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Will climate change exacerbate water stress in Central Asia?

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Abstract Millions of people in the geopolitically important region of Central Asia depend on water from snow- and glacier-melt driven international rivers, most of all the Syr Darya and Amu Darya. The riparian countries of these rivers have

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experienced recurring water allocation conflicts ever since the Soviet Union collapsed. Will climate change exacerbate water stress and thus conflicts? We have developed a coupled climate, land-ice and rainfall-runoff model for the Syr Darya to quantify impacts and show that climatic changes are likely to have consequences on runoff seasonality due to earlier snow-melt. This will increase water stress in unregulated catchments because less water will be available for irrigation in the summer months. Threats from geohazards, above all glacier lake outbursts, are likely to increase as well. The area at highest risk is the densely populated, agriculturally productive, and politically unstable Fergana Valley. Targeted infrastructural developments will be required in the region. If the current mismanagement of water and energy resources can be replaced with more effective resource allocation mechanisms through the strengthening of transboundary institutions, Central Asia will be able to successfully address these future climate-related challenges.

1 Introduction

Recent research shows that even small-scale natural climate fluctuations have had large impacts on glaciers over the past 100,000 years. It also shows that hydrological regimes of snow- and glacier-melt driven rivers will be impacted by a warming climate (Schaefer et al. 2006; Barnett et al. 2005; Immerzeel et al. 2010). The recent controversy about overestimated melting rates of the Himalayan glaciers suggests, however, that our knowledge of high-altitude snow/ice and its response to climate forcing is still highly incomplete (Bagla 2009, 2010; Cogley et al. 2010; Metz 2007). Avoiding major water allocation conflicts within and between countries will require improved water management and planning, and the latter requires major advances in our understanding of how impacts from climatic changes are likely to unfold in these basins.

Many world regions that are likely to experience climate-induced changes in snow- and glacier-melt already suffer from water stress, socio-economic conflicts, political violence, and weak institutions (Parry et al. 2007; Gleditsch and Nordås 2007; Mearns and Norton 2010). Central Asia belongs to the most important areas in this category (Fig. 1).

Complex allocation tradeoffs exist in the region. The energy-poor yet water-rich upstream countries (Kyrgyzstan and Tajikistan) use water for hydropower production in the winter. Conversely, the downstream states (Uzbekistan, Turkmenistan and Kazakhstan) consumptively utilize water in the summer irrigation season. Around 22 million people depend on irrigated agriculture for their livelihoods there, and 20–40% of the economic output of these countries is derived from agriculture, most of which is irrigated (Bucknall et al. 2003). The extensive development of irrigation since the 1950s is associated with severe environmental problems, most notably the desiccation of the Aral Sea, which has lost up to 90% of its pre-1960 volume (Micklin 2007).

Water and energy sharing problems in Central Asia are complicated by the fact that the region's major catchments, the Syr Darya and Amu Darya, extend across political boundaries. Ever since the collapse of the Soviet Union in 1991, the new countries of Central Asia have experienced conflicts over the region's water resources. Efforts to establish effective international institutions for water

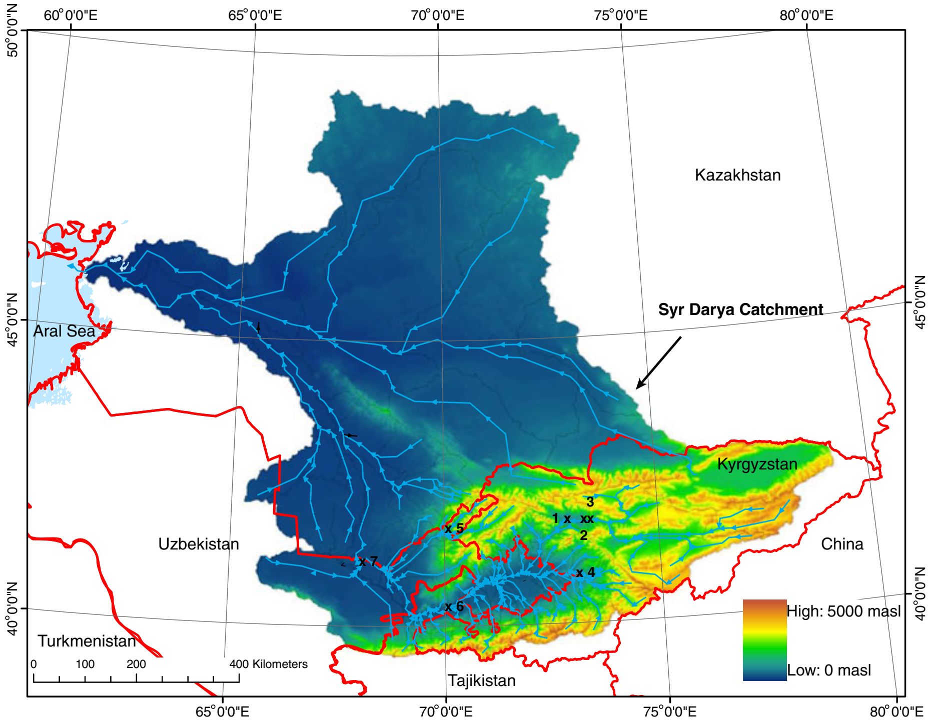

Fig. 1 Central Asian region and depiction of the Syr Darya basin and river network as implemented in the rainfall runoff model. The topography inside the basin is shown. The river network is depicted in *bright blue color* with *arrows* indicating water flow direction. Major reservoir locations are shown and indicated with crosses (*x*). They are: *1* Toktogul, *2* Kambarata I, *3* Kambarata II (planned), *4* Andijan, *5* Charvak, *6* Kayrakum and *7* Chardara. *Red lines* are country borders

and energy allocation have thus far failed (Siegfried and Bernauer 2007). Moreover, large new dam projects in Kyrgyzstan (Kambarata I and II) and Tajikistan (Rogun) are provoking hostile reactions from downstream Uzbekistan where it appears that a growing number of agricultural communities are affected by falling income in agriculture due to deteriorating water supply and drainage systems and land degradation.

Influenced by the complex topography in the region, Central Asia's climate is highly variable. Western and central Pamir regions and the western Tien Shan (including north ridge of Fergana valley, Talas, Susamir and Chu valleys) receive the bulk of precipitation during winter and spring seasons. Conversely, eastern Pamir and northern Tien Shan (including Zailiiskiy Alatau) together with the main runoff formation area of the Syr Darya in central Tien Shan, have spring-summer maximum precipitation.[1]

[1] We are grateful to an anonymous reviewer for details on the climate and precipitation characteristics in the different Central Asian regions.

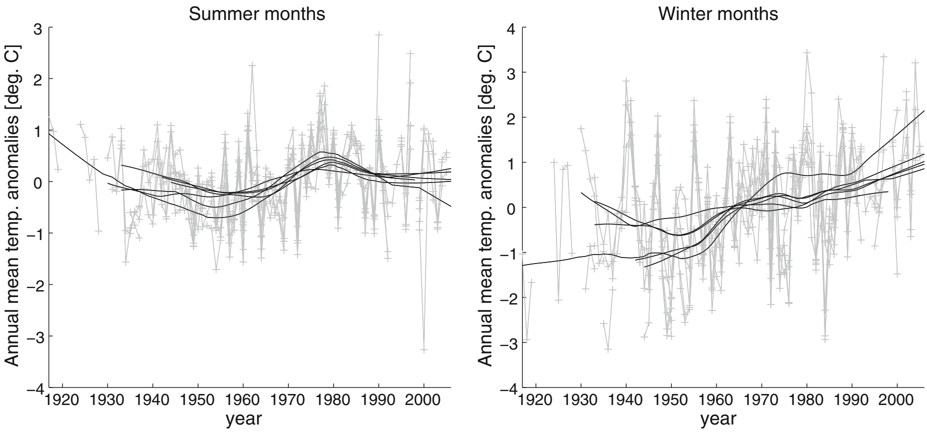

Fig. 2 Temperature anomalies for six stations in the Tien Shan mountains are shown from 1917–2006 (stations: Naryn (41°26′ N, 75°59′ E), Tian Shan (41°26′ N, 75°59′ E), Pskem (41°54′ N, 70°20′ E), Chatkal (41°55′ N, 71°20′ E), Padsha-Ata (41°35′ N, 71°40′ E), Ak-Terek-Gava (41°20′ N, 72°42′ E). Source: station data provided by UzHydromet). The *left plate* shows summer (April through September) anomalies, the *right plate* shows winter anomalies for the months October through March. A pronounced warming trend in the winter months over the second half of the 20th century is discernible. From 1990 onwards, the mean trend over all stations was 0.3°C per decade which is approx. half of the ensemble mean temperature trend per decade as derived from the GCM SRES A2 runs (Table S1). Gray lines: actual data, *black lines*: 25 year robust local regression filtered time series

Instrumental records show increasing long-term temperature trends in the Tien Shan mountains, the main source of the Syr Darya, since 1950 — the average trend coefficient has been 0.2°C per decade, with winter temperatures rising most strongly (Fig. 2).[2] Many observers of Central Asia expect worse to come as a significant increase of this trend coefficient in the 21st century is expected, with considerable climate uncertainty and unknown consequences on water availability (Solomon et al. 2007). On top of that, the region's population is likely to grow by about twenty million over the next 40 years, which implies a 30% increase relative to today, with Uzbekistan contributing 50% and Tajikistan 25% to this growth (UN World Population Database 2011) and water demand is very likely to increase proportionally. This appears highly problematic when juxtaposed on potential impacts from climatic changes. These include increasing risks from geohazards such as catastrophic flooding due to glacial lake outbursts (Nayar 2009), the destabilization of mountain slopes and more landslides due to thawing of permafrost (Haeberli and Beniston 1998), and higher reservoir siltation rates caused by an increased load of suspended solids (Wilson 1973).

Against this background, two opposing views on the hydro-political future of Central Asia are frequently voiced. The pessimistic view is that a warming climate

[2]We have also analyzed the 0.5-degree gridded temperature data from the CRU TS2p1 dataset (available at: http://iridl.ldeo.columbia.edu/SOURCES/.UEA/.CRU/.TS2p1/) which exhibits broadly similar trends to those seen at the six stations.

will reduce available water and, particularly if combined with rising water demand, increase the propensity for water-related conflicts among the riparian countries.[3] Another, more optimistic view is that increasing temperatures cause a depletion of snow and glacier storage in higher altitude regions that translates into additional runoff, which at least in the next few decades, will avoid a deterioration of the supply-demand ratio[4] Malone (2010).

Systematic assessment of these opposing views is urgently needed, but far from easy, since runoff patterns of snow- and glacier-melt dominated rivers respond in complex ways to a warming climate. Policy-makers in Central Asia (and elsewhere) act on their *perception* of existing and projected reality (Merton 1995). Which of the two opposing views they believe in thus has important political implications. In the worst case, faulty projections of rising water scarcity due to climatic changes could make decision-makers in this geopolitically important region even more concerned about their water future than they already are and produce self-fulfilling prophecies, perhaps even a major international conflict over access to and control of natural resources in the region, including water.

The aim of this study is to assess how water availability in Central Asia could be affected by climate change. We use the Syr Darya as a test case and report results from a new coupled climate, land-ice and hydrological model. In Section 2, data sources and individual model components are presented. Results are discussed in Section 3. We conclude with policy recommendations for adaptation and conclusions in Section 4.

2 Methods and materials

The Syr Darya catchment is approximately 400'000 km^2 in size. Its annual (largely winter) precipitation average is 320 mm and there are pronounced differences between the mountainous Tien Shan region (500–1500 mm), where the Syr Darya originates, and the low land steppes (100–200 mm). Annual runoff averages around 39 km^3, with 80% occurring between March and September due to combined snow- and glacier-melt (Pereira-Cardenal et al. 2011). An estimated 200 km^3 of water is stored in glaciers in the Tien Shan (Aizen et al. 2007).

The idea here is to drive rainfall-runoff and land-ice models of the Syr Darya by two climate scenarios: a baseline scenario (BL) assuming that the recent historic anthropogenic warming trend continues into the future and a pronounced warming scenario based on the IPCC SRES A2 scenario.[5] The coupled model is then used to project runoff at the basin scale and in individual sub-catchments of the Syr Darya

[3] A recent Oxfam report on Central Asia, for instance, argues that "retreating glaciers and more extreme weather could dangerously erode food security, livelihoods and even regional stability in 2050" (Swarup 2010).

[4] This additional contribution to runoff will however only be available over a strictly limited time until land-ice and snow storage are depleted.

[5] In view of future GHG emissions projected by the IPPC, the IEA, and other institutions, the A2 temperature trend may well become reality over the next decades.

until 2050, including the contributions from glacier-melt. Conceptual diagrams of the overall modeling approach are shown in the Online Supplementary Material in Figs. S1 and S2.

2.1 Hydrological model of the Syr Darya

The runoff processes are modeled by a lumped, conceptual hydrological model and implemented in the NAM (Nedbor—Afstromningsmodel, Danish Hydrological Institute 2000) modeling system.[6] The NAM model allows for explicit representation of a) snow storage, b) surface storage, c) soil zone storage and d) groundwater storage from which runoff is generated by baseflow at the subcatchment scale. Due to limited amounts of observed in-situ discharge data, a robust version of the NAM model was developed using five free calibration parameters only (see below). Figure S1 in the Online Supplementary Material shows the model architecture.

Catchment delineation is based on a 1 km digital elevation model obtained from the Shuttle Radar Topography Mission (SRTM) (Rabus et al. 2003). 110 subcatchments were delineated. Each subcatchment is divided into ten elevation zones for precipitation discrimination where typical temperature lapse rates of the region were used (i.e. −0.7°C/100 m and −0.5°C/100 m, see Pereira-Cardenal et al. (2011) for more detail). If temperature T is below 0°C, precipitation falls as snow. For each elevation zone, snow melt is modeled using a degree-day approach (see Online Supplementary Material for more details on the hydrological model).

The Tropical Rainfall Measuring Mission (TRMM) Multisatellite Precipitation Analysis from 01.01.2000 to 31.12.2009 was utilized for obtaining precipitation values for the Syr Darya catchment (Huffman et al. 2007). For the temperature, an ECMWF 2-meter operational dataset was used (ECMF 2009). For the BL and A2 future climate runs, $T_{\max}$ and $T_{\min}$ for corresponding 10 day periods were randomly drawn from empirical distributions based on data from the ECMWF dataset from 2000–2010.

Subcatchments with continuous discharge records of 8 years or more were used for calibration, while those with 3–7 years of discontinuous records were used for model validation. Calibration was carried out with the automatic module that is available for NAM. Prediction subcatchments are those with no available runoff data but expected considerable runoff due to topography and land cover. Areas with no expected runoff were considered inactive subcatchments. Model performance in relation to 3 major sources of uncertainty were assessed, i.e. the TRMM precipitation product, the runoff processes and the irrigation water use (see Pereira-Cardenal et al. 2011 for more details.).

The river network topology was designed and implemented in Mike Basin ("Mike Basin—River Basin Management in GIS". Retrieved May, 2009, from http://www.dhigroup.com/Software/WaterResources/MIKEBASIN.aspx). Water is instantaneously routed from node to node along the network. Information on the major

[6]The development and calibration of the rainfall-runoff model for the Syr Darya is described in detail in Pereira-Cardenal et al. (2011).

reservoirs in the Syr Darya Basin was obtained from the Interstate Commission for Water Coordination in Central Asia www.icwc-aral.uz. Reservoirs are implemented as rule curve reservoirs and level-area-volume curves are used to convert volume to water level (information provided by Operational Hydrological Forecasting Department (UzHydromet), Tashkent, Uzbekistan).

Irrigation water demand in the downstream area was lumped into 6 major demand sites, i.e. High Naryn, Fergana, Mid Syr, Chakir, Artur and Low Syr from upstream to downstream. Data on irrigation extent and crop choice were obtained from Raskin et al. (1992) and irrigation water demand was calculated using the FAO-56 methodology (Allen 2000).

2.2 Land-ice model

Modeling ice dynamics is complex. First, long-term in situ observational records on climate-forced cryosphere dynamics in the Tien Shan mountains are currently lacking or only available for a number of selected glaciers (Aizen et al. 2004). Second, differential impacts from a warming climate on different glacier sizes are expected and the dependence of ice wastage/accumulation on temperature and precipitation above the equilibrium-line altitude. For example, large glaciers may respond to climate changes with decadal lags, whereas small ice bodies respond to higher frequency variability at annual to inter-annual scales (Dyurgerov et al. 2009). Finally, radiative fluxes and the particular geometry of individual ice masses play a role.

Mass balance modeling of a large number of glacier, however, has shown that changes in the mass balance at annual time scales or larger are mainly driven by temperature, and that a climate sensitivity in terms of changes in glacier length can be defined as a function of changes in temperatures (Oerlemans 2001; Greuell and Smeets 2001). Using a first-order theory of glacier response to climate forcing, we employed a dynamical model approach that relates changes in temperature to fluctuations in glacier length at the level of individual glacier records. This is the simplest model that can deal with lag effects and differences in climate sensitivity (Oerlemans 2005).

For this purpose, data on land-ice were extracted from the GLIMS database (Armstrong et al. 2005). 5,143 glaciers from the database are located within the catchment boundaries. The primary source of that data is the Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) instrument on the TERRA satellite (see http://asterweb.jpl.nasa.gov/). Information on the latitude and longitude as well as maximum, mean and minimum elevations and the length of individual glaciers were obtained. Data show that a significant glaciation in the region of the source of the Naryn River as well as in the northern and southern branches of the Tien Shan mountains occurs (top panel in Fig. 3).

The individual glacier dynamics is specified as

$$\frac{dL'(t)}{dt} = -\frac{1}{\tau}\left(cT'(t) + L'(t)\right) \tag{1}$$

where

$$L(t) = L_0 + L'(t) \tag{2}$$

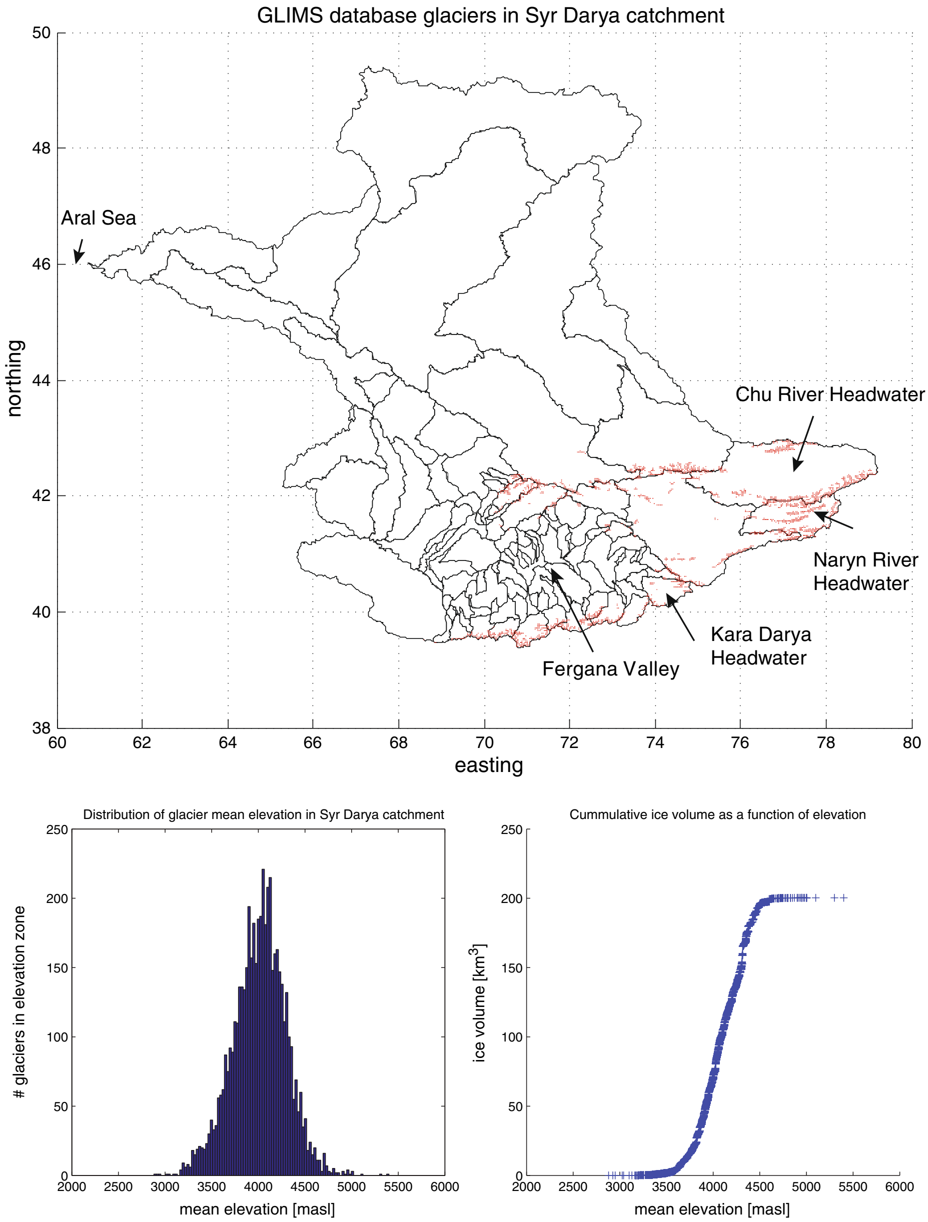

Fig. 3 *Top panel*: glacier locations (*red dots*, Armstrong et al. 2005) in the Syr Darya sub-catchments (*blue polygons*, Pereira-Cardenal et al. 2011). *Bottom left panel*: distribution of glaciers mean elevations in the Syr Darya catchment. Using the scaling relationships reported in Eqs. 5–8, the GLIMS data can be converted into data on glacier volumes. The *bottom right panel* shows the cumulative volumetric distribution of the retrieved glaciers

is the length of a glacier in meters at year t and $L'(t)$ thus the change in glacier length relative to the reference state L_0 and $T'(t)$ [°C] is a temperature perturbation with respect to a reference state (Oerlemans 2005).

For the climate sensitivity and the response time, we utilize the parameterization as proposed by Oerlemans (2005). The response time τ [a] is parameterized as

$$\tau = \frac{2266.67}{s\sqrt{L_0(1+20s)P(t)}} \tag{3}$$

with s being the average glacier slope [-] and $P(t)$ is the annual precipitation in meters. The climate sensitivity c [m/°C] is given by

$$c = 2.3\frac{P(t)^{0.6}}{s} \tag{4}$$

Here, $P(t)$ is in mm/a. s was calculated using the data on glacier length, minimum and maximum elevation in the GLIMS database.

Aizen, et al. report glacier length/surface area and surface area/volume scaling relationships for the Tien Shan mountain ranges (Aizen et al. 2007). These are

$$S = \left(\frac{L}{1.6724}\right)^{\frac{1}{0.561}} \tag{5}$$

$$V = 0.03782S^{1.23} \text{ for } S < 0.1 \text{ km}^2 \tag{6}$$

$$V = \frac{0.03332S^{1.08}e^{0.1219L}}{L^{0.08846}} \text{ for } 0.1 < S < 25 \text{ km}^2 \tag{7}$$

$$V = 0.018484S + 0.021875S^{1.3521} \text{ for } S > 25 \text{ km}^2 \tag{8}$$

with S being the glacier surface area [km^2] and V is the glacier volume [km^3]. Utilizing Eqs. 1 and 5–8 and a particular temperature and precipitation forcing, we can estimate volumetric fluctuations for each of the 5,143 glaciers and attribute their contributions to individual catchments and study the cumulative impact from glacier runoff in the catchment. The GLIMS data on glacier lengths as well as the scaling relationships reported above suggest that there is approximately 200 km^3 of ice in the Syr Darya catchment which compares very well with the estimates reported by Aizen et al. (2007).

Since the NAM model has no means of representing the land-ice component directly, we model glacier dynamics separately without explicit accounting for snow/ice conversion. Furthermore, for runoff generation, we only take into account melting (i.e. $V(t+1) - V(t) < 0$) and distribute the annual volumetric change of a particular glacier with a simple degree day approach (where $T > 0$) throughout the year and subsequently add it to the daily runoff from the NAM model. Equation 1 was solved for corresponding precipitation and temperature forcings using a numerical integration scheme in MATLAB (The MathWorks 2003).

2.3 Climate scenarios

Global climate models (GCMs) perform poorly at the local scale, especially for surface variables (Giorgi et al. 2001), since regional climate is determined by the large-scale climate state as well as local physiographic features. Additionally, there is the usual spatial and temporal mismatch between GCM output (typically at the 300–500 km scale) and input requirements for river-runoff modeling. Hence we developed a statistical downscaling and calibration approach to produce stochastic climate realizations from regional observations and GCM output. The basic idea is thus to establish empirical relationships between regional-scale climate indices and sub-grid scale surface quantities to be predicted, i.e., temperature and precipitation (Wilby et al. 1999).

To generate spatially disaggregated daily precipitation data for each subcatchment from 2010–2050, a Non-Homogeneous Hidden Markov Model (NHMM) was utilized (Kirshner 2005). NHMMs are multi-site stochastic daily weather generators that have been used extensively to downscale GCM simulations to local, both on seasonal forecasting time scales (Robertson et al. 2004, 2006, 2009; Verbist et al. 2010) as well as for climate change downscaling (Greene et al. 2011; Timbal et al. 2008). For the precipitation model in this study, an eight state NHMM was employed.

The NHMM was trained on 10 years of daily TRMM precipitation data from January 1st, 2000 to December 31st, 2009. Because of the large seasonal changes in precipitation within the Tien Shan region (winter/spring time rainy season versus summer time dry season), the NHMM relies on a predictor for generating a realistic seasonal distribution of precipitation. Baseline catchment predictors are derived running a 60 day low-pass filter on daily TRMM precipitation values as a univariate slowly-varying input to the NHMM, from which daily stochastic rainfall sequences for the individual sub-catchments are then generated. Conceptually, the synoptic-scale climate driving of rainfall of interest here is modulated on a seasonal time scale and longer, while the daily Markov character of the NHMM supplies daily stochastic rainfall sequences that are calibrated against the observed TRMM data. The NHMM states can be thought of as weather types whose occurrences are modulated on these longer time scales. The predictor is checked for seasonal biases within the NHMM by comparing the predictor mean monthly precipitation values with the mean monthly precipitation values from the TRMM observations.

For the NHMM future simulation runs from January 1st, 2010 to December 31st, 2049, our goal was to also account for the natural low-frequency variation at annual to inter-decadal time scales, in addition to the mean historical seasonality and the future trends projected by the GCMs. Hence, the idea was to develop a layered predictor that accounts for these three components of climate variability.

First, all available IPCC AR4 Global Circulation Models (GCM) simulation data for climate of the 20th century (20C3M) experiments were obtained (see Table S1 in the Online Supplementary Material). They were analyzed regarding their ability to reproduce properly the seasonal distribution of precipitation for the Tien Shan region (latitude 40–50 N and longitude 60–80 E). A total of 11 models M were considered adequate in the comparison of the particular model's mean monthly precipitation values with TRMM mean monthly observations from 2000–2009 were discarded. GCM monthly precipitation and temperature series from January 2000 to December 2099 were used to extract 30 year trends for precipitation P and temperature T in the Tien Shan region. These linear trends (T: 1.83 ± 0.48°C/30 a, -0.04 ± 0.08 mm/30 a) provide guidance on precipitation and temperature trends for the Tien Shan region until 2050 (Table S1) and were used as a first predictor component in the NHMM model.[7] This first-order approach was chosen in order to reduce sampling variability in the GCM regional precipitation trends.

Second, the GCM-change in the mean seasonal cycle of the precipitation between the two periods 2070–2099 (A2) and 1950–1999 (20C3M runs) was computed on a monthly basis for each of the 11 GCMs individually. The monthly delta values Δ were then standardized. Based on these delta values, interpolated predictors $\hat{P}$ from 2010–2050 for seasonal change were defined by multiplying the baseline predictors P with the delta values, i.e. $\hat{P} = P \times (1 + \Delta \times (t_E - t)/(t_E - t_S))$, with t_S being the start of the simulation period and t_E being the end.

Third, for each model M, we create five multi-decadal scenarios S based on an first-order autoregressive model AR(1) which was trained on a near-continuous 70 year mean composite time series of decadal (10 days) precipitation in the Tien Shan mountains from 1936–2006 . The final normalized NHMM predictors were then derived by adding climate trend, seasonality and its change as well as the multi-decadal variability components together. For each of the $M \times S$ predictors, $r = 3$ NHMM realizations were run to arrive at at total of 165 future climate realizations. This methodology is a simple and straightforward way to extract and use GCM information on climate projections and climate states for regions under consideration.

A precipitation matching 50 years temperature time series was generated by statistical modeling. The historic relationship between wet and dry days precipitation from the TRMM data and ECMWF was utilized to generate monthly Gaussian parametric distributions of temperature as a function of dry/wet precipitation states for each of the catchments. A cutoff value of 1 mm/day precipitation was utilized to distinguish wet from dry days. Daily realizations of temperature were then constructed using random sampling from these distributions depending on whether the NHMM precipitation output was in a wet or a dry state. GCM temperature trends were added for the A2 simulation. Similarly, historic temperature trends from 1950–2006 were identified based on data from six stations and utilized for the baseline (BL) temperature trends.

The method for the generation of climate scenario presented here lends itself for a coherent partitioning of total uncertainty (i.e. the spread of the multi-model ensemble) in the $M \times S \times r$ climate predictions. 3 different sources of uncertainty are accounted for: a) *model uncertainty* due to different modeling approaches of physical processes in GCMs, b) *scenario uncertainty* due to incomplete information about multi-decadal variability and c) aleatoric *internal variability* . For the quantification of individual uncertainty components, the simple model-based ANOVA approach presented in Yip et al (2010) was utilized.

The multi-model variance decomposition shows that the main contributions to total climate uncertainty over the long-run (2040–2049) originate from GCM model uncertainty (variance of GCM means around ensemble mean as percentage of total variance: 21.9%) together with GCM—multi-decadal scenario interaction uncertainty (69.9%), i.e. the contribution to total uncertainty from variation across

[7] A number of challenges in extracting regional information and trends from IPCC AR4 GCMs have been noted and are discussed elsewhere (Sellars et al., Simulating climate variability and change in Central Asia using a coupled NHMM-AR1 model, in preparation).

multi-decadal scenarios of model deviations from the ensemble mean. A better understanding of regional climate variability at decadal to multi-decadal scales could reduce total climate uncertainty significantly, with important implications for better water resources management and planning.

3 Results

Our analysis has produced three important results. The first result is that, depending on the emissions scenario, glacier-melt will continue to contribute to runoff during the first half of the 21st century. Under the SRES A2 emissions scenario, approximately one third of present total land-ice volume will melt over this period, with an expected volumetric loss of 31% ± 4% (Fig. 4). The mean annual runoff is expected to be on the order of 50 m^3/s under this scenario. This corresponds to roughly 2.7% ± 2% of total natural basin runoff, or around one third of present average inflow into the Aral Sea after all upstream consumptive water use has been accounted for. Basin-wide glacier-melt contributions to river flow are and will likely remain small when compared with the natural runoff regime.

The second result is that the most important impacts of climate change in the Syr Darya basin emerge from significant changes in the seasonality of runoff (Fig. 5). Weekly runoff contributions from unregulated catchments that drain directly into the Fergana Valley are shown in the upper left plate of Fig. 5. This area is by far the most densely populated and agriculturally productive area in Central Asia. Contributions from 2000–2009 are compared with the runoff regime for 2040–2049 under the SRES A2 scenario. The other plates in Fig. 5 show weekly runoff contributions to the major surface reservoirs in the Syr Darya catchment under the assumption of unregulated flow and zero consumptive upstream use (no human interference with the natural runoff regime). Under these conditions, the runoff peak under the SRES A2 scenario shifts by 30–60 days from the current spring/early summer towards a late winter/early spring runoff regime. In comparison, the shift of the mean peak runoff under the BL

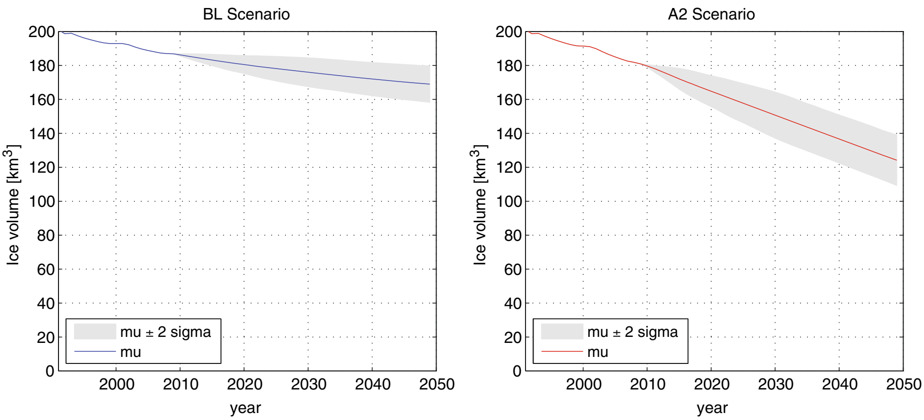

Fig. 4 Total ice volume in the Tien Shan from 2010–2050 as a function of temperature and precipitation forcings (BL and A2 scenarios)

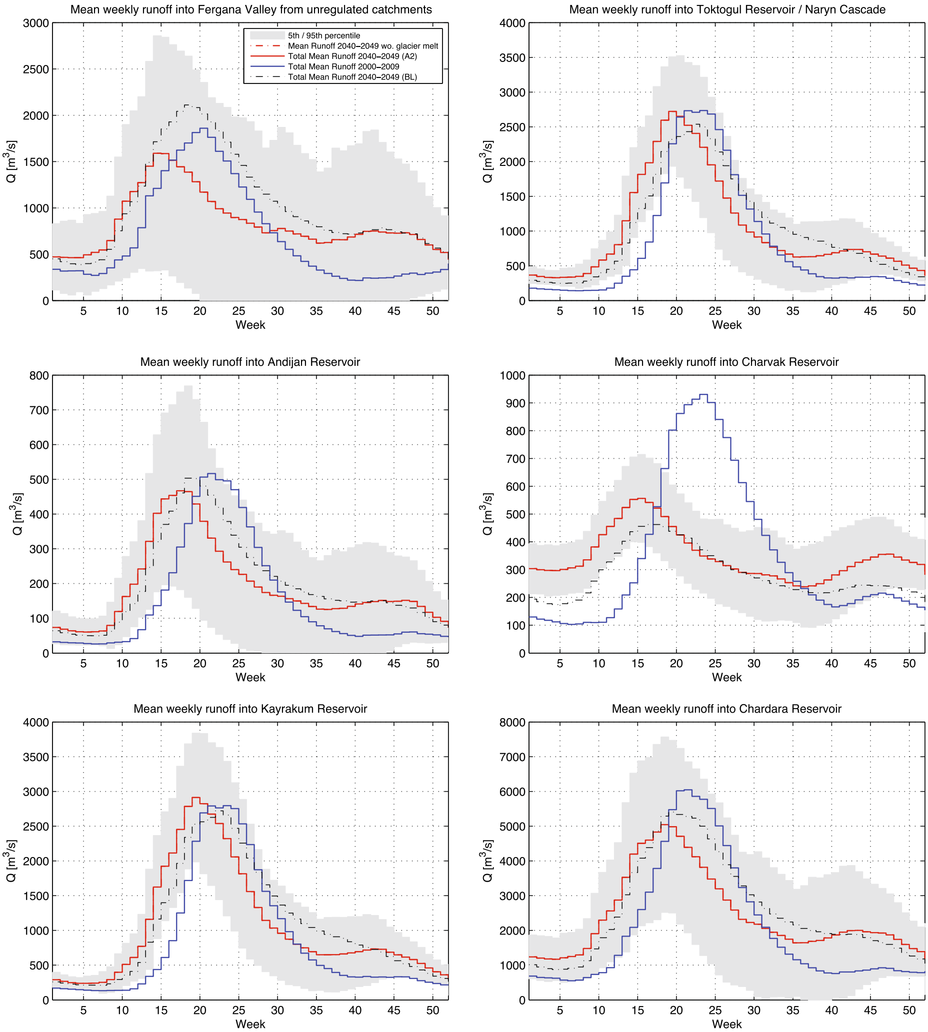

Fig. 5 Mean weekly runoff figures for selected aggregates of subcatchments (see Fig. 1 for reservoir locations). Beginning of century regimes are compared with mid-century ones for the SRES A2 AR(1) and BL scenarios. Fifth and 95th percentile ranges are derived from the 165 NHMM realizations and shown for the SRES A2 AR(1) runs

scenario is less pronounced and, especially for the high altitude catchments, hardly noticeable (i.e. see upper right Panel in Fig. 5). It confirms our intuition about the critical temperature sensitivity of the runoff regime in snow- and glacier-melt driven basins and how they may react to different climate forcings. It also points to large scenario uncertainty.

This shift has important repercussions for reservoir management because it leads to a major deficit in the vegetation period. More than 90% of total average annual consumptive water use at present is for irrigation purposes during that period. Existing manmade infrastructure is able to store the early irrigation season runoff

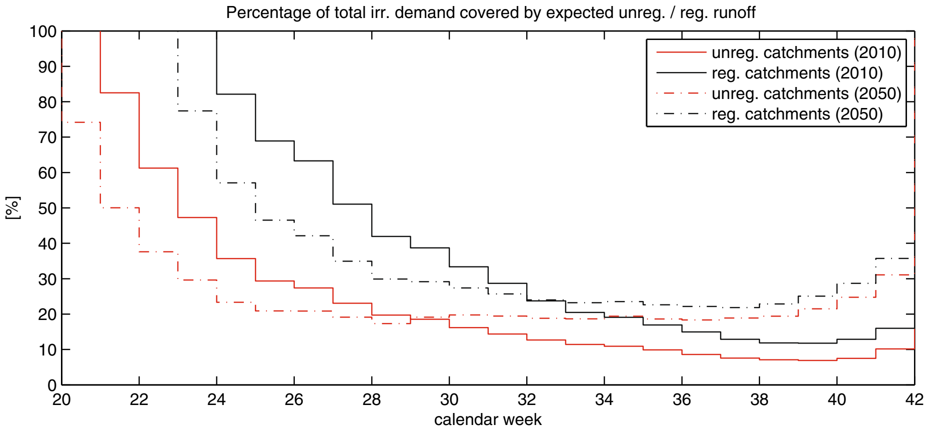

Fig. 6 Development of irrigation water demand coverage in the Fergana Valley due to changes in runoff seasonality and increases in evapotranspirative requirements. Maximum demand coverage deficits are expected to occur in the early growing stages which are the most sensitive periods for plant growth regarding water stress. Careful management interventions, most likely coupled with additional manmade storage in unregulated catchments together with corresponding conveyance will be required to cover this deficit

intermittently in regulated catchments (approx. 50% of total runoff in the Fergana Valley). But the expected temporal shift in runoff translates into less direct water availability in subcatchments that are unregulated and not served by controlled reservoir releases. For illustration, Fig. 6 shows expected water availability in corresponding subcatchments (regulated/unregulated) in the Fergana Valley relative to expected irrigation water demand. This estimate assumes that a) irrigated area remains constant, b) the crop mix remains unchanged and c) increases in downstream evapotranspirative requirements (+12 % ±1.7% relative to 2000–2009 levels) are determined by increases in temperature.

The main reason for projected changes in seasonality are early snowmelt, as driven by rising temperatures. Especially the low-lying catchments, such as the one feeding the Charvak reservoir, will probably experience a significant shift in runoff patters. The headwater catchments that feed into Toktogul reservoir[8] will experience less impact due to their high elevations. The total contributions from glacier-melt are hardly visible. They do not offset the widening gap in the availability of water for irrigation during the vegetation period.

These developments will gradually put additional pressure on the weak existing transboundary water- and energy-sharing institutions (for a detailed discussion, see also Bernauer and Siegfried (2011)). At the same time, negative implications of seasonal shifts in runoff are likely to be exacerbated by strong population growth, which reduces per capita water availability. This effect could be particularly strong downstream, especially in the Fergana Valley which, for economic, ethno-political

[8]With 19.5 km^3 total capacity, the Toktogul reservoir is the largest storage facility in the Syr Darya basin. Together with four smaller downstream reservoirs, the facilities have a combined hydropower generation capacity of 2,870 MW (The World Bank 2004).

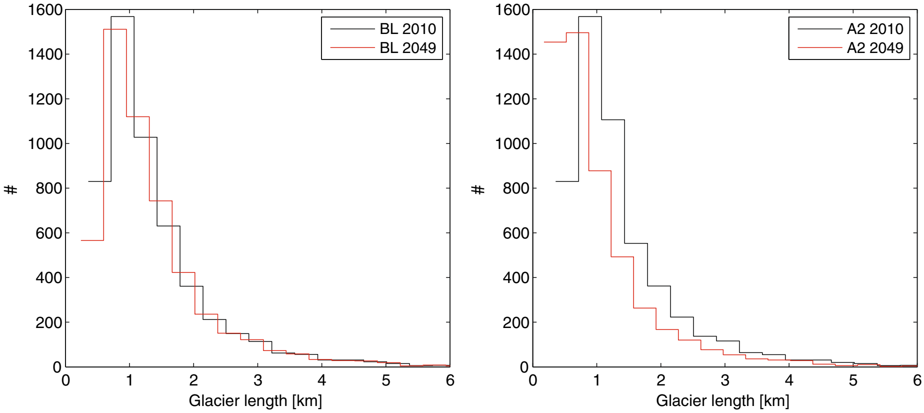

Fig. 7 Distribution of glacier lengths for each of the two climate scenarios. Statistics for 2010 (*black*) and 2049 (*red*) are shown. Data for 2049 are ensemble means over the 165 climate realizations

and religious reasons, arguably is the most sensitive area in Central Asia. There, population is expected to grow by 40% by 2050, relative to 2010 levels, which is significantly higher than the corresponding 25% growth in upstream Kyrgyzstan over the same period of time.[9]

The third result is that glacier lengths will decline across all size categories (Figs. 7 and 8). As glaciers retreat, large volumes of meltwater can get trapped behind unstable terminal moraines. If these moraines collapse, glacier lake outbursts can occur. Such outbursts can potentially cause catastrophic flooding downstream. As shown in Fig. 8, the Fergana Valley region is particularly exposed to these geohazards under the A2 scenario. The significantly affected subcatchments, depicted in this hazards map, are low-lying and mostly along the northern fringe of the Fergana valley, i.e. in the Chatkal and Kuramin ranges.[10]

In summary, climate change will affect the Syr Darya basin mainly through temperature effects on the snow and ice cover in the Tien Shan mountains. Drastic changes in annual water availability in absolute terms, relative to current conditions, are unlikely as impacts from climate change are likely to unfold gradually over the next 40 years. Neo-Malthusian scenarios of acute water scarcity and conflict over the Syr Daryas water resources are unrealistic. However, the expected runoff regime

[9]To estimate population growth at the subcatchment level we used a logistic growth model to extrapolate gridded population figures in 2010 (CIESIN 2010) and national growth rates as reported by the United Nations (2007).

[10]This hazards map can guide initial monitoring efforts towards the subcatchments which show the largest climate sensitivity of land ice towards climatic changes. However, we would like to emphasize that for this assessment, a *linear* dynamic model was used. Whereas the linearity assumption of land ice sensitivity towards climate is certainly a good first-order approximation for small-scale volumetric fluctuations, it is problematic in the case of large-scale changes. Hence, solely relying on such model-based output is certainly not the most advisable strategy for the identification of best mitigation strategies in relation to these distributed hazards. Rather, a detailed analysis should utilize remotely sensed data, combined with in-situ observations, to ultimately produce more reliable and detailed hazard maps.

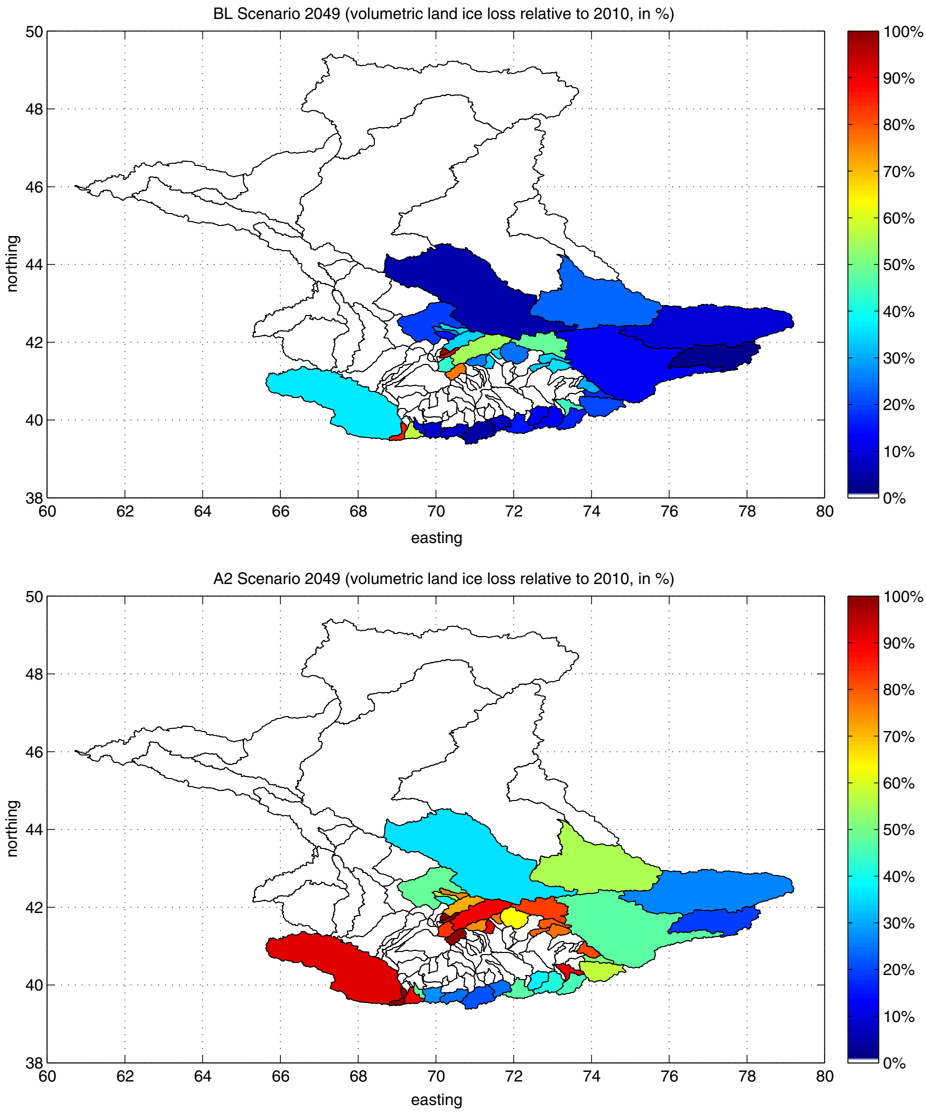

Fig. 8 Hazards map showing catchment level, mean percentage loss of land ice by 2049, relative to 2010. The *red dots* are GLIMS database glacier locations (Armstrong et al. 2005)

changes call for preparedness through proper climate adaptation which is discussed in the following section.

4 Discussion and conclusions

Our results indicate that gambling on increased water availability due to climate-induced glacier- and snow-melt to solve the international water and energy allocation conflict would be a risky political strategy. The seasonal shift in runoff, as projected by our model, is likely to cause serious problems, notably in unregulated subcatchments, that can only be addressed by targeted construction of new storage and conveyance infrastructure and better management. In this respect, the multi-year storage of Kambarata I (planned) and the constant head reservoir Kambarata II (constructed), both upstream of Toktogul, will add management flexibility for upstream reservoir operation in terms of added hydropower capacity and allow for winter hydropower production at these sites without harmful releases of water to the downstream since the water can be stored intermittently in the Toktogul reservoir and be put to effective use in the subsequent summer irrigation season. Greater flexibility, however, comes with increased complexity for transboundary management as the riparian countries need to incorporate the two major dams in effective water and energy sharing regimes. Current water-sharing institutions should be modernized and existing ineffectiveness eliminated by deliberately targeting mismanagement and partisanship.

With regard to this, innovative approaches should be explored in light of our findings. For example, instead of the current compensation of direct water releases with hydrocarbon energy equivalents, Kyrgyzstan could be compensated for winter water savings and summer releases in a mixed incentive scheme. Compensation levels could, furthermore, be tied to expected future climate variability, with water savings in the non-vegetation period preceding an expected below-average hydrological year (as determined by probabilistic forecasts) carrying a higher value for compensation than water-savings in normal or above-normal periods.

Risks of glacial lake outbursts need to be addressed as glaciers are retreating. Such outbursts could occur throughout the glaciated northern and southern Tien Shan mountains. Targeted and coordinated efforts in upstream Kyrgyzstan are required, such as carefully monitored lake drainage. Investments towards this end will be most effective if they are closely coordinated at the international level. The complex geography in the vicinity of the Fergana Valley will complicate any international effort, as the valley floor is almost entirely under Uzbek control, whereas the surrounding mountain ranges are mostly Kyrgyz and partly Tajik.

Despite the fact that Central Asia is facing several climate- and water-related challenges, there remains a substantial window of opportunity for adaptation and mitigation. Scientific research can support these efforts and directly inform decision-making. At the same time, a young and knowledgable workforce should be educated that can successfully takeover from the gradually retiring hydropower and irrigation engineering elite in the region. This would greatly help to put effective and cooperative resource sharing and management at the top of the agenda in the region.

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