THE ARAL SEA BASIN

Water for Sustainable Development in Central Asia

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Chapter 8

The status and role of the alpine cryosphere in Central Asia

8

The status and role of the alpine cryosphere in Central Asia

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Key messages

- The alpine cryosphere, including snow, glaciers and permafrost, is critical to water management in the Aral Sea Basin (ASB) and larger Central Asia (CA) under the changing climate, as it stores large amounts of water in its solid forms. Most cryospheric components in the Aral Sea Basin are close to melting point, and hence very vulnerable to a slight increase in air temperature with significant consequences to long-term water availability and to water resources variability and extremes.

- Current knowledge about different components of the cryosphere and their connection to climate in the Basin and in the entire Central Asia region varies. While it is advanced in the topics of snow and glaciers, knowledge on permafrost is rather limited.
- Observed trends in runoff point in the direction of increasing water availability in July and August at least until mid-century and increasing possibility for water storage in reservoirs and aquifers. However, eventually this will change as glaciers waste away. Future runoff may change considerably after mid-century and start to decline if not compensated by increasing precipitation.
- Cryosphere monitoring systems are the basis for sound estimates of water availability and water-related hazards associated with snow, glaciers and permafrost. They require a well-distributed observational network for all cryospheric variables. Such systems need to be re-established in the Basin after the breakup of the Soviet Union in the early 1990s. This process is slowly emerging in the region. Collaboration between local operational hydro-meteorological services and the academic sector, and with international research networks, may improve the observational capabilities in high-mountain regions of CA in general and in the ASB in particular.

Introduction

Water resources in arid continental regions like Central Asia (CA) depend strongly on cryosphere components: snow, glaciers and permafrost (Figure 8.1). Two of the world's largest mountain systems, the Tien Shan (also: Tian Shan) and Pamir Mountains, serve as water towers for CA, of which the Aral Sea Basin (ASB) is a major part. The cryosphere components of these mountain systems store large amounts of water in a solid form and play a key role for current and future water availability and management under a changing climate. Several recent studies (Hagg *et al.* 2007; Hagg *et al.* 2013; Huss and Hock 2018; Kaser *et al.* 2010) indicate that a) in arid regions like CA, water release by snow and glaciers is fundamental to maintaining sufficient runoff during the dry summer months and b) by the end of this century the water contribution of glaciers will be drastically reduced and some catchments may completely dry out. This may pose significant challenges to water resources management, energy production, the environment, disaster risk reduction, security and public health. High-quality baseline data on cryosphere components may help develop sound climate-based scenarios of future water availability.

Snow is temporally and spatially the most variable component of the cryosphere. It has a strong influence on the climate system but is also strongly controlled by climate. Recent observed trends derived from remote sensing (Adnan *et al.* 2017; Immerzeel *et al.* 2009; Peters *et al.* 2015), and ground measurements (e.g., Marty 2008; Serquet *et al.* 2013) indicate a seasonally reduced duration of snow cover, as well as reduced extent of snow cover, especially at lower elevations. Such changes are important as snow has strong feedback processes, particularly over its strong albedo difference in comparison to surfaces like water, vegetation, bedrock or sediments. While glaciers release most of their melt water during the hot summer months, water from snowmelt mostly comes in spring (April, May, June). Therefore, snow storage can be seen as a temporary water reservoir accumulating snow in winter and releasing water to rivers and streams in spring and early summer. The melt water from seasonal snow cover is vital for the environment, economic development and social security of CA (e.g., (Aizen *et al.* 1995; Sorg *et al.* 2012; Unger-Shayesteh *et al.* 2013). Many ground-based stations measuring snow were abandoned after the breakup of the Soviet Union in the early 1990s, and a new observational network is only slowly evolving in the region.

Figure 8.1 Abramov glacier: one of the reference glaciers in Central Asia, where measurements were re-established in 2011 after a gap of 12 years

Source: Martin Hoelzle, August 2011

Glaciers today are the most well-known symbol of changing climate as they are at many places close to melting point and therefore highly sensitive to changes in air temperatures. Their response to warming trends is well-manifested by fast-retreating glacier tongues or even whole glaciers collapsing and decaying over very short time periods (Kääb *et al.* 2018; Paul and Mölg 2014; Zemp *et al.* 2006). These images have become icons of climate change (Haeberli 2008). CA is especially vulnerable to glacier changes, because runoff during the dry summer months is mainly dependent on the vast glacierized areas in Tien Shan and Pamir. In the coming decades, enhanced melting may lead to an increased runoff in spring and summer (Kaser *et al.* 2010) and cause glacier lake outburst floods (GLOF), debris flow and landslides, which can be very damaging to settlements and agriculture (Bolch *et al.* 2011; Erokhin *et al.* 2018; Kapitsa *et al.* 2017; Petrov *et al.* 2017; Stoffel and Huggel 2012). Towards the end of this century, runoff during the dry summer months is likely to continuously decrease due to reduced ice volumes (Hagg *et al.* 2007; Hagg *et al.* 2013; Huss and Hock 2018; Kure *et al.* 2013). Similar to *in situ* measurements of snow, long-term monitoring programs in CA and the ASB collapsed after the break-up of the Soviet Union and are currently being re-established with great national and international efforts.

Permafrost is defined by ground temperatures, which are continuously below 0°C over a period of at least one year. It mainly occurs in continental areas at high latitudes, but also in high mountains. Climate-induced changes in permafrost can lead to strong feedbacks with the

climate system, for example, by releasing bound methane or carbon dioxide through thawing of permafrost soils, which in turn reinforces the greenhouse effect (Koven *et al.* 2011). In addition, ice melting in permafrost soils causes land subsidence due to the loss of its volume. Furthermore, on inclined topography and with an increasing active layer,[1] erosion can intensify. Infrastructure can directly heat the permafrost in the ground, leading to local destabilization with associated prevention and maintenance costs. In high-mountain regions, recent increases in air temperature cause rock falls, landslides, debris flows and increased creep rates in rock glaciers (Delaloye *et al.* 2010; Sorg *et al.* 2015), and increased runoff from permafrost zones with high ice contents (Bolch and Marchenko 2009; Mateo and Daniels 2018). CA and the Tibetan Plateau host the largest permafrost area outside the polar regions (Gruber 2012). It covers around 3.5×10^6 km^2, which corresponds to about 15 per cent of the total areal extent of permafrost in the Northern Hemisphere. Permafrost research in high mountains only began in the late twentieth century, but since then considerable progress has been made in understanding mountain permafrost processes (Haeberli et al., 2010).

The following sections examine each of the three cryosphere components in the ASB and larger CA in more detail.

Alpine snow cover

The ASB river flow during the vegetation period in summer months is dominated by snowmelt, followed by glacier melt in late summer. Thus, high mountains of the ASB can be considered natural water towers of the region where winter precipitation is stored in the form of snow and melts during a warm period. The meltwater from seasonal snow cover is vital for the economic development and social security (e.g., Aizen *et al.* 1995; Sorg *et al.* 2012; Unger-Shayesteh *et al.* 2013). Also, through the snow-albedo feedback, changes in seasonal snow cover may affect local and regional climate and reinforce surface warming in ASB headwaters (e.g., Aizen *et al.* 2000).

Despite the importance of snow, the snow-related data (snow depth, snow cover, snow water equivalent, snow density) are limited in the ASB. Snow depth and snow water equivalent data are mainly available from the meteorological stations of national hydrometeorology services. In addition to station data, field survey and airborne snow data were collected during the Soviet era (Krenke 1998)[2]. Snow measurement surveys of this type were regularly carried out in CA, predominantly in Kyrgyzstan, Tajikistan and Uzbekistan, to assess snow storage and corresponding water availability during the vegetation period. Snow density and snow water equivalent were also recorded during these surveys. Unfortunately, the frequency of field and airborne snow surveys decreased dramatically after the breakup of the Soviet Union in 1991 (Unger-Shayesteh *et al.* 2013). Uzbekistan and Tajikistan continued a few airborne surveys but there were no such surveys in Kyrgyzstan (Glazirin 2007).

There are few studies of the long-term trends and shorter-term variability in snow cover. Aizen *et al.* (1997) analyzed snow data from 110 stations for the time period from 1940 to 1991 and found a decrease of mean annual snow depth of 8–14 cm at elevations below 2000 masl (meters above sea level) and of 6–19 cm at higher elevations. They also concluded that the number of days with snow cover decreased by nine days during this period. Glazirin (2006) analyzed snow cover duration at the Oigaing and Tashkent stations from the 1930s and reported slight negative trends, which were, however, not statistically significant. Tsarev (2006) analyzed snow depth, precipitation and temperature data to estimate how climate change impacts on the maximum snow storage in the mountains of Central Asia based on a temperature-precipitation

approach. According to his results, scenarios of a temperature increase of 2°C and a precipitation decrease of 30 per cent would lead to about 30 per cent less snow storage in March when snow accumulation peaks. Merkushkin and Tsarev (2007) introduced an empirical relationship between snow parameters and elevation that can be used to estimate snow parameters for any basin and assess impacts of climate change scenarios.

Remote sensing products have become an important source of snow data in mountainous areas of the ASB in the past three decades. Moderate-resolution imaging spectroradiometer (MODIS) and advanced very-high-resolution radiometer (AVHRR) data are among those that are widely used in the ASB to assess water availability. Yakovlev (2005) used the end-of-March AVHRR snow cover data for runoff modeling in the Pyanj Basin in Tajikistan. Gafurov et al. (2013) assessed the quality of MODIS snow cover data against manual observations from stations in the ASB and reported about 93 per cent accuracy. However, cloud cover prevents the efficient use of optical remote sensing in hydrological studies. Gafurov and Bàrdossy (2009) developed a methodology for cloud removal and applied it in the Kokcha River Basin of the ASB. Zhou *et al.* (2013) used cloud-removed AVHRR snow cover data to understand snow characteristics in the ASB and reported that in the plain areas maximum snow coverage can reach up to 32 per cent of the total area and in the mountainous areas this value can exceed 80 per cent. Dietz *et al.* (2014) used combined AVHRR and MODIS snow cover data to understand the elevation–dependent snow cover characteristics and reported a snow cover duration rise of ~4 days per 100 m elevation. Gafurov *et al.* (2016) developed an all-in-one package MODSNOW-Tool, which includes all processing steps of raw MODIS data including cloud removal. This tool allows operational and automated monitoring of snow coverage at predefined river basins using the MODIS data. The MODSNOW-Tool is officially implemented in all five Central Asian countries (Kazakhstan, Kyrgyzstan, Tajikistan, Turkmenistan and Uzbekistan) and is currently used to improve seasonal river flow forecasts based on snow cover information obtained from remote areas (Apel *et al.* 2018; Kalashnikova and Gafurov 2017). Besides MODIS and AVHRR optical remote sensing snow cover maps, LANDSAT snow cover maps with high spatial resolution (30 m) were used to reconstruct glacier mass balance in selected glaciers in the ASB (Barandun *et al.* 2018; Kronenberg *et al.* 2016). Satellite radar systems, e.g., Sentinel–1, are being tested for their capability to detect snow water equivalent (Conde *et al.* 2019). Overall, snow cover maps, obtained from remote sensing, can significantly improve understanding of the hydrological processes in the ASB. Maps of mean monthly snow–covered area and snowmelt for the periods 1961–1990 and 2001–2010 for six major river basins in Asia, including the Amu Darya and the Syr Darya, are available at http://waterdata. iwmi.org/Applications/Glacier_Snow_Asia/.

Alpine glaciers

The Tien Shan Mountains host almost 15,000 glaciers, covering a surface area of about 12,400 km^2 (RGI Consortium 2017; Sorg *et al.* 2012), while both reported glacier coverage and glacier number in the Pamir (incl. Pamir Alay) Mountains are slightly higher according to the most recent inventory (~13,800 km^2, No. ~17,000 (Mölg *et al.* 2018)). The mountain ranges are conventionally divided into Western/Northern Tien Shan (glacierized area: ~2,265 km^2), Eastern Tien Shan (~2,210 km^2), Central Tien Shan (~7,270 km^2) and Jetisu (Dzhungarsky Alatau) (~520 km^2), Pamir-Alay (~2,080 km^2), Western Pamir (~9,470 km^2) and Eastern Pamir (~2280 km^2) (Aizen *et al.* 1995; Bolch *et al.* 2019; RGI Consortium 2017; Mölg *et al.* 2018). A significant part of this glacierized area is situated in the ASB (Figure 8.2). The median glacier
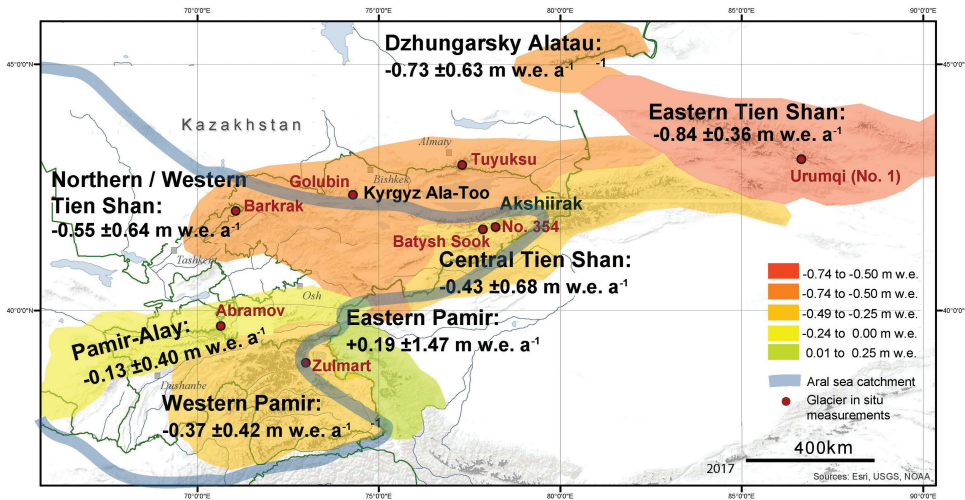
Figure 8.2 Overview map of the study region. The ASTER–derived geodetic mass change for each
    subregion of the Tien Shan and the Pamir derived in Barandun *et al.* (2019) are shown.
    The locations of all glaciers with continuous, long-term mass balance series are indicated red.

Source: Constructed by authors

elevation is highest in the Eastern Pamir (>5000 masl), slightly less than 4900 masl in the
Western Pamir, approximately 4200 masl in the Central Tien Shan, and lowest in the Western
and Northern Tien Shan (3700 to 3900 masl) (Mölg *et al.* 2018; Sakai *et al.* 2015). Glaciers
in the west receive more precipitation during winter, whereas summer accumulation regimes
become predominant towards the east (Dyurgerov *et al.* 1994; Sakai *et al.* 2015) where a com-
bination of low temperature and summer precipitation maximum is more common (Kutuzov
and Shahgedanova 2009).

Glacier mass balance

In the 1950s, an extensive system of cryospheric monitoring in Central Asia was launched
under the auspices of the USSR Committee for the International Hydrological Decade and the
measurements intensified during the following years (Dyurgerov 2002; Kuzmichenok 2006;
WGMS 2017). Monitoring included extensive glacier mass balance measurements on sev-
eral glaciers (e.g., Central Tuyuksu, Golubin, Karabatkak, Abramov in the Soviet Union and
Urumchi Glacier No. 1 in China, (WGMS 2017)). The majority of these *in situ* monitoring
programs stopped in the early 1990s after the breakup of the USSR. Regular mass balance
measurements continued only on Central Tuyuksu (Shahgedanova *et al.* 2018) and Urumchi
Glacier No. 1 in China (WGMS 2017), neither of which, however, is in the ASB. Efforts to
re-establish *in situ* glacier monitoring of the formerly monitored glaciers located in the ASB and
nearby catchments have started since around 2010 through intensive international and national
collaboration projects (Hoelzle *et al.* 2017). At present, mass balance is monitored on more
than ten glaciers with longer measurement series. These glaciers are distributed throughout the
mountain ranges of Central Asia, and Abramov, Barkrak, Batysh Sook and Glacier No. 354 are
located in the ASB.

Despite this success, relative to the large number of glaciers located in this area, data remain sparse. To fill the gap in direct glaciological observations and to cover larger mountain areas, glacier volume changes were assessed on different catchment scales from local (e.g., Aizen *et al.* 2007; Bolch *et al.* 2011; Goerlich *et al.* 2017; Holzer *et al.* 2015; Li *et al.* 2017; Pieczonka and Bolch 2015) to regional studies (e.g., Brun *et al.* 2017; Gardelle *et al.* 2013; Gardner *et al.* 2013; Lin *et al.* 2017; Wang *et al.* 2017) using remote sensing. Furthermore, several mass balance time series are available from modeling studies (Farinotti *et al.* 2015; Li *et al.* 2011; Liu and Liu 2016). However, detailed region-wide mass balance time series with a high temporal resolution are still lacking.

In the Tien Shan, region-wide geodetic mass balance assessments agree on a glacier mass loss during the past two decades. Results of mass change estimates range from about −0.3 m w.e. a^{-1} to −0.7 m w.e. a^{-1} (Brun *et al.*, 2017; Farinotti *et al.*, 2015; Gardner *et al.*, 2013). Accelerated mass loss since the 1970s was reported for most regions (e.g., Farinotti *et al.*, 2015; Pieczonka *et al.* 2013; Sorg *et al.*, 2012). No significant acceleration of glacier mass loss could be identified since the onset of the century through snowline-constrained mass balance modeling (Barandun 2019). However, an increase in inter-annual variability was observed, pointing toward a change in the mass balance regime from a more continental to a more maritime setting, as described by Dyurgerov and Dwyer (2001). The highest geodetic mass loss was observed in the Eastern Tien Shan (not in the ASB). The lowest rates of mass loss were found in the Central Tien Shan (Figure 8.2). Comparison of the different geodetic assessments showed a good agreement for the Inner and Central Tien Shan (Brun *et al.* 2017; Farinotti *et al.* 2015; Gardner *et al.* 2013) and for the Northern/Western Tien Shan (Bolch 2015; Brun *et al.* 2017; Gardner *et al.* 2013). For the two aforementioned regions, an ASTER-derived average mass loss of approximately −0.5 m w.e. a^{-1} and −0.4 m w.e. a^{-1}, respectively, was calculated from 2004 to 2012.

Published mass change assessments for *the Pamir* show quite large divergence and range from a close to balanced budget (+0.14 to −0.13 m w.e. a^{-1}; Brun *et al.* 2017; Gardelle *et al.* 2013; Gardner *et al.* 2013; Kääb *et al.* 2015) to strongly negative mass balances (−0.48 to −0.52 m w.e. a^{-1}; Kääb *et al.* 2015; Pohl *et al.* 2017). There are still discrepancies between the assessments, leading to debates over the ambiguous mass balance regime and its change. Important methodological differences, input data quality, inconsistent study periods and spatial divisions can explain the differences to some extent. A compilation and reassessment of the different published geodetic estimates revealed, on average, a mass loss of 0.26 m w.e. a^{-1} for Western Pamir and balanced budgets for the Eastern Pamir (−0.02 m w.e. a^{-1}) for the period after 2000 (Bolch *et al.* 2019). This is in line with recent geodetic estimates by Barandun (2019), who reports −0.37 ± 0.42 m w.e. for the Western Pamir and +0.19 ± 1.47 m w.e. for the Eastern Pamir.

The reanalyzed historical glaciological measurements, reconstructed mass balance data and re-initiated *in situ* measurements provide a comprehensive and complete mass balance time series for Abramov, Golubin, Batysh Sook and Glacier No. 354 (Barandun *et al.* 2018; Barandun *et al.* 2015; Kenzhebaev *et al.* 2017; Kronenberg *et al.* 2016). Modern direct measurements revealed mass losses ranging from −0.25 to −0.51 m w.e. a^{-1} (2011–2016) and reconstructed mass balances confirmed the negative signal for the last decades for these glaciers (−0.30 to −0.43 m w.e. a^{-1} from 2000 to 2014; Barandun *et al.* 2018; Barandun *et al.* 2015; Hoelzle *et al.* 2017; Kenzhebaev *et al.* 2017; Kronenberg *et al.* 2016). The first mass balance calculations reported moderate mass loss of −0.10 to −0.25 m w.e. a^{-1} for Barkrak Middle Glacier in Uzbekistan for 2017–2018 (unpublished results). For Abramov, geodetic

mass change of −0.36 ±0.07 m w.e. a^{-1} derived from aerial photographs and high–resolution optical satellite data for 1975 to 2015 also agreed with reanalyzed and reconstructed time series (Denzinger 2018). Unfortunately, meaningful comparison between the different studies was not always straightforward due to a very limited number of studies assessing the mass change of individual glaciers in the region and due to differences in study periods. New developments try to implement tools allowing for an optimal reconstruction of annual mass balance time series of a large amount of unmeasured and remote glaciers on mountain range scales based on a sophisticated combination of *in situ* and remote measurements coupled with different models. The resulting mass balance time series permit the determination of annual mass balance variability for a large number of glaciers in the Tien Shan and Pamir, with minimal cost and labor effort (Barandun 2019).

Glacier area changes

Several studies employed remote sensing techniques to map glacier area fluctuations (e.g., Bolch 2007; Khromova *et al*. 2003; Khromova *et al*. 2006; Narama *et al*. 2010; Ozmonov *et al*. 2013; Shangguan *et al*. 2006). Glacier retreat and reduction in glacier area are observed throughout the Tien Shan but rates of retreat vary (Sorg *et al*. 2012; Unger-Shayesteh *et al*. 2013). In the Pamir, glacier change follows a more heterogeneous pattern (Knoche *et al*. 2017). Generally, the highest loss of glacierized area is observed in the outer regions and at lower elevations, while in the inner regions, in the inter-mountain basins and in the higher-elevation regions of the Pamir and Tien Shan the observed glacier shrinkage is slower (Aizen *et al*. 2014; Narama *et al*. 2010; Sorg *et al*. 2012; Unger-Shayesteh *et al*. 2013). A comparison of glacier area change in the Pskem (the western part of the ASB, with a mean elevation of the glacierized area of 3000 masl), At Bashy and the southeastern Ferghana ranges (inner ranges in the southeastern part of the ASB with a mean elevation of 3500 masl) show that in the Pskem Basin glaciers lost 19 per cent and 5 per cent in the 1970–2000 and 2000–2007 periods, while in the At Bashy and Ferghana ranges they lost 12 per cent and 4 per cent, and 9 per cent and 0 per cent in the same periods, respectively (Narama *et al*. 2010). For the Naryn Basin, Kriegel *et al*. (2013) reported a glacier area reduction of 23 per cent for the 1970s–mid-2000s period. In most basins (e.g., Pskem, At Bashy, Naryn) an acceleration in glacier shrinkage is reported in the twenty-first century, particularly in the catchments where small glaciers (which also tend to be located at lower elevations) prevail.

Climate considerations

The sensitivity of glaciers to increasing summer temperatures is assumed to be responsible for the long-term retreat (Glazirin *et al*. 2002); however, changes in precipitation should not be disregarded. In particular, a well-documented step reduction in precipitation observed in Central Asia in the 1970s, driven by changes in atmospheric circulation, led to a decrease in annual mass balance due to a reduction in accumulation (Cao 1998; Shahgedanova *et al*. 2018). More recent changes in precipitation are non-uniform across the region. Many studies report no statistically significant long-term trends in annual or seasonal precipitation while stressing strong inter-annual variability (Chevallier *et al*. 2014; Finaev 2006; Kriegel *et al*. 2013; Narama *et al*. 2010; Shahgedanova *et al*. 2018). An increasing number of positive-degree days in the high-elevation regions suggests a growing frequency of days with liquid precipitation (Kriegel *et al*., 2013) which results in lower accumulation and further enhancement of glacier

melt through suppressing surface albedo. Some of the earlier studies, considering changes in precipitation in the 1970s–2000s, reported increasing trends (Unger-Shayesteh *et al.* 2013). Considering the negative mass budget of the glaciers in the ASB, these did not compensate for the increase in air temperature (Khromova *et al.* 2006).

Alpine permafrost

Tien Shan and Pamir permafrost distribution

Continuous permafrost exists above 3600 masl in the central-northern Tien Shan Mountains. The discontinuous zone extends from 3200 to 3600 masl, while the sporadic zone is present from 2700 to 3200 masl (Figure 8.3). Within these zones, permafrost spread may be strongly influenced by local topography and other ground conditions.

Since the end of the Little Ice Age, permafrost in the Tien Shan Mountains experienced a continuous warming until present (Marchenko *et al.* 2007). The first systematic permafrost temperature measurements in the Northern Tien Shan began in 1973 (Gorbunov and Nemov 1978). Initial geothermal observations (1974–1977) in boreholes in the Northern Tien Shan showed that permafrost temperatures within loose deposits and bedrock at an altitude of 3300
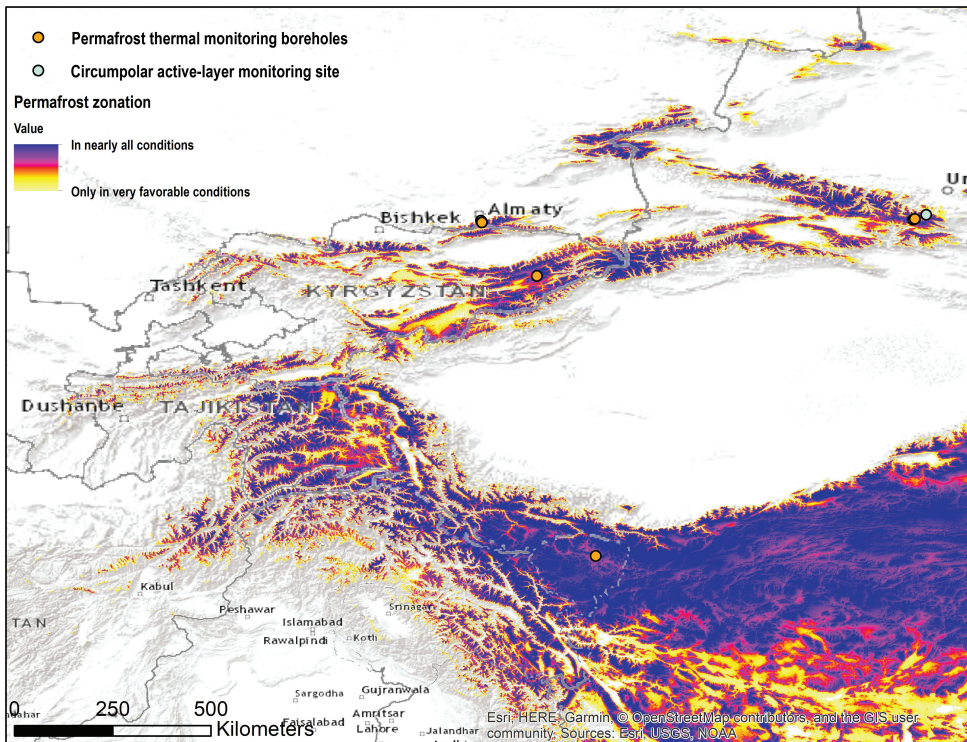

Figure 8.3 World Terrain Base map showing permafrost zonations, locations of boreholes and active-layer monitoring sites in Central Asia (after Gruber 2012)

Source: Constructed by authors

masl vary from −0.3°C to −0.8°C (Gorbunov and Nemov 1978). Thickness of permafrost in this area varied from 15 to 90 m and the maximum active-layer thickness reached 3.5–4.0 m (Gorbunov and Nemov 1978). Permafrost investigations in the Inner Tien Shan were performed between 1985 and 1992. The results of these investigations included permafrost temperature records, active-layer thickness measurements, descriptions of the cryogenic structures of frozen ground maps, and charts of the distribution of permafrost, ground ice, and periglacial landforms. Ground temperature measurements were carried out in 20 boreholes in the Akshiirak massif (42°N, between 4000 and 4200 masl), and in more than 25 boreholes in the Kumtor Valley (between 3560 and 3790 masl). In the Akshiirak Mountain Range, at elevations of 4100–4200 masl, the lowest measured ground temperature was −5°C in the bedrock (Paleozoic schist) and −6.7°C in the ice-rich Late Pleistocene moraines. The corresponding thickness of permafrost was 350–370 m and 250–270 m, respectively (Gorbunov *et al*. 1996). Thickness of the active layer on the western slope of the Akshiirak massif decreased from 2.5–3.5 to 0.5–0.7 m within 3200–4000 masl. In the southwestern part of the Tien Shan (Chatyr-Kol and Aksai depressions, 40°30'N), at an elevation of 3500–3600 masl, the thickness of permafrost in loose deposits was 60–90 m and its temperatures were between −1.2 and −1.6°C. The geothermal gradient in the Tien Shan changes from 0.01°C m^{-1} at the mountain ridges and up to 0.02–0.03°C m^{-1} at the bottom of the valleys and within the mountain depressions (Schwarzman 1985).

It is important to note that the 3D topography of the mountains strongly controls the heat flow direction. In steep mountainous topography the heat flow in the area of mountain peaks in the Northern Hemisphere is in general not vertical but more horizontal from the warm southern side to the cold northern side (Magnin *et al*. 2015; Magnin *et al*. 2017; Noetzli and Gruber 2009; Noetzli *et al*. 2007). This is particularly important when interpreting temperature measurements in deep boreholes as the temperature profiles are heavily impacted by the topography (Gruber *et al*. 2004). Relict Pleistocene permafrost was found in the Aksai depression (40°55'N, 76°25'E) at an elevation of 3160 masl. A 400-meter-deep borehole revealed a two-layered permafrost structure with a lower layer of frozen clay at a depth between 214 and 252 m (Aubekerov and Gorbunov 1999). The thickness of the modern upper layer of permafrost is 90–110 m. This is the one single observation of relic permafrost in the Tien Shan Mountains.

Permafrost temperature observations during 1974–1977 and 1990–2009 indicate that the ground has warmed in the Kazakh part of Tien Shan Mountains over the past 35 years. The increase from 1974 to 2009 varies from 0.38°C to 0.68°C at depths of 14–25 m. Based on interpolation of borehole temperature data, the active layer increased in thickness from 3.2 to 3.4 m in the 1970s to a maximum of 5.2 m in 1992 and to 5.0 m in 2001 and 2004. The average active-layer thickness for all measured sites increased by 23 per cent in comparison to the early 1970s (Marchenko *et al*. 2007).

In the Pamir, knowledge on permafrost distribution, properties and impacts is limited. Müllebner (2010), using datasets provided by the Tajik hydro-meteorological service, derived an elevation of 3300 masl for the 0°C isotherm. This elevation was interpreted as the approximate lower boundary (without considering surface offsets) for permafrost in Tajikistan. That constitutes approximately 44.3 per cent of the total area of Tajikistan as potential permafrost area and up to 84.1 per cent of the eastern Pamir (Gruber and Mergili 2013; Mergili *et al*. 2012).

The few thickness measurements in the Karakul lake area suggest relatively thin and unevenly distributed permafrost. Reported thicknesses range from 21–22 m near the eastern coast of Lake Karakul (elevation approximately 3900 masl), while approximately 1 km to the east

of this site a permafrost thickness of 120–140 m has been reported from drill sites (Gorbunov *et al*. 1996). Further south, in the Rangul depression, the permafrost thickness is just 15 m at an altitude of 3800 masl, while at the elevation range from 4050–4150 masl it varies from 25 to 110 m (Gorbunov 1978).

Permafrost and changing climate

Overall, very little progress has been made so far in quantifying changes of permafrost under future climate in CA. Mean annual air temperature is the primary climate control on permafrost extent, further modified by surface–atmosphere interactions (mainly snow cover thickness and duration) controlled by topography and surface cover. Clear increasing trends in mean temperature have been observed throughout the CA region (Figure 8.4) with the possible exception of the central Pamir region, which may be affected by the so-called *Karakoram anomaly* (Forsythe *et al*. 2017). These trends are expected to continue in the future, as projected by all scenarios from the most recent Coupled Model Intercomparison Project- Phase 5 (CMIP5) and hence widespread permafrost degradation in CA may be expected.

As mountain permafrost slopes warm, they tend to destabilize, primarily through reduced mechanical strength, potentially leading to various types of mass movements such as debris flows, rock avalanches, or, in the case of ice-cored moraine dams, glacial lake outburst floods (GLOFS). Mass movements are complex phenomena and while climate-induced permafrost degradation (observed at GTNP[3] sites in Tien Shan, e.g., Marchenko *et al*. 2007) can be a key driver of such events, it is not straightforward to disentangle the climate signal from normal erosional processes in mountain regions. However, there is increasing evidence that increased incidence of thermally induced slope instabilities should be expected as high-mountain regions warm. Due to the high potential energy inherent in steep environments and the possibility of compound events that entrain moisture sources (glacier ice, snow or water), the consequences of mass movements can be far-reaching and affect communities many kilometers downstream.
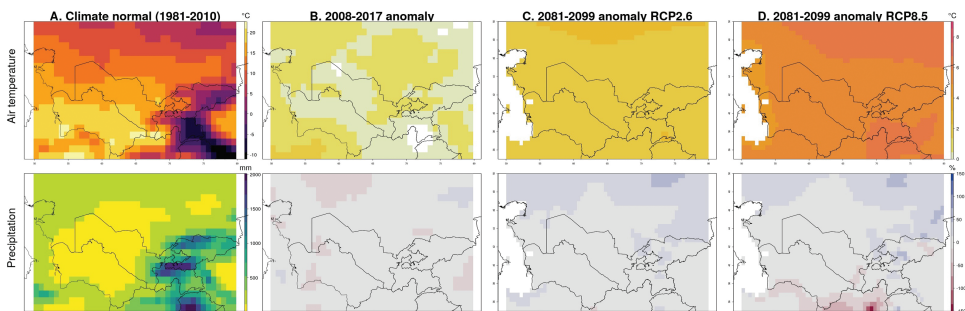

Figure 8.4 Observed and projected climate change in Central Asia as reported by ERA-Interim reanalysis for climate normals: (A) and current anomaly (B) and GCM multimodal means (Hempel *et al*. 2013) for RCP2.6 (C) and RCP8.5 (D) (projected changes 2081–2099). Cooling of up to 1°C is shown in white in panel (B) and corresponds to the so-called 'Karakoram anomaly'. Note all temperature scales are in °C, precipitation normal is in mm whereas precipitation anomalies are in % change

Source: Constructed by authors

Permafrost as a potential water resource

Central Asia is a relatively arid region where permafrost ice could be a significant contributor to the hydrological cycle as compared to more humid regions, e.g., the European Alps, particularly in the latter half of the twenty-first century, when glacial contributions are projected to be sharply reduced (Huss and Hock 2018). According to Gorbunov *et al.* (1996) the total volume of ground ice in the Northern Tien Shan is 56 km^3, which equals 62 per cent of the surface ice volume for the same territory, underscoring its potential value as a water resource (Bolch and Marchenko 2009). Furthermore, it has been estimated that the ratio of rock glacier to surface ice in CA is several times higher than in the European Alps. Permafrost responds more slowly to climate due to the insulating effect of the overlying active layer together with ventilation effects, mainly caused by coarse blocky surface material. Permafrost-based water resources are therefore likely to be available long after surface ice is heavily depleted.

Improving permafrost monitoring

While much research activity has focused on permafrost of the Northern Tien Shan (Bolch and Gorbunov 2014; Bolch and Marchenko 2009; Gorbunov and Titkov 1992; Marchenko *et al.* 2007; Sorg *et al.* 2015), to date there is a paucity of information throughout the Pamir region. The region has a total of two permafrost boreholes listed in the GTNP database.[4] Continuous *in situ* measurements and monitoring in remote mountain areas of CA are challenging due to difficult access, complex topography, financial and logistic constraints, political instability, as well as lack of appropriate infrastructure (Hoelzle *et al.* 2017; Unger-Shayesteh *et al.* 2013). There are very few datasets above 3000 masl and virtually none above 5000 masl. If meteorological stations are present at all, they are usually located at lower elevations where most of the population lives. Remote sensing data as well as model-assimilated observations (from reanalysis data) are used to fill the observational gap. However, the relatively short time series and coarse resolution do not allow for robust assessments of changes in mountain areas with complex topography (Prein *et al.* 2015). This makes the case for denser observational networks in remote mountain areas ever more urgent.

Runoff trends and water-related hazards in headwater catchments

While a decline in the streamflow of the Amu Darya and Syr Darya are well documented (Micklin 2007), changes in discharge of their tributaries, particularly in the headwater catchments, have received less attention (Chevallier *et al.* 2014). Existing studies suggest that long-term (50–60 years) trends in streamflow in the unmodified headwater catchments (where cryosphere components are present) annually or during the melt season are either insignificant or inconsistent. Contrasting runoff trends were reported by Khan and Holko (2009), who analyzed the reconstructed natural flow time series for the gauges Chinaz (close to the border between Uzbekistan and Kazakhstan, taken as representative for the upper Syr Darya Basin) and Kerki (near the border between Afghanistan and Turkmenistan, representing the upper Amu Darya Basin). Kriegel *et al.* (2013) examined the long-term time series of monthly streamflow in the headwaters of the Big Naryn and the Small Naryn, concluding that August is a month in which glacier melt is expected to make the most prominent contribution to discharge. According to these observations, streamflow declined by 20 per cent and increased by 21 per cent in the Small Naryn and Big Naryn respectively, but there were no significant trends in summer streamflow of either river between 1960 and 2007.

Studies analyzing trends in streamflow over shorter time periods show an increase in streamflow; for example, Finaev (2006) reported positive trends at several gauges in the Pamir for the 1990–2005 period but acknowledges that poor data quality may have affected the results. Although few, the existing analyses of discharge in the headwater catchments of the ASB and some neighboring basins (Shahgedanova *et al.* 2018; Duethmann *et al.* 2015; Krysanova *et al.* 2015; Kundzewicz *et al.* 2015) show that, to date, summer streamflow has not declined. However, the relative contributions of glacier, snow and permafrost may need more insights.

The current observed trends in streamflow and runoff point in the direction of increased water availability in July and August at least until mid-century and increased possibility for water storage in reservoirs and aquifers. However, eventually this will change as glaciers waste away; runoff patterns may change considerably after mid-century (Sorg *et al.* 2014). In a global effort to model runoff changes of more than 50 glacierized basins worldwide, Huss and Hock (2018) found that annual glacier runoff from about half of the basins will continue to increase until *peak water* is reached, and will start to decline afterwards (Figure 8.5).

Peak water will occur later in areas with a higher glacierized fraction and a higher altitudinal distribution of the ice masses. Seasonal runoff is expected to increase in early summer but decrease in late summer. Depending on the climate scenarios employed, peak water will occur in 2030 ± 2 (RCP2.6, mitigation scenario), and 2044 ± 15 (RCP8.5, business-as-usual scenario) in the ASB. Correspondingly, their model predicts an annual runoff increase for the ASB until peak water of 37 per cent (RCP2.6) and 53 per cent (RCP8.5). The increasing rate of evapotranspiration in a warmer climate combined with reduced water flow once peak water has been reached might further intensify challenges for water availability and management (Cretaux *et al.* 2013). However, studies focusing on predicting peak water on a smaller scale (individual catchments) are still lacking for the region and they are necessary in order to better assess the vulnerability of the local populations in the coming decades.

Changes in water resources are to be understood also in terms of changes in the frequency and distribution of water-related hazards, such as river floods, glacier lake outburst floods (GLOFs) and rain-on-snow events (rapid melting of snow combined with intense precipitation). Recent studies have reported that the number and extent of glacier lakes is increasing around the world as a consequence of increased temperatures in high-mountain areas (Carrivick and Tweed 2013; Tweed and Carrivick 2015; Wang and Zhang 2013) and that this trend will continue into the future (Kapitsa *et al.* 2017). The formation of ice- and moraine-dammed lakes from increased glacier melt has the potential to generate glacier lake outburst floods (GLOFs) hazards. The Dasht event in 2002 in the Shakhdara Valley (southwestern Tajik Pamir) is a stark reminder of the destructive power of such events. During the event 250,000 m^3 of water was released. The flow of water and entrained debris travelled about 10 km downstream to Dasht village. Large sections of the village were destroyed and the event claimed the life of more than 20 people (Komatsu and Watanabe 2014). Another more recent GLOF event in the Teztor Valley (Ala-Archa River catchment in the Tien Shan) in northern Kyrgyzstan in 2012 entrained a debris flow that caused minor disruption to the capital Bishkek (Erokhin *et al.* 2018). The event was preceded by intense precipitation and rapid rise in temperature, which are believed to have been the cause (Erokhin *et al.* 2018).

More than 1500 lakes extending across Tajikistan, Kyrgyzstan and Afghanistan have been identified through satellite remote sensing (Mergili *et al.* 2013). Kyrgyzstan alone counts about 2000 glacial lakes in its territory, of which 20 per cent are considered at potential risk of outburst due to unstable dams and frequent overflows (Janský *et al.* 2008). A new glacier lake inventory for the Uzbekistan territory (Petrov *et al.* 2017) identified 242 in the four Uzbekistan
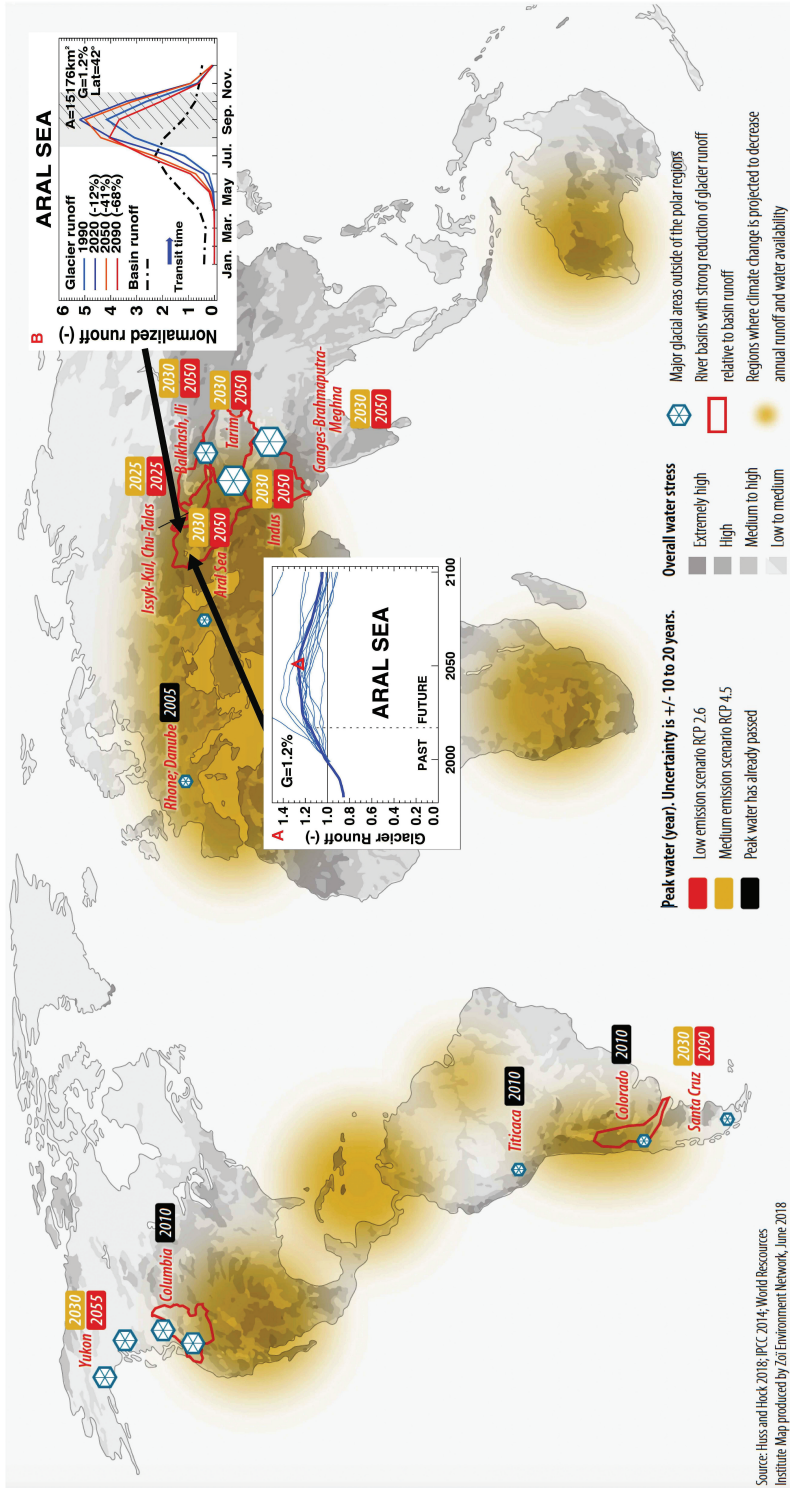
Figure 8.5 Simulated timing of peak water for individual macro-scale glacierized drainage basins (Huss and Hock 2018). Results refer to runoff from the initially glacierized area and are based on the multi-model mean of 14 GCMs and the RCP4.5 emission scenario. Inset (A) shows calculated annual glacier runoff normalized by average runoff in 1990–2010 for the ASB. The red triangle depicts peak water and the thin lines show results for individual GCMs. Inset (B) shows monthly mean basin runoff and calculated mean glacier runoff (shifted by water transit time) for four 20-year periods (1980–2000, 2010–2030, 2040–2060, 2080–2100). All series are normalized by mean monthly basin/glacier runoff in 1980–2000. The modeled change in glacier area for 2020, 2050, and 2090 relative to model initialization (around 1990) is stated in brackets, and present glacier area (A), glacierization (G) and geographic latitude (Lat.) of the basin's center are given. Shaded areas on the Inset indicate a monthly share of glacier runoff relative to total basin runoff of >30 per cent and hatched areas denote months. Basin-specific transit times are indicated with the blue arrow

Source: Constructed by authors

mountain regions, with more than half (131) located in the Tashkent region. Forty per cent of these (97 lakes) were classified to have a high outburst potential.

The increase in number and extent of glacier lakes does not appear to be accompanied by an increase in glacial floods (Harrison *et al.* 2018). Conversely, some studies have suggested a global decline in glacier floods since the 1990s, possibly associated on the one side with delayed response of glacier flood activities with glacier retreat (Harrison *et al.* 2018), and on the other side with the capacity of successive floods to give rise to river channels, which are better suited to accommodate subsequent flood events (Carrivick and Tweed 2016).

Global and regional climate models point in the direction of future increase in the intensity and frequency of extreme precipitation (Seneviratne *et al.* 2016). At high altitude and/or latitude, extreme precipitation and higher temperature might exacerbate the frequency of rain-on-snow flood events, which are responsible for the most damaging floods in mountain areas (Würzer *et al.* 2016). Furthermore, precipitation extremes combined with reduced snow and ice might be responsible for increased sediment transport and subsequent deterioration of water quality, infiltration in hydropower reservoirs and damage to infrastructure and agriculture (Huss *et al.* 2017). A wide knowledge gap exists on the future evolution of extreme events and their impacts on people, infrastructure and livelihoods in Central Asia (Unger-Shayesteh *et al.* 2013; Xenarios *et al.* 2019).

Conclusions

With its two large mountain ranges, Tien Shan and Pamir, Central Asia contains a large part of the worldwide alpine cryosphere, which has a fundamental function as a water storage reservoir with very different temporal scales, as described in this chapter. The state of current knowledge about the different cryospheric components, their processes, and their connection to climate in the Central Asian mountains and in the ASB catchment in particular varies. In the areas of snow and glacier research, knowledge in CA is quite advanced, whereas in permafrost research it is still marginal. Considerable work has been undertaken since the 1990s to address existing research gaps. One basic prerequisite for sound future estimates of cryospheric changes in the Central Asian mountains is the re-establishment of high-quality monitoring sites and capacity building, i.e., the education of young local scientists being able to continue the existing as well as new monitoring programs and to independently build up local research capacities. Currently such capacities and innovations are strongly supported through international projects such as the Central Asia Water project (CaWA[5]), an international consortium of German and Central Asian institutions, the Capacity Building and Twinning Climate Observing System and Cryospheric Climate Services for Improved Adaptation of the Swiss Agency for Development and Cooperation (CATCOS[6] and CICADA[7]), and the Central Asia Hydrometeorology Modernization Project (CAHMP[8]) of the World Bank, and many projects supported by the UK Newton Fund and Global Challenges Research Fund.

The modern alpine cryospheric network of Switzerland can serve as a role model for the mountainous countries in Central Asia. Swiss cryospheric monitoring networks (such as PERMOS, GLAMOS, or the snow monitoring network) are mainly funded by the Swiss government and are implemented primarily by researchers of different universities and research institutions. This is a reliable model that has extended operational monitoring capabilities beyond regions traditionally serviced by standard operational centers. A focus on collaboration between traditional operational hydro-meteorological services with academic sectors and the international networks they leverage could also be a model for improving the observing capabilities in high-mountain regions of CA in general, and the ASB in particular.

Notes

1 Active layer corresponds to the layer of ground that is subject to annual thawing and freezing in areas underlain by permafrost.
2 Data from National Snow and Ice Data Center, Central Asian snow cover from hydrometeorological surveys, 1932–1990, https://nsidc.org/data/g01171.
3 Global Terrestrial Network for Permafrost mandated by Global Climate Observing System/WMO.
4 http://gtnpdatabase.org/boreholes.
5 http://cawater-info.net/.
6 www.meteoschweiz.admin.ch/home/forschung-und-zusammenarbeit/projekte.subpage.html/de/data/projects/2011/catcos.html.
7 www.unifr.ch/geoscience/geographie/en/research/integrated-themes/international-cooperation-capacity-building.
8 http://projects.worldbank.org/P120788/central-asia-hydrometeorology-modernization-project?lang=en.

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