnitude since 1950. Recently, Aliyar et al. (2021) performed precipitation trend analysis for all of Afghanistan for 1951-2010 using the APHRODITE gridded dataset with a 0.25°× 0.25° spatial resolution, and found a spring season precipitation reduction in south-western and north-eastern Afghanistan by 1.5 to 6 mm yr^{-1}; but a slight increase in summer precipitation and the frequency of very heavy (10mm) and extremely heavy precipitation (20mm) in central, eastern, and southern Afghanistan.

Regarding future projection of precipitation, Savage *et al.* (2009) indicate a precipitation increase over much of Afghanistan by the 2030s but only by a small amount, 10-20 mm in total. Annual precipitation by the 2090s is predicted to decline, but by a degree dependent on emissions scenario (40 mm high, 20 mm medium, 10 mm low) (Savage *et al.* 2009). NEPA and UNEP (2016) obtained precipitation projections with more uncertainty, with no clear annual trend and less distinct differences between scenarios. However, they give some evidence of a clearer signal in certain regions, with a predicted increase of about 10% to the 2100s for the east and Hindukush (north-eastern Afghanistan) and decreases to a smaller extent in the central highlands and the north (NEPA and UNEP 2016).

For the Kabul river basin (Figure I-1) in eastern Afghanistan, the mean annual precipitation is projected to increase under both scenarios (RCP 4.5 and RCP 8.5) by 70 to 125 mm to the 2080s as compared with the 1961-1980 baseline (Table II-1) mainly in the summer and autumn (Sidiqi *et al.*, 2018); in spring and winter, the projections yield a decrease by 120 mm and 17 mm respectively under RCP 4.5. Likewise, this precipitation change pattern is showed by Ghulami et al. (2022) who compared the future period 2060-2079 to a baseline scenario of 1986-2005 that predicted precipitation decreases of 4.1% in winter and spring under RCP 4.5. Under RCP 8.5, winter precipitation was predicted to decrease further by -6.5% and summer to increase by 2.4% in the Kabul river basin. Azizi and Asaoka (2020) found similar patterns for the Panjshir sub-basin, north of the Kabul river basin, predicting 1.1% to 12.3% decreases in spring and winter precipitation but 0.1% to 29% increases in summer and early autumn precipitation by 2080-2100 under RCP 4.5.

Table II-1 Comparisons of climate study findings at the national scale. X indicates "does not apply" or information not available.

No	Reference	Study Area	Dataset and resolution	Baseline Data	Data validation period	Trend Analysis Period	Trend		Future Projection	
							Temperature	Precipitation	Temperature	Precipitation
1	Savage et al. 2009	Afghanistan	15GCMs 2.5° grid size	1950-1970 observed data; 1970-1999 baseline data	X	1960-2008	+0.6°C since 1960	+0.5 mm/month or 2% increase/decade	+1.4°C by the 2030s +2°C to +6°C by the 2090s	+10 to +20 mm increase by 2030 -10 to -40 mm decrease by 2090
2	NEPA and UNEP 2016	Afghanistan	CORDEX5 0.5° grid size	8 Observed meteorological stations (1960-1990); baseline for future projection (1970-2005)	1950-2010 GSPW3 Reanalysis data	1951-1980 to 1981-2010	+1.8°C	No consistent pattern at the scale of Afghanistan but -40 mm decrease in Spring precipitation	+1.4°C by 2050 +2.6°C by 2100	+122 mm for the Hindukush highlands -33.8 mm for the north, 1976-2005 to 2021-2050
3	Aich et al. 2017	Afghanistan	CORDEX5 0.5° grid size	8 Observed meteorological stations (1960-1990	1950-2010 GSPW3 Reanalysis data	1951-1980 to 1981-2010	+1.8°C	-1% average -10 to +10 %	+1.7°C from 2006-2050 +2.7°C from 2006-2090	-1.6%, 2006-2050 -13%, 2006-2090
4	Sidiqi et al. 2018	Afghanistan-Kabul River Basin	3GCMs 0.4°× 0.4° to 2.8°× 2.8° grid size	1961-1980	1971-1980 4 Observed meteorological stations	X	X	X	+1.8°C by the 2020s +3.5°C by the 2050s +4.8°C by the 2080s	+30 to +100 mm in the 2020s +50 to +110 mm in the 2050s +70 to +125 mm in the 2080s
5	Aawar et al., 2019	Afghanistan-Kabul Province	8 ground station in 7005 km^2 area	2000-2018	X	2000-2018	0.02 to 0.71 °C	+4.88 to +30.42 mm	X	X
6	Azizi and Asaoka 2020	Panjshir sub-basin of the Kabul River basin	8GCMs 0.7°× 0.7° to 2.5°× 2.0° grid size	2000-2020	2009-2015	X	X	X	Under RCP 4.5 +1.45°C (2049-2055) +2.51°C (2089-2095)	Under RCP 4.5 -4.7 % (2049-2055) -5.4% (2089-2095)
7	Ghulami et al. (2022)	Kabul River basin	6 GCMs 0.5°× 0.5° grid size	1951-2007 APHRODITE 0.25°× 0.25° grid size	1986-2005	X	X	X	X	2020-2039 Under RCP 4.5 -7.2% to +7.8% RCP 4.5 -3.5% to +6.0% RCP 8.5 2060-2079 -9.3% to +6.9% RCP 4.5 -15.1% to +6.2% RCP 8.5

APHRODITE = Asian Precipitation - Highly-Resolved Observational Data Integration Towards Evaluation; CORDEX5 = Co-ordinated Regional Climate Downscaling Experiment 5 (CORDEX5); GCM= Global Climate Model; GSWP3 = Global Soil Wetness Project 3; RCP = Representative Concentration Pathw

II.3.2 Local-scale climate studies

Lack of availability and accessibility of the climate data in Afghanistan have limited local-scale climate change determination (Masood and others, 2020), although more recently data from individual weather stations is becoming increasingly available. The Government of Afghanistan's Ministry of Energy and Water had a newly established Hydro-Meteorological Data Centre that can be accessed by researchers (see data availability statement). To further understand sub regional differences, we have compared ground observed precipitation and temperature data for four stations originating from the Afghanistan Meteorological Department for 1964-1977 and 2007-2018 (Figure I-1). Data are calculated seasonally based on monthly means for each period; we were, however, not able to perform a proper trend analysis due to data gaps.

II.3.2.1 Change in temperature

Changes in temperature were assessed through individual meteorological stations for the earlier (1964-1977) and more recent (2007-2018) period of data availability. Figure II-3a shows that mean temperature has increased for all seasons and for all stations (Figure II-3a). There is also an increase for all minimum mean temperatures (minimum of long-term mean monthly temperature) by season, except for winter at Faizabad in the far north, where there has been a small decrease (Figure II-3b). The minimum mean winter temperature at Gardez, located at a lower elevation and in the east has only increased slightly. The maximum mean winter (maximum of long-term mean monthly temperature) temperature has increased for all stations (Figure II-3c) although there is quite substantial inter-station variability for all seasons. Perhaps the station that differs most clearly than the others, notably for temperature, is Faizabad. Particularly in winter, it has a reduced increase in mean temperature (Figure II-3a), and no significant change in the minimum mean (Figure II-3b) and maximum mean (Figure II-3c) temperatures. Thus, whilst there has been a shift towards warmer temperatures in most years, the minimum mean and maximum mean temperature have changed less. It is still possible to get cold years but they are less frequent; and the increase in mean temperature is more a reflection of a general increase across most years rather than an increase in temperature in warm years. Such inter-station variability may be due to local or regional climate characteristics, Faizabad is located to the north of the main Afghan mountain ranges, in a Mediterranean continental climate according to the Köppen-Geiger climate classification (Shroder *et al.* 2014) whilst the other three stations are in desert or semi-arid climate zones. That said, Figure II-3a confirms the national- and regional -scale observations reported above of increases in temperature in autumn, winter and spring which will have important implications for precipitation that falls as snow, and hence snow and ice accumulation.

II.3.2.2 Change in precipitation

Precipitation changes (Figure II-3d) vary between seasons and stations. There is a tendency for increases in summer and autumn precipitation for all stations, albeit very variable in magnitude, as also confirmed by national-scale studies (Savage *et al.* 2009, NEPA and UNEP 2016, Aich *et al.* 2017). Additionally, three out of four stations show decreases in winter and spring precipitation aligned with national scale studies.

However, Faizabad in northern and Gardez in eastern Afghanistan showed increases in winter and spring precipitation respectively. With only four stations, explaining these patterns needs some care. A much more in-depth analysis of a larger number of sites is needed to quantify and to explain such differences. The precipitation changes for Gardez are markedly higher than other stations, despite its location in the east of the country where it is subject to monsoonal airflows associated with the Intertropical Convergence Zone (ITCZ) (Shroder 2014; Shokory et al. 2017). The presence of very steep local precipitation gradients emphasizes the difficulty of generalizing precipitation changes regionally for Afghanistan.

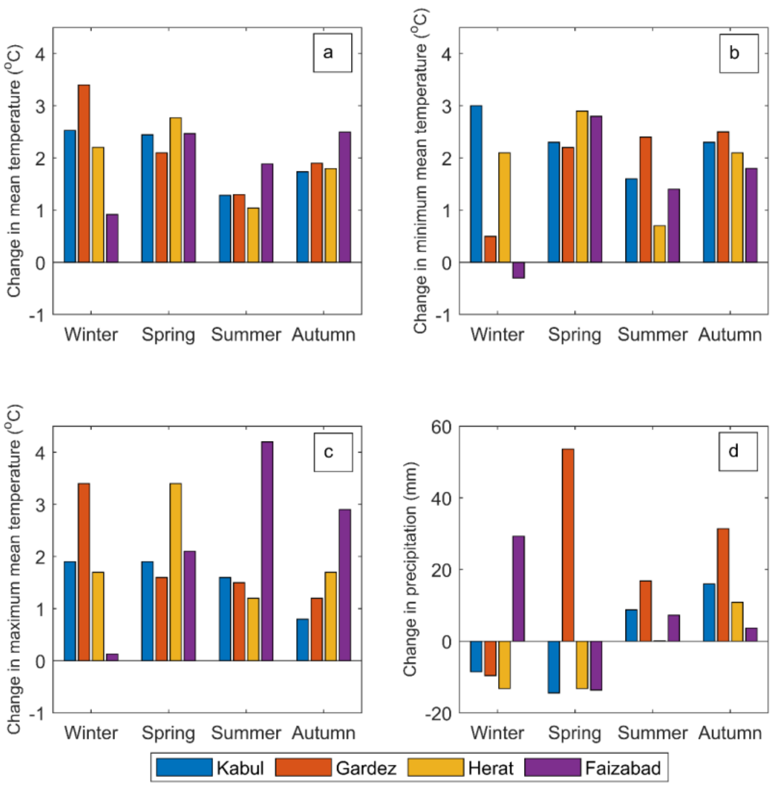


Figure II-3 Changes in mean (a), minimum mean (b), maximum mean (c) temperature and precipitation (d) by season between 1964-1977 and 2007-2018. The two periods shown for are those for which data availability is common to all four stations.

II.3.3 Summary of changes in climate

All available national- and local- scale studies reveal similar patterns but differences in detail, as is common in studies from other regions. The clear pattern is a rising temperature signal and a relatively stable precipitation signal. There is perhaps a clearer signal for the spring in terms of declining precipitation. However, comparing the results from different studies is difficult as they use very different reference periods, and these are relatively short, meaning that conclusions may be impacted by short (multi-year) time-scales of variability.

Projections of the future show strong climate change scenario dependence but confirm, largely, a strong warming trend. The main challenge with these studies is that the resolution of predictions remains very coarse as compared to topographical gradients within Afghanistan as well as compared to spatially differentiated exposure to different sources of moisture (e.g. Mediterranean versus Monsoon/Indian Ocean sources). These national and local-scale studies and analyses confirm the need to consider climate changes at a sub-regional or sub-basin scale given the topographic complexity of Afghanistan (Figure I-1). This is particularly the case for precipitation, to distinguish between regions more sensitive to changing teleconnection with the North Atlantic and Mediterranean and those more sensitive to teleconnection with the South Asian monsoon (Linderholm et al. 2011). Indeed, the latter's importance suggests a need to regionalise Afghan precipitation records in different ways to isolate the effect of hemisphere-scale teleconnections.

II.4 Changes in the Cryosphere

The largest glaciers outside of the Polar Region exist in the Himalayan and Tibetan Plateau ranges, and these are showing systematic decreases of snow cover and widespread retreat (Prasad *et al.* 2009, Chen *et al.* 2017). There are studies suggesting that some glaciers in the Karakoram region are advancing, whilst those in the Western, Central, and Eastern Himalaya are retreating (Scherler *et al.* 2011, Laghari *et al.* 2012, Farinotti et al., 2020).

Formally, Afghanistan is a part of the Himalayan region, but as it is in its far west it differs from the central and eastern regions in terms of climate influences (see above). This matters as the sensitivity of glacier and snow to climate change will depend on climate influences, albeit to an extent which remains unclear (Immerzeel *et al.* 2010). Knowledge of the cryosphere is important in terms of its contribution to streamflow. In many river basins within mountainous regions, the upstream seasonal storage of water as snow and ice and its delayed release is essential for maintaining downstream river flows (Vanham and Rauch 2008). In particular, meltwater from glaciers reduces the risk of summer droughts and may protect downstream populations from the worst effects of droughts (Pritchard 2019). This applies to Afghan river basins that provide water to downstream areas, including also areas in neighbouring countries. Thus, current Afghan river flows reflect the history of ice accumulation and ablation associated with past climates and there is therefore a strong memory effect, with different time-scales of variation from annual to decadal. The cryosphere is highly vulnerable to climate change as small changes in temperature can rapidly change whether water is solid or frozen, and this impacts both the accumulation (which needs snowfall) and the melting of snow and ice. Both temperature and precipitation changes in mountainous regions can have a dramatic effect on the water cycle, on snowmelt and on the temporal and spatial availability of water resources (Immerzeel *et al.* 2010, Ma *et al.* 2015, Shrestha *et al.* 2016, Sidiqi and Ninsawat 2018).

II.4.1 National-scale glacier studies

There is a serious lack of systematic cryosphere studies with field observations in Afghanistan and those that exist were focused on the period 1965 to 1980. Such studies are mostly in Russian, Dutch, and very rarely in English, and mostly are not available online (Shroder and Bishop 2010). Shroder (1980) initiated the first glacier inventory for Afghanistan supported by U.S. Geological Survey using Landsat-3 satellite imagery (40m ground resolution), and field observations. The results were confidential for military reasons until published in the work of Shroder and Bishop (2010). Their inventory identified 3,000 separate glaciers in Afghanistan with an estimated area of ~2,700 km^2, concentrated in the higher north-eastern drainage basins of the country (Amu Darya, Panjshir, Kunar, Kabul) (Shroder 1980, Shroder and Bishop 2010, Shroder and Ahmadzai 2016). The official glacier inventory of Afghanistan was created by the Afghanistan Ministry of Energy and Water and the International Centre for Integrated Mountain Development using satellite Landsat imagery in 2018 (Maharjan *et al.* 2018). Glaciers were mapped using semi-automatic object-based image analysis methods. They identified 3,782 glaciers, covering a total area of 2,539 km^2 concentrated at mean elevations between 3,200 and 6,900 m a.s.l., although 78% of glaciers had mean elevations higher than 4,500 m a.s.l. The study reported 13.4% of glacier area had been lost at a rate of 5.4% per decade between 1990 and 2015. Maharjan *et al.* (2018) report that the highest rates of loss were between 4,700 and 5,000 m a.s.l., and the lowest rates of loss were above 5,500 m a.s.l. As pointed out by Maharjan *et al.* (2018) it is unclear why the highest rates of loss were not found for the glaciers at lowest elevations (< 4,700 m a.s.l.). This emphasises the fact that there is a need for more systematic studies of rates of glacier retreat in Afghanistan. It requires analyses that are sensitive to significant differences in patterns of climate change over relatively short distances (see previous section).

One of the possible reasons for finding lower rates of retreat at low elevations is the feedback effects relating to increased debris accumulation as a glacier retreats, a hypothesis that has however not been investigated so far in Afghanistan. Retreating glaciers tend to increase their debris cover, which above a certain thickness may reduce ice melt rates substantially (Østrem 1959). Scherler *et al.* (2011) argued that debris cover might be a key missing link in the understanding of retreat of the Hindukush Himalayan glaciers. The same may apply for Afghanistan and make satellite-based studies problematic unless they take into account debris-covered ice (Shroder and Bishop 2010).

II.4.2 Local-scale – glacier studies

Past studies commonly used planimetric maps and topographic diagrams to assess the state of individual Afghan glaciers, and only 7 out of 44 reports undertook more detailed analysis including fieldwork. Only one large-scale glaciological sketch map and two conclusive glacier maps have been produced in Afghanistan; for the Mir Samir area (Gilbert *et al.* 1969); and for the Keshnikhan, and the Wakhan Pamir ranges in 1978 (but not published until Shroder and Bishop 2010).

Haritashya *et al.* (2009) evaluated the margins of 30 Alpine valley glaciers in the Wakhan Corridor of Afghanistan (northeastern region, Figure I-1) for the period 1976 to 2003, 28 glacier tongues that have retreated by between 1.3 and 36 m yr^{-1} were identified. The study also shows an increase in the number and area of new proglacial lakes, from 46,600 m^2 to 166,600 m^2 (Haritashya *et al.* 2009). Sarikaya *et al.* (2012) used the same methodology to assess the Eastern Hindukush including areas along the Afghanistan–Pakistan border. They studied three time periods (1976-1992, 1992-2001, and 2001-2007) and made an overall comparison between 1976 and 2007. They found that 68% of glaciers retreated, 19% advanced and 14% showed no net change between 1976 and 1992. These numbers changed to 41% retreating for 1992-2001 and 76% retreating for the period 2001-2007. Retreat rates ranged from -15.5 to 10.2 m yr^{-1}. Recently, Joya et al. (2021) assessed the equilibrium line altitude in Kokcha sub catchment of Panj Amu river basin (Figure I-1), an average of 722 ± 145 m changes observed in altitude since the Late Pleistocene to the present.

Since 2018, only the Ykhchaal-e-Sherq (East Glacier) of the Mir Samir glacier system (Gilbert *et al.* 1969) has been monitored with the newly given name of PirYakh by Ministry of Energy and Water and Kabul University (Sajood 2020). The result of one year of monitoring (2018-2019) revealed spatial patterns of ablation between 1.8 m and 4 m ablation and a negative balance of 1.7 million m^3 of water equivalent (Sajood 2020).

II.4.3 Snow cover studies

There are very few detailed and systematic snow cover studies in Afghanistan. Although Soviet scientists used satellite imagery and field measurements, assessed seasonal snow distribution and depth, and recorded dynamics of the snow boundary, seasonal snow-lines, and duration of snow cover (Shroder and Bishop 2010) these studies are not publicly available. Later, a series of individual studies of transient snow lines (TSL) performed by Haritashya *et al.* (2009), Shroder and Bishop (2010) and Sarikaya *et al.* (2012), with data for the period 1960 to 2012, suggested no clear patterns of change. Most recently, Nepal et al. (2021) modelled snow cover evolution throughout the 21st century (2071-2100) compared to the historical period (1981-2010) in the Panjshir catchment of the northern Kabul river basin. They projected a 10 to 18% reduction in annual snow cover area with the most optimistic condition (i.e., cold-wet models). At the seasonal scale, autumn and spring season snow covers are projected to reduce by as much as 25%. Spatial and temporal changes at the sub catchment scale in Kokcha and Panjshir basins highlight a need for systematic multi-year studies of TSLs in Afghanistan and this is a key weakness in linking climate change to water resources at present.

II.4.4 Summary of cryosphere changes

Glaciers in Afghanistan are retreating by 0.54 % yr^{-1} (Maharjan *et al.* 2018), however, the rate varies by sub region (Haritashya *et al.* 2009, Sarikaya *et al.* 2012) to a degree that is only poorly known. More work is required in this sense. There is no doubt that glaciers are a highly important part of water resources in Afghanistan, because glacier melt provides an almost guaranteed water supply, notably in summer when agricultural demands are highest. Predicted declines in winter snowfall in the future will make this meltwater-dependence stronger as more precipitation will fall as rain rather than accumulate as snow in winter. A deeper understanding of the linkages between glaciers and water resources in Afghanistan is urgently needed. Only one monitoring site is not enough to assess the state of the entire country's cryosphere (Sarikaya *et al.*, 2012) especially given its geographical complexity in hydro-climatological terms (Figure I-1) and the likely different response of regions to temperature and precipitation forcing by climate change. Cryospheric monitoring should be extended to eastern, northern, and central Afghanistan, especially to those regions monitored in the past (Yakhchaal-e-Gharb Mir Samir area (Gilbert *et al.* 1969); the Keshnikhan, and the Wakhan Pamir ranges in 1978 (Shroder and Bishop 2010). At the national scale, studies of debris-covered glaciers are missing in Afghanistan.

Understanding snow cover and its changes is also under-developed and this is important not only for glacier mass balance studies now and in the future but also for planning hydropower development (Saloranta et al. 2019). More research is required to characterize accurately changes in the seasonal variability of snow-line elevation through time (Shroder and Bishop 2010).

II.5 Changes in River Streamflow

Studies of snow-dominated basins around the world have suggested that climate warming results in streamflow increases during the accumulation season and during the early melt season, due to seasonal shifts in snow accumulation, snowmelt and the amount of winter rainfall (Lettenmaier and Gan 1990, Burn 1994, Hagg *et al.* 2007, Wang *et al.* 2012). In arid river basins, where climate change is expected to have a significant impact on snow and ice cover, climate change may have a serious impact on water resources (Wang *et al.* 2012). 80 % of Afghanistan water resources have some contribution from snow and glaciers, including water required for summer irrigation (Lebedeva and Larin 1991, Favre and Kamal 2004) and hence food production. Hence, warming in combination with precipitation changes has led to a strong decrease in river discharge for snow-fed basins in Afghanistan (Akhundzadah et al. 2020). Casale et al. (2020) and Muhammad *et al.* (2017) showed that winter snowfall was a crucial influence on the likelihood of summer drought in the Afghan lowlands. Glacier meltwater supply also contributes to sustaining summer water availability and aquifer recharge (Gellasch 2014). An early study estimated that with a 1°C increase in mean annual air temperature, the amount of glacial meltwater in Afghanistan rivers is likely to decline by as much as 14% (Lebedeva 1997). Scaling this estimate to the current measured increase of 1.8 °C, a decline of about 25% should have occurred. Here we consider more precisely changes in river streamflow at National and local scales in Afghanistan.

II.5.1 National-scale River Streamflow studies

In 2016, the Ministry of Energy and Water reported a mean 13% decrease of river streamflow in five major river basins (Figure I-1) between the period 1969-1980 and 2007-2016 based on measured hydrological data (Table II-2; Bromand 2017). By 2030, all of these decreases were expected to continue to amplify.

*Table II-2 Surface water volume in five Afghan river basins between (1969-1980) and (2007-2016) (Source: Bromand 2017). * BCM: Billion cubic meters*

River Basins (RB)	Surface water volume in (BCM) for (1969-1980)	Surface water volume in (BCM) for (2007-2016)	Decreases in (%) for (2007-2016)	Projected by 2030 in (BCM)	Decreases by 2030 in (%)
Kabul - RB	19.271	17.1	-11%	15.3	-21%
Panj-Amu- RB	21.5	18.7	-13%	16.2	-25%
Helmand- RB	10.4	8.4	-19%	7.1	-32%
H.Murghab- RB	3.4	2.53	-26%	1.7	-50%
North- RB	2.1	2.2	5%	2	-5%
Total	57	49	-13%	42.3	-26%

Bromand (2015) studied future streamflow changes in the Kabul river basin, focusing upon the impacts of climate change. Results suggested that with an increase of mean temperature of 2.9°C for the period 2046-2064, the Kabul river basin will experience severe summer water scarcity with a reduction of about 24% in water availability despite, by 2046-2064, a potentially positive precipitation anomaly (Sidiqi *et al.* 2018).

Akhtar et al. (2021) also studied the impact of climate change on streamflow in the Kabul river basin using the soil water assessment tool (SWAT) hydrological model under RCP 4.5 by 2030. The results predicted an average 4.2% decrease in streamflow except for the eastern part of the basin where an increase of 2.4% was estimated. The decrease arises from two processes. The first is an increase of 18% in potential evapotranspiration. The second is a reduction of precipitation in spring and winter (Savage et al. 2009, NEPA and UNEP 2016). The Kabul river has no scope to store water (e.g. storage dams) at present and winter streamflow cannot be used for summer crop production.Masood et al. (2020) studied the Kabul River Basin further downstream in Pakistan and indicated an increase in summer streamflow due to larger contribution from snow and ice melt under both RCPs 4.5 and 8.5 in near future (2011-2030), which contradicts the findings of the studies of Bromand (2015) and Akhtar et al. (2021). These contradictory findings are most probably related to the hydrological model, SWAT , used by Bromand (2015) and Akhtar et al. (2021), which is not able to simulate the runoff contribution from glaciers (Omani et al. 2017, Singh et al. 2021) and may underestimate summer streamflow. In addition to streamflow, there is a general trend to a decline in water availability, Salehie et al. (2022) assessed equivalent water thickness to provide an estimation of total water availability (groundwater, soil moisture storage, surface water storage, and snow water equivalent) for Panj Amu river basin (Figure I-1). The findings suggest a decline in northern Afghanistan by -0.05 to -0.1 cm/year from 2002-2019. Sediqi et al. (2019) showed an even higher decline in the north, of up to -0.44 cm/year and a decline of up to -3.47 cm/year (2002 to 2016) in the central region of Afghanistan.

II.5.2 Local-scale River streamflow studies

In the absence of more detailed studies, we have analysed daily discharge data from individual gauging stations for six glacierised and one snow-rain fed basin for two different time periods (1969-1977) and (2008-2016) (Figure II-4) to illustrate how a glaciated, non-glaciated and snow-dominated basins have responded to climate change. In Afghanistan, due to the history of armed and political conflict, there is a gap in records between 1977 and 2008. Recently, station-wise data became available from the Ministry of Energy and Water of Afghanistan upon request. Figure II-4 shows increases in the summer discharge peaks for the glacier-fed basins (Taloqan, Keshelm, Bamyan, Omarz, Nazdik-i-Jurm, Nazdik-i-Baharak) in the period 2008-2016 compared to 1969-1977, implying an increase in glacial melt rate given no consistent trend in summer precipitation (Savage *et al.* 2009, NEPA and UNEP 2016, Aich *et al.* 2017).

For Dawlatyr (Figure II-4g), the one station with no glacial influence, there is a clear reduction in summer daily mean discharges. The peak streamflow for Dawlatyr occurs earlier in the year for the period 2008-2016 than for the period 1970- 1978, suggesting an earlier onset and end of snowmelt.

For the four most northerly glacier-fed stations (Taloqan, Keshem, Nazdik-i-Bahakrak and Nazdik-i-Jurm), peak flow is displaced to slightly later in the year, although this signal is weaker for Keshem and Nazdik-i-Baharak (Figure II-4b, c). Reduced spring streamflow would reflect the decreases in spring precipitation reported by NEPA and UNEP (2016) and Aich *et al.* (2017). Omarz and most notably Bamyan are the stations influenced by the smallest glaciers and at the lowest elevations. They have no real change in the timing of the peak streamflow. Streamflow in Bamyan, the lowest in elevation, has increased throughout the year and markedly in winter months. The shift in streamflow is almost systematic suggesting that there may have been a rating curve shift that is not properly accounted for. This conclusion may apply to all of the data shown here, emphasising the difficulty of using hydrological records alone in data poor settings like Afghanistan, in making clear conclusions about hydrological change. However, the other stations match more directly the expected response to observed climate changes (Figure II-4) and there is no evidence of a systematic shift. Thus, Bamyan may be an anomaly.

II.5.3 Summary of changes in river streamflow

Afghanistan straddles regions responding to global climate change in different ways in terms of temperature and precipitation, suggesting that a more careful sub-regional analysis of climate change impacts on streamflow from glaciated basins in Afghanistan is needed. There are epistemic uncertainties in available model-based predictions because the SWAT hydrological model (as used by (Bromand 2015, Ayoubi and Kang 2016, Akhtar et al. 2021) is not able to simulate the runoff contribution from glaciers (Omani et al. 2017, Singh et al. 2021). For future work, extra care is needed in selecting models appropriate for Afghanistan river basins that can take into account debris-covered glaciers and the strong topographic and vegetation gradients.

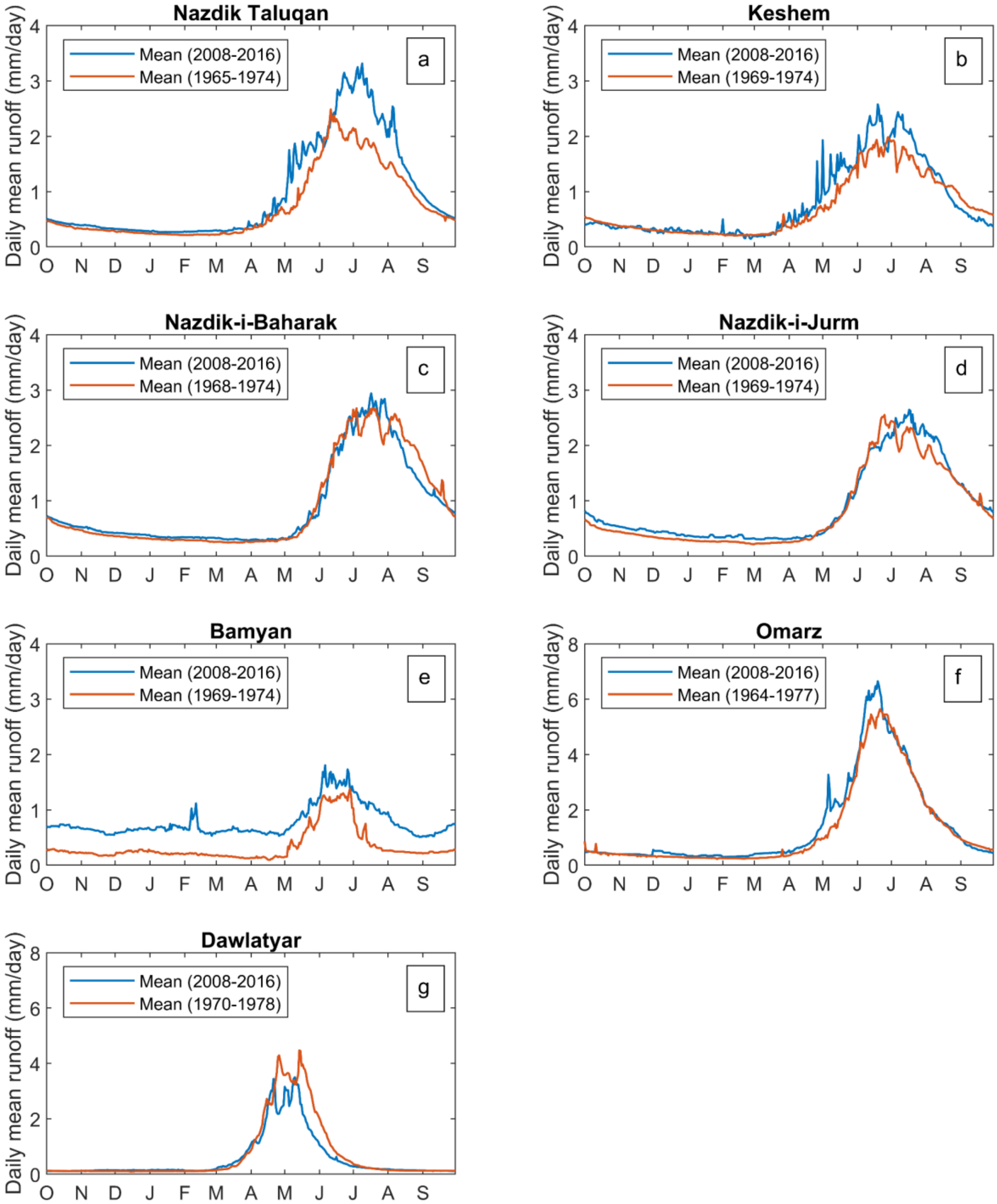


Figure II-4 Hydrographs from individual gauging stations for six glacierised basins (3a-3f) and one snow-fed basin (3g) for two time periods (1969-1977) and (2008-2016).

II.6 Changes in groundwater

Geological and hydrogeological studies in Afghanistan were more frequent between the 1960s and the 1980s with collaborations between Russian and Afghan scientists. This led to the first hydrogeological map of Afghanistan being published between 1975 and 1977 (Saffi and Leendert 2007), recently digitized by Hamidi and Safi in 2017 (Saffi et al. 2019) (Figure II-5). This map was highly generalized although it did introduce major aquifer regions for Afghanistan (Malyarov et al. 1977; Shroder et al. 2022). It indicates that groundwater availability is generally restricted to river valley-fill aquifers in the southern and northern plains of Afghanistan and that the largest aquifers occur within alluvium-filled, fault-bounded structures: These provide water to the largest cities within Afghanistan (Sinfield and Shroder 2016) (Figure II-5) which emphasises the need to consider change in groundwater in assessments of Afghanistan’s water resources. To date, a detailed assessment of groundwater development potential for different geologies (especially sedimentary and igneous) has not been completed (Shroder and Ahmadzai 2016, Nasimi et al. 2020).

In Afghanistan’s major cities, as well as in rural areas, groundwater withdrawal for drinking and agriculture is common-place (Shroder and Ahmadzai 2016). Much of the traditional Afghan groundwater systems, such as karezes (qanats), springs, and shallow wells provide more than 15% of Afghanistan’s irrigation water (Sinfield and Shroder 2016). Uhl and Tahiri (2003) concluded that more than 95% of the groundwater usage is for irrigation, however more up-to-date data are not available.

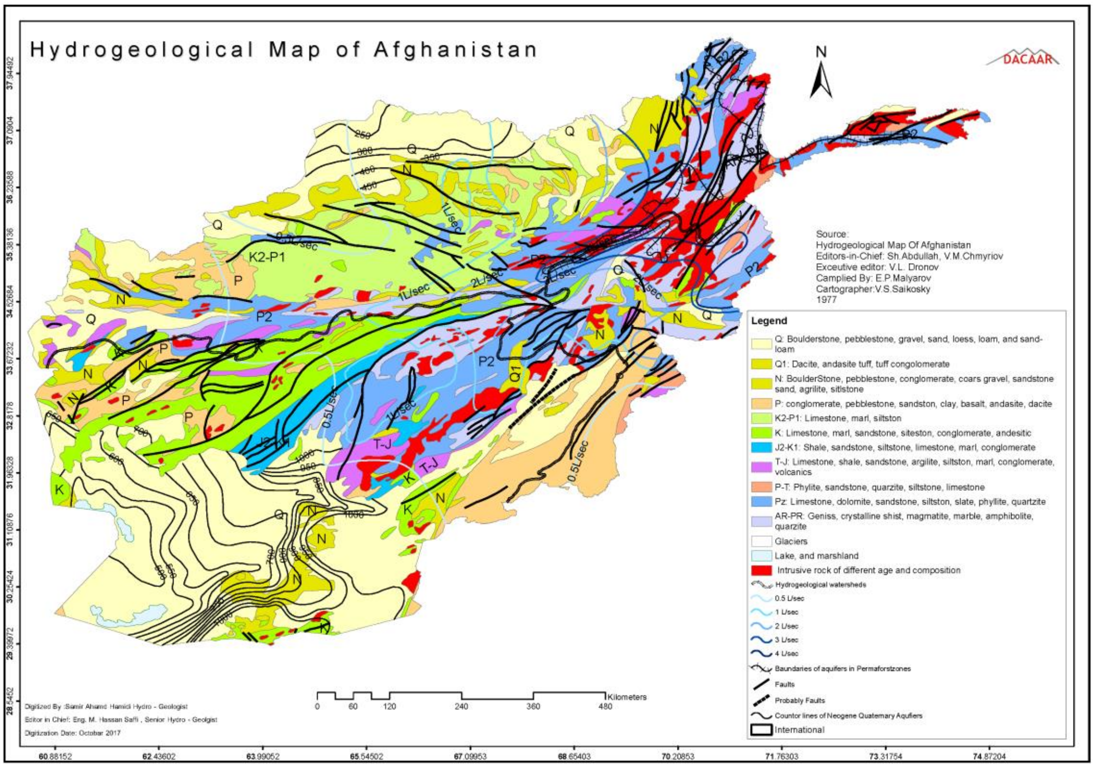


Figure II-5 Hydrogeological map of Afghanistan compiled by Malyarove and digitized by Hamidi and Safi in 2017 (Saffi et al. *2019).*

II.6.1 Changes in groundwater quantity

A lack of up-to date and detailed information on aquifer potential (storage and withdraw) has been considered a major challenge for sustainable groundwater management (Shroder et al. 2022). Major studies that focused on groundwater availability in Afghanistan have concentrated on the Kabul basin (Lashkaripour and Hussaini 2008, Houben et al. 2009, Mack 2018, Karim 2018, Jawadi et al. 2020; Noori and Singh 2021). This basin has experienced decreases in water quantity and more frequent drought events linked to urban development, land use change, climate change and wider socio-economic development (Saffi 2011, Shroder and Ahmadzai 2016). Added to this, there is pressure on groundwater due to population increases and changes in water consumption (Noori and Singh 2021). Population growth also induces urbanization, which reduces infiltration and groundwater recharge: According to Tani and Tayfur 2021, only 18% of total average annual precipitation currently contributes to groundwater recharge in Kabul city. The combined effect of increased water needs with an increasing population and reduced groundwater recharge may explain why Kabul city is facing a rapid groundwater drawdown, estimated at between 1 and 5 m yr-1 (Houben et al. 2009a, 2009b; Shokory and Rabanizada 2020; Zaryab et al. 2022b). More locally, 60% of shallow groundwater wells in the city of Kabul are projected to become dry or unusable due to poor groundwater quality (Mack et al. 2013, Mack 2018). Figure II-6 shows data for groundwater level in four monitoring wells collected by the Ministry of Energy and Water of Afghanistan; W2 and W6 located in the western part of the city, KN5 in the eastern part, and LG10 in the southern part of the city. There are drastic decreases in groundwater table elevations at W2 and W6 and a more severe condition at KN5, with a 40m groundwater drawdown between 2006 and 2020. On the other hand, LG10 in the southern part of city shows a more stable condition, mainly due to recharge by the Logar river flows close to its southern aquifer (Mack et al. 2013).

Additional evidence for declining groundwater resources is available from monitoring of traditional irrigation systems: In Afghanistan, there is a tradition of using groundwater supply called Karez; also known as qanats or foggara in other areas. Such supply involves anthropogenic structures that tap shallow groundwater and transfers it through underground tunnels by gravity to downstream fields or villages (Macpherson et al. 2017). According to a report made available by the Ministry of Rural Rehabilitation and Development of Afghanistan (1978), approximately 6741 Karezes existed in Afghanistan, irrigating about 163,000 ha of land (Hussain et al. 2008). Shobair and Alim (2004) noted that 36% of Karezes had dried out, and the remaining operating Karezes had flow reduced by as much as 83%. There is no more recent report available on the status of Karezes across Afghanistan.

Besides effects related to increased groundwater use and urbanisation, groundwater recharged might also be reducing as a result of changing snow cover (Gellasch 2014). In Kabul city, there is a famous proverb saying, “Let Kabul be without gold but not without snow”, reflecting the importance of snowmelt for groundwater recharge in the city. Decreasing snow cover in Afghanistan has particularly affected recharges to the alluvial fan aquifers from snowmelt that supplied water to the karezes (Macpherson et al. 2017). This is a topic that needs further work, especially considering declining ice cover impacts on recharge.

Figure II-6 Groundwater fluctuations in Kabul city between 2006 to 2020 at four main locations (KN5 in east, W6 and W2 in west, and LG10 in south part of the city).

II.6.2 Changes in groundwater quality

Groundwater quality is now a major issue in the most populated cities of Afghanistan, as population increases in the country's main cities has not only increased consumption but also groundwater vulnerability to pollution (Gesim and Okazaki 2018; Mahaqi et al. 2018). Over the last two decades major groundwater quality studies were concentrated on Kabul basin (Broshears et al. 2005; Lashkaripour and Hussaini 2008; Houben et al. 2009a,b; Mack et al. 2010; Sundem 2014; Mack et al. 2014; Mack 2018; Karim 2018; Noori and Singh 2021; Zaryab et al. 2022a) and there are very few for the other regions of Afghanistan (Hayat and Baba 2017). Safi and Kohistani (2013) studied groundwater quality in Afghanistan using data from 205 groundwater wells (1758 samples) unequally-distributed from 19 out of 34 provinces (this limitation was related to security issues to access the rest of provinces (Hayat and Baba 2017)). In general, 9 contaminants have been found which represents a concern for human health and agriculture (Hayat and Baba 2017). The contaminants which increased above World Health Organization (WHO) standards were; boron (79.5% of the samples ranged from sensitive to very sensitive for agriculture crops <2µg/L), fecal coliform bacteria (60% of the samples), salinity (51.1% of the samples ranged 751- 2250 µs/cm), sulphate (32% of the samples), sodium (27% of the samples), fluoride (15.9% of the samples in centre and north western provinces), nitrate (8.6% of the samples and mostly in urban areas) and nitrite (2.1% of the samples) (Safi and Kohistani 2013; Hayat and Baba 2017). Arsenic exceeding WHO limits (10µg/L) was found mostly in the central provinces of Farah, Panjshir, Laghman, Faryab, Logar and Kabul (19% out of 72 samples), and the Ghazni (58% out of 348 samples) province (Figure I-1) (Safi and Kohistani 2013; Hayat and Baba 2017). A higher concentration was later found in Ghazni and Maidan Wardak provinces in 61% of the water samples (out of 764 samples) (Safi and Eqrar 2016). Arsenic contamination in groundwater is a high matter of concern, yet no complete data exists that can cover the entire country (Hayat and Baba 2017).

The major factors that threaten groundwater resources in Afghanistan are identified as domestic and industrial wastes, septic tanks that are rapidly increasing in cities, and agricultural activities (Safi and Kohistani 2013; Hayat and Baba 2017). Zaryab et al. (2022a) suggests that ~81% of the nitrate contamination in Kabul city originates from sewage, 10.5% from natural soil losses, and only 8.5% from chemical fertilizer (8.5%). In the wet season, contamination from sewage increases to ~87.5% due to a poor sewage system. Whereas in Kabul city only 20% of households are connected to wastewater treatment system or used toilets with storage tanks, others used cesspit and dry toilets (Barati et al. 2019). From hydrogeochemical aspects, groundwater quality in the Kabul basin has been labelled as very hard due to high calcium and magnesium concentration (Jawadi et al. 2020) and in lower Kabul basin the major factors controlling groundwater chemistry in the aquifer were found as dissolution of carbonate, gypsum anhydrite minerals, weathering of silicates, ion exchange and mixing (Zaryab et al. 2021).

The absence of groundwater policies and regulations in place poses a serious risk to groundwater quality over the next 10–20 years due to likely population growth, significant mining activities (which are only just beginning), increased industrial activities, and expansion of agriculture (Hayat and Baba 2017). This requires urgent attention from the policy makers.

II.7 Changes in the Frequency of Hydrological Extremes

II.7.1 Floods

Afghanistan has always been exposed to floods due to intense rainfall, rapid snowmelt, or a combination of both (Shokory *et al.* 2016). Floods are the most frequent natural hazard in the country, causing on average $54 million of damage per year (World Bank 2017). In May 2014, floods in 14 northern provinces caused more than $100 million in damage (World Bank 2017). Climate projections and dependence of the water cycle in Afghanistan on the cryosphere suggests that there may be new and increased flood hazards for Afghanistan (Savage *et al.* 2009). Iqbal *et al.* (2018) analysed flood frequency and intensity in the Kabul basin for the period of (1981-2015) and also projected changes for 2031-2050 and 2081-2100 using the RCP4.5 and 8.5 scenarios. The flood magnitude that currently has a return period of 50 years is predicted to shift to return period of 9 to 10 years by 2031-2050 and even to 2 or 3 years by

2081-2100. There are three broad sets of processes responsible for these changes: (1) an increase in the frequency of extreme precipitation events; (2) increases in temperature are likely to lead to reduced storage of snow in all basins in winter with a shift towards higher winter peak flows; as most precipitation in Afghanistan falls in winter, more liquid precipitation may lead to less snow storage and more runoff (Goes *et al.* 2016); and (3), despite declining spring precipitation (NEPA and UNEP 2016), more precipitation may be falling as rain to a higher elevation when basins are still snow covered. The latter might thus increase the probability of "rain-on-snow" events, which often cause high flows (Li *et al.* 2020).

A lack of past flood records (30-40 years) in Afghanistan reduced applicability of standard methods for developing reliable flood hazard maps (Shroder 2016). However, since 2001 new gauging stations were installed by Ministry of Energy and Water of Afghanistan, which can be used along with available regional datasets (Iqbal *et al.* 2018) to reduce uncertainty in the analysis and produce vulnerability maps for the entire country. In general, to minimize the hazard in a feasible manner in Afghanistan, new scientific measurement and mapping is needed and to be transferred for the communities at risk, avoid building homes and infrastructures in very vulnerable places down on flood plains and too close to the riverbanks (Shroder 2016).

A second concern is the danger of Glacial Lake Outburst Floods (GLOFs) associated with glacier retreat that leave behind glacial lakes, which are then at risk of bursting due to destabilization of moraine dams (Mukherji *et al.* 2015). In July 2018, a severe GLOF event occurred in the Peshghor valley of Panjshir province in the northern region (Figure I-1). The initial volume of the lake was estimated at 0.88 x 106 m^3, and it produced a river flow with an average 16 m depth above baseflow (Azizi 2018). Mergili *et al.* (2013) confirmed that 40% (266 out of 652) of glacial lakes grew in their spatial extent from 1968 to 2009 for the Amu Darya region, in the glacierised high-mountain areas of Tajikistan, Kyrgyzstan and Afghanistan. Their analysis also showed a shift in the growth of glacial lakes from the southwestern Pamir to the central and eventually the northern Pamir during the observation period. Joya et al. (2021) reported 18 new glacier lakes formed with an area of 1.7 km^2 between 1990 and 2015 in the Kokcha sub catchment of Panj Amu river basin. An increase in the frequency of GLOFs is of concern and evidence suggests that the formation of glacier lakes following glacier recession has been significant since the late 1990s (Bajracharya *et al.* 2007, Lei and Yang 2017). Historic records confirm incidences of GLOF events causing catastrophic flash floods from the mountains in the HKH region. Glacial lakes may pose a threat to the life of the inhabitants of the mountain valleys in Afghanistan, therefore, it needs to be studied through a systematic approach that classifies glacier lakes that are in danger of breaching.

II.7.2 Droughts

The socioeconomic condition of Afghanistan has kept the country high sensitive to drought because of high dependency on agriculture for the generation of employment and income. On the other hand, access to improved water resources and generally poor rural access means strong geographical variation in extreme vulnerability to drought (Shroder 2016). For instance, droughts in Afghanistan have affected 6.5 million people since 2000, and caused major displacement in recent years (World Bank 2017). The corollary of reduced storage of precipitation as snow is an increase the risk of summer drought (Mishra and Singh 2010, Qutbudin *et al.* 2019). In Afghanistan, during the last 75 years, significant droughts occurred in 1940, 1970-1972, and 2000-2002. The drought in 2002 had more impacts than 22 years of war, with 700,000 people displaced to neighbouring countries (Shobair and Alim 2004). The drought frequency in Afghanistan could potentially even increase in the future because of significant increases in the Heat Wave Magnitude Index (HWMI) and the Standardized Precipitation Evapotranspiration Index (SPEI) (Aich *et al.* 2017).

In terms of magnitude, Aliyar et al (2022) reported severe droughts in rain-fed areas compare to irrigated areas, which contribute to more than 50% of agricultural lands in Afghanistan (Tiwari et al. 2020). Increasing temperatures have also impacted agricultural yield and have been linked to declining production of rice, maize, and wheat in recent decades (Mishra and Singh 2010). It is also projected that crop and irrigation water requirements will increase for all major crops in Afghanistan (Jami *et al.* 2019).

In addition to climatic drivers, land use changes might increase the impact of droughts and reduce water availability. Najmuddin *et al.* (2017) projected land use changes in the Kabul river basin between 2020 and 2030 under a set of economic development scenarios. The results indicated a significant increase in cultivated land, grassland and built-up areas; while forested areas, open water and unused land will significantly decrease. These changes are likely to increase water demand for agriculture and direct consumption and so may compound reductions in streamflow. They will also modify evapotranspiration processes which have hardly been studied for Afghanistan at all.

II.8 Glacial Subsidy and the Under-Estimation of Future Water Resource Shortages

Our final focus is on whether changing streamflow and flow extremes in Afghanistan are likely to reflect not only climate change but also the effects of historical accumulation of ice in glaciers. As climate warms, glacier retreat leads to a transient glacial subsidy (Collins 2008) with higher streamflow than would be expected from snowmelt alone. The transience is thought to be manifest as a temporary increase in streamflow over a limited time period, followed by declining streamflow when glaciers become too small to considerably increase summer river flow; passing through a state of "peak water" (Baraer *et al.* 2012, Miller *et al.* 2012, Glas *et al.* 2018).

This state of peak water should, however, not only be understood from a total available streamflow perspective (which is highest at peak water). We can conceptualise peak water as a shift in the winter snowfall – summer streamflow relationship. In a basin with no or little glacier cover, we expect a positive relationship between winter snowfall and streamflow during the subsequent melting period (spring, early summer), albeit with unclear effects at the annual scale (Berghuijs *et al.* 2014). This may be reversed in basins with significant glacier cover: ice has a lower albedo than snow and thus melts faster. Higher winter snowfall will insulate ice from melt in the following summer.

Glaciated basins are then a form of "insurance policy" in water resource terms: where low winter snowfall is compensated by glacier melt. As glaciers retreat, this insurance policy will progressively come to an end, and streamflow response will become more closely related to winter snow accumulation. Accordingly, inter-annual streamflow variability will increase and follow the relatively high inter-annual variability in snowfall (for the Alps, see e.g. Horton *et al.* 2006).

It follows that the transition from glacier-melt influenced streamflow to snow-dominated streamflow after peak water should also come with a shift of streamflow drought drivers. In a glacier-melt influenced system, streamflow droughts are summer temperature-driven, where cold summers result in reduced snow and ice melt (Van 2015). In a snow-dominated system, droughts are driven by variability in winter snowfall. This shift of the drivers might ultimately modify the drought occurrence.

The extent to which the moment of peak water has happened or may happen in Afghanistan has yet to be established. A particular challenge is that, once peak water is reached, how rapidly water yield decreases, and streamflow variability increases, depends on the volume of water stored in glaciers in the associated basins and on how this compares to groundwater storage. This is very poorly known in Afghanistan, not least because it requires data on ice thickness over large spatial extents and data on potential groundwater storage. Similarly, as the review of glacier retreat above points out, the extent to which stored ice remains available for melt depends on the development of glacier debris cover as the latter eventually leads to insulation of the glacier surface from solar radiation and surface air temperatures, and so to reductions in melt.

Despite the fact that the timing of peak water in Afghanistan is yet to be established, future studies on changes in streamflow in Afghanistan as well as on changes in flow extremes should consider the effects of glacier subsidy. As this subsidy comes to an end, reduced yield and greater variability in yield may be a severe negative consequence.

II.9 Conclusions and Future Research

This study has reviewed 131 scientific papers and reports on the changing hydrology of Afghanistan to synthesise implications for Afghan water resources and how these may evolve in the future in the context of what is known for adjacent regions. It is important to state that Afghanistan is a poor country in terms of scientific research and so there are significant knowledge gaps. Whilst hydrological measurements from before 1980 and since 2004 are available, there is a major gap between these two dates. That said, there are some key findings, as well as important implications for research in this region.

Available data suggest that temperature has already risen significantly in Afghanistan, by between 0.6 and 1.8°C since 1950. The signal is clear and likely to become amplified throughout the 21st century based upon climate model projections. The precipitation signal is less clear at the annual scale, but there are marginally clearer trends at the seasonal scale, notably with higher summer and autumn precipitation and reduced spring precipitation. However, these results may improve using newly available in situ data for bias correction and downscaling of regional climate models.

Given the warming trend, even with relatively little precipitation change, there will be more likely a shift from snow to rain, albeit a function of elevation given the very high-elevation range within the country. Rising temperature is likely to reduce winter snow accumulation with important implications for summer streamflow and groundwater recharge, notably in basins that have no glacier cover or which are rapidly losing it.

There is little data that quantify the rapidly evolving state of the cryosphere. Most data are for the period 1965 to 1980. The few data that exist for the more recent period suggest a net 13.4% reduction in glacier surface area since 1990. A serious weakness associated with these studies is the fact that few have considered true ice loss versus the effects of increasing debris cover that follows from glacier retreat. In addition, there remains very little systematic recording of snow cover in Afghanistan and its changes through time.

The available data further suggests that total surface water volume has decreased in Afghanistan based on comparing streamflow records for 1969-1977 with 2008-2016. The nature of these changes differs between basins with glacier cover and those without. The non-glaciated basins have seen a marked reduction in summer streamflow and an increase in winter and spring streamflow, which both result from reduced winter snow accumulation and earlier spring snowmelt. The glaciated basins are generally showing a higher peak summer streamflow, although there is some variation according to where the basins are with respect to the wider western Himalayan context and according to their elevation range.

The dominance of glacier retreat means that Afghanistan water resources are currently receiving a glacial subsidy, with the effects of temperature rise (e.g. on evapotranspiration) and precipitation change masked by increasing ice melt. It is possible that future water shortages are currently being under-predicted because of insufficient representation of this subsidy in predictive models of future streamflow. In addition, the disappearance of the glacial subsidy will most likely lead to a shift of streamflow drought drivers and thereby of streamflow drought frequency. There is an urgent need to improve quantification of current and future climate change-induced modifications of streamflow with hydrological models that are able to simulate streamflow contributions from glaciers.

Retreating glaciers may also increase the probability of Glacier Lake Outburst Floods. Simultaneously with increasing drought frequency (meteorological and hydrological droughts), the prognosis for Afghanistan is serious. The country does not have well developed water management systems and is already extremely prone to floods and droughts. These potential changes need to be better quantified and used to inform the development of appropriate management plans. It is also important to quantify the population growth and the ensuing direct and indirect increases of water demand, in order to develop water resource management plans that are adapted to future climate change impacts.

Given the very poor knowledge of the state of the cryosphere, and the dependence of Afghan water resources on snow and ice melt, additional detailed analyses must be a particular priority. This includes:

- The new generation of climate models should be updated through time and this needs to be bias corrected with in situ data which is becoming increasingly available.
- Studies of changing evapotranspiration and its representation in hydrological models are needed.
- Systematic groundwater studies are required and their relation to groundwater availability quantified, not only as a function of changing climate but also changing land use and the drivers of groundwater pollution.
- Detailed research is required to determine the spatial patterns of glacier retreat, debris cover accumulation and the extent to which localised glacier advance in neighbouring regions is

also present in some parts of Afghanistan.

- Analysis of climatological data from glaciated basins is required to understand the steep gradients of precipitation change in the context of climate change.
- Modelling of snow and ice accumulation and ablation is needed to understand where and when basins will go through a condition of peak water.
- Analysis of how glacial subsidy modifies observed streamflow trends in the future has to be determined with the help of hydrological models that can represent glacier melt processes.

Based on the unstable political situation in Afghanistan, use of remote sensing technic is a support tool to achieve above points. Once complete, the above analyses will need to be combined with existing models of Afghanistan's water cycle, that represent for example changing evapotranspiration, land use and water demand, to enable improved water resource planning for the future.

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Data Availability Statement

The climate data of four meteorological stations from Afghanistan Meteorological Department (AMD) http://www.amd.gov.af/ and discharge data of seven hydrological station (Figure I-1) obtained from Ministry of Energy and Water of Afghanistan https://mew.gov.af/en by an official request letter from University of Lausanne.

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Conflicts of Interest

The authors declare no conflict of interest and the funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, or in the decision to publish the results.

III PATTERNS AND DRIVERS OF GLACIER DEBRIS-COVER DEVELOPMENT IN THE AFGHANISTAN HINDU KUSH HIMALAYA

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This chapter reviews existing methodologies that map debris-covered ice and explains the limitations and potential possibilities to overcome the limitations. It presents two new indices that mapped debris-covered ice in Afghanistan using remote sensing techniques. This article discusses methodological workflow, calibration, and validation processes. Consequently, assessed the patterns and drivers of glacier debris-cover development in the Afghanistan Hindu Kush Himalaya using principle component analysis.

Abstract

Debris-covered ice is widespread in mountain regions with debris an important control on surface ice melt and glacier retreat. Quantifying debris cover extent and its evolution through time over large regions remains a challenge. This study develops two Normalized Difference Supraglacial Debris Indices for mapping debris-covered ice based on thermal and near Infrared Landsat 8 bands. They were calibrated with field data. Validation suggests that they have a high level of accuracy. They are then applied to Landsat data for 2016 to produce the first detailed glacier inventory of the Afghanistan Hindu Kush Himalaya that includes debris cover. 3408 glaciers were identified which, for those ⩾0.01 km^2 in area, gives an ice cover of 2,222 ± 11 km^2 and a debris cover of 619 ± 40 km^2. Principal components analysis was used to identify the most influential drivers of debris-covered ice extent. Lower proportions of debris cover were associated with glaciers with a higher elevation range, that were larger, longer and wider. These relations were statistically clearer when the dataset was broken down into climate and geological zones. A glaciers continue to shrink, the proportion of debris cover will become higher, making it more important to map debris cover reliably.

III.1 Introduction

Glacier inventories exist for most regions of the world (e.g. Bajracharya and Shrestha, 2011; Pfeffer et al., 2014; Nuimura et al., 2015; Mölg et al., 2018; Scherler et al., 2018; Herreid and Pellicciotti 2020). These are generally based upon satellite imagery (Racoviteanu et al., 2009; Shukla et al., 2010). Clean ice can be mapped relatively easily, notably using thermal bands, though the threshold used to define ice cover needs calibration as they can vary both spatially and temporally (Veettil, 2012; Benjamin et al., 2015; Haireti et al., 2016). However, mapping debris-covered ice remains a challenge (Bolch and Kamp, 2005; Raup et al., 2007; Racoviteanu et al., 2009; Mölg et al., 2018). Mountain glaciers can develop significant debris cover that can substantially modify glacier melt processes and response to climate warming (Nicholson and Benn, 2006; Jouvet et al., 2011; Scherler et al., 2011; Zhang et al., 2011; Pratap et al., 2015; Rowan et al., 2015; Vincent et al., 2016; Nicholson et al., 2018; Ferguson and Vieli, 2020).

Mapping debris-covered ice from satellite imagery has made use of two primary approaches. The first is geomorphometric (e.g. Paul, 2003; Paul et al., 2004; Bolch and Kamp, 2006; Shukla et al., 2010; Veettil, 2012; Bhardwaj et al., 2014) where debris in ice marginal zones is classified as ice cored if local slope is below a certain threshold (the critical slope angle for debris movement). This may be problematic in some regions, such as where the transition from a glacier margin to an unglaciated region is gentle but still relatively debris free (Paul, 2003; Bolch and Kamp, 2006). In addition, no detectable change in surface slope may occur at the interface between clean-ice and debris-cover (Bhambri et al., 2011); post-depositional sedimentation by mass movement, a commonly found process in the polygenetic environment of the Himalayas (Benn and Owen, 2002; Bhambri et al., 2011), may cause confusion (Bhambri et al., 2011); and the available topographic data may not have the right resolution (Bolch and Kamp, 2006; Racoviteanu et al., 2009).

One alternative is to use differences in temperature between debris-covered ice and the temperature of the surrounding ice-free zones. Taschner and Ranzi (2002) analyzed the surface temperature and physical properties of both debris layers on glaciers and non-ice containing zones (debris, rocks, grass) using ground measurements obtained for temperature and heat flux. They found significant temperature differences between debris-covered ice and other land surfaces with higher temperatures on average for surfaces without underlying ice. Amschwand et al. (2021) recorded such differences to a debris thickness of 5 m. Subsequent studies have exploited this observation in satellite data. Scherler et al. (2018), Herreid and Pellicciotti (2020) and Fleischer et al. (2021) have used the proportion of near infrared (NIR) and shortwave infrared (SWIR) to map debris cover on glaciers. Stewart et al. (2021) attempted to estimate debris thickness on glaciers using 60 m x 60 m Landsat Enhanced Thematic Mapper + data resampled to 30 m by 30m. Herreid (2021) used ASTER data processed to give surface kinetic temperature at a 90 m resolution and then used an unmixing approach to estimate the extent of debris-covered ice within a pixel, emphasizing the need for downscaling of the generally coarse thermal bands especially for mountain glaciers.

There are three issues that follow from these thermal band satellite based approaches. First, with very thick debris cover, the signal of ice temperature will diminish (Racoviteanu et al., 2009; Shukla et al., 2010) resulting in zones of debris-covered ice being classed as non-glacier. We assume that the importance of this problem is likely to increase with rapid glacier retreat, leading to potentially extensive areas of debris-covered ice that may be patchy and/or disconnected from the glacier itself. It emphasizes the need for further research to identify the limits of satellite-based estimation of debris-cover thickness. Second, following from the typical resolutions reported above, satellite-based studies have struggled to map small glaciers. Herreid and Pellicciotti (2020), for instance, excluded glaciers <1 km^2 even if for some mountainous regions a large proportion of glaciers fall in this class (Maharajan et al. 2018). One solution could be to downscale coarser thermal using higher resolution panchromatic bands as has been done in other applications (Choi, 2006; Aiazzi et al. 2007; Choi et al., 2011, Jung and Park, 2014, Rai and Mukherjee, 2021). Third, it is not yet clear whether or not a single index can map ice-covered debris regardless of the geological composition of such debris. If weathering processes lead to significant accumulation of fine-grained sediments on debris-covered glaciers then the debris cover will have small void spaces. This may result in greater capacity for water retention leading to wet surfaces (Juen et al., 2013; Blum et al., 2018) with different thermal properties to dry ones. As water and ice affect the thermal properties of a debris layer (Giese et al., 2020) more than one index may be needed to capture the spatial extent of debris-covered ice fully.

Given that debris cover remains a major cause of uncertainty in quantifying the retreat of glaciers in mountain regions (Scherler et al., 2011), there is a need for further development and testing of indices that can be used to map debris-covered ice in mountain regions, notably ones that can address the three issues identified above. Thus, the primary aim of this paper is to develop indices for mapping ice and debris-covered ice extent for mountainous regions that; (a) yield sufficient spatial resolution for mapping of valley-confined glaciers, including those < 1 km^2 in size; (b) are sensitive to geological controls on the caliber of accumulated sediment; (c) are suitable for long-term analyses so as to quantify change; and (d) use freely-available datasets.

The focused is on Afghanistan in the western part of Hindu Kush Himalaya where there remains only a poorly-developed understanding of the cryosphere despite its impact on both water resources and environmental hazards (Chapter II). Most glaciological studies in Afghanistan are for the period 1965 to 1980 and are in Russian, Dutch, and very occasionally English, and most are not available online (Shroder and Bishop, 2010). In 1980, Shroder initiated a glacier inventory for Afghanistan supported by the U.S. Geological Survey using Landsat-3 satellite imagery (40m ground resolution), and field observations (Shroder and Bishop, 2010). This research identified ca. 3,000 separate glaciers in Afghanistan with an estimated area of ca. 2,700 km^2 (Shroder, 1980; Shroder and Bishop, 2010; Shroder and Ahmadzai, 2016). A glacier inventory of Afghanistan was published by the Afghanistan Ministry of Energy and Water and International Centre for Integrated Mountain Development (ICIMOD) using satellite Landsat imagery (Maharajan et al., 2018). Glaciers were mapped using semi-automatic object-based image analysis methods and debris-covered ice was mapped using slope thresholds (0-24°). Maharajan et al. (2018) identified 3,782 glaciers, covering a total area of ca. 2,540 km^2 (excluding glaciers with an area of less than 0.01 km^2) concentrated at elevations between 3,200 and 6,900 m a.s.l. Thus, a subsidiary aim of the work is to produce a new glacier inventory for Afghanistan. As our method leads to one of the first inventories that can map very small (< 1km^2) glaciers, we seek to identify the regional-scale, systematic controls that explain spatial variation in debris-covered ice extent for Afghanistan using our inventory.

III.2 Study Area

Afghanistan is a mountainous country located in the subtropics, extending from 29°21′N to 38°30′N latitude and from 60°31′E to 75°E longitude (Gopalakrishnan, 1982) (Figure III-1). It has an arid and semi-arid continental climate, characterized by temperature and precipitation regimes characteristic of deserts, steppe and highland environments (Humlum et al., 1959; Shroder, 2014). It has four main glacier regions (Figure III-1). We aim to produce a glacier inventory for all of Afghanistan. To support this work, we looked at two cases within Afghanistan in greater detail.

We undertook field data collection at the Mir Samir Glacier (Figure III-1) for index calibration and validation, which is the only glacier monitored by the Ministry of Energy and Water (MEW) of Afghanistan. This glacier is located at 70.171°N longitude and 35.596°E latitude (Figure III-1). Its highest altitude is 5060 m and it extends over a distance of 2.9 km to 4200 m altitude. The Mir Samir Glacier was mostly debris-covered in its snout zone, with some large boulders present. The proglacial margin also contains debris-covered ice. The geology around and under the glacier varies from slightly metamorphosed sedimentary rocks to hard gneisses and schists

(Gilbert et al. 1969). This glacier was the primary focus of the first index we develop for mapping debris cover.

A second case, the Noshaq glacier range (Figure III-1) was also studied more intensively, albeit without a field visit. This glacier range was identified during the study as having debris-covered ice that was not being detected using our first index and so became the focus of the second index we developed. The Noshaq glacier range was studied in detail by Shroder (1978) (Figure III-1, Figure III-7, Supplementary Material). It contains one of the longest and largest glaciers in Afghanistan, starting from Noshaq peak, the highest peak in Afghanistan (7,492 m), and extending for 14 km to an elevation of about 3,580 m (Shroder, 1978) (location 36˚ 25ˈ N, 71˚ 47ˈ E).

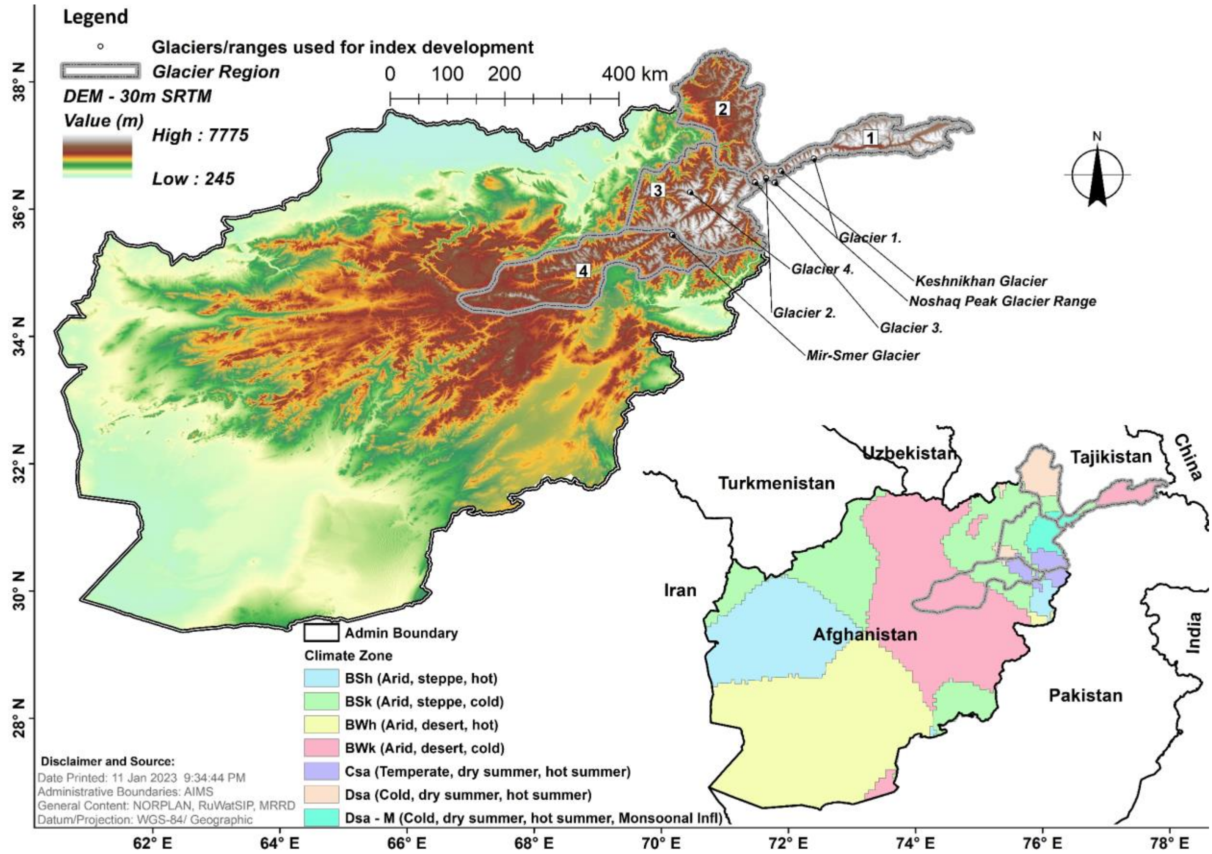

Figure III-1 Afghanistan showing the four glacier regions and their climatic zones (inset) based on the Köppen-Geiger climate classification (Peel et al.*, 2007) modified to include Dsa - M (monsoonal Influence) following Shroder (2014).*

III.3 Methodology

The approach makes use of freely available imagery from the Landsat 8 Operational Land Imager (OLI). The spatial resolution of its thermal bands is 90 – 120 m which creates particular uncertainty where clean ice and debris-covered ice are in juxtaposition (Bhambri et al., 2011; Kääb et al., 2014) or glaciers are small in size (< 1 km^2). Thus, the two indices developed herein aim to improve the spatial resolution of thermal-based mapping and to resolve debris-covered ice where there is only a weak thermal signal.

III.3.1 Datasets

Data were obtained for ten L8 image tiles for the end of the 2016 ablation season (primarily in September) from http://earthexplorer.usgs.gov/ (Figure III-8, Supplementary Material), and on dates with no seasonal snow or cloud cover present in the scenes. The indices we developed used bands directly provided by Landsat 8; blue-B2, near infrared (NIR)-B5, shortwave Infrared (SWIR)-B6, panchromatic (PAN)-B8, and thermal (TIR)-B10. The B2, B5 and B6 bands have 30 m resolution, the B8 band 15 m resolution, and the B10 band 100 m resolution that supplied already downscaled to 30 m. To correct for top of atmosphere reflectance, before all further analyses, we applied the radiometric rescaling coefficients provided in the associated metadata files delivered with the Landsat Level-1 NIR and SWIR products. We address the correction of PAN and TIR bands below.

Digital elevation models (DEMs) with resolutions of 5 m or 10 m (according to region) were provided by the Department of Statistics, Ministry of Agriculture Irrigation and Livestock of Afghanistan (MAIL, 2020). In areas where no Afghan DEMs were available we used 30 m resolution DEMs downloaded from the ALOS global digital surface model (ALOS, 2022). The Russian geological vector map of Afghanistan and high resolution (0.29 m) 2016-RGB images were obtained from Ministry of Mines and Petroleum of Afghanistan (MoMP, 2020).

III.3.2 Indices for mapping ice and debris cover

To map bare ice, we used the NIR to SWIR band ratio (Paul et al., 2002; Taschner and Ranzi, 2002; Paul, 2003; Paul et al., 2004; Bolch and Kamp 2005; Shukla et al., 2010; Veettil, 2012; Bhardwaj et al., 2014). Whilst methods for mapping debris-covered ice are available (see Supplementary Material), we develop a new index based upon a combination of L8 TIR and PAN bands. The principle behind this combination is that the TIR band is the one most likely to contain the thermal signal that allows identification of thicker debris layers. However, the L8 supplied TIR band is coarser (30m). The PAN band is 15 m and, whilst theoretically less sensitive to thermal properties, it provides a means of downscaling the coarser TIR band to the resolution needed for mountain valley glaciers. This was done by assigning to each PAN value the nearest TIR value. The structural characteristics of debris-covered ice lead to a unique texture and panchromatic data have the potential to detect it (Bishop et al., 1995).

The PAN band has a reversed reflectance value (lower to higher) over debris to ice compared to TIR (higher to lower) (Figure III-9, Supplementary Material). On this basis we define a

Normalized Difference Supraglacial Debris Index ($NDSDI_{c1}$):

$$Normalized\ Difference\ Supraglacial\ Debris\ Indix\ (NDSDI_{c1}) = \frac{PAN - TIR}{PAN + TIR} \qquad (1)$$

During application we noted for a small number of glaciers in certain geological regions that the $NDSDI_{C1}$ suggested no debris-covered ice when there was likely to be ice present. Looking at the Russian geological map of Afghanistan (MoMP, 2020), we noted such regions were associated with detrital sedimentary rocks (mainly sandstone, siltstone, argillite, shale) (Shroder, 1980; Shroder and Bishop 2010) which are highly erodible and result in smaller grain-size debris and likely wetter sediment. As the visible to near infrared (VNIR) single band ratio has been used previously to detect moist surfaces (Lobell and Asner, 2002; Amani et al., 2016), we use this to define a second index to capture ice covered by small-grained and moist debris:

$$Normalized\ Difference\ Supraglacial\ Debris\ Indix\ (NDSDI_{c2}) = \frac{NIR}{Blue} \qquad (2)$$

III.3.3 Application of the indices

The indices were applied using the eCognition software (Trimble ©). Figure III-2 shows the workflow for applying the indices and key steps are illustrated in Supplementary Material, Figure III-10.

As an initial step, radiometric calibration was performed to convert digital numbers (DNs) for NIR and SWIR bands to reflectance values to map bare ice. Radiometric calibration and atmospheric correction was necessary for the NIR and SWIR bands (Figure III-10b, Supplementary Material). Radiometric calibration decreased the numerical range of NDSDI values during debris-covered ice mapping and also caused loss of resolution (Figure III-11, Supplementary Material). Thus, we used the original band DNs in (1) and (2).

Research has shown that misclassifications of pixels as debris-covered ice (e.g. Supplementary Material, Figure III-10d) can occur where there are steep debris-free slopes (Zollinger, 2003) and cold-water bodies. Following others (e.g. Bolch et al., 2007; Bhambri et al., 2011; Veettil, 2012; Bhardwaj et al., 2014), we first applied a local slope threshold of 37° on a pixel basis to remove bare rock surfaces but this did not eliminate the problem. Hence, we merged pixels into zones (clean ice, debris-covered ice, ice-free) and then calculated the mean slope of each debris-covered ice zone. The average value of slope was calculated by zone and those zones with slopes >24° were reclassified as ice-free.

Even with these thresholds, some areas of supposed debris-covered ice remained that were unlikely to be correct as they were too low in altitude compared with known glacier snout margins (Figure III-10e, Supplementary Material). For this we identified a minimum altitude threshold that differs based on each region (3500-4000 m a.s.l). Shadowed snow patches and bedrock misclassified as debris-covered were identified by using a minimum area (<0.01 km^2) of debris cover (following Tielidze et al., 2020). Lastly, some snow cover area was mapped as ice (e.g. Figure III-10i, Supplementary Material) and more recent imagery was used to identify and to remove such errors.

In summary, the following parameters need to be calculated and calibrated in our analyses: (1) a threshold for the NIR/SWIR ratio to identify clean ice; (2) threshold ranges for the two new indices of debris cover ice $NDSDI_{c1}$ and $NDSDI_{C2}$; (3) a slope threshold applied to merged debris-covered glacier zones to remove those erroneously identified as debris-covered ice; (4) a minimum altitude threshold; and (5) a minimum area threshold.

III.3.4 Calibration, validation and inventory comparison

Our approach to calibration and validation had six steps. First, we visually identified plausible parameter values and ranges by looking across a set of glaciers using the high resolution RGB image. For all parameters except the two NDSDI indices, the result was a set of plausible parameter values. For the two NDSDI indices it was plausible parameter ranges.

Second, we formally acquired field data for the Mir Samir glacier (Figure III-1) in September 2020, and randomly-selected a subset of this dataset to calibrate the ranges for the $NDSDI_{c1}$ index (eq. 1). Security issues meant we could only map one glacier, and even then we had to undertake field data collection with the support of armed guards. The Mir Samir Glacier is mostly debris-covered at its snout, with bigger boulders and potentially ice-cored debris in the proglacial margin. A total of 219 GPS points were collected under a stratified-random sampling approach using a Garmin GPSMAP 64s GPS (±3 meter positional uncertainty) from three ground types; clean ice zones, zones of debris-covered ice and non-ice zones (Figure III-12, Supplementary Material). Thin and partially debris-covered ice was determined visually. Thicker debris-covered ice was identified by the presence of ice under large boulders. The full dataset was randomly divided in half for calibration and validation.

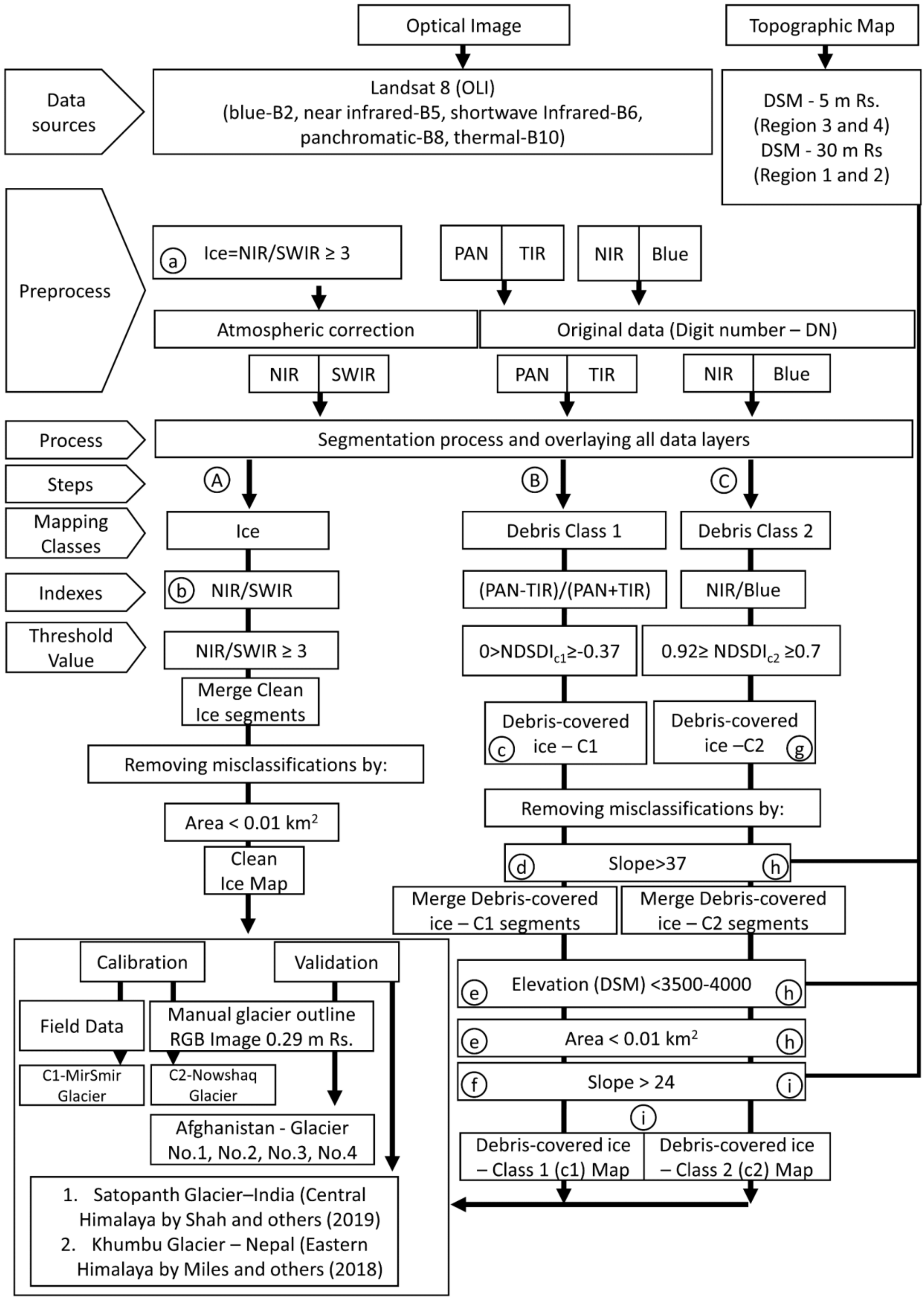

Figure III-2 Methodological steps used in the study. The letters shown link to supplementary material Figures S4a to S3i, DEMs used for each image tiles are showed in supplementary material Figure III-8.

Third, as the field validation site for $NDSDI_{c1}$ did not include fine-grained sedimentary debris-cover, and required to validate $NDSDI_{c2}$ debris-cover classifications, we turned to the Noshaq range (Figure III-1). High resolution MoMP (2020) imagery was used to visually identify debris-covered ice by the presence of supraglacial ponds and crevasses (Bodin et al., 2010; Mölg et al., 2018). We then randomly selected points from ice-covered, debris-covered ice and non-ice zones, which were also randomly separated into calibration and validation datasets.
Fourth, in order to assess the transferability of our approach, we manually mapped four other debris-covered glaciers in Afghanistan from the high resolution RGB imagery. We also test our approach at the Santopath Glacier in the central Himalaya, India and the Khumbu Glacier in Nepal (Miles et al., 2018). Both sites have reliable published maps of debris-covered-ice. We applied our methodology (Figure III-2) to these glaciers.

Finally, we compared the glacier outlines of our study with datasets published by (1) Mahrajan et al. (2018) that used only a slope threshold >24° to identify debris-covered ice and the NDSI index for clean ice; (2) Scherler et al. (2018) who used the Randolph Glacier Inventory (RGI) version 6.0 outline and then used 2013-2017 Landsat and 2015-2017 Sentinel optical satellite images to map where glaciers were debris-covered; and (3) Harreid and Pellicciotti (2020) who used the NIR/SWIR satellite band ratio to map debris cover and clean ice using Landsat data for 2013-2015. The outlines provided by Harreid and Pellicciotti (2020) came with on-line available datasets and so we also assessed their approach quantitatively for our 8 glaciers (two Afghan glacier used for calibration and validation; four additional glaciers in Afghanistan used for validation; and the Satopanth and Khumbu glaciers) where the datasets were available.

For both calibration and validation we used an error matrix approach (Congalton and Green, 2019) as used to evaluate land-cover classifications based on reference data (Foody, 2002; Congalton and Green, 2019). We calculated classical error statistics (total, user and producer accuracies) but also the Kappa statistic as the latter corrects accuracy assessments for chance agreement between classes (Lillesand et al., 2015). The commission errors define the user accuracy (i.e. the reliability of information derived from the classification; Story and Congalton, 1986) and so they can be used as proportional uncertainties to calculate uncertainty in mapped areas.

III.3.5 Inventory and exploration of controls on debris cover

We applied our methodology (Figure III-2) to all glaciers in Afghanistan to produce a new inventory. We then explored controls on debris cover percentage using Principal Components Analysis (PCA;Table III-1). Catchments were identified using watershed delineation in ArcGIS at the outlet of each glacier. Catchment boundaries were then used to determine catchment area (1), and mean slope (2). Glacier length (3) was calculated following the Machguth and Huss (2014) method that determines and measures the centerline of the glaciers. However, for smaller glaciers (<0.07 km^2) we found that the method miscalculated glacier length as such glaciers often had their long axis tangential to the glacier surface slope rather than along it. For such glaciers, we used ArcGIS to calculate the longest distance between upper and lower points of the glacier. Herreid and Pellicciotti (2020) suggested determining glacier width as the linear distance orthogonal to glacier flow at the widest location of the main centerline. However, considering the complexity of glaciers in Afghanistan (Figure III-3) this method may not represent glacier width correctly. Thus, we calculated an effective glacier width (4) for individual glaciers by dividing glacier area to the glacier length. The debris influence area (5) was determined by intersecting each glacier outline with the glacier catchment outline (using the intersect toolbox in ArcGIS) and defining the influence area as that having altitudes higher than the lowest altitude of debris-covered ice. The DEM was used with the glacier boundaries to calculate glacier mean elevation (6), glacier elevation range (7) and glacier mean slope (8) using the zonal statistic tool in ArcGIS. The geological information for each glacier (9) was extracted from the geological map of Afghanistan provided by the Ministry of Mines and Petroleum of Afghanistan (MoMP, 2020). The geological information consists of 27 geological type grouped into 6 geological categories. In addition, the Köppen-Geiger climate classification (Peel et al., 2007) was used to represent the climate characteristics of the glaciers.

Table III-1 Glacier parameters derived for the multivariate analysis

Parameter	**Rationale**
1 Catchment Area	Catchment area is a scale effective variable with catchments with a smaller area likely to be more debris-covered
2 Catchment Mean Slope	Steeper mean slope is likely to lead to valley sidewalls and headwalls where there is more debris supply by erosion
3 Glacier Length	Longer glaciers are likely to have proportionally less headwall debris delivery
4 Glacier Mean Width	Wider glaciers are likely to have proportionately less sidewall debris delivery
5 Debris Influence Area	The area of a catchment containing a glacier that is not ice covered or debris-covered ice, representing a measure of potential debris supply
6 Glacier Mean Elevation	Higher glaciers have higher accumulation and lower ablation so reducing debris cover at the surface
7 Glacier Elevation Range	Glaciers with a bigger elevation range are likely to have a more extensive accumulation zone, so reducing debris cover at the surface
8 Glacier Mean Slope	Steeper glaciers are likely to encourage less debris accumulation
9 Geological Hardness Grade	A measure of the resistance to erosion and hence inversely related to potential debris supply
10 Climatic zone	Geographical classification to capture different potential climatic influences on temperature and precipitation and hence accumulation and ablation.

Due to potential inter-correlation between these variables, Principal Components Analysis (PCA) was used to reduce this dataset to a set of linearly independent principal components that were then used to explain the statistical controls on debris cover (Gupta et al., 2013; Ghosh et al., 2014). First, we standardized the data by dividing each variable by its standard deviation. Second, the PCA was applied and the variance and factor loadings were calculated (Jensen, 1996; Ghosh et al., 2014). Orthogonal rotation (orthomax) that maximizes a criterion based on the variance of the loadings was used to simplify the interpretation of the resulting factors, and to ensure that the components remained pairwise uncorrelated for subsequent linear modeling. We used a 5% contribution to the original data variance as the cut off for retaining a component. We then interpreted each component with respect to its loadings.

Finally, we established relationships between percentage of debris cover and the new principal components. For this purpose, we used an optimizing stepwise regression where components were added to the model in order of decreasing importance provided that their individual contribution to the total explanation of the model was significant at $p < 0.05$. We undertook this modelling for both the entire dataset, but also the dataset divided in two ways: by climatic zones and by geological classes.

III.4 Results

III.4.1 Index calibration, validation and comparison

For the clean ice NIR/SWIR threshold, visual comparison of results with the imagery suggested that a value of NIR/SWIR ≥3 appeared to map clean ice effectively. The mean zonal slope for the removal of zones (not pixels) misclassified as debris-covered ice was 24°. We found that an elevation threshold altitude of < 3500 m for regions 2, 3 and 4 and altitude < 4000 m for region 1 (Figure III-1) was appropriate for the minimum altitude condition (Supplementary Material, Figure III-10e,h). Finally, we removed zones classified as glacier or debris-covered glacier < 0.01 km² if detached from ice and/or debris-covered ice (Supplementary Material, Figure III-10e,i). The visual analysis suggested the following two parameter ranges for debris-covered ice 0> $NDSDI_{C1}$ ≥-0.32; and 0.88 ≥ $NDSDI_{C2}$ ≥ 0.70.

Based on the ground observations from glacier, pixels with $NDSDI_{C1}$≥-0.37 were classified as debris-covered and was optimal, therefore adopted for this study. The calibration accuracy assessment (Table III-2) gave very encouraging results; the overall accuracy was 0.98 and the Kappa coefficient was 0.91. For the second index, a range of 0.92 ≥ $NDSDI_{C2}$ ≥ 0.70 was chosen to maximise the accuracy of the approach. The overall accuracy for the Noshaq glacier range was 0.92 and the Kappa coefficient for both clean ice and debris-covered ice was 0.91 (Table III-2).

Table III-2 Calibration results for the Mir Samir and Noshaq glaciers

Accuracies	Clean ice	Debris-covered ice	Not ice
Mir Samir glacier : overall accuracy 0.98			
Commission error (Com)	0.02	0.09	0.00
Producer's accuracy (PrAc)	0.98	0.91	1.00
Omission error (Om)	0.01	0.17	0.00
User's accuracy (UsAc)	0.99	0.83	1.00
Kappa coefficient	0.92	0.98	0.98
Noshaq glacier : overall accuracy 0.92			
Commission error (Com)	0.12	0.14	0.06
Producer's accuracy (PrAc)	0.88	0.86	0.94
Omission error (Om)	0.08	0.18	0.07
User's accuracy (UsAc)	0.92	0.82	0.94
Kappa coefficient	0.91	0.91	0.86

Table III-3 shows the validation results for the Mir Samir and the Noshaq glaciers and also for the four other glaciers considered in Afghanistan and the two outside of Afghanistan (Figure III-13Supplementary Material). The results are encouraging as there is only a very slight degradation in the overall accuracy and the Kappa coefficient in transferring the calibrated index both within and between glaciers.

Table III-3 Validation results and comparison with the Herreid and Pellicciotti (2020) index

Validation datasets	Overall Accuracy (OcAc)	Producer's accuracy (PrAc)		User's accuracy (UsAc)		Kappa coefficient	
		Ice	Debris cover	Ice	Debris cover	Ice	Debris cover
Indices used in this paper							
Mir Smir Glacier, Image 8	0.98	0.99	0.88	0.99	0.88	0.92	0.98
Noshaq Glacier, Image 5	0.93	0.88	0.85	0.92	0.82	0.92	0.93
Glacier 1, Image 3	0.96	0.98	0.93	0.96	0.89	0.95	0.96
Glacier 2, Image 6	0.89	0.99	0.85	0.75	0.97	0.89	0.87
Glacier 3, Image 6	0.94	0.95	0.86	0.85	0.96	0.94	0.94
Glacier 4, Image 6	0.95	0.98	0.79	0.95	0.96	0.94	0.95
Satopanth Glacier, India	0.94	0.83	0.91	0.91	0.90	0.94	0.94
Khumbu Glacier, Nepal	0.94	0.91	0.87	0.90	0.92	0.94	0.93
Herreid and Pellicciotti (2020) inventory							
Mir Smir Glacier	Not included in Herreid and Pellicciott (2020) inventory						
Noshaq Glacier	0.81	0.80	0.90	0.41	0.59	0.81	0.81
Glacier 1	0.79	0.89	0.89	0.58	0.68	0.77	0.78
Glacier 2	Not included in Herreid and Pellicciott (2020) inventory						
Glacier 3	0.79	0.91	0.73	0.78	0.18	0.78	0.79
Glacier 4	Not included in Herreid and Pellicciott (2020) inventory						
Satopanth Glacier	0.90	0.84	0.89	0.71	0.79	0.90	0.89
Khumbu Glacier	0.89	0.75	0.87	0.89	0.83	0.88	0.88

For the Afghan glaciers 1-4 (Figure III-3) the extent of debris-covered ice in the glacier marginal zone is revealed by supraglacial ponds and crevasses and these zones tend to be missed in part by other inventories as compared with our method (Figure III-3, Glacier 2). Compared with the Herried and Pellicciotti (2020) approach, we obtained higher Kappa coefficient accuracy with our method for Glacier 1 (0.95 and 0.96 for clean ice and debris-covered ice respectively as compared to 0.77 and 0.78 respectively) mainly due to better estimation of ice presence in the margin of the glacier (Figure III-3, Glacier 1). Similarly, for Glacier 3, debris cover ice was missed around the terminus and margins by the Herried and Pellicciotti (2020) index resulting also in lower accuracies and Kappa coefficients (Table III-3).

Our method also shows higher accuracies level for those glaciers outside of Afghanistan in the Himalaya (Table III-3). We obtained 0.94 Kappa accuracy for clean ice and debris cover ice for both glaciers using our method. The Herried and Pellicciotti (2020) index gives lower values for both the Satopanth glacier and the Khumbu glacier.

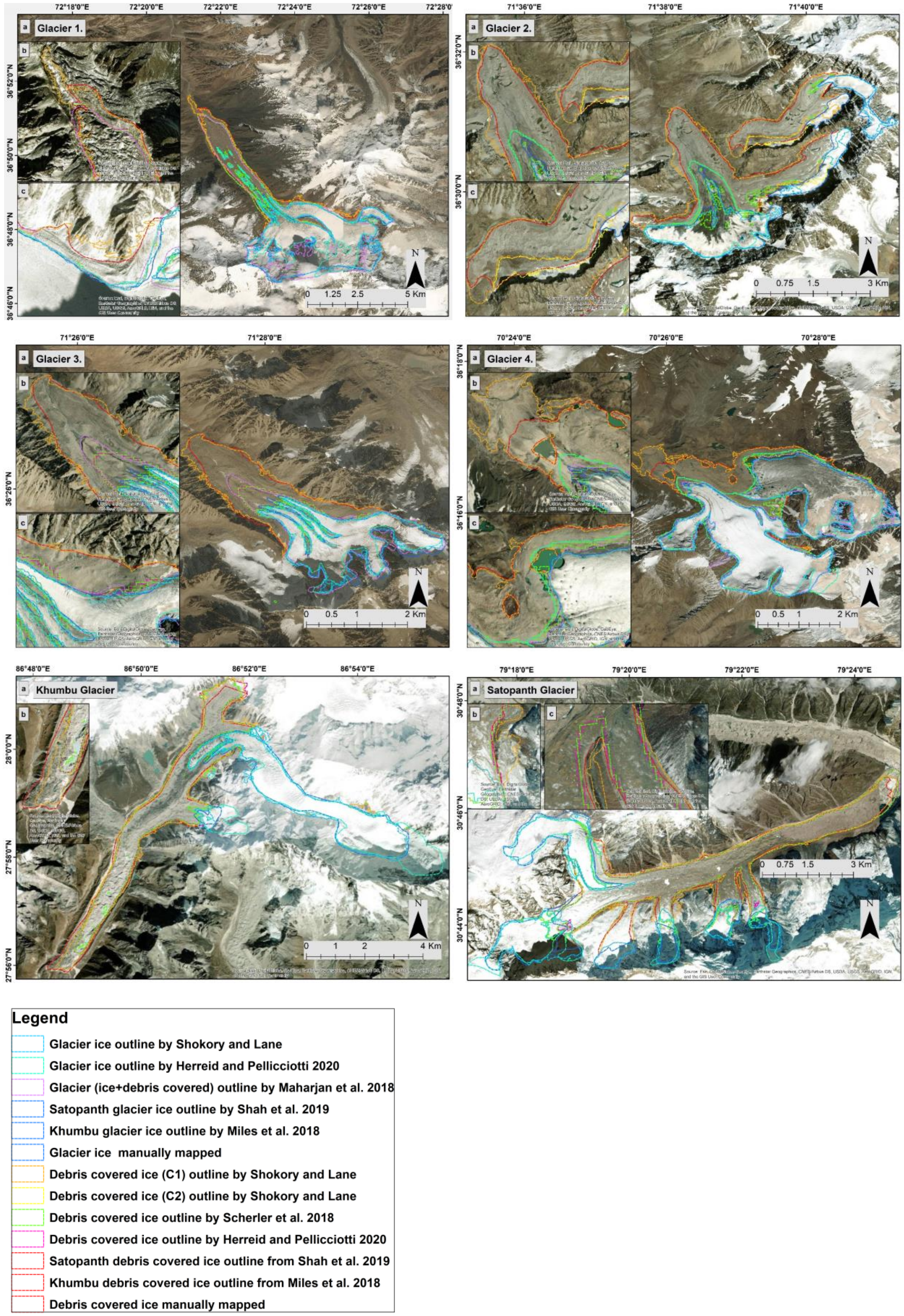

Figure III-3 Comparison of the index results for Afghanistan glaciers 1 to 4 and the Satopanth and Khumbu glaciers with those using other indices. Blue and red outlines used as reference outlines.

III.4.2 Glacier inventory

We identified (Table III-4) 3,408 glaciers which, considering those ≥0.01 km^2, sums to 2,222 ± 11 km^2 of ice cover, 619 ± 40 km^2 of debris-covered ice, and glacier surface areas up to 21.2 km^2. Differences in the number of glaciers by region varied reflecting different climatic, elevation, and geological zones. Region 1 has the highest number of glaciers, with a larger mean and variability of glacier area (1.21 ± 2.25 km^2). The percentage of debris-covered ice is highest in Region 4 (42%) where there are also fewer and smaller glaciers. Regions 1, 2, 3, and 4 have 69%, 4%, 25% and 2% of the total debris cover. The glaciers differ markedly in altitudinal range (Table III-4).

Table III-4 Summarize the glacier inventory of Afghanistan for 2016

Glacier Regions	Glacier Elevation Range (m)	Glacier cover for this Elevation Range (%)	No. of Glaciers	Ice Cover (km^2)	Debris-covered ice extent (km^2)	Mean glacier size (km^2)	Percentage debris cover (%)
R1- Northeast	3800-7380	18	1499	1397 ±7	426 ±25.6	1.21 ±2.25	22
R2- North	3500-5500	6.4	666	299 ±1.5	23 ±1.4	0.48 ±0.69	8
R3- Center-North	4100-6900	5.9	1136	514 ±2.6	156 ±9.3	0.58 ±0.83	21
R4- Center-West	4000-5200	0.6	107	12 ±0.06	15 ±0.9	0.24 ±0.29	42

There is a clear regional association in both size and debris cover (Figure III-4) and these associations were significant (Kruskal-Wallis H, $p < 0.05$).

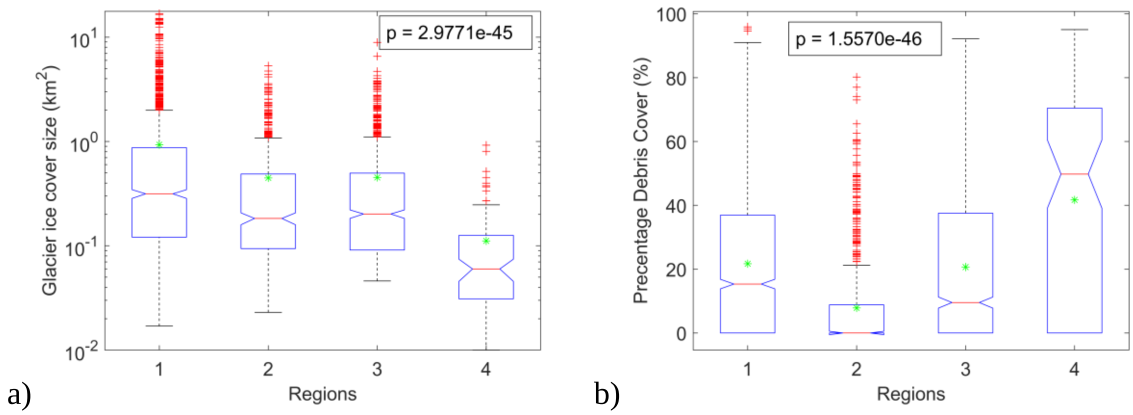

Figure III-4 Box plots of glacier ice cover size a) and percentage debris cover b) at four regions. The upper and lower box margins mark the 75th (Q75) and the 25th (Q25) quartiles respectively, with the mid box line showing the median. The whiskers show the extremes of the data (maximum and minimum) except for situations where outliers are present, defined as either Q75 + 1.5(Q75 - Q25) for the maximum and Q25 - 1.5(Q75 - Q25) for the minimum.

Hypsometric distributions (Figure III-5) suggest that glaciers are distributed between 3,500 and 7,380 m a.s.l, but that debris-covered ice is limited to altitudes below 5,500 m. There is between region-variability. Glaciers in Region 1 and 3 concentrate on 5,000 m a.s.l altitude and Region

2 and 4 on 4,500 m a.s.l. Comparing glacier elevation ranges, Region 1 and 3 are at higher elevations than Region 2 and 4 (Table III-4). This shows a clear signal of altitudinal effects on glacier distribution in Afghanistan.

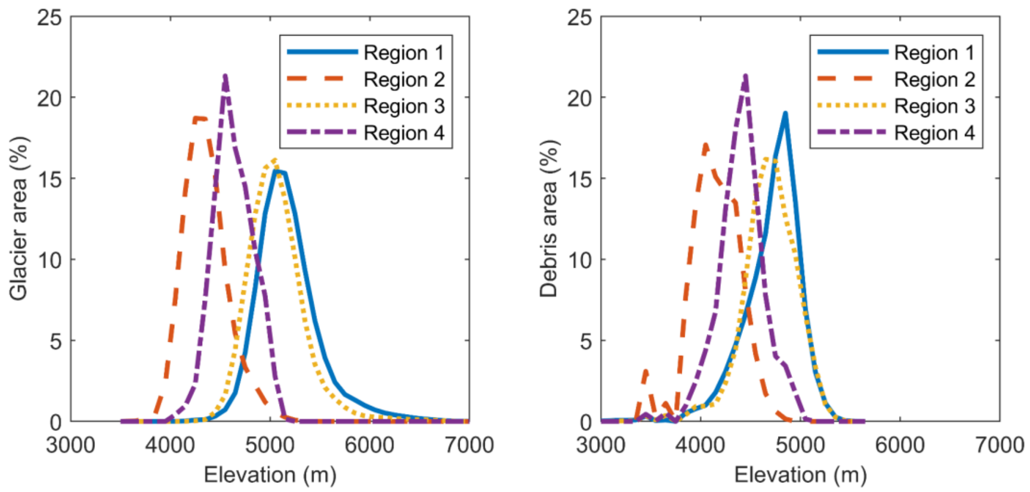

Figure III-5 Hypsometric distribution curve of glaciers (a) and debris cover (b) in percentage grouped in bins of 100 m and by region.

Regions 1 and 3 tend to have larger glaciers than 2 and 4 (Figure III-6). The percentage debris-covered ice shows significant correlation with glacier size; smaller glaciers have more debris-covered ice than larger glaciers, notably for Regions 1, 2 and 3. The relation is non-linear to varying degrees and heteroscedastic (Figure III-5), small glaciers in Region 2 and 3 in particular having disproportionately higher percentage debris cover but also a greater range of debris cover.

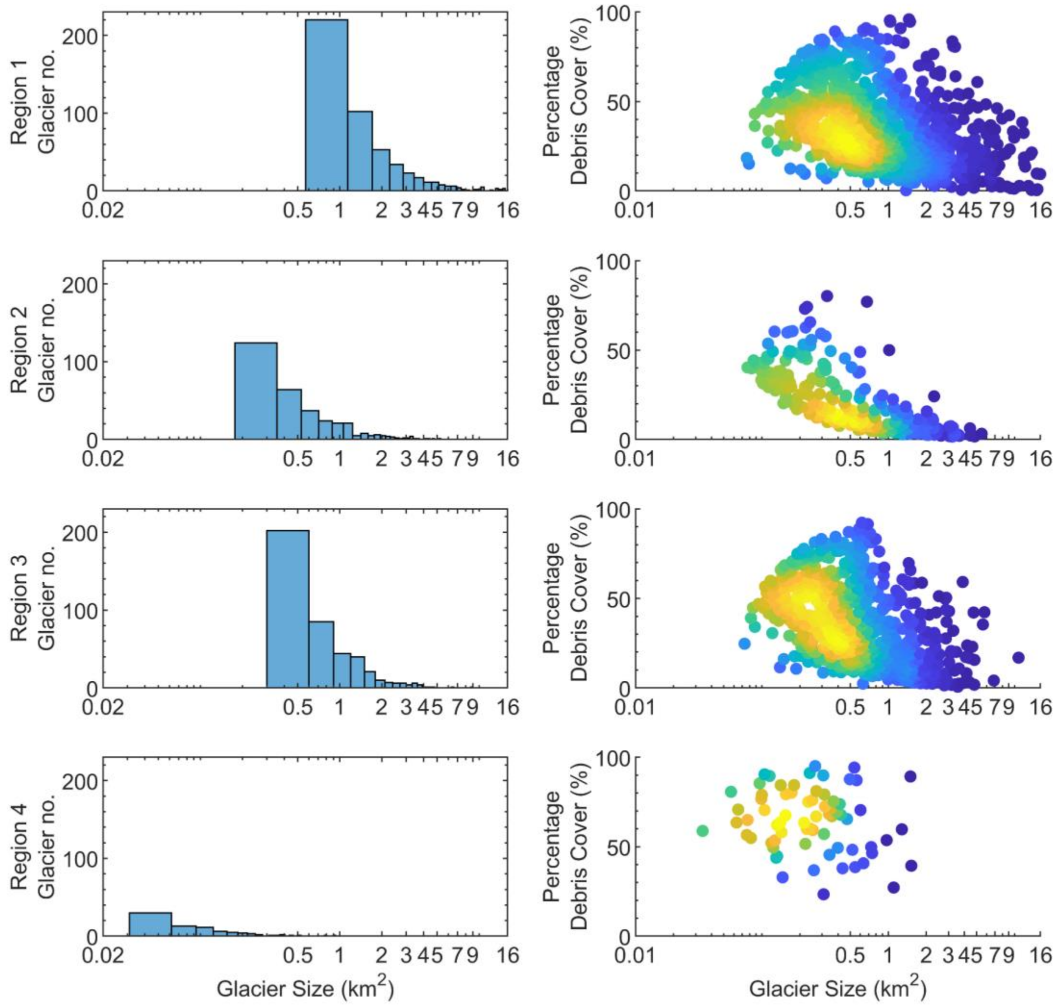

Figure III-6 Description of glacier number by glacier area and plots of percentage debris-covered ice against glacier size for each geographical region show in Figure III-1.

Median aspect ratio of glaciers at four sub glacier regions in Afghanistan showed orientation towards the northeast and northwest (Figure III-14, Supplementary Material).

III.4.3 Drivers of debris cover based on PCA-based analysis

The initial attempt to identify controls on debris cover fractions considers the complete glacier database. The PCA identified five principal components (PCs) that represented 72% of the original dataset (Table III-5). Only components with significance loadings were included in the stepwise regression. The latter used percentage debris-covered ice as the dependent variable (Table III-5) which had a resultant R^2 of 43.7%.

Table III-5 Loadings of each original variables (all dataset) on each principal component with more than 5% contribution to the variance of the original data. Important variables are flagged in bold (correlations >0.7 or <-0.7).

Loadings (all dataset) R^2= 43.7 %	**PC1**	**PC2**	**PC3**	**PC4**	**PC5**
Catchment Area	**0.760**	0.379	-0.225	0.337	0.252
Catchment Mean Slope	-0.021	0.063	0.590	-0.351	-0.153
Glacier Length	0.454	***0.639***	-0.405	0.235	0.401
Glacier Width	0.335	0.367	-0.204	**0.840**	0.028
Debris Influence Area	**0.975**	0.145	-0.095	0.108	-0.059
Mean Altitude	0.029	0.413	0.037	0.034	0.019
Elevation Range	0.356	**0.900**	0.005	0.233	-0.061
Glacier Slope Mean	-0.097	0.158	**0.883**	-0.120	-0.088
Geological Hardness Grade	-0.045	-0.060	0.207	0.014	0.028
Explained Variance (%)	*22.0*	*19.1*	*16.0*	*12.0*	*2.9*
PC added	*/*	*1*	*3*	*2*	*/*
Coefficient		-0.095	0.066	-0.087	
pValue		0.00	0.00	0.00	

Note: Data in Bold typeface are identified with correlations >0.7 or <-0.7
(/) indicates variable is not entered into the stepwise regression

There are 6 variables that contribute to the PCs (Table III-5) and each PC is then labeled based on these contributions (Table III-6). The first most important component identified in the regression was PC2 which is associated with variables that describe glacier length and elevation range. It explained 19.1 % of the original data and was negatively associated with percentage debris cover. Thus, larger glaciers with greater elevation ranges tend to have lower percentage debris-covered ice. The second most important component ranked was PC4, which represented glacier width and which explained 12 % of total variability in original data (Table III-6). This suggests that wider glaciers have lower percentage debris-covered ice. The third most important component ranked was PC3, which represented glacier/catchment slope parameters and which explained 16 % of the total variability in the original data (Table III-6). The sign of association suggests that steeper glaciers are more prone to higher percentage debris-covered ice. PC1 that corresponds to catchment size explained 22% of total variability in the original data but was not included in the stepwise regression.

Table III-6 PCA results based on the complete dataset. Rows are sorted vertically by importance of contribution to the stepwise regression model. N indicates no PC identified with this interpretation. / indicates not added to the stepwise regression.

Interpretation of the PC	% of original data explained by PC	Loading sign	Sign of association in Stepwise Regression	Order of addition to Stepwise Regression (Rank)
PC2. Glacier Length and Elevation Range	19.1%	+	-	1
PC4. Glacier Width	12.0%	+	-	2
PC3. Glacier/Catchment Slope	16.0%	+	+	3
PC1. Catchment Size	22.0%	+	/	/
PC5. Glacier Altitude	N			

Given the possibility of strong spatial dependence in these analyses associated with broad-scale regional controls (e.g. climate, geology), it is possible that analysis of the entire dataset masks underlying drivers of debris cover. Thus, we undertook the same analysis but by climate zone and geological region. The Table III-10 and Table III-11in Supplementary Material contains the full results and we only present summary tables here.

A consistency and coherence in terms of the sign of the association of individual PCs and debris cover was found in general for all datasets whether classified by climate or geology; although there were some differences, such as in the details of the variables that contributed to each component.

For all climate zones, the PC that is associated with glacier length and elevation range is ranked as the most or second most important component (Table III-7). PCs associated with glacier width are ranked as the second or third most important component. They are negatively associated with percentage debris cover through all climate zones and suggests that longer and wider glaciers have less debris-covered ice. Glacier altitude is ranked as the most important in climate zones 2 and 4 and the fourth most important component in climate zone 1, but is not significant in zones 3 and 5. Glacier altitude is negatively associated with percentage debris cover, suggesting higher altitude glaciers have proportionately less debris-covered ice. The glacier/catchment slope component is positively associated with debris cover in all climate zones, ranked as the second most important component in zone 3, the third most important component in zones 1, 4 and 5, and the fourth in zone 2. The sign suggests that steeper ice and catchment slopes lead to greater percentage debris cover. Catchment size in zones 2, 3 and 4 was not included in the stepwise regression. However in zone 1 it was ranked the fifth most important component with a positive association; and in zone 5 it was ranked as the fourth most important component with a negative association. The positive sign of association suggests that bigger catchment areas have higher percentage debris cover. However, the negative sign of association may be due to the fact that catchment size is also related to glacier length, width, and elevation range parameters. This indicates that longer and wider glaciers are associated with larger catchments, and therefore negatively associated with percentage debris-covered ice.

Table III-7 PCA results based on climatic zone classifications. N indicates no PC identified with this interpretation. / indicates not added to the stepwise regression.

Interpretation of the PC showing the sign of the loading on each variable	% of original data explained by PC	C Z1 R^2= 52%		% of original data explained by PC	C Z2 R2= 58%		% of original data explained by PC	C Z3 R2= 55%		% of original data explained by PC	C Z4 R^2= 48%		% of original data explained by PC	C Z5 R^2= 67%	
		Associatio n	Rank		Association	Rank		Association	Rank		Associatio n	Rank		Associatio n	Rank
Glacier Length (+)and Elevation Range (+)	21	-	1	26	-	1	21	-	1	12	-	2	19	-	1
Catchment Size (+)	17	+	5	/			/			/			27	-	4
Glacier Width (+)	6	-	2	6	-	2	7	-	3	N			11	-	2
Glacier Altitude (+)	10	-	4	//	-	1	/			15	-	1	N		
Glacier/Catchment Slope (+)	16	+	3	15	+	4	20	+	2	18	+	3	14	+	3

C Z1: Climate Zone 1 (Arid, desert, cold)
C Z2: Climate Zone 2 (Arid, steppe, cold)
CZ3: Climate Zone 3 (Cold, dry summer, hot summer)
C Z4: Climate Zone 4 (Cold, dry summer, hot summer, Monsoonal Influence)
C Z5: Climate Zone 5 (Temperate, dry summer, hot summer)

Table III-8 shows the results when glaciers are classified into the six geological categories. This classification leads to higher levels of explanation (R^2) for some classes as compared with modelling using the full dataset or divided into climatic zones. It suggests that the assumed linear ranking of resistance to erosion used for the full dataset does not represent geological effects well and that once divided into geological zones, geological controls on debris production are represented more effectively. As with the significant majority of the preceding analyses the principal component that represents glacier length and elevation range is ranked as the first most important in zones 2, 3, 5, and also first but combined with catchment size in zone 6. It is ranked the second most important in zones 1 and 4. The associations with debris cover remain negative. The component representing the glacier width ranked the most important in zone 1 and second in zones 2 and 3, whereas it combined with the variables glacier length and elevation range for other zones and with negative associations.

Components representing catchment size were the fourth most important in zones 2 and 3. In zone 4 the debris influence area in the catchment was ranked as the third most important component. In these three cases there was positive association. In zone 6 and zone 4 (catchment area only) combined with glacier length, width, and elevation range and there were negative association signs. These indicate that glaciers with bigger debris influence areas also tend to have higher percentage ice-covered debris while larger catchments do not necessarily have bigger debris influence areas and are more influenced by glacier length, width, and elevation range. The principal component that represents variables relating to glacier/catchment slope is ranked third in geological zones 2, 3, and 5 but is not identified for other zones. The positive association with debris cover suggests that glaciers, and their catchments, with steeper slopes tend to have higher percentage ice-covered debris in certain geological zones. The principal component associated with glacier altitude appears only for geological zone 4, and is the most important component, and with a negative sign of association.

Table III-8 PCA results based on glacier geological zones. N indicates no PC identified with this interpretation. / indicates not added to the stepwise regression.

Interpretation of the PC	% of original data explained by PC	Geo Z1 R^2 = 51%		% of original data explained by PC	Geo Z2 R^2 = 54%		% of original data explained by PC	Geo Z3 R^2 = 52%		% of original data explained by PC	Geo Z4 R^2 = 79%		% of original data explained by PC	Geo Z5 R^2 = 54%		% of original data explained by PC	Geo Z6 R^2 = 63%	
		Association	Rank		Association	Rank		Association	Rank		Association	Rank		Association	Rank		Association	Rank
Glacier Length (+) and Elevation Range (+)	18	-	2	23	-	1	20	-	1	43	-	2	26	-	1	45	-	1
Catchment Size (+)	24	/		24	+	4	26	+	4				26	/				
Width (+)	22	-	1	11	-	2	10	-	2	N			9	-	2			
Glacier Altitude (+)	N			N			N			15	-	1	N			N		
Glacier/Catchment Slope (+)	20	/		20	+	3	20	+	3	16	/		17	+	3	N		

Geo Z1: Geological Zone 1 (Chemical organic)
Geo Z2: Geological Zone 2 (Detrital Sedimentary)
Geo Z3: Geological Zone 3 (Igneous)
Geo Z4: Geological Zone 4 (Igneous and Detrital Sedimentary)
Geo Z5: Geological Zone 5 (Metamorphic)
Geo Z6: Geological Zone 6 (Metamorphic and Igneous)

III.5 Discussion

III.5.1 Indices of glacier debris cover

Glaciers in the Himalaya are commonly associated with debris-laden ice avalanches and rockfall onto glacier surfaces from steep surrounding slopes (Shroder et al., 2000; Kaushik et al., 2019). Thus, mapping glacier extent and its change through time needs to take into account debris-covered ice. Paul et al. (2015) have reported that errors involved in mapping glaciers can be significant when glaciers are heavily debris-covered and that this is a major challenge for glaciological studies (Shukla et al., 2010; Paul et al., 2015). The complex physical characteristics of debris-covered ice makes it difficult to map with optical remote sensing (Holobâcă et al., 2021). Most studies are limited to small geographical regions and where only a small number of glaciers (<5) are analyzed (Robson et al., 2015; Kaushik et al., 2019).

Inventories also exist with more specific region-based calibration but these have tended to focus on glaciers >1km^2 in size (e.g. Scherler et al., 2018; Herreid and Pellicciotti 2020; Fleischer et al., 2021). In this study, a combination of two thermal indices showed encouraging results for remote sensing of debris-covered ice over a spatially extensive zone. Whilst Lougeay (1974) argued that thicker layers of debris may weaken TIR signals, field data for the Mir Samir Glacier clearly show that signals could be captured under thicker debris cover, even if the maximum depth that can be measured was not established in this study. It emphasizes the value of continued research with thermal infrared data, and necessary downscaling methods.

As is standard practice, our NIR and SWIR datasets were corrected for top of the atmosphere effects. However, such correction introduced more noise into the thermal based debris cover index and coarsened the resolution of the outputs (Figure III-11, Supplementary Materials). Thus, we did not correct the thermal band used in (1) for TOA effects. We can justify the lack of correction in three ways. First, we note that converting TIR DNs to TOA is a linear correction process that should not make much difference and which is also undertaken because it is dependent on local meteorological data that are themselves highly uncertain especially in remote regions (USGS, 2022). Second, using non atmospheric corrected imagery at high altitudes appears to have minimal influences on mapping (Bishop et al., 2000) and other researchers have obtained better results and transferability using DNs for mapping glaciers (Bhambri et al., 2011; Haireti et al., 2016). Third, we undertook checks by comparing the DN-TOA relationships for different images (Supplementary Material). These showed very little variation in the range of ToA values used for image thresholding, suggesting our index is likely less sensitive to ToA variations and the index thresholds should be transferable. By extending validation to multiple glaciers within Afghanistan and beyond might require ToA correction due to use of images obtained at different times/dates. However, even without ToA correction we did not find a clear pattern of degradation in accuracy statistics (Table III-3), and the threshold for identifying debris-covered ice seemed to transfer without further calibration. We nonetheless suggest that this conclusion is checked if this index is applied elsewhere.

Most of the TIR signals suggesting debris-covered ice were associated with igneous rocks (mainly granite and granodiorite) less prone to weathering and leading to coarser and likely drier surface debris. In our case, we identified a second situation where the TIR signal was absent but it was clear that there was debris-covered ice. The second index (2) was crucial for glaciers whose geology was associated with detrital sedimentary rocks, more readily weathered and leading to smaller grain-sizes and a wetter surface. This is an important finding for debris-covered ice mapping from remote sensing, but one that needs further testing.

As with other studies (e.g. Stewart et al., 2021; Herreid, 2021), the real challenge with developing new indices such as ours is obtaining data for calibration and/or validation and calibration suggested that the classification thresholds were important. We found that using a relatively low threshold for the debris cover indices increased the commission error, but using a relatively high threshold increased the omission error (Wang et al., 2020). Therefore, selecting an optimal threshold is still a challenging task. A weakness of this study is having field observations from only one glacier; but the remoteness of glaciers in Afghanistan combined with on-going security problems makes this a challenge. That said, the transferability of the threshold we optimized from field-based calibration to other glaciers (Table III-3) is reassuring. The combination of TIR with panchromatic imagery was central to allowing us to map glaciers much smaller than those typically mapped by others using remote sensing. For instance, Herreid and Pellicciotti (2020) set a minimum glacier size as 1 km^2 and Scheler et al. (2018) obtained poorer mapping accuracies for glaciers less than 1 km^2. Figure III-6 shows that Afghanistan's glaciers are mainly smaller than 1 km^2. Figure III-3 also shows that our indices produce greater extents of debris-covered ice than in published inventories. The presence of crevasses and ponds in these zones confirms that these enlarged zones are indeed ice-cored. The zones tend to be somewhat irregular and also contain holes, commonly where glacier retreat has left exposed bedrock patches, rather than debris-covered ice. This corresponds to the fact that debris-covered ice in High Mountain Asia tends to have a complex morphology and hummocky, rugged topography (Miles et al., 2020).

The identification of more extensive zones of debris-covered ice in our index largely explains why our accuracy statistics are better (Table III-3) but these also emphasizes a key point. Our goal was to map debris-covered ice, and not simply debris-cover on glaciers. Rapid glacier retreat is likely leading to extensive debris-covered ice that may become progressively disconnected from the glacier. Whether such zones are included as "glacier" or not is a debatable point. In our case, with a long-term goal of understanding glacier retreat for Afghan water resources, our interest is in debris-covered ice whether or not it remains connected to the glaciers. Thus, we do not argue that our approach is better, rather that it is more appropriate if the scientific goal is mapping debris-covered ice rather than debris cover on glaciers.

III.5.2 The glacier inventory

We identified 3,408 glaciers ($\geq$ 0.01 km^2) covering 2,841±51.1 km^2 in area using datasets for 2016. Maharjan et al. (2018) identified 3,782 glaciers ($\geq$ 0.01 km^2) with 2,539 km^2 of area for 2015. One year is not enough for these differences to be real and we think that they arise because Maharjan et al. (2018) used the normalized difference snow index (NDSI) for glacier mapping and a single slope threshold for mapping debris-covered ice. The larger number of glaciers then relates to the fact that they considered glaciers with size ≥ 0.01 km^2; and underestimation of glacier area corresponds to the fact that the NDSI could not detect zones of glaciers under shadow as well as ice covered by thicker debris. In addition, the slope threshold of <24°, used by Maharjan et al. (2018), may not detect debris cover when the glacier tongue transition to the unglaciated zone is gentle (Paul, 2003; Bolch and Kamp, 2005; Frey et al., 2012).

This study estimated 619 ± 40 km^2 of debris-covered ice for Afghanistan and a total debris cover as a percentage of glacier area of around 22%. This is higher than for south-west Asia as a whole (Herreid and Pellicciotti, 2020) but it also masks substantial within-region variation (Table III-4) of between 8% and 42% debris cover. It also reflects the fact that we consider debris-covered ice and not just debris-covered glacier.

III.5.3 Controls on debris cover

Assessment of debris-cover development on Afghan glaciers by principal component analysis showed that considering all glaciers in a single analysis masked sensitivity to certain drivers. Dividing the dataset into two classes based on climate zones and geological zones produced more clear findings. Components that represented variables related to glacier length, width, and elevation range were uniformly found to be highly important, with bigger glaciers (in terms of length/width) inevitably having a higher range, and less debris-covered ice.

Components associated with glacier mean altitude were only found to be important for certain climate zones, notably zones 2 and 5 (Table III-7), for geological zone 4 (Table III-8). The importance of altitude no doubt reflects the fact that the lower glaciers are more ablation prone and so more prone to accumulating debris, as others observed (e.g. Fleischer et al., 2021). However, the relative lack of importance of altitude-related as compared with size-related components, and the relatively low correlation of altitude with width (r=0.281) and length (r=0.233) emphasizes that altitude is not a primary driver of the extent of debris cover in Afghanistan.

Geology was rarely correlated with significant principal components for the full dataset. However, separating by geological zones resulted in sets of principal components that explained higher proportions of debris cover (Table III-8) and clearer and consistent results across zones in terms of the association between components their most correlated variables and debris cover. Few studies have investigated lithological controls on rockfalls and glacier debris cover at regional scales, and data are usually not available for larger areas (Marquinez et al., 2003; Messenzehl et al., 2017; Fleischer et al., 2021). Geological drivers of differences in debris-cover development on glaciers merit further work.

Globally, the relative percentage of debris cover areas systematically decreases from 14% to 0% as glacier size increases although this pattern is not the same for all the regions (Scherler et al., 2018). We found a similar association, albeit with a higher percentage debris cover variation (between 0 and 80 %) (Figure III-6). Huang et al. (2021) suggested a latitudinal variation with the regional percentage of debris cover a negative exponential function of distance from the equator, implying that warmer climatic zones are more dynamic and conducive to supraglacial debris production. However, orographic factors such as mountain-range, age, relief and lithology may cause regional-scale exceptions to this relation (Herreid and Pellicciotti, 2020).

Chowdhury et al. (2021) observed that a relatively gentle slope with lower elevations in ablation areas could be favorable for the abundant accumulation of supraglacial debris. However, for all climate zones and geological zones (Table III-7, 8) whilst it is clear that low slopes encourage debris accumulation, our results suggest that steep slopes can lead to high debris cover likely because of their impacts on sediment production.

III.6 Conclusion

Using field observations and manual glacier maps, we developed two new indices to map glaciers and debris-covered ice in Afghanistan with promising results. During the mapping process, we were able to distinguish between different debris-covered ice in terms of their geological formations and thermal characteristics. The result of the mapping was a new glacier inventory for Afghanistan. Our analysis, based on 3,408 glaciers, showed that Afghan glaciers are highly debris-covered, at 21.7±1.4 % of total glacier area, although this varies regionally; regions with smaller glaciers tend to have higher percentage debris cover. The characteristics of glaciers in Afghanistan, and their debris cover, are dependent on climate and geology. Debris cover is predominantly affected by measures of glacier length, width, and elevation range; higher values of these measures tend to be associated with glaciers with less debris cover. Catchment size effects are complex and vary by region. The proportion of non-glacier area in a catchment appears to an important influence on debris cover development. Drier climate tend to produce higher debris cover as do glaciers in geological zones with more readily-weathered sediment.

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III.7 Supplementary Materials

III.7.1 Available approaches to map debris-covered glaciers in remote regions and their challenges

Table S1 reviews approaches to glacier debris cover quantification. Geomorphological mapping of glacier debris cover in complex mountain environments is difficult (Bishop et al., 2001), the accuracy of the resulting maps is highly dependent on the expertise of the image analyst and their visual interpretation (Paul et al., 2004; Bhambri et al., 2011; Kaushik et al., 2019), and it is labor and time intensive for large regions.

The geomorphometric characteristics of satellite-derived DEM data may indicate the presence of debris-covered glaciers. For instance, researchers (e.g. Paul, 2003; Paul et al., 2004; Bolch and Kamp, 2006; Shukla et al., 2010; Bhardwaj et al., 2014) have used slope thresholds under the assumption that above a certain slope (the critical slope angle for debris movement), debris will not accumulate. This may be problematic in some regions, such as where the transition from a glacier margin to an unglaciated region is gentle but still relatively debris free (Paul, 2003; Bolch and Kamp, 2006). In addition, no detectable change in surface slope may occur at the interface between clean-ice and debris-cover (Bhambri et al., 2011); post-depositional sedimentation by mass movement, a commonly found process in the polygenetic environment of the Himalayas (Benn and Owen, 2002; Bhambri et al., 2011), may cause confusion (Bhambri et al., 2011); and the available data may not have the right resolution (Bolch and Kamp, 2006; Racoviteanu et al., 2009).

More advanced approaches seek to combine satellite imagery with DEM data and more sophisticated automated classification methods. For instance, neural networks or Fuzzy C Mean clustering classifications gave good results for different types of debris cover (Bishop et al., 1999), but the long processing times associated with them may limit their applicability over large areas (Racoviteanu et al., 2009). Bishop et al. (1999) report errors with such classification approaches where white ice was sometimes classified as shallow debris and/or thick debris, and shallow debris was sometimes classified as thick debris. Atwood et al. (2010) and Racoviteanu and Williams (2012) applied decision tree algorithms and texture analysis combining DEM and thermal data to map debris cover. They concluded that the sophisticated and laborious processing of a decision tree prevents a completely automated process for delineating debris-covered glacier tongues. Moreover, this method requires several post-processing steps (e.g. digital terrain analysis) to achieve reliable results (Bhambri et al., 2011). Recently, researchers used high resolution photogrammetric mapping using drone surveys based on DEM differencing and manual feature tracking to map debris-covered ice (Robson et al., 2015). Whilst, this method provides very accurate results it is labor intense, costly, and not applicable over large regions, especially for inaccessible glaciers (Immerzeel et al., 2014).

Researchers (Scherler et al., 2018; Herreid and Pellicciotti 2020; Fleischer et al., 2021) used the proportion of near infrared (NIR) and shortwave Infrared (SWIR) to map debris cover on glaciers. However, they encountered misclassification of snow and ice as debris (Fleischer et al., 2021), the maximum mapping accuracy in this method corresponds to threshold values that reduce the debris cover to a minimum insufficient image coverage to map debris cover (Scherler et al., 2018) or an over estimation can be observed (Fleischer et al., 2021). This method could not map thicker debris and ice-cored debris although this index is usually well-suited for mapping clean ice (Paul et al., 2002; Taschner and Ranzi, 2002; Paul, 2003; Paul et al., 2004; Bolch and Kamp, 2006; Shukla et al., 2010; Bhardwaj et al., 2014). Given that many methods exist, inter-comparison is important. Racoviteanu et al. (2009) considered a number of semi-automated approaches for mapping debris-covered glaciers that coupled morphometric analysis (slope-based) with thermal information, a neural network algorithm and concluded that there is no single optimal algorithm for debris-cover mapping that can be applied to large regions without some manual correction of resulting outlines. Such progress aside, delineation of debris-covered glaciers remains a major problem for rapid, automated inventorying of glaciers from satellite data (Paul et al., 2004; Bolch and Kamp, 2006; Bolch et al., 2008; Shukla et al., 2010). In global scale assessment, there are challenges in mapping debris cover glaciers more precisely, suitable image selection is time-consuming especially when summer snow falls, a very short event could bury supraglacial debris cover quickly in accumulation areas. There are more uncertainties with small glaciers (<1 km2) if there is a mismatch between the time of glacier delineation and debris-cover mapping once the glacier has changed its extent. On the other hand, selecting the best index for mapping ice and debris cover is another main challenge. Motivated by a need to map glacier cover over the Afghan Hindu Kush, where debris cover is common, and given the above review, this paper seeks to develop two indices that can be applied to: freely-available data sets; that yield sufficient spatial resolution for mapping of valley-confined glaciers; and that could be used for long-term analyses so as to quantify change.

Sentinel satellite imagery has good spatial resolution for spectral bands but lacks thermal information and long-term datasets. ASTER has a better spatial resolution for the thermal band but data were not always available both spatially and temporally for Afghanistan. Thus, we used Landsat imagery and we explain the bases of these indices below.

Table III-9 (Table S1 in the article): A review of glacier mapping studies

Methodology	Reference	Parameters	Data Input	Processing flow	Remarks
Manual delineation	Stokes et al. (2007)	Clean Ice and Debris-covered Ice	Landsat TM and ETM+, a false-color composite of bands 5, 4, 3 (red, green, blue)	Manual digitizing	Accuracy is extremely dependent on the expertise of the image analyst and individual's visual interpretation. Moreover, it is time consuming and labor intensive to apply to a large number of glaciers (Paul et al., 2004; Bhambri et al., 2011; Ghosh et al., 2014; Kaushik et al., 2019).
Automatic or Semi-automated method	Bishop et al. 2001	Clean Ice and Debris-covered Ice	DEM	Geomorphometric based	1. Requires high resolution DEMs for better accuracy that are not always available (Bolch and Kamp, 2006; Racoviteanu et al., 2009); furthermore, issues associated with data modeling and an object-oriented approach are still debated 2. DEM-based methods require intense user interaction by specialists (Paul et al., 2004) 3. The geomorphometric-based method fails in mapping a debris-covered glacier when the glacier tongue transition to the unglaciated zone is gentle (Bolch and Kamp, 2006).
	Shukla et al. 2010	Clean Ice and Debris-covered Ice	Thermal image - IRS-P6 AWiFS and Optical image - TERRA-ASTER	Geomorphometric and optical based: 1. TM4/TM5 2. DEM (aspect and slope), Debris-covered ice based binary Slope <15	
	Paul et al. 2004; Paul 2003; Bolch and Kamp 2005; Veettil 2012; Bhardwaj et al. 2014	Clean Ice and Debris-covered Ice	Landsat Thematic Mapper (TM) DEM	Combination of Geomorphometric, optical, and thermal based: 1. TM4/TM5 2. TIR 3. Debris-covered ice based on Slope 1-24 ratio	
	Bhambri et al. 2011; Bolch et al. 2007	Clean Ice and Debris-covered Ice	ASTER - digital elevation model (DEM) and thermal	1. ASTER3/ASTER4 2. ASTER - thermal 2. DEM-morphometeric parameters (Slope, profile curvature, plan curvature	
	Bishop et al. 1999	Clean Ice and Debris-covered Ice	SPOT Panchromatic data Sentinel-2 imagery	Artificial neural network (ANN) technology	1. This method results in rapid and good quality maps of clean- and debris-covered ice but still errors occur due to existence of shadow, cloud cover, and seasonal snow in the imagery (Bolch and Kamp, 2006; Frey et al., 2012; Kaushik et al., 2019).

			using texture, topographic, and spectral data		2. Neural networks or Fuzzy C Mean clustering classifications may provide more accurate results, especially for various types of debris cover (Bishop et al., 1999), but the long processing time may limit their applicability over large regions (Racoviteanu et al., 2009)
	Atwood et al. 2010; Robson et al. 2015	Clean Ice and Debris-covered Ice	Advanced Land Observing Satellite (ALOS) Phased Array L-band SAR (PALSAR)	Decision tree Object-Based Image Analysis (OBIA)	1. This method requires several post-processing steps (e.g. digital terrain analysis) to achieve promising results (Bhambri et al., 2011). 2. SAR coherence data require expertise knowledge and expensive software in order to be processed (Frey et al., 2012)
	Racoviteanu and Williams 2012	Clean Ice and Debris-covered Ice	ASTER - digital elevation model (DEM) and thermal	1. Decision tree 2. Texture analysis	1. These methods are sophisticated but require heavy processing; the decision tree prevents a completely automated process for delineating debris-covered glacier tongues. 2. The texture approach is limited by the fact that while debris-cover training areas (ROIs) may have distinctive texture values, these values or patterns may not be characteristic for all the debris cover across a region (Racoviteanu and Williams, 2012).
	Paul et al. 2002	Clean Ice	Landsat Thematic Mapper (TM) data and a digital elevation model (DEM)	Optical based: TM4/TM5	Distinguishing the supraglacial debris (SGD) on the glacial surface and periglacial debris (PGD) appearing outside the glacier boundary has been recognized as a major constraint due to similar surface reflectance (Shukla et al., 2010; Paul et al., 2015; Kaushik et al., 2019).
	Taschner and Ranzi 2002	Clean Ice and Debris-covered Ice	Landsat Thematic Mapper (TM)	Thermal and optical based: TM4/TM5 Thermal band: TIR	The infrared radiometer may not record the thermal gap between pure debris and thicker debris superimposed on ice, the thicker debris layer may lead to a thermal insulation of the cooling ice (Taschner and Ranzi, 2002).
	Immerzeel et al. 2014	Clean Ice and Debris-covered Ice	Unmanned Aerial Vehicle (UAV)	Based on DEM differencing and manual feature tracking	This method provides more accurate results but it is labor intense, costly, and not applicable for large regions, and glaciers that are inaccessible (Immerzeel et al., 2014)
	Fleischer et al. 2020	Clean Ice and Debris-covered Ice	Landsat Thematic Mapper (TM) data and a digital elevation model (DEM)	NIR/SWIR	This index misclassifies the snow/ice as debris. This method is not able to map thicker debris and ice-cored debris while usually well suited for mapping clean ice (Paul et al., 2002; Taschner and Ranzi, 2002; Paul, 2003; Paul et al., 2004; Bolch and Kamp, 2006; Shukla et al., 2010; Veettil, et al., 2014; Bhardwaj et al., 2014).

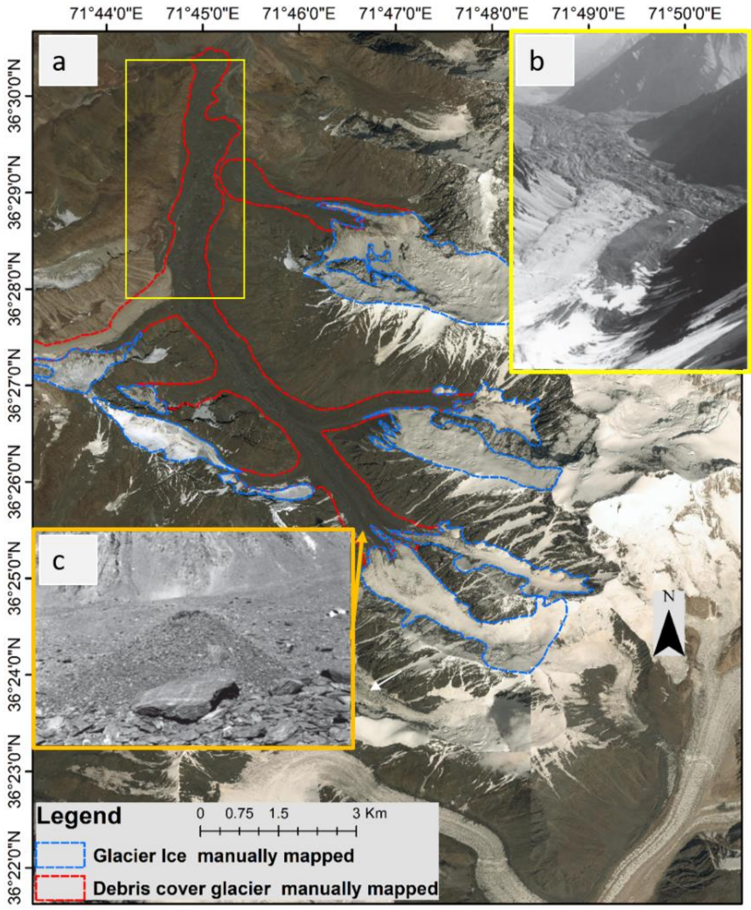

Figure III-7 (Fig. S1 in the article): Noshaq Glacier range (Figure III-1); 3a shows the 0.29 m RGB image in background (MoMP, 2020), with red lines showing the manually-mapped debris-covered ice extent and blue lines the manually-mapped ice extent. The view shown in Figure S1b (B. Ehmann) is bounded by the yellow box shown in 3a and shows the terminus of the debris-covered Qadzi Deh Glacier and, in the foreground, the Rakhe Kuchek Glacier, covered in part by lighter-colored debris. 3c shows argillite-covered glacier ice at an elevation of about 5,075 m on the Qadzi Deh Glacier (7,492 m) (Shroder, 1980).

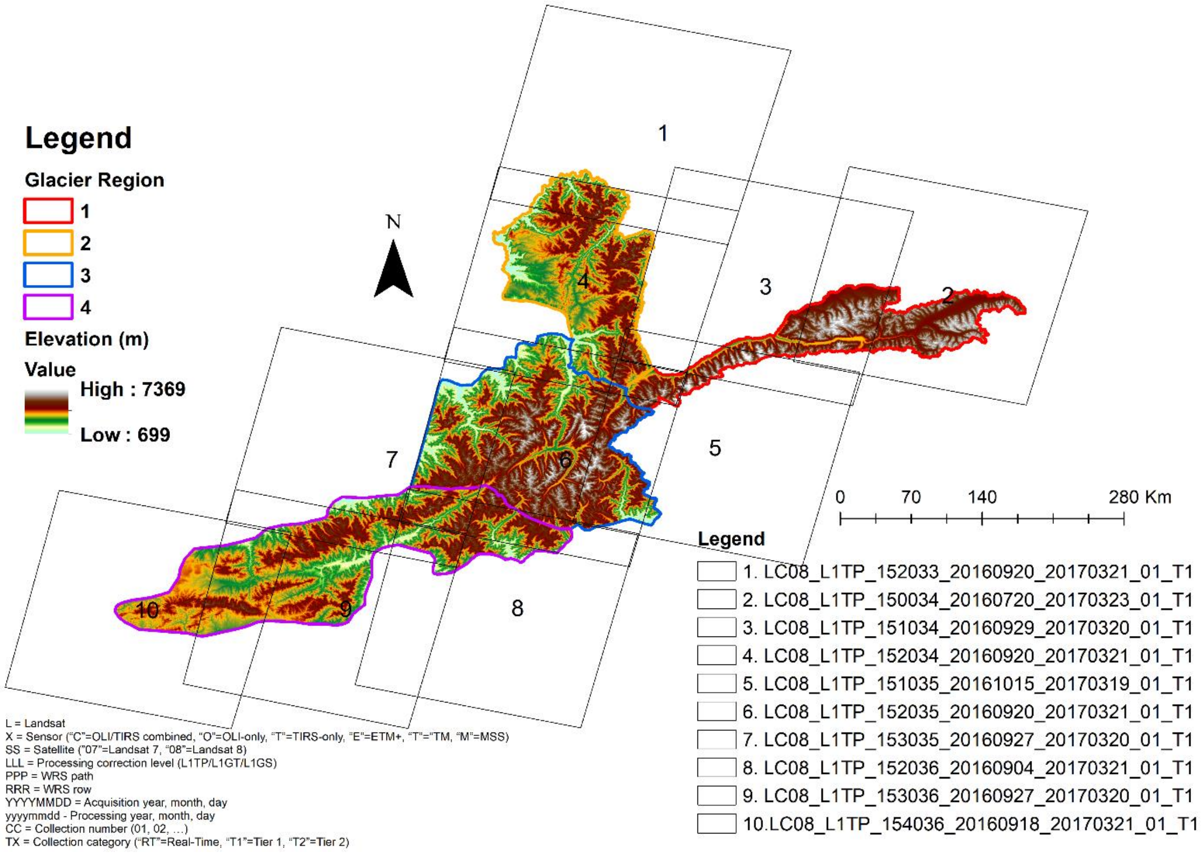

Figure III-8 (Fig. S2 in the article): Landsat image tile used for the study with details of date that images were obtained.

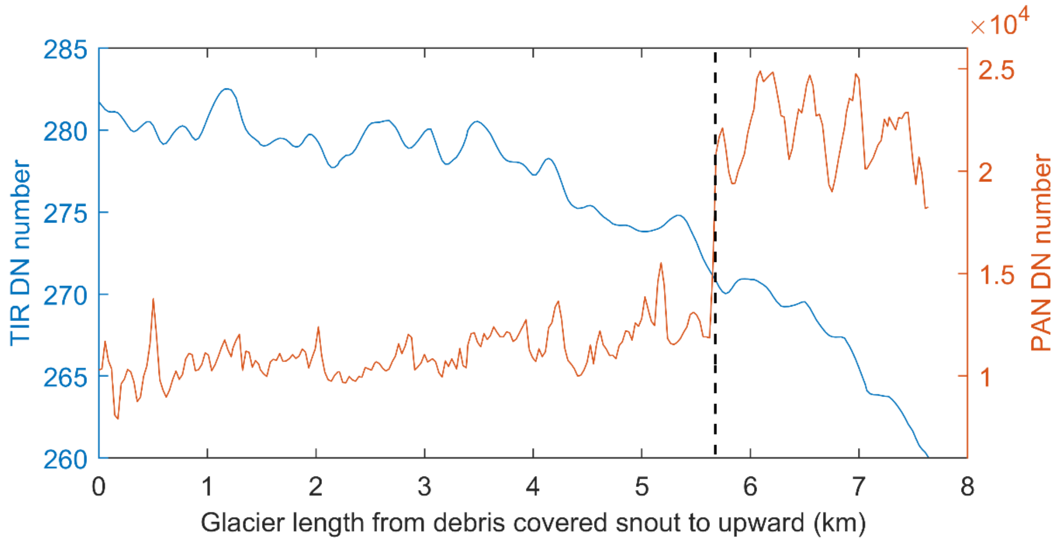

Figure III-9 (Fig. S3 in the article): Sectional profile of TIR and PAN band information for the Keshnikhan glacier (Figure III-1), the TIR and PAN profile were drawn across the centerline of the glacier and are based on pixel values; the crossing point illustrated by the dashed black line is the transition point between debris cover and clean ice.

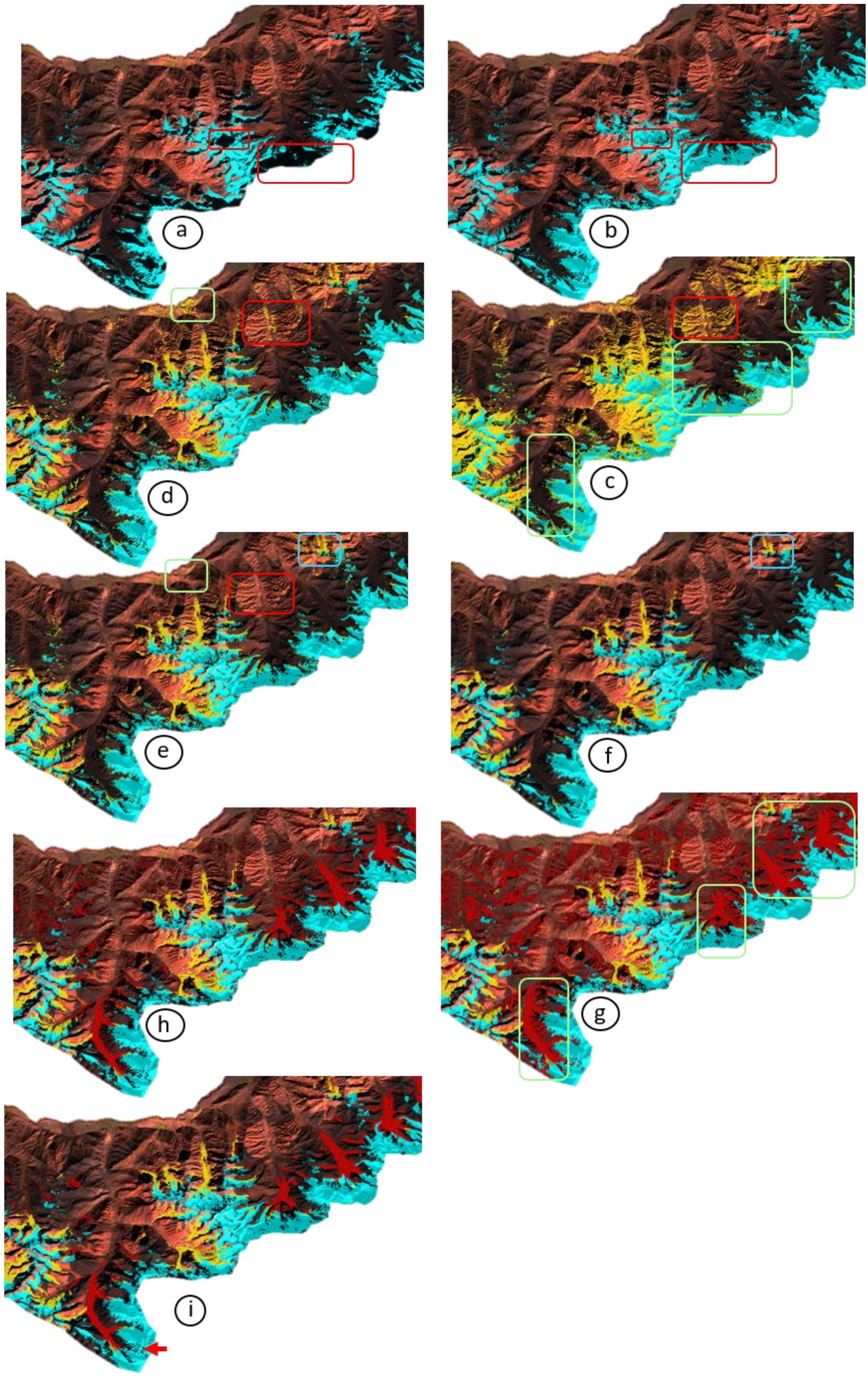

Figure III-10 (*Fig. S4 in the article): Illustration the effects of each step in Figure 2; a through i refer to labels in Figure 2. a. indicates that the index for clean ice mapping did not detect the ice area under* *shadow (red boxes). b. illustrates that the results improved after atmospheric correction was performed. c. shows that the debris-covered C1 index mapped debris-covered ice but missed zones for a range of glaciers shown in green boxes, as well as misclassified zones in the red box. d. using slope threshold slope>37° removed the misclassifications in the red box, while still misclassified lower elevation zones shown in the green box. e. an elevation and an area threshold removed those misclassifications, while still some misclassifications remained, shown in the blue box f. a second slope threshold slope>24o removed those misclassifications. g. shows the second index for debris- covered ice C2 was applied and the missing debris area mapped (green boxes). h. Slope, elevation, and the area threshold applied to debris-covered glacier C2. i. the second slope threshold slope >24o is applied to remove remaining misclassifications and the results improved, red arrows showing the snow-cover area mapped as ice that is manually removed.*

III.7.2 Top of Atmospheric Reflectance and Digital Number effect on indices

We examined the differences in debris cover raster based on the calculation of the index (eq. 1 main manuscript) using original bands with DNs and bands with TOA correction. The test was performed on MirSmir glacier. Figure S5 shows that the DNs for 2016 and 2020 followed a typical pattern of glacier retreat, the 2020 DN line decreased in the snout and was stable in the middle and slightly increased near to the glacier. On the other hand, the index calculated using the TOA bands was of coarser spatial resolution and has a noisier signal.

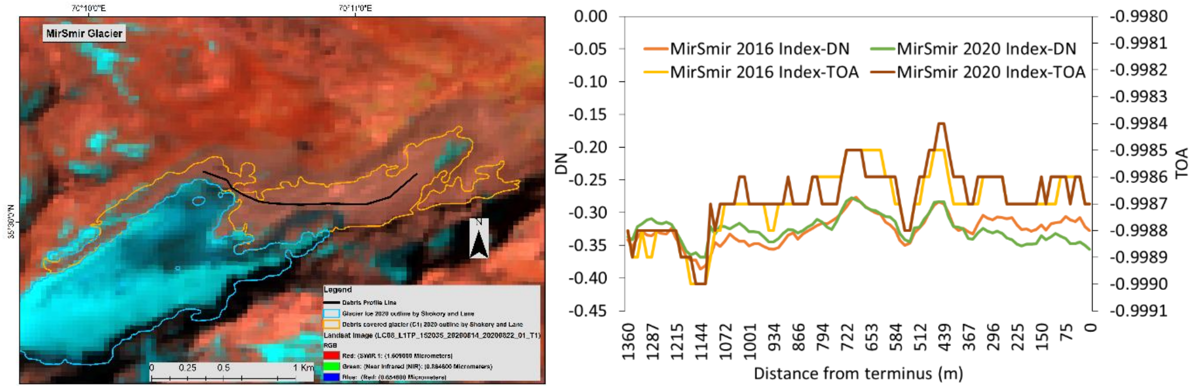

Figure III-11 (Fig. S5 in the article): Image shows MirSmir glacier with glacier outlines for 2020, black line is the debris profile shown in the graph.

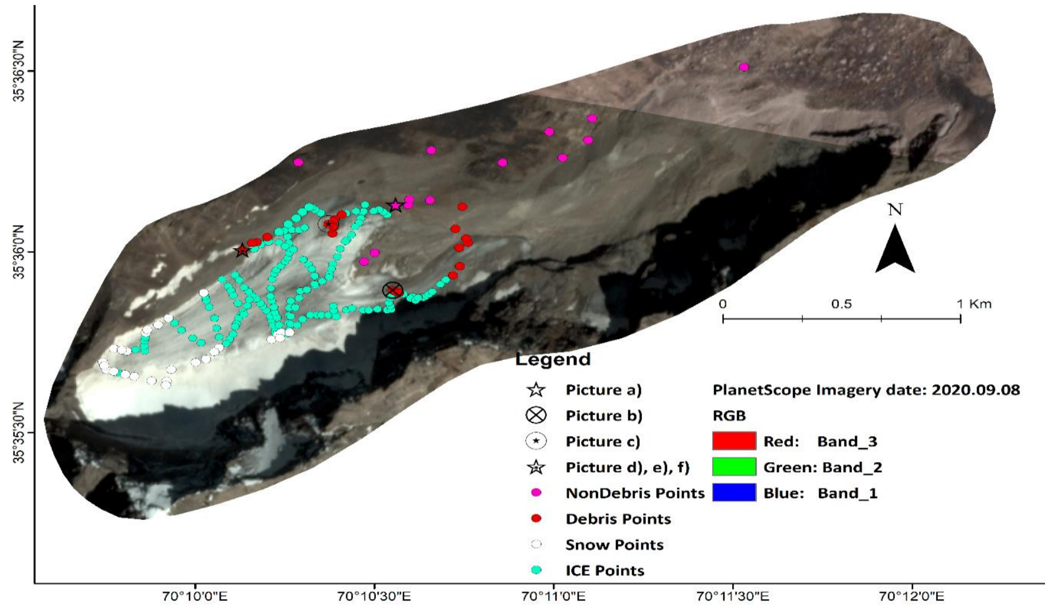

Figure III-12 (Fig. S6 in the article): Mir Samir Glacier, background is 3 m resolution RGB image of PlanetScope imagery captured just three days after the fieldwork.

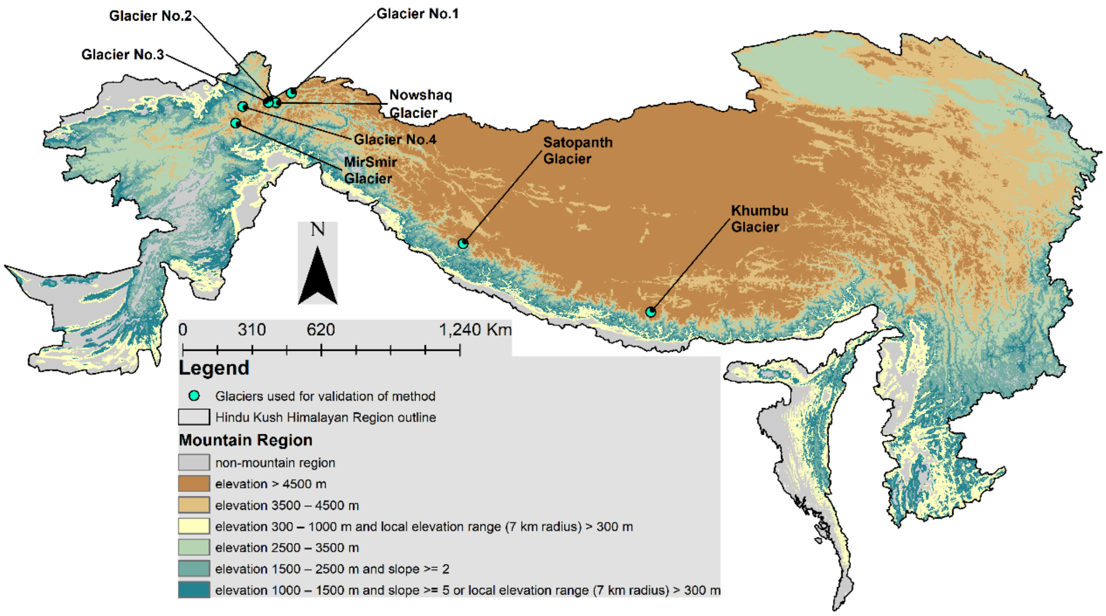

Figure III-13 (Fig. S7 in the article): Location map of the glaciers used for validation, background map is the elevation map of Himalayan region (ICIMOD 2022).

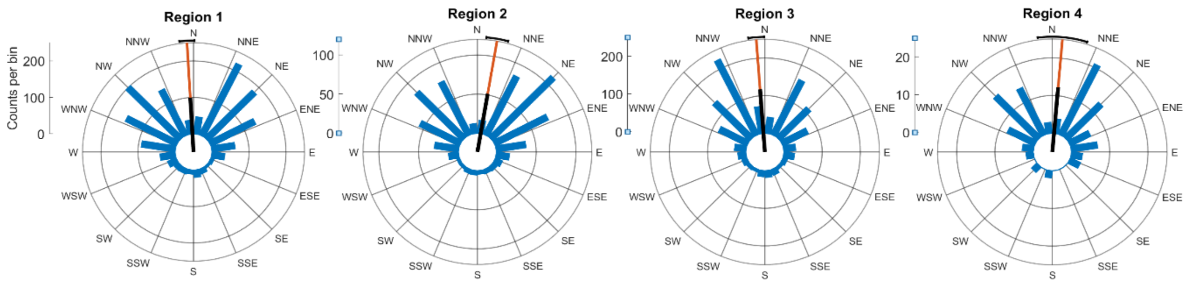

Figure III-14 (Fig. S8 in the article): Median aspect ratio of glaciers at 4 sub glacier regions, the black bar is the mean aspect.

Table III-10 (Table S2 in the article): Loadings of each original variables based on climatic zones on each principle component.

PCA loadings based on climate classification	**Loadings (Climate Z1) R^2= 52.4 %**					**Loadings (Climate Z2) R^2= 57.7 %**					**Loadings (Climate Z3) R^2= 54.9 %**				
Variables	PC1	PC2	PC3	PC4	PC5	PC1	PC2	PC3	PC4	PC5	PC1	PC2	PC3	PC4	PC5
% of original data explained by PC	21.2	17.0	15.7	9.8	6.3	26.3	23.4	15.2	11.4	5.5	21.4	20.8	19.6	12.8	7.3
Catchment Area	0.557	**0.747**	-0.299	0.053	0.186	0.469	**0.821**	-0.267	-0.091	0.149	0.522	-0.261	**0.776**	0.033	0.225
Catchment Mean Slope	-0.119	-0.064	**0.687**	-0.014	-0.235	0.013	-0.183	**0.661**	-0.089	-0.178	-0.020	**0.821**	-0.036	0.124	-0.138
ICE Length	**0.803**	0.421	-0.403	0.098	0.043	**0.799**	0.506	-0.312	-0.060	-0.003	**0.833**	-0.395	0.368	0.061	0.087
ICE Width	0.512	0.360	-0.367	0.031	**0.684**	0.504	0.538	-0.236	-0.045	**0.627**	0.390	-0.501	0.234	-0.068	**0.730**
Debris Influence Area	0.280	**0.842**	-0.121	0.061	0.097	0.205	**0.835**	-0.044	-0.084	0.091	0.264	0.004	**0.928**	0.084	0.044
Mean Elevation	0.298	-0.069	-0.103	**0.936**	0.119	**0.658**	0.094	0.329	-0.186	0.114	0.113	0.031	0.022	**0.946**	0.059
Elevation Range	**0.846**	0.294	-0.013	0.145	0.222	**0.863**	0.369	0.160	-0.108	0.155	**0.836**	0.054	0.311	0.201	0.187
ICE Slope Mean	-0.101	-0.177	**0.827**	0.081	0.039	0.086	-0.030	**0.755**	0.000	0.060	-0.154	**0.842**	-0.070	0.093	-0.085
Geological Hardness Grade	-0.019	0.043	0.042	0.251	-0.020	-0.163	-0.106	-0.077	**0.975**	-0.015	0.033	0.092	0.040	0.424	-0.048
PC rank	1	5	3	4	2	1	/	4	3	2	1	2	/	/	3
Coefficient	-0.10	0.03	0.05	-0.04	-0.07	-0.14		0.03	-0.06	-0.06	-0.10	0.07			-0.05
pValue	0.00	0.00	0.00	0.00	0.00	0.00		0.00	0.00	0.00	0.00	0.00			0.00

PCA loadings based on climate classification	**Loadings (Climate Z4) R^2= 47.8 %**					**Loadings (Climate Z5) R^2= 66.7 %**				
Variables	PC1	PC2	PC3	PC4	PC5	PC1	PC2	PC3	PC4	PC5
% of original data explained by PC	25.7	17.5	15.4	11.6	8.4	26.9	18.6	14.2	11.5	5.1
Catchment Area	**0.894**	-0.144	0.222	0.326	-0.045	**0.905**	0.284	-0.065	0.278	0.074
Catchment Mean Slope	-0.045	**0.723**	0.155	-0.166	-0.230	-0.129	0.101	0.472	-0.137	0.471
ICE Length	0.458	-0.305	0.371	**0.738**	-0.101	0.514	**0.820**	-0.149	0.123	-0.107
ICE Width	0.484	-0.216	0.611	0.121	0.570	0.393	0.241	-0.173	**0.863**	0.095
Debris Influence Area	**0.944**	-0.003	0.057	0.105	-0.188	**0.961**	0.060	-0.013	0.181	0.187
Mean Elevation	0.049	0.075	**0.666**	0.145	-0.182	-0.091	0.601	-0.137	0.061	0.322
Elevation Range	0.396	0.211	0.585	0.559	0.105	0.474	**0.678**	0.184	0.370	0.034
ICE Slope Mean	-0.082	**0.917**	-0.074	0.083	0.368	0.010	-0.163	**0.972**	-0.064	-0.074
Geological Hardness Grade	-0.110	0.040	-0.074	-0.022	0.385	-0.105	-0.030	0.021	-0.048	-0.249
PC rank	/	3	1	2	N	4	1	3	2	N
Coefficient		0.06	-0.11	-0.09		-0.03	-0.15	0.05	-0.12	
pValue		0.00	0.00	0.00		0.00	0.00	0.00	0.00	

Table III-11 (Table S3 in the article): Loadings of each original variables based on geological classifications on each principle component.

PCA loadings based on geological classifications	**Loadings (Geo Z 1) R^2= 50.8 %**					**Loadings (Geo Z 2) R^2= 53.6 %**				
Variables	PC1	PC2	PC3	PC4	PC5	PC1	PC2	PC3	PC4	PC5
% of original data explained by PC	23.5	21.9	20.5	17.8		24.0	23.3	20.3	11.5	
Catchment Area	**0.788**	0.384	-0.145	0.443		**0.828**	0.449	-0.192	0.267	
Catchment Mean Slope	0.000	-0.191	**0.757**	-0.125		-0.014	0.067	**0.767**	-0.256	
ICE Length	0.359	0.359	-0.242	**0.824**		0.491	**0.782**	-0.345	0.153	
ICE Width	0.249	**0.936**	-0.110	0.210		0.411	0.306	-0.283	**0.807**	
Debris Influence Area	**0.952**	0.203	-0.103	0.191		**0.842**	0.193	0.085	0.147	
Mean Elevation	0.108	0.448	-0.065	0.165		0.098	0.485	0.272	0.028	
Elevation Range	0.343	0.562	0.129	**0.650**		0.326	**0.819**	0.234	0.296	
ICE Slope Mean	-0.180	0.056	**0.973**	0.017		-0.049	0.110	**0.814**	0.013	
PC rank	/	1	/	2		4	1	3	2	
Coefficient		-0.155		-0.073		0.032	-0.104	0.067	-0.094	
pValue		0.00		0.01		0.00	0.00	0.00	0.00	

PCA loadings based on geological classifications	**Loadings (Geo Z 3) R^2= 52.1 %**					**Loadings (Geo Z 4) R^2= 79.3 %**				
Variables	PC1	PC2	PC3	PC4	PC5	PC1	PC2	PC3	PC4	PC5
% of original data explained by PC	26.3	19.5	19.3	9.6		43.0	20.0	16.7	14.4	
Catchment Area	**0.852**	0.368	-0.287	0.226		**0.811**	0.522	-0.201	0.075	
Catchment Mean Slope	-0.063	-0.033	**0.682**	-0.225		-0.334	-0.516	0.466	-0.444	
ICE Length	0.513	**0.711**	-0.466	0.100		**0.901**	0.228	-0.232	0.235	
ICE Width	0.370	0.383	-0.372	**0.757**		**0.877**	0.070	-0.274	0.302	
Debris Influence Area	**0.899**	0.109	-0.048	0.114		0.167	**0.963**	-0.175	0.096	
Mean Elevation	0.015	0.343	0.011	0.034		0.422	0.123	0.148	**0.809**	
Elevation Range	0.391	**0.802**	0.019	0.260		**0.919**	0.131	-0.028	0.353	
ICE Slope Mean	-0.126	-0.003	**0.799**	-0.004		-0.205	-0.205	**0.947**	0.122	
PC rank	4	1	3	2		2	3	/	1	
Coefficient	0.023	-0.116	0.068	-0.081		-0.126	0.091		-0.145	
pValue	0.00	0.00	0.00	0.00		0.00	0.00		0.00	

PCA loadings based on geological classifications	**Loadings (Geo Z 5) R^2= 53.7 %**					**Loadings (Geo Z 6) R^2= 63.0 %**				
Variables	PC1	PC2	PC3	PC4	PC5	PC1	PC2	PC3	PC4	PC5
% of original data explained by PC	26.4	26.1	16.7	9.2		44.6	9.2	7.9	6.7	
Catchment Area	**0.846**	0.441	-0.130	0.262		**0.788**	0.125	0.476	0.354	
Catchment Mean Slope	-0.006	-0.041	**0.698**	-0.012		-0.021	-0.010	-0.211	0.008	
ICE Length	0.529	0.418	-0.257	**0.689**		**0.901**	-0.012	0.015	0.356	
ICE Width	0.398	**0.894**	-0.183	-0.060		**0.905**	-0.347	0.230	-0.046	
Debris Influence Area	**0.894**	0.257	-0.006	0.111		**0.634**	0.387	0.549	0.376	
Mean Elevation	0.132	0.495	0.128	0.176		-0.051	0.064	-0.001	-0.356	
Elevation Range	0.362	**0.762**	0.269	0.380		**0.956**	0.281	0.017	-0.035	
ICE Slope Mean	-0.094	0.155	**0.802**	-0.057		0.021	0.602	0.056	-0.103	
PC rank	/	1	3	2		1	N	N	N	
Coefficient		-0.114	0.059	-0.074		-0.147				
pValue		0.00	0.00	0.00		0.00				

IV GLACIER RETREAT AND DEBRIS COVER EVOLUTION IN THE AFGHANISTAN HINDU KUSH HIMALAYA (AHKH), BETWEEN 2000 AND 2020

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This chapter presents estimated changes in glaciers for both bare ice and debris-covered ice in Afghanistan for two timespans (2000-2008) and (2008-2020) using the methodology which was developed in the previous chapter. Further, it discusses the spatial changes in glaciers, considering different scales and the glacier sizes. Consequently, glaciers with different sizes showed a different response to the current warming. Additionaly, glacier changes were considerably different for different geographical regions.

Abstract

Glaciers in Afghanistan are crucial elements of water resource supply, sustaining summer river flows for both agriculture and water supply. They are also potentially threatened by rapid climate warming. This study presents an up-to-date, country-wide assessment of glacier change for the entire country during the 21st century using a newly-developed remote sensing index that includes a more reliable determination of changing debris cover. We focus on two periods, 2000-2008 and 2008-2020 and compare the national scale results with regional and sub-regional responses. The results suggest an estimated glacierised area of 2684±100.7 km^2 in 2020, that was 75±0.7 % clean ice and 25±3.0 % debris-covered ice. Total glacier area retreated by 4.5±0.5 km^2 yr^{-1} (-0.15±0.01 % yr^{-1}) between 2000 and 2008 and 12.3±1.5 km^2 yr^{-1} (-0.43±0.05 % yr^{-1} between 2008 and 2020). Almost 60% of the loss of glacier surface area (2000-2020) related to glaciers with a size ≤ 2.5 km^2, which accounted for 60 % of the total glacier area in the year 2000. Minimum glacier ice elevation increased for both 2000 to 2008 and 2008 to 2020 (+2.70 m yr^{-1}; +1.72 m yr^{-1}; respectively) and the maximum ice elevation declined (-4.63 m yr^{-1}, and -1.57 m yr^{-1}). This indicates that glaciers not only experienced retreat in the ablation zone but also,via reduced accumulation and increased mass loss in the accumulation zone. However, the analysis revealed substantial spatial variation in these retreat rates based upon geographical region, glacier size and climate region. In the eastern regions which are geographically close to or part of the north-west Karakoram, retreat rates were either substantially lower, even stable or advancing slightly, as compared with the northern and central regions of Afghanistan.

IV.1 Introduction

Glaciers play a crucial role in the hydrological cycle (Viviroli et al., 2003; Kaser et al., 2010; Sorg et al., 2012), notably in arid environments where they provide water in summer when it is most needed for irrigation (Hagg et al., 2007; Sorg et al., 2012). Global warming is leading to glacier retreat and enhanced summer runoff in the short-term, forecast to continue until glaciers become small enough that this "glacial subsidy" ends and summer runoff is reduced (Rees and Collins 2006; Scherler et al., 2011). At the end of the 20th century, glaciers covered c. 30,000 km^2 or about 17% of the HKH (Ahmad et al., 2004). A decline and eventual end of glacier melt in this region is likely to impact water supply to the 1.3 billion people living downstream (HKH, Williams 2013; Wahid et al., 2014; Quincey et al., 2018; Rowan et al., 2018; Pritchard, 2019). Although the dependence on glacier melt of these communities is greatest for those people in river basins with lower annual rainfall (notably those not affected by the South Asian summer monsoon) a globally significant number of people may be impacted by glacier retreat (Wahid et al., 2014; Pritchard, 2019; Chowdhury et al., 2021). For this reason, quantifying and explaining glacier change in the HKH is of paramount importance.

This poses a number of challenges. First, the response of HKH glaciers to climate change is regionally complex (Wiltshire 2014; You et al., 2017). Large-scale generalisations may overlook within-region differences in glacier mass balance and runoff which in turn may cause regional differences in water resource impacts. For instance, the eastern-most sites of the Himalaya are strongly influenced by the Indian and southeast Asian summer monsoons. Ice accumulation tends to be driven by summer precipitation (Fujita 2008). Towards the northwest (the Pamirs, the Hindu Kush and the Karakoram), the climate is dominated by westerly air masses and glaciers are of more of the winter-accumulation type. Monsoon-type glaciers are expected to be more sensitive than winter-accumulation type glaciers due to a likely rise in the rain/snow limit driven by an increase in temperature (Fujita 2008). This shift may be exacerbated by an albedo feedback if reduced summer snow accumulation on glaciers then reduces summer albedo and so enhances melt (Gardelle et al., 2013). Thus, whilst it has been observed that most HKH glaciers retreated during the last century (Kulkarni and Bahuguna 2002, Dobhal et al., 2004, Hansen et al., 2005; Prasad et al., 2009; Bhambri and Bolch 2009; Pandey et al., 2011) there is substantial within-HKH variation in the response of glaciers to climate warming. Continuous retreat has been reported in the Central Himalaya (with an average retreat rate of 5.5–8.7 m yr^{-1}, 1966-2002; Ren et al., 2004, 2006); and for 65% of monsoon-influenced glaciers in the greater Himalaya (between 2000 and 2008; Scherler et al., 2011). In contrast, westerly rainfall-influenced glaciers in the same region advanced or were stable in more than 50% of cases (Scherler et al., 2011; Azam et al., 2018). This emphasizes the need to consider regionally-variable climate influences when quantifying climate warming impacts on HKH glaciers.

Second, HKH glacier response may be conditioned by the development of extensive glacier debris cover. Glaciers in the Himalaya are often debris-covered, notably in their ablation areas, associated with large volumes of ice avalanche and rock fall onto glacier surfaces from steep surrounding slopes (Shroder et al., 2000; Bolch et al., 2007; Bhambri et al., 2011; Gardelle 2013). Globally, 7.3% of mountain glacier areas are debris-covered rising to 12.6% in at the scale of south-west Asia (Scherler et al., 2018; Herreid and Pellicciotti 2020). Knowledge of debris cover distribution on glaciers is important as glacier retreat tends to be most rapid for glaciers without debris cover (Marzeion et al., 2012; Radìc et al., 2014; Huss and Hock, 2015; Hock et al., 2019; Marzeion et al., 2020; Anderson et al., 2021). Although a complex process (Nicholson and Benn, 2012; Gibson et al., 2017), debris accumulation alters the surface energy balance (Anderson and Mackintosh 2012; Collier et al., 2015) an effect that is strongly dependent on its thickness (Scherler et al., 2018; Kraaijenbrink et al., 2017; Mölg et al., 2018; Nie et al., 2021). Up until a few centimeters thick, debris cover reduces albedo and so enhances melt (Østrem 1959; Kayastha et al., 2000; Nicholson and Benn 2006; Kaab et al., 2012; Reid and Brock, 2014; Evatt et al., 2015; Pratap et al., 2015; Anderson and Anderson, 2016; Vincent et al., 2016). Above a certain thickness, debris cover begins to insulate the ice (Østrem 1959). Debris extent and thickness is dynamic in time and space (Scherler et al., 2018; Mölg et al., 2018; Nie et al., 2021). Substantial debris cover development may extend the lifespan of glaciers as water resources (Lardeux et al., 2016; Zhang et al., 2019), an issue that has not been fully addressed in studies on future water resources or glacier lifetimes (Zemp et al., 2006; Bates et al., 2008; Farinotti et al., 2016; Shannon et al., 2019). Information on debris extent needs to be included in large-scale glacier inventories (Kraaijenbrink et al., 2017; Mölg et al., 2018).

Third, there is increasing evidence that glacier response to climate change can be influenced by more local factors. It appears that smaller glaciers (<1 km^2) are losing a higher percentage of area than larger glaciers for the same time period, whereas longer valley glaciers covered with thick debris appear to be losing area more slowly (Racoviteanu et al., 2014). Chowdhury et al. (2021) investigated glacier evolution in in the Sikkim Himalaya, India and found that maximum glacier area loss takes place for glaciers with lower terminus elevations and on the lower slopes of large valley glaciers compared to other glaciers. They found that debris-covered glaciers are losing ice more slowly but that the extent of debris-cover effects depends on supraglacial debris supply. The latter appears to have broad regional variations; Chapter III quantified geographical variation in debris cover for Afghanistan glaciers and found that that debris cover development was not only related to glacier size but also broad-scale climatological and geological influences.

Given these three complexities, a comprehensive and methodologically consistent sub-regional analysis on glacier changes over the HKH in the early 21st century is so far missing (Brunner et al., 2019). Here, we focus on Afghanistan in the north western HKH. The aim of our study is to make use of a new method for deriving glacier inventories from remotely-sensed data that explicitly quantifies both bare and debris-covered ice (Chapter III) to quantify the regional patterns of ice loss and debris cover development in Afghanistan. The study uses datasets compiled for three dates (2000, 2008, and 2020) to test the following hypotheses:

1. Despite only covering a small percentage of the HKH region (11.3%) the complexity of Afghanistan's mountain regions are such that there can be substantial variation in glacier response to climate warming.
2. Development of debris cover in response to negative mass balance is reducing the sensitivity of Afghan glaciers to climate change through time.
3. Glacier size effects interact with local climate variability to drive the complexity of glacier response to climate change.

With the impact of climate change glaciers are not only experiencing snout retreat but also reductions in accumulation and/or increased down valley flux but this response is locally variable depending on the existing distribution of ice mass with altitude.

IV.2 Study focus: Afghanistan

Afghanistan is a mountainous country (Figure IV-1) with arid and semi-arid continental climates, characterized by temperature and precipitation regimes characteristic of deserts, steppe and highland environments (Humlum et al., 1959; Shroder, 2014). A combination of conflict and political tensions has made field-based research difficult, long-term monitoring almost non-existent and the curation of datasets describing glacier response to climate change very rare. Glacier down-wasting and retreat was more intensively observed until about 25 years ago (Shroder and Bishop 2010; Bishop et al., 2014). Only one glacier in Afghanistan, the Mir Samir located in the northeastern part of the country, has ever had any mass balance work done on it (in 1965), and it has now down-wasted so much that it has divided into two distinct ice masses (Bishop et al., 2014). Maharjan et al. (2018) initiated the first updated glacier inventory of Afghanistan with assessment of changes between 1990 and 2015 using remote sensing. They found that over a 25 years period, glacier cover decreased by 13.4% with an average loss of 5.4% per decade. However, this work did not undertake a systematic study of how both ice and debris-cover is changing in Afghanistan, nor did it report sub-regional variations on glacier response.

Glaciers in Afghanistan are primarily centered on the north-east of the country (Figure IV-1) and here we consider glaciers in four regions defined in Figure IV-1; (1) north-eastern, (2) northern, (3) center-north, and (4) center-west, the regions are categorized based on its geographical locations and climates (Chapter III), . The fourth region, the most westerly, contains only a very small glacier coverage and is not considered further in this paper. Within these regions, we also identified sub-regions based on the difference in elevation range that separated by valleys (Figure IV-1).

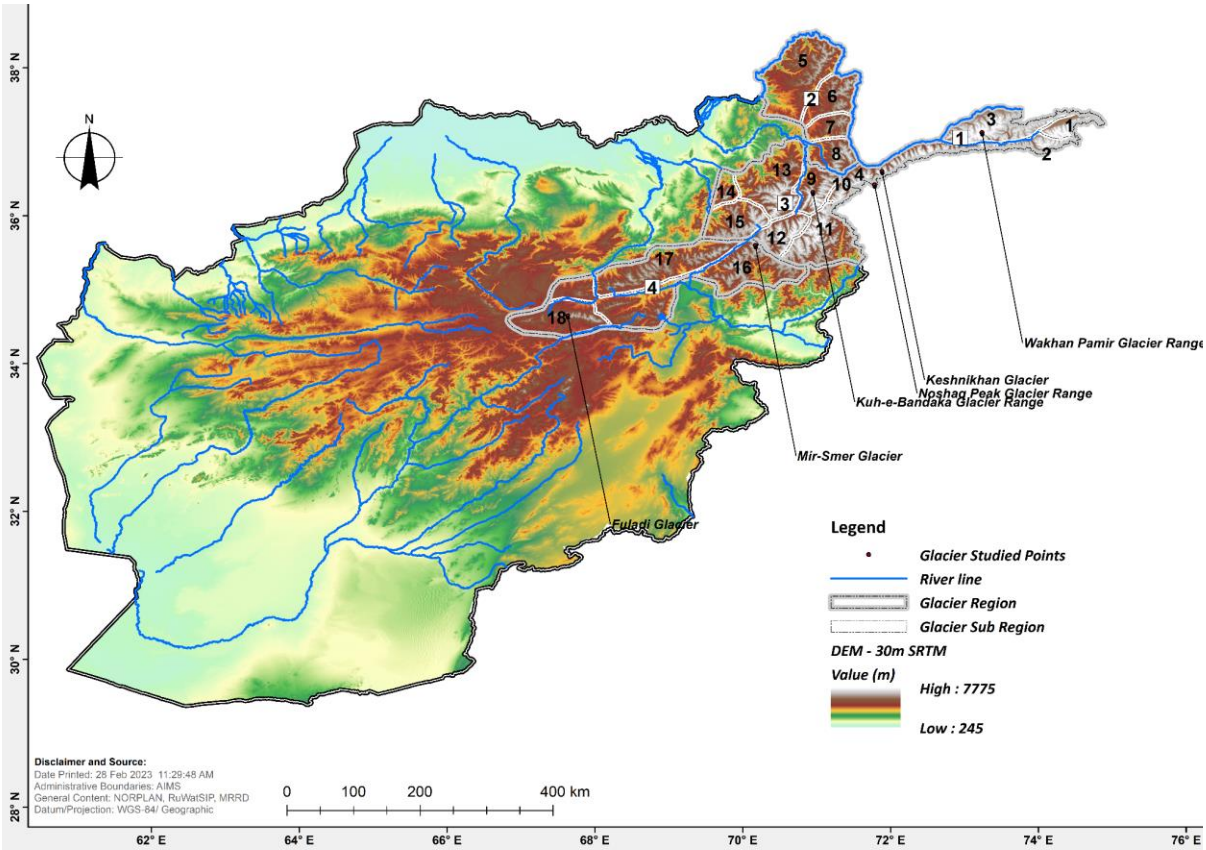


Figure IV-1 Elevation map of Afghanistan with determined glacier sub regions. The numbers in the box refer to the four main regions 1 - eastern, 2 - northern, 3 - central and 4 - western. Numbers from 1-18 refers to the sub regions.

IV.3 Materials and Methods

This paper applies the indices developed by Chapter III to simultaneously determine ice and debris-covered-ice. Chapter III developed and tested these indices with field data, published glacier outlines and additional outlines manually-digitised from high resolution imagery using Landsat imagery for 2016.

Moreover, they used the associated glacier inventory to describe the broad geographical controls on the distribution of ice and debris-covered ice. This paper applies the same methods but to a sequence of dates; 2000, 2008, and 2020. The three dates studied reflected the availability of data in the ablation season, the need to minimize cloud coverage, and the spatial coverage of all glaciated regions. To summarise the Chapter III approach (Figure IV-2), there was no segmentation but uses pixel based approach for the mapping process. The Landsat 7 swath gaps was filled using ENVI v5.1 software, the method used single file gap fill triangulation approach (https://yceo.yale.edu/how-fill-gaps-landsat-etm-images). For mapping clean ice we used the NIR to SWIR band ratio that allows ice to be detected including under shadow (Paul et al., 2002; Taschner and Ranzi, 2002; Paul, 2003; Paul et al., 2004; Bolch and Kamp 2005; Shukla et al., 2010; Veettil, 2014; Bhardwaj et al., 2014). A band ratio threshold of ≥ 3 was used to define clean ice. Two types of debris-covered glaciers are mapped based on two different indices. The first is a thermal index which is based upon combination of thermal (TIR) and panchromatic (PAN) bands. The principle behind this combination is that the TIR band is most likely to allow identification of debris-covered glaciers mainly with igneous and metamorphic geology. However, the TIR band is coarse (100m). The PAN band is 15 m and, whilst theoretically less sensitive to thermal properties, it provides a means of downscaling the coarser TIR band to the resolution needed for mountain valley glaciers (eq. 1). In this paper, a range of 0 to -0.37 is used to define debris-covered ice (Chapter III).

$$Normalized\ Difference\ Supraglacial\ Debris\ Indix\ (NDSDI_{c1}) = \frac{PAN - TIR}{PAN + TIR} \qquad (1)$$

Second, the NIR to Blue band index was used (eq. 2) for the second class of debris-covered glaciers, with no TIR signal (at a specific threshold range) and commonly covered by detrital sedimentary rocks (mainly sandstone, siltstone, argillite, shale) (Chapter III):

$$Normalized\ Difference\ Supraglacial\ Debris\ Index\ (NDSDI_{c2}) = \frac{NIR}{Blue} \qquad (2)$$

Debris-covered ice was defined for the range 0.70 to 0.92 as used by Chapter III.

Tests of the accuracy of these indices gave a 98% overall accuracy, and a 0.92 Kappa coefficient (Chapter III).

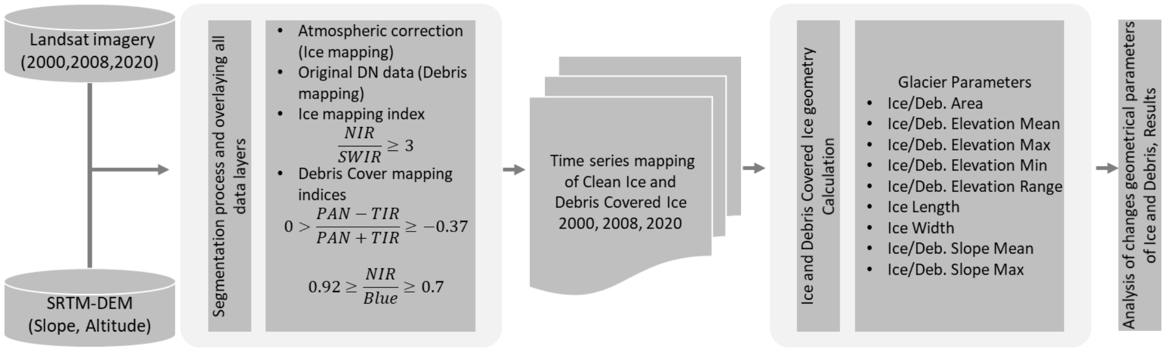


Figure IV-2 Methodological workflow used in this study.

The workflow uses Landsat data obtained from USGS website http://earthexplorer.usgs.gov/ (the list of all Landsat scenes used in this study is provided as supplementary material Table IV-2). The bands used were; blue-B2, near infrared (NIR)-B5, shortwave Infrared (SWIR)-B6, panchromatic (PAN)-B8, and thermal (TIR)-B10. The B2 and B5 bands have 30 m resolution, the B8 band 15 m resolution, and the B10 band 100 m resolution (downscaled to 30 m by provider). Glacier elevation and slope characteristics were extracted from digital elevation models (DEM), varying in resolutions of 5 m, 10 m, and 30 m resolution according to region. The 5 m and 10 m resolution DEMs were obtained from Ministry of Agriculture Irrigation and Livestock of Afghanistan (MAIL 2020) and the 30 m DEM was obtained from ALOS global digital surface model https://www.eorc.jaxa.jp/ALOS/en/aw3d30/index.htm.

This paper focuses on glacier change for two time periods 2000-2008 and 2008-2020. For change detection, we mapped glaciers onto 2,409 watersheds that were delineated in an ArcGIS framework. As glaciers can change shape and area rapidly through time, using watersheds allowed a watershed analysis that accounted for fragmentation of single glaciers as they retreated. Watersheds were then grouped into 18 sub-regions (Figure IV-1) and basic statistics (mean, minimum, maximum) were calculated. We used the omission and commission errors (±1% for clean ice and ±12% for debris-covered ice) as proportional uncertainties followed the data quality assessment reported in Chapter III. A second source of uncertainty was associated with glaciers covered by cloud or smaller than the Landsat image SWOT gap area for images between 2000 and 2008. Thus, there were zones with frequent snow cover and covered by clouds was not considered during mapping in any year (2000, 2008, and 2020) compare to Chapter III (further in the discussion section). However, smaller snow patchs that incorrectly mapped, were removed with a size filter of 0.01 km^2. Then, snow attached to glaciers was manually removed after visual inspection, and in some regions a different scene (with less snow but possibly more clouds) was chosen to improve results (Mölg et al., 2018). Cloud-free scenes were available for most of the study region while in the few cases we used additional scenes from years close to the inventory years (Paul et al., 2017; Mölg et al., 2018). Glacier changes within the ±2 years difference to the target year are likely within the uncertainty of the glacier outlines and should thus not matter (Mölg et al., 2018) (supplementary material Table IV-2).

IV.4 Results

IV.4.1 Afghanistan-scale changes in total glacier cover, clean-ice and debris-covered ice

We mapped a total glacier area of 2869 ± 98 km^2 (including glaciers greater than 0.01 km^2 in size) in the year 2000 (Table IV-1). This had decreased by 36.4±4.9 km^2 to 2008 and by 148.7±4.5 km^2 to 2020 (Table IV-1). The latter suggests a marked increase in retreat rate for the last 12 years to -0.43±0.05 % yr^{-1} (computed as total percentage change divided by the number of years). Of the 185.1±8.2 km^2 (6.45±1.05 % or 0.32±0.04 % yr^{-1}) total loss of glacier surface area (2000-2020), almost 60% related to glaciers with a size ≤ 2.5 km^2, which accounted for 60 % of the total glacier area in the year 2000. This loss explains why the number of glaciers initially increased between 2000 and 2008 (Table IV-1) as individual glaciers separated into smaller ones, before those newly-separated smaller ones began to disappear by 2020. A constant increase in debris-covered area mapped using index C1 0.7±0.08 % yr^{-1} was recorded for 2000-2008 and 0.39±0.04 % yr^{-1},for 2008-2020. The C2 debris-cover increased by 0.65±0.07 % yr^{-1} from 2000-2008 but decreased by 1.02±0.12 % yr^{-1} from 2008-2020. Clean ice declined by 0.39±0.003 % yr^{-1} between 2000 and 2008 and 0.62±0.005 % yr^{-1} between 2008 and 2020 (Table IV-1). An example of the glacier outline resulting from the mapping is shown in Figure IV-3.

Table IV-1 Area of glacier ice and debris cover at different time steps (undefined units are in km^2)

Years		**2000**	**2008**	**2020**
No. Glaciers		3548	3705	3623
Mean ice area		0.63±0.006	0.58±0.005	0.55±0.005
Total clean ice		2246.3±22.5	2174.8±21.7	2011.9±20.1
Total debris-covered ice (C1)		526.5±63.8	556.4±66.8	582.9±69.9
Total debris-covered ice (C2)		96.3±11.5	101.5±12.2	89.2±10.7
Total glacier area		2869.1±97.8	2832.7±100.7	2684±100.7
Periods		**2000-2008**	**2008-2020**	**2000-2020**
Area change	km^2	-36.4±4.7	-148.7±19.3	-185.1±24.0
	%	-1.3±0.1	-5.2±0.6	-6.4±0.8
Rate of area change	km^2 yr^{-1}	-4.5±0.5	-12.3±1.5	-9.2±1.1

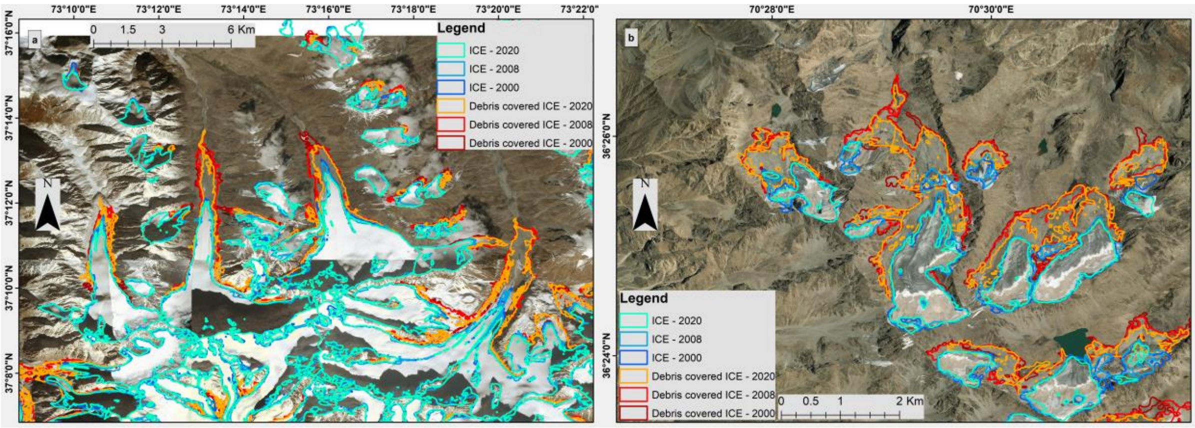
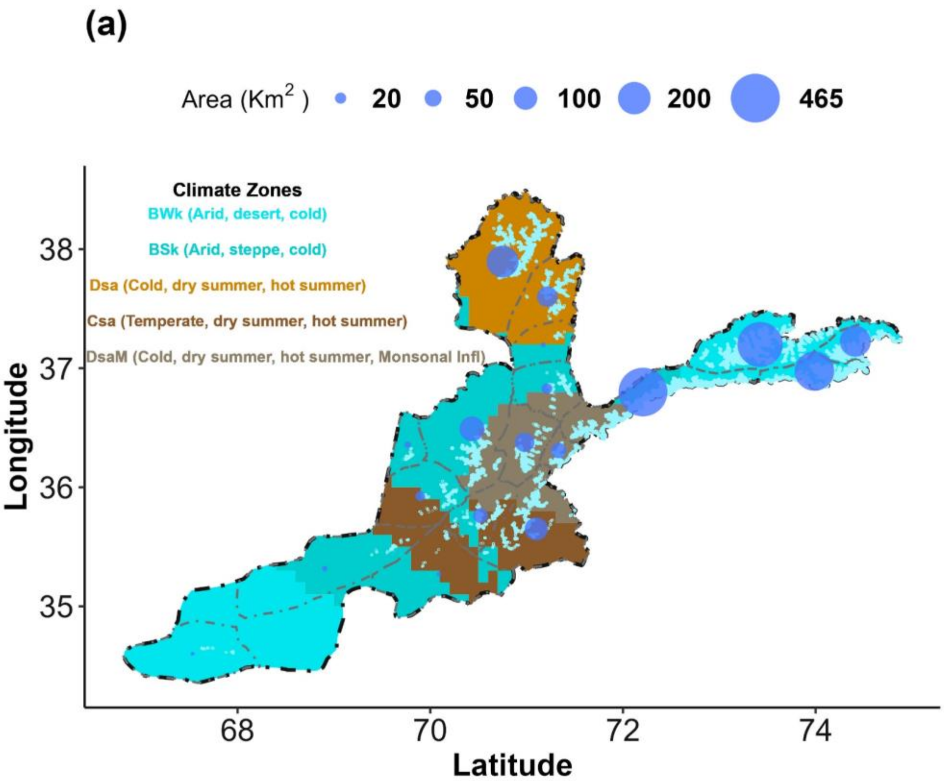


Figure IV-3 Glacier outlines for the year 2000, 2008, and 2020, for examples of a) glaciers in the east, b) glaciers in the northwest, of Afghanistan. Background image is the high resolution image of 2016.

IV.4.2 Within-Afghanistan variation in ice and debris cover

The spatial distribution of glaciers in Afghanistan differs (Figure IV-4), 64% of all glaciers (clean ice and debris-covered) are located in eastern Afghanistan (sub regions 1-4, Figure IV-1), 21% in the central sub regions (9-15, Figure IV-1), 12% in the north (sub regions 5 and 6, Figure IV-1), and the rest in the south-west. Debris-covered glacier extent accounts for 22% of the total glacierized area in 2020 but the highest contribution from the eastern part (65% of the total debris-covered ice area).



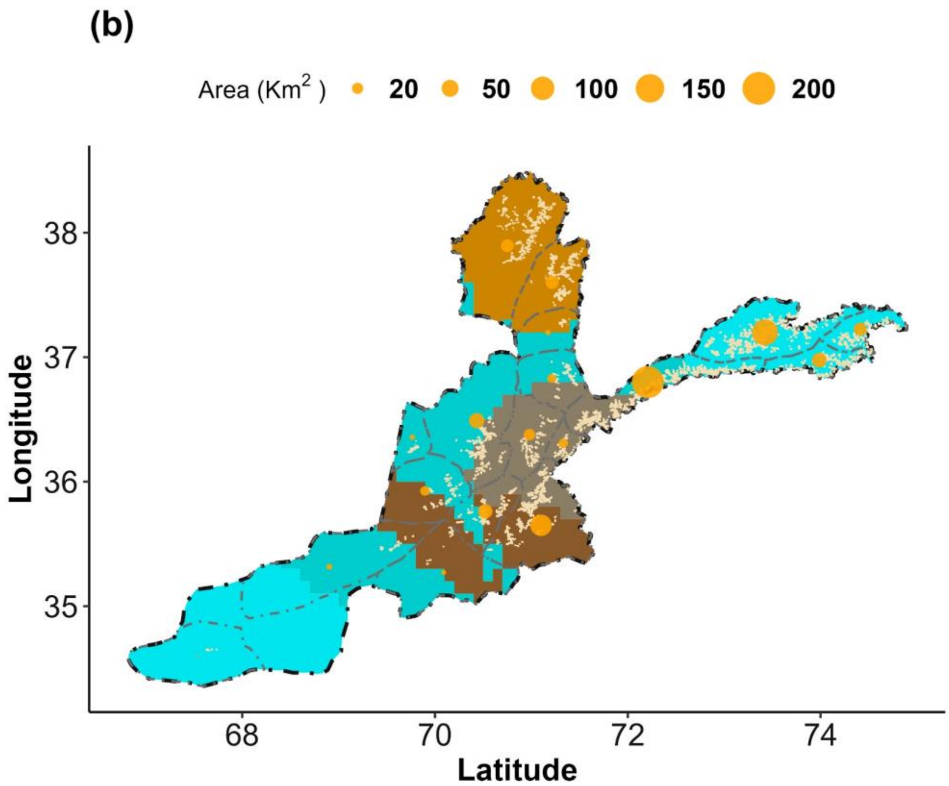


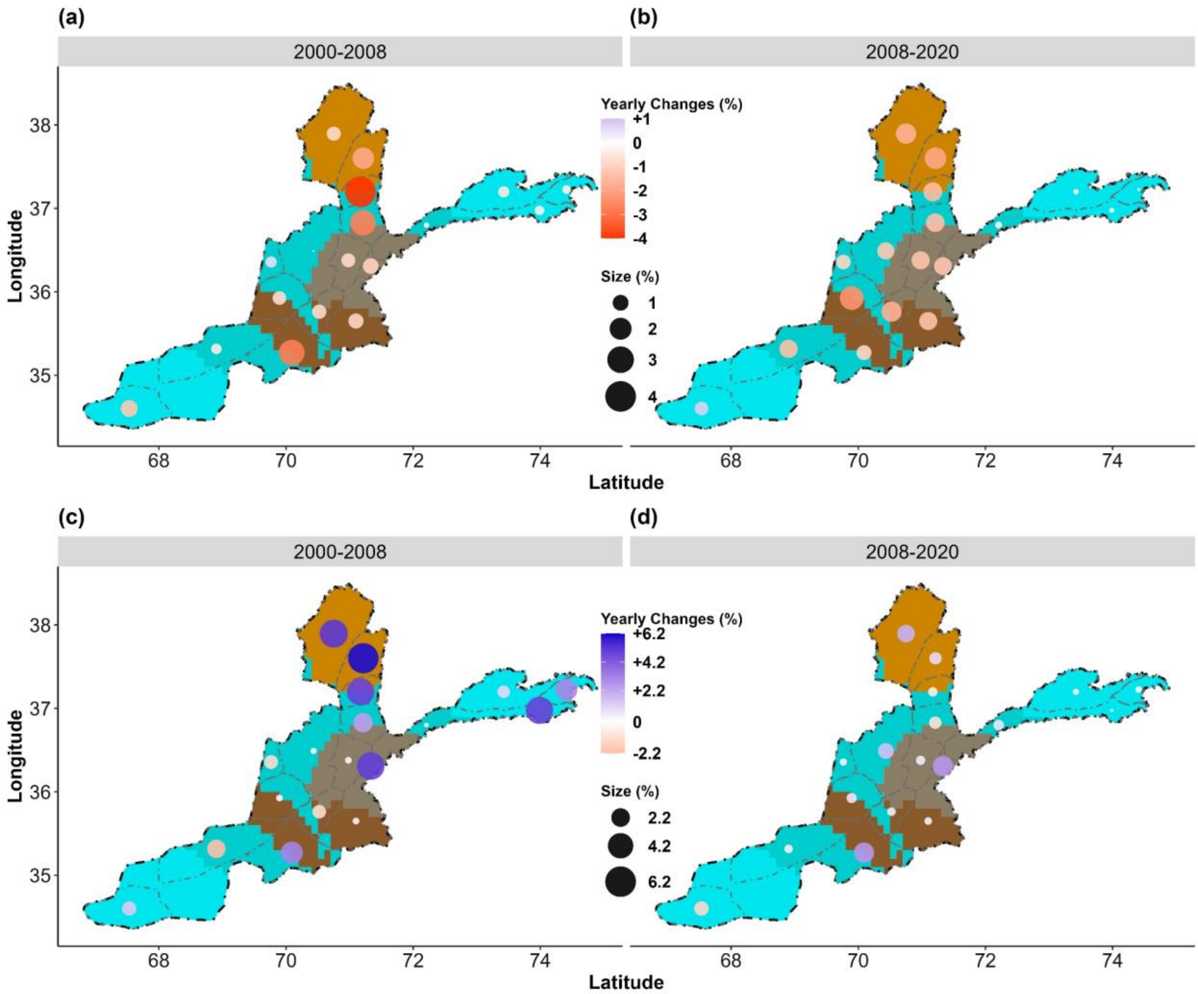
Figure IV-4 Afghanistan climatic zones showing the areas by sub-region of glacier ice (a) and debris-covered ice (b) in 2020.

We found differences in total (i.e. clean ice and debris-covered ice combined) glacier change as a function of geographical location, and closely related to the climate characteristics (Figure IV-4) and also varying according to the time period considered (Figure IV-5). The most notable retreat rates were in Northern Afghanistan (sub regions 5-7), associated with cold winters and dry and hot summers, where clean ice extent decreased from 2000 to 2008 (-2.3±0.02 % yr^{-1}) and 2008 to 2020 (-1.7±0.01 % yr^{-1}); whilst debris-covered ice increased (+4.6±0.5 % yr^{-1} and +0.4±0.04 % yr^{-1}) for the same periods (Figure IV-5). However, combining the changes in glacier ice and debris-covered ice, reduced the retreat rate and the total sensitivity of glacier retreat through time. Total glacier area decreased from 2000 to 2008 by -0.52±0.06 % yr^{-1}, this doubling for 2008 to 2020 (-1.2±0.1 % yr^{-1}).

In Central Afghanistan (sub regions 9-16 except 14), there are commonly dry and hot summers but two distinct regional patterns; drier periods with cold conditions coming from the east; and more temperate periods with warmer and often wetter conditions from the south and west. In this region, Clean ice cover decreased for both 2000 to 2008 (-0.53±0.005 % yr^{-1}) and 2008 to 2020 (-1.4±0.01 % yr^{-1}); and debris-covered ice showed an increased for both periods (+0.4±0.04 % yr^{-1} and +0.9±0.1 % yr^{-1} respectively). The total glacier area also declined (-

0.33±0.04 % yr^{-1} and -0.80±0.1 % yr^{-1}).

Despite having the highest percentage of glaciers, the eastern part of Afghanistan (sub regions 1-4) had the lowest retreat rates. This region is located in an arid zone, comprising desert and steppe with a cold (mean annual temperature <18°C) climate. Clean ice cover decreased from 2000 to 2008 (-0.2±0.002 % yr^{-1}) but increased slightly from 2008 to 2020 (+0.06±0.006 % yr^{-1}) except in sub region 4 where it decreased (-0.16±0.001 % yr^{-1}). Debris-covered ice increased by 2.2±0.2 % yr^{-1} from 2000 to 2008 and decreased 0.14±0.01 % yr^{-1} from 2008-2020 except for sub region 4 where it increased (+0.64±0.07 % yr^{-1}). Taken together, this resulted in a decrease in total glacier area of 0.06±0.007 % yr^{-1} from 2000 to 2008, but with a slight increase of 0.01±0.001 % yr^{-1} in sub regions 1-3 from 2008 to 2020.



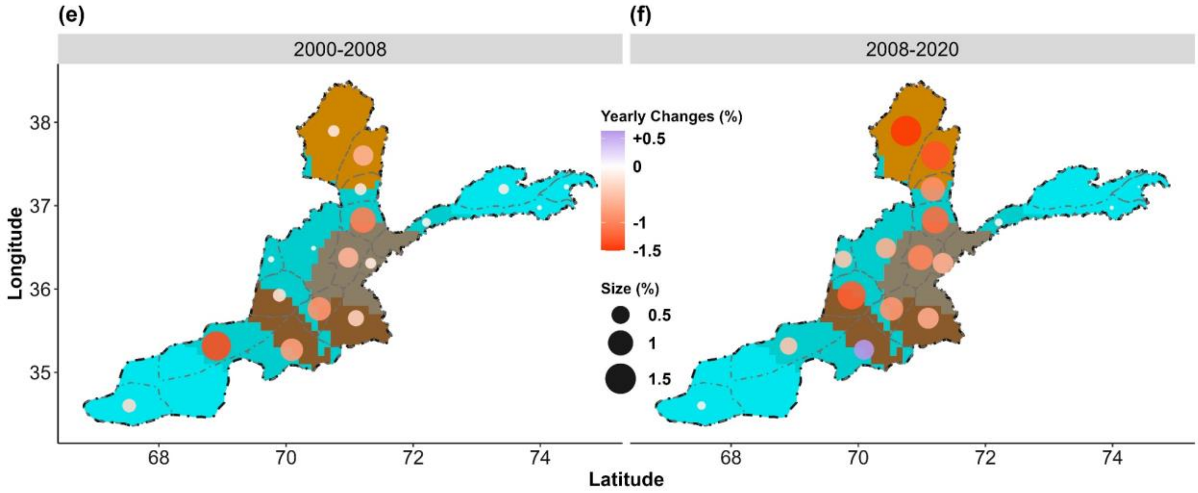


Figure IV-5 Mean annual percentage changes in bare ice area (a, 2000-2008; b, 2008-2020), debris-covered ice area (c, 2000-2008; d, 2008-2020), and total glacier area (ice and debris-covered ice) (e, 2000-2008; f, 2008-2020). Background shading is the climatic zonation shown in Figure IV-4.

IV.4.3 Changes in glacier length and altitudinal limits

Glacier length decreased at the highest rates for the more northerly regions (-24 m yr^{-1}) from 2000 to 2008, but this rate of decrease declined for 2008-2020 (-5.5 m yr^{-1}) (Figure IV-6). The rate of decrease was lower in more central regions (-4.5 m yr^{-1}) from 2000 to 2008 albeit more rapid from 2008 to 2020 (-7.79 m yr^{-1}) (Figure IV-6). In Eastern Afghanistan glacier length declined from 2000 to 2008 (-15.0 m yr^{-1}) (Figure IV-6) but increased from 2008 to 2020 (+8.0 m yr^{-1}).

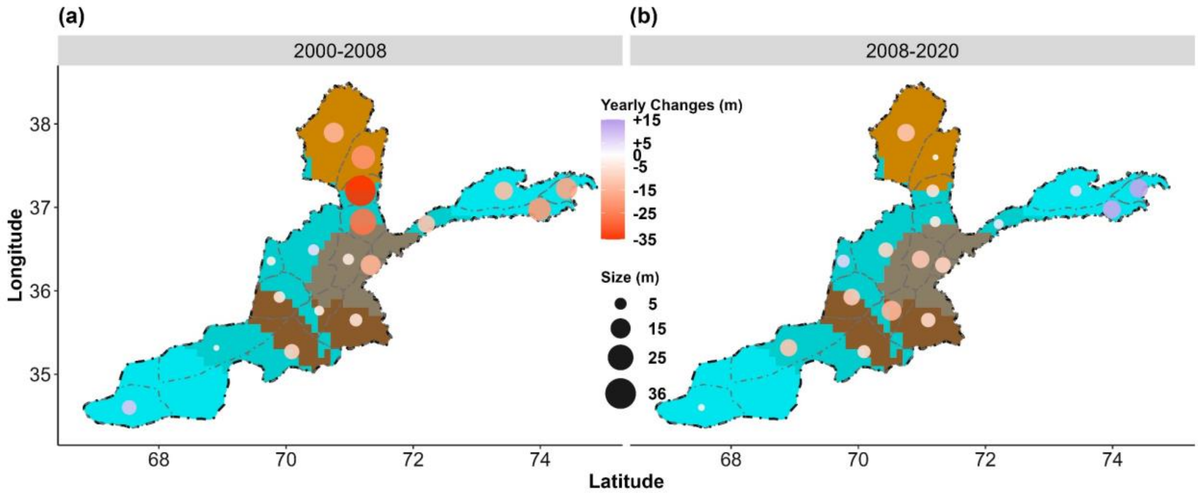


Figure IV-6 Mean annual changes (m) in glacier ice length for (a) 2000 to 2008 and (b) 2008 to 2020. Background shading is the climatic zonation shown in Figure IV-4.

Similar to changes in glacier area, the elevation of glacier ice has changed. In northern Afghanistan (sub regions 5-8), minimum glacier ice elevation increased for both 2000 to 2008 and 2008 to 2020 (+2.70 m yr^{-1}; +1.72 m yr^{-1}; respectively). The maximum ice elevation declined (-4.63 m yr^{-1}, and -1.57 m yr^{-1}). In central Afghanistan (subs region 9-15) changes in minimum glacier ice elevation from 2000 to 2008 varied from -1.00 m yr^{-1} to +2.12 m yr^{-1} (center east and center west) but increased by +2.50 m yr^{-1} from 2008 to 2020. Maximum elevation decreased by 3.68 m yr^{-1} and 1.61 m yr^{-1} from 2000 to 2008 and 2008 to 2020 respectively (Figure IV-7). In eastern Afghanistan (sub region 1-4) minimum glacier ice elevation increased from 2000 to 2008 (+2.54 m yr^{-1}) then decreased from 2008 to 2020 (-1.71 m yr^{-1}); and maximum elevation declined (2000 to 2008; -2.22 m yr^{-1}) but then slightly increased (+0.78 m yr^{-1}, 2008 to 2020) (Figure IV-7).

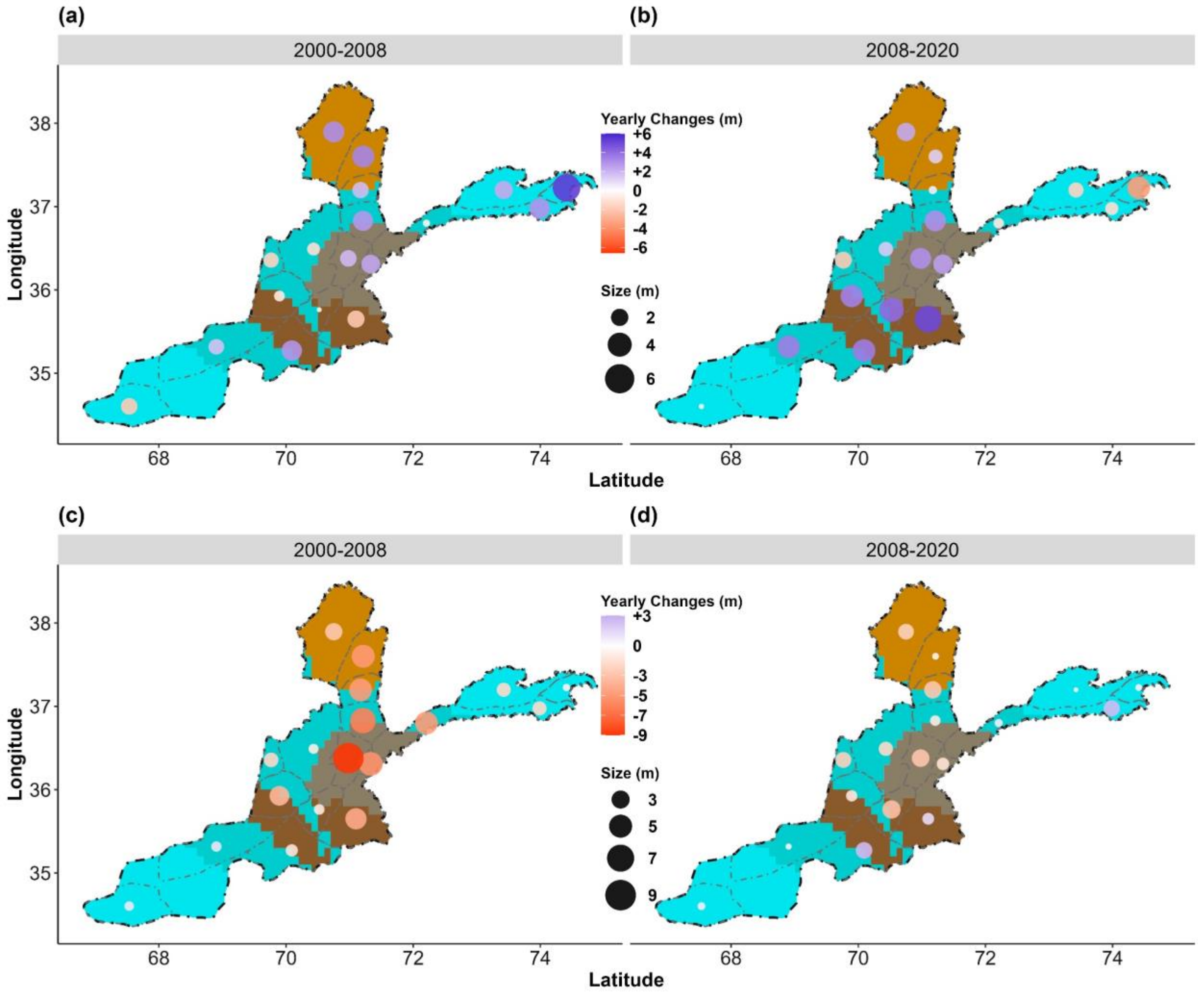
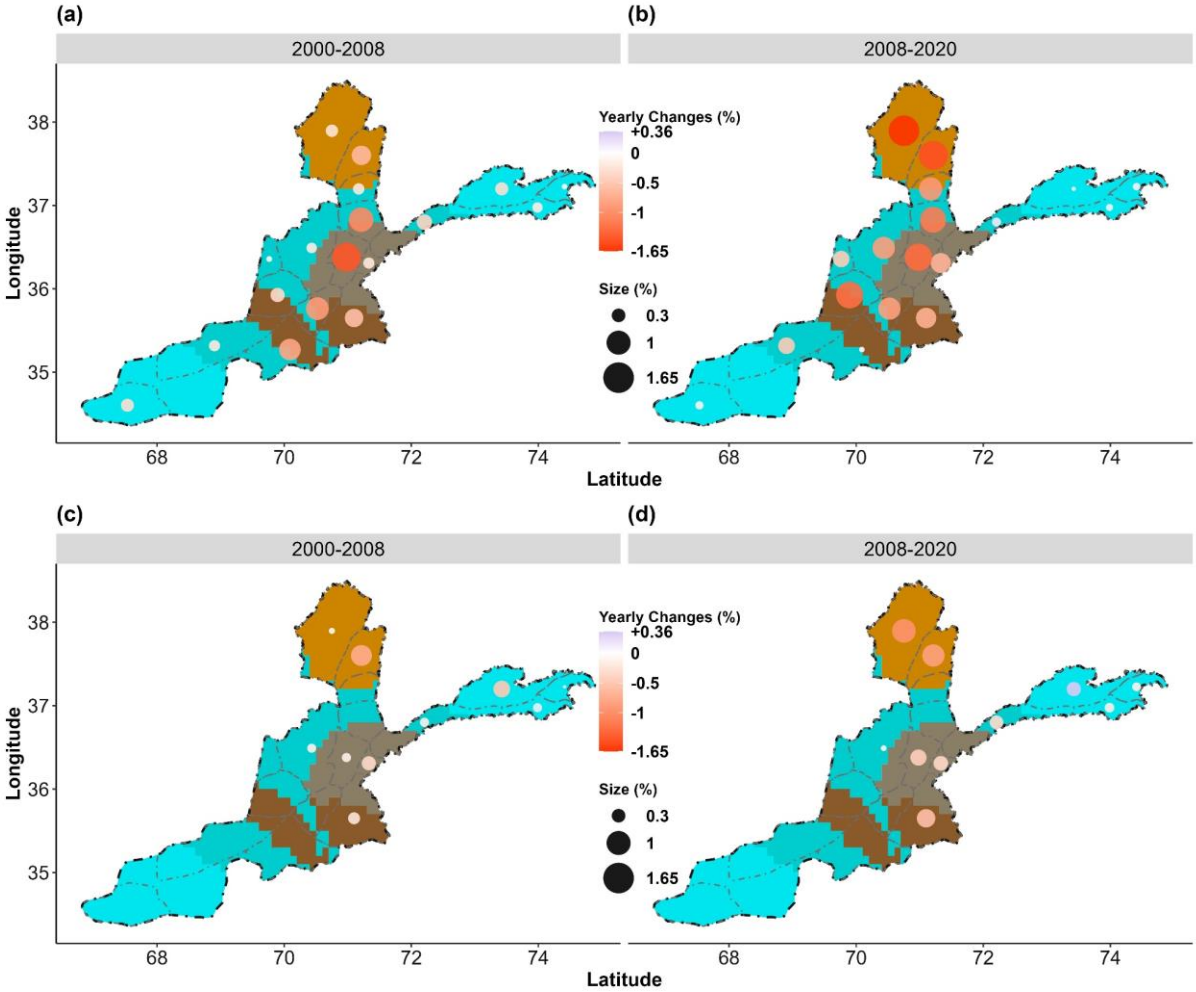


Figure IV-7 Mean annual changes (m) in glacier ice minimum elevation for 2000-2008 (a) and 2008-2020 (b) and maximum elevation for 2000-2008 (c) and 2008-2020 (d). Background shading is the climatic zonation shown in Figure IV-4.

IV.4.4 Glacier size effects on glacier change

It is possible that some of these changes are variable with glacier area, which varies systematically by region (Chapter III). Hence, we grouped changes in glacier area (total, ice and debris cover) into three sizes (<2.5 km^2, 2.5-5 km^2, and > 5 km^2).

The total glacier area of smaller glaciers (< 2.5 km^2) declined more rapidly over all regions with highest rate in the north and lowest in the east (Figure IV-8). In addition, from 2000 to 2008 the level of changes increased between 2008 and 2020. In the north, from 2000 to 2008 the glacier area of smaller glaciers (< 2.5 km^2) declined by 0.53±0.06 % yr^{-1} and this rate doubled from 2008 to 2020 (-1.30±0.16 % yr^{-1}), however the level of decline decreased as glacier size increases for both periods (Figure IV-8). In central regions, smaller glacier (< 2.5 km^2) area declined at a lower rate for both 2000 to 2008 (-0.52±0.06 % yr^{-1}) and 2008-2020 (-0.87±0.11 % yr^{-1}). The eastern region showed the lowest retreat rate for smaller glaciers for both 2000 to 2008 (-0.20±0.02 % yr^{-1}) and small glaciers in this region grew from 2008 to 2020 (+0.07±0.009 % yr^{-1}) (Figure IV-8).



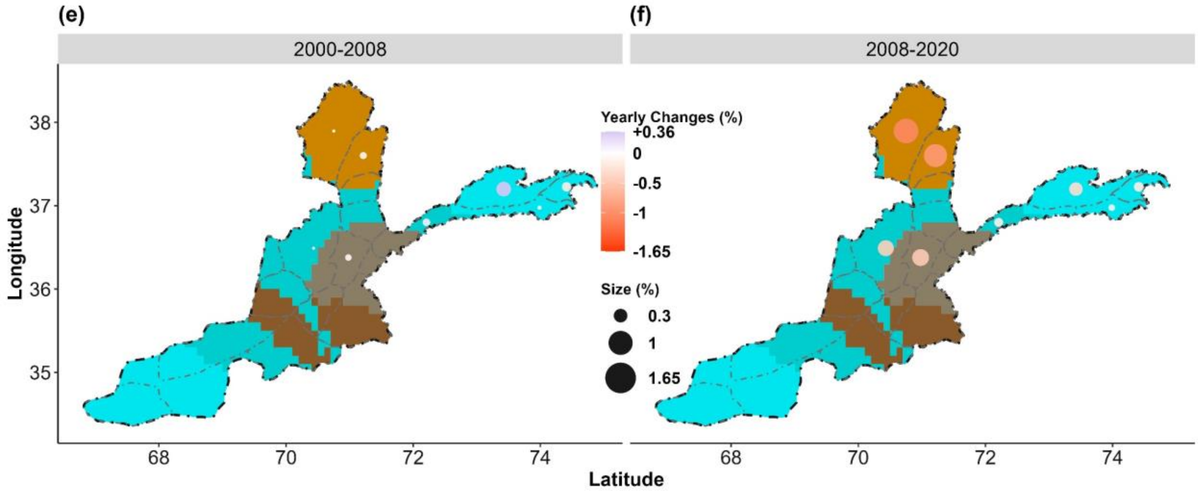


Figure IV-8 Changes in total glacier area (clean ice and debris cover) by glacier size <2.5 km^2 for 2000-2008 (a) and (2008-2020 (b); 2.5-5 km^2 for 2000-2008 (c) and (2008-2020 (d); and > 5 km^2 for 2000-2008 (e) and (2008-2020 (f). Background shading is the climatic zonation shown in Figure IV-4.

If this analysis is restricted to ice only, loss of ice cover was highest in the northern region for the smallest glaciers for both 2000 to 2008 (-2.40±0.31 % yr^{-1}) than the larger glaciers (-1.15±0.14 % yr^{-1}, size 2.5-5 km^2; and -0.45±0.05 % yr^{-1}, size >5 km^2) (Figure IV-9). These rates of bare ice loss also slowed from 2008 to 2020 (-1.80±0.23 % yr^{-1}, size <2.5 km^2; -1.12±0.14 % yr^{-1}, size 2.5-5 km^2; and -0.77±0.10 % yr^{-1}, size >5 km^2). The central regions mirrored this size dependence for 2000 to 2008 (-0.79±0.10 % yr^{-1}, size <2.5 km^2; -0.29±0.03 % yr^{-1}, size 2.5-5 km^2; and -0.11±0.01 % yr^{-1}, size >5 km^2). However, in contrast to the north, the retreat rate in the central regions increases slightly from 2008 to 2020 even if it remains lower than the north (-1.53±0.19 % yr^{-1}, size <2.5 km^2; -0.81±0.10 % yr^{-1}, size 2.5-5 km^2; and -0.34±0.04 % yr^{-1}, size >5 km^2). In the eastern region, the size effect was also found for 2000 to 2008, even if the retreat rates were lower (-0.50±0.06 % yr^{-1}, size <2.5 km^2; -0.39±0.05 % yr^{-1}, size 2.5-5 km^2; and -0.06±0.007 % yr^{-1}, size >5 km^2). From 2008 to 2020, retreat rates were close to zero (+0.13±0.01 % yr^{-1}, size <2.5 km^2; -0.02±0.002 % yr^{-1}, size 2.5-5 km^2; and -0.06±0.007 % yr^{-1}, size >5 km^2) (Figure IV-9).

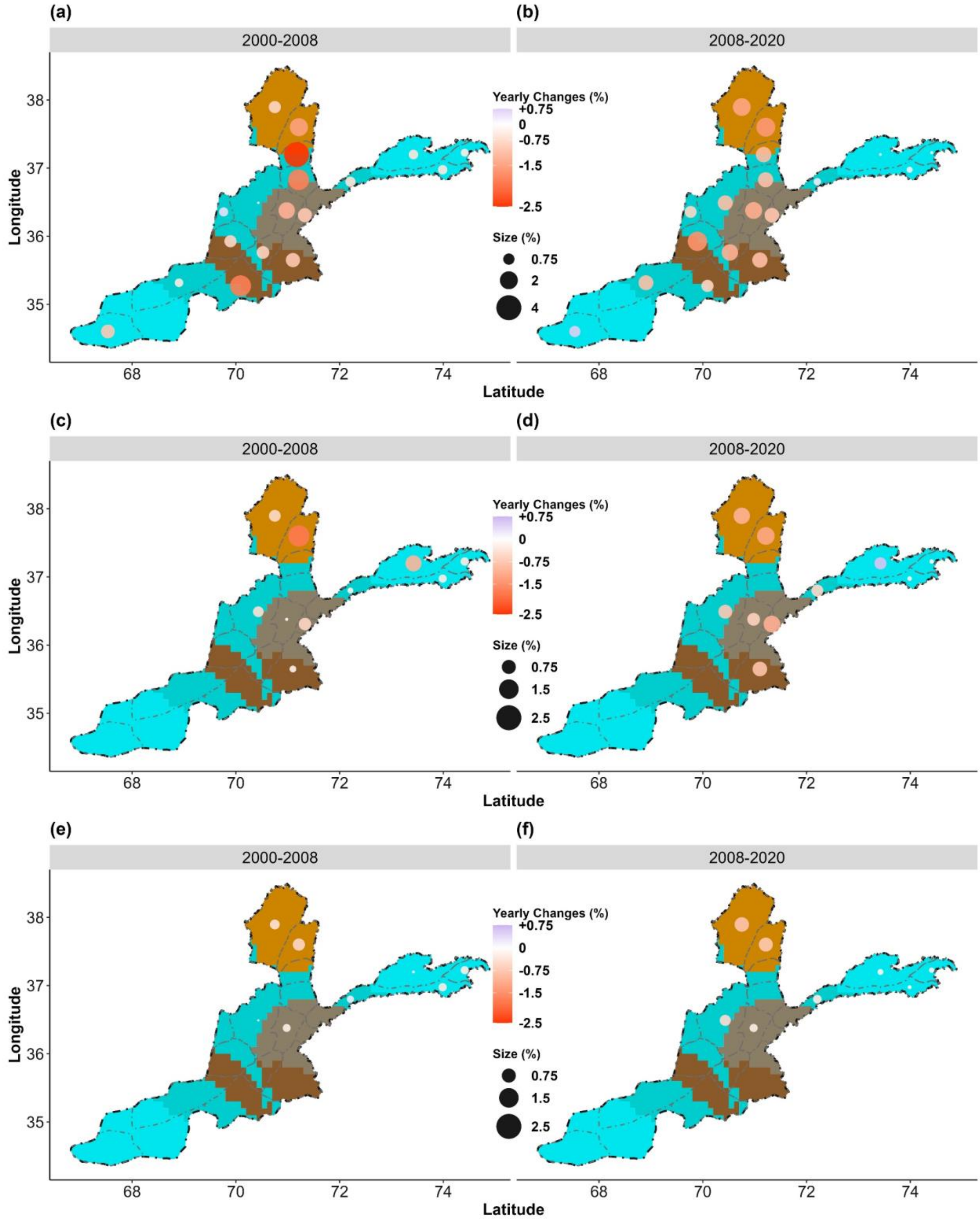
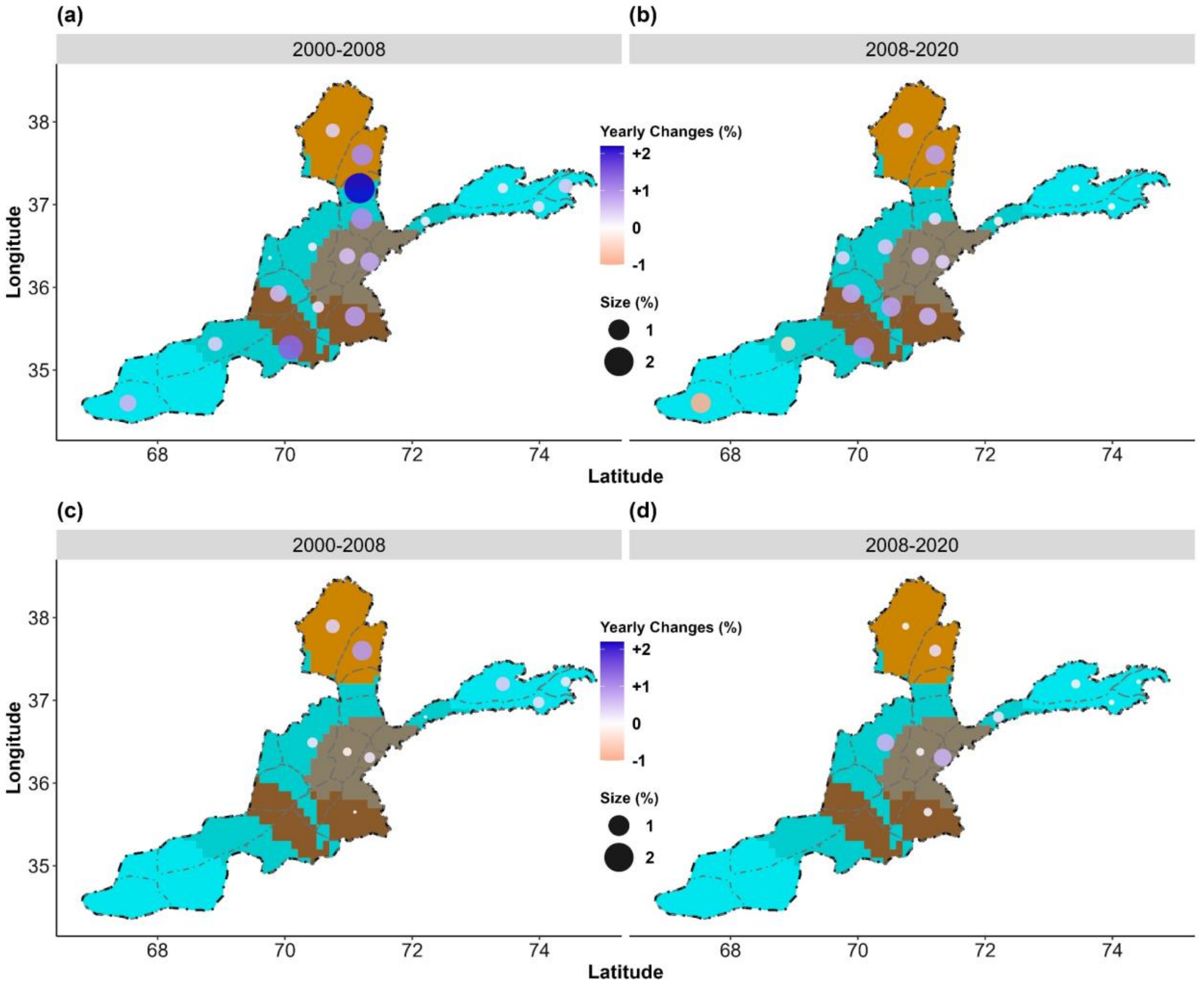


Figure IV-9 Changes in bare ice area by glacier size <2.5 km^2 for 2000-2008 (a) and (2008-2020 (b); 2.5-5 km^2 for 2000-2008 (c) and (2008-2020 (d); and > 5 km^2 for 2000-2008 (e) and (2008-2020 (f). Background shading is the climatic zonation shown in Figure IV-4.

Debris-covered ice showed a different behavior temporally and by geographical region (northern, central, and eastern). Debris cover grew more rapidly for smaller glaciers (< 2.5 km^2) between 2000 and 2008 (Figure IV-10) than for larger glaciers (2.5-5 km^2, > 5 km^2); from 2008 to 2020 the trend continued but with lower rates (Figure IV-10). There was some evidence that these changes were geographically variable. In the central regions glaciers had higher rates of increase in percentage debris cover for all ranges of glacier size, although rates of changed decreases when glacier size increased (+1.16±0.15 % yr^{-1}, size <2.5 km^2; +0.66±0.08 % yr^{-1}, size 2.5-5 km^2; and +0.34±0.04 % yr^{-1}, size >5 km^2) from 2000 to 2008. Although the size effect remained the same, the rates of change decreased from 2008 to 2020 (+0.47±0.06 % yr^{-1}, size <2.5 km^2; +0.15±0.01 % yr^{-1}, size 2.5-5 km^2; and +0.07±0.009 % yr^{-1}, size >5 km^2). The lowest rates of change in percentage debris cover were found in the eastern regions between 2000 and 2008 (+0.27±0.03 % yr^{-1}, size <2.5 km^2; +0.23±0.02 % yr^{-1}, size 2.5-5 km^2; and +0.16±0.02 % yr^{-1}, size >5 km^2). However, from 2008 to 2020, negative changes in percentage debris cover were observed in eastern regions (-0.08±0.01 % yr^{-1}, size <2.5 km^2; -0.002±0.0002 % yr^{-1}, size 2.5-5 km^2; and -0.06±0.007 % yr^{-1}, size >5 km^2) and as well as for all glaciers with size >5 km^2 (-0.16±0.02 % yr^{-1}, in the north; -0.01±0.001 % yr^{-1}, in the center). Glaciers with size > 5 km^2 seem to be undergoing a stable or slightly negative debris cover trend (Figure IV-10).



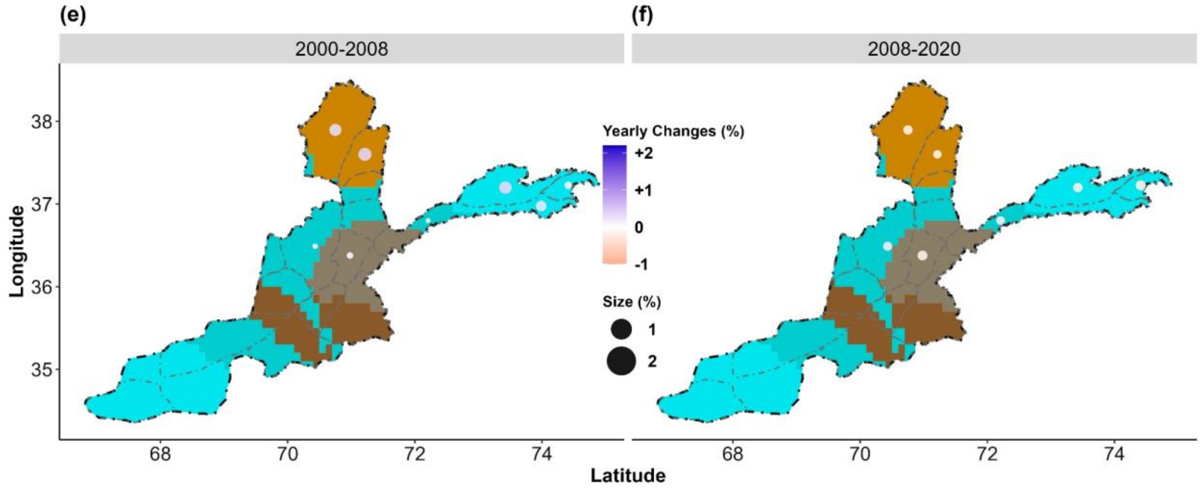


Figure IV-10 Changes in debris-covered ice area (clean ice and debris cover) by glacier size <2.5 km^2 for 2000-2008 (a) and (2008-2020 (b); 2.5-5 km^2 for 2000-2008 (c) and (2008-2020 (d); and > 5 km^2 for 2000-2008 (e) and (2008-2020 (f). Background shading is the climatic zonation shown in Figure IV-4.

IV.5 Discussion

Seasonal snow made it problematic on some dates to identify the ice boundary for some glaciers, mainly in the eastern region of Afghanistan; Mölg et al. (2018) report that this region has frequent seasonal snow captured in Landsat scenes. Therefore, zones with frequent snow and cloud cover were not considered in the mapping. It should be emphasized that the 2016 dataset (Chapter III), is not comparable with 2000, 2008, and 2020 datasets because of 1) a decision to exclude the latter three datasets zones that were predominantly cloudy, and 2) because of a change in the way glaciers were segmented at catchment divides.

Landsat datasets provide information acquired using different sensors; for instance, for the years 2000 and 2008 we used Landsat 7 that uses Enhanced Thematic Mapper Plus sensor (ETM+), and for the year 2020 we used Landsat 8 which used Operational Land Imager (OLI). Roy et al. (2016) reported that OLI reflectance is slightly greater that the ETM+ for all bands. Therefore, we also observed slightly changes in the index threshold values with ±5% variation between those two datasets of Landsat 7 and 8. Then was carefully monitored for the each period using six benchmark glaciers (Figure III-13) in the validations of this study (Chapter III).

IV.5.1 Glacier retreat in Afghanistan and surrounding regions

There is a clear regional variation in how Afghanistan glaciers are responding to climate change, both in space and time (Figure IV-11). In the eastern regions which are geographically close to or part of the north-west Karakoram glacier retreat rates have been either substantially lower or near stable/advancing, as compared with the northern and central regions of Afghanistan. Others have observed that the more strongly westerly-influenced Karakoram has glaciers that were generally advancing or stable in the first decade of the 20th century (Scherler et al., 2011; Bhambri et al., 2013; Minora et al., 2016; Azam et al., 2018; Farinotti et al., 2020) but also that glacier response is strongly heterogeneous (Bolch et al., 2019). Similar observations of increasing glacier extent in the last two decades have been made for the eastern Pamir to the south-east of the eastern regions of Afghanistan (Lv et al., 2020); and the north-west Himalayan range of India, where (Pandey et al., 2011). The northern regions of Afghanistan are responding most sensitively to climate change and loss of glacier area seems to be accelerating (Figure IV-11). This reflects observations of individual glaciers in the Pamir-Alay to the north (such as Abramov Glacier to the north, 1985 to 2015; Denzinger et al., 2021) but also generalized observations of negative mass balance for glaciers within the Pamir-Alay (1999-2011; Brun et al., 2017), the western Pamirs (2000-2018; Shean et al., 2020) and the Pamirs more widely (e.g. 2003-2008, Kääb et al., 2015; 2003-2009, Gardner et al., 2013). Glaciers in the central region were, like the northern region, undergoing area loss throughout the two periods considered, albeit at lower rates than in the northern region. The central region is part of the northern Hindu Kush where there are fewer studies of changes in glacier area (Bolch et al., 2019). However, Joya et al. (2021) recently reported significant glacier area loss (c. -15%, or -0.75% per year) for the Kocha basin between 1990 and 2015 and this basin corresponds to a significant part of our central region. Our central region rates for smaller glaciers (<2.5 km^2) are similar to this rate for both periods. Taken together, these observations mirror within Afghanistan a wider observation of strong intra-regional variability of glacier response within the HKH glacier to climate warming (Brun et al., 2017); and potentially over spatial scales of only 10s of km (Huang et al., 2021); such that studies of individual glaciers can provide contradictory messages (e.g. Debnath et al., 2019; Chowdhury et al., 2021).

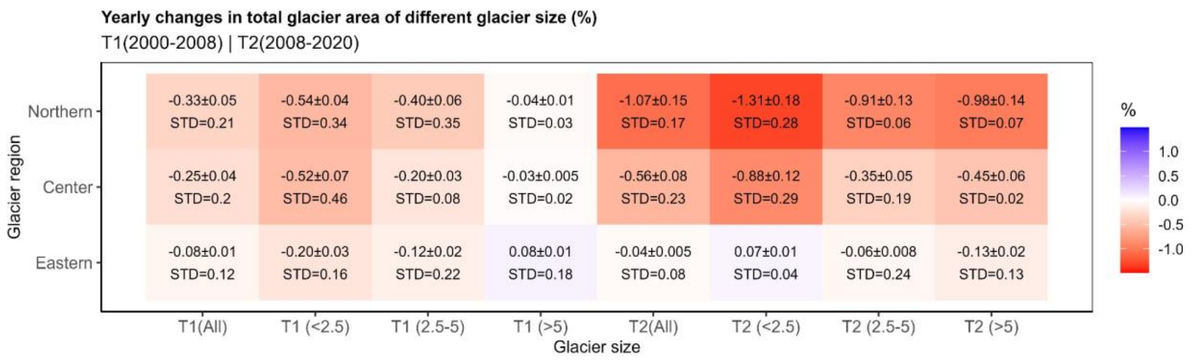


Figure IV-11 Heat map of glacier recession rate in three geographical location of Afghanistan under two timespan T1-T2.

IV.5.2 Debris cover evolution

Observations suggest that long valley glaciers covered with thick debris are generally stagnant

(Racoviteanu et al., 2014). This has been reported in the eastern part of Afghanistan which has the highest debris-covered ice area, and more long valleys covered with thick debris characteristics (Shroder and Bishope 1980). Such glaciers have the lowest retreat rate with more stagnant debris-covered termini (Figure IV-10). On the other hand, in the northern and central glaciated regions of Afghanistan we noted higher glacier ice rates of loss (Figure IV-9) and increases in percentage debris cover (Figure IV-10). This pattern is also confirmed by Bishop et al. (2014) who observed that glaciers that were down-wasting and back-wasting were more debris-covered in northern Afghanistan than elsewhere in the country. However, this may not simply be a function of melt rate but also climate effects. These regions have drier and hotter summer climates that may lead to an increase in debris cover (Herreid and Pellicciotti, 2020). Additionally, the relative percentage of debris cover areas systematically decreases with increasing glacier size, a pattern observed globally (Scherler et al., 2018) as well as in Afghanistan (Chapter III). As smaller glaciers shrink faster than larger glaciers (Figure IV-11) this facilitates the rate of debris cover increase on such glaciers (Narama et al., 2010; Scherler et al., 2018).

IV.5.3 Climate influences on glacier retreat

A primary explanation of these regional differences is the climatic complexity of Afghanistan. It is well known that for the wider HKH there are broadly two distinguishing influences on glacier mass balance (Fujita, 2008); glaciers dominated by the westerlies and winter-accumulation; and those dominated by monsoon with a tendency to summer accumulation. Fujita (2008) showed that monsoon-dominated glaciers are more sensitive to climate change than westerly-dominated glaciers due to a rise in the rain/snow limit related to increasing temperature. By contrast, Racoviteanu et al. (2014) found much higher glacier retreat rates in the dry areas of the western Himalaya (Ladakh) than the monsoon-dominated eastern Himalaya (Sikkim). In Afghanistan, the eastern and northern regions presented here are westerly-influenced glaciers. The south Asian monsoon can penetrate into the central region to an extent that depends on its annual intensity. Our data suggest that the northern region, with a cold winter and a dry and hot summer is where retreat rates are most rapid. The eastern region which is arid, but which has a colder climate, has the lowest glacier retreat (Figure IV-11) and this region borders on zones where others have made similar observations (Scherler et al., 2011; Bhambri et al., 2013; Minora et al., 2016; Azam et al., 2018; Farinotti et al., 2020; Lv et al., 2020). The central region has a mix of both northern and eastern climate with influences from south Asian monsoon, therefore, a median retreat in between is observed. Thus, there is a strong signal of summer temperature, and hence altitude and glacier area, in determining glacier response to climate warming.

IV.5.4 Glacier elevation change

We observed glacier shrinkage in the accumulation zone, with highest rates in the northern regions (minimum glacier ice elevation increased for both 2000 to 2008 and 2008 to 2020 by +2.70 m yr^{-1}; +1.72 m yr^{-1}; respectively). In addition, the maximum ice elevation declined by 4.63 m yr^{-1}, and 1.57 m yr^{-1} respectively. This rate reduced towards central and eastern Afghanistan (Figure IV-7). Such patterns have been observed, albeit with much higher rates, in the European Alps between 2000 and 2012 (Sommer et al., 2020). This study reported average regional surface lowering of up to 5 m yr^{-1} even if this rate of lowering was lower that that found at glacier termini caused by the complete downwasting of glacier frontal areas (Sommer et al., 2020). Between 2003 and 2016 in the North-Western Himalaya (Parvati Glacier), Chand et al. (2020) observed a surface lowering in accumulation zones of 1.3 ± 0.9 m yr^{-1}. Certainly in Afghanistan, it seems that ice loss is occurring in accumulation zones as well as in ablation zones albeit to an extent that is likely dependent on accumulation zone altitudes.

IV.6 Conclusion

This research studied glacier changes in Afghanistan in terms of both total glacier area, clean ice and debris-covered ice for timespan (2000-2008 and 2008-2020). Glacier inventories were developed, for 2000, 2008, and 2020 to enable this. In 2020, 2684±100.7 km^2 glacier area were mapped, split between 75±0.74 % clean ice and 25±3.0 % debris-covered ice. Across the country, there has been an acceleration of glacier retreat from 4.5±0.5 km^2 yr^{-1} (0.15±0.01 % yr^{-1}) between 2000 and 2008 to 12.3±1.5 km^2 yr^{-1} (0.43±0.05 % yr^{-1}) between 2008 and 2020. Our analysis showed that glacier response in Afghanistan to climate warming is regionally variable and depends on glacier size, and this despite Afghanistan being only a small percentage of the HKH region (11.3%). Glaciers with cold winters and dry and hot summer climates (the northern region) had the highest recession rates, and arid, desert and steppe, cold climate (the eastern part) had the lowest recession rates. In between, a mix of both regions, climates (northern and eastern) with summer Asian monsoon influence had a median retreat rate..

Debris cover on Afghanistan glaciers is increasing, but mainly for smaller glaciers. This response is important at it may influence climate–glacier dynamics and reduce the sensitivity of glacier mass loss to rising temperature, so extending the lifespan of glaciers as water resources (Lardeux et al., 2016; Zhang et al., 2019). However, whilst debris cover development is likely an important negative feedback in response to climate warming, the fact that the largest glaciers are not yet showing increases in cover suggests that there will continue to be significant ice loss in some regions of Afghanistan.

It is generally accepted that smaller glaciers are more sensitive to and good indicators of climate change because of their faster response to relatively short-term climate variations (Paul et al., 2004b). However, we found variable response of small-size glaciers to climate change. Smaller glaciers in northern Afghanistan are retreating at a higher rate than those of central regions with those in eastern Afghanistan having much lower recession rates. However, this regional difference is found for all sizes of glacier and it seems that in Afghanistan regional differences in climate are more important than glacier size effects.

Finally, we found that the maximum elevation of glacier ice has decreased but mainly in the north and center of Afghanistan. This indicates that glaciers not only experiencing retreat from the ablation zone but also reduced accumulation in or increased ice flux out of their accumulation zones. This observation is important as it may take time for accumulation changes to be seen in changes in snout margin retreat rates.

This work has focused on general changes by regions. It may be possible using this database to tease out other local scale drivers of variations in glacier change, in futures studies. For instance glacier lake formation has also been shown to be an important driver of glacier retreat in the HMA (King et al., 2017). In addition, the three inventories should become the basis of improving water resource assessments for the region by identifiying the relationship between regional patterns ice loss and the distribution of downstream populations.

IV.7 Supplementary Materials

Table IV-2 List of Landsat data scenes and date that used to compile three timespan (T1-T3) glacier datasets inventories

Sub Regions	WRS path-row	Acquisition Date	Scene ID	Sensor
1-4		2 Sep 2000	LE07_L1TP_150034_20000902_20170210_01_T1	ETM+
1-4	150034	7 Aug 2008	LE07_L1TP_150034_20080807_20161228_01_T1	ETM+
1-4		16 Aug 2020	LC08_L1TP_150034_20200816_20200822_01_T1	OLI
3,4		9 Sep 2000	LE07_L1TP_151034_20000909_20170210_01_T1	ETM+
3,4	151034	15 Sep 2008	LE07_L1TP_151034_20080915_20161225_01_T1	ETM+
3,4		23 Aug 2020	LC08_L1TP_151034_20200823_20200905_01_T1	OLI
4		9 Sep 2000	LE07_L1TP_151035_20000909_20170210_01_T1	ETM+
4	151035	15 Sep 2008	LE07_L1TP_151035_20080915_20161225_01_T1	ETM+
4		21 Aug 2019	LC08_L1TP_151035_20190821_20190903_01_T1	OLI
5-8		3 Sep 2002	LE07_L1TP_152034_20020906_20170128_01_T1	ETM+
5-8	152034	19 Aug 2007	LE07_L1TP_152034_20070819_20170101_01_T1	ETM+
5-8		29 Sep 2019	LC08_L1TP_152034_20190929_20191017_01_T1	OLI

9-15		2 Aug 2001	LE07_L1TP_152035_20010802_20170204_01_T1	ETM+
9-15	152035	17 Sep 2006	LE07_L1TP_152035_20060917_20170108_01_T1	ETM+
9-15		29 Sep 2019	LC08_L1TP_152035_20190929_20191017_01_T1	OLI
16-18		22 Aug 2000	LE07_L1TP_153036_20000822_20170210_01_T1	ETM+
16-18	153036	28 Aug 2008	LE07_L1TP_153036_20080828_20161225_01_T1	ETM+
16-18		22 Sep 2020	LC08_L1TP_153036_20200922_20201006_01_T1	OLI

V GLACIER-INFLUENCED HYDROLOGICAL REGIMES OF AFGHANISTAN HINDU KUSH HIMALAYA (AHKH) UNDER CURRENT AND FUTURE CLIMATE

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In preparation for publication.

This chapter is the continuation of the previous chapter and uses the glacier inventory data that was developed into a glacio-hydrological model to assess the glacio-hydrological regimes of three catchments in Afghanistan. It presents the methodology of a modified glacio-hydrological model that is used in this study, the dynamics of land cover evolution in the model, model calibration, and the validation process. This chapter also discusses the importance of data quality and bias corrections of current and future climate data in hydrological modeling. Consequently, the chapter presents results of the glacio-hydrological models for the year 2000 to 2100 and more importantly the role of debris cover effects on streamflow.

Abstract

Glaciers in Hindu Kush Himalaya (HKH) are an important freshwater resource for the human and natural systems found downstream. In more arid parts of the HKH, glacier melt compensates for the effects of rainfall deficits during meteorological droughts. Glacier recession may make this resource insecure if glaciers become sufficiently small that runoff decreases significantly. Research is needed to quantify both the current and possible future dependence of stream flow upon glacier melt. This study focuses Afghanistan, a country in the western Himalayas with an arid to semi-arid climate, where despite strong societal and ecosystem dependence upon mountain water resources, the contribution of glacier melt is poorly known. Hydrobricks, a new semi-lumped, glacio-hydrological modeling framework based on a C++ core with a Python interface, is applied on three representative catchments with different glacier cover; the Sust catchment (4609 km^2, with 15.6% glacier cover) eastern Afghanistan; the Taqchakhana (264.4 km^2 area, 2.8% glacier cover) in northern Afghanistan; and the Bamyan catchment (325.3 km^2, 0.7% glacier cover) in central Afghanistan. Recognising the importance of accumulating debris cover in moderating the melt of retreating glaciers, we include a debris cover treatment for the first time in this scale of study. Climate and streamflow data were obtained for 43 stations from the Ministry of Energy and Water and the Ministry of Agriculture, Irrigation, and Livestock of Afghanistan. The model was calibrated and validated using these data for the period 2012-2019. Validation of the calibrated model produced good values of the Kling-Gupta efficiency (KGE) for simulated daily streamflow (KGE >~0.8). Glacier runoff dominated the Sust catchment (76%); rain and snow runoff the Taqchakhana catchment (50%) and baseflow the Bamyan catchment (61%). Projected streamflow under RCP 2.6 suggests that mean annual glacier runoff for the Sust and Taqchakhana catchments will increase until 2050, following an increase in temperature (0.9 ˚C). Then runoff declines to the end of the 21st century. The Bamyan is predicted to have declining runoff throughout the 21st century. However, under RCP 8.5 glacier runoff increases more markedly in the Sust and Taqchakhana catchments as temperature rises are larger, climate change mitigation measures do not reverse them. These catchments are likely to pass through a phase of peak water not due to temperature limitation on runoff as under RCP 2.6, but due to progressively diminishing glacier size.

V.1 Introduction

Glaciers are essential water sources for drinking water supply, irrigation, hydropower generation, and downstream ecosystems. In addition, they are crucial in increasing streamflow during meteorological drought conditions (Marshall, 2014; Li et al., 2015). Such increases are more severe in arid regions where glaciers contribute the most to streamflow and compensate for precipitation deficits (Kaser et al., 2010; Tiel et al., 2021). Glaciers cover around 30,000 km^2, or about 17% of the Hindu Kush Himalaya (HKH) region (Sarfaraz et al., 2004). They are one of the most sensitive systems to climate change (Immerzeel et al., 2020).

Changes in glacier volume or area directly affect meltwater runoff in terms of both annual totals and seasonal and inter-annual variability. In the short to medium term, glacier retreat generally enhances summer streamflow until glaciers become small enough that this “glacial subsidy” ends and summer runoff starts reducing (Rees & Collins, 2006; Scherler et al., 2011). The transition from glacial subsidy to glacial penury is known as “peak water” (Huss & Hock, 2018). Such changes will influence water availability in downstream rivers and affect longer-term groundwater recharge. Therefore, determining the impacts of climate change on the cryosphere is essential to understand future water supply changes (Quincey et al., 2018; Kraaijenbrink et al., 2021). Such understanding requires catchment-wide glacio-hydrological models that take into account the uncertainties relating both to models and the climate predictions used to force them (Azam et al., 2021).

In this paper, we focus on Afghanistan in the northwestern HKH, which has a complex climate and which has rarely been studied in terms of glacio-hydrological regimes. Glaciers are essential to the water resources of Afghanistan; they provide water, particularly in summer when there is little precipitation but the highest demand for agricultural water use (Chapter II). Winter snowfall is predicted to decline in this region, and summer temperatures will continue to rise (Savage et al., 2009; NEPA and UNEP, 2016; Aich et al., 2017). Such changes will impact both the annual mean and the intra-annual distribution of streamflow. However, they will also impact glacier mass balance, the volume of water stored as ice, and hence the magnitude of glacial meltwater supply. In the context of Afghanistan, there are three broad challenges.

First, there is evidence of geographically-variable impacts of climate change on glaciers within Afghanistan and surrounding countries; for instance, the more strongly westerly-influenced Karakoram glaciers (in the western HKH) are typically stable or advancing slightly (Scherler et al., 2011; Bhambri et al., 2013; Minora et al., 2016; Azam et al., 2018, Farinotti et al., 2020); but those glaciers in Pamir-Alay to the north appear to have strongly negative mass balances and to be retreating (e.g., Gardner et al., 2013; Kääb et al., 2015; Brun et al., 2017; Shean et al., 2020; Denzinger et al., 2021). The result is likely to be a regionally differentiated change in glacier melt regimes and hence in future streamflow regimes. However, such changes have not yet been established, and regional variation remains a primary source of uncertainty in assessing the regional hydrological impacts of climate change (Lutz et al., 2014).

Second, the assessment of glacial contribution to future streamflow requires hydrological models. However, models that represent glacier dynamics are relatively poor or highly demanding of input data (Horton et al., 2022). Chen et al. (2017) noted that numerous applications of hydrological modeling in central Asia do not explicitly model glacier contributions. Those models that do so are commonly very demanding in terms of computing time, which makes them challenging to implement (Shafeeque et al., 2022). These general observations apply equally to Afghanistan. For instance, the SWAT hydrological model has been widely used to simulate streamflow in Afghanistan (Bromand, 2015; Ayoubi and Kang, 2016; Akhtar et al., 2021). However, it does not explicitly represented glacial contributions (Omani et al., 2017; Singh et al., 2021). The J2000 hydrological model has also been used and added glacier area as an input for the model in the Kabul river basin, Afghanistan (Figure V-1) (Ghulami, 2017; Nepal et al., 2021), but it does not account for the changing spatial extent of glacier areas through time (Nepal et al., 2014) nor for debris cover impacts. Sophisticated ice dynamics models are available (e.g., Jouvet et al., 2009), but these require data that are not always available. More superficial treatments based on volume-area scaling may fail to describe time lags between the area and the volume response to prevailing climate (Lüthi, 2009; Radic´ and Hock, 2014; Li et al., 2015). Further work is required to develop hydrological models suited to data-poor settings like Afghanistan, which improve the representation of key glacial melt processes.

Third, a particular influence on glacier melt is commonly missing in these models, especially for larger catchments modelled over longer periods; debris cover effects (Fyffe et al., 2019). Debris-covered glacier response to climate change is heterogeneous (Banerjee, 2017; Benn et al., 2012; Mihalcea et al., 2006; Reid et al., 2012; Rounce et al., 2018). Debris cover is generally assumed to reduce melt rates as compared to bare ice, except where debris is thin or patchy, it may locally increase ice melt (Østrem, 1959; Mihalcea et al., 2006; Lejeune et al., 2013; Fyffe et al., 2014; Minora et al., 2015; Fyffe et al., 2019). The effect on downstream streamflow can vary significantly even in the same geomorphological, geological, and climatological settings due to different hydrological responses of bare ice and debris-covered glaciers (Miles et al., 2020; Shafeeque et al., 2022). However, only a few glacio-hydrological modeling studies account for the effect of debris (Fujita and Sakai, 2014; Fyffe et al., 2019; Miles et al., 2019;

Miles et al., 2020). Many of these have only been applied to smaller catchments (Reid et al., 2012; Ayala et al., 2016; Carenzo et al., 2016). Ignoring the difference in melt response of bare ice and debris-covered glaciers may result in uncertainties in quantitative meltwater estimates for larger catchments. In general, debris-covered glaciers are frequent in the Himalayas region (Gardelle, 2013; Scherler et al., 2018) and specifically in Afghanistan (Chapter IV). Therefore, representing debris cover effects on ice melt in models is crucial for estimating future glacier runoff.

Given these three issues, the aims of this study are (1) to develop a suitable glacio-hydrological precipitation-streamflow model suitable for data-poor glaciated mountain settings that includes a debris cover representation; and (2) to use this to estimate how glacier-influenced streamflow in Afghanistan might evolve under future climate change taking into account glacier melt. This is done for three catchments in Afghanistan (Figure V-1) that were chosen to represent different climatic regions because they had more reliable hydro-meteorological and glaciological data. In the paper, we (a) use in-situ discharge and climate data to set up a streamflow model, (b) couple it to bias-corrected historical and future climate forcing, (c) incorporate remotely-sensed based glacier observations to account for current debris cover and debris cover trends, and (d) use a simple approach to represent glacier retreat effects.

V.2 Study Area

Afghanistan had an estimated glacier extent of 2684±101 km^2 in 2020, 75±1 % bare ice and 25±3.0 % debris-covered ice (Chapter IV). It has an arid and semi-arid continental climate characterized by desert, steppe, and mountain temperature and precipitation regimes (Humlum et al., 1959; Shroder et al., 2014). Mediterranean cyclonic systems and westerlies mainly cause winter precipitation (Glantz, 2005; Sorrel et al., 2007). In the summer, the South Asian monsoon associated with the Intertropical Convergence Zone (ITCZ) influences the country (Shroder, 2014), with occasional snowfall during summer in the highest mountain peaks in the northeastern region.

Afghanistan has five major river basins (Shohokry et al., 2023): (1) Panj-Amu, (2) North, (3) Harrirud Murghab, (4) Helmand, and (5) Kabul (Figure V-1) with very different contributions to the total volume of streamflow leaving the country (Bromand, 2017). The Panj-Amu and Kabul river basin produces the highest water volumes (38% and 35%, respectively) despite having smaller percentage basin areas (14% and 11% of the country). This is due to glaciers, and these basins account for 96% and 4% of the total glacier area of Afghanistan, respectively (Chapter IV). The other three basins have lower streamflow volumes than expected given their area, with 17% volume but 52% area for the Helmand river basin, 5% volume but 12% area for the Harrirud Murghab river basin, and 4.5% volume for the Northern river basin but 11% area (Mahmoodi, 2008; Bromand, 2017) (Figure V-1).

The three catchments used for this study are located in the Panj Amu river basin, in the central region (the Bamyan catchment), the northern region (the Taqchakhana catchment), and the eastern region (the Sust catchment) (Figure V-1). The catchments were selected based on both practical and scientific reasons. Practically, these three basins have relatively reliable streamflow data, which is needed for model validation and calibration. Scientifically, they represent three different degrees of glacier cover (Table V-1) and reflect climatic differences. The Sust catchment has the highest glacier extent (15.6% by area), the lowest daily mean temperature (-0.3 ˚C), and the lowest mean annual precipitation (320 mm yr^{-1}) (Table V-1). The Taqchakhana catchment has the highest daily mean temperature (+9.2˚C) and mean annual precipitation (1397 mm yr^{-1}) but a lower glacier extent (2.8% by area). The Bamyan catchment has the lowest glacier extent (0.7% by area), intermediate mean daily temperature (+4.2 °C), and mean annual precipitation (414 $mmyr^{-1}$) (Table V-1).

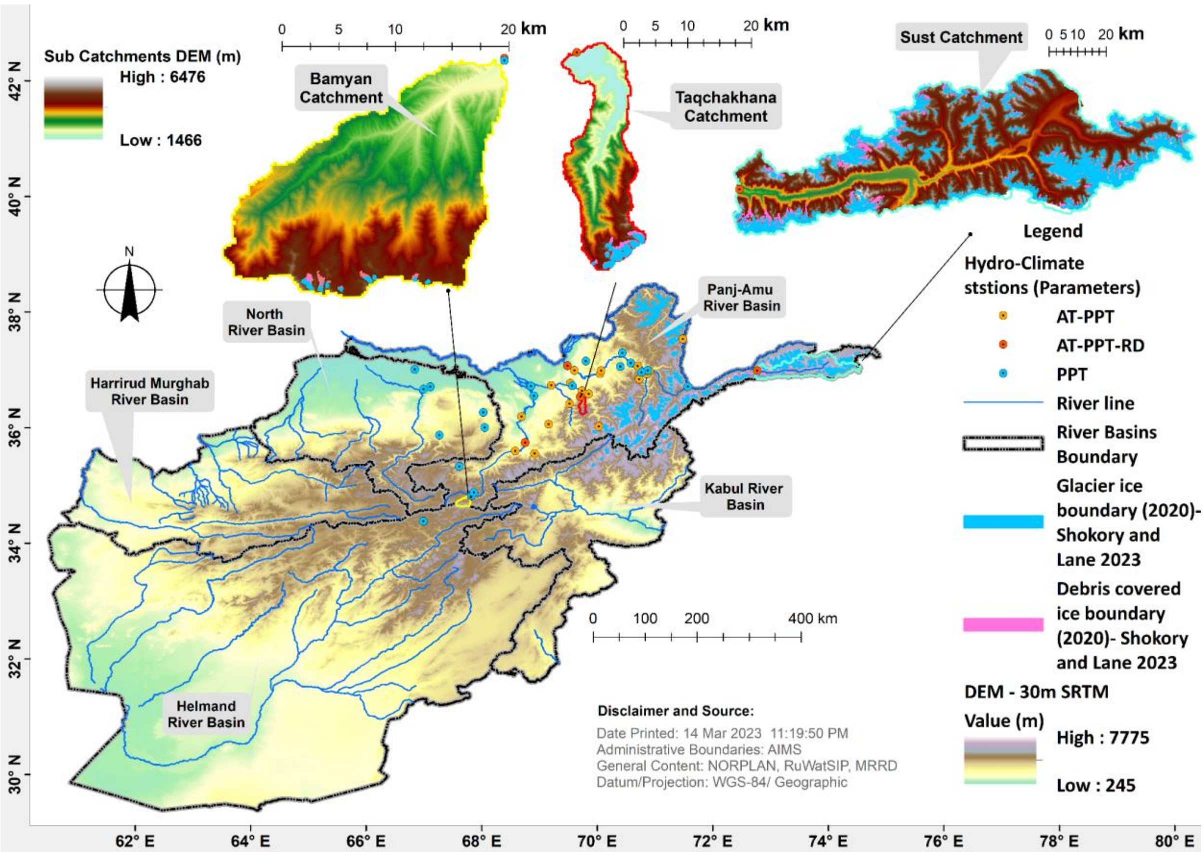


Figure V-1 Geographical map of Afghanistan showing the five major river basins, the three catchments used in this study and the corresponding hydro-climate stations (AT stands for air-temperature, PPT for precipitation, and RD for river discharge).

Table V-1 Characteristics of the three catchments used in this study

Catchments	Area (km^2)	Glacier ice (km^2)	Glacier debris (km^2)	Glacier change 2000-2020 (%)	Relative glacier area	Elevation range (m asl.)	Mean annual precipitation (mm/yr)	Mean temperature (˚C)	Data period
Sust	4608	592.8	124.8	-1.5	15.6 %	2860-6475	320	-0.3	01.04.2013-26.10.2017
Taqchakhana	264.4	4.5	3.0	-3.4	2.8 %	1466-5030	1397	+9.2	01.01.2015-30.09.2019
Bamyan	325.3	1.3	0.002	-22.7	0.7 %	2525-5100	414	+4.2	01.01.2012-30.09.2019

V.3 Methodology

In this section, we present the model, the data used for the glacio-hydrological modeling and model calibration and validation.

V.3.1 Modelling framework

V.3.1.1 Model overview

This study used a new hydrological modeling framework, Hydrobricks (v.0.4.11; Horton, 2023), based on a C++ core with a Python interface. The model structure is a modified version of the GSM-SOCONT (Glacier and SnowMelt – SOil CONTribution) glacio-hydrological model, which is a semi-lumped model (Schaefli et al., 2005) especially well suited to high-altitude catchments (Horton et al., 2022). The model is composed of: (a) the reservoir-based SOCONT model, which comprises a linear reservoir approach for the slow soil contribution and a non-linear reservoir approach for quick runoff, and (b) the GSM model for glacier-covered areas.

The model discretizes the catchment into elevation bands for each land cover type. Meteorological time series are interpolated to the mean elevation of each band using temperature and precipitation lapse rates. Surface and subsurface runoff components and baseflow (from melt and rainfall) are computed per elevation band and integrated at the outlet. The same parameter set is used for all land cover units of the same type. The model workflow is presented in Figure V-2. Whether precipitation falls as snow or rain is computed based on a temperature threshold. Melt is computed following a degree-day approach. On the glacier-covered land units, runoff from melt and rainfall is computed with two parallel linear reservoirs, one for ice melt, and one for snowmelt and rainfall. For the non-glacier covered land units, surface and subsurface runoff are computed with two reservoirs in series (for full details, see Schaefli et al., 2005).

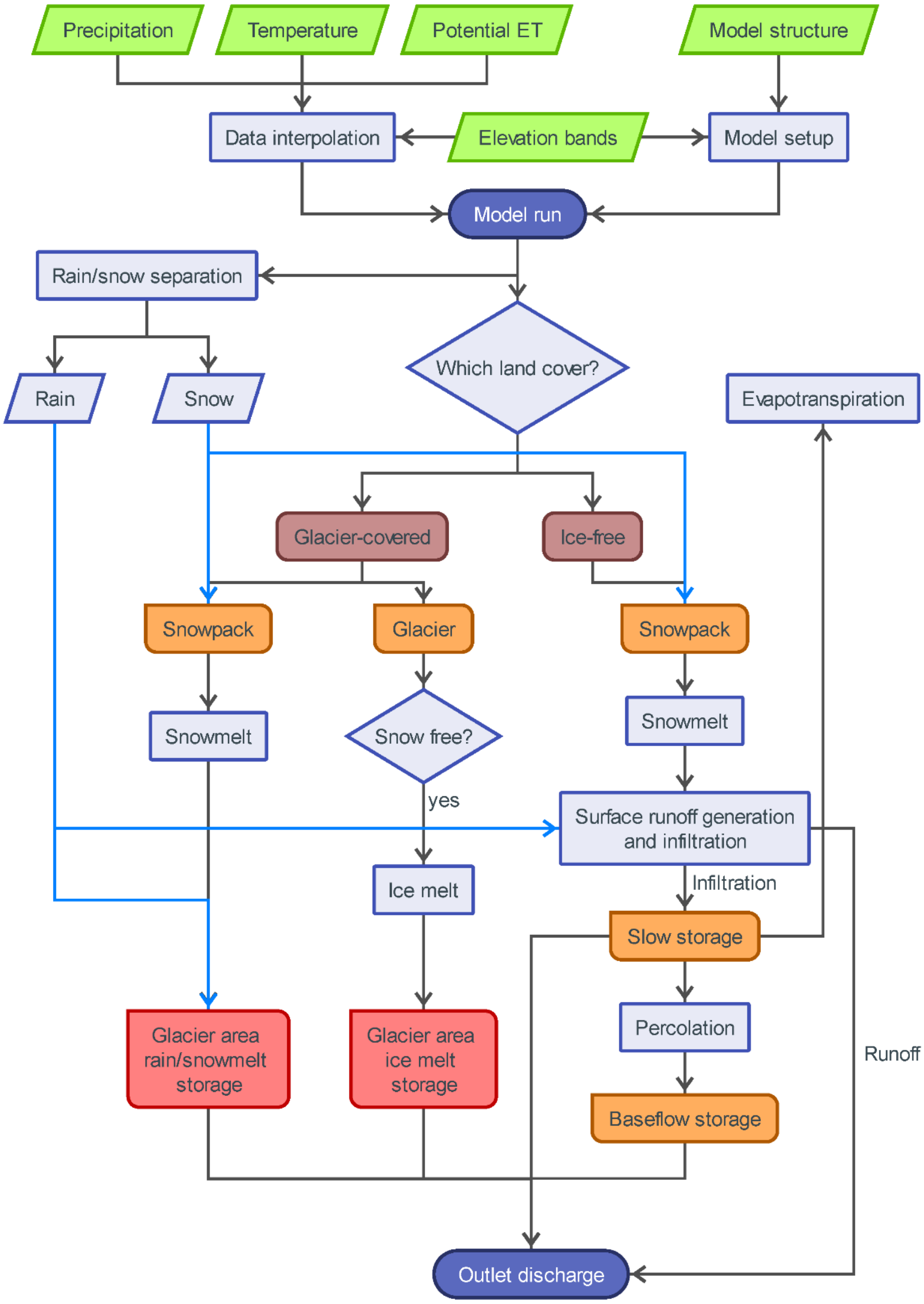


Figure V-2 Illustration of the model workflow used in this study. The glacier-covered part illustrates the behavior of both the bare ice and debris-covered glaciers. Orange reservoirs are distributed over all elevation bands, and red reservoirs are lumped over the catchment.

The main advantage of Hydrobricks over the original Matlab-based version of GSM-SOCONT is the possibility of having multiple land cover types and a dynamic evolution of the land cover fractions over time. This allowed us to add debris-covered ice as a separate land cover type to the model such that we have (1) non-ice land cover, (2) bare ice, and (3) debris-covered ice. The two glacier types differ in how melt is simulated.

Besides adding a debris-covered glacier type and making the land cover evolution more dynamic to account for the retreat of both glacier types, the model was improved by using a fuzzy transition from rainfall to snowfall and by adding an additional baseflow reservoir (a linear reservoir) to improve the representation of groundwater-fed baseflow. For the purpose of this work, quick runoff is computed with a linear reservoir approach, since the parameters of the non-linear approach are difficult to calibrate. Percolation of the slow storage reservoir to the baseflow storage reservoir (Figure V-2) is simulated using a constant percolation rate, which is a parameter to calibrate.

V.3.1.2 Debris-covered ice and dynamic land cover evolution

Here we considered three land cover types: bare ice, debris-covered ice, and others. Some hydrological models considered do not distinguish between ice and debris-covered ice and do not allow cover to evolve (Nepal et al., 2014; Azam et al., 2021). A failure to represent debris cover and to allow glacier contributions to decline may then substantially overestimate streamflow (Tiel et al., 2020).

To address this challenge we modified Hydrobricks in two ways. First, we added a degree-day treatment (Hock, 2003) for debris-covered ice as used by others (e.g. Kayastha et al., 2000; Hagg et al., 2008; Immerzeel et al, 2015). The limits of the degree day approaches for modelling glacier melt are well known (Nicholson and Benn, 2006) but given the data availability, requirements of more complex treatments it was preferred to use a simpler approach but to include a full uncertainty analysis in the modelling approach. This is a compromise between existing models of runoff in Afghanistan that have no or only a partial glacier representation (Bromand, 2015; Ayoubi and Kang, 2016; Akhtar et al., 2021) and the more complex treatments that are more data dependent. To assess the effects of debris-covered ice on streamflow prediction, the model was set up and calibrated twice; 1) with the distinct treatment of bare ice and debris-covered ice, and 2) with the treatment of bare ice and debris-covered ice as a single land cover band.

Second, we recognized that progressive ice loss during the 21st century is likely to limit glacier-originating runoff as the available ice to melt declines below some threshold. Again, it might be possible to develop a deterministic treatment of this process, but we instead chose to develop a simpler empirical treatment based upon measurements of bare ice and debris-covered ice evolution for our catchments from 2000 and 2020 (Chapter IV). Future glacier evolution was calculated using a simple linear decline to the end of the 21st century for bare ice. It is assumed at this time-scale that once ice is covered by a sufficient debris thickness, it remains ice cored for some decades, even if it progressively loses ice mass via melt (e.g. Bolch et al., 2019). Then, the area of bare ice (A) in year *n* compared to a reference year 0 is defined by an empirical bare ice loss factor (Δ_{ice}), the rate of percentage ice loss per year. Lost ice can become either debris-covered ice or ice free.

$$A_{Ice}(n) = \begin{cases} A_{Ice}(r) - n\,A_{Ice}(r)\,\Delta_{Ice} \\ if\ A_{Ice}(n-1) > 0,\ A_{Ice}(r) - n\,A_{Ice}(r)\,\Delta_{Ice} > 0 \\ else \\ 0 \end{cases} \quad (1)$$

$$A_{Deb}(n) = \begin{cases} (A_{Ice}(n-1) - A_{Ice}(n))\,\Delta_{Deb} + A_{Deb}(n-1) \\ if\ A_{Ice}(n-1) > 0 \\ else \\ A_{Deb}(n-1) \end{cases} \quad (2)$$

$$A_{Gr}(n) = A_{Gr}(n-1) + A_{Ice}(n-1) + A_{Deb}(n-1) - A_{Ice}(n) - A_{Deb}(n) \quad (3)$$

where *n* is the present year, *r* is the reference year, A_{Ice} is the area of bare ice elevation bands, A_{Deb} is the area of the debris-covered ice elevation bands, and A_{Gr} is the area of the ice-free elevation bands. Δ_{Ice} is the yearly relative change of bare ice area in percentage, Δ_{Deb} is the relative yearly change of debris-covered ice area. Δ_{Deb} and Δ_{Ice} are obtained from observed remote sensing and satellite images, averaged over 2000-2020 (Chapter IV) for individual catchments (Sust catchment, $\Delta_{Deb} = +15.90\%\ yr^{-1}$ and $\Delta_{Ice} = -0.10\%\ yr^{-1}$; Taqchakhana catchment, $\Delta_{Deb} = +36.70\%\ yr^{-1}$ and $\Delta_{Ice} = -0.46\%\ yr^{-1}$; Bamyan catchment, $\Delta_{Deb} = +0.19\%\ yr^{-1}$ and $\Delta_{Ice} = -1.48\%\ yr^{-1}$). As we have no physically-based treatment of these changes, our predictions are effectively scenarios, that is they are possible futures under the condition that current rates of change for 2000-2020 remain constant.

V.3.2 Model calibration and validation

The model presented here has 12 parameters to calibrate (Table V-2). Some parameters were kept constant, based on other studies, or were estimated based on observed data. The fuzzy transition between rainfall and snowfall was set to start at 0 °C and end at 2 °C (Schaefli and Huss, 2011). As in the original GSM-Socont, the melt temperature for snow and ice was set to 0 °C, and ice melt occurs only when the glacier surface of the considered spatial unit is not covered by snow. The monthly temperature lapse rates and elevation threshold were estimated from observed data (Table V-8, Supplementary Material). The *a priori* parameter ranges were taken from previous work (Schaefli et al., 2005). The debris-covered ice melt factor is considered lower than bare ice, based on the study of Mihalcea et al. (2006) in the same region.

Table V-2 Parameters and their ranges as applied to the model. The precipitation gradient has different a priori maximum values for each catchment, further explained in the data preparation section (S indicates Sust catchment, T, Taqchakhana, and B, Bamyan).

	Component	Parameter	Unit	Abbreviation	Min	max
1	Snowpack	degree-day factor	mm/d/°C	a_{snow}	2	5

2	Clear glacier	degree-day factor	mm/d/°C	a_{ice}	4	10
3	Debris-covered glacier	degree-day factor	mm/d/°C	a_{deb}	2	6
4	snowmelt+rain Runoff from glacier area	reservoir response factor	1/d	k_{snow}	0	1
5	Ice melt from glacier area	reservoir response factor	1/d	k_{ice}	0	1
6	Surface-runoff	reservoir response factor	1/d	k_{quick}	0	1
7	Slow-reservoir	maximum storage capacity	mm	A	100	500
8	Slow-reservoir	reservoir response factor	1/d	$k_{\_slow}$	0	0.005
9	Slow-reservoir	Percolation rate	mm/d	ρ_{per}	0	1
10	Slow-reservoir-2	reservoir response factor	1/d	k_{base}	0	0.005
11	Precipitation	precipitation gradient 1	mm/100m	$\delta_{precip,1}$	0	S: 0.1 T: 0.2 B: 0.2
12	Precipitation	precipitation gradient 2	mm/100m	$\delta_{precip,2}$	0	S: 0.12 T: 0.2 B: 0.2

We used the Shuffled Complex Evolution Algorithm (SCE-UA) for automatic parameter optimization. SCE-UA was used in this study via the Statistical Parameter Optimization Tool for Python (SPOTPY) (Houska et al., 2015). SCE-UA is a global optimization algorithm that was developed for the calibration of conceptual rainfall-runoff models with a small number of parameters (Duan et al., 1992). It has been widely used in many hydrologic modeling studies, and it is now considered one of the most robust and efficient algorithms for parameter calibration (Seong et al., 2015) for comparable models. SCE-UA is used here to find the best performing model parameter set using the modified Kling-Gupta efficiency (KGE) criterion as the objective function (Kling et al., 2012). The KGE is increasingly used as a performance indicator based on the equal weighting of three sub-components: linear correlation between observed and simulated discharge, the bias ratio, and the ratio of standard deviations of the simulated and the observed runoff (Kling et al., 2012). In order to assess the performance of the model beyond a calibration period, we divided the available data (Table V-1) into two periods, one for model calibration and one for assessment of the quality of model predictions beyond the calibration period. The model with two optimized parameter sets, one with the debris cover melt treated separately and one with it combined, was then run from 2000 to 2100 using the bias-corrected climate scenarios for two Representative Concentration Pathways (RCPs, Table V-3). This was undertaken so as to evaluate the effects of debris-cover representations on streamflow simulations and so understand how debris cover representation influences predictions of future melt.

V.3.3 Data collection

The model requires four main input data sets, which are i) hypsometric distributions of elevation for each land cover (bare ice, debris-covered ice, and others) for each catchment, ii) daily precipitation; iii) daily mean temperature, and iv) potential evapotranspiration from at least one observation station. The model does not calculate potential evapotranspiration but rather spatially distributes it across elevation bands.

The catchment hypsometry was computed based on a Digital Elevation Model (DEM) with a resolution of 30 m using Advanced Land Observing Satellite (ALOS, 2023) data. Glacier shape files and retreat rates between 2000 and 2020 are provided in Chapter IV. Meteorological data (temperature and precipitation) and daily river streamflow were obtained from two Afghanistan governmental entities, the Ministry of Energy and Water and the Ministry of Agriculture Irrigation and Livestock (Figure V-1, Table V-8, Supplementary Material). A total of 41 meteorological station data time series were obtained (at elevations < ~ 3000 m.a.s.l). Each catchment contained one of these stations at the catchment outlet where streamflow was also measured. These were used in the modelling. These and the remaining meteorological stations were also used to calculate precipitation gradients and temperature lapse rates for the catchments during data preparation. The potential evapotranspiration data were calculated based on the Hargreaves–Samani method using maximum and minimum daily temperatures (Hargreaves and Samani, 1985) recorded at the meteorological stations.

Subsequently, to analyze the impacts of climate change on future water availability, we forced the model with the latest ensemble of climate models. We collected data from eight General Circulation Models (GCMs) and corresponding Regional Climate Model (RCM) runs from the latest generation of the Coordinated Regional Climate Downscaling Experiment (CORDEX-CMIP6) (Table V-3) and applied bias correction (see below). Then GCMs are used as input to the hydrological model under two RCPs; 2.6 (the concentration of carbon that delivers global warming at an average of 2.6 W/m^2 across the planet 2.6); and 8.5 (8.5 W/m^2). We used RCMs from the South Asia domain (WAS-22) at a daily time step with a horizontal resolution of 0.22° (about 22 km) provided by the Earth System Grid Federation (ESGF https://esgf-node.llnl.gov/search/cmip6/). We used three climate variables from CORDEX, namely, near-surface temperature (tas), precipitation (pr), and potential evapotranspiration (evspsbl) at the daily time scale. We defined the coordinates to obtain the data by the location of the outlet of each catchment (Table V-2). Historical periods were not considered in the analysis, and we had only recent years observed data to perform bias correction. Two periods were considered for the climate change assessments: mid-future (2040 to 2060) and late future (2080 to 2100) to compare with a baseline period of 2000 to 2020.

Table V-3 Summary of the three RCMs and eight GCMs used in this study and their corresponding institutions (His indicates historical period).

Regional Climate Model (RCMs)	Driving model	Scenario	Contributing CMIP6 Modeling Center
COSMO-crCLIM-v1-1_v1	MPI-ESM-LR	His (1950-2005) 2.6 (2006-2099) 8.5 (2006-2099)	Max Planck Institute for Meteorology (MPI-M), Germany
	NorESM1-M		Norwegian Climate Centre (NCC), Norway
REMO2015_v1	HadGEM2-ES	His (1970-2005) 2.6 (2006-2099) 8.5 (2006-2100)	Met Office Hadley Centre for Climate Change (MOHC), United Kingdom
	MPI-ESM-LR		Max Planck Institute for Meteorology (MPI-M), Germany
	NorESM1-M		Norwegian Climate Centre (NCC), Norway
RegCM4-7_v0	MIROC5	His (1970-2005) 2.6 (2006-2099) 8.5 (2006-2099)	Model for Interdisciplinary Research On Climate (MIROC), Japan Agency for Marine-Earth Sci. & Tech., Japan
	MPI-ESM-MR		Max Planck Institute for Meteorology (MPI-M), Germany
	NorESM1-M		Norwegian Climate Centre (NCC), Norway

V.3.4 Data preparation

V.3.4.1 Bias correction of observed station data

The quality of observed precipitation and streamflow data of the catchment stations was assessed using double-mass curves at the daily time scale to evaluate data consistency (Searcy and Hardison, 1960).

For the precipitation data, this was achieved by comparing the individual catchment stations with the average of many records from other stations of the same basin (Figure V-1), with the objective of identifying unexpected slope breaks in the double mass curve. Then, the best reference station with no inconsistency was selected to adjust the catchment stations datasets. For streamflow data, we also used a double-mass curve analysis for individual streamflow datasets of the catchment stations with the average of many station records (Figure V-11, Supplementary Materials). This technique was applied only to the Bamyan and Taqchakhana stations, where neighboring stations were available, but not to the Sust station (Figure V-1).

The data quality of the catchment stations were improved by applying :

$$P_a = \frac{b_a}{b_o} P_o \tag{4}$$

where P_a [mm] is the adjusted precipitation or streamflow of the catchment stations where inconsistency were observed. P_o [mm] is the observed precipitation or streamflow data with best fit double-mass curve (reference station).

b_a [-] is the slope of the double-mass curve in the catchment station to be adjusted.

b_o [-] is the slope of the double-mass curve for the reference station.

V.3.4.2 Bias correction of climate model data

RCMs have biases compared to ground stations, partly inherited from the driving GCMs (Rummukainen, 2010; Hall, 2014; Maraun, 2016). Such biases were also observed for the three catchments used in this study, for both precipitation and temperature data (Figure V-12, Figure V-14, Supplementary Material). To remove these biases and adjust the distribution of RCMs to resemble the observed data, we applied the quantile mapping bias correction method, which is frequently used in water resources studies (Gudmundsson et al., 2012). Gudmundsson et al. (2012) presented three transformation approaches, 1) distribution-derived, 2) parametric, and 3) nonparametric, in which they obtained the highest skill in systematically reducing biases with nonparametric transformation. Therefore, we also applied nonparametric transformation for further analysis in our study.

V.3.4.3 Precipitation gradients and temperature lapse rates

Precipitation gradients and temperature lapse rates have a significant impact on the water balance in glacio-hydrological models, especially in mountain regions, and may vary based on elevation and season (Immerzeel et al., 2014). Afghanistan rivers are generally fed by snow and ice at altitudes > 3000 m a.s.l. At these altitudes, data are scarce (Chapter II). This makes the estimation of lapse rates challenging. In addition, complex topography, the dominance of solid precipitation, and strong winds at high elevations likely result in unreliable precipitation measurements (Freudiger et al., 2017). Moreover, there is a known, large regional variation in the precipitation gradient in the mountains region of Afghanistan (Azizi and Asaoka 2020).

To obtain reasonable catchment-scale precipitation estimates, elevation-dependent precipitation gradients have to be estimated based on available station data (Immerzeel et al., 2014). In our study, the precipitation gradient approach was based upon the observation from all 41 stations combined that above a certain altitude there was a break point of threshold in the relationship between precipitation and altitude (Figure S5, Supplamentary Material), but that this threshold was fuzzy. We found that this break point was commonly close to the modal value of the hypsometric curve; that is the altitude of the most frequent altitude band of the catchments for the 41 stations. Thus, we use this altitude but calculated for each catchment as the break point in the precipitation-altitude relationship (Figure S6, Supplamentary Materials). Further work is needed to assess the suitability of this approach and how sensitive model predictions are to it.

From the observed data of 41 station showed that the rate of increase of precipitation as a function of altitude below the elevation threshold ($\delta_{precip,1}$) was higher than above the elevation threshold ($\delta_{precip,2}$). However, in each catchment there was only one precipitation recording station. So it was not possible to determine ($\delta_{precip,1}$) and ($\delta_{precip,1}$) and these had to be treated as calibration parameters. The calibration process was able to profit from the observation that if precipitation was too great at high altitudes the model would over-accumulate snow, what is known as “snow towers”, multi-year accumulation of snow at high elevations and an incorrect water balance (Freudiger et al., 2017). Initial model simulations focused only on snow accumulation to identify maximum possible precipitation gradients for both ($\delta_{precip,1}$) and ($\delta_{precip,1}$) in the calibration process; 10 mm/100 m in the Sust; and 20 mm/100m for the other two catchments. The minimum possible values were set to 0 in all cases.

The need for monthly variation in temperature lapse rates is well known (Aizen et al., 2000; Immerzeel et al., 2014; He et al., 2025). Thus, for the temperature lapse rate, we assessed the observed mean monthly temperature data of 23 out of 41 stations which had temperature measurement (Figure V-1) (Table V-8, Supplementary Materials) for each month of the year to calculate the lapse rates.

V.4 Results

V.4.1 Data correction: double mass curves and bias

Double mass curves suggested a slight inconsistency in observed precipitation and streamflow data for Bamyan station (Figure V-11b,d, Supplementary Materials). Thus, these data were adjusted and improved (Figure V-11a,c, Supplementary Materials) using the Keshem and Balaye Kelagai stations (Figure V-11e, f, Supplementary Materials). In addition, we observed a significant deviation in the streamflow of the Taqchakhana catchment (Figure V-11g, Supplementary Materials). This inconsistency was adjusted with the Khwajaghar station, and the data improved (Figure V-11h,i, Supplementary Materials).

Projected climate data had substantial overestimations of GCM precipitation for all three catchments, mainly for Spring (MAM) and Summer (JJA) months (Figure V-12, Supplementary Materials). On the other hand, the projected temperature data from the original GCMs had an underestimation of mean temperature compared with the Sust and Taqchakhana catchments observed data (Figure V-14, Supplementary Materials). At the same time, Bamyan had an overestimated temperature compared with the observed data. Bias correction considerably improved the projected precipitation and temperature quality (Figure V-13, Figure V-14, Supplementary Materials). The evaluation was done for monthly precipitation and temperature values throughout the available observed data (Table V-1), with a reduced mean area error (MEA) for evaluation. However, we found that precipitation data of for RegCM4-7_v0 continuously overestimated summer precipitation after the bias correction. Therefore, we removed it from further consideration in the modeling and used only five GCMs. The temperature data of three catchments showed a more acceptable fit with GCMs after the bias correction (Figure V-14, Supplementary Materials).

V.4.2 Precipitation gradients and temperature lapse rates

In most years, the annual precipitation of 41 stations showed an altitudinal dependence to c. 2000 m.a.s.l elevation (Figure V-15, Supplementary Materials) and this was taken as the lower threshold for the Taqchakhana catchment. The threshold appeared to be higher for the Sust and much higher for the Bamyan catchments, at 2800 m a.s.l. and 4800 m a.s.l. respectively (Figure V-16, Supplementary Materials).

The optimized lower elevation precipitation gradients ($\delta_{precip,1}$) were smaller than the higher elevation gradients ($\delta_{precip,2}$) for the TaqchaKhana. However, for the Sust they were more similar and for the Bamyan catchment in the center of Afghanistan, optimal precipitation gradients were the same for both low and high elevations (Table V-4). Thus, it seems that there is likely only a sensitivity to the threshold in the precipitation-altitude relationship for the TaqchaKhana. The monthly mean temperature data for 23 observed stations showed importantly different lapse rate for each month of the year (Figure V-17, Supplementary Materials). A lower lapse rate was observed in winter and early spring months: 0.28 °C/100 m in December, rising to 0.55 °C/100 m in June. However, observed data only covered the altitudinal range of 488 to 3076 m.a.s.l, and whether this lapse rate is constant or changes at a higher elevation is unclear.

V.4.3 Scenarios for future ice cover

Figure V-3 shows the scenarios for future bare ice and debris-covered ice based on (1) through (3). It shows that extrapolation of current rates of change leads to ice loss in the Sust, but that by the end of the 2100s this remains small in magnitude compared with the initial ice cover. The debris-covered ice extent increses but at a slower rate than the rate of bare ice loss, showing that there is a net loss in total ice cover. In proportional terms, bare ice loss and debris-covered ice gain are greater for the TaqchaKhana but both are still present by the 2100s. In the Bamyan, there is a prediction of declining bare ice and debris-covered ice, and bare ice disappears entirely before the 2100s.

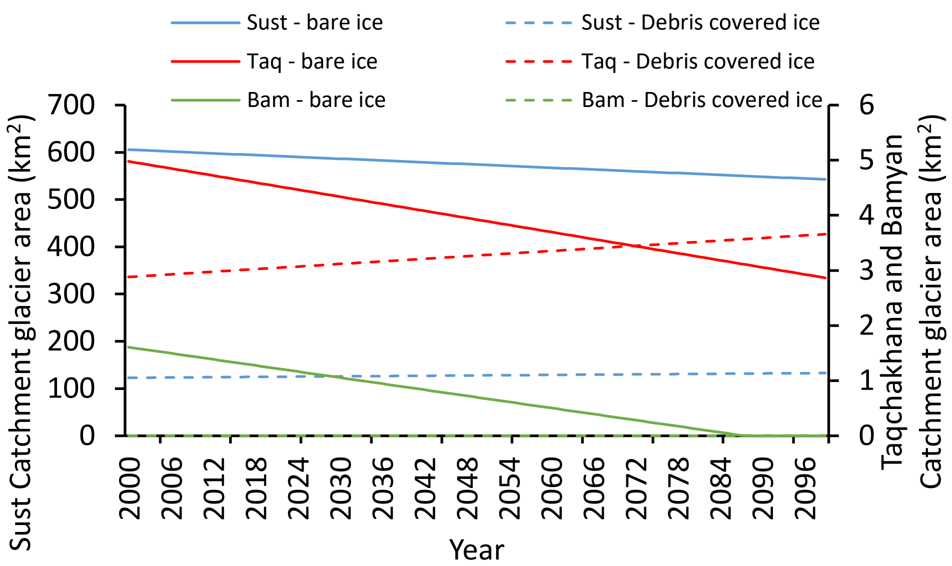


Figure V-3 Glacier evolution for the Sust and Taqchakhana catchments

V.4.4 Model calibration and validation

Optimal model parameter sets (Table V-4) were obtained after 30,000 iterations for each catchment (Sust, Taqchakhana, and Bamyan) for the model version that included bare ice and debris-covered ice separately. After calibration, the KGE values for the daily streamflow series were more than 0.8 for all catchments (Table V-4). For the Sust, the KGE improved during validation, but it declined for the Taqchakhana and the Bamyan catchments, although the values remained high (Table V-4). Comparing the parameter sets suggested the identification of real differences in model behavior.

The optimized lower elevation precipitation gradients ($\delta_{precip,1}$) were smaller than the higher elevation gradients ($\delta_{precip,2}$) for the Sust and the Taqchakhana. However, for Bamyan catchment in the center of Afghanistan, optimal precipitation gradients were the same for both low and high elevations (Table V-4).

Table V-4 Parameters set for calibration of model for individual catchment, and KGE objective function value for calibration (Cal.) and validation (Val.) periods for (a) the model with separate bare ice and debris-covered ice treatments and (b) without. Parameter uncertainty added as standard deviation associated with simulations with KGE>0.8

(a)

Model Parameters	**Unit**	**Sust Catchment**		**Taqchakhana Catchment**		**Bamyan Catchment**	
		Cal. KGE	**Val. KGE**	**Cal. KGE**	**Val. KGE**	**Cal. KGE**	**Val. KGE**
		0.83	**0.87**	**0.91**	**0.80**	**0.83**	**0.73**
a_{snow}	mm/d/°C	4.99±0.26		4.99±0.65		2.70±0.06	
a_{ice}	mm/d/°C	7.16±0.46		9.98±0.43		9.94±0.22	
a_{deb}	mm/d/°C	4.97±0.50		5.98±0.42		4.99±0.19	
k_{snow}	1/t	0.30±0.10		0.03±0.16		0.52±0.03	
k_{ice}	1/t	0.23±0.05		0.89±0.11		0.75±0.03	
k_{quick}	1/t	0.60±0.07		0.01±0.003		0.15±0.04	
A	mm	498±64.0		493±31.8		320±6.76	
k_{slow}	1/t	0.004±0.0003		0.001±0.0006		0.004±0.0001	
ρ_{per}	mm/d	0.99±0.11		0.49±0.09		0.42±0.01	
k_{base}	1/t	0.004±0.0007		0.0008±0.0004		0.004±0.0003	
$\delta_{precip,1}$	mm/100m	0.09±0.01		0.07±0.01		0.18±0.0005	
$\delta_{precip,2}$	mm/100m	0.11±0.02		0.15±0.01		0.18±0.001	

(b)

Model Parameters	**Unit**	**Sust Catchment**		**Taqchakhana Catchment**		**Bamyan Catchment**	
		Cal. KGE	**Val. KGE**	**Cal. KGE**	**Val. KGE**	**Cal. KGE**	**Val. KGE**
		0.83	**0.86**	**0.91**	**0.81**	**0.83**	**0.70**
a_{snow}	mm/d/°C	4.99±0.33		4.99±0.53		2.60±0.08	
a_{ice}	mm/d/°C	6.67±0.30		9.81±0.27		9.96±0.31	
a_{deb}	mm/d/°C						
k_{snow}	1/t	0.28±0.09		0.03±18		0.42±0.04	
k_{ice}	1/t	0.23±0.06		0.69±0.05		0.85±0.09	
k_{quick}	1/t	0.60±0.08		0.01±0.005		0.23±0.07	
A	mm	499±64.4		499±30.0		327±8.75	
k_{slow}	1/t	0.004±0.0004		0.002±0.0005		0.004±0.0001	
ρ_{per}	mm/d	0.99±0.11		0.63±0.06		0.40±0.02	
k_{base}	1/t	0.004±0.0008		0.0007±0.0005		0.004±0.0004	
$\delta_{precip,1}$	mm/100m	0.09±0.01		0.03±0.01		0.18±0.0005	
$\delta_{precip,2}$	mm/100m	0.11±0.02		0.17±0.01		0.18±0.0009	

Table V-4 allows us to compare the effects of the separate bare ice and debris-covered ice treatment (Table V-4a) with the single glacier land cover treatment (Table V-4b). Most notably, when the separate debris-covered ice treatment is removed, the melt factor for ice declines the most in the most glaciated catchment (the Sust) and hardly changes in the least glaciated catchment (the Bayman). This is as expected as a failure to represent debris-covered ice explicitly should result in a lower catchment wide ice melt factor as compensation. Most other parameterisations do not change much, perhaps the notable exception being some of the TaqchaKhana catchments and this may reflect the calibration process having difficulties in finding the right parameter values.

Visual comparison of the optimized daily simulated and observed streamflow showed that the model reproduced well the hydrological responses of all three catchments (Figure V-4). There were some exceptions for a few individual years, which may be due to data quality (Sect. V.3.2.1). The high flow corresponding to the snow and ice melt seasons is illustrated in the modeling results, representation of which is essential for water resource assessment.

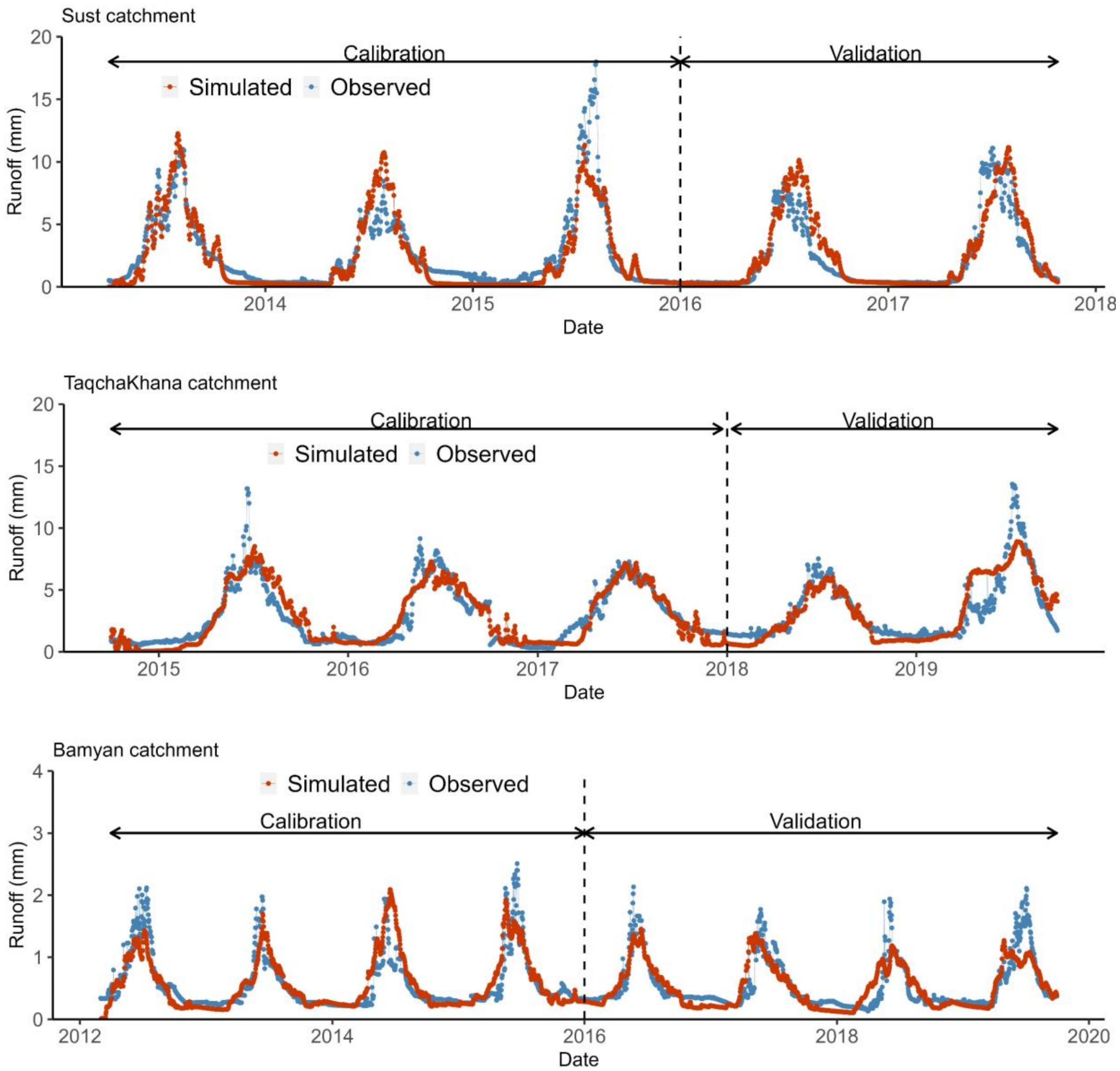


Figure V-4 Daily simulated and observed runoff for three catchments with an indication of the calibration and validation periods.

V.4.5 Runoff components

The three main streamflow components (1. rain and snow runoff, 2. glacier runoff, and 3. baseflow, Figure V-5) showed different contributions between the three catchments the the model using separate bare ice and debris-covered ice degree day models. The Sust had the highest contribution from glacier runoff (76% of the total streamflow), the Taqchakhana 33%, and the Bamyan 17%. The yearly mean glacier runoff was more notably different, at 0.65 m yr^{-1} for the Sust, 0.35 m yr^{-1} for the Taqchakhana, and 0.04 m yr^{-1} for the Bamyan. On the other hand, the Taqchakhana catchment had the highest contribution (50%) from rain and snow runoff, reflecting its higher annual rainfall (Table V-1). The Bamyan catchment had the highest contribution from baseflow (61%) and the lowest contribution from glacier runoff (17%), reflecting the smaller glacier area (Table V-1).

The distribution of water production by elevation band (weighted by the land cover fraction and the elevation band area, Figure V-5) suggests that the Sust catchment produces water mainly through glacier melt in the 4000 to 6000 m.a.s.l elevation range, with a peak at 5000 m.a.s.l. The Taqchakhana catchment streamflow originates predominantly between 4000 and 5000 m.a.s.l., along with a substantial contribution from rain and snow runoff between 3000-4000 m.a.s.l elevations, mainly in the spring months (Figure V-5b,e). The Bamyan catchment has a substantial contribution between 4000 and 5000 m.a.s.l and substantial baseflow at lower elevations (Figure V-5).

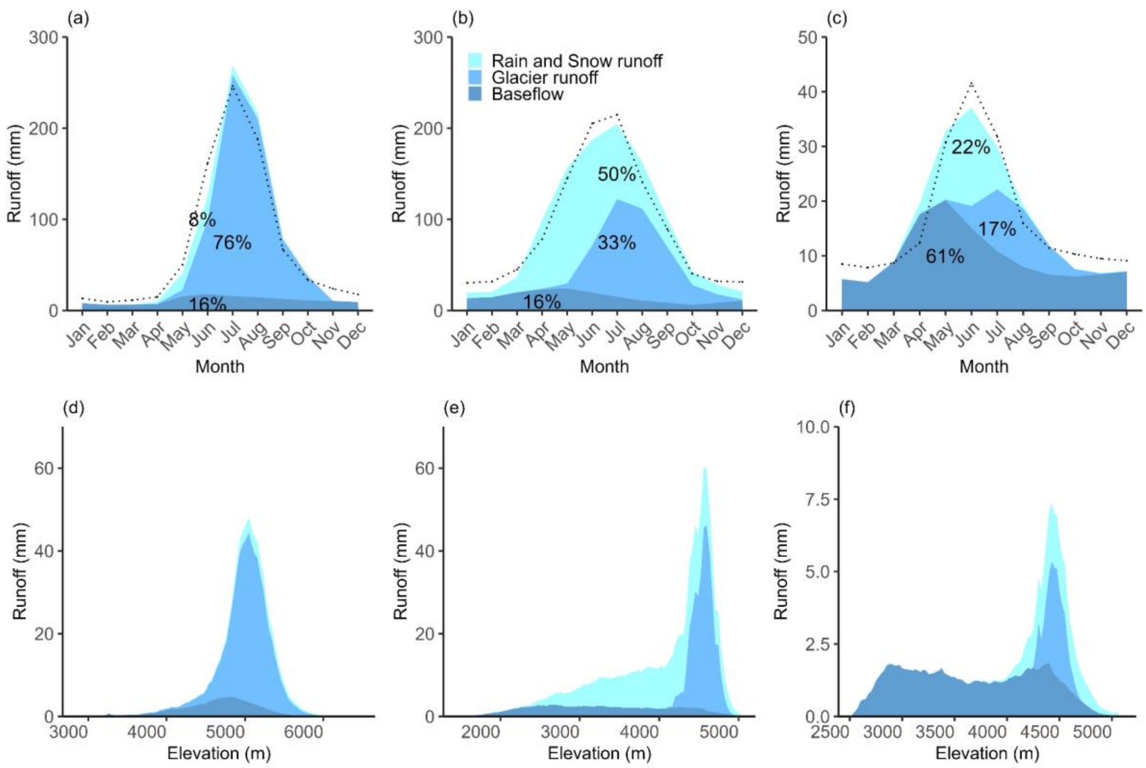


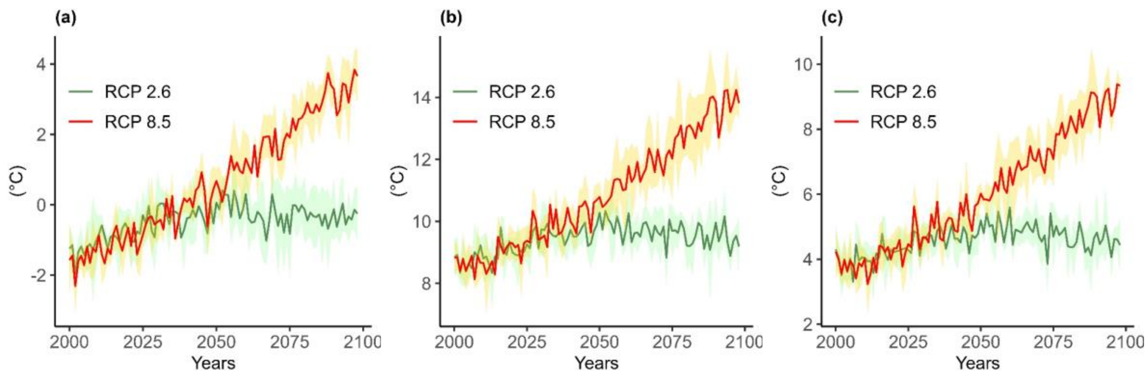
Figure V-5 Contribution of runoff components (Rain and snow runoff, Glacier runoff, and Baseflow) presented for individual catchments, (a and d) Sust catchment, (b and e) Taqchakhana catchment, and (c and f) Bamyan catchment). a-c show mean monthly runoff for the whole availible data periods (Table 1) with percentage contribution of three different component. d-f present mean annual runoff at each elevation bands.

V.4.6 Projection of future climate and streamflow

This section presents future projected climate (precipitation and temperature) and streamflow for two RCPs, (low emission 2.6 and high emission 8.5) and averaged over two timespans (2040 to 2060) labeled as the 2060s and (2080 to 2100) as 2100s, compared with the baseline period that is considered from 2000 to 2020 as 2020s. Baseline with each timespans are tested for significant differences by Mann-Whitney test (Tallarida et al., 1987). The results are illustrated for two timescales, 1) at the annual scale with uncertainties calculated including the standard deviation of the five ensembles (i.e. Table V-2, except RegCM4-7_v0) and 2) at a seasonal scale that show all data. Therefore, numbers should be carefully examined concerning the uncertainties in the relevant figures.

V.4.6.1 Changes in temperature and precipitation

The mean annual temperature is projected to increase under RCP 2.6 to about 2050 (by ~ 0.9˚C) and then decline (by ~ 0.6˚C) until the end of the 21st century as compared with the baseline. Under RCP 8.5, the temperature is projected to rise more rapidly and throughout the 21st century (by ~1.8˚ C by 2060s and ~ 4.4˚C by 2100s) and for all three catchments (Figure V-6a-c). Seasonal variations in temperature from all ensembles are plotted for three timespans (2020s, 2060s, 2100s) and all catchments (Figure V-7a-f). Table V-5 summarizes these results and shows a significant temperature increase for all seasons, lower in spring and summer but higher for autumn and winter under both RCPs (2.6 and 8.5). However, as with the annual patterns under RCP 2.6, the severity is lower by the 2100s (Table V-5).



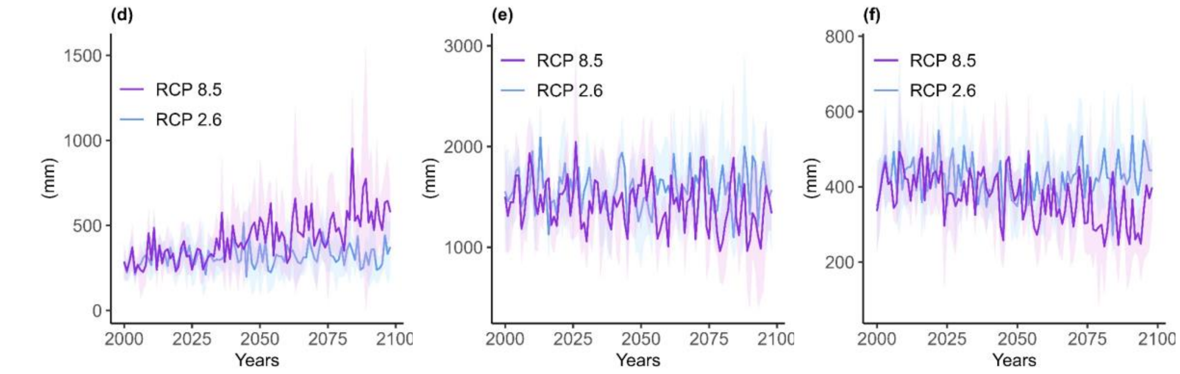
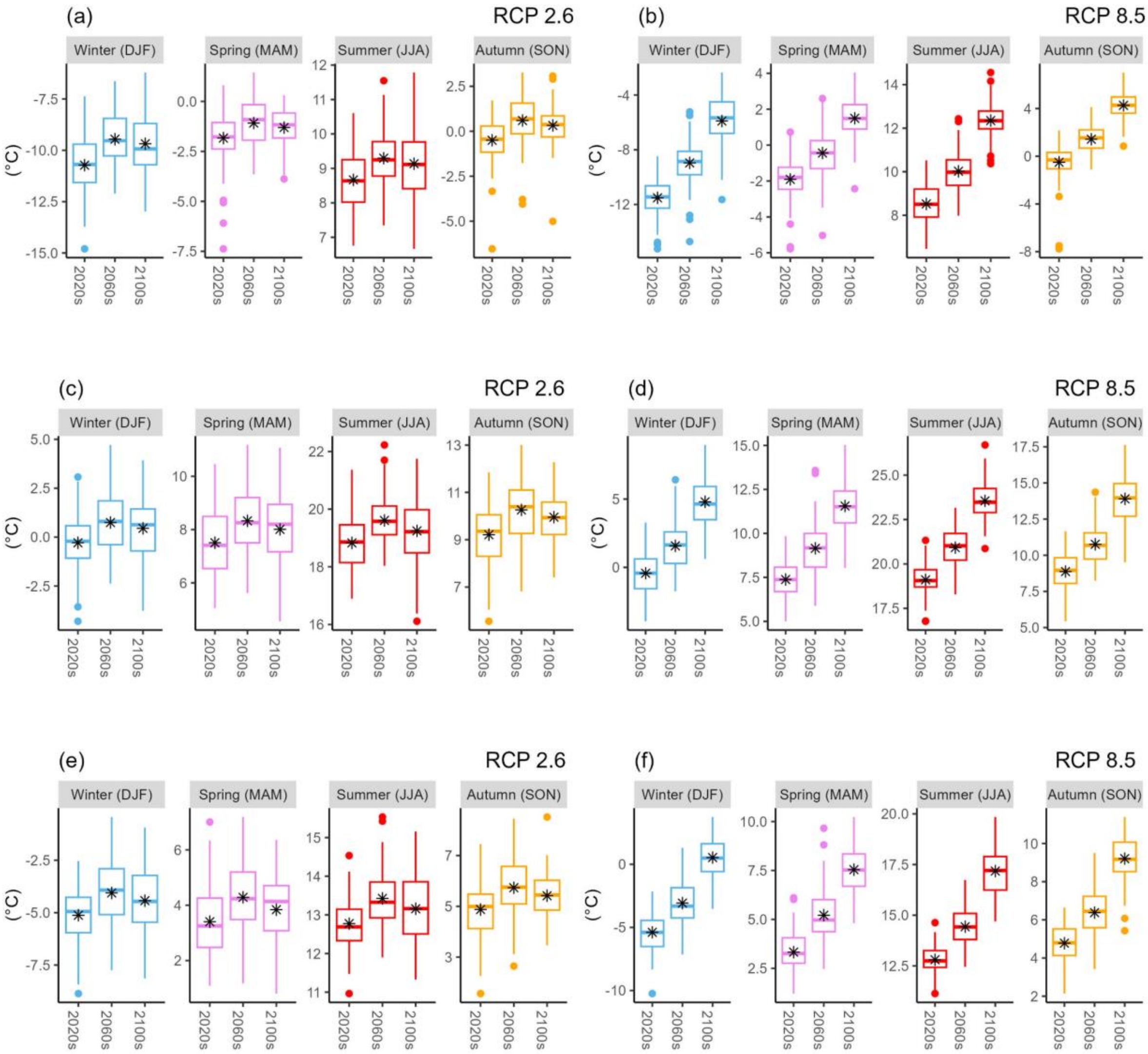


Figure V-6 Shows projected mean annual temperature (a-c) and precipitation (d-f) in three catchments (a,d Sust; b,e Taqchakhana; and c,f Bamyan catchment), estimated by the ensembles. Shading represents the standard deviation of the five model ensembles (Table V-3).



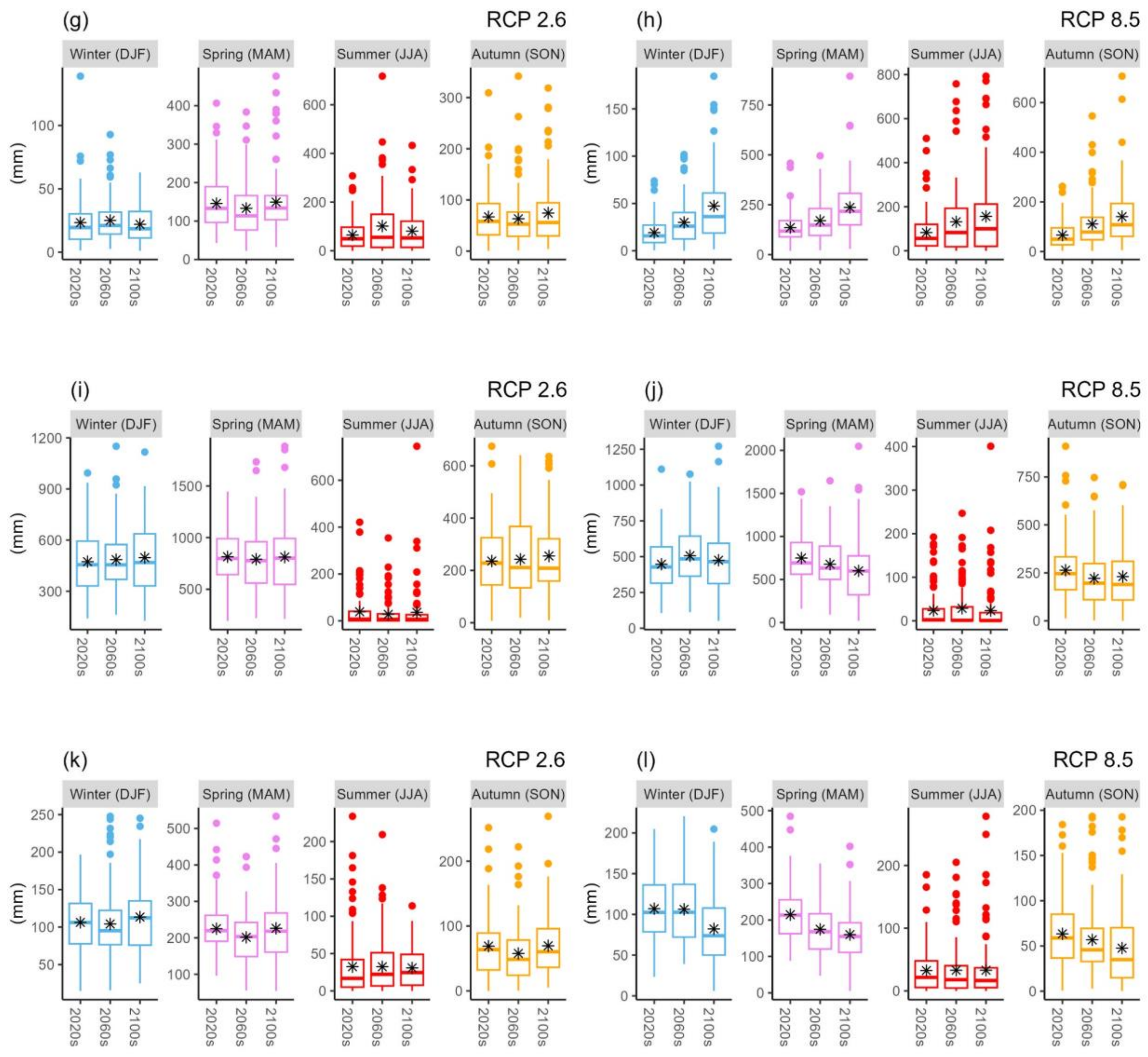


Figure V-7 Illustrates projected mean seasonal temperature (a-f) and precipitation (g-l) from five ensembles under RCP 2.6 and 8.5 and three timespans (2020s, 2060s, 2100s) and three catchments (a,b, g,h presents Sust catchment; c,d,i,j presents Taqchakhana catchment; e,f,k,l presents Bamyan catchment). The upper and lower box margins mark the 75th (Q75) and the 25th (Q25) quartiles, respectively, with the mid box line showing the median. The whiskers show the extremes of the data (maximum and minimum) except for situations where outliers are present, defined as either Q75 + 1.5(Q75 - Q25) for the maximum and Q25 - 1.5(Q75 - Q25) for the minimum. The star symbol shows the mean seasonal value for particular periods.

Table V-5 Changes in projected precipitation and temperature compared with 2000-2020 baseline. Statistically significant changes ($p<0.05$) are marked for a two-tailed Student's t test.

Runoff components		Precipitation (mm)				Temperature (°C)			
RCPs		2.6		8.5		2.6		8.5	
Catchment		2060s	2100s	2060s	2100s	2060s	2100s	2060s	2100s
Sust	Winter	1.7	-1.3	**6.6**	**23.9**	**1.3**	**1.0**	**2.6**	**5.6**
	Spring	-12.5	3.5	24.6	**90.8**	**0.8**	**0.5**	**1.5**	**3.4**
	Summer	36.5	15.8	**66.7**	**91.1**	**0.6**	**0.5**	**1.5**	**3.8**
	Autumn	-3.8	7.4	**43.5**	**73.3**	**1.1**	**0.8**	**1.9**	**4.8**
	Annual	21.8	26.2	138.0	268.0	**0.9**	**0.7**	**1.9**	**4.4**
Taqchakhana	Winter	11.7	24.1	32.6	0.0	**1.0**	**0.7**	**2.0**	**5.2**
	Spring	-23.4	-2.6	**-136.0**	**-214.0**	**0.8**	**0.5**	**1.8**	**4.2**
	Summer	-11.0	-2.4	-10.0	**-15.2**	**0.8**	**0.4**	**1.8**	**4.4**
	Autumn	6.9	19.3	-14.3	-5.2	**1.0**	**0.7**	**1.9**	**5.0**
	Annual	-15.8	35.8	-128.0	-244.0	**0.9**	**0.6**	**1.9**	**4.8**
Bamyan	Winter	-2.1	7.1	0.0	**-24.0**	**1.1**	**0.7**	**2.3**	**5.9**
	Spring	**-23.6**	0.0	**-50.6**	**-65.3**	**0.9**	**0.4**	**1.9**	**4.2**
	Summer	0.0	-1.6	0.0	0.0	**0.7**	**0.4**	**1.6**	**4.4**
	Autumn	**-11.2**	0.0	**-12.2**	**-21.4**	**0.9**	**0.5**	**1.6**	**4.4**
	Annual	**-37.0**	7.8	**-62.4**	-113.0	**0.9**	**0.5**	**1.9**	**4.8**

Table V-5 also indicates changes in precipitation and it is clear that these are less clearly statistically significant and then primarily then only under RCP 8.5. The exception is for the Bamyan catchment where under both RCPs (2.6 and 8.5) significant decreases in mean annual precipitation for are predicted by the 2060s (-37.0 mm yr^{-1}, -62.4 mm yr^{-1}, respectively, by 2060s) (Table V-5, f) and primarily in spring and autumn (Table V-5). However, these changes are only clear to the 2100s under RCP 8.5. The Sust is forecast to have statistically significant precipitation increases but only under RCP 8.5 (Figure V-6d, Table V-5). The Taqchakhana catchmentis forecast to have significant precipitation decreases in spring under RCP 8.5 both to the 2060s and 2100s and in summer only to the 2100s. The magnitude of the Taqchakhana catchments are large but not always significant and this is because this basin has the highest baseline and forecast interannual variability.

V.4.6.2 Changes in streamflow

We presented the future mean annual streamflow for the three catchments in Figure V-8a-f. Our evaluation of changes in streamflow is summarized in Table V-6 and Figure V-9 (including all seasonal mean of ensembles) in terms of the three components: (1) runoff from rain and snow of the whole catchment (glacier and nonglacier part); (2) glacier runoff includes runoff from bare ice and debris-covered ice, although they are modelled separately; and (3) baseflow.

Table V-6Model results with debris covere treatments, changes in streamflow runoff components (mm) under two RCPs (2.6 and 8.5) in two timespans (2060s and 2100s) as compared with the 2000-2020 *baseline. Statistically significant changes ($p<0.05$) are marked for a two-tailed Student's t test.*

Runoff components		Baseflow (mm)				Rain and Snow runoff (mm)				Glacier runoff (mm)				Total Streamflow (mm)			
RCPs		2.6		8.5		2.6		8.5		2.6		8.5		2.6		8.5	
Catchment		2060s	2100s	2060s	2100s	2060s	2100s	2060s	2100s	2060s	2100s	2060s	2100s	2060s	2100s	2060s	2100s
Sust	Winter	3.0	3.9	**18.5**	**35.1**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	3.0	3.9	**18.5**	**35.1**
	Spring	**3.4**	**4.1**	**19.5**	**41.1**	**3.1**	**3.1**	**10.4**	**29.1**	**8.4**	**4.5**	**21.4**	**64.0**	**14.9**	**11.7**	**51.3**	**134.2**
	Summer	4.3	5.5	**23.6**	**41.7**	1.0	-2.3	8.4	9.5	**45.5**	10.6	**120.0**	**322.0**	**50.8**	13.8	**152.0**	**373.2**
	Autumn	4.5	5.8	**24.4**	**41.2**	-0.3	1.2	**10.6**	**26.2**	**36.3**	**11.5**	**58.5**	**198.0**	**40.5**	**18.5**	**93.5**	**265.4**
	Annual	15.3	19.5	**81.2**	**154.5**	3.9	2.0	**30.2**	**67.3**	**90.4**	26.4	**187.7**	**576.2**	**109.6**	**47.9**	**299.1**	**798.0**
TaqchaKhana	Winter	2.2	**6.0**	0.6	0.0	**18.7**	**27.3**	**16.0**	**40.6**	**2.6**	**1.3**	**6.2**	**30.9**	**23.5**	**34.6**	**22.8**	**71.5**
	Spring	**1.2**	**1.8**	1.3	-1.6	31.0	29.8	41.2	28.7	**6.4**	**5.5**	**21.7**	**69.6**	**38.6**	37.1	64.2	**96.7**
	Summer	**-3.8**	-2.3	**-4.3**	**-10.3**	**-38.0**	-11.5	**-64.4**	**-134.0**	3.2	**-35.5**	**31.5**	**55.7**	**-38.6**	**-49.3**	**-37.2**	**-88.6**
	Autumn	-1.6	0.0	**-2.4**	**-2.9**	-10.8	2.1	**-18.5**	**-38.3**	**7.2**	**-10.6**	**23.2**	**63.0**	-5.2	**-8.5**	**2.3**	21.8
	Annual	-1.9	5.5	-4.9	**-15.1**	0.0	47.8	**-92.4**	**-169.0**	**19.5**	**-39.2**	**84.4**	**221.0**	**17.6**	14.1	-12.9	**36.9**
Bamyan	Winter	-2.3	1.6	-2.9	**-7.5**	**0.0**	**0.0**	**0.0**	0.0	**0.0**	0.0	**0.0**	**0.0**	-2.3	1.6	-2.9	**-7.5**
	Spring	-1.3	2.3	-2.6	**-10.1**	5.6	**9.5**	**7.3**	2.9	**-0.1**	-0.5	**0.0**	**-0.3**	4.2	**11.3**	4.7	**-7.5**
	Summer	**-7.0**	-1.1	**-14.2**	**-28.6**	**-23.7**	-8.5	**-36.3**	**-53.4**	**-11.2**	**-26.4**	**-8.6**	**-25.9**	**-41.9**	**-36.0**	**-59.1**	**-107.9**
	Autumn	**-4.5**	-1.7	**-8.0**	**-15.7**	**-0.6**	**-0.7**	**-0.4**	**-0.1**	**-3.8**	**-9.0**	**-2.8**	**-8.8**	**-8.9**	**-11.4**	**-11.2**	**-24.6**
	Annual	**-15.8**	1.2	**-27.8**	**-62.1**	**-18.7**	0.4	**-29.4**	**-50.3**	**-15.1**	**-36.1**	**-10.5**	**-35.1**	**-49.6**	**-34.5**	**-67.7**	**-147.5**

The prediction for the Bamyan catchment suggest decreases in all mean annual streamflow components under both RCP 2.6 and RCP 8.5 and for both simulated periods (Figure V-8, Table V-6) except for projections for baseflow and rain/snow runoff under RCCP 2.6 to the 2100s. The Taqchakhana catchment is projected to have a significant trend of increasing glacier runoff under RCP 8.5 to both the 2060s and 2100s; but under RCP 2.6 the 2100s are marked by decreases in glacier runoff. There is a marked change in seasonality associated with increased rain/snow runoff in winter and declining rain/snow runoff in summer (RCP 2.6 to the 2100s excepted). Under RCP 2.6 there is some evidence of higher winter and spring baseflow and lower summer and autumn baseflow, under both RCPs. Table V-5 shows that the dominant effect of these changes is the winter increases and summer/autumn decreases in snow/rain runoff which are then seen in major changes in total flows in the TaqchaKhana in summer; even if the annual streamflow changes are only significant for RCP 8.5 to the 2100s. The TaqchaKhana does not seem to have a sufficient glacier distribution at the right altitudes (where temperature, even if increasing, is sufficient to cause melt) for it to be able to fully compensate for declining winter snow accumulation and summer runoff.

The most glacially-covered catchment, the Sust, differs in many senses. Annual total streamflow is forecast to rise under both RCPs, but notably RCP 8.5, and to the 2060s and 2100s. Under RCP 2.6, the changes are much smaller than under RCP 8.5. The generalized increases in total stream flow can be found across all seasons, except under RCP 2.6 and for winter and summer to the 2100s. These increases in flows can also be seen to differing degrees in all runoff components and this reflects the implications of wetter conditions, notably for RCP 8.5 (Table V-5) which will impact both baseflow and rain/snow melt runoff; and warmer conditions (Table V-5) which should increase glacier melt in the catchment which has the highest ice cover.

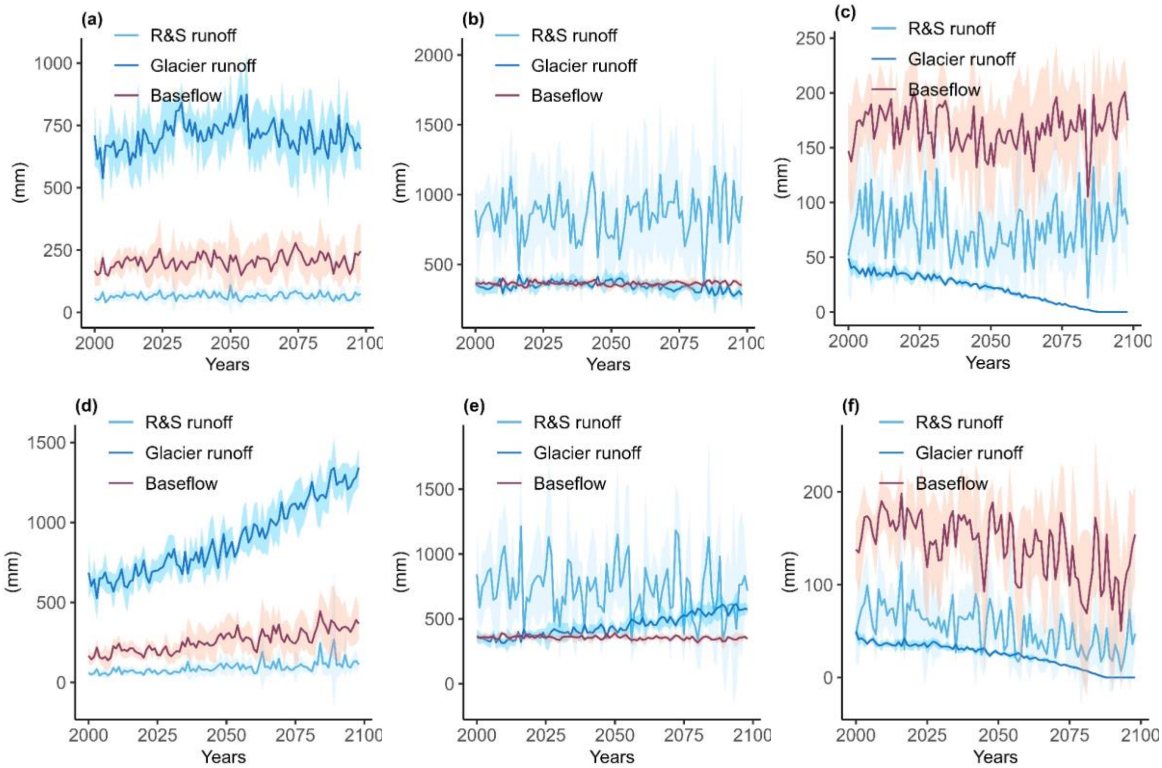
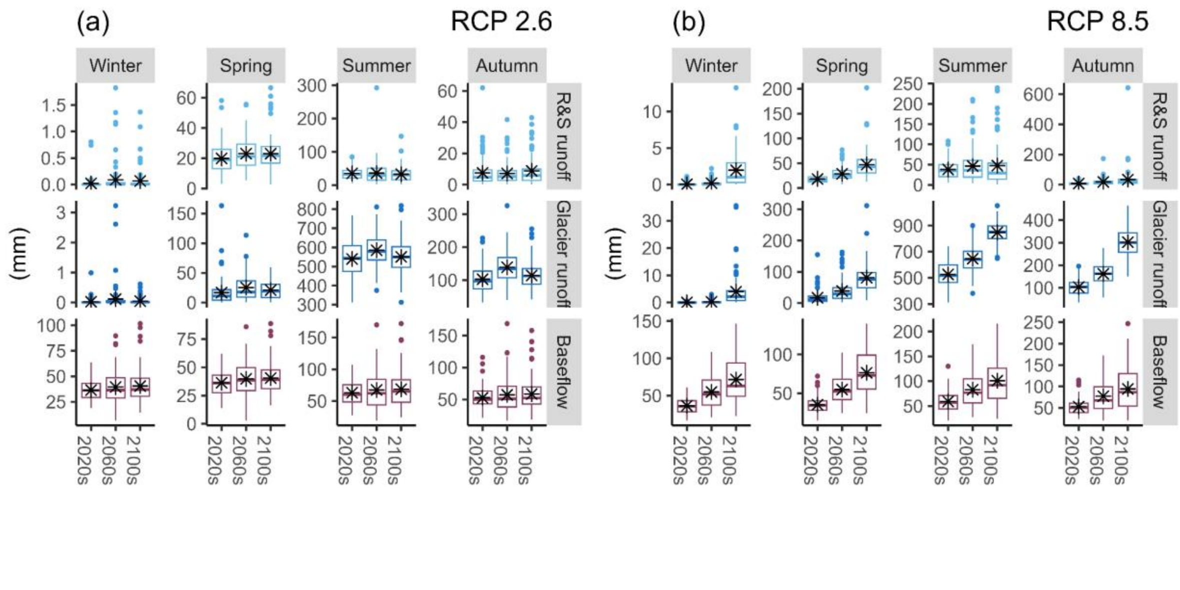


Figure V-8 Mean annual runoff component presented under two scenarios (a-c, RCP 2.6 and d-f RCP 8.5), and for three catchments, a) Sust, b)Taqchakhana, and c) Bamyan. R&S indicates rain and snow runoff. The shading indicates standarded deviation of the five ensamles.



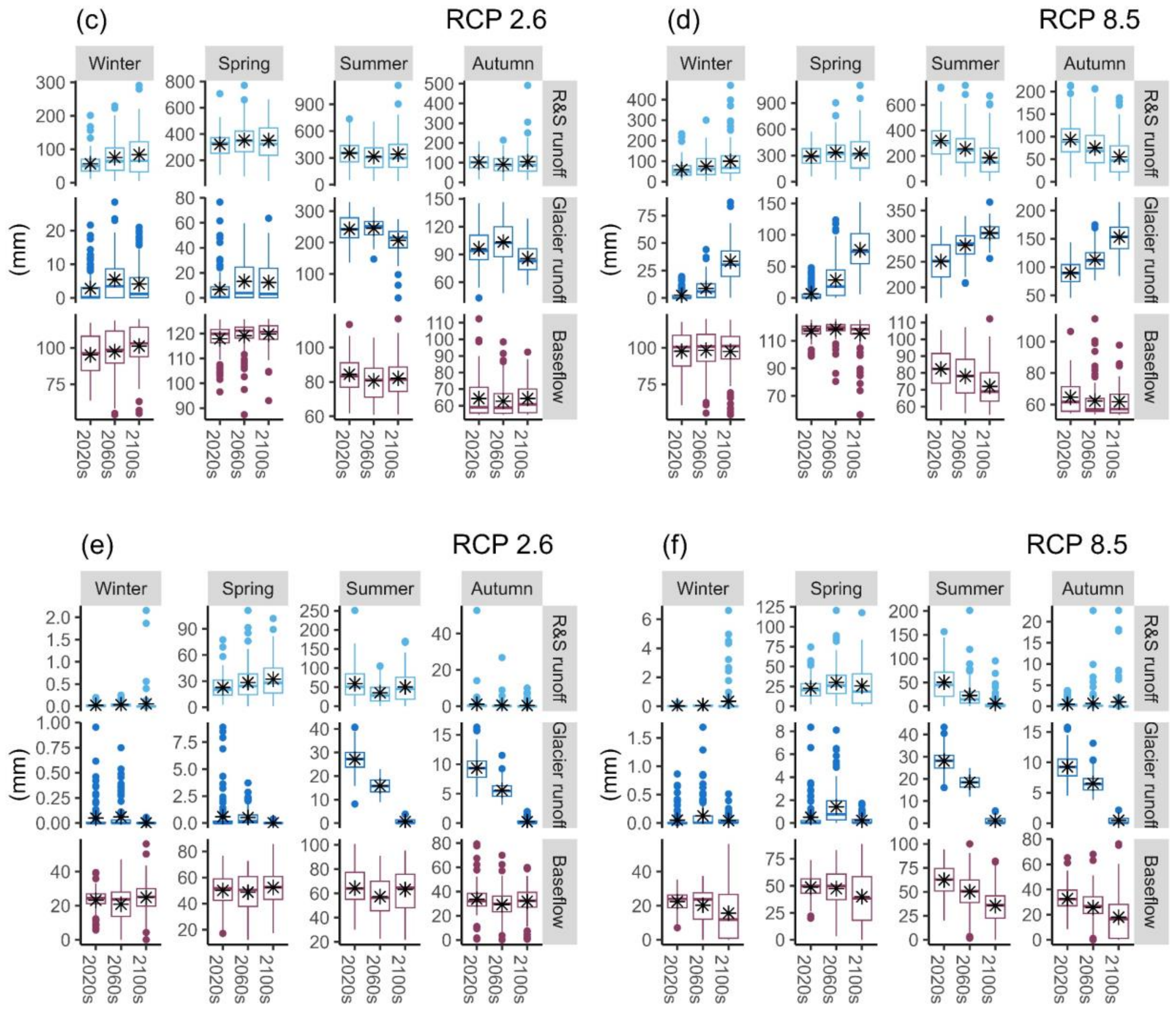


Figure V-9 Illustrates changes in projected streamflow with different runoff components for the three catchments. On the left, it presents the mean monthly runoff for the baseline period 2020s (mean over 2000 to 2020). On the right, it shows changes in mean monthly runoff over 2060s and 2100s under two RCPs (2.6 and 8.5).

V.4.7 Debris cover effects on streamflow

Here we compare how these predictions change when we treat glaciers as a single land cover, without distinguishing between bare ice and debris-covered ice.

For the Sust and Bamyan catchments, little difference was observed in glacier runoff with or without debris-covered ice treatments (Figure V-10a,b,e,f). This was due to the two main reasons. The first is lower percentage debris-covered in these catchments (17.4% and 0.15%, respectively, calculated from Table V-1). The second is that the parameterization resulted in a lower melt factor for the ice in the Sust catchment (compare Table V-4a and 4b) when there was no explicit debris cover treatment. Thus, this parameterization compensated for the lack of an explicit debris land cover.

In contrast, for the Taqchakhana catchment we obtained considerable difference in glacier runoff with and without debris cover treatments (Figure V-10c,d). More significantly, the differences were obtained in summer and autumn seasons, showing about 100% more reduction in glacier runoff without debris cover treatements compare to with debris treatments (Table V-7). Glaciers in this catchment are 40% debris-covered (calculated from Table V-1) and have a higher ice melt factor than the Sust (Table V-4a,b). The parameterisation of the ice melt factor did not change significantly (Students *t*, p>0.05) when the sepereate debris cover treatment was removed. Figure V-10c and 10d show how a separatre debrid over treatment reduces glacier melt for the Taqchakhana, clearly for the baseline scenario, but where the differences progressively decline through time to become negligible by the 2100s. The initial reduction in runoff is because the melt factor for bare ice (Table V-4a) and a single ice cover (Table V-4b) are similar; but the separate debris-covered ice melt factor is much lower (Table V-4a), and so when debris-covered ice is included separately it melts more slowly.

Table V-7Model results without debris covere treatments, changes in streamflow runoff components (mm) under two RCPs (2.6 and 8.5) in two timespans (2060s and 2100s) as compared with the 2000-2020 baseline. Statistically significant changes (p<0.05) are marked for a two-tailed Student's t test.

Runoff components		Baseflow (mm)				Rain and Snow runoff (mm)				Glacier runoff (mm)				Total Streamflow (mm)			
RCPs		2.6		8.5		2.6		8.5		2.6		8.5		2.6		8.5	
Catchment		2060s	2100s	2060s	2100s	2060s	2100s	2060s	2100s	2060s	2100s	2060s	2100s	2060s	2100s	2060s	2100s
Sust	Winter	3.2	4.2	**18.7**	**35.6**	**0.1**	**0.0**	**0.2**	**1.9**	**0.1**	**0.0**	**0.2**	**4.0**	3.3	4.3	**19.1**	**41.4**
	Spring	**3.5**	**4.4**	**19.7**	**41.7**	2.8	2.5	**10.0**	**28.0**	**8.5**	**3.8**	**21.6**	**63.3**	**14.9**	**10.6**	**51.3**	**132.9**
	Summer	4.6	6.0	**23.9**	**42.4**	0.6	-3.1	8.0	8.8	**38.2**	-2.5	**111.6**	**299.0**	**43.4**	0.4	**143.5**	**350.2**
	Autumn	4.7	6.2	**24.7**	**41.8**	-0.4	1.1	**10.5**	**25.7**	**34.5**	8.6	**56.5**	**190.8**	**38.9**	**15.9**	**91.6**	**258.3**
	Annual	16.0	20.9	**82.2**	**156.6**	3.1	0.5	**29.2**	**64.9**	**81.3**	9.9	**177.5**	**544.6**	**100.4**	31.3	**289.0**	**766.2**
TaqchaKhana	Winter	2.0	**6.8**	**0.2**	-0.6	**14.8**	**21.5**	**13.2**	**36.0**	**2.8**	**0.6**	**6.9**	**30.0**	**19.6**	**28.9**	**20.4**	**65.3**
	Spring	1.2	2.6	1.5	**-2.5**	27.0	23.5	35.8	23.8	**6.7**	3.3	**24.4**	**66.0**	34.9	29.4	61.7	**87.3**
	Summer	-4.0	-2.1	**-5.2**	**-13.4**	**-33.7**	-8.2	**-58.0**	**-115.8**	**-25.4**	**-95.2**	2.8	-12.2	**-63.0**	**-105.5**	**-60.5**	**-141.4**
	Autumn	-3.0	0.4	**-3.9**	**-5.6**	-8.2	2.4	**-13.9**	**-27.8**	-2.5	**-33.3**	**15.5**	**39.0**	**-13.8**	**-30.5**	**-2.3**	5.6
	Annual	-3.8	7.7	**-9.8**	**-24.4**	-0.1	39.3	**-79.2**	**-140.2**	**-18.4**	**-124.7**	**51.2**	**124.2**	-22.3	**-77.6**	-37.8	**-40.4**
Bamyan	Winter	-2.3	1.9	-2.6	**-5.9**	**0.0**	**0.0**	**0.0**	**0.2**	**0.0**	**0.0**	**0.1**	0.0	-2.3	1.9	-2.5	**-5.7**
	Spring	-1.0	2.4	-1.8	**-8.3**	5.5	**9.7**	**7.2**	2.6	**-0.1**	**-0.5**	**0.8**	-0.3	4.4	**11.6**	6.2	**-6.0**
	Summer	**-7.4**	-1.2	**-14.7**	**-30.1**	**-23.2**	**-8.7**	**-35.5**	**-51.8**	**-11.1**	**-26.2**	**-8.4**	**-25.8**	**-41.7**	**-36.2**	**-58.6**	**-107.6**
	Autumn	**-5.4**	-1.9	**-9.3**	**-17.3**	**-0.6**	**-0.7**	**-0.5**	**-0.2**	**-3.8**	**-9.1**	**-2.8**	**-8.9**	**-9.7**	**-11.6**	**-12.5**	**-26.4**
	Annual	**-16.1**	1.2	**-28.3**	**-61.6**	**-18.3**	0.3	**-28.8**	**-49.2**	**-14.9**	**-35.9**	**-10.4**	**-35.0**	**-49.3**	**-34.4**	**-67.4**	**-145.7**

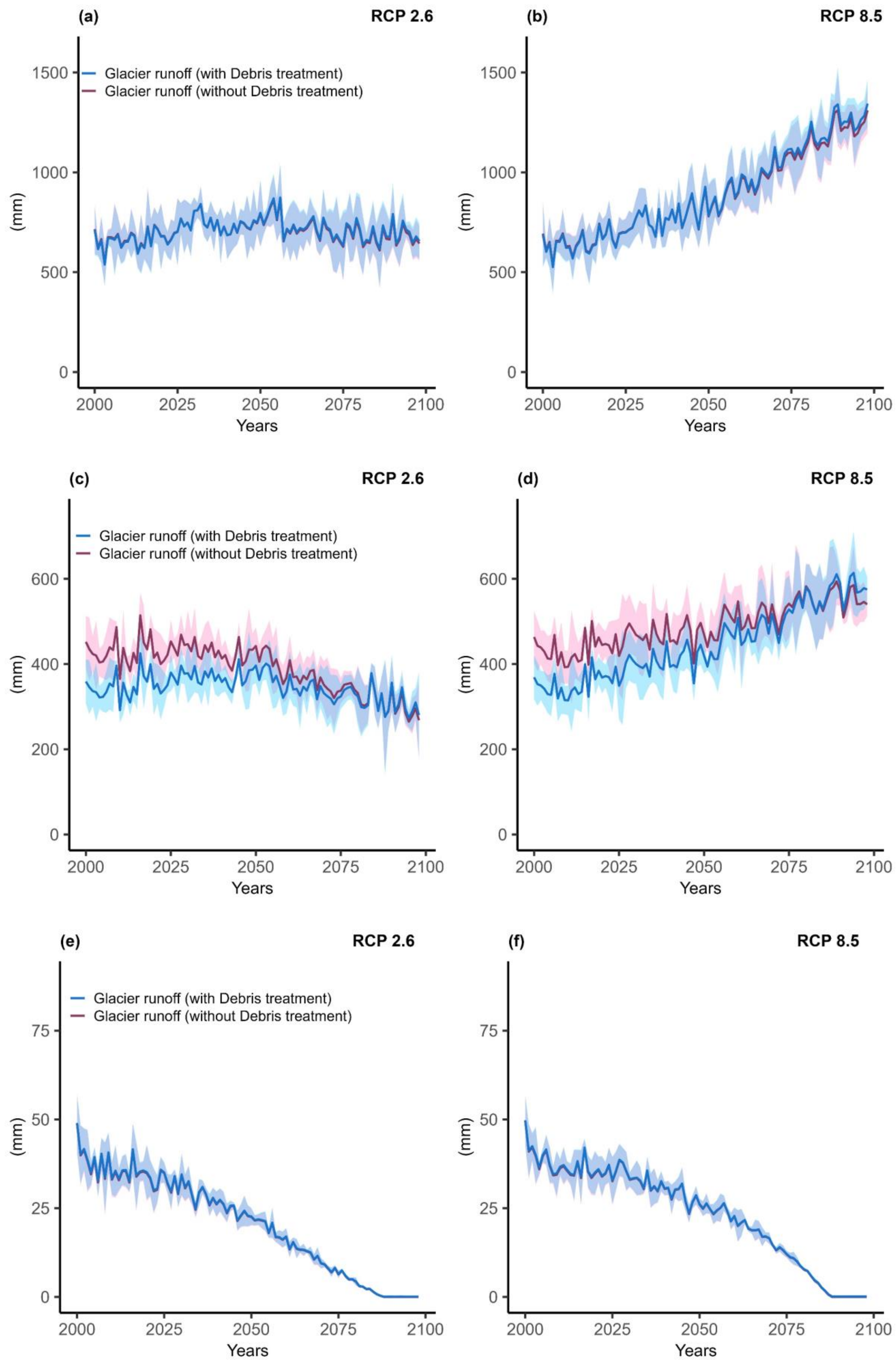


Figure V-10 Glacier runoff (with and without debris cover ice treatments) response to the projected climate under two RCPs (2.6 and 8.5) for three catchments (Sust catchment a,b; Taqchakhana catchment *c,d; and Bamyan catchment e,f). Ice runoff is the runoff from the bare ice glacier bands and debris-covered ice runoff is the runoff from the debris cover band and both are included in the glacier runoff with debris treatments. Glacier ice without debris-covered ice treatment is the glacier runoff only from bare ice. Shaded areas describe standarded deviation of the five ensamles.*

V.5 Discussion

V.5.1 Regional variability of glacio-hydrological regime in Afghanistan

This paper has revealed substantial differences in glacio-hydrological regimes for three Afghanistan catchments with different climates and geographical settings. The driest catchment, the Sust in eastern Afghanistan, with a mean annual precipitation of only 320 mm yr^{-1} had the largest contribution from glacier runoff, estimated at 76% contribution under current conditions. Chapter IV also found that glaciers in the eastern region of Afghanistan, with an arid, desert, cold climate, follow the Karakoram anomaly; glaciers are declining at a slower rate, stagnating or even advancing as compared to other parts of the Himalayan region (Wiltshire, 2014; Azam et al., 2021). The Hindu Kush Karakoram and the eastern Afghanistan region receives most winter precipitation through westerly and southwesterly air masses (Lutz et al., 2014). This would suggest some climatic differences as compared with the other two catchments. However, there is also clearly a relationship with debris cover. For the model version without a separate treatment of bare and debris-covered ice (Table V-4b) the optimized degree day factor was 6.67 mm/d/ºC, substantially lower than those for the Taqchakhana and Bamyan glaciers. When treated separately they were 7.16 mm/d/ºC for bare ice, closer to but still smaller than the other two glaciers and 4.97 mm/d/ºC for debris-covered ice. The fact that the degree day factor did not change much when bare ice and debris-covered ice were treated separately for the other two factors suggests that debris cover needs to be treated separately for the Sust, reflecting the spatial extent of debris-covered ice in this catchment, even if its proportion is much lower, as compared with the other catchments (Table V-1).

The streamflow was more dominated by rain and snowmelt driven runoff in the Taqchakhana catchment in the northwestern part of Afghanistan (50% contribution to the streamflow). This catchment located at the margin between cold and temperate and dry and hot summer climates, mainly receives precipitation as snow during the winter season. Glacier melt runoff is lower (33% contribution to the streamflow) but still important. The hydrological regime of this basin is characteristic of the Upper Indus basin more generally where snowmelt is recognized as contributing more than glacier melt to the annual streamflow (Azam et al., 2021).

The Bamyan catchment in the center-west had a completely different hydrological regime. This catchment presented the highest contribution from baseflow by 61%, is located in an arid, steppe, cold climate, and receives much lower annual precipitation.

What is clear from these results is that the relative contributions of snowmelt and glacier melt to runoff in these basins is variable, according to both glacier cover and annual precipitation. It is not possible to generalise that either glacier melt or snowmelt (cf. Kraaijenbrink et al., 2021) is more dominant and future water resource projections need to be sensitive to geographical location in this region of the HKH mountain area. Generalisations also need to be sensitive to scale effects because as the spatial extent of a catchment increases (with distance downstream) so the proportion of the catchment that is glaciated, and the degree of influence of glacier melt to water supply, will decrease (Quincey et al., 2018).

V.5.2 Future glacio-hydrological response to climate change

Several RCMs are available to predict future hydrological responses to climate change, however, due to biases in the RCMs, their direct application will negatively impact the results (Teutschbein and Seibert 2012). Studies suggest bias correction that improves the quality of RCMs in the hydrological modeling (Teutschbein and Seibert 2012), for Afghanistan, very few studies applied bias corrections using observed data to simulate the future hydrological response (Chapter II). With recently available observed data, here we provide one of the first studies that applied bias correction of future climate for the implication of hydrological response of the Afghan catchments.

The temperature is projected to increase for all catchments and seasons by 2050 and will reduce until the end of 21st century under RCP 2.6, while constantly increasing under RCP 8.5. Projected precipitation showed decreasing spring and autumn precipitation for Bamyan catchment under RCP 2.6 by 2060s but fewer changes were significant for Sust and TaqchaKhana catchments. In comparison, precipitation was reduced signigicantly for spring season under RCP 8.5 for Bamyan and Taqchakhana catchments by 2060s and by 2100s.

Such climate forcing could greatly affect the glacio-hydrological regime of the catchments. The warming should reduce winter snow accumulation and increase winter runoff; reduced snow accumulation should then reduce summer runoff. Where the warming effects snow accumulation on glaciers, a function of glacier hypsometry, reduced snow accumulation should lead (1) to an earlier exposure of glacier ice during summer melt, earlier albedo reduction, and enhanced melt; and (2), albeit only if accumulation zones are at a low enough altitude, a reduction in mass accumulation. These together should enhance glacier loss (Azam et al., 2021) which in turn should impact the hydrological regime where glacier melt provides an important contribution. It was clear that the TaqchaKhana in particular is likely to see much stronger seasonality in annual flow, with wetter winters and drier summers (Table V-6). We attributed this to the fact that this catchment did not have a sufficient glacier cover (Table V-1) for rising temperatures (Table V-5) to cause a significant increase in runoff from melting ice.

In contrast, the Sust catchment is projected to have an increase in precipitation under RCP 8.5 for all seasons, which will increase high elevation snow accumulation, leading to less negative or even positive mass balance (Azam et al., 2021). Data on glacier change in Afghanistan confirm that this is currently the case (Chapter IV). This is likely to be countered in the longer term if temperature rises and ablation increases (the Sust is too high for winter temperatre rise to cause much snow to fall as rain). Our simulations of runoff under RCP 8.5 do suggest an increase in glacier runoff (reflecting higher glacier melt rates) as well as increases in baseflow and rain/snow melt due to increasing precipitation.

V.5.3 Peak water

In the simulations presented, it is difficult to see clear evidence of peak water except for the Sust under RCP 2.6 where there is a peak glacier runoff around the 2050s (Figure V-8a). Glacier runoff consistently rises otherwise for the Sust and TaqchaKhana under RCP 8.5 (Figure V-8d and 8e), declines for the Bamyan under both scenarios (Figure V-8c and 7f) and does not change appreciably for the TaqchaKhana under RCP 2.6 (Figure V-8b). There is little research that has identified unequivocally the percentage to which glacier cover in a river catchment must decline for peak water to occur. That is not surprising because it is likely also influenced by other parameters such as basin hypsometry, glacier aspect as well as local climate forcing. The three catchments here, despite having very different percentage ice covers (Table V-1) are responding very differently to climate change in terms of glacier cover (Chapter IV). The climate forcing we identify (Table V-5) is also very different as the glaciers are in different regions. For instance, if we take the warmest scenario (RCP 8.5) for the Sust catchment, increases in winter precipitation should in average sustain winter accumulation. There is a progressive increase in glacier melt (Figure V-8d) but the ice cover is so high, and its rate of decline is likely reduced via increases in winter accumulation, that it is not yet possible to see peak water. Of course, this result is dependent on the way we modelled future glacier change and it suggests the need to look further at what is happening in some of these regions of the HKH with high altitudes, high glacier cover and likely future wetter conditions. Rounce et al. (2020) suggest that "peak water" will likely hit the Indus and other westerlies-fed river basins after 2050 due to significant contributions from excess glacier meltwater. Rounce et al. (2020) assessed glacier mass change in High Mountain Asia through 2100 and suggested that glacier runoff in all river basins will have reached peak water by ~2080 for all RCP scenarios. It should be noted that they did not consider the debris cover effect in their assessment, and this could lead to earlier peak water. This is what we observed in the Taqchakhana catchment; when we removed the debris cover effect in the model. As a result, glacier runoff started decreasing by ∼2080 under RCP 8.5.

The one catchment that suggested peak water was the Sust under RCP 2.6 (Figure V-8a). However, this emphasizes an additional issue with the forecasting we are presenting. By the 2050s, under RCP 2.6, temperatures in the Sust may have stabilized or even be declining (Figure V-6a). This is of course a highly optimistic scenario but it is likely that given that there is still extensive ice cover in the Sust in the 2050s (Figure V-3), that the peak in glacier runoff is not a result of ice cover falling below a critical level but a result of stabilizing or even decreasing temperature.

V.5.4 Debris cover effects on catchment glacio-hydrology

Our study is one of the first glacio-hydrological model studies that has considered debris cover effects on catchment runoff at larger scales in this region. Compagno et al. (2022) emphasized the need to do this at the regional scale, especially for regions with a significant extent of debris-covered glaciers. There have been recent efforts to undertake high resolution modelling of the effects of debris cover development on surface melt using energy balance models and to combine this with a dynamic treatment of ice and debris flux (Huss and Hock, 2015; Compagno et al., 2022). However, such models require extensive input data relating to local surface mass balance parameters, glacier thickness (ice and debris-covered) and so on, that are not available at the spatial extents of the catchments used in this study especially given the data poor setting of Afghanistan. Application of the more complex dynamic glacier models is therefore rare for large catchment in glacio-hydrological modeling (Azam et al., 2021). Therefore, we used a simple area-based approached to estimate future glacier evolution. This could be improved by using more physical-based approaches supported by field observations.

We found different effects based on the catchment characteristics. For instance, no significant effects were found for the Sust catchment because of the lower percentage debris cover in the catchment. However, we found identified more important impacts in the Taqchakhana catchment; glacier runoff without debris treatment had greater runoff than with a debris treatment under both RCPs (2.6 and 8.5); but this difference declined through time. This effect was not manifest in the Sust because whilst it has a high ice cover, it has generally lower proportions of debris-covered ice; and not in the Bamyan as whilst glaciers there can have a higher propotion of debris cover, the glacier extemt is so small, that any change in glacier representation has little impact. The declining differences through time to the 2100s are likely because parameterization of the melt factor with a single land cover glacier treatment in the Taqchakhana is dominated by debris effects. As debris cover progressively increases through time with a separate debris-covered ice treatment, the effect of two separate melt factors (Table

V-4a) becomes more similar to the single melt factor (Table V-4b). That said, because in the Taqchakhana catchment the extent of total ice (bare and debris-covered) is small, the dominant effects in terms of total runoff were related to baseflow and rain/snow melt impacts (Table V-6). In the Sust, the results of model calibration suggested that a different melt factor was needed for debris-covered ice to that for bare ice. But, whether debris-covered ice was treated separately or not made very little difference to model predictions of glacier melt to the 2100s. This is because the relative importance of debris cover in the Sust is relatively much lower than in the Taqchakhana (Figure V-3).

Thus, the conclusion that debris cover matters has to be moderated by the relative importance of bare ice and debris-covered ice in a catchment and not just the presence of debris-covered ice. If the extent of a glacier upstream of a critical point in a catchment is extensive and this is a catchment that is able to produce significant amounts of debris, which is itself spatially variable (Chapter III), then debris may insure against rapid ice loss due to global warming. In such situations, the correct representation of debris is likely necessary.

As with future runoff and partitioning of runoff into different sources, these results are sensitive to the way we parameterized changing bare and and debris-covered ice (Figure V-3). For instance, with a greater rate of bare ice loss and debris-covered ice gain, the Sust might see lower rates of glacier runoff to the 2100s. Equally, our treatment of bare ice and debris-covered ice is not temperature-dependent as it is an empirical extrapolation, and so it is not sensitive to the RCP we used. Given differences in future temperature under these scenarios (Table V-5) this is a particular weakness. This emphasizes the need for a more physically-based treatment of debris cover formation. Frameworks have been ptoposed that could inform such an approach (Nicholson et al., 2021). That said, the simulations of both bare ice and debris-covered ice change match wider predictions of increasing debris cover for High Mountain Asia as a whole (Compagno et al., 2022), as well as other studies that suggest increasing debris cover fractions as a consequence of glaciers with negative mass balances through time (Shukla and Qadir, 2016; Tielidze et al., 2020; Compagno et al., 2022).

V.6 Conclusion

In this study, we assessed the glacio-hydrological regime of three catchments in Afghanistan that represent different geographical contexts in terms of climate and glacier cover. We used a parsimonious conceptual precipitation and ice melt-runoff model combined with a new representation of debris-covered ice effects to assess current and future runoff. Climate change scenarios are based on bias-corrected runs for RCP 2.6 and RCP 8.5 of the recent CORDEX simulations. First, we found that the pre-processing of streamflow and climate data is a key step to setting up a hydrological model in comparably data sparse areas. Our results show that particular attention should be paid to elevation precipitation gradients and temperature lapse rates, which differ spatially and temporally. Second, as shown for other regions, bias correction is presented to be of prime importance for reliable hydrological modeling the regions of Afghanistan impacted by snow and glacier melt.

Third, whilst all studied catchments had seasonal streamflow patterns, with runoff peaks in June and July, these result from very different contributions of rain and snow runoff versus glacier runoff. The latter varied significantly between catchments and emphasizes the need to contextualise future water resource changes due to rapid climate change in terms of both glacier cover and local meteorological drivers.

Fourth, the primary signal of climate change under both RCP 2.6 and 8.5 was changing temperature with precipitations being less significant. As expected the rate of change under RCP 8.5 is greater and continuous through to the 2100s; but under RCP 2.6, temperatures stabilize or begin to decline. The main precipitation changes were forecast to be drying in the more westerly catchments but only significantly in spring; and under RCP 8.5, increases in precipitation for all seasons to the 2100s, the easterly catchment. These results emphasize that the impact of climate change on precipitation in Afghanistan is likely to be regionally variable, potentially over small distances.

Fifth, streamflow projections associated with these possible climate changes suggest differences in likely basin response along a gradient from the most westerly catchment consiudered, where there is a tendency towards reduced annual runoff; to the central catchment where there is a tendency for no clear change in annual runoff but a clear change towards increased seasonality; to the eastern catchment where annual runoff is projected to increase. These patterns are reinforced under RCP 8.5 as compatred with RCP 2.6. Projected total precipitation changes are evident in both baseflow declines and because of interactions with rising temperatures, runoff from combined rainfall and snow melt, which increases seasonality. In the most glaciated eastern catchment under both scenarios and the central catchment under RCP 8.5, glacier runoff also increases substantially. The extent to which runoff is increased by glacier melt under climate warming then depends on both glacier cover and the distribution of ice with altitude.

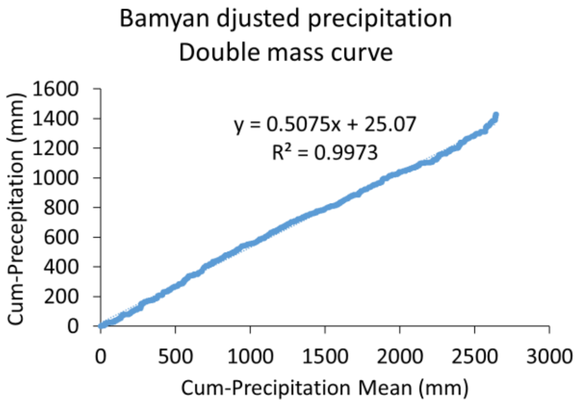
Finally, we have shown the importance of including an explicit treatment of debris-covered ice in modelling glacier runoff in certain sitiatiuons. It can reduce estimated runoff from glacier melt in situations where debris cover is important and there is still a reasonably important glacier cover, as in the central catchment we considered here. More process-based glacier evolution models for large catchments need to be developed to refine this result, which remains challenging for debris-covered glaciers.

V.7 Supplementary Material

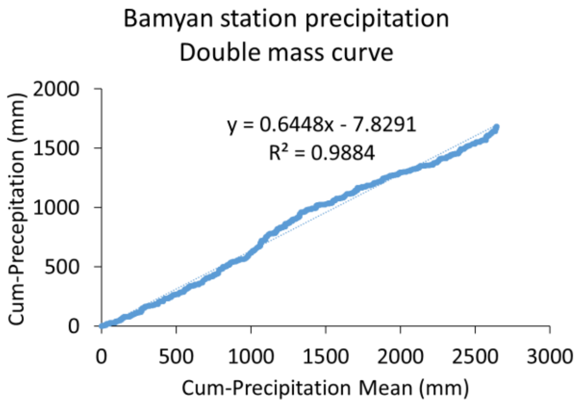
Table V-8 (Table S1) Hydro-climate stations metadata, the data was obtained from Ministry of Energy and Water (MEW), Ministry of Agriculture Irrigation and Livestock (MAIL) of Afghanistan. (AT= Air-temperature, PPT= Precipitation, RD= River discharge).

S/N	Station Name	Latitude (ºE)	Longitude (ºN)	Elevation (m)	Province	Responsible Entity	Availible Parameters (Daily)
1	Farkhar-AWS	36.5823	69.8554	1137	Takhar	MEW	AT-PPT
2	Kalafgan-SSS	36.4116	69.5223	2243	Takhar	MEW	AT-PPT
3	Keshem	36.9332	70.0498	808	Badakhshan	MEW	AT-PPT
4	Khash-SSS	36.8364	70.7268	3076	Badakhshan	MEW	AT-PPT
5	Khenjan	35.5527	68.9175	1265	Baghlan	MEW	AT-PPT
6	Khwajaghar-AWS	36.9882	69.6050	603	Takhar	MEW	AT-PPT
7	Nazdik Taluqan	36.6354	69.7374	1008	Takhar	MEW	AT-PPT
8	Nazdik-i- Baharak	36.9724	70.9108	1478	Badakhshan	MEW	AT-PPT
9	Nazdik-i-Jurm	36.9258	70.8576	1438	Badakhshan	MEW	AT-PPT
10	Pul-i-Bangi	36.7304	69.2081	556	Takhar	MEW	AT-PPT
11	Pul-i-Kundasang	35.5932	68.5811	893	Baghlan	MEW	AT-PPT
12	Pul-i-Teshkan	36.9845	70.0700	818	Badakhshan	MEW	AT-PPT
13	Sheghnan-AWS	37.5307	71.4839	2284	Badakhshan	MEW	AT-PPT
14	Sumdara	37.0635	70.7012	1316	Badakhshan	MEW	AT-PPT
15	Taluqan-AWS	36.7674	69.5364	847	Takhar	MEW	AT-PPT
16	Tang-i-Nahrin	36.0579	69.1608	1190	Baghlan	MEW	AT-PPT
17	Tapa-i-Farhat-AWS	36.1882	68.6918	562	Baghlan	MEW	AT-PPT
18	Worsaj-SSS	36.0187	70.0281	2666	Takhar	MEW	AT-PPT
19	Bamyan	34.8235	67.8251	2507	Bamyan	MEW	AT-PPT-RD
20	Khwajaghar	37.0687	69.4867	488	Takhar	MEW	AT-PPT-RD
21	Sust	36.9859	72.7685	2856	Badakhshan	MEW	AT-PPT-RD
22	Taqcha Khana	36.5337	69.7082	1472	Takhar	MEW	AT-PPT-RD
23	Balay-i- Kelagai	35.7406	68.7551	749	Baghlan	MEW	AT-PPT-RD
24	Ali Abad	36.5490	68.9060	436	Kunduz	MAIL	PPT
25	Aybak	36.2610	68.0280	969	Samangan	MAIL	PPT
26	Baharak	36.9870	70.8770	1434	Badakhshan	MAIL	PPT
27	Bamyan	34.8218	67.8250	2531	Bamyan	MAIL	PPT
28	Fayzabad	37.1149	70.5813	1209	Badakhshan	MAIL	PPT
29	Ishkashem	36.7090	71.5710	2677	Badakhshan	MAIL	PPT
30	Khash	36.9530	70.7680	2329	Badakhshan	MAIL	PPT
31	Kohmard	35.3270	67.6130	2069	Bamyan	MAIL	PPT
32	Kunduz	36.7160	68.8560	406	Kunduz	MAIL	PPT
33	Mula Ghulam	34.8760	67.8670	3096	Bamyan	MAIL	PPT
34	Rostaq	37.1510	69.8030	1230	Takhar	MAIL	PPT
35	Sarbagh	35.9995	68.0550	1425	Samangan	MAIL	PPT
36	Shebar	34.5525	66.7990		Bamyan	MAIL	PPT
37	Taluqan	36.7220	69.5689	825	Takhar	MAIL	PPT
38	Urgo	37.0560	70.4030	1700	Badakhshan	MAIL	PPT
39	Yaftal Sofla	37.2890	70.4350	1625	Badakhshan	MAIL	PPT
40	Dara-e-Soof	67.2690	35.8680	1556	Samangan	MAIL	PPT
41	Dawlat Abad	66.8416	37.0037	308	Balkh	MAIL	PPT
42	Mazar	67.1122	36.7070	365	Balkh	MAIL	PPT
43	Panjab	66.9940	34.3790	3171	Bamyan	MAIL	PPT
44	Takhtapul	66.9962	36.6632	396	Balkh	MAIL	PPT

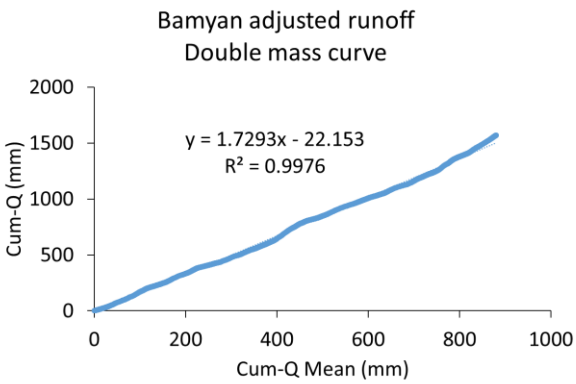
a)


Bamyan djusted precipitation
Double mass curve
y = 0.5075x + 25.07
R² = 0.9973
Cum-Precepitation (mm)
Cum-Precipitation Mean (mm)

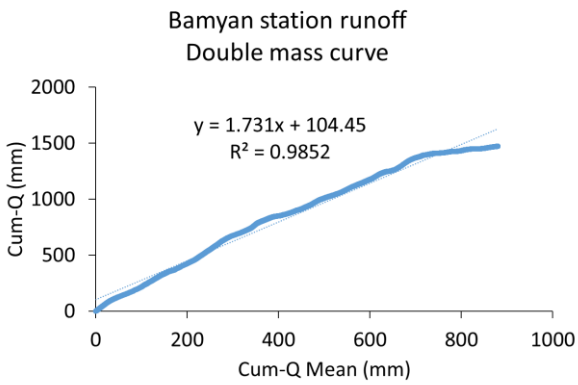
b)


Bamyan station precipitation
Double mass curve
y = 0.6448x - 7.8291
R² = 0.9884
Cum-Precepitation (mm)
Cum-Precipitation Mean (mm)

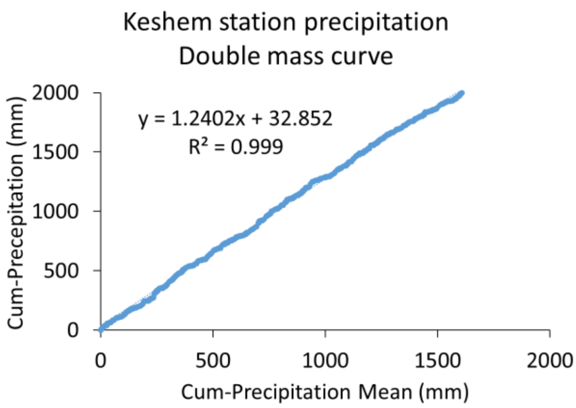
c)


Bamyan adjusted runoff
Double mass curve
y = 1.7293x - 22.153
R² = 0.9976
Cum-Q (mm)
Cum-Q Mean (mm)

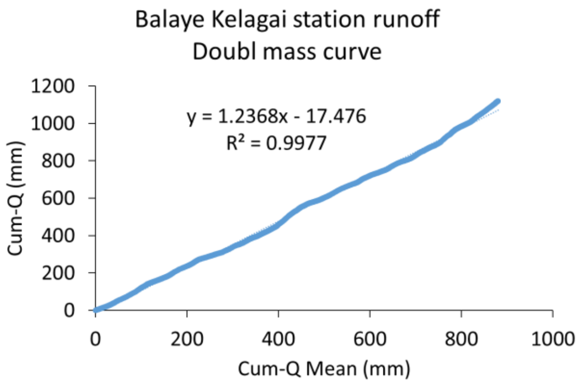
d)


Bamyan station runoff
Double mass curve
y = 1.731x + 104.45
R² = 0.9852
Cum-Q (mm)
Cum-Q Mean (mm)

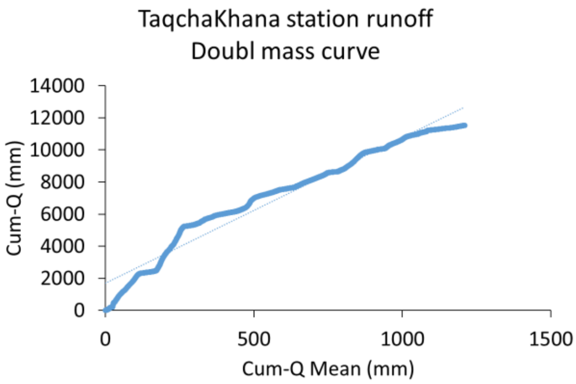
e)


Keshem station precipitation
Double mass curve
y = 1.2402x + 32.852
R² = 0.999
Cum-Precepitation (mm)
Cum-Precipitation Mean (mm)

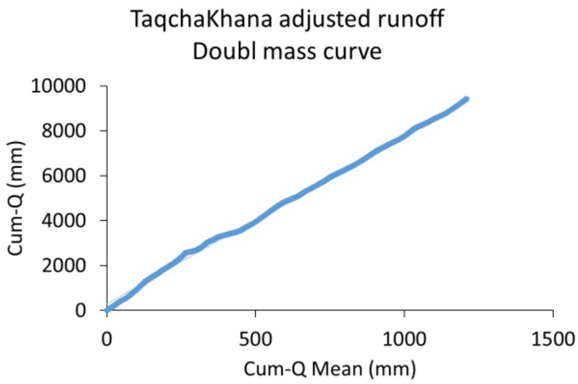
f)


Balaye Kelagai station runoff
Doubl mass curve
y = 1.2368x - 17.476
R² = 0.9977
Cum-Q (mm)
Cum-Q Mean (mm)

g)


TaqchaKhana station runoff
Doubl mass curve
Cum-Q (mm)
Cum-Q Mean (mm)

h)


TaqchaKhana adjusted runoff
Doubl mass curve
Cum-Q (mm)
Cum-Q Mean (mm)

i) j)

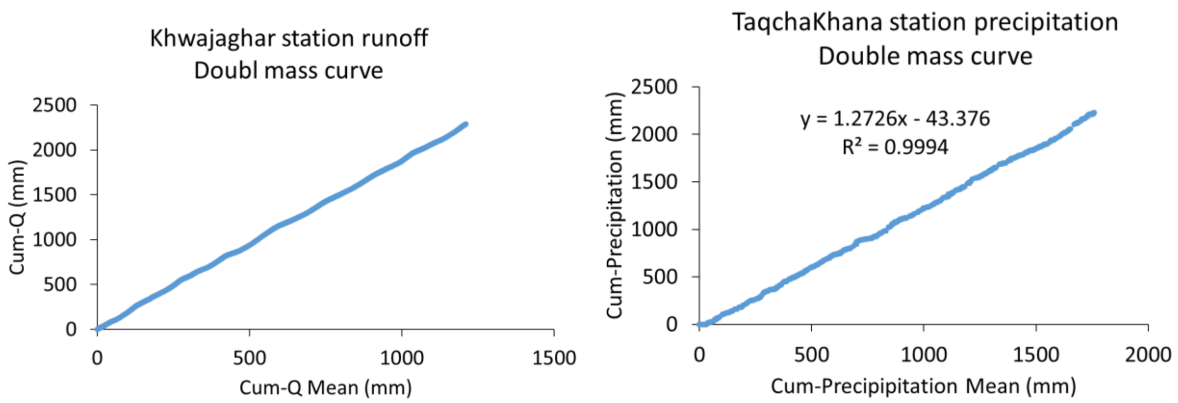


Figure V-11 (Figure S1) Shows double-mass curve plots for individual precipitation and streamflow data sets (a-j) used with the average of many station records

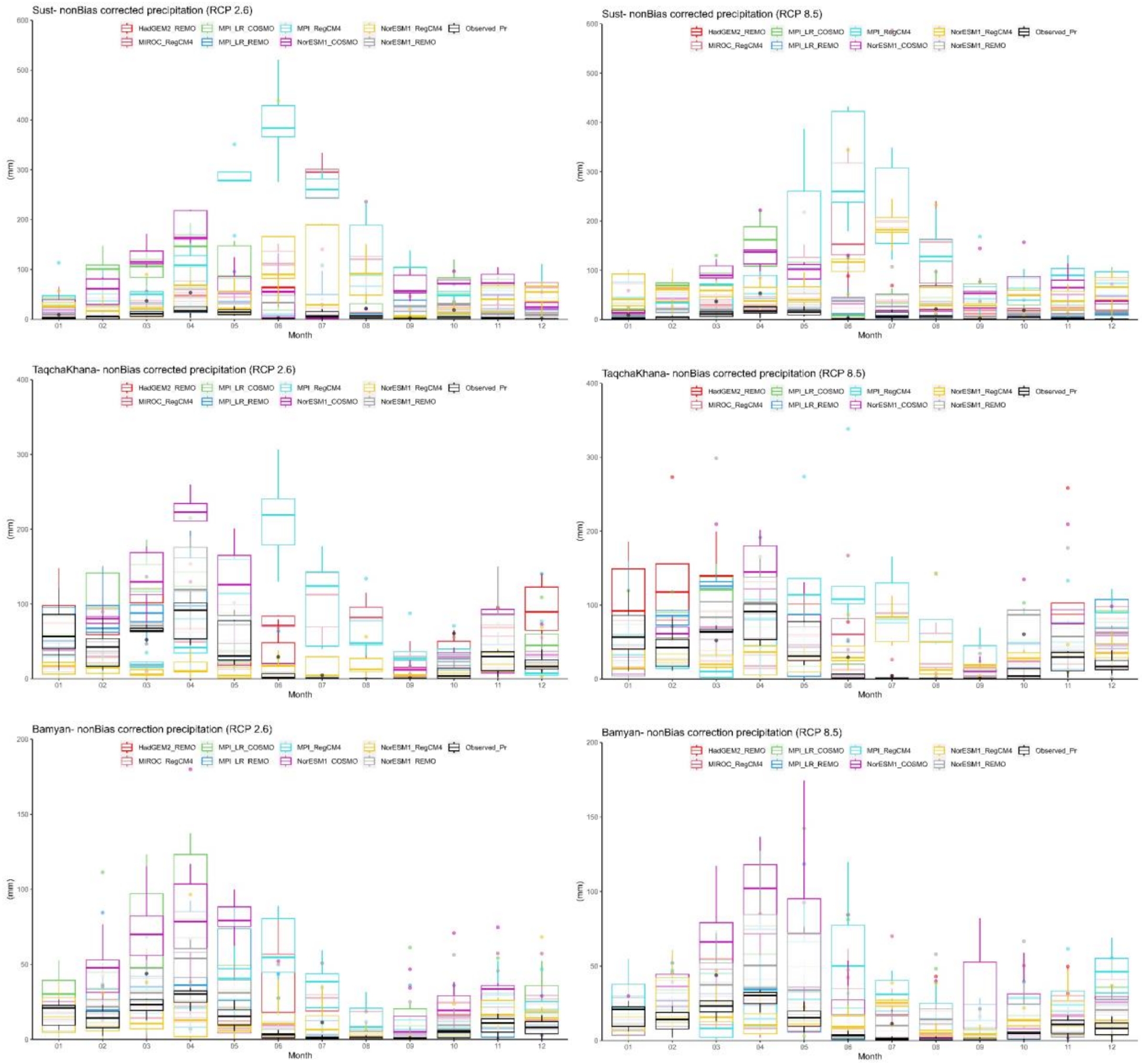


Figure V-12 (Figure S2) Box plot of observed daily precipitation data and original projected precipitation under two RCPs (2.6 and 8.5) and for three catchments (Sust, Taqchakhana, and Bamyan catchments).

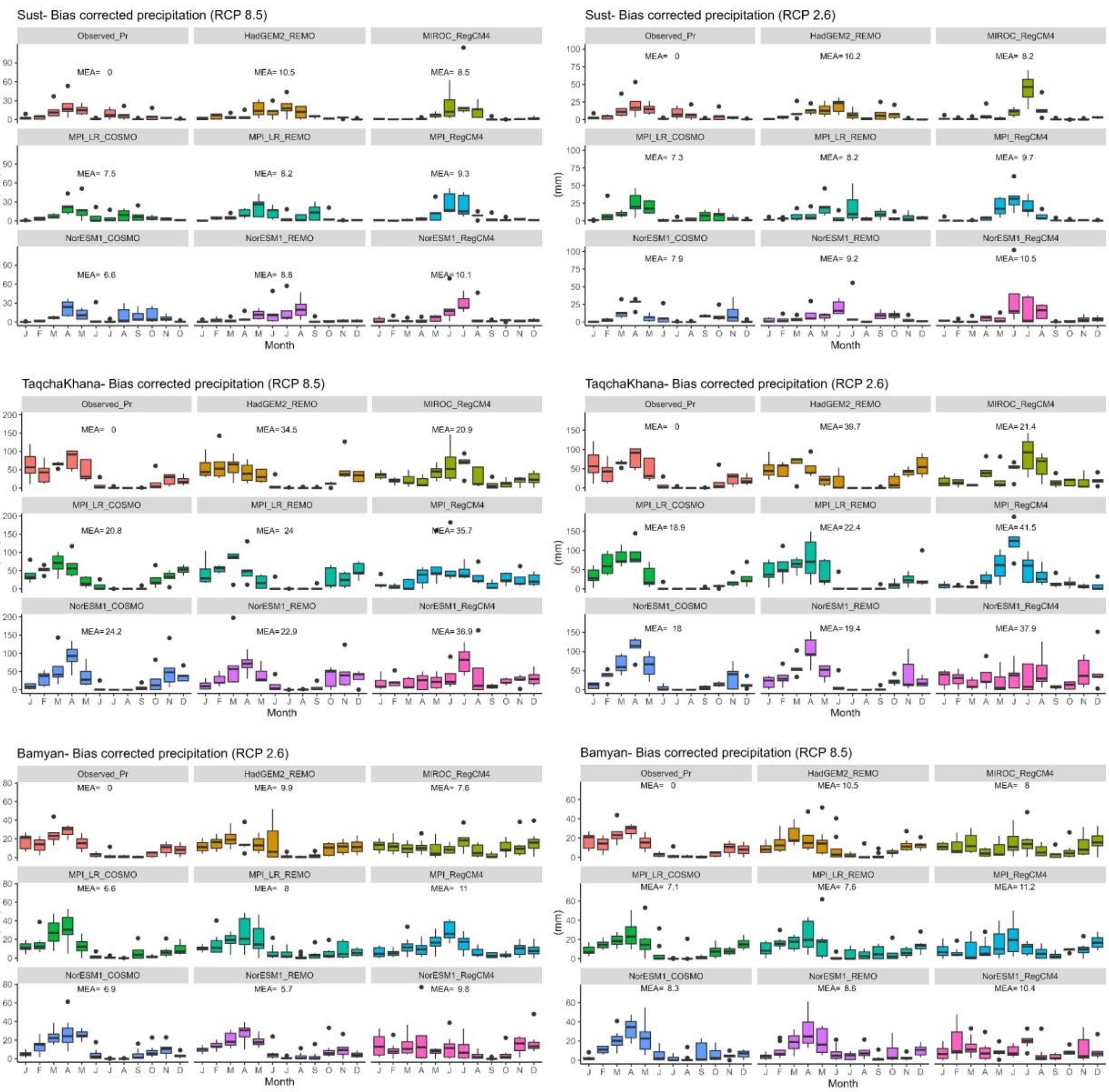
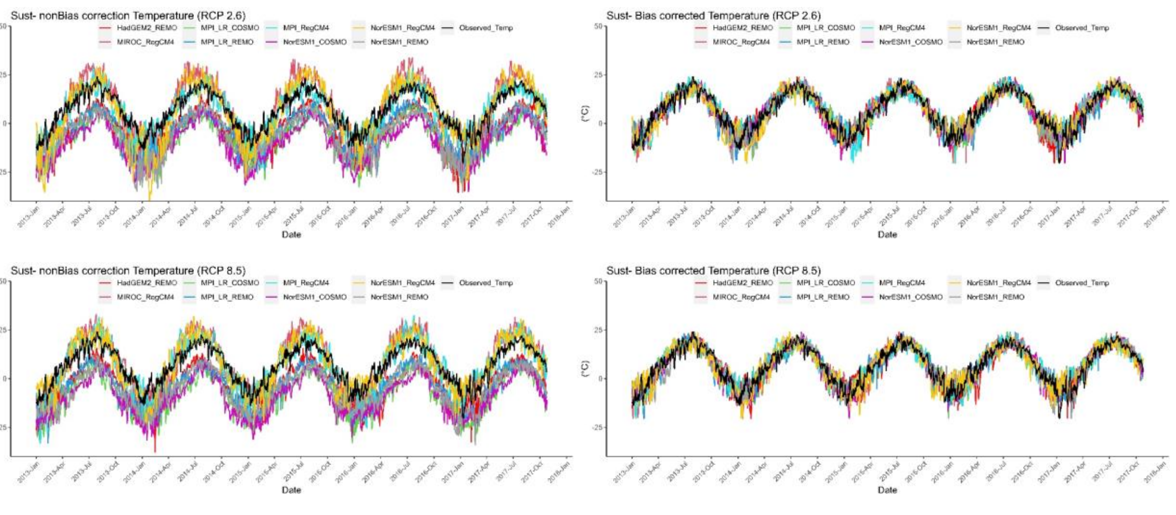


Figure V-13 (Figure S3) Box plot of observed precipitation data and bias corrected RCM precipitation data under two RCPs (2.6 and 8.5) in the three catchments.



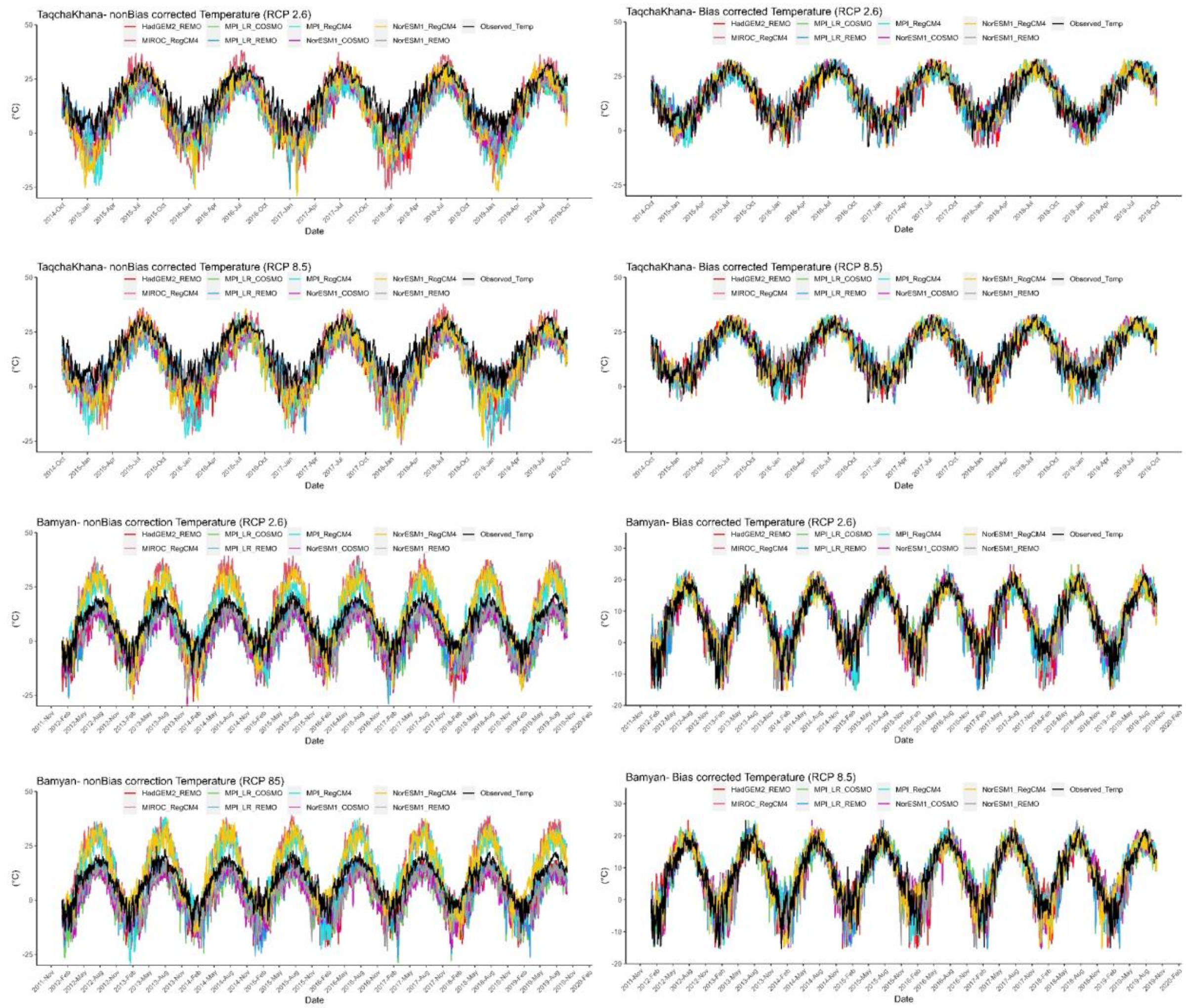


Figure V-14 (Figure S4) Temperature observed data plotted versus original projected data (on the left) and bias correction (on the right) for two RCPs (2.6 and 8.5) and the three catchments (Sust, Taqchakhana, and Bamyan catchments).

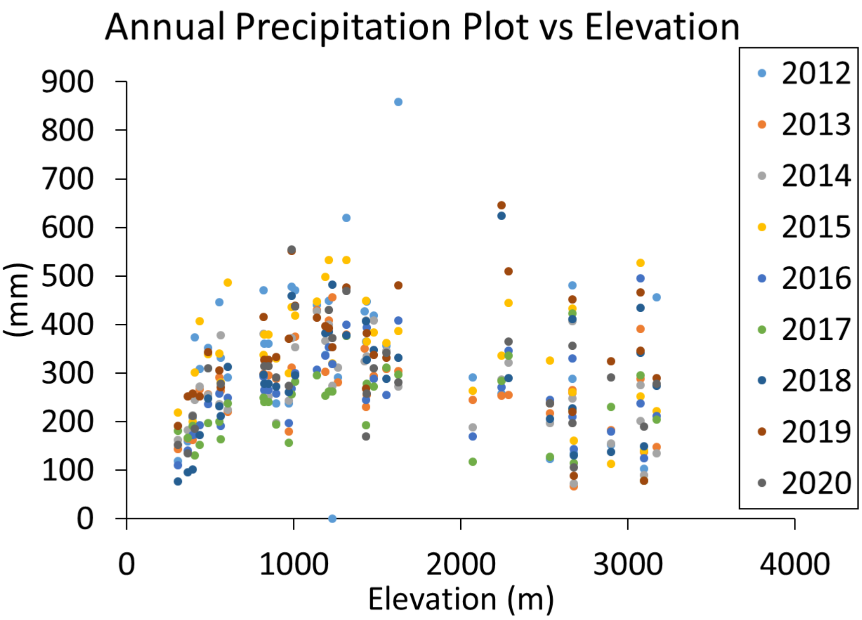


Figure V-15 (Figure S5) Mean annual precipitation of 41 observed station plotted against the station *elevation.*

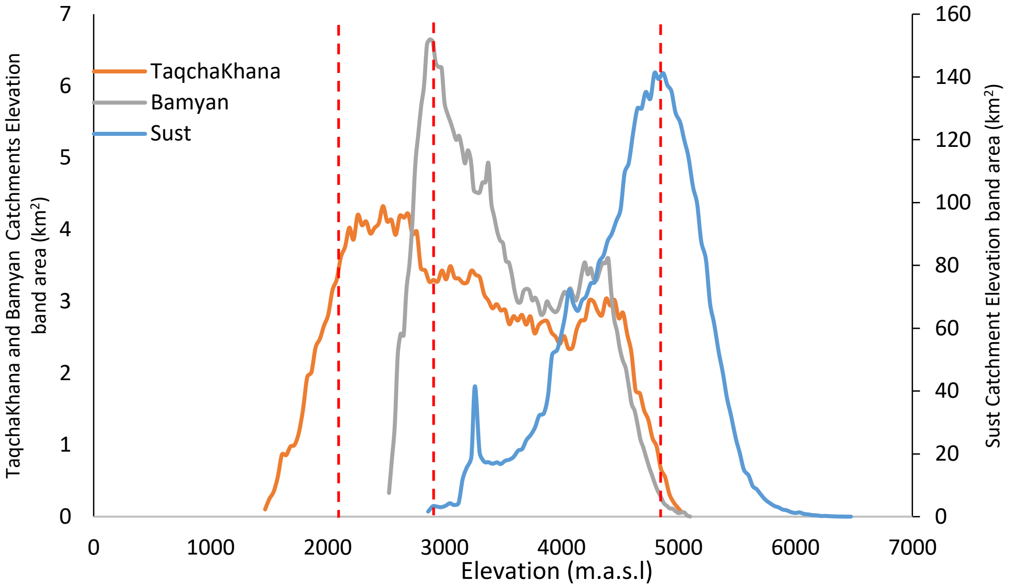


Figure V-16 (Figure S6) Shows catchments band area by its elevation, dashed lines are the precipitation elevation thresholds that is considered for individual catchments (2000 m.a.s.l for Taqchakhana, and 4800 m.a.s.l for Sust and 2800 m.a.s.l for Bamyan catchments).

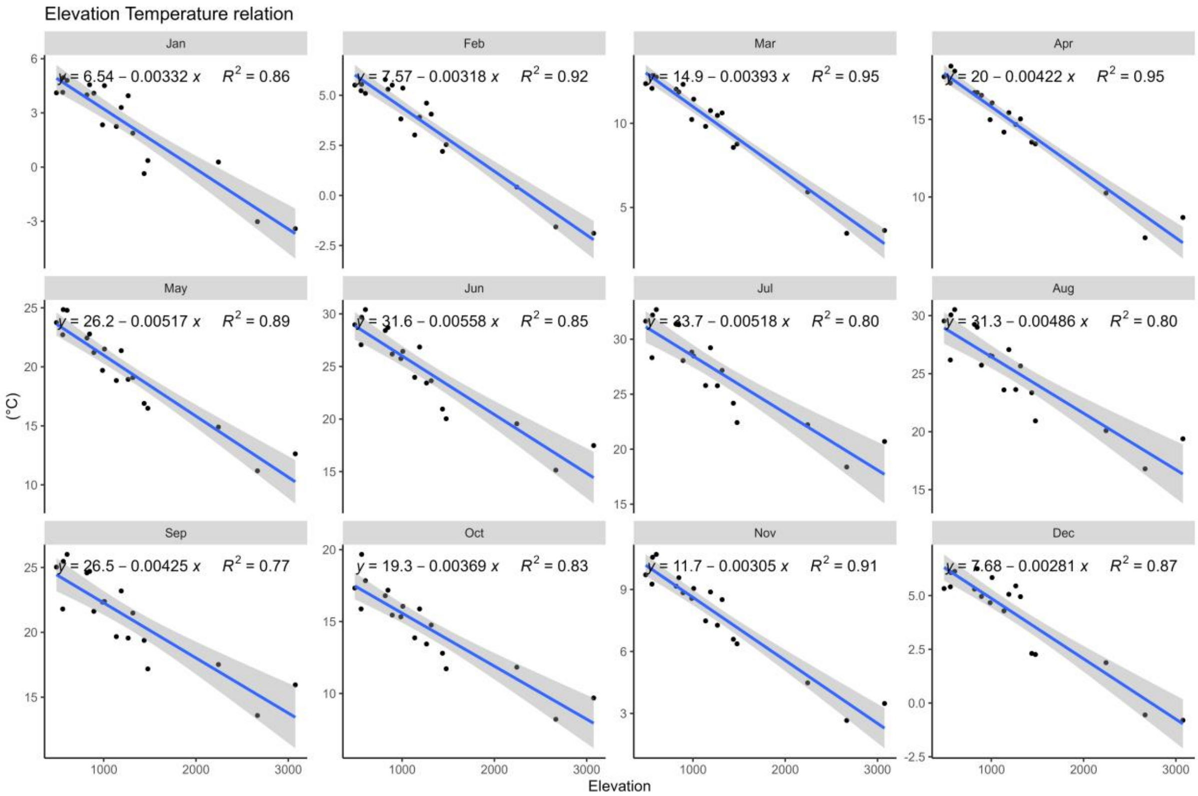


Figure V-17Figure S7. Mean monthly temperature of 23 observed station plotted against the station elevation at monthly scale.

VI CONCLUSION AND FUTURE RESEARCH PERSPECTIVE

VI.1 Introduction

This thesis aimed to address how glaciers in Afghanistan are currently responding to rapid climate warming and what this might mean for mountain water resources in Afghanistan both now and later in the 21st century. Chapter I identified four research objectives:

R1: Is it possible to improve remote sensing techniques for glacier monitoring in Afghanistan to allow mapping of not only ice cover but also debris-covered ice at the scale of the entire country?

R2: How have the total, bare ice and debris-covered ice extents of Afghanistan's glaciers changed in recent decades with the onset of rapid warming?

R3: Is it possible to develop a glacier-snow melt runoff model suitable for application over large scales in the data poor context of Afghanistan?

R4: How has and how will climate change influence future glacier runoff in Afghanistan?

These four objectives were supported by an in-depth review of the state of knowledge regarding the water resources of Afghanistan and related hazards under rapid climate warming, which resulted in the identification of knowledge gaps that justified the objectives outlined above.

VI.2 Key knowledge gaps

There are significant knowledge gaps in environmental research in Afghanistan due to the history of armed and political conflict. Chapter II showed that, in particular, little peer-reviewed literature is available concerning Afghanistan's climate and water resources and their recent trends (Savage et al., 2009; Aich et al., 2017) as compared with other regions. Hydro-meteorological records are only available between ~1960 to ~1980 at a monthly time scale. There is then a data gap until ~2004, and even since then the quality of available data has been questioned (World Bank Group 2018). Data gaps and quality issues have limited both local and regional climate change studies in the country (Masood et al., 2020). The lack of long-term hydro-meteorological measurements in the country has made it difficult to quantify recent hydrologically changes and to apply hydrological models at the catchment scale (Savage et al., 2009; Mohanty et al., 2012; Hrachowitz et al., 2013; Ghulami, 2017; Qutbudin et al., 2019; Aawar and Khare, 2020; Mianabadi et al., 2020). Larger scale studies have focused on entire geographical regions (e.g., Hindukush Himalayan and the Panj-Amu region in central Asia) (NEPA and UNEP 2016) and these include Afghanistan but with a relatively coarse spatial resolution. Climate variables important for water balance studies (e.g., humidity, wind, evapotranspiration, etc.) are rarely quantified. This lack of data remains a serious challenge for obtaining a complete assessment of Afghanistan's water resources, their change through time and associated hydro-climatic drivers. This makes it important: (1) to develop and to use whatever methods are available to reconstruct past changes; and (2) to develop predictive models to assess the impacts of climate futures that are parsimonious with the relatively restricted amount of data that are available.

As noted in Chapter II, cryosphere studies in Afghanistan mostly focus on the period ~1965 to ~1980, are predominatly written in Russian and Dutch, very rarely in English, and are generally not available online (Shroder and Bishop, 2010). Since then, only one glacier has been monitored by field observation, the Mir Samir, in the Panjsher valley in the center of Afghanistan (Sajood, 2020). The review in Chapter II showed that there is a serious lack of systematic cryosphere studies in Afghanistan, whether in terms of snow and snow hydrology, glacier mass balance and its drivers, the relative contribution of glacier runoff to catchment runoff and water resources, and the wider implications for development such as planning hydropower development (Saloranta et al., 2019).

Chapter II reviewed the climate of Afghanistan, which is arid to semi-arid climate but influenced by complex interactions between the mid-latitude westerlies, the southern Asian monsoons and the Himalayan Mountain Area (HMA) (Humlum *et al.* 1959, Shroder *et al.* 2014). The data presented showed that this leads to a need for careful sub-regional analysis of climate and climate change; and hence of climate impacts on streamflow. This complex climate leads also to a wide spatial variation in the relative importance of the cryosphere, both glaciation and snow accumulation. This is rarely appreciated at the scale of Afghanistan as key drivers of glacier mass balance, such as debris cover, have not been factored into analyses (Shroder and Bishop 2010).

Chapter II also showed that groundwater, a critical element of water resources in Afghanistan, is poorly understood (Shroder et al. 2022). There is a lack of up-to-date and detailed information on aquifer potential (storage and withdrawal), which has been considered a major challenge for sustainable groundwater management (Shroder et al., 2022). At the same time, datasets are focused on groundwater availability in the Kabul basin and is commonly lacking in other catchments (Lashkaripour and Hussaini, 2008; Houben et al., 2009; Mack, 2018; Karim, 2018; Jawadi et al., 2020; Noori and Singh, 2021). Groundwater vulnerability to pollution has increased due to an increase in the population of the country’s main cities and has become a major issue. The scale of this impact is not yet clear (Gesim and Okazaki, 2018; Mahaqi et al., 2018). This has affected the formulation of groundwater policies and regulations through increased industrial and mining activities and the expansion of agriculture (Hayat and Baba, 2017). This requires urgent attention not only from the scientific communities but also from the policymakers. Yet, all of this research has overlooked the fact that groundwater recharge is directly linked to runoff from upstream catchments, themselves impacted upon by climate change and potentially changing snow accumulation and glacier melt. Chapter II set this in the context of "peak water" (Baraer *et al.* 2012, Miller *et al.* 2012, Glas *et al.* 2018) and introduced the possibility that climate warming increases in glacier melt and runoff could be compensating for over-abstraction and declines in recharge due to increased evapotranspiration. Once peak water is passed, the current water scarcity could become more serious.

Socio-economic conditions and lack of infrastructure make Afghanistan highly sensitive to hydrological extremes, both floods and droughts. There are few records of past extreme events (over the last 30 to 40 years), which has reduced the applicability of standard methods for developing reliable related hazard maps (Shroder, 2016). In addition, there is very little research that has provided knowledge of glacier lake outburst floods in Afghanistan, while retreating glaciers under future climate may increase the probability of them occurring (Mukherji et al., 2015). Chapter II showed that to address these wider implications, beyond water resources, we need a much better understanding of hydro-climate changes in the past in Afghanistan and how these will change in the future.

VI.3 Mapping of debris-covered ice and quantification of the drivers of glacier debris cover – research objective 1

Give the importance of the cryosphere to Afghanistan water resources, it is vital that there is a developed understanding of the distribution of glaciers in the country and their change through time. The last few decades have emphasized the crucial role played by debris cover in influencing glacier melt. Debris cover is generally assumed to reduce melt rates as compared to bare ice, except where debris is thin or patchy, which can lead to a local increase in ice melt and these characteristics can substantially modify glacier melt response to climate warming (Østrem, 1959; Mihalcea et al., 2006; Lejeune et al., 2013; Fyffe et al., 2014; Minora et al., 2015; Fyffe et al., 2019). Knowledge of debris-covered ice is well developed for the Hindu Kush Himalayan region but less so for Afghanistan (Chapter III, Supplementary Materials). A review of existing methods for mapping the extent of debris-covered ice from satellite data and some preliminary tests for Afghanistan resulted in a decision to develop new indices (Chapter III). The indices are based upon freely available imagery from the Landsat 8 Operational Land Imager (OLI) and were based upon fusing thermal and panchromatic bands to allow debris cover to be mapped to a resolution of 15 m. The results were validated using field observations, manual digitization of high-resolution imagery and comparison with mapped data reported by other researchers. The validation results were encouraging. It was clear that two indices were needed to represent debris cover reliably because of geological controls on the kind of debris cover that developed and its thermal signature. Application of the method to all glaciated regions in Afghanistan identified 3,408 glaciers in Afghanistan with debris-covered ice representing 21.7±1.4 % of the total glacier area. A high proportion of glaciers were found to be smaller than 1 km^2 (32% of bare ice), emphasizing the importance of the data downscaling allowed by the fusion of two bands. It was also clear that the method identified more irregular glacier marginal zones of debris-covered ice than is typical in the literature. This is because the method identifies ice at depth; but it also raises the semantic question of whether disconnected zones of buried ice should still be labelled as “glacier”. As such zones may still have an important water resource potential, we included them.

We noticed regions with smaller glaciers tend to have a higher percentage of debris cover. A statistical analysis of the characteristics of glaciers in Afghanistan in Chapter III, showed that debris cover was related to climate and geology. Glacier length, width, and elevation range were identified to be the most important factors in controlling differences between debris cover development. Glaciers that were longer, wider and with a greater elevation range tended to have lower percentage debris cover. Glaciers with steeper ice and catchment slopes tended to have higher percentage debris cover. However, these effects were complex and varied by region as a result of the effects of climate and geology; drier climates tend to produce higher debris cover, as do glaciers in geological zones with more readily-weathered sediment.

VI.4 Glacier retreat and debris cover evolution – research objective 2

Understanding the evolution of glaciers through time is important for the arid regions where there is considerable dependency on glacier melt during summer and when water is most needed for irrigation (Kaser et al., 2010; Viviroli et al., 2003; Sorg et al., 2012; Hagg et al., 2007; Sorg et al., 2012). However, a comprehensive and methodologically consistent sub-regional analysis of glacier changes over the HKH in the early 21st century still needs to be done (Brunner et al., 2019). Chapter IV presented three glacier inventories for Afghanistan in the northwestern HKH for 2000, 2008, and 2020 to quantify the regional patterns of ice loss and debris cover development in the country. Analysis of the inventories allowed changes total glacier area, clean ice, and debris-covered ice to be calculated for two timespans; 2000-2008; and 2008-2020.

Results indicated a glacier area of 2684±100.7 km^2 in 2020 with 75±0.74 % clean ice and 25±3.0 % debris-covered ice. This compared with 2869±97.8 km^2 in 2000 with 79±0.80 % clean ice and 21±2.5 % debris-covered ice. Thus, glaciers are becoming smaller. Further, analysis showed that the response of glaciers to climate warming in Afghanistan is regionally variable and highly dependent on geographical location which could in turn be related both to climate but also the characteristics of the glaciers themselves. For instance, glaciers in the north had the highest retreat rate in general and this was particularly the case for glaciers with an area < 2.5 km^2. This region has a cold winter and dry and hot summer climate. In contrast, glaciers with arid, desert, and steppe cold climates in eastern Afghanistan had the lowest recession rates and in some cases were stagnant or advancing albeit at a low rate. Glaciers in the center, where there is also a summer Asian monsoon influence, had a median retreat rate. One point stood out, however; in all regions, smaller glaciers had the highest retreat rate. Where glaciers had a higher retreat rate they tended to have a higher rate of increase of debris cover. This suggests that debris cover is an important and dynamic response of Afghanistan glaciers to climate warming and ice melt. As it is known to have an impact upon melt rates, it follows that representing debris cover in assessment of Afghanistan water resources is likely to be crucial. This is addressed in Chapter V of the thesis. The inventory resulting from this research will be made open access via the Zenodo platform.

VI.5 Glacier-influenced hydrological regimes under current and future climate – research objectives 3 and 4

Chapter V presented a successful implementation of a glacio-hydrological model for three Afghanistan catchments including: (1) a specific treatment of debris-covered ice impacts on ice melt; and (2) a very basic scenario for future glacier retreat based upon observations presented in Chapter IV. There catchments were selected for application of the model, chosen both for scientific (spanning a geographical and climate gradient from west to east) and practical reasons (data availability, notably for calibration and validation). Calibration and validation used a split sample test. Very encouraging values of the Kling-Gupta efficiency (KGE) were obtained for the validation of simulated daily streamflow for three catchments.

Five key points followed. First, during data pre-processing, effective model application required; (1) quality control of observed data; (2) consideration of elevation effects in precipitation gradient calculation; (3) reliable estimation of monthly temperature lapse rates, and (4) bias correction of future climate data.

Second, model simulations showed clear regional differences in glacio-hydrological regimes for the three catchments; the Sust catchment in the east had the highest contribution from glacier runoff (76% of the total streamflow); the Taqchakhana in the north had the highest contribution from the rain and snow runoff (50% of the total streamflow) and the Bamyan catchment in the center had the highest contribution from baseflow (61% of the total streamflow).

Third, future climate warming possible in the catchment was for an increase under RCP 2.6 to about 2050 (by ~ 0.9˚C) and then declined (by ~ 0.6˚C) until the end of the 21st century. Under RCP 8.5, their temperature rose more rapidly throughout the 21st century (by ~1.8˚ C by 2060s and ~ 4.4˚C by 2100s). These effects were more homogeneous between the catchments suggesting that warming trends are more climate scenario specific than they are geographically variable. However, even given the relatively small distances between the three catchments, precipitation changes were strongly dependent upon each catchment's geographical location, geography (e.g. catchment hypsometry) and sources of moisture. The projections for precipitation under both RCPs (2.6 and 8.5) suggest decreases in mean annual precipitation for the most easterly catchment located geographically in the center of Afghanistan (Bamyan catchment) by 2050 (2060s), mainly in spring and autumn; it was insignificant for other catchments under RCP 2.6. Under RCP 8.5, a decrease in spring and summer precipitation for the next catchment to the west, also located to the north (Taqchakhana catchment) and spring and autumn for the Bamyan catchment was predicted by the 2060s and 2100s. These changes were markedly different to those for the Sust, which tended to be coming wetter notably under the RCP 8.5 scenario.

Fourth, and following predicted climate changes, the predicted annual streamflows suggest a decrease in the mean annual runoff for the Bamyan catchment where precipitation changes were most clear. In the Taqchakhana catchment, annual changes were less clear, but there was a marked increase in seasonality of runoff predicted to the 2100s, with more winter runoff and less summer runoff. In the Sust, forecast to become wetter through the 2100s, runoff is forecast to increase across all seasons and very markedly for RCP 8.5. Glacier runoff was forecast to increase due to rising temperatures in the Sust under both climate scenarios and in the TaqchaKhana under RCP 8.5 but it was only really in the Sust where the glacier cover was sufficient for this to be seen clearly in annual runoff changes. In water resource terms, these results are important as it suggests markedly different responses to climate change. The simple concept established for the HMA that river basins will go through a phase of peak water is clearly more complex in an Afghanistan context. This is not only for the obvious reason that the passage of peak water depends on where they are in their history of glacier cover loss. It is also because different catchments have different climate change regimes, potentially different sensitivities to climate warming (e.g. related to the distribution of ice with altitude) and may also slow ice loss via the development of debris cover. Thus, the general conclusion that the HMA may witness peak water within the 21st century, with important political and economic repercussions (Pritchard, 2019; Rounce et al., 2020) cannot be generalized to all river basins within the HMA. Indeed, in this study only one of the basins modelled (the Sust) suggested a clear peak water pattern; and even that appeared to be more related to the climate project RCP 2.6 than it did to changes in ice cover. As we note below, this conclusion needs to be cautioned to recognize that we only consider future glacier scenarios in this paper, as well as only three catchments.

Finally, Chapter V showed that it is important to include an explicit treatment of debris-covered ice in the glacier runoff modeling, although with a caveat. Debris cover reduced melt significantly in the short term for the Taqchakhana catchment (glaciers in this catchment are 40 % debris-covered). Catchments where proportionately total glacier cover is small (the Bamyan) or where percentage debris cover is low, even if total glacier cover is high (the Sust) do not necessarily need a separate treatment of debris-covered ice and bare ice. That said, as the Sust catchment calibration showed, not having a separate treatment for bare ice and debris-covered ice leads to a lower bare ice melt factor. That is, the simulation produces the right results but not necessarily for the right reasons (Beven, 1989). If progressive glacier retreat in the Sust does lead to significant debris accumulation, then separate representation of bare ice and debris-covered ice may be needed. For this reason, treating a glacier as having a separate bare ice and debris-covered ice is likely to provide more reliable future predictions.

The datasets resulted from this study for future climate and streamflow will be made open access via the Zenodo platform.

VI.6 Research limitations

The limitations of this research can be summarised into (1) debris-covered glacier mapping methods and detection of glacier change; and (2) glacio-hydrological modelling.

Although Chapter III suggested that the debris-covered ice indices performed effectively, especially as compared with other methods, there remain uncertainties. The first thermal based index developed by this study was only calibrated by one field observation due to security issues in the study area. The second index was calibrated with the help of high resolution image. Further validation is really required. The results suggested that calibration of segmenting thresholds is still needed. There was also uncertainty associated with the top of atmosphere correction and its effects. As suggested by Stewart et al, (2021) and Herreid (2021) classification thresholds are important and this suggests to explore more the transferability of these thresholds using a wider set of validation data. Indeed, it may be argued that Afghanistan was not the best place to do this index development; but this thesis is motivated by the need to understand Afghanistan water resources better. Similary, Landsat image availability was variable for Afghanistan. Sometimes it was hard to find a cloud free image especially in the eastern part of Afghanistan (Mölg et al., 2018). There was also evidence of misclassification of snow cover as glacier ice. In particular, fresh snow on talus slopes was sometimes misclassified as a glacier because of having similar reflectance and slope with the snow on the accumulation zone of glaciers (Tielidze et al., 2020). This required manual correction using other imagery which was not always easily findable or available (Mölg et al., 2018). This resulted, in Chapter IV, in the need to remove about ~100 km^2 of total glacier area from the 2020 inventory because of frequent cloud and snow cover mainly in the eastern and northern region of Afghanistan. The method also can only detect glaciers with a surface ≥ 0.01 km^2 due to Landsat image resolution and minor misclassifications, including of water bodies, snow patches, and talus slopes (Racoviteanu et al., 2022). Thus, although the method represents an improvement in resolution, it should be noted that recent research has shown that there may be important controls on glacier and related melt response to climate change at smaller spatial scales (Watson et al., 2016; King et al., 2020) than those that the downscaling method used here can represent. Equally, the glacier changes addressed in Chapter IV did not consider all the controls that could drive glacier change, such as the response of glaciers to glacial lake formation which has been observed as important in some parts of the HMA (King et al., 2017).

Chapter V addressed the influence of glaciers and the wider cryosphere on hydrological regimes in Afghanistan under current and future climate. Three broad limitations stand out in this assessment. First, in these high mountain basins, winter snow accumulation, and hence both summer runoff and longer term glacier mass balance, is strongly dependent on getting the precipitation right at high altitudes. Chapter V showed that extrapolating precipitation at a higher elevation with the absence of observed data may limit the quality of model simulations (Charbonneau et al., 1981; Immerzeel et al., 2014). Indeed, precipitation gradients had to be treated as a calibration parameter. Indeed, the wider modelling approach was dependent on calibration and hence critically available on data (Azizi and Asaoka, 2019). This made the inclusion of uncertainty in our analyses of critical importance. Finally, and perhaps most importantly, we considered future water resources using scenarios for possible future glacier change. The linear extrapolation on which these scenarios are based are highly likely to be unreliable to the 2100s. This means that the conclusions made in Chapter V and in Section 6.5 above must be treated with caution; they are possible projections under the scenarios considered. What is likely needed is a more formal coupling of glacier evolution to evolving climate.

VI.7 Perspectives for future research

Given the above limitations, there are new topics and research questions that arise from this study, with relevance both to Afghanistan and more generally.

As reviewed in Chapter II, there is very little peer-reviewed literature on Afghanistan's water resources. This thesis has sought to make a small contribution but it also flags some important research questions for the future.

First, there is a serious lack of climate studies at the local scale in Afghanistan. Even over short distances, and notably with respect to precipitation (Chapter V), there can be complex spatial variations reflecting both the complex topography of Afghanistan and its interaction with larger-scale atmospheric systems (notably the mid-latitude westerlies and the south Indian monsoon). This merits further investigation, as does research into evapotranspiration processes more generally.

Second, Chapter V considered only three catchments. It would be very valuable to extend the model, including making predictions with uncertainty, to many more if not all catchments. This is the promise of the model presented in Chapter V. Assembling the datasets that the model would need is relatively straightforward; and the calibration results in Table 5 suggested at least some similarities in parameter valuess across catchments. Doing this, although a large computational undertaking as uncertainty would need to be included, would allow a much clearer sense of the geography of climate change impacts on Afghan water resources and how these might scale up to cities like Kabul. It would allow an explicit assessment of the scale effect referred to by Quincey et al. (2018); that is how dependence upon glacier water supply changes as a function of distance from glaciated parts of a catchment. It would also allow a more thorough testing of where the peak water concept is most relevant in Afghanistan.

Third, although Chapter II flagged the crucial issue of groundwater in its review, this was not considered further in this thesis. Most of Afghanistan's population directly relies on groundwater for drinking purposes, and groundwater studies are only available for Kabul and rarely for other provinces of Afghanistan. Therefore, systematic groundwater studies focused on availability, quality, demand, and withdrawal at provincial scale are needed and which should in turn be coupled to the effects of future glacio-hydrological changes on groundwater recharge.

Finally, in terms of Afghanistan, there may opportunities to apply these methods beyond water resources management. For instance, the dataset on satellite imagery could easily be identified to quantify the formation of glacier lakes, of crucial important in relation to potential hazards associated with glacier lake outburst floods (Chapter II). As another example, the HMA remains poorly researched in relation to the ecosystem response to deglaciation such that we do not know whether models developed for Europe and North America (Miller and Lane, 2019) will transfer to the HMA even though such work is crucial for understanding of regional ecosystem and biodiversity changes in the future. Again, the assimilated remote sensing datasets could be used to begin to quantify these processes.

In more general terms, this thesis raises wider questions that should be considered in different regions and potentially at the global scale. The first is the importance of looking carefully at regional responses of cryosphere dominated systems to rapid climate change. It is hard to state whether or not the local complexity of Afghanistan might be found elsewhere and particularly for less well-researched regions this would be valuable. Unfortunately, such work is always going to be limited by data availability, especially for modelling and this is likely to mean that less well-studied regions remain a challenge.

Second, the indices for mapping debris-covered ice used in this study have the potential to allow for debris-cover thickness estimation, as shown for the Khumbu and Stopanth glaciers in Annex 1. Calibrating and validating the method with in situ measurements would increase the applicability of the method for such studies. Equally, the indices merit extension to other regions as Chapter III showed the importance of small glaciers, overlooked in many attempts to map debris cover, but which in mountain regions may be of some significance.

Third, a comparative study of glacio-hydrological models using more process-based glacier evolution and the simple observation-based treatment used in this study is worth doing. The complexity of glacier melt, debris cover development and glacier dynamical changes is only now being fully appreciated (e.g. Gibson et al., 2017; Rowan et al., 2021); but, as Rowan et al. show, this complexity seems to be important in driving glacier recession and debris cover changes. There are also complex influences of debris cover on runoff processes (e.g. Benn et al., 2017; Irvine-Fynn et al., 2017) that were not included in this model. We do not know whether such processes influence only sub-seasonal runoff variations, or whether they scale up to influence seasonal or even annual scale runoff. This is likely to lead to a more physically-based but perhaps reduced complexity treatment of debris cover development such that the advantages of the approach described in Chapter V (notably its parsimony) can be maintained whilst more realistic treatments of future ice loss and debris cover development are developed. There are frameworks that have been developed to inform what is likely to be needed for developing a physically-based approach (Nicholson et al., 2021). Indeed, a key reminder from this study is that debris cover can, in certain situations, make an important difference to the response of mountain glaciers to climate change in water resource terms.

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