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REVIEW

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Water resources of Afghanistan and related hazards under rapid climate warming: a review

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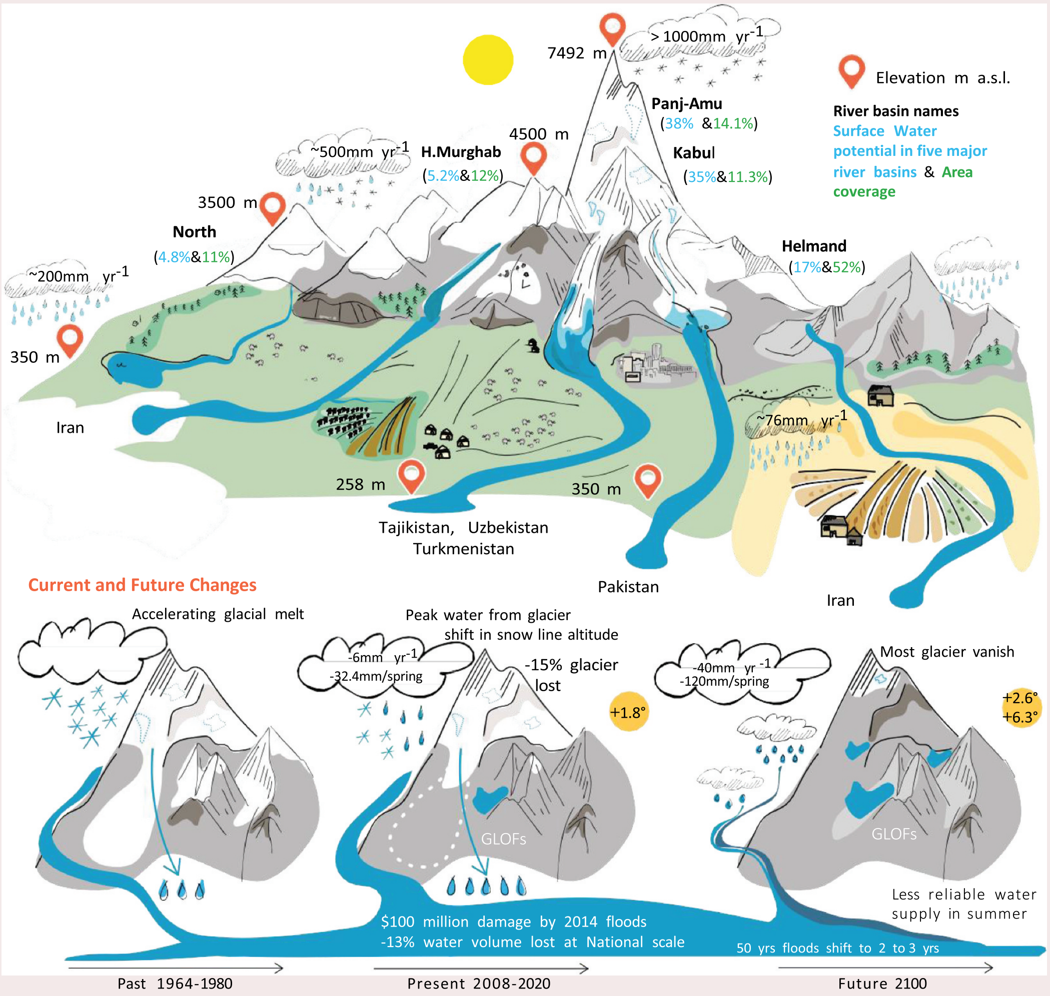
ABSTRACT

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.



Source: Clip-arts modified from World Bank 2019 - Weather, Climate and Water in Central Asia.

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1 Introduction

Climate change impacts on water resources have been widely observed and future impacts are likely to cause significant harm to water resources at both regional and global scales (Pörtner *et al.* 2022). Water shortages, 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 (Pörtner *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 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 in such a way that they are now strongly dependent upon mountain water resources (Unger-Shayesteh *et al.* 2013) including summer snow- and ice-melt (Ma *et al.* 2015). These resources are potentially threatened by 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 the spring and early summer seasons (Hussainzada and Lee 2021, Mahmoodzada *et al.* 2022). Many Afghans rely on snowmelt for irrigated croplands, and snow drought occurring alongside ongoing conflicts, violence, and economic challenges can further stress the country (Huning and AghaKouchak 2020). Such sensitivity can decrease when enough snow is accumulated at higher elevations (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 possible changes is lacking. There is no national-scale water resource assessment available. This article contributes to filling this gap by developing an initial baseline.

A key challenge in water resources assessment for Afghanistan is the lack of long-term measurement of hydrometeorological variables (Savage *et al.* 2009, Mohanty 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 and Hock 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 it 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 the use of comprehensive search terms we have been able to identify 131 scientific papers and reports that relate to Afghanistan’s water resources, and we use these as the basis of our review.

The review is organized 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 contextl (4) analyses of streamflow data for glacierized and non-glacierized 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.

2 The geographical context of Afghanistan

Afghanistan is a mountainous country located in the subtropical zone, extending from 29°21′ to 38°30′N latitude and from 60°31′ to 75°E longitude (Gopalakrishnan 1982) (Fig. 1). It has an arid and semi-arid continental climate, characterized by temperature and precipitation regimes characteristic of deserts, steppe and highlands (Humlum *et al.* 1959, Shroder 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 north-eastern region of the country.

The lowland plains to the west and the north of the country experience low annual rainfall (~50–100 mm year^{-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. ~1000 mm year^{-1}) (Fig. 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)

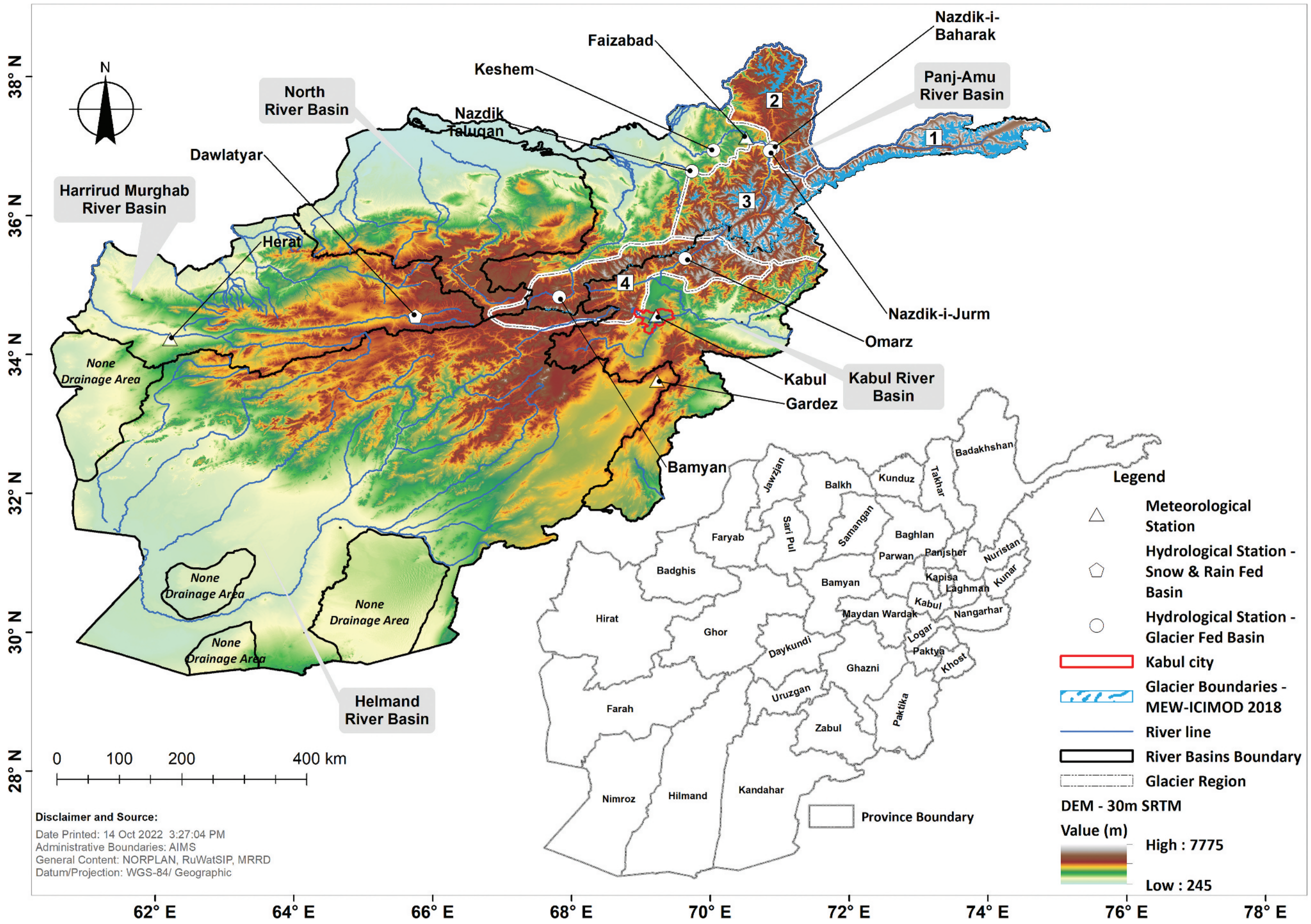

Figure 1. Geographical map of Afghanistan, showing elevation, river lines, hydro-meteorological stations, and glacier coverage, and identifying the four most glacier-covered regions. The subordinating map shows the provincial boundaries of Afghanistan.

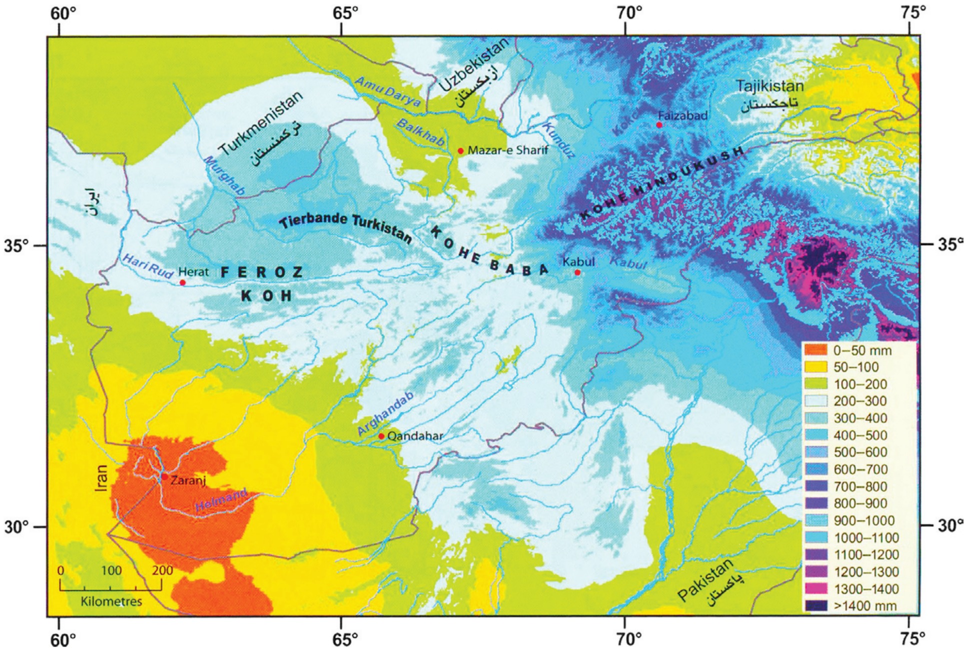

Figure 2. Precipitation map of Afghanistan and the nearest parts of the neighbouring countries (after Breckle and Rafiqpoor 2010, Shroder 2014). Source: Natural Resources in Afghanistan, Shroder, J.F., Soil and Vegetation In extremis, 116-137., 2014, with permission from Elsvier.

Kabul (Mahmoodi 2008) (Fig. 1). The elevation range of these basins is very large – from glaciated basins extending to over 7000 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) (Fig. 1).

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

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.

3.1 National-scale climate studies

3.1.1 Changes in temperature

Only two studies have assessed changes in climate for the whole of Afghanistan. The first regional climate trend and future projection assessment for the country was published in 2009 (Savage *et al.* 2009) (see Table 1 for a summary of all studies cited hereafter). Savage *et al.* (2009) used the output of global climate models from the Coupled Model Intercomparison 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. A report by the National Environmental Protection Agency and the United Nations Environmental Programme (NEPA and UNEP 2016) updated the previous study with better resolution (0.5° grid size) reanalysis data for 1950 to 2010 and regional climate model (RCM) and general circulation model (GCM) combinations generated from Coordinated Regional Climate Downscaling Experiment 5 (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 and 6.2°C by the 2090s depending on the scenario chosen, with the most rapid rates of change in the north and central plains (Savage *et al.* 2009).

The study by NEPA and UNEP (2016) estimated that under an "optimistic" (Representative Concentration Pathway (RCP) 2.6) 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" (RCP 8.5) scenario, temperature was projected to increase by 2°C to the 2050s and by 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 (Fig. 1) using the outputs of three GCMs varying in resolution (from 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 would increase by 1.8, 3.5 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 (spatial resolution of 0.7° × 0.7° to 2.5° × 2.0°). Their study suggested a higher increase in temperature under RCP 4.5, of 2.51°C by 2089–2095.

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 year^{-1} between 1960 and 2009, mainly due to decreases in spring precipitation (32.4 mm year^{-1}), partially compensated for by small increases in summer and autumn precipitation (Savage *et al.* 2009). Likewise, NEPA and UNEP (2016) reported a 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 1 mm 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 Asian Precipitation - Highly-Resolved Observational Data Integration Towards Evaluation (APHRODITE) gridded dataset with a 0.25° × 0.25° spatial resolution, and found a reduction in spring season precipitation in southwestern and northeastern Afghanistan by 1.5 to 6 mm year^{-1}, but a slight increase in summer precipitation and the frequency

Table 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 2006–2050; +2.7°C 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 year^{-1}	+4.88 to +30.42 mm year^{-1}	X	X
6	Azizi and Asaoka 2020	Panjshir sub-basin of the Kabul River basin	8 GCMs 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 Pathway of very heavy (10 mm) and extremely heavy (20 mm) precipitation in central, eastern, and southern Afghanistan.

Regarding projections of future precipitation, Savage *et al.* (2009) indicate there will be a precipitation increase over much of Afghanistan by the 2030s but only by a small amount, 10–20 mm in total. Annual precipitation is predicted to decline by the 2090s, but by a degree dependent on the chosen emissions scenario (40 mm – high; 20 mm – medium; 10 mm – low) (Savage *et al.* 2009). NEPA and UNEP (2016) obtained more uncertain precipitation projections, with no clear annual trend and with 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 (northeastern Afghanistan) and decreases to a smaller extent in the central highlands and the north (NEPA and UNEP 2016).

For the Kabul River basin (Fig. 1) in eastern Afghanistan, the mean annual precipitation is projected to increase under both RCP 4.5 and RCP 8.5 scenarios, by 70 to 125 mm year^{-1} by the 2080s, as compared with the 1961–1980 baseline (Table 1), mainly in the summer and autumn (Sidiqi *et al.* 2018); in spring and winter, the projections yield a decrease by 120 and 17 mm year^{-1}, respectively, under RCP 4.5. Likewise, a similar pattern of precipitation change is found 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 precipitation 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 decreases by 1.1–12.3% in spring and winter precipitation but increases by 0.1–29% in summer and early autumn precipitation by 2080–2100 under RCP 4.5.

3.2 Local-scale climate studies

Lack of availability and accessibility of climate data in Afghanistan have limited local-scale determination of climate change (Masood *et al.* 2020), although more recently data from individual weather stations is becoming increasingly available. The Government of Afghanistan's Ministry of Energy and Water has recently established a Hydro-Meteorological Data Centre that can be accessed by researchers (see this article's 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 (Fig. 1). Data are calculated seasonally based on monthly means for each period; we were not, however, able to perform a proper trend analysis due to data gaps.

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) periods of data availability. Figure 3(a) shows that mean temperature has increased for all seasons and for all stations (Fig. 3(a)). 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 (Fig. 3(b)). The minimum mean winter temperature at Gardez, located at a lower elevation and in the east, has increased only slightly. The maximum mean winter (maximum of long-term mean monthly temperature) temperature has increased for all stations (Fig. 3(c)) although there is substantial inter-station variability for all seasons. Perhaps the station that differs most clearly from the others, notably for temperature, is Faizabad. Particularly in winter, it has a reduced increase in mean temperature (Fig. 3(a)), and no significant change in the minimum mean (Fig. 3(b)) and maximum mean (Fig. 3(c)) 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 have 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 2014); whilst the other three stations are in desert or semi-arid climate zones. That said, Fig. 3(a) 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 for snow and ice accumulation.

3.2.2 Change in precipitation

Precipitation changes (Fig. 3(d)) 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 also 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 those for other stations, despite its location in the east of the country where it is subject to monsoonal airflows associated with the 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.

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

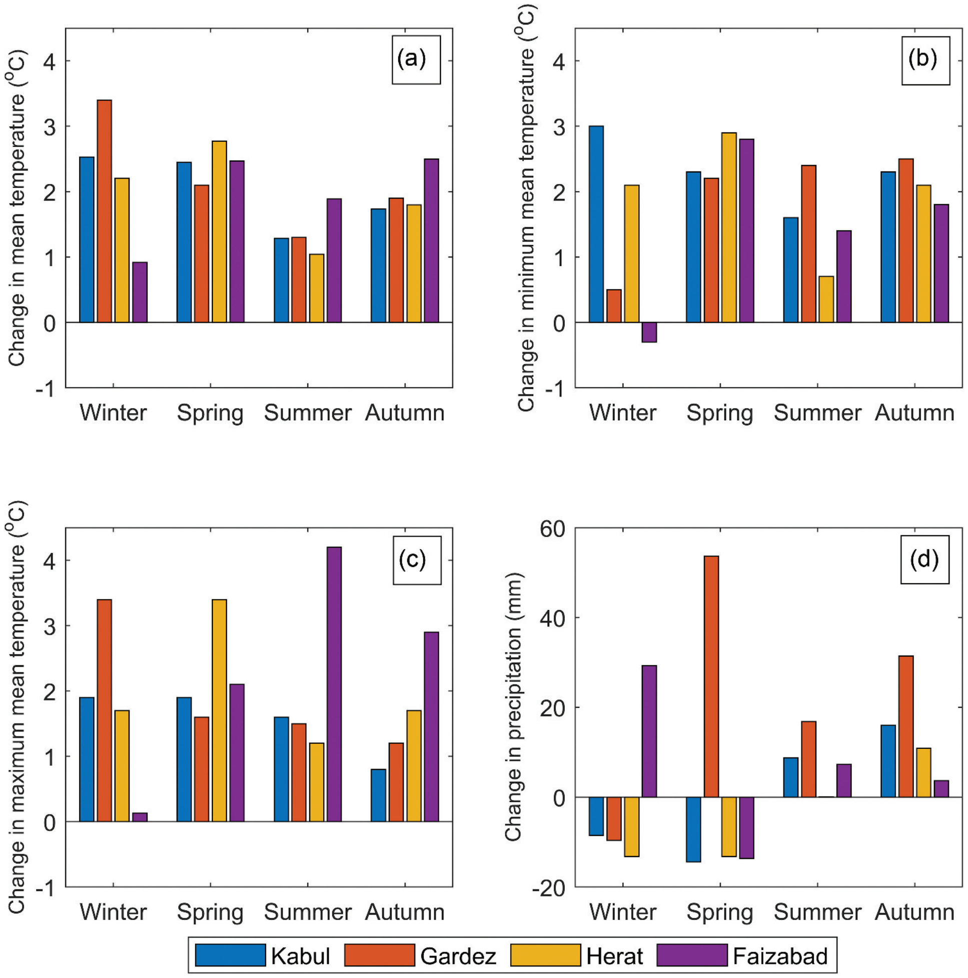

Figure 3. Changes in (a) mean temperature, (b) minimum mean, (c) maximum mean and (d) precipitation by season between 1964–1977 and 2007–2018. The two periods shown for are those for which data availability is common to all four stations.

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 (Fig. 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 regionalize Afghan precipitation records in different ways to isolate the effect of hemisphere-scale teleconnections.

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). Some studies suggest 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).

Formally, Afghanistan is a part of the Himalayan region, but as it is in the region's 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 that 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 are essential for maintaining downstream river flows (Vanham *et al.* 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 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 alter 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 Shrestha 2021).

4.1 National-scale glacier studies

There is a serious lack of systematic cryosphere studies with field observations in Afghanistan, and those that exist focused on the period 1965 to 1980. Such studies are mostly in Russian or Dutch, and very rarely in English, and most are not available online (Shroder and Bishop 2010). Shroder (1980) initiated the first glacier inventory for Afghanistan, supported by the US Geological Survey using Landsat-3 satellite imagery (40 m 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 3000 separate glaciers in Afghanistan with an estimated area of ~2700 km^2, concentrated in the higher northeastern 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 Landsat satellite imagery in 2018 (Maharjan *et al*. 2018). Glaciers were mapped using semi-automatic object-based image analysis methods. They identified 3782 glaciers, covering a total area of 2539 km^2 concentrated at mean elevations between 3200 and 6900 m a.s.l., although 78% of glaciers had mean elevations higher than 4500 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 4700 and 5000 m a.s.l., and the lowest rates of loss were above 5500 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 the lowest elevations (< 4700 m a.s.l.). This emphasizes 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 the 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 not, however, 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 understanding the retreat of the Hindukush Himalayan glaciers. The same may apply for Afghanistan, making satellite-based studies problematic unless they take into account debris-covered ice (Shroder and Bishop 2010).

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 seven 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 Wakhan Pamir ranges (produced 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, Fig. 1) for the period 1976 to 2003, and identified 28 glacier tongues that have retreated by between 1.3 and 36 m year^{-1}. The study also found an increase in the number and area of new proglacial lakes, from 46 600 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 year^{-1}. Recently, Joya *et al*. (2021) assessed the equilibrium line altitude in Kokcha sub-catchment of Panj Amu River basin (Fig. 1), and observed an average change in altitude of 722 ± 145 m from 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 and a negative balance of 1.7 million m^3 of water equivalent (Sajood 2020).

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 (TSLs) 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 decrease 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.

4.4 Summary of cryosphere changes

Glaciers in Afghanistan are retreating by 0.54% year^{-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 hydroclimatological terms (Fig. 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 underdeveloped, 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 accurately characterize changes in the seasonal variability of snow-line elevation through time (Shroder and Bishop 2010).

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). In Afghanistan, 80% of 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. Therefore, 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). Muhammad *et al.* (2017) and Casale *et al.* (2020) 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.

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 (Fig. 1) between the period 1969–1980 and 2007–2016 based on measured hydrological data (Table 2; Bromand 2017). By 2030, all of these decreases were expected to continue to amplify.

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 and Water Assessment Tool (SWAT) hydrological model under RCP 4.5 by 2030. The model 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

Table 2. Surface water volume in five Afghan river basins between 1969–1980 and 2007–2016 (source: Bromand 2017). BCM: billion cubic metres.

River basins (RB)	Surface water volume in (BCM) (1969–1980)	Surface water volume in (BCM) (2007–2016)	Decreases in (%) (2007–2016)	Projected by 2030 (BCM)	Decreases by 2030 (%)
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%

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 farther downstream in Pakistan and indicated an increase in summer streamflow due to larger contribution from snow and ice melt under both RCP 4.5 and 8.5 in the near future (2011–2030), which contradicts the findings 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 towards 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 (Fig. 1). The findings suggest a decline in northern Afghanistan by −0.05 to −0.1 cm/year^{-1} from 2002 to 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.

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 glacierized and one snow-rain fed basin for two time periods (1969–1977) and (2008–2016) (Fig. 4) to illustrate how 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 4 shows increases in the summer discharge peaks for the glacier-fed basins (Taloqan, Keshelm, Bamyan, Omarz, Nazdik-i-Jurm, Nazdik-i-Baharak)

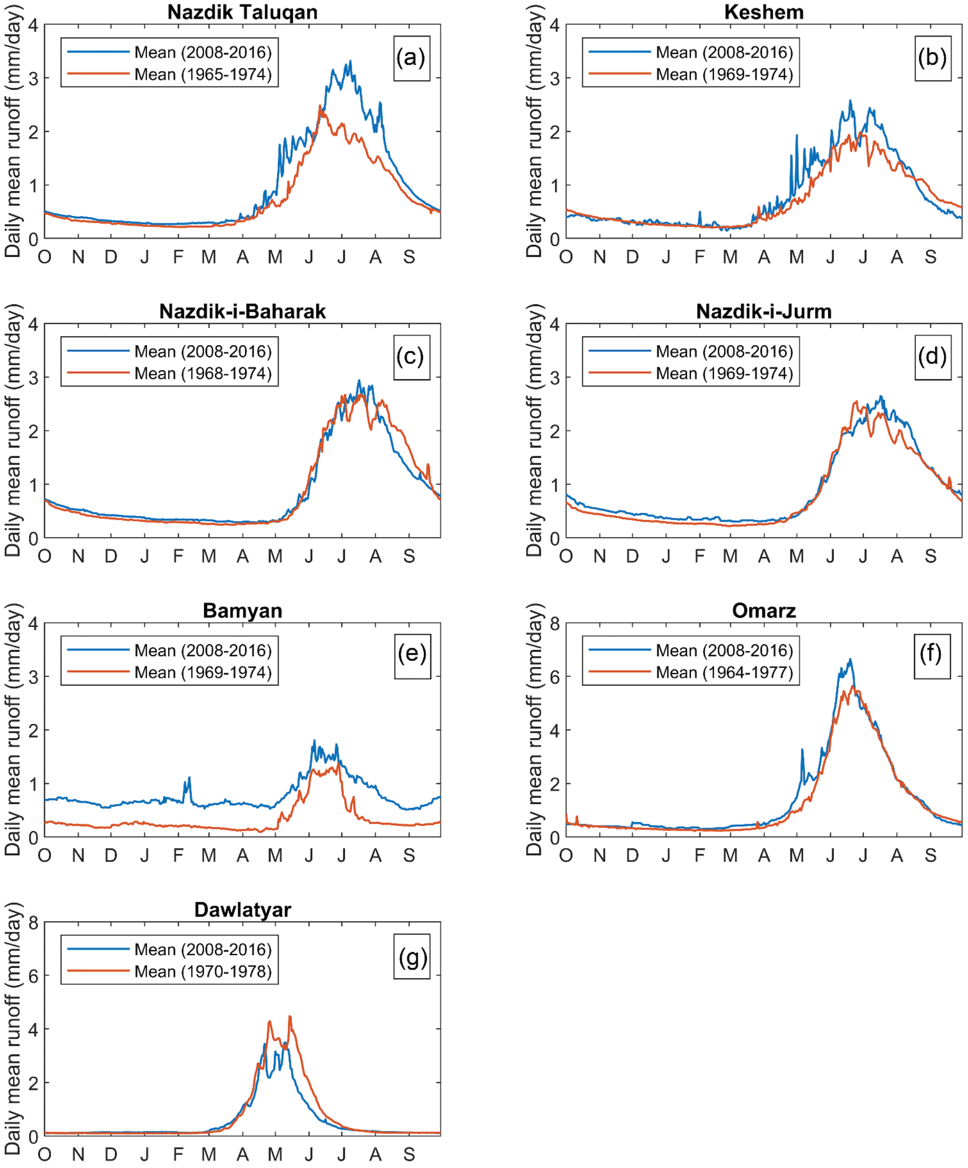

Figure 4. Hydrographs from individual gauging stations for six glacierized basins (a–f) and one snow-fed basin (g) for two time periods (1969–1977 and 2008–2016).

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 (Fig. 4(g)), 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 (Fig. 4(b) and (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 shown 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, emphasizing the difficulty of using hydrological records alone in data-poor settings like Afghanistan, in trying to draw clear conclusions about hydrological change. However, the other stations match more directly the expected response to observed climate changes (Fig. 4) and there is no evidence of a systematic shift. Thus, Bamyan may be an anomaly.

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.

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 Saffi in 2017 (Saffi *et al.* 2019) (Fig. 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) (Fig. 5), which emphasizes 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 commonplace (Shroder and Ahmadzai 2016). 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; more up-to-date data are not available.

6.1 Changes in groundwater quantity

A lack of up-to-date and detailed information on aquifer potential (storage and withdrawal) 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.* 2009a, 2009b, Karim 2018, Mack 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 year^{-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 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 40 m groundwater drawdown between 2006 and 2020. On the other hand, LG10, in the southern part of the city, shows a more stable condition, mainly due to recharge by the Logar River, which flows close to its southern aquifer (Mack *et al.* 2013).

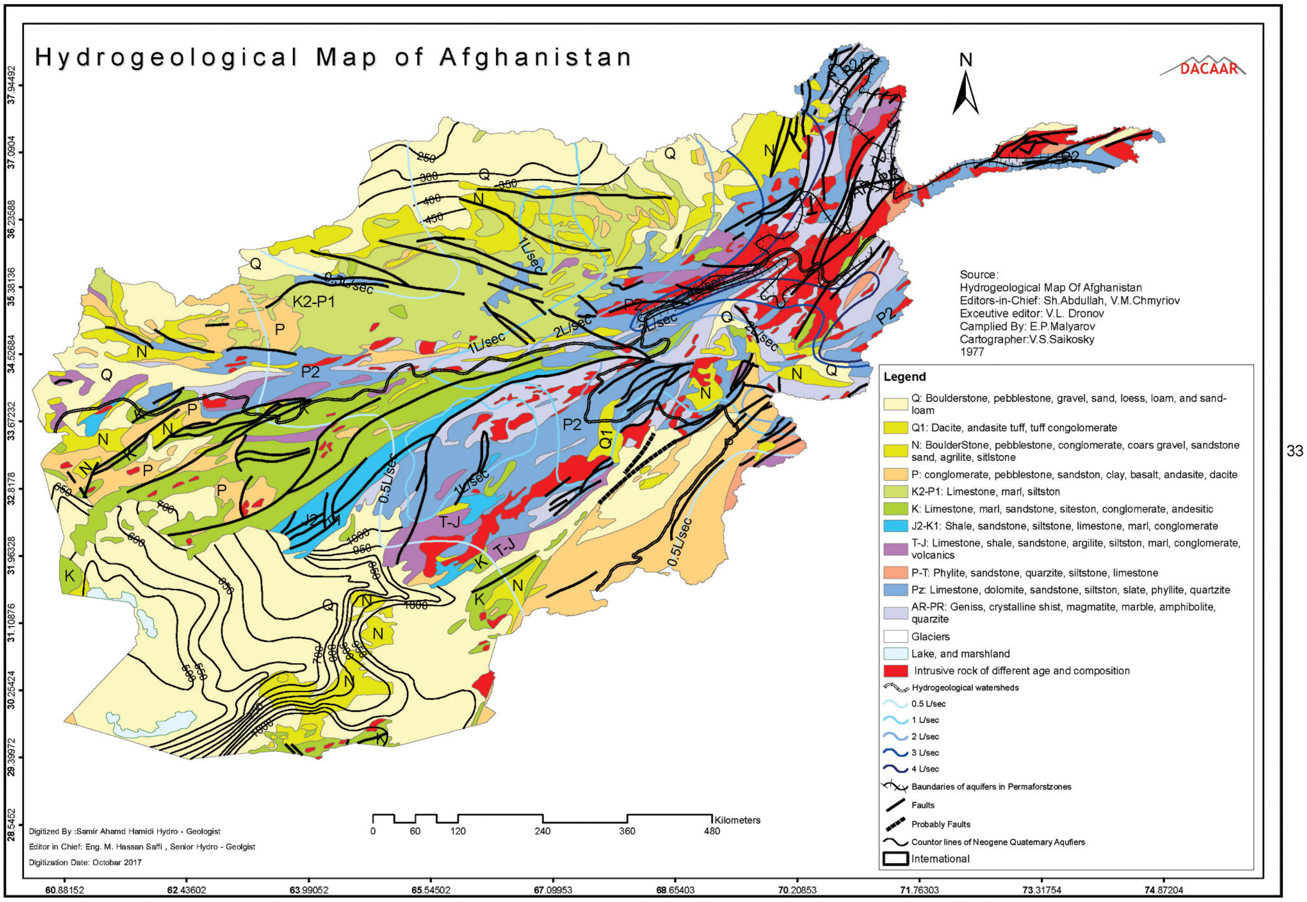

Figure 5. Hydrogeological map of Afghanistan. Compiled by Malyarove and digitized by Hamidi and Saffi in 2017 (Saffi *et al.* 2019).
Source: Hydro-geological booklet Sar-i-Pul province. Saffi et al, Danish Committee for Aid to Afghan Refugees. Kabul, Afghanistan. p.44, 2019. with permission from Saffi M.H.

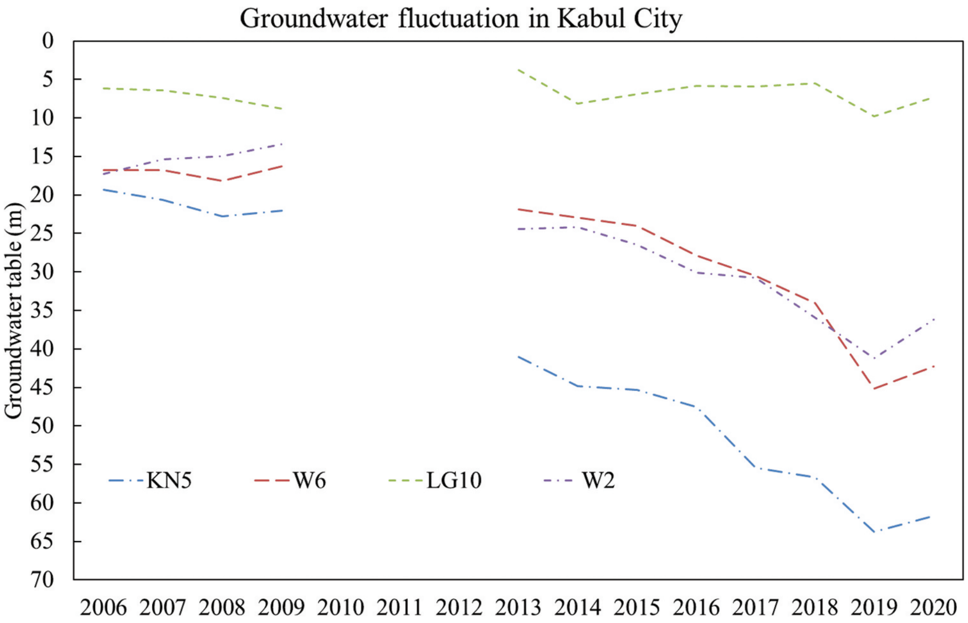

Figure 6. Groundwater fluctuations in Kabul city between 2006 to 2020 at four main locations (KN5 in the east, W6 and W2 in the west, and LG10 in the south part of the city).

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; these are also known as qanats or foggara in other areas. Such supply involves anthropogenic structures that tap shallow groundwater and transfer 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 then 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 urbanization, groundwater recharge might also be decreasing 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.

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 have increased not only 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, 2009b, Mack *et al.* 2010, 2014, Sundem 2015, Karim 2018, Mack 2018, Noori and Singh 2021, Zaryab *et al.* 2022a), and there are very few for the other regions of Afghanistan (Hayat and Baba 2017). Saffi 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 regarding accessing the other provinces (Hayat and Baba 2017)). In general, nine contaminants have been found, which represents a concern for human health and agriculture (Hayat and Baba 2017). The contaminants that were above World Health Organization (WHO) standards were: boron (79.5% of the samples ranged from sensitive to very sensitive for agriculture crops <2 μg/L), faecal coliform bacteria (60% of the samples), salinity (51.1% of the samples ranged from 751 to 2250 μs/cm), sulphate (32% of the samples), sodium (27% of the samples), fluoride (15.9% of the samples in the central and northwestern provinces), nitrate (8.6% of the samples and mostly in urban areas) and nitrite (2.1% of the samples) (Saffi and Kohistani 2013, Hayat and Baba 2017). Arsenic exceeding WHO limits (10 μg/L) was found mostly in the central provinces of Farah, Panjshir, Laghman, Faryab, Logar and Kabul (19% out of 72 samples), and in the Ghazni (58% out of 348 samples) province (Fig. 1) (Saffi 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) (Saffi and Eqrar 2016). Arsenic contamination in groundwater is a matter of great concern, yet no complete dataset exists that covers 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 (Saffi 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. In Kabul city only 20% of households are connected to wastewater treatment system or used toilets with storage tanks; others used cesspits and dry toilets (Brati *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 to be dissolution of carbonate, gypsum anhydrite minerals, weathering of silicates, ion exchange and mixing (Zaryab *et al.* 2021).

The lack 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 policymakers.

7 Changes in the frequency of hydrological extremes

7.1 Floods

Afghanistan has always been exposed to floods due to intense rainfall, rapid snowmelt, or a combination of the two (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 1981–2015 and also projected changes for 2031–2050 and 2081–2100 using the RCP 4.5 and 8.5 scenarios. The flood magnitude that currently has a return period of 50 years is predicted to shift to a 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 the applicability of standard methods for developing reliable flood hazard maps (Shroder 2016). However, since 2001 new gauging stations have been installed by the 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 measurements and mapping are needed, and this information needs to be conveyed to the communities at risk, avoid building homes and infrastructures in very vulnerable places 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 2015). In July 2018, a severe GLOF event occurred in the Peshghor valley of Panjshir province in the northern region (Fig. 1). The initial volume of the lake was estimated at 0.88 × 106 m^3, and it produced a river flow with an average depth of 16 m 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 glacierized 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). Historical records confirm incidences of GLOF events causing catastrophic flash floods from the mountains in the Hindu-Kush-Himalaya (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.

7.2 Droughts

The socioeconomic condition of Afghanistan has kept the country highly 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 is reduced storage of precipitation as snow increases 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 a greater impact 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 compared to irrigated areas, which contribute 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.

8 Glacial subsidy and the underestimation 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 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 conceptualize 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 Loon 2015). In a snow-dominated system, droughts are driven by variability in winter snowfall. This shift in 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 has 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.

9 Conclusions and future research

This study has reviewed 131 scientific papers and reports on the changing hydrology of Afghanistan to synthesize 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 likely be a shift from snow to rain, albeit as 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 are rapidly losing it.

There is little data to 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 the total surface water volume has decreased in Afghanistan, based on comparing streamflow records for 1969–1977 with those for 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 the 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 GLOFs. 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 in 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 following:

- The new generation of climate models should be updated over time, and should 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 in terms of 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 localized 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 must be carried out, with the use of hydrological models that can represent glacier melt processes.

Based on the unstable political situation in Afghanistan, use of remote sensing techniques would be a valuable support tool to achieve the above goals. 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 were acquired from the Afghanistan Meteorological Department (AMD) http://www.amd.gov.af/ and discharge data of seven hydrological stations (Fig. 1) were obtained from the Ministry of Energy and Water of Afghanistan https://mew.gov.af/en by an official request letter from the University of Lausanne.

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