Environ Earth Sci
DOI 10.1007/s12665-013-2988-5

THEMATIC ISSUE

Water quality, potential conflicts and solutions—an upstream–downstream analysis of the transnational Zarafshan River (Tajikistan, Uzbekistan)

M. Groll · Chr. Opp · R. Kulmatov · M. Ikramova · I. Normatov

Received: 24 June 2013 / Accepted: 28 November 2013

Abstract The Central Asian countries are particularly affected by the global climate change. The cultural and economic centers in this mostly arid region have to rely solely on the water resources provided by the rapidly melting glaciers in the Pamir, Tien-Shan and Alay mountains. By 2030, the available water resources will be 30 % lower than today while the water demand will increase by 30 %. The unsustainable land and water use leads to a water deficit and a deterioration of the water quality. Documenting the status quo of the water resources needs to be the first steps towards an integrated water resource management. The research presented here provides a detailed overview of the transboundary Zarafshan River, the lifeline for more than six million people. The findings are based on field measurements, existing data from the national hydrometeorological services and an extensive literature analysis and cover the status quo of the meteorological and hydrological characteristics of the Zarafshan as well as the most important water quality parameters (pH, conductivity, nitrate, phosphate, arsenic, chromate, copper, zinc, fluoride, petroleum products, phenols and the aquatic invertebrate fauna). The discharge of the Zarafshan is characterized by a high natural discharge dynamic in the mountainous upper parts of the catchment and by sizeable anthropogenic water extractions in the lower parts of the catchment, where on average 60.6 % of the available water is diverted for irrigation purposes in the Samarkand and Navoi provinces. The water quality is heavily affected by the unsustainable land use and inadequate/missing water purification techniques. The reduced discharge and the return flow of untreated agricultural drainage water lead to a critical pollution of the river in the lower parts of the catchment. Additional sources of pollutants were identified in the Navoi special economic area and the mining industry in the Tajik part of the catchment. The impact of the global climate change and the socio-economic growth on the water availability and the water demand will aggravate the detected problems and might lead to severe local and transboundary upstream–downstream water conflicts within the next decades.

Keywords Zarafshan · IWRM · Water quality · Water availability · Irrigation · Climate change

M. Groll (✉) · Chr. Opp
Fachbereich Geographie, Philipps-Universität, Deutschhausstr. 10, 35037 Marburg, Germany
e-mail: mgroll@gmx.net

R. Kulmatov
Department of Applied Ecology, National University of Uzbekistan, Tashkent, Uzbekistan

M. Ikramova
Central Asian Scientific Research Institute for Irrigation (SANIIRI), Tashkent, Uzbekistan

I. Normatov
Tajik Academy of Sciences, Institute of Water, Hydropower and Ecology, Dushanbe, Tajikistan

Introduction

Water is a valuable resource and has to be managed efficiently, especially in Central Asia, a land-locked arid region where 65.3 million people are relying on the limited water resources of the two large streams Amu-Darya and Syr-Darya. These two rivers and the Aral Sea as their terminal lake are the lifelines of a region as large as the European Union. The history of the oasis cities and their elaborate irrigation systems in the land between those two streams ("Beyond the Oxus River" = Transoxania) dates back more than two millennia (Dukhovny and de Schutter 2011). During the twentieth century, the land and water use intensified beyond sustainable measures and grand irrigation farming and hydropower generation plans were implemented. This overexploitation of the water resources led to a water deficit of 21.3 km^3/year in 2010 (Agaltseva 2008; Dukhovny and de Schutter 2011; Spektorman and Petrova 2008; Uzhydromet 2008) and to the largest man-made ecological disaster known as the Aral Sea syndrome (Groll 2011; Groll et al. 2013; Opp 2007; Opp and Groll 2009; Saiko and Zonn 2000). This deficit is, however, not caused by insufficient water availability as the two large streams Amu-Darya and Syr-Darya originate in the high mountains of the Pamir and the Tien Shan which are among the most glaciated regions of Eurasia. According to the Catalogue of Glaciers of the USSR and the Glacier Inventory of China, compiled using data from the 1950–1970s, there are approximately 16,000 glaciers in the Tien Shan alone, occupying more than 15,000 km^2 and storing 845 km^3 of water (Agaltseva 2004, 2008; Cherkasov 1969; Sysenko 1973; Yafeng et al. 2010). Overall, the available water per capita in 2005 in Central Asia was 2,460 m^3/person and year well above the UN thresholds for famines (1,600 m^3/person) and extreme water deficits (1,000 m^3/person) (Dukhovny and de Schutter 2011). The deficit is thus rather a problem of uneven distribution and inefficient resource management than a problem of availability. Furthermore, the quality of the water resources is, especially in the downstream parts of the catchments, often impaired by large amounts of salts, fertilizers, pesticides (DDT, HCH), defoliant chemicals (Butifos), urban pollutants (Benzopyrene, oil products) and geogenic and anthropogenic heavy metals (antimony, arsenic, copper and mercury) (Aparin et al. 2006; Crosa et al. 2006; Fayzieva et al. 2004; Fedorov et al. 1998; Froebrich et al. 2006, 2007; Giuseppa et al. 2006; Ikramova 2005; Kulmatov 1994; Kulmatov and Hoshimhodjaev 1992; Kulmatov and Hojamberdiev 2010; Kulmatov and Nasrulin 2006; Saito et al. 2010; Scott et al. 2011; Shanafield et al. 2010; Toderich et al. 2002, 2004; UNDP 2007). The breakdown of the Soviet Union in 1991 not only meant independence and sovereignty for the five Central Asian countries, it also caused the disintegration of the region-wide water quality monitoring network and the transboundary resource management efforts. This has led to a considerable loss of knowledge (Chub 2002; Green and Bauer 1998; Klugman 1999) and created the potential for international water conflicts—like the tensions between Uzbekistan and Tajikistan over the Rogun hydropower project illustrate (Eshchanov et al. 2011; Wegerich et al. 2007). This problematic status quo will further worsen as Central Asia is impacted by the global climate warming and an ongoing economic growth. The Central Asian countries are characterized by a strong population growth (+1.7 % per year) and pursue policies of an accelerated economic growth (+8 % per year in 2010) (Djanibekov et al. 2010; http://www.cia.gov 2013; http://www.indexmundi.com 2013; http://www.worldbank.org 2013). In 2020, the irrigated area in Uzbekistan will be between 5 and 11 % larger than today which will lead to an increase of the water demand by 4.7–19 % (depending on the percentages of cotton and wheat) (Abdullaev et al. 2009; Dukhovny and de Schutter 2011; http://www.indexmundi.com 2013). The rising air temperatures on the other hand (+2 °C in the Aral Sea basin since the middle of the 20th century and another +2 °C until 2030) will lead to longer vegetative periods and higher evapotranspiration rates (which equals a further increase of the water consumption by +5 % in 2030 and up to +16 % in 2080) (Aizen et al. 2006; Agaltseva 2004; Chub 2002; Ibatullin et al. 2009). At the same time the global warming will reduce the discharge of the Central Asian rivers by up to 50 % in 2050 as the glaciers feeding those rivers are receding or vanishing completely (Agaltseva 2008; Bates et al. 2008; Chub et al. 2002; Cruz et al. 2007; Golubtsov and Lineitseva 2010; Hagg et al. 2007; Hoelzle and Wagner 2010; Ibatullin et al. 2009; Konovalov and Agaltseva 2005; Kutuzov and Shahgedanova 2009; Lioubimtseva and Henebry 2009; Perelet 2008; Spektorman and Petrova 2008; UNECE 2011; Worldbank 2009). Balancing the water demands for the irrigation farming, hydropower generation, household and industrial purposes in transboundary catchments with an uneven distribution of the limited resources (Abdolvand et al. in this issue; Novikov and Rekacewicz 2005) will be the most important challenge in this region for the twenty-first century (Oud 2002). This process will require a profound knowledge of the present availability, quality and usage of the water resources as a basis for future scenarios and management plans. But the data availability in the Central Asian countries is often limited and fragmented. The once region-wide network of hydroposts has been minimized, the maintenance of the scientific infrastructure has been neglected and the essential interregional data exchange is nonexistent (Chub 2002; Green and Bauer 1998). As a result the large-scale efforts for a Central Asian integrated water resource management have mostly not been successful (Bichsel 2011; Boonstra and Hale 2010; Dukhovny 2002; Marat 2008).

The research presented here is contributing to the preparation for the upcoming challenges by collecting new data and by making existing data widely available. The research area chosen for this was the Zarafshan River catchment. The Zarafshan is the lifeline for the ancient Silk Road oases of Samarkand and Bukhara. But unlike the Amu-Darya and the Syr-Darya, the Zarafshan is not in the focus of the scientific community. This is unfortunate as the size of the catchment, its transboundary character and its complex water use patterns not only make research done here very relevant for

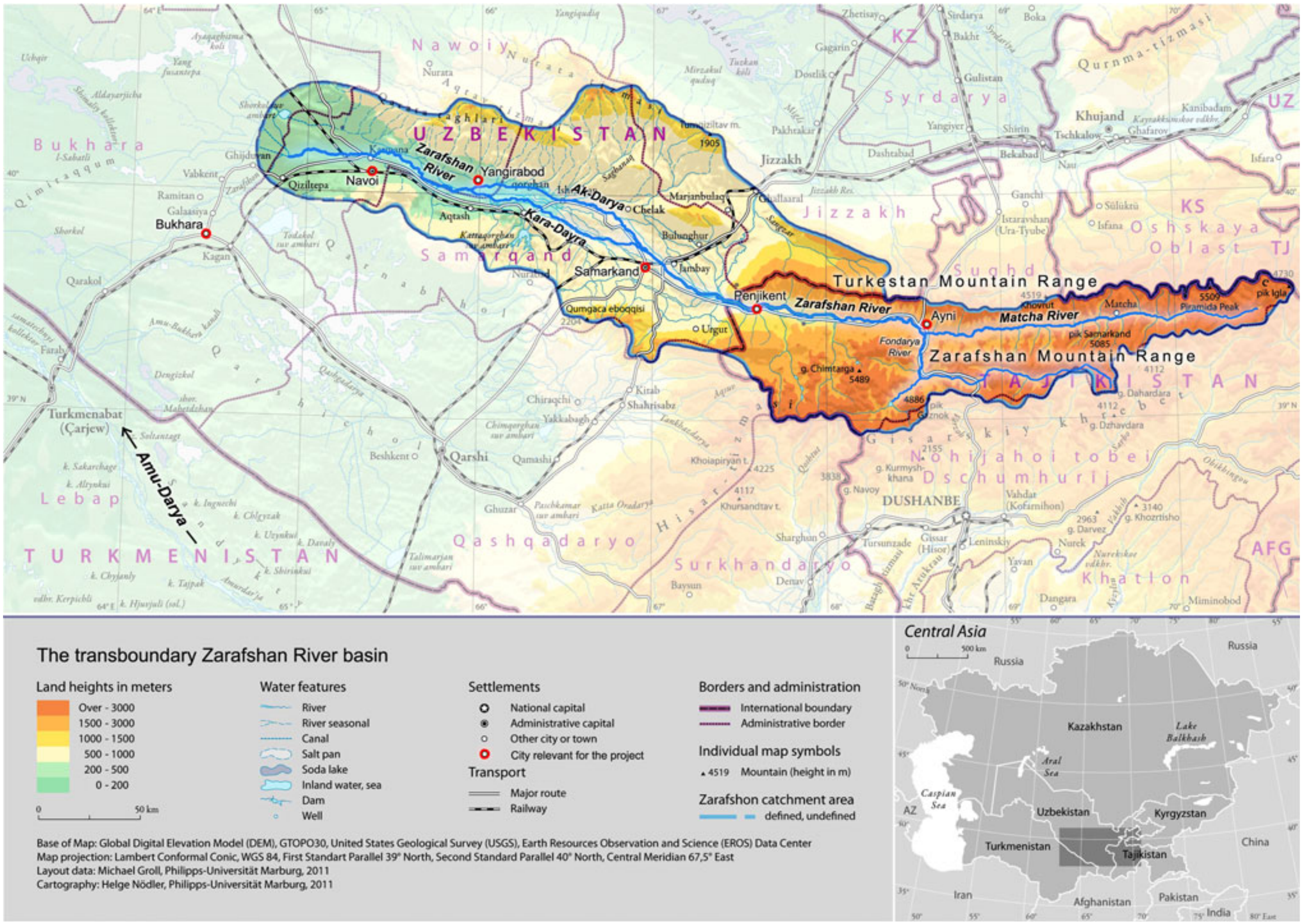


Fig. 1 The Zarafshan catchment in Central Asia

solving the local water related challenges but also make the Zarafshan an ideal model river for the whole region.

Research area

The Zarafshan catchment

The Zarafshan is one of the most important tributaries of the Amu-Darya and provides more than six million people in Tajikistan and Uzbekistan with the water resources for their household, economic and agricultural demands. The headwaters of the river are located at the Zarafshan glacier between the Turkestan and Zarafshan mountain ranges in Northern Tajikistan at 2,810 m a.s.l. (Fig. 1).

From there the river runs with an inclination of 5.1 ‰ for 260 km in western direction through the canyon like valley formed by the two mountain ranges as the Matcha River (Fig. 2a). Near Aini the Matcha is joined by the Fondarya River coming from the South and is now called the Zarafshan River. Downstream of Aini the river valley widens, the inclination is 3.3 ‰ much smaller and the mountain slopes are less steep (Fig. 2b). This part of the catchment is characterized by small-scale agriculture and a higher population density. After another 170 km the river crosses the border to Uzbekistan downstream of Penjikent and enters the lowlands of the Aral Sea basin. The flat topography (the average inclination of the Zarafshan River in the Uzbek part of the catchment is 1.5 ‰, Fig. 2c) and the warm climate have led to the development of an intensive irrigation agriculture which uses most of the available water resources of the Zarafshan. A considerable part of the river water is diverted directly below the border into the Bulungur and Dargom canals and used for the irrigation farming in the Samarkand region. After passing the city of Samarkand 50 km downstream of the border, the Zarafshan is divided into two branches—the Ak-Darya in the North and the Kara-Darya in the South. Both river branches are subject of further water diversions and the Kattakurgan and Akdarya reservoirs used for regulating the water availability for irrigation forms the largest freshwater body in the whole catchment (Rakhmatullaev et al. 2011). Near Yangirabod in the Khatyrchi district of the Navoi province the two river branches are re-united and form

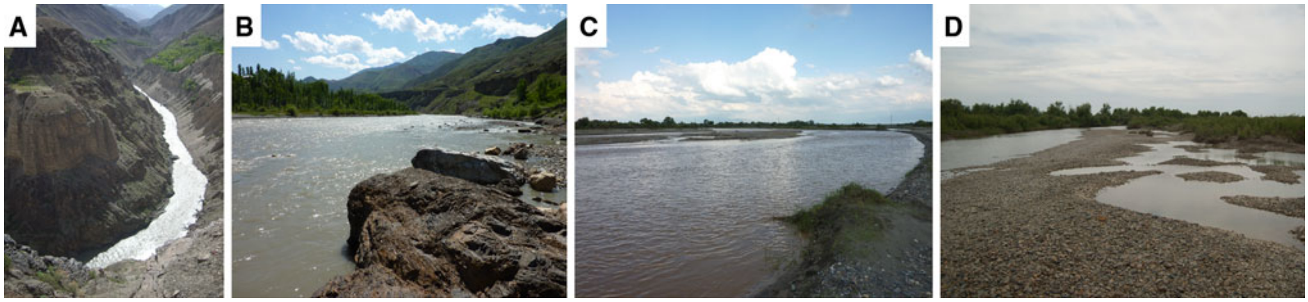


Fig. 2 Character of the Zarafshan River in the upper and lower Tajik catchment (**a** and **b**), in the Aral Sea basin lowland near Samarkand (**c**) and at the "official end" near Bukhara (**d**) (Photos: M. Groll and C. Opp, May 2010)

once more the Zarafshan River. After passing the province capital and industrial center Navoi, the Zarafshan officially "ends" close to the settlements Qiziltepa and Ghijduvan at the border between the Navoi and Bukhara provinces (Fig. 2d). The remaining water is distributed into the irrigation network and the collected drainage water is dumped into a depression near Bukhara. Originally, the Zarafshan provided water for the whole Bukhara oasis and reached the Amu-Darya near Turkmenabat (the former Chardzhev) until 1957. But due to the extensive water withdrawals for irrigation purposes the river does not reach Bukhara since 1960s and today the Bukhara oasis is sustained by water from the Amu-Darya which is transported to the Todakol reservoir through the Amu-Bukhara canal.

The total length of the Zarafshan River is 870 km with an average inclination of 2.9 ‰ and its present catchment size is 40,600 km^2 (compared to 131,000 km^2 before 1957; Olsson et al. 2010). Roughly 29 % of that catchment is located in Tajikistan (11,700 km^2, 8.4 % of the Tajik territory) and the remaining 71 % is located in Uzbekistan (28,900 km^2, 6.5 % of the Uzbek territory). The river is mainly fed by glacier melt water, resulting in a maximum discharge during the late spring and early summer months and a minimum discharge during the winter (Olsson et al. 2010). The long-term average discharge at the Tajik–Uzbek border is 158 m^3/s and the annual discharge is approximately 5 km^3.

The research setup

A variety of different data sets and own measurements were used for this research. For a sound meteorological and climatological analysis, monthly average air temperature and precipitation data from the Global Historical Climate Network database (http://www.ncdc.noaa.gov 2013), the Northern Eurasia Earth Science Partnership Initiative database (http://www.neespi.sr.unh.edu 2010) and the Russian Weather Archive (http://www.meteo.infospace.ru 2013) and from eight meteorological stations along the Zarafshan River were used. Four of them (M1–M4: Dehavz, Madrushkent, Sangiston and Penjikent) are located in Tajikistan and the other four (M5–M8: Samarkand, Kattakurgan, Navoi and Bukhara) are located in Uzbekistan (Fig. 3). The meteorological station in Samarkand provided the longest timeline of ongoing measurements since 1891 while most other stations started recording in the 1920s and 30s.

The meteorological stations were supplemented by 11 hydrological stations along the Matcha, Fondarya and Zarafshan Rivers (Fig. 3). The first five stations in the Tajik part of the catchment (D1–D5: Kudgiph, Oburdan, Sangiston, Aini and Dupuli) provided monthly discharge data since 1960s, while for the Uzbek stations in the lower Zarafshan catchment (D8–D10: Khatyrchi, Ziadjin and Navoi) only annual discharge data since 1990 was available. The longest timeline was provided by the Ravathodja station (D6) at the Tajik–Uzbek border with hydrological measurements starting in 1913. For the Fondarya River (D11) on the other hand, only the long-term average discharge was available. The hydrological data point immediately downstream of Ravathodja (D7) provided valuable information about the amount of water diverted from the Zarafshan River for irrigation purposes in the Samarkand and Navoi provinces. The hydrological data for the Uzbek part of the catchment was collected by the UZHYDROMET and provided by the Uzbek National University and the SANIIRI. Additional data was used from the NEESPI database (http://www.neespi.sr.unh.edu 2010), the UNESCO Intergovernmental Scientific Cooperative Programme in Hydrology and Water resources (IHP) (Shiklomanov 1999) and from the Global River Discharge Database (http://www.sage.wisc.edu/riverdata 2010).

The water quality of the Zarafshan, its tributaries and the irrigation network was analyzed within the Waza Care project (Water quality and quantity analyses in the transboundary Zarafshon River basin—Capacity building and Research for sustainability, Groll et al. 2012) in May 2010 for 49 sampling points (P1–P49, Fig. 3). The central aim of this initiative project (2010–2011) funded by the German Federal Ministry of Education and Research (BMBF) through the International Bureau was to conduct

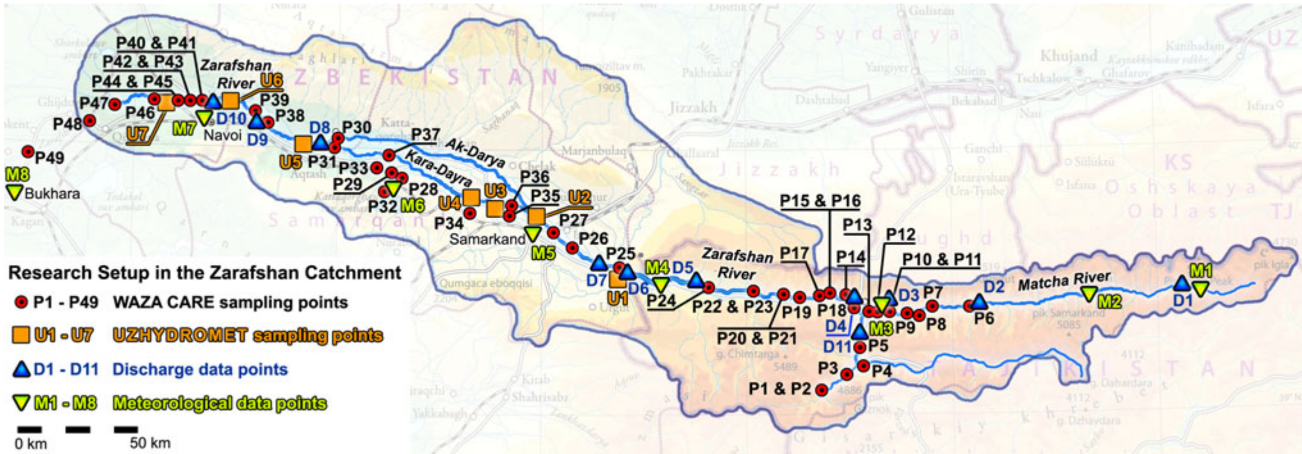


Fig. 3 Location of the sampling points within the Zarafshan catchment

a field measurement survey of the water quality of the whole Zarafshan River as a preparation for larger research activities and an integrated water resource management concept. The field campaign was the first transboundary water quality research done in this region since the collapse of the Soviet Union and provided comparable data for the Tajik and the Uzbek parts of the catchment. The Zarafshan, Matcha and Fondarya Rivers were covered by 28 samples (12 in Tajikistan and 16 in Uzbekistan), taken between the 8th and 15th of May in 2010. Furthermore, 13 smaller tributaries, 3 irrigation canals, the Kattakurgan reservoir and 4 drainage water collectors were analyzed. In addition to physical–chemical analysis of the water quality, the macrozoobenthos as an indicator for the long-term characteristics of the Zarafshan River system was sampled and determined for 29 of the 49 sampling points.

As the field measurements were only done once, they were complemented by laboratory data from seven hydrological stations in Uzbekistan (U1–U7, Fig. 3), based on monthly samples from 2002 to 2010. This data was provided by the UZHYDROMET.

Methods

Field methods used during the measurement campaign in 2010

During the transboundary measurement campaign along the Zarafshan River in May 2010, a water quality analysis was done using a portable WTW multi-parameter instrument and analytical test kits from Aquamerck. This allowed the rapid determination of a large number of samples within a short time frame and thus ensured the comparability of the results from different regions within the catchment. The following parameters were analyzed during the field campaign:

- Water temperature (in °C);
- pH value;
- electric conductivity (in µS/cm);
- mineralization (in mg/l) as the sum parameter for the overall amount of dissolved solids (WHO 1996) primarily used in Central Asia (in comparison to the conductivity used in Europe);
- oxygen concentration (O_2 in mg/l);
- nitrate concentration (NO_3^- in mg/l);
- nitrite concentration (NO_2^- in mg/l);
- ammonium concentration (NH_4^+ in mg/l);
- phosphate concentration (Orthophosphate PO_4^{3-} in mg/l).

The macrozoobenthos samples were taken using the multihabitat-sampling approach developed within the AQEM project (e.g., Sandin et al. 2000, 2001; Hering et al. 2004; Meier et al. 2006). Due to logistic limitations, the initial assessment of the habitat composition of each sampling site with the TRiSHa method (Groll and Opp 2007) was limited to the river banks where the majority of different microhabitat structures with relevance for the species of the macrozoobenthos can be found (Groll 2011). The taxonomic determination of the individuals contained in each sample was done in situ as samples of aquatic species could not be exported to Germany and the application of these methods was part of the capacity building aspects of the WAZA CARE project.

Laboratory methods used by UZHYDROMET

The Uzbek Hydrometeorological Service is analyzing the water quality of the Zarafshan River on a monthly basis using well-established laboratory analytical methods (flame atomic absorption spectrometry and ion chromatography).

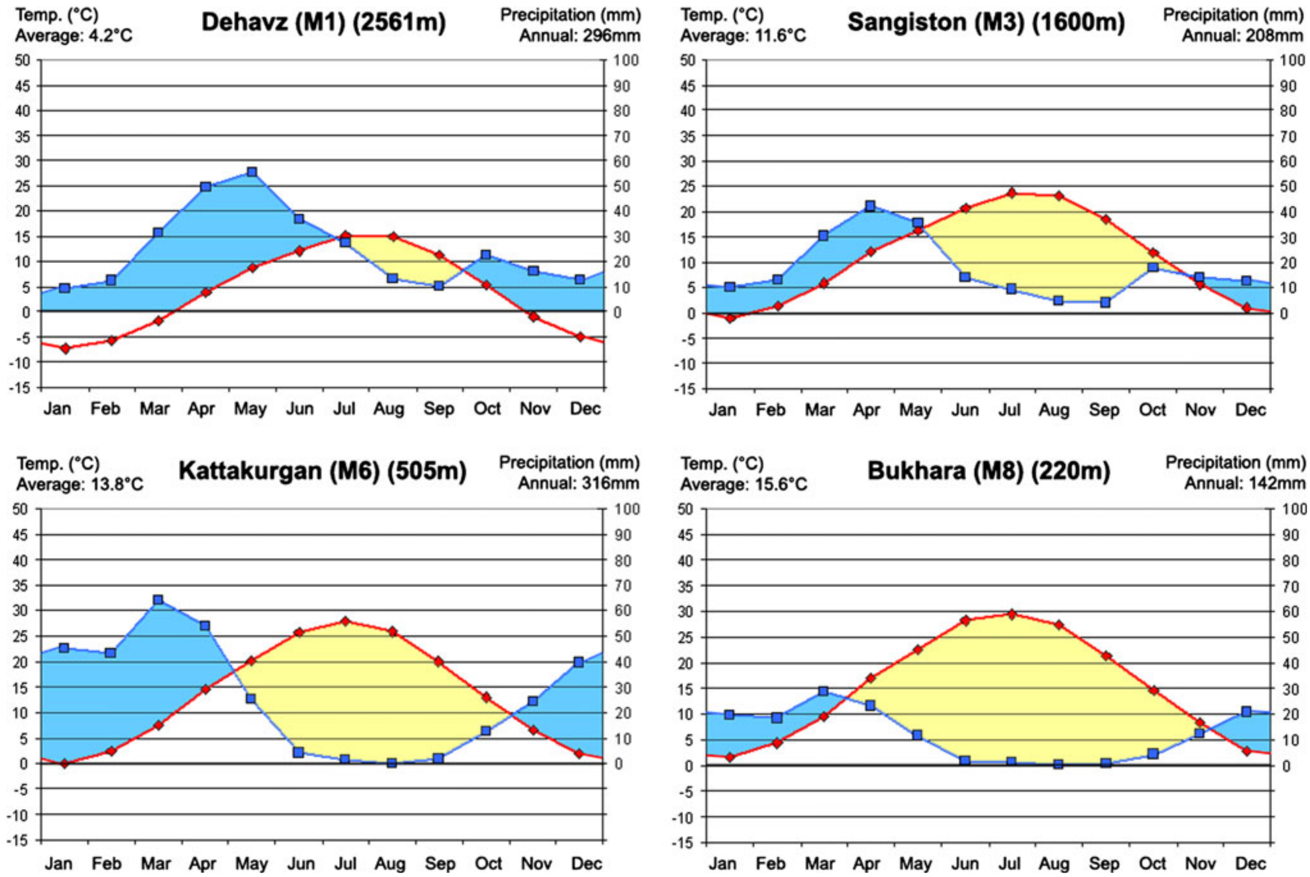


Fig. 4 Meteorological characterization of the Zarafshan catchment

For this study, data for the following parameters was supplied:

- Mineralization (in mg/l);
- nitrate concentration (NO_3^- in mg/l);
- phosphate concentration (orthophosphate PO_4^{3-} in mg/l);
- the heavy metals arsenic, chromate-VI, copper and zinc (all in mg/l);
- the urban pollutants fluoride, petroleum products and phenols (all in mg/l).

Results and discussion

Meteorological characterization of the Zarafshan catchment

Based on the topography, the meteorological and climatic properties of the Zarafshan catchment can be divided into two distinct parts.

The mountainous eastern part of the catchment (station Dehavz—M1) is humid with an average air temperature of below 5 °C and an annual precipitation of below 300 mm, while the western lowland parts of the catchment (station Bukhara—M8) are arid with an average air temperate of above 15 °C and an annual precipitation of below 150 mm. Between those two stations at the edge of the catchment both the temperature and the precipitation show a gradual transition (Fig. 4) with the precipitation peaking at the Uzbek–Tajik border where the Turkestan and Zarafshan mountain ranges start.

Hydrological characterization of the Zarafshan

The Zarafshan River and its upstream tributaries are mostly fed by glacier and snow melt water with a maximum discharge during the summer months (Fig. 5).

The annual average discharge reaches its maximum of 157.9 m^3/s at the hydropost Ravathodja (station D5) near the Tajik–Uzbek border and is characterized by a strong discharge dynamic. The highest average annual discharge recorded between 1913 and 2012 was 213.2 m^3/s while the lowest discharge was 108.0 m^3/s (Fig. 6) and the overall standard deviation during this period was 23.5. The average change of the discharge from 1 year to the next was

Fig. 5 Long-term average discharge of the Zarafshan River in the Tajik part of the catchment (1913–2012)

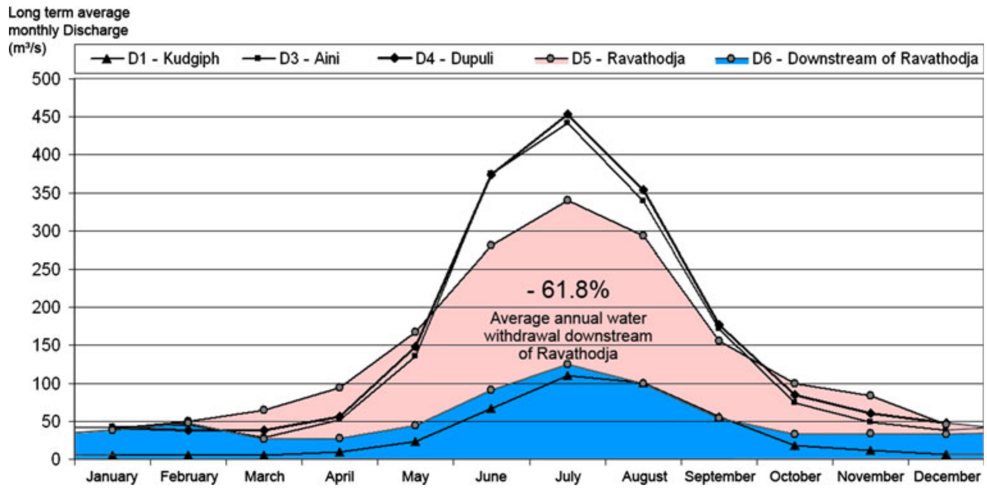
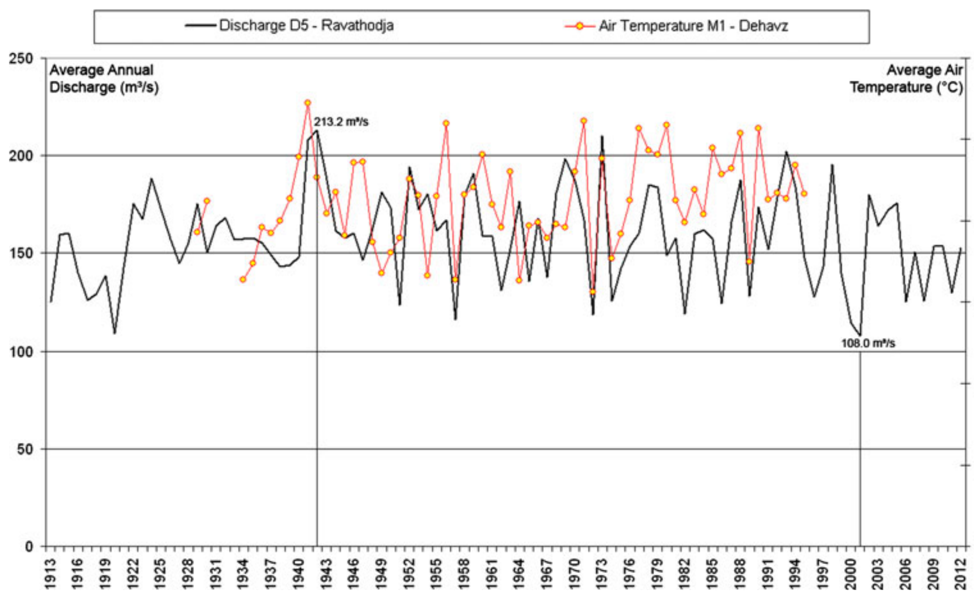


Fig. 6 Discharge at the Ravathodja station and air temperature at the Dehavz station between 1913 and 2012



13.5 % and the biggest change within the last 100 years was 43.5 % (from 1972 to 1973). These discharge fluctuation correspond best with the average annual air temperature in the upper catchment (Station M1—Dehavz) as the Zarafshan River is mainly fed by glacier melt water.

The analysis of the interannual changes of the air temperature at the Dehavz station (M1) and the discharge at the Ravathodja station (D5) with datasets from 1929 to 1995 (Fig. 7) shows that in one-third of all years (33.3 %) the average air temperature in the upper catchment was (up to 53 %) higher than in the year before which resulted in a (up to 77 %) higher discharge at the downstream hydropost. In another quarter of all years (25.4 %) the average air temperature in Dehavz was (up to 40 %) lower than in the year before which resulted in a (up to 40 %) reduced discharge at the Ravathodja Hydropost. But there are also datasets where an increase of the air temperature led to a decrease of the discharge (23.8 % of all years) and where a decrease of the air temperature was related to an increase of the discharge (17.5 % of all years). This means that the discharge at the Ravathodja station is not only influenced by the temperature driven glacier melt water from the Zarafshan glacier. This is obvious as the Matcha River, which originates at the Zarafshan glacier, is providing only 57 % of the discharge of the joined Zarafshan River at Aini (170 km upstream of the Ravathodja Hydropost) while the Fondarya as the most important tributary is providing 43 % of the discharge.

However, the average air temperature in the upper catchment which is the driving force of the discharge, is especially articulate in years with a very strong interannual change of the air temperature. If only all data sets with an

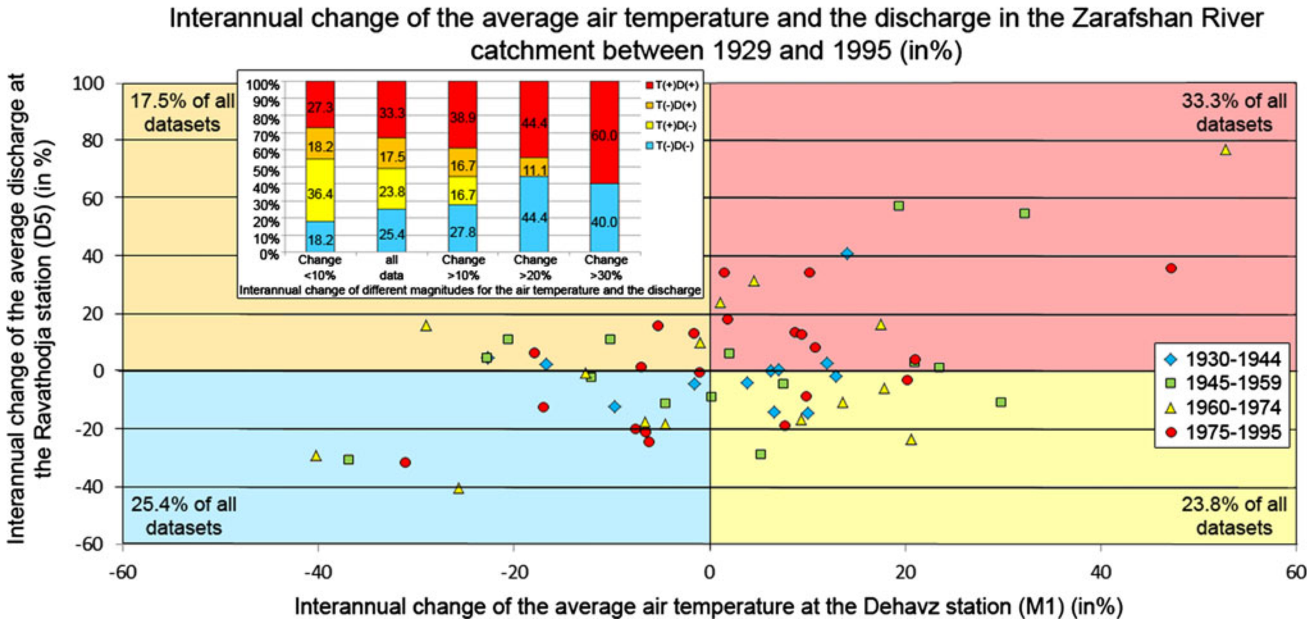


Fig. 7 Interannual connections between the air temperature and the discharge in the Zarafshan River catchment

interannual change of more than 10 % are considered, the percentage of years with a correlation between the air temperature and the discharge increases from 58.7 to 66.7 % (R^2 for that correlation is 0.48) and for years with an interannual change of more than 20 % the percentage increases to 88.9 % ($R^2 = 0.73$).

The explanation for this is that those exceptional large interannual changes of the air temperature are occurring on a regional scale (and thus influencing all the tributaries of the Zarafshan River) while smaller interannual changes are more likely to be limited to a local scale, which means that their impact on the overall discharge of the river is less distinct. This can also be seen in the correlation between the air temperature data of the Dehavz station (M1) and the two downstream stations Pendjikent (M4) and Samarkand (M5). The correlation between all three stations is much higher for years with an exceptional interannual change of the air temperature ($R^2 = 0.83$ for Pendjikent and 0.82 for Samarkand) than for years with a small interannual change ($R^2 = 0.45$ and 0.5) (Table 1).

Other meteorological parameters that could explain some of the deviation between the interannual changes of the air temperature and the discharge are the temporal distribution and variability of the precipitation and a potential time shift between an increase of the air temperature and the corresponding increase of the discharge. As the annual precipitation for all the stations along the Zarafshan River is below 350 mm (and in the upper parts of the catchment even below 300 mm), the direct influence of the precipitation on the discharge is much smaller than the influence of the air temperature driven glacier melt,

Table 1 Coefficient for determination of the linear regression of the interannual changes of the average air temperature for three meteorological stations along the Zarafshan River

Coefficient for determination (R^2) (1934–1995)	Pendjikent (M4)	Samarkand (M5)
Dehavz (M1) (<10 % interannual change)	0.45	0.50
Dehavz (M1) (>10 % interannual change)	0.70	0.68
Dehavz (M1) (>20 % interannual change)	0.83	0.82
Dehavz (M1) (all data)	0.62	0.62

which shows in a weak correlation between the annual precipitation at the Dehavz, Pendjikent and Samarkand meteorological stations and the discharge at the Ravathodja Hydropost ($R^2 = 0.096$, 0.073 and 0.091). Secondly the available data did not show any evidence of a time shift between rising temperatures and increasing discharge, at least not the interannual level supported by the long-term data ($R^2 = 0.098$). It is, however, to be expected that a seasonal time shift occurs and that some of that shifting carries over into the next year, but the available monthly data for the precipitation and the discharge are at the moment not sufficient to further investigate this.

Downstream of the Tajik–Uzbek border 61.8 % of the water is annually withdrawn for irrigation purposes in the Samarkand and Navoi provinces and for leaching areas prone to salinization. It is distributed through a vast network of canals and reservoirs. The main irrigation network in the Uzbek part of the catchment has a length of

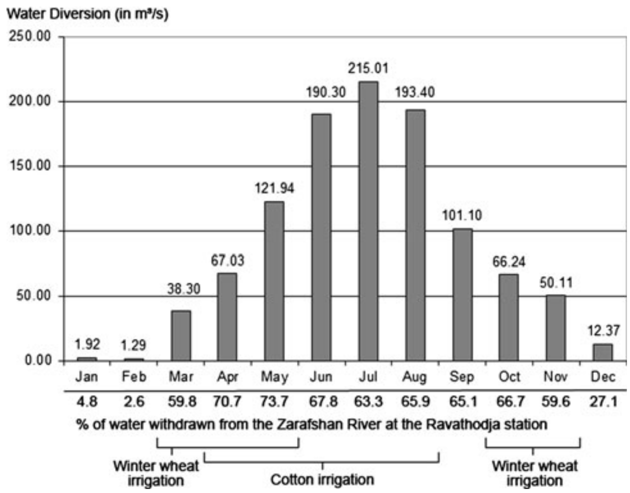


Fig. 8 Monthly water withdrawal at the Ravathodja station (D5)

3,140 km (41 % of them lined with concrete and 59 % of them reinforced). This is supplemented by a network of smaller interfarm canals with a total length of 17,400 km of which only 11 % are lined. The total irrigated area in the Zarafshan catchment is 540,000 ha and the losses due to evaporation and percolation are extremely high. Dukhovny and de Schutter (2011) state that the irrigation efficiency in the Zarafshan catchment was below 50 % in 1936 and most likely the canal system is even less efficient today.

The main crops grown in the Uzbek part of the Zarafshan River catchment are winter wheat and cotton which leads to consistently high water withdrawal rates from March (59.8 %) until November (59.6 %). The highest relative water diversion (up to 73.7 %) takes place in spring when both winter wheat and cotton need to be irrigated, but the highest total water withdrawal takes place during the summer months (up to 215 m^3/s in July) when the evapotranspiration losses are highest and the cotton is in full growth (Fig. 8). This massive alteration of the natural discharge regime is characterizing the whole Uzbek part of the catchment and is leading to severe ecological problems and socio-economic upstream–downstream water user conflicts.

Figure 9 shows the change of several hydrological and meteorological parameters from the glaciated headwaters to the official end of the river near Bukhara. As the elevation of the riverbed is steadily decreasing from the Zarafshan glacier in the east (2,810 m a.s.l) to the Bukhara oasis in the west (220 m a.s.l.) the average annual air temperature is increasing from 4.2 to 15.6 °C. The precipitation shows a different pattern as it is rather determined by the orography in the catchment. The highest annual average precipitation rates occur with up to 341 mm at the foothills of the Turkestan and Zarafshan mountain ranges near the Uzbek–Tajik border while the lowlands to west (which are close to the Kyzyl-Kum desert) and the narrow parts of the Zarafshan valley between the two mountain ranges are characterized by much lower precipitation rates. The discharge of the Matcha River is steadily increasing from the headwaters down to the city of Aini (D4) where it is joined by the Fondarya River and forms the Zarafshan River. The impact of the aforementioned water withdrawal for irrigation purposes downstream of the Uzbek–Tajik border can clearly be seen as well as the actual discharge in the Uzbek part of the river remains well below the potential natural discharge as it would be determined by the precipitation and evaporation rates in this arid region.

Downstream of Samarkand (M5) the Zarafshan River is split into two branches—the Ak-Darya and the Kara-Darya—which reunite after 160 km near Yangirabod and Khatyrchi (D8). The water diverted for the irrigation farming is in parts drained from the fields and discharged back into the river untreated. All in all 94,800 ha of irrigated land is drained and the total length of the drainage water collector system in the Zarafshan catchment is 3,292 km. This return flow and the balancing impact of the Kattakurgan reservoir on the Kara-Darya river branch lead to a mitigated discharge hydrograph of the Khatyrchi hydropost (D8) (Fig. 10). The western parts of the catchment are also heavily impacted by soil salinization. This leads to an extensive leaching of the irrigated fields during the winter months, which can be seen in the discharge hydrograph of the Navoi hydropost (D10).

Water quality

The anthropogenic impairment of the discharge regime and the intensive water usage in the Uzbek part of the catchment affect not only the quantity of the water resources but also their quality. The mineralization is a very good parameter to visualize the overall mineral load of the river and the level of chemical degradation. Figure 11 shows an exponential increase ($R^2 = 0.926$) of the mineralization from the Tajik–Uzbek border (P25—Ravathodja: 243.1 mg/l) to the official end of the Zarafshan near Ghijduvan (P48: 1,799.0 mg/l) measured during the field campaign in May 2010. The discharge during that month was slightly higher than the average for that month (173.6 m^3/s in 2010 versus 166.9 m^3/s at the Ravathodja station), which coincides with the heavy rainfalls and flood events in the upper parts of the catchment. This of course influences the mineralization of the river as well as the season in which the samples were taken. But as the water quality is influenced by the intense agriculture throughout the year (irrigation and application of agrochemicals for winter wheat and cotton from March to November and leaching during the winter months) there seem to be no

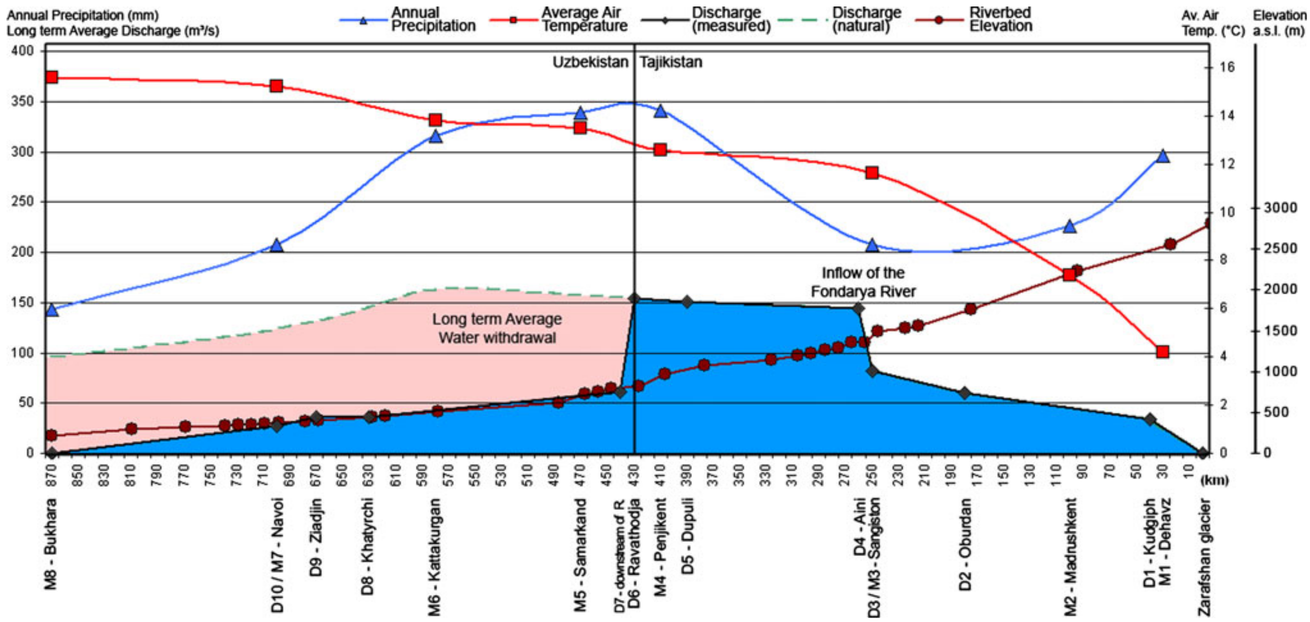


Fig. 9 Gradual change of meteorological and hydrological parameters in the Zarafshan

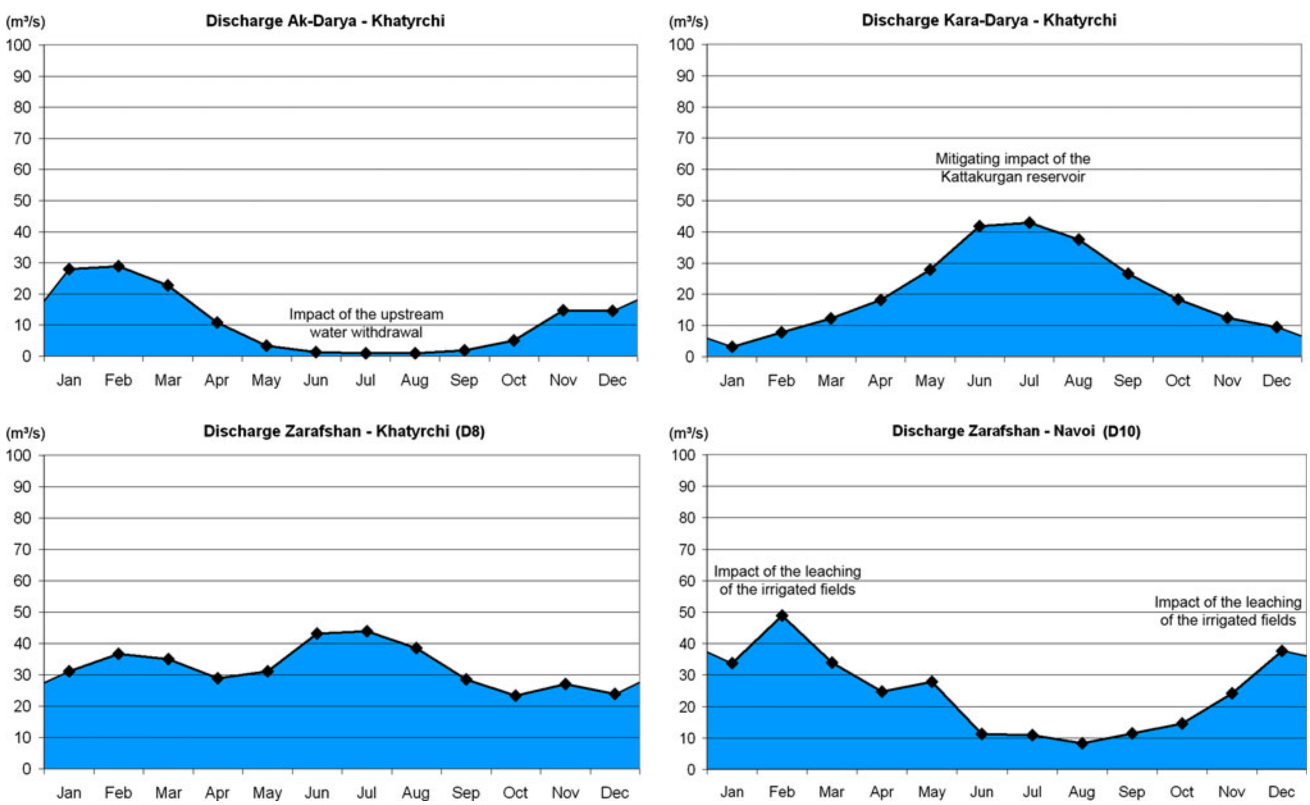


Fig. 10 Seasonal discharge in the lower Zarafshan catchment

phases where the pollution is significantly lower than during the time of the field campaign presented here. This also shows in the long-term data from the UZHYDROMET which display a similar increase of the mineralization in the Uzbek part of the catchment. The long-term mineralization in the lower Zarafshan catchment is high enough to exceed the Uzbek threshold of 1,000 mg/l. The mineralization in the Tajik part of the catchment on the other hand

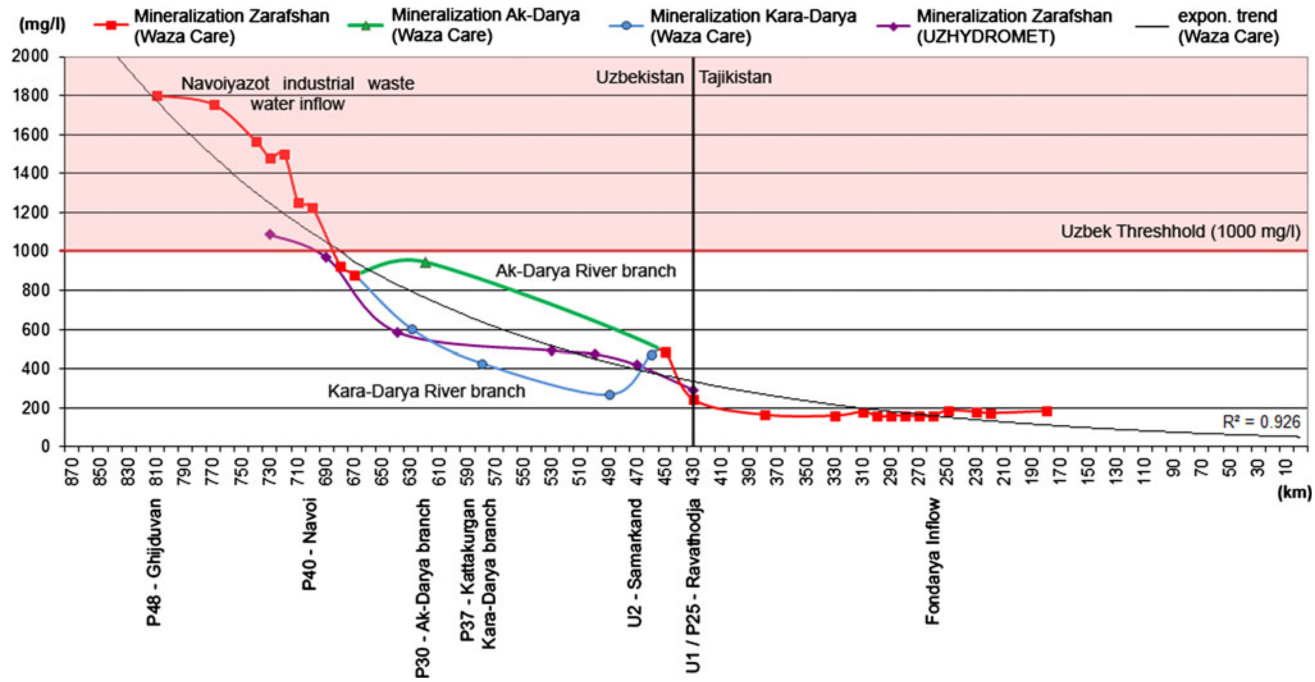


Fig. 11 Mineralization of the Zarafshan River

was very homogeneous at all sampling points with concentrations between 161 and 188 mg/l.

This high mineral load of the river in the lower part of the catchment has considerable effects on the usability of this water. Especially the rural population living along the Zarafshan and the irrigation canals is using the river directly as their source of drinking water and the data suggests that this practice could lead to increased health risks downstream of Navoi. Furthermore the mineral content in the water contribute to the salinization of the irrigated fields and the pollutants might accumulate in the crops grown.

The UZHYDROMET data can also be used to estimate the total mineral load of the Zarafshan. At the Ravathodja station (U1), the total load between 2002 and 2010 was 1.42×10^9 kg/year. 200 km downstream, at the confluence of the Ak-Darya and the Kara-Darya River branches (U5—Khatyrchi), the total load during that time period was only 0.67×10^9 kg/year. This reduction in the overall mineral load of the Zarafshan can most likely be explained by the Kattakurgan reservoir and its function as a sediment sink. Downstream of Navoi (U7) and 100 km downstream of Khatyrchi the total mineral load increased again to 0.9367×10^9 kg/year and there are two main sources for this mineral input. The city of Navoi is not only an urban agglomeration with approximately 125,000 inhabitants but also the site of the Navoi special economic area. One of the biggest companies located here is Navoiyazot, the largest manufacturer of mineral fertilizers in Uzbekistan. The second source of mineral input is the aforementioned return flow from the irrigated fields. This drainage water is loaded with fertilizers and pesticides during the vegetative period and dissolved salts from the leaching during the winter months and is characterized by a very high mineral load. The average mineralization in the drainage water collectors sampled during the field campaign in 2010 was 2,235 mg/l and the highest mineralization detected was 2,594.8 mg/l (at P43 downstream of Navoi), which is more than 2.5 times the national threshold.

Among the agrochemicals, nitrate and phosphate are the substances with the highest concentration in the river water. During the 2010 field campaign, the nitrate fluctuated within the Tajik part of the catchment, but the concentration stayed well below the threshold for potable water of 50 mg/l. In the Uzbek part of the catchment, however, the nitrate concentrations quickly reached concentrations of up to 75 mg/l (Fig. 12). The highest nitrate concentrations in the Zarafshan were detected in the Ak-Darya river branch and downstream of the Navoiyazot waste water inflow. The concentration in the Kara-Darya river branch was much lower and did not exceed 25 mg/l. The long-term data from the UZHYDROMET also shows an increase of the nitrate pollution in the lower catchment, but no threshold exceedance.

Despite the long-term data not exceeding the threshold the annual total load of Nitrate downstream of Navoi is 8.45×10^6 kg very high and equals an annual loss of nitrate of 15.65 kg per irrigated hectare in the Uzbek part of the Zarafshan catchment.

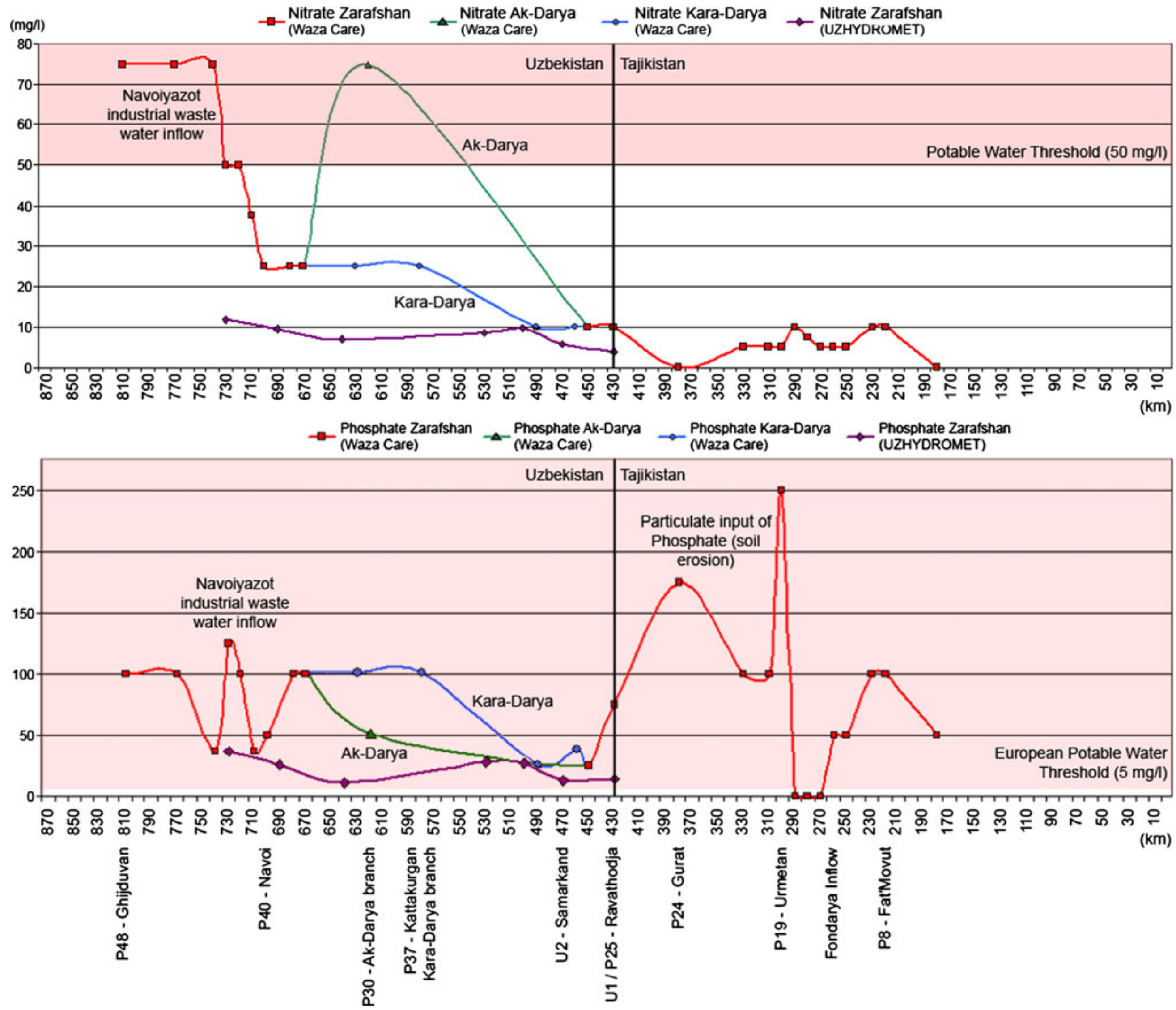


Fig. 12 Nitrate and phosphate concentrations along the Zarafshan River

The phosphate concentration showed a different pattern during the 2010 field campaign. While the Uzbek part of the catchment was characterized by an increase of the phosphate pollution from the border to the official end near Ghijduvan, the highest concentrations were measured in the upper regions of the Zarafshan River. This punctual high phosphate load was most likely caused by the heavy rainfall in the Tajik part of the catchment and the thereto related intensified soil erosion.

Soil erosion is an important problem in the mountainous regions of Central Asia, especially on slopes of southern exposition and overgrazing on marginal lands has been identified as the main cause for this process (Akhmadov 2003; Breckle 2003; Schickhoff and Zemmrich 2003; Wolfgramm et al. 2007). In Tajikistan soil erosion often occurs in the form of hazardous landslides of which 50,000 were reported by the Taj Glavgeology during the 1990s (Barbone et al. 2010; UNDAC 2006). In the Tajik part of the Zarafshan catchment landslides, floods and mudflows are a major concern and cause significant losses of livestock, damage the infrastructure and can lead to casualties. The most active season is the late spring from April to June (Saidov 2007) and the most active areas within the catchment are the slopes of the Gissar and Turkestan ranges (UNDAC 2006) between Aini and Pendjikent. This is exactly when and where the highest phosphate concentrations were registered during the field campaign. Members of the German Agro Action in Pendjikent reported that the rainfalls prior to the WAZA CARE field campaign lead to a mudflow destroying several houses and killing cattle in the midstream region between Aini and Penjikent. Annually between 500 and 1,000 t/km^2 of arable topsoils and

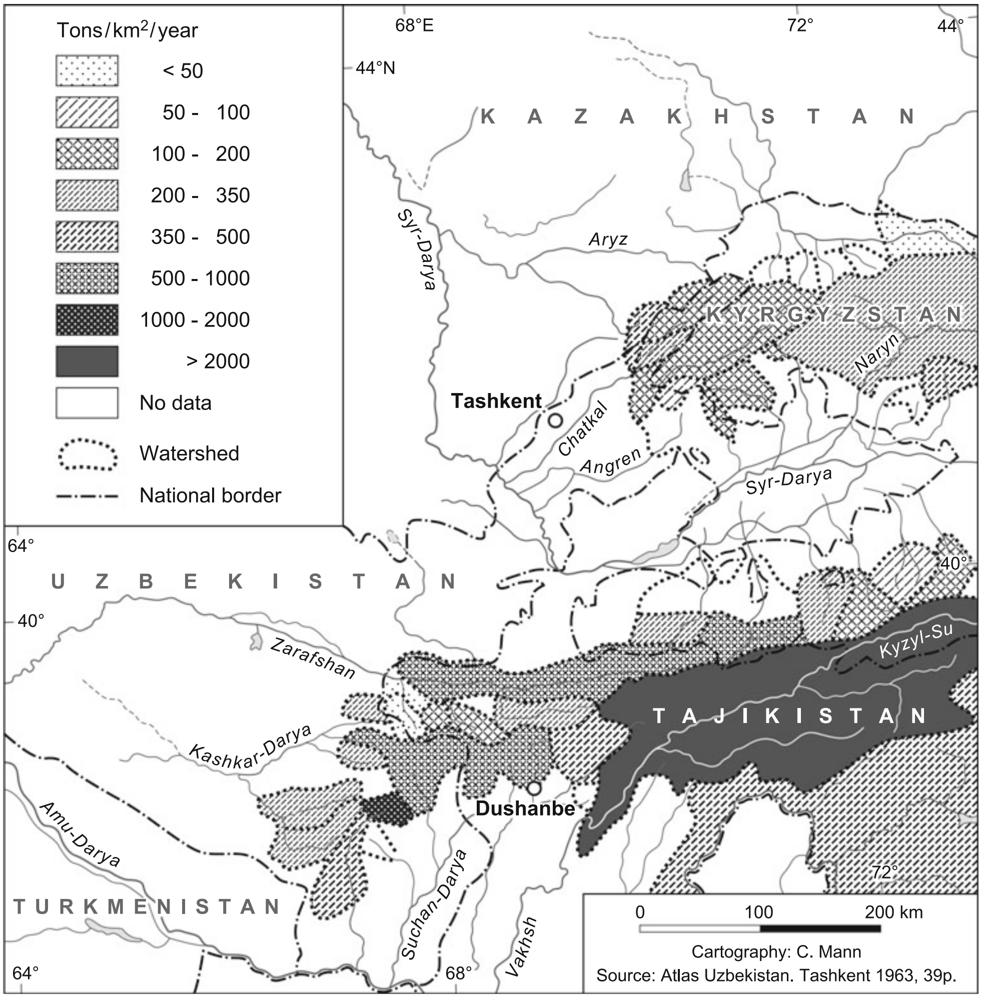


Fig. 13 Soil erosion rates in the mountainous regions of Central Asia (data: RAS 1963, p. 39)

nutrients are lost in the upstream parts of the Zarafshan catchment (Fig. 13).

The pollution in the Uzbek part of the catchment is most likely caused by urban waste water inflow from the Samarkand metropolitan area and the Navoi municipal and industrial waste water. The long-term data from the UZHYDROMET indicates again lower concentrations, but the main sources Samarkand and Navoi can be easily identified as well.

Even more important than the urban and industrial waste water inflow is the drainage water from the irrigated fields. The samples from this category of water bodies showed the highest average nitrate and phosphate pollution with maximum concentrations of 175 mg/l for nitrate and 250 mg/l for phosphate (Fig. 14). The analysis of the different water body categories also revealed that the minimum concentrations for both parameters were much higher in the artificial water bodies than in the natural ones. This is an indicator for the intensive use of the irrigation canals

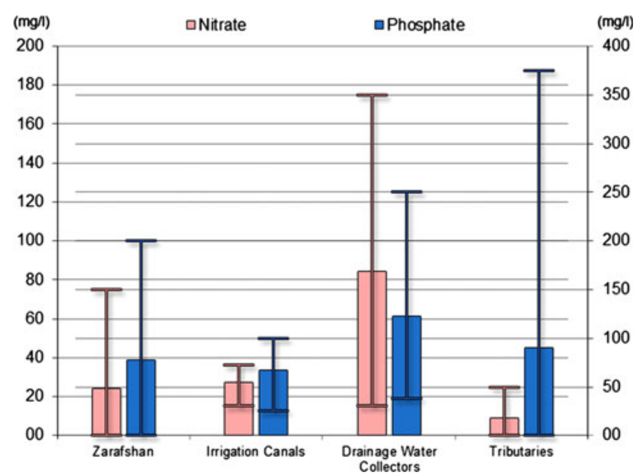


Fig. 14 Average, minimum and maximum nitrate and phosphate concentrations in different water body categories

and the drainage water collectors by the rural population, small-scale discharge of waste water and non-point pollution from the irrigated fields.

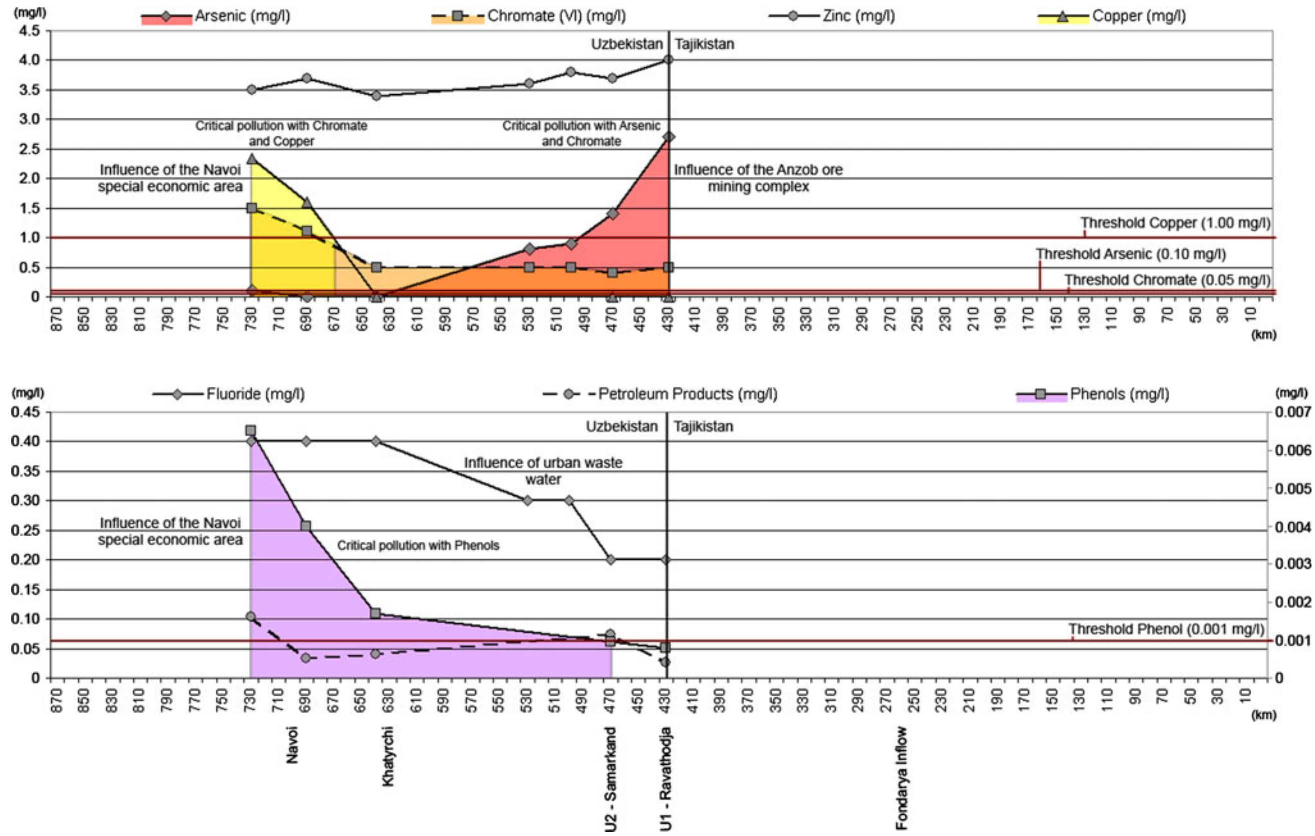


Fig. 15 Concentrations of urban and industrial pollutants along the Zarafshan River

These results are insofar alarming as the rural population living in the irrigated areas uses the untreated water from the irrigation canals as their primary drinking water source and the drainage water is used for further irrigation by downstream water users. This is necessary as the water demand in the Zarafshan catchment is higher than the water availability and the untreated drainage water is the only source of additional water to close the annual gap of 1.6 km^3 of water needed for maintaining the status quo.

While the agrochemicals from the irrigation farming in the Uzbek part of the Zarafshan catchment are the most important pollutants, two other sources for the impairment of the water quality are relevant. The first one is seen in the Anzob ore mining and processing complex located in the upper Zarafshan catchment at the Yagnob River (a tributary to the Fondarya River), resulting in a heavy metal pollution of the Zarafshan. The second source is the urban and industrial waste water from the cities Samarkand and Navoi, leading to increased concentrations of petroleum products, phenols and fluorine. Figure 15 shows the contamination of the Zarafshan River with several of these pollutants based on long-term data from the UZHYDROMET. Unfortunately, the spatial and temporal resolutions of the data in the Uzbek part of the catchment are not high enough to come to definite conclusions about the impact of the urban and industrial complexes and there is no data available for the Tajik part of the catchment. A broader and deeper research approach would be needed for a thorough interpretation of the status quo in this regard and such a field study should be considered for future research activities. But the results as they are never the less reveal some interesting trends and emphasize the difference in scale between the pollution of the Zarafshan River with agrochemicals and with industrial and municipal wastewater. Furthermore, these pollutants might have a major impact on the aquatic biocoenoses as they can be already toxic at very small concentrations. The basic analysis presented here will, therefore, be helpful for the interpretation of the faunistic research done within this study as well.

Arsenic was the only pollutant analyzed here which showed a very high concentration at the Tajik–Uzbek border with rapidly decreasing values in the Uzbek part of the catchment. Toxic concentrations of arsenic are causing several severe illnesses such as dermal lesions, anemia or liver damage (Patrick 2003) and the concentration of up to 2.7 mg/l exceed the WHO threshold for arsenic (0.1 mg/l) by far. Only 200 km downstream of the Tajik–Uzbek border does the arsenic pollution fall below this threshold.

This suggests that the Arsenic concentration in the Tajik part of the catchment up to Aini and especially in the Fondarya River catchment is even higher and a continuous monitoring program is strongly recommended.

Zinc was a second element which seems to originate mainly in the Tajik part of the catchment, but the decline of the zinc concentration in the Uzbek part took place at a much slower rate than for arsenic. There are no thresholds for zinc as the toxicity is much lower than for arsenic, though it can cause lethal gill inflammation in fish species (Skidmore and Tovell 1972). But there is a recommendation for a critical limit of 5 mg/l found in the older version of the German drinking water ordinance and all the measured concentrations stayed well below this threshold. In contrast to this, chromate (VI), copper, fluoride, phenols and petroleum products showed an opposing trend with increasing concentrations in the Uzbek part of the catchment. Especially the pollution with copper and phenols was rapidly increasing near Navoi, pointing at the special economic area as the main source. Only fluoride and the petroleum products did not exceed the national or international thresholds while the thresholds for chromate and phenols were exceeded at all sampling points and the copper concentration reached critical levels in the Navoi province.

Chromate (VI) is easily accumulated in human and animal tissue and can cause different types of cancer (Costa 1997), copper causes cellular damage and disrupts the osmoregulation in fish species (Erikson et al. 1996; Gaetke and Chow 2003) and a prolonged exposure to even low concentrations of fluoride can lead to chronic toxications and accumulation in the aquatic food chains (Groth III 1975; Whitford 1990). Phenol and petroleum compounds finally which are by-products of the industrial oil-refining and plastic production processes and common in urban waste waters are having negative effects on the reproductive success of a wide range of aquatic species (Au et al. 2003; Ghosh 1983; Kordylewska 1980; Law and Yeo 1997). These studies demonstrate the implications those pollutants can have on the aquatic ecosystems and on the human health in the lower Zarafshan catchment and further research especially about the drinking water quality in the Navoi province is strongly recommended.

In order to assess the long-term water quality and the structural integrity of the Zarafshan River, the aquatic invertebrate fauna was analyzed at 29 sampling points within the Zarafshan catchment. This part of the study represents the first internationally published research of the macrozoobenthos as an ecological quality indicator in the transboundary Zarafshan catchment. During the last decades sporadic research has been conducted about the invertebrate fauna of Central Asia, but the main focus has been the fauna of the Aral Sea (Aladin and Potts 1992; Aladin et al. 1999; Andreev et al. 1992; Filippov 1997, 2001; Filippov and Riedel 2009) which is adapted to the lentic and saline environment of that lake and has thus no relevance for the aquatic communities populating the rivers and streams of the Aral Sea basin.

The macrozoobenthos communities in the Tajik part of the main river were characterized by very low population densities between 0 and 160 ind./m^2 (with an average of 60.0 ind./m^2) and a low taxa count (Fig. 16). This reflects the low mineralization of the river and an overall small productivity. The exception to this is the river section downstream of Aini, where most likely the urban waste water and the increased phosphate input leads to a proliferation of the aquatic fauna. As more nutrients are available algae and aquatic macrophytes are thriving which in turn provide a better livelihood for specific types of macroinvertebrate species (grazers, active and passive filter feeders). And as those are the food basis for predatory taxa the overall richness of the aquatic cenosis is increasing. The most prominent taxonomic orders in the Tajik part of the river are the *Ephemeroptera* (may flies) with 67 % of the total abundance, followed by the *Diptera* (flies and mosquitoes) with 30 %. The results for the Uzbek part of the river show an overall higher productivity (as is to be expected in a lowland river). The macrozoobenthos fauna is more diverse, but both the total abundance and the taxa count are subject to dynamic changes over the course of the river. The population density ranged between 16 and 1,280 ind./m^2 with an average abundance of 398.5 ind./m^2. Like in the Tajik part of the river the *Ephemeroptera* and the *Diptera* are the two dominant taxonomic orders. But in the Uzbek part they are complemented by the *Trichoptera* (caddies flies), *Crustacaea* (mostly *Gammarus* sp. and *Asellus aquaticus*) and to a smaller extend the *Acari* (acarian), *Gastropoda* (water snails) and *Heteroptera* (water bugs). The low abundances correspond very well with the areas of the riverbed dominated by clay as the primary microhabitat. Clay has a very limited hyporheic zone and is thus difficult to be colonized by the aquatic fauna (Groll 2011). The high abundances on the other hand are related to the inflow of urban waste water (increasing mineralization downstream of Samarkand, see Fig. 11) and drainage water from the irrigated fields (threshold excess of the mineralization, nitrate and phosphate concentrations downstream of Khatyrchi and Navoi).

The high nutrient load in the drainage water led to a colonization of the collectors which was ten times higher than that in the main river (Fig. 17). But as the diversity of the benthic fauna was not higher in the drainage water collectors, the high abundances detected there are the result of the mass occurrence of only a few species. The non-biting midge (*Chironomidae Gen* sp., *Diptera*) had a share of 48.1 % of the total abundance and the amphipod

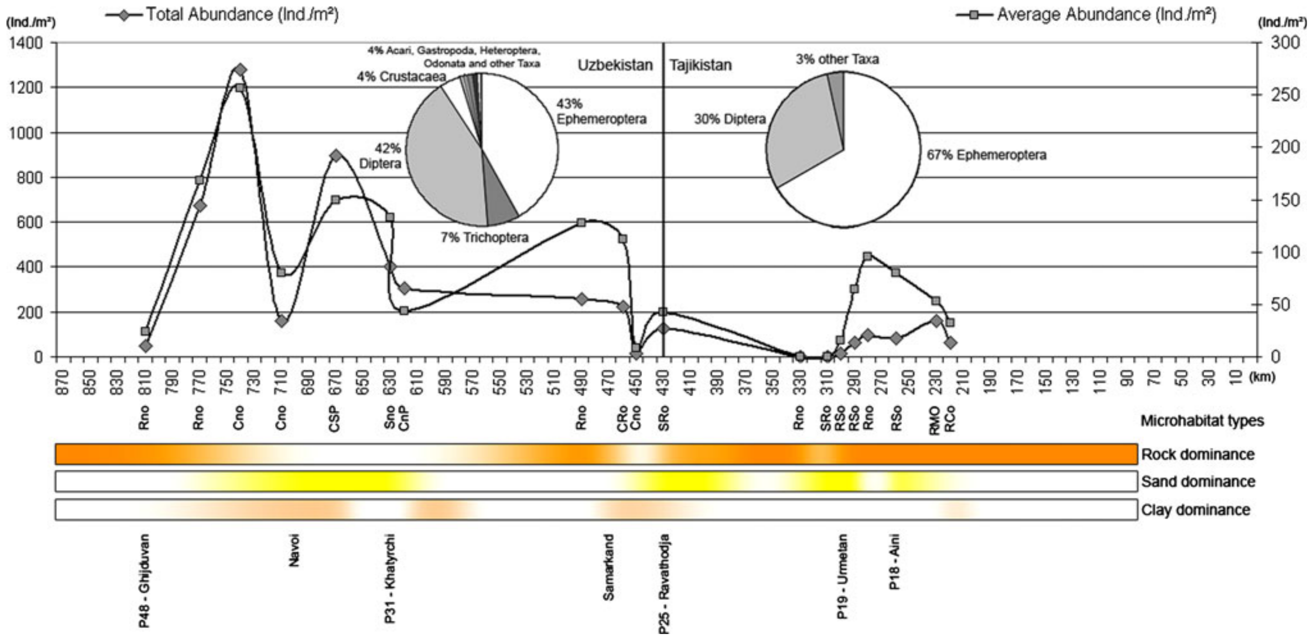


Fig. 16 Microhabitat distribution, total abundance of all taxa and average abundance per taxonomic order of the macrozoobenthos along the Zarafshan River

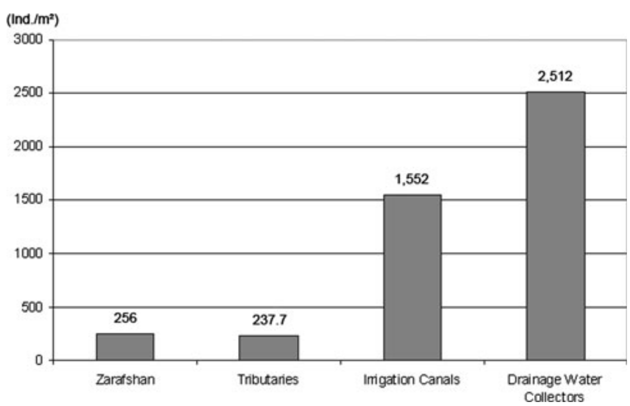


Fig. 17 Average abundance of the macrozoobenthos in different water body categories

Gammarus sp. (*Crustacaea*) had a share of 33.4 %. Both taxa are indicators for an impaired water quality (Groll 2011). A similar increase of the abundance was recorded in the irrigation canals, where these two taxa accounted for 79.4 % of the macrozoobenthos population. In the main river and the natural tributaries, the value of this metric was much lower (45.1 and 19.4 %), which indicates a better water quality and a more stable aquatic ecosystem.

Near the official end of the Zarafshan River the macrozoobenthos abundance declines dramatically. Over the course of 70 km the population density declined from 1,280 to 48 ind./m^2. The only species found at the last sampling point (P48) were *Chironomidae Gen* sp. and *Gammarus* sp. This is testament of the combined effects of the high pollution of the Zarafshan with nitrate, phosphate, chromate, copper and phenols and the reduced discharge which leads to an increase of the water temperature and a decrease of the oxygen concentration.

Overall these results present an interesting overview of the current state of the macroinvertebrate fauna. But in order to use this information as a monitoring tool, e.g., by assessing the ecological quality for different water bodies within the catchment, a more in-depth research setup has to be applied. Because of the complexity of the irrigation and drainage network a larger number of sampling points will be needed and the taxonomic determination has to be refined to allow the determination of all taxa down to the species level.

Outlook

The availability and the quality of the water resources in the Zarafshan catchment are both important issues, but in their combination they create a challenge which will be difficult to overcome. The enormous water extractions for irrigation purposes in the Uzbek part of the catchment result in a heavily modified discharge regime and a considerable lack of water in the downstream province of Navoi. The water demand of the catchment as a whole is 6.58 km^3/year already 32 % higher than the available resources (UNDP 2007). This water deficit will further increase as the global warming will lead to an accelerated glacier recession. During the first half of the twentieth century the Central Asian glaciers receded by 0.026–0.5 %

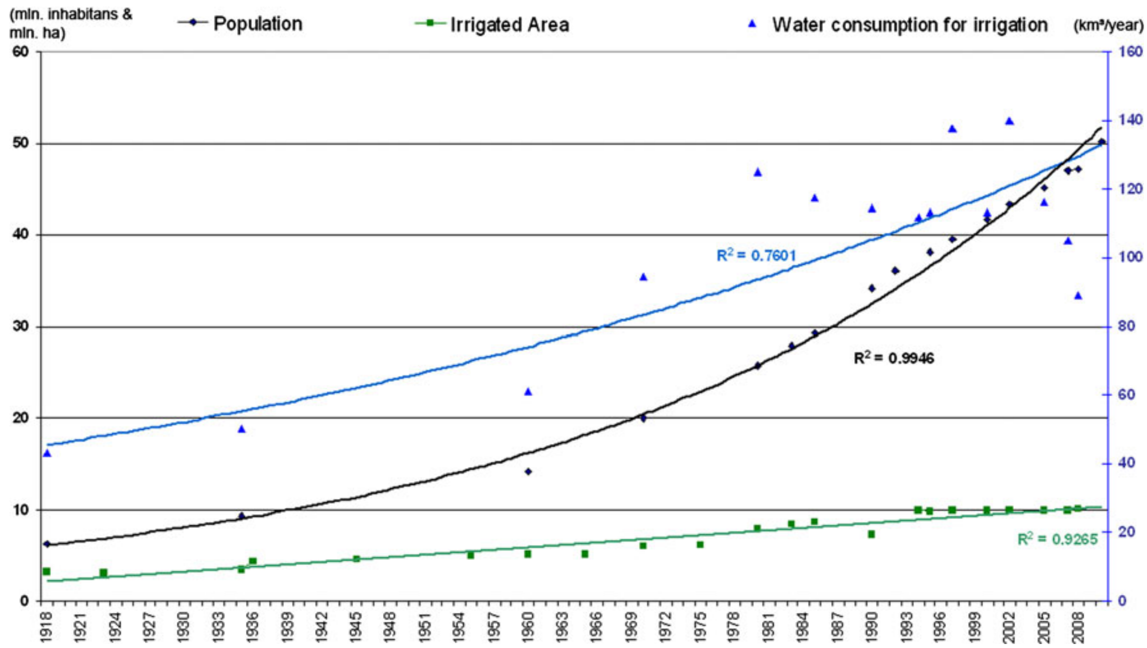


Fig. 18 Development of the population, the irrigated area and the water consumption for irrigation in the Aral Sea basin between 1918 and 2010 (data: Dukhovny and de Schutter 2011; http://www.unescap.org 2013; http://www.fao.org 2013)

per year. Between 1950 and 2000 the melting process accelerated considerably, resulting in recession rates between 0.14 and 1.0 % (Aizen et al. 2006; Chub 2002; Glazirin 2009; Hagg et al. 2007; Hoelzle and Wagner 2010; Homidov 2010; Konovalov and Agaltseva 2005; Normatov 2011, 2003; Perelet 2008; Yakovlev 2010). By 2030, the discharge of the Central Asian rivers will be 25–50 % lower than today and by 2050 all small glaciers (area <1 km^2) in the Zarafshan catchment will have vanished and based on the current annual recession rates of 0.25–0.33 % the Zarafshan glacier itself will by then be reduced to half of its present size (Agaltseva 2008; Dukhovny and de Schutter 2011; Spektorman and Petrova 2008; UZHYDROMET 2008). The demand for water on the other hand will equally increase during the next decades. The increase in the average air temperature (+2 °C in the Turan depression since the middle of the 20th century and an additional +2 °C until 2030) alone will lead to a higher water consumption (+5 % in 2030, +7–10 % in 2050 and +12–16 % in 2080) based on a longer vegetative period and higher evapotranspiration rates (Agaltseva 2004, 2008; Ibatullin et al. 2009). Another factor influencing the water consumption is the dynamic development of the Aral Sea basin. During the last 100 years, the population grew exponentially from 6.21 million in 1918 to 50.2 million in 2010 (Dukhovny and de Schutter 2011; http://www.unescap.org 2013, Fig. 18). During the same time the irrigated area increased from 3.2 million ha in 1918 to 10.1 million ha in 2010. As a result, the water consumption for irrigation purposes increased from 43.2 km^3/year in 1918 to 140 km^3/year in 2002.

During the next decades, the population and the economy will continue to grow (+1.7 % and +8 % per year) in the region and the planned expansion of the irrigated areas (in Uzbekistan +5–11 % until 2020) will increase the water demand by another 4.7–19 % in 2020 (Abdullaev et al. 2009; Dukhovny and de Schutter 2011; http://www.cia.gov 2013; http://www.indexmundi.com 2013; http://www.worldbank.org 2013). This combination of a reduced water availability (−30 % in 2030) and a higher demand (+30 % in 2030) will increase the total water deficit in Central Asia from 21.3 km^3/year to 92–120 km^3/year in 2030.

The development in the Zarafshan River catchment will follow this general trend—if not surpass it as the lower catchment is characterized by an intensity of the agricultural land use which is above average. Furthermore, there are detailed plans for the utilization of the water resources in the upper catchment for the generation of hydropower and for irrigation farming. The Tajik government has plans for 16 small- to medium-sized hydropower projects along the Iskandarya, Yagnob, Fondarya, Matcha and Zarafshan River (43 % of all planned hydropower projects within Tajikistan) with a total installed capacity of 2,300 MW. The largest projects (near Dupuli and Yagnob) could generate 200–250 MW while the three smallest ones are planned in a cascade near Penjikent with individual capacities of 45, 50 and 65 MW (MFA 2010; SCISPM

2007, 2008). If any or all of those projects will ever be implemented are uncertain as the upper catchment is difficult to develop due to a lack of reliable infrastructure and as the projects have to rely on foreign investors. But as hydropower is the most important resource in Tajikistan and the country still has to import energy from its neighbors (Desilets and Lambert 2011; MIE 2007; Musayeva et al. 2009; Nazirov 2002) it is sure to assume that until 2030 at least some of those projects will have been implemented. This will impact the discharge and sediment regime of the Zarafshan River, with difficult to predict ramifications for the downstream water users and the potential for a transnational water conflict. These conflicts would be intensified by the planned water diversion from the Zarafshan catchment into the Syr-Darya catchment which has been proposed by the Tajik government (MIWa 2006). In order to support and expand the irrigation farming in the Northern Sughd province, water from the Zarafshan could be transferred from Sangiston (upstream of Aini) through the Turkestan mountain range to Istaravshan (Ura-Tyube). This would reduce the discharge of the Zarafshan River, especially during the summer months and would lead to a further deterioration of the water quality in the lower catchment.

The results and their possible implications presented here have been discussed with several authorities both in Tajikistan and in Uzbekistan but the overall dataset is too limited for promoting a water resource management plan based on these findings. The main focus of the WAZA CARE project was, therefore, to prepare a larger transboundary research project which will allow a more holistic analysis of the water–food–energy nexus of the Zarafshan River catchment (see also Lioubimtseva in this issue).

Summary

The results presented here show that the problems related to the water sector in Central Asia as a whole and the Zarafshan River in particular are manifold and heavily intertwined. The availability of the water resources is influenced by a high natural discharge dynamic, anthropogenic water diversions and extractions as well as by the effects of the global climate change. The quality of the water resources is impaired by the water availability, unsustainable land use and inadequate/missing water purification techniques. For the Zarafshan catchment, the drainage water from the large-scale irrigation farming in the Samarkand and Navoi oasis is the main pollution source, but the industrial waste water from the Navoi special economic area, the impact of the mining industry in the Tajik part of the catchment and the soil erosion in the mountainous regions are also contributing to the overall pollution of the river. A widespread excess of thresholds for various pollutants was detected throughout the whole catchment. This alarming situation requires a fast and concise action plan and responding quickly is even more important in the face of the upcoming challenges caused by the changing climate and a reduced future water availability. These challenges can only be overcome through a true transnational cooperation and a transboundary, integrated water resource management (see also Janusz-Pawletta in this issue).

Each attempt of creating a sustainable resource management plan must be based on a detailed knowledge about the status quo and possible future scenarios. Unfortunately the data availability for the Zarafshan catchment (and for most parts of Central Asia) is inconsistent and fragmentary at best. Since the breakdown of the Soviet Union there is no official water monitoring program in the Tajik part of the catchment and the vast network of irrigation canals and drainage water collectors in the Uzbek part is hardly monitored at all. The research conducted for this study delivered the first transboundary water quality data for the Zarafshan River using the same methods on both sides of the border since the independence of the Central Asian countries and grants valuable insights in the longitudinal changes of the rivers characteristics. As a preparation for the challenges of the next decades such transboundary measurements not only have to be repeated but a long-term monitoring program has to be initiated so that scenarios and management plans can be based on reliable data. And finally, the improvement of the data base, the data availability, the data exchange and the international cooperation are essential prerequisites for the successful implementation of an integrated water resource management.

Acknowledgments The research presented here was conducted within the WAZA CARE initiative project (Water quality and quantity analyses in the transboundary Zarafshon River basin—Capacity building and Research for sustainability) funded by the German Federal Ministry of Education and Research (BMBF) and running from 2010 to 2011.

References

Abdolvand B, Winter K, Mirsaeedi-Gloßner S (this issue) The security dimension of water—insights from Central Asia. Environ Earth Sci

Abdullaev I, Kazbekov J, Manthritilake H, Jumaboev K (2009) Participatory water management at the main canal—a case from South Ferghana canal in Uzbekistan. Agric Water Manag 96:317–329

Agaltseva N (2004) Climate change impact on the mountains river runoff in the Central Asian region. In: Institut für Geoökologie (eds.) Landschaftsökologie und Umweltforschung 47. Extended abstracts of the international conference on hydrology of mountain environments berchtesgaden, pp 7–8

Agaltseva N (2008) Assessment of the river extreme runoff for climate scenarios conditions. Climate change effects, adaptation issues. NIGMI Bull 7:5–9

Aizen VB, Aizen EM, Joswiak DR, Fujita K, Takeuchi N, Nikitin SA (2006) Glacier changes in the central and northern Tien Shan during the last 140 years based on surface and remote-sensing data. Ann Glaciol 43:202–213

Akhmadov HM (2003) Soil and desertification processes in the Pamirs. Bielefelder Ökologische Beiträge 18:20–24

Aladin NV, Potts WTW (1992) Changes in the Aral Sea ecosystems during the period 1960–1990. Hydrobiologia 237:67–79

Aladin NV, Potts WTW, Plotnikov IS, Filippov AA, Orlova MI (1999) Recent changes in the hydrobiology of the Aral Sea. Chem Ecol 15(4):235–272

Andreev NI, Andreeva SI, Filippov AA, Aladin NV (1992) The fauna of the Aral Sea in 1989—the benthos. Int J Salt Lake Res 1:103–110

Aparin V, Kawabata Y, Ko S, Shiraishi K, Nagai M, Yamamoto M, Katayama Y (2006) Evaluation of geoecological status and anthropogenic impact on the Central Kyzylkum Desert (Uzbekistan). J Arid Land Stud 15:129–133

Au DWT, Yurchenko OV, Reunov AA (2003) Sulethal effects of phenol on spermatogenesis in sea urchins (*Anthocidaris crassispina*). Environ Res 93(1):92–98

Barbone L, Reva A, Zaidi S (2010) Tajikistan—key priorities for climate change adaptation. In: Worldbank policy research working paper, vol 5487, p 24

Bates B, Kundzewicz ZW, Wu S, Palutikof J (eds) (2008) Climate change and water. Technical paper. Intergovernmental panel on climate change, Geneva, p 10

Bichsel C (2011) Liquid challenges—contested water in Central Asia. Sustain Dev Law Policy 12(1):24–30, 58–60

Boonstra J, Hale J (2010) EU assistance to Central Asia—back to the drawing board. In: EUCAM Working Paper 8, pp 4–17

Breckle SW (2003) Einführung zum Symposium. Bielefelder Ökologische Beiträge 18:12–14

Cherkasov PA (1969) Katalog Lednikov SSSR 13. Tsentral'nyy i yuzhnyy Kazakhstan. Vypusk 2. Basseyn oz. Balkhash. Chast' 7. Reki Tentek, Rgayty. Gidrometeorologicheskoye Izdatel'stvo

Chub VE (2002) Exchange of hydrologic data and information among Aral Sea Basin States. In: ADB (eds) Cooperation in shared water resources in Central Asia—past experiences and future challenges, workshop proceedings, vol 26–28. Almaty, pp 97–99

Chub VE, Agaltseva N, Myagkov S (2002) Climate change impact on the rivers runoff for the Central Asian River

Costa M (1997) Toxicity and carcinogenicity of CR(VI) in animal models and humans. Crit Rev Toxicol 27(5):431–442

Crosa G, Stefani F, Bianchi C, Fumagalli A (2006) Water security in Uzbekistan—implication of return waters on the Amu Darya water quality. Environ Sci Pollut Res 13(1):37–42

Cruz RV, Harasawa H, Lal M, Wu S, Anokhin Y, Punsalmaa B, Honda Y, Jafari M, Li C, Huu Ninh N (2007) Asia. In: Climate change 2007—impacts, adaptation and vulnerability. Contribution of working Group II to the fourth assessment report of the intergovernmental panel on climate change, pp 469–506

Desilets B, Lambert M (2011) Beyond rogun—the Tajik hydropower sector. http://www.claretconsult.com

Djanibekov N, Frohberg K, Djanibekov U (2010) Income-based projections of water demand for food consumption in Central Asia—the case of Uzbekistan. In: Merz B, Dukhovny V, Unger-Shayesteh K (eds) Water in Central Asia, volume of abstracts, international scientific symposium, November 2010. Tashkent, p 87

Dukhovny VA (2002) Future issues related to long-term agreements between states in the Aral Sea Basin. In: ADB (eds) Cooperation in shared water resources in Central Asia—past experiences and future challenges. Workshop Proceedings, September 2002. Almaty, pp 100–116

Dukhovny VA, de Schutter JLG (eds) (2011) Water in Central Asia—past, present, future

Erikson RJ, Benoit DA, Mattson VR, Nelson HP, Leonard EN (1996) The effects of water chemistry on the toxicity of copper to Fathead Minnows. Environ Toxicol Chem 15(2):181–193

Eshchanov BR, Stultjes MGP, Salaev SK, Eshchanov RA (2011) Rogun Dam—path to energy independence or security threat? Sustainability 3(9):1573–1592

Fayzieva DK, Atabekov NS, Usmanov IA, Azizov AA, Steblyanko SN, Aslov S, Khamzina AS (2004) Hydrosphere and health of population in the Aral Sea Basin. In: Fayzieva DK (ed) Environmental health in Central Asia—the present and future, pp 51–100

Fedorov YA, Kulmatov RA, Rubinova F (1998) The Amudarya, in a water quality assessment the former Soviet Union. In: Kimstach V, Maybeck M, Baroudy E (eds) A water quality assessment the former Soviet Union, pp 413–445

Filippov AA (1997) Macrozoobenthos in the inshore zone of the Northern Aral Sea. Int J Salt Lake Res 5:315–327

Filippov AA (2001) Macrozoobenthos of the small Aral Sea. Russian J Mar Biol 27(6):401–403

Filippov AA, Riedel F (2009) The late Holocene mollusk fauna of the Aral Sea and its biogeographical and ecological interpretation. Limnologica 39(1):67–85

Froebrich J, Ikramova M, Razakov R (2006) Improved groundwater management strategies at the Amudarya River. In: NATO science series IV—earth and environmental sciences 70, groundwater and ecosystems, pp 153–165

Froebrich J, Bauer M, Ikramova M, Olsson O (2007) Water quantity and quality dynamics of the THC-Tuyamuyun hydro engineering complex—and implications for reservoir operation. Environ Sci Pollut Res 14(6):435–442

Gaetke LM, Chow CK (2003) Copper toxicity, oxidative stress, and antioxidant nutrients. Toxicology 189(1–2):147–163

Ghosh TK (1983) Effect of phenol pollution on aquatic life. Environ Ecol 1:1–3

Giuseppa C, Fabrisio S, Camilla B, Alessandro F (2006) Water Security in Uzbekistan—implication of return waters on the Amu-Darya water quality. Environ Sci Pollut Res 13(1):17–22

Glazirin G (2009) Hydrometeorological monitoring system in Uzbekistan. Assess Snow Glacier Water Resour Asia 8:65–83

Golubtsov V, Lineitseva A (2010) Receipt of water in the rivers of Northern slope of Jetisu Alatau because of glacier degradation. In: Merz B, Dukhovny V, Unger-Shayesteh K (eds) Water in Central Asia, volume of abstracts, international scientific symposium, November 2010. Tashkent, p 87

Green DJ, Bauer A (1998) The costs of transition in Central Asia. J Asian Econ 9(2):345–364

Groll M (2011) Beziehungen zwischen der Gewässermorphologie und dem Makrozoobenthos an renaturierten Abschnitten der Lahn. PhD-Thesis, Department of Geography, University of Marburg

Groll M, Opp C (2007) Gewässerbettmorphologie und Habitate in einem renaturierten Abschnitt der Lahn—Exemplarische Anwendung des TRiSHA-Verfahrens. Natur und Landschaftsplanung 39:369–376

Groll M, Opp C, Kulmatov R, Lewanzik M, Normatov I (2012) Transnational up-stream and downstream water resource analysis at the Zarafshan River with special consideration of land use and climate change influences. In: Bendig J, Butsch C, Gnyp M, Kretschmer H, Tilly N (eds) 32nd International geographical congress—book of abstracts, p 534

Groll M, Opp C, Aslanov I (2013) Spatial and temporal distribution of the dust deposition in Central Asia—results from a long term

monitoring program. Aeolian Res 9:49–62. doi:10.1016/j.aeolia.2012.08.002
Groth III E (1975) Fluoride pollution. Environ Sci Policy Sustain Dev 17(3):29–38
Hagg W, Braun LN, Kuhn M, Nesgaard TI (2007) Modelling of hydrological response to climate change in glacierized Central Asian catchments. J Hydrol 332(1–2):40–53
Hering D, Böhmer J, Haase P, Schaumburg J (2004) New methods for assessing freshwaters in Germany. In: Limnologica 34:281–282
Hoelzle M, Wagner S (2010) Glacier volume changes in the Panj and Vakhsh Basins—application of simple parameterizations to estimate past and future glacier change in the Panj and Vakhsh river basins and its comparisons to other mountain ranges. In: Merz B, Dukhovny V, Unger-Shayesteh K (eds) Water in Central Asia. volume of abstracts, international scientific symposium, November 2010. p 48
Homidov A (2010) Dynamics of glaciers and mountain lakes of Zarafshan river basin in changing climate. In: Presentation during the workshop “regional climate risk resilience—fostering resilience to remote geo-hazards”, June 2010
http://www.cia.gov (2013) The world Factbook. http://www.cia.gov/library/publications/the-world-factbook/. Accessed 12 Mar 2013
http://www.fao.org (2013) The FAO aquastat data base. http://www.fao.org/nr/water/aquastat/main/index.stm. Accessed 15 May 2013
http://www.indexmundi.com (2013) Worldwide statistical database. http://www.indexmundi.com/asia.html. Accessed 13 Mar 2013
http://www.meteo.infospace.ru (2013) Russia’s Weather Server – Weather Archive. http://www.meteo.infospace.ru/wcarch/html/e_sel_country.sht?cont=3. Accessed 08 Feb 2013
http://www.ncdc.noaa.gov (2013) The Global historical climate network database. http://www.ncdc.noaa.gov/oa/climate/ghcn-daily/. Accessed 12 Feb 2013
http://www.neespi.sr.unh.edu (2010) Meteorological and hydrological data for Central Asia. http://www.neespi.sr.unh.edu/stations/. Accessed 15 Jan 2013
http://www.sage.wisc.edu/riverdata (2010) The Global River Discharge Database. Center for Sustainability and the Global Environment, University of Wisconsin-Madison. http://www.sage.wisc.edu/riverdata. Accessed 15 Jan 2013
http://www.unescap.org (2013) Data centre of the economic and social commission for Asia and the Pacific. http://www.unescap.org/stat/data/. Accessed 20 May 2013
http://www.worldbank.org (2013) Statistical data about countries and economies. http://data.worldbank.org/country. Accessed 02 Apr 2013
Ibatullin S, Yasinsky V, Mironenkov A (2009) Impacts of climate change on water resources in Central Asia. Sector report of the Eurasian development bank
Ikramova I (2005) Water conservation issues in the lower reaches of the Amudarya River and the ecological crisis. In: Central Asian water resources vol 4. Dushanbe, pp 46–59
Janusz-Pawletta B (this issue) Current legal challenges to governance of transboundary water resources in Central Asia and joint management arrangements. Environ Earth Sci
Klugman J (1999) Financing and goverance of education in Central Asia. MOCT MOST Econ Policy Trans Econ 9:423–442
Konovalov VG, Agaltseva N (2005) Projected change of glaciers size and river runoff in the different scenarios of future climate. Exch Intellect Prop 4(8):37–47
Kordylewska A (1980) Effect of phenol on the cell structure of the embryos of *Limnea stagnalis* (*Gastropoda*, *Pulmonata*)—light microscopic and electron microscopic study. Acta Biol Cracoviensia Ser Zool 22:89–98
Kulmatov RA (1994) Laws of distribution and migration of toxic elements in river waters of the Aral Sea basin. Tashkent, p 135
Kulmatov RA, Hojamberdiev M (2010) Speciation analyses of heavy metals in the transboundary rivers of Aral Sea basin—Amudarya and Syrdarya rivers. J Environ Sci Eng 4:36–45
Kulmatov RA, Hoshimhodjaev M (1992) Spatial distribution and speciation of microelements in water of Zarafshon River. Water Resour 11:103–114
Kulmatov RA, Nasrulin AB (2006) Spatial-temporary distribution of polluting substances in Amu-Darya River. In: Water problems of arid territories, Tashkent, pp 20–30
Kutuzov S, Shahgedanova M (2009) Glacier retreat and climatic variability in the eastern Terskey-Alatoo, inner Tien Shan between the middle of the 19th century and beginning of the 21st century. Glob Planet Chang 69:59–70
Law AT, Yeo ME (1997) Toxicity of phenol on *Macrobrachium rosenbergii* (de Man) eggs, larvae, and post-larvae. Bull Environ Contam Toxicol 58(3):469–474
Lioubimtseva E (this issue) A multi-scale assessment of human vulnerability to climate change in the Aral Sea Basin. Environ Earth Sci
Lioubimtseva E, Henebry GM (2009) Climate and environmental change in arid Central Asia—impacts, vulnerability, and adaptations. J Arid Environ 73:963–977
Marat E (2008) Central Asian states fail to cooperate on water management. Central Asia Cauc Anal 10(18):19–20
Meier C, Haase P, Rolauffs P, Schindehütte K, Schöll F, Sundermann A, Hering D (2006) Methodisches Handbuch Fließgewässerbewertung—Handbuch zur Untersuchung und Bewertung von Fließgewässern auf der Basis des Makrozoobenthos vor dem Hintergrund der EG-Wasserrahmenrichtlinie—Stand Mai 2006
MFA—Ministry of Foreign Affairs of the Republic of Tajikistan (eds) (2010) Hydro energy potential in Tajikistan—present and future
MIE—Ministry for Industry and Energy of the Republic of Tajikistan (eds) (2007) Strategy for development of small scale hydropower of the Republic of Tajikistan. Report prepared for the UNDP
MIWa—Ministry of Irrigation and Water Management of the Republic of Tajikistan (eds) (2006) Water sector development strategy in Tajikistan. Report prepared fort he UNDP and the executive committee of the international fund for saving the Aral Sea
Musayeva RG, Rakhimov MZ, Akhrorova AD, Valiev DA, Khabibov BA (2009) Electricity governance in Tajikistan—applying the EGI indicator toolkit in Tajikistan. Preliminary report
Nazirov AA (2002) Development of the Water management system in Tajikistan. In: ADB (eds) Cooperation in shared water resources in Central Asia—past experiences and future challenges. Workshop Proceedings, September 2002. Almaty, pp 32–37
Normatov IS (2011) Monitoring of the modern state of the Zeravshan glaciers of the Tajikistan. In: Abstracts of 6th EARSeL Workshop “cryosphere, hydrology and climate interactions”
Normatov IS (ed) (2003) Water resources of the Republic of Tajikistan. Dushanbe
Novikov V, Rekacewicz P (2005) Water withdrawal and availability in the Aral Sea basin. Map based on data from the diagnostic report on water resources in Central Asia (ICWC 2000)
Olsson O, Gassmann M, Wegerich K, Bauer M (2010) Identification of the effective water availability from streamflows in the Zerafshan river basin, Central Asia. J Hydrol 390:190–197
Opp C (2007) Vom Aralsee zur Aralkum—Ursachen, Wirkungen und Folgen des Aralseesyndroms. In: Glaser R, Kremb K (eds) Asien (Reihe Planet Erde), pp 90–100
Opp C, Groll M (eds) (2009) Dust & sand storms and desertification. In: Proceeding of the Marburg international dust and sandstorm symposium. 29th September–3rd October. Marburg
Oud E (2002) The evolving context for hydropower development. Energy Policy 30:1215–1223

Patrick L (2003) Toxic metals and antioxidants—part 2—the role of antioxidants in arsenic and cadmium toxicity. Altern Med Rev 8(2):106–128

Perelet R (2008) Central Asia—background paper on climate change. In: UNDP human development report 2007/2008—fighting climate change—human solidarity in a divided world

Rakhmatullaev S, Marache A, Huneau F, Coustumer PL, Bakiev M, Motelica-Heino M (2011) Geostatistical approach for the assessment of the water reservoir capacity in arid regions—a case study of the Akdarya reservoir, Uzbekistan. Environ Earth Sci 63:447–460

RAS—Russian Academy of Sciences (eds) (1963) Atlas Uzbekskoj Sovetskoj Socialsticeskoj Respubliki (Atlas of Uzbekistan)

Saidov MS (2007) The remote monitoring of environment for disaster risk reduction in the territory of Tajikistan. J Environ Res Dev 2(2):258–263

Saiko T, Zonn IS (2000) Irrigation expansion and dynamics of desertification in the Circum-Aral region of Central Asia. Appl Geogr 20:349–367

Saito L, Fayzieva D, Rosen MR, Nishonov B, Lamers J, Chandra S (2010) Using stable isotopes, passive organic samplers and modeling to assess environmental security in Khorezm, Uzbekistan. In: NATO science for peace project no. 982159, final report, p 40

Sandin L, Sommerhäuser M, Stubauer I, Hering D, Johnson R (2000) Stream assessment methods, stream typology approaches and outlines of a European stream typology. In: AQEM—the development and testing of an integrated assessment system for the ecological quality of streams and rivers throughout Europe using benthic Macroinvertebrates—1st deliverable, August 2000

Sandin L, Hering D, Buffagni A, Lorenz A, Moog O, Rolauffs P, Stubauer I (2001) Experiences with different stream assessment methods and outlines of an integrated method for assessing streams using benthic macroinvertebrates. In: AQEM—the development and testing of an integrated assessment system for the ecological quality of streams and rivers throughout Europe using benthic macroinvertebrates—3rd deliverable, August 2001

Schickhoff U, Zemmrich A (2003) Assessing grazing land carrying capacity in West Mongolia/Altai Mountains—Basis for deriving strategies towards sustainable pastoral land use. Bielefelder Ökologische Beiträge 18:81–87

SCISPM—State Committee on Investment and State Property Management of the Republic of Tajikistan (eds) (2007) National development strategy of the Republic of Tajikistan for the Period to 2015

SCISPM—State Committee on Investment and State Property Management of the Republic of Tajikistan (eds) (2008) Power usage of Zeravshan the River

Scott J, Rosen MR, Saito L, Decker DL (2011) The influence of irrigation water on the hydrology and lake water budgets of two small arid-climate lakes in Khorezm, Uzbekistan. J Hydrol 410(1–2):114–125

Shanafield M, Rosen M, Saito L, Chandra S, Lamers J, Nishonov B (2010) Identification of nitrogen sources to four lakes in the agricultural region of Khorezm, Uzbekistan. Biogeochemistry 101:357–368

Shiklomanov IA (1999) World water resources and their use—a joint SHI/UNESCO product. http://www.webworld.unesco.org/water/ihp/db/shiklomanov. Accessed 13 Feb 2013

Skidmore JF, Tovell PWA (1972) Toxic effects of zinc sulphate on the gills of rainbow trout. Water Res 6(3):217–228

Spektorman T, Petrova E (2008) Application of the climatic indices for the assessment of Climate Change impact on the health of Uzbekistan population. Climate change effects, adaptation issues. NIGMI Bull 7:37–46

Sysenko VI (1973) Katalog lednikov SSSR, Vol. 14; Srednyaya Azia. Vypusk 1. Syrdar'ya. Chast' 4. Basseyny pravyk pritokov r. Naryna ot ust'ya r. Kyekyemerena do ust'ya r. Malogo Naryna. Gidrometeorologicheskoye Izdatel'stvo, Leningrad

Toderich KN, Tsukatani T, Mardonov BK (2002) Water quality, cropping and small ruminants—a challenge for the future agriculture in dry areas of Uzbekistan. In: Discussion paper no. 553. Kyoto Institute of Economic Research, Kyoto University, p 9

Toderich KN, Abbdusamatov M, Tsukatani T (2004) Water resources assessment, irrigation and agricultural developments in Tajikistan. In: Discussion paper no. 585. Kyoto Institute of Economic Research, Kyoto University, p 33

UNDAC (eds) (2006) Disaster response preparedness in Tajikistan. p 60

UNDP (eds) (2007) Technical report on the Zarafshon River Basin. UNDP project report

UNECE (eds) (2011) Second assessment of transboundary rivers, lakes and groundwaters. UN economic commission for Europe; convention on the protection and use of transboundary watercourses and international lakes, p 448

UZHYDROMET (eds) (2008) Second national communication of the Republic of Uzbekistan under the United Nations framework convention on climate change

Wegerich K, Olsson O, Froebrich J (2007) Reliving the past in a changed environment: hydropower ambitions, opportunities and constraints in Tajikistan. Energy Policy 35(7):3815–3825

Whitford GM (1990) The physiological and toxicological characteristics of fluoride. J Dent Res 69:539–549

WHO (eds) (1996) Total dissolved solids in drinking-water—background document for development of WHO guidelines for drinking-water quality. In: Guidelines for drinking-water quality, Health criteria and other supporting information, vol. 2. p 96

Wolfgramm B, Seiler B, Kneubühler M, Liniger H (2007) Spatial assessment of erosion and its impact on soil fertility in the Tajik Foothills. EARSeL Proc 6(1):12–25

Worldbank (eds) (2009) Adapting to climate change in Europe and Central Asia. p 116

Yafeng S, Chaohai L, Ersi K (2010) The glacier inventory of China. In: Annals of glaciology. International glaciological society vol 50(53). pp 1–4

Yakovlev A (2010) Estimation of current mountain glaciers of selected regions of Gissar–Alay and its changing during 45 years with use of ASTER images. In: Merz B, Dukhovny V, Unger-Shayesteh K (eds) (2010) Water in Central Asia. Volume of abstracts, international scientific symposium, November 2010. p 49